BE CIVIL ENGINEERING
PROJECT REPORT

GEO-PORTAL DEVELOPMENT OF LANDSLIDES AND SUSCEPTIBILITY MAPPING ALONG KARAKORAM HIGHWAY USING MULTI CRITERIA GEOSPATIAL ANALYSIS

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MILITARY COLLEGE OF ENGINEERING
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This to certify that the

BE Civil Engineering Project entitled

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Has been accepted towards the partial fulfillment of the requirements for

BE Civil Engineering Degree

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DEDICATION

Dedicated to our beloved Parents and Teachers, whose prayers and guidance have always been source of inspiration and motivation.

ACKNOWLEDGEMENT

All thanks and praise to Allah Almighty.

The research is the results of contributions of many people and various institutions. Our deepest and sincere gratitude goes to our respected teachers especially our advisor Dr. Sarfraz Ali and co-advisor Ms. Iqra Atif. The driving force behind the research was the encouragement, inspiration and valuable guidance given by the beloved advisors. Special Thanks to our parents for their prayers and never-ending love. To all those who contributed in way of this research your gentleness means a lot to us.

ABSTRACT

The China Pakistan Economic Corridor (CPEC) is important development in Pakistan and is starting from Khunjrab pass to Gawadar, Pakistan. The KKH is one of the most important part of CPEC and at the same time is very active interms of geohazards. Several geomechanichal challlanges are present along KKH which has to be take care of for success of CPEC as the KKH is known as the geological disaster museum owing to frequent natural disasters. With this in mind this project was conceptulaized with the objectives to (i) design and development of GIS based AHP model for landslide susceptibility mapping of KKH using geomorphological datasets; (ii) development of detailed field based landslide inventory database of past events occurred along KKH (from 2014 till 2018); and to design and development of comprehensive webGIS based landslide geoportal for mapping and visualization of potential risks and past landslide events along KKH. All the datasets including geology, seismic-tectonic, rainfall, elevation of the area were georeferenced and digitized with attribute information. A detailed field visit was conducted on KKH from Haripur to Sust (Khunjrab Pass) to map landslide events and collection of other datasets. Using advanced GIS and Remote sensing techniques spatial relationship between twelve causative factors (Elevation, slope, aspect, plane curvature, distance from drainage, rainfall, Stream Power Index SPI, topographical wetness index TWI, Strahler order network, Normalized Difference Vegetation Index NDVI, lithology, distance from faults) and past occurred landslides was developed. The results showed that about 16% of the study area fall in very high susceptible zone while 36% in high susceptible zone. Whereas 28% and 18% of the area along fall into moderate and low susceptible areas respectively. Analytical Hierarchy Process Model was proved to be very useful and its performance was evaluated using the relative operating curves (ROC) with 84% area under the curve with $p \leq 0.05$. Landslides inventory was prepared based on temporal, seasonal, volumetric and type of events. A comprehensive landslide geoportal was developed which along with other findings of the study will provide the identification of potential risks of landslides in the region and severs as the basis for engineers and decision makers for the safe future planning and sustainable development of the KKH.

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LIST OF ABBERIVATIONS

KKH	Karakoram Highway
CPEC	China Pakistan Economic Corridor
ASTER GDEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer
LANDSAT	Land Remote-Sensing Satellite (System)
Landsat ETM+	Landsat Enhance Thematic Mapper
RS	Remote Sensing
GIS	Geographical Information System
GPS	Global Positioning System
SPI	Stream Power Index
TWI	Topographical Power Index
NDVI	Normalized Difference Vegetation Index
FWO	Frontier Work Organization
GSP	Geological Survey of Pakistan
USGS	United State Geological Survey
GEOSS	Group on Earth Observations system of systems
REDD+	Reducing Emissions from Deforestation and Forest Degradation
ISRO	Indian Space Research Organization
ROC	Receiver Operating Characteristics
SPOT	Satellite for observation of Earth
IRS	Indian Remote Sensing
AHP	Analytical Hierarchy Process

WLC	Weighted Overlay Combination
SMCE	Spatial Multi criteria Evaluation Approach
TIFF	Tagged Image Format File
TRMM	Tropical Rainfall Measuring Mission
MKT	Main Karakoram Thrust
MMT	Main Mantle Thrust

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Landslides are natural and unpredictable phenomenon that constitutes natural hazards aﬀecting people from various perspectives including casualties, socio-economic loss and natural harm. Pakistan has been oftentimes subjected to assortment of regular dangers like earthquakes, floods, avalanches and landslides. In natural hazards landslides are at third in degree of devastation, damaging the northern areas of Pakistan frequently. Complex topography, complicated geology, glacial erosion, dynamic seismicity, quickened disintegration and high rainfalls make the Himalaya and Karakoram ranges more inclined towards landslides.

The Karakoram Highway is a 1300 km national thoroughfare that links Pakistan and china, starting from Hassan Abdal to the Kunjerab Pass. It passes through the Karakoram mountain range, at 36°51′00″N 75°25′40″E with an elevation of 4,714 meters (15,466 ft).The Karakoram highway traverses through the region having natural rock slopes, river terraces, debris covered slopes, alluvial fans, moraines, and debris-flow fans that's make the region more prone towards. The uncertain and reoccurring of landslides along KKH poses danger to the safety of inhabitants, travelers and damaging the highway at several places, massive landslide event observed at of Attabad in Hunza during January 2010. China Pakistan Economic Corridor CPEC has a high value for both countries; China and Pakistan, because of "One Belt One Road" initiative policy. Expansion of KKH is being carried out under the CPEC, but due to extreme geological complexities in the region, the potential threat posed by the natural hazards need to be addressed.

For the successful completion of CPEC, landslides hazard assessment along KKH is required. Geospatial innovations like the utilization of Remote Sensing (RS), Geographical Information System (GIS) and Global Positioning System (GPS) are valuable in the hazard evaluation, risk identification and disaster management for landslides. GIS based susceptibility mapping is one of the best technique for the landslides hazards analysis. The important perquisite for landslides risk investigation is landslides inventory. In order to get the landslides inventory there is a need to archive the extent of landslides events in a region, to know the pattern, types, distribution, frequency and statistics of past slope failures, that will help us to determine landslide associated risks, susceptibility hazards, and vulnerability along the KKH.

To attain the best outcomes of landslides information coupled with susceptibility mapping a platform is required through utilizing advance tools. Geoportals are best to utilize the effective use of geo-informatics and landslides information. An open source web-based geoportal easily accessible to everyone that will help engineers and decision makers to integrate, monitor and manage the landslides susceptible areas. This will also help in management and sharing of geo spatial information across border (China and Pakistan) for the mitigation of hazards and future developments along KKH.

1.2 PROBLEM STATEMENT

Landslides are natural disasters that are hard to model and simulate. Due to continuous mass movement in the northern areas of Pakistan, the frequency of landslide events is very high. Karakorum highway is the world highest-altitude cross-boundary highway, twisting along the Khunjerab, Hunza, Gilgit and the Indus River while passing through the Karakorum Mountains, and the Hindukush Mountains. For the success of CPEC expansion of Karakoram Highway (KKH) is pre-requisite, facing severe geo hazards challenges. Due to extremely complex geological conditions natural disasters like earthquakes, landslides, avalanches happen constantly. It is known as the “Geological Disaster Museum” due to the occurrence of frequent natural disasters. For the visualization and identification of landslide prone areas in a region, a web-based geo portal is required as a basis which can be only possible while having an inventory of past occurred landslide events, coupled with susceptibility mapping of the area.

1.3 CONCEPTUAL FRAMEWORK

The project was divided into three parts i.e. (1) landslides inventory database, (2) Susceptibility Mapping and (3) Geoportal development. The visit was conducted along whole KKH for the data collection of past occurred landslides including locations, latest imagery, geometry, GPS coordinates and more. Landslides susceptibility mapping of area will be done through using geo-informatics techniques Analytical Hierarchy Process(AHP). RS and GIS datasets were utilized to extract information about topography, hydrology, geology and landcover of the study area. Each parameter is divided into classes and rating from 1 to 9 will be assigned being 1 least susceptible and 9 most susceptible. Specialized web-based geoportal was developed to facilitate geospatial analyses that has the capability to visualize and download landslides information along KKH

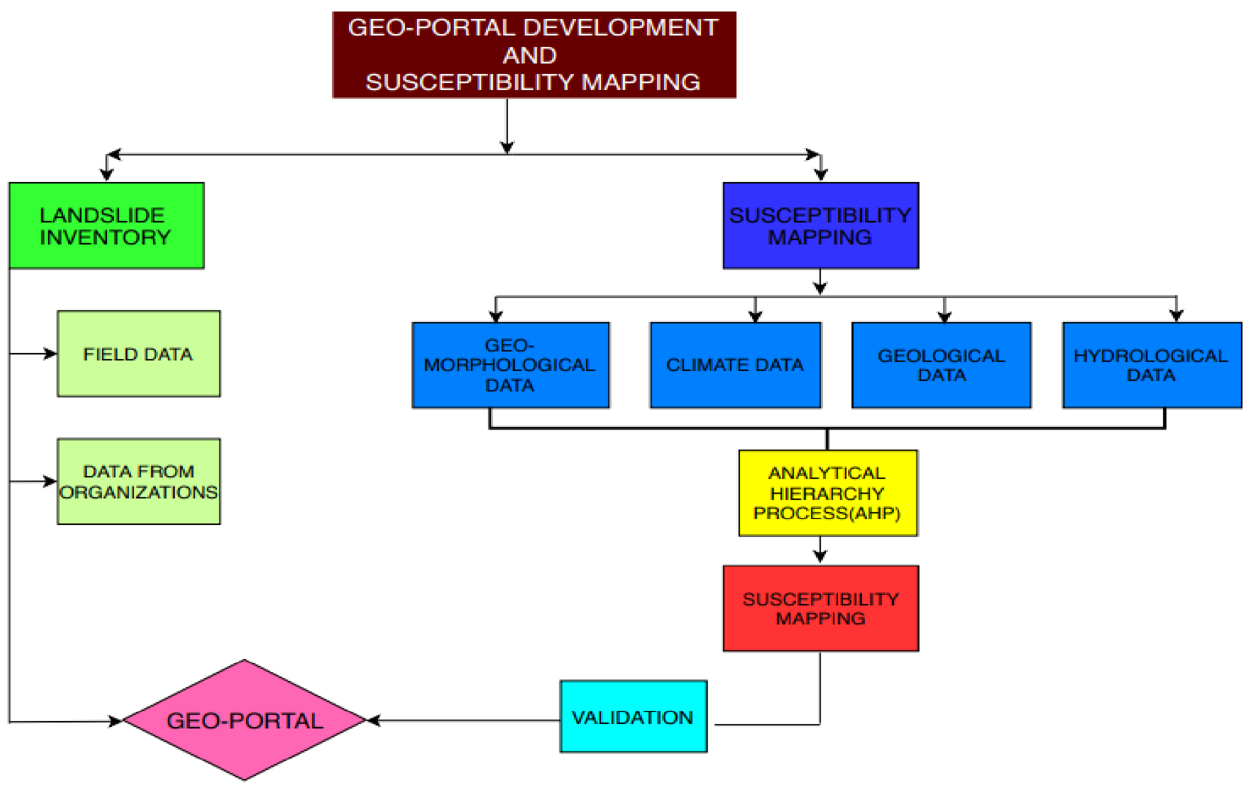

Fig 1.1 Conceptual Framework of research

1.4 SCOPE AND OBJECTIVES

The scope of the research is the identification of landslides potential risks along KKH using advanced geospatial techniques and development of geoportal of past events occurred in the region.

The objectives of this study are:

1. Development of landslide inventory database of past events occurred along KKH (from 2014 till 2018)
2. Landslide susceptibility mapping of mountainous terrain along KKH using geo-informatics techniques.
3. Development of geoportal for identification of potential risks and visualization of past landslide events along KKH.

1.5 RESEARCH QUESTIONS

1. Can a combined Remote sensing and GIS approach be used to create a landslide susceptibility map for selected region along KKH?
2. Can a combination of remote sensing and ancillary data be used to recognize conditions leading up to historical landslide events and their triggering mechanisms?
3. Why there is a need for the development of landslide inventory database?
4. What is the frequency, distribution and pattern of landslides along KKH?
5. What are the parameters required for the development of landslide inventory database?
6. How the KKH is influenced by landslides in past?
7. What is the geo-mechanical characteristics of the region along KKH?
8. What will be the limitations of developed geoportal and database?
9. What are the social implications of the landslides along the KKH?
10. How the geoportal is useful for the local communities and prosperity of CPEC?

1.6 SIGNIFICANCE

1. A landslide inventory pertaining to the KKH will be available for future reference.
2. Geo hazards information along the KKH will be available as an open source platform.
3. GIS based susceptibility mapping of landslide hazard can be used for early warning to the local communities about future disasters along KKH
4. This project will help in future developments along KKH through collaboration with China under CPEC.

1.7 CONCLUSION

This project will provide a tool for the identification, risk assessment and hazard evaluation of landslides susceptible areas along KKH. A way forward for the future sustainable development of the region and the flourishing to China Pakistan Economic Corridor.

LITERATURE REVIEW

The literature review was done to find out knowledge gaps in the research and to study the existing knowledge including substantive findings, as well as theoretical and methodological contributions towards the research. The flowchart for the literature review carried out at the research topic is shown in Figure 2.1

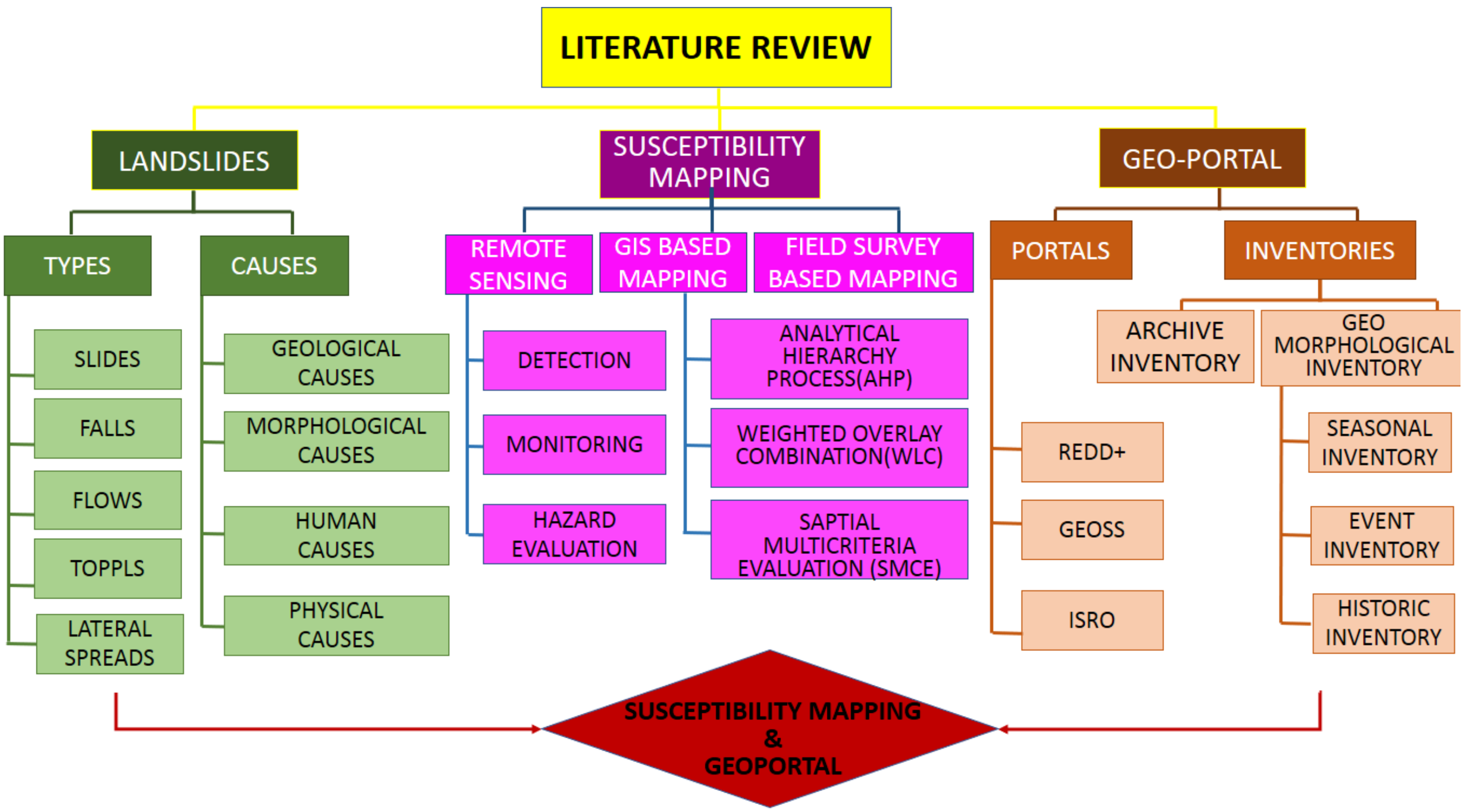

Figure 2.1 Literature Review flow chart

2.1 LANDSLIDES

Landslide is defined as "the outward and downward gravitational movement of earth material without the aid of running water as a transporting agent" (Crozier, 1986), or "the movement of a mass of rock, debris or earth down a slope" (Cruden, 1991).

Landslides have been classified based on certain factors as following:

1. Material (rock, soil, lithology, structure, geotechnical properties)
2. Geometry of landslide body (depth, length, width, volume)
3. Climate (temperate, precipitation, snowfall etc.)
4. Triggering mechanism (earthquake, rainfall etc.)
5. Geomorphic attributes (weathering, slope form, aspect)
6. Water (dry, wet, saturated)
7. Type of movement (flow, slide, falls topples.)
8. Speed of movement (very slow, slow, rapid.)

2.2 TYPES OF LANDSLIDES

Landslides are natural damaging most significant disasters in hilly terrains (Ayala et al.2006). Based on landslides types, they are further categorized into five as following:

2.2.1 SLIDES

Slide material is separate out from the stable underlying material due to the presence of weakness zone. Further divided into two parts

1) Rotational slides
2) Translational slides

2.2.2 FALLS

Detachment of boulders and rocks from steep slopes and cliffs due to abrupt movements. Separation happens along discontinuities like fractures, joints, and bedding planes.

2.2.3 TOPPLES

It is the forward rotation of mass about pivotal point, due to the forces exerted by adjacent materials or by cracked filled by fluids under the action of gravity.

2.2.4 FLOWS

Flows are further categorized into five basic types as mentioned below:

2.2.4.1 **Debris flow** The downslope rapid mass movement of loose soil, boulders, organic matter, water and air mobilize as slurry.

2.2.4.2 **Debris avalanche** Based on velocity, a very rapid to extremely rapid debris flows.

2.2.4.3 **Earthflow:** Formation of depression or bowl at the head when the lose material of slope liquifies and run out.

2.2.4.4 **Mudflow** The earthflow containing the wet material that can flow rapidly and that consist of minimum 50 percent silt, sand and clay particles.

2.2.4.5 **Creep** It is a downward slow and steady movement, of slopes formed of soil or rocks. Movements are due to shear stress that are enough to develop permanent deformations, but too small to produce shear failures. Creep is further divided into three types:

I. Seasonal
II. Continuous
III. Progressive

2.2.5 LATERAL SPREADS It is a spreading of soil mass combined with a facture mass into softer underlying material (Cruden and Varnes, 1992). Lateral spreads commonly occur on shallow slopes.

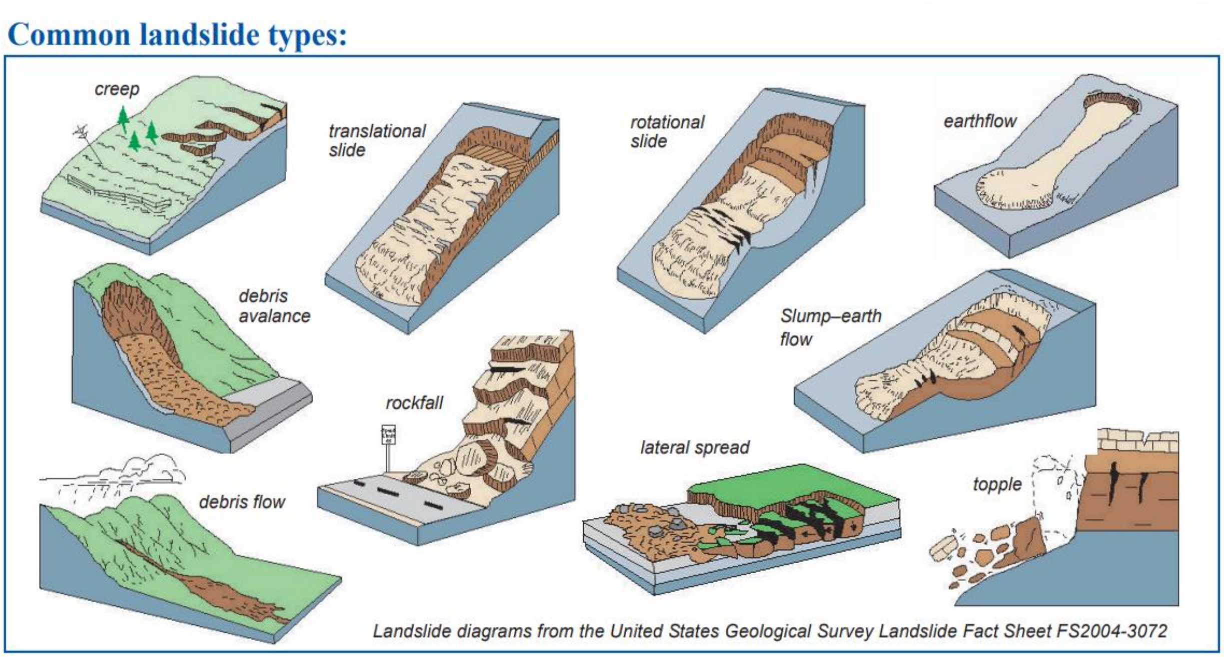

Figure 2.2 Shows The Common Landslides Types

2.3 LANDSLIDE CAUSES

2.3.1 GEOLOGICAL CAUSES

The geological causes are like: Weathered materials; Weak materials; Sheared materials; Sensitive materials; Adversely oriented structural discontinuities (fault, unconformity, contact, etc.); Jointed or fissured materials; Adversely oriented discontinuities (bedding, fault, unconformity, contact); Contrast in the stiffness (stiff, dense materials over plastic materials); Contrast in permeability; aspect of bed-rock; etc.

Mainly weathering, type of regolith material, unstable bedding, and the tectonic setting of the region influence the geological causes for the occurrence of landslides. There is a relationship between regolith materials and the slope instability it either may be strong or weak depending upon the material type. Weathering contributes major part in slope instability as it alters the mechanical and hydrological properties of materials (Maharaj, 1995; Yokota, Iwamatsu, 1999). Unstable bedding sequence get importance when the pore water pressure between the two layers (e.g. sandstone and claystone) is developed that triggers the mass movement. The strength of regolith material depends upon the past tectonic activity of region which evolves the factors like joints, factures and faults that become a source of slope instability which are considered for landslides risk assessment (Long, Khanh, 2008).

2.3.2 MORPHOLOGICAL CAUSES

The morphological causes are like: Tectonic or volcanic uplift; Erosion of lateral margins; Fluvial erosion of slope toe; Glacial rebound; Glacial erosion of slope toe; Subterranean erosion; Deposition loading slope or its crest; and Vegetation removal.

Slope shape, slope gradient, aspect and altitude of region impact the morphological causes for the events of landslides. The principle causative and the triggering factor of landslides is slope gradient (Long, 2008). Slope gradients are figure out from the digital elevation models of the regions and can be displayed spatially using GIS (O'Neill, Mark, 1987; Gao, 1993). Slope shapes are classified as divergent(convex), planar or straight, and convergent(concave). Convergent slopes concentrate the surface and sub surface water into small areas of slopes that increases the pore water pressure in and reduces the shear strength of soil that makes the slope more susceptible towards landslides (Hack, Goodlett, 1960; Dietrich, Dunne, 1978; Benda, Cundy, 1990). Hydrological processes like evapotranspiration that controls the weathering effects, vegetation and root development of the region are strongly influenced by slope aspect (Sidle, Ochiai, 2006). Altitude or elevation plays important role in the occurrence of landslides by linking with other factors like lithology, weathering, slope gradient, ground motion, precipitation, and land use.

2.3.3 HUMAN CAUSES

Human causes are such as: Excavation of slope or its toe; Construction of highways and railroads; Loading of slope or its crest; Rapid drawdown; Irrigation; Deforestation; Mining; Water leakage from utilities; Artificial vibration.

Human activities are directly or indirectly linked with landslides. Inappropriate cutting of slopes during construction of roads and railways, houses construction loading on the slopes, removal of vegetation/trees enhancing soil erosion and the vibrations due to explosives in underground mining are the common causes of slopes failures induced by humans. Based on official reports, on average 75 major landslides occur in Nepal that costs the country $130,000 annually are due to construction works (www.downtoearth.org.in). Same phenomenon is observed in the landslides of Bhutan (Karma Keunza, Yeshi Dorji, Dorji Wangda).

2.3.4 PHYSICAL CAUSES

Physical causes are such as: Intense rainfall; Prolonged precipitation; Rapid drawdown (of floods and tides); Thawing; Shrink-and-swell weathering; Volcanic eruption; Earthquake.

There are numerous manmade and natural factors that can trigger landslides but in general rain fall and earthquake are the considered as two major mechanisms (Keefer, 1984; Dai et al, 2002). On 8th October 2005 the landslide of Hattian Bala, Pakistan was triggered by earthquake which causes the devastation of three villages and thousand people were killed (Harp and Crone, 2006). Another study on landslides was carried out in the Umbria region of Italy, the triggering factor evaluated for the occurrence of landslides was intense rain fall and rapid snow melt (Guzzetti et al., 2006).

Karakoram highway is such a diverse scenario that's covers all the four major causal categories of landslides. Variety of materials including soft soils to stiff rocks are present along the highway. On higher altitudes glacial erosion is the main triggering factor of landslides. Road was blocked on several places during the earthquake of 8th October 2005 that shows how the region is physically susceptible towards landslides. Slopes are unstable on numerous points along the highway due to non-engineering cuts during the construction of highway.

2.4 GEOLOGY AND GEOMORPHOLOGY ALONG KKH

Natural hazards evaluation along KKH is very extensive and demanding task. Harsh environment, difficult terrain and the strategic location of highway makes it harder. Northern areas of Pakistan contain mountains that have highest peaks on planet. The region contains Himalayan Karakorum and Hindukush ranges. The mountains are typically covered with ice forming steep slopes with elevations greater than 8500m. The major drainage pathway is Indus river in the region.

The highway traverses through the major four geological terrains i) Karakoram Sedimentary Series (in the north), ii) Karakoram Batholith iii) Karakoram Metamorphic Complex iv) Chalt Green Schist Zone. Most of the highway length passes through approximately perpendicular to lithological and structural trends (SEARLE 1991). The Karakoram Sedimentary Series comprises of jointed and weathered Paleozoic and Mesozoic slates, dolomites and limestones. Due to cryogenic weathering steep cliffs surmount by long scree slopes are formed. The Karakoram Batholith contains granite and diorite. The Karakoram Metamorphic Complex includes schist marbles gneiss, pelite, phyllites, and amphibolite's, greenschist, and agglomerates.

From Hassanabdal to Thakot the geology is governed by alluvial deposits. These are in form of traces and flood plains deposits in the valley slopes and near the banks of major drainage areas. These deposits are interlayered with sandy gravel and are well developed in areas of Haripur, Abbotabd, Hassannabdal and Batagram. The presence of gravel and boulders with alluvial patches are also observed along the road. The formation of granite in Mansehra is the source of alluvial deposits in Batal area.

The topography Thakot to Gilgit is somehow rough and rugged but highway traverses through steep slopes as well. Variety of igneous and metamorphic rocks are present in the area due to high tectonic activities. Glaciation process played an essential role in the formation of Indus valley.

Geomorphic forms of region contain naturally formed rock slopes, debris-flow fans debris covered slopes, scree, alluvial fans, moraines, and river terraces. Natural rock slopes differ in form depending upon the discontinuity patterns and lithology. Slopes vary from 40^{o} from highly fractured to sub vertical slopes in un weathered massive igneous rocks. Debris and scree slopes are formed due to the accumulation of rock fragments (scree) and debris. Mechanical weathering is a source of scree formation whereas debris comes from glacial erosions and rock falls.

The slopes along KKH contains coarser pieces of intact rocks as highly permeable structures but the debris slopes have major portion of fine-grained materials the makes it low permeable. The coarser slopes are subject to the movement of boulders and rock falls whereas due to low permeability the debris slopes are more inclined towards debris flows. The slopes vary in heights, extents and slope angles depending upon the lithology and formation of strata of area.

Rainfall or snow melt are the main factors for debris flows. Debris flows mainly consists of material from silt to boulders, the slopes are usually of low angles ranges from 7^{o} -20^{o}. While the intact rocks when moves becomes a source of rock falls and the reason behind their movement is tectonic activity or the human activities like inappropriate cut along the road. The rock falls are more damaging along the highway many meters of the roads are washed away during the rock fall past events.

2.5 REOMTE SENSING TECHNIQUES FOR LANDSLIDES HAZARDS ASSESMENT

Remote sensing is defined as “the science of obtaining information about an object area, or phenomenon through the analysis of data acquired by a device that is not in direct contact with the object, area or phenomenon under investigation, except perhaps with energy emitted from the sensor''. It uses the relation of electromagnetic radiations and matter for the acquiring, processing and interpretation of data in the form of high resolution satellite imagery. Several satellites such as LANDSAT, SPOT, Geo Eye, IRS are used for the collection of multispectral, high resolution data. These satellite uses the remote sensors and the electromagnetic radiations emitted from the objects to obtain the data, this data is further pre-processed for better results in form of imagery. Preprocessing involves the radiometric and geometric corrections along with lineament extraction and image enhancement that produces better landcover maps. Landslides data like geo morphology and hydrology of area is determined through remote sensing, using this data with aerial photographs of various periods of area we can determine the cause, occurrence, extent and frequency of landslides.

We can detect, monitor and evaluate the hazards of landslides using remote sensing. Detection includes the recognition (is it a landslides) and classification (type of landslide) of landslides through using remote sensing imagery. Stereoscopic imagery is used for the clear view of mass movements and the features such as scraps, deviation in moisture content of soil, drainage pattern, vegetation and landcover. Monitoring means the comparison of landslides parameters such as speed of movement, areal extent, change in topography, and soil moisture content for the assessment of activity of landslides over the period. The monitoring of landslides can be done through various techniques using the landscapes and surface topography of area (Agostini et al 1991). Global positioning System (GPS) is widely used for the marking of landslides on the terrain which is used further of the monitoring moreover it can be done through using aerial photographs.

Hazard is the probability of happening of damaging phenomenon in a given area with in a specific time (Varnas, 1984). The ideal hazard map of landslides shows the temporal and spatial probability, magnitude, type, rate of movement of landslides in a certain area (Hartlen and Virbeg 1988). Site investigation techniques consumes lot of efforts, cost and time dependent therefore not beneficial for the hazards mapping. It also requires extensive field data to make the process decision making. To tackle these approaches, remote sensing advance tools are used of the hazards mapping that consumes less resources and time while the results are also decision making.

2.6 LANDSLIDES SUSCEPTIBILITY MAPPING

Landslides are the natural destructive processes that causes the destruction of roads, houses bridges and may lead to loss of life. To identify the potential risks associated with landslides there is a need of landslides susceptibility mapping. The first step for the susceptibility mapping is landslides inventory. The second step is the generation of landslides susceptible maps. There are two different approaches for the landslides hazards mapping

1. Field Survey based Landslides Hazard Mapping
2. GIS based Landslides Hazard Mapping

2.6.1 FIELD SURVEY BASED LANDSLDIES HAZARDS MAPPING

This method is appropriate for the small study areas. It’s a conventional method for mapping involves uncertainties during the marking of landslides like may be the size of landslide is that large to be seen completely in the field, investigator often can’t see all parts of landslides or the past landslides were covered by forests or human actions. This method is not suitable for extensive study areas as it consumes more time for the identification of landslides in field. Not much details can be provided on these maps. The validation of these maps become also problematic.

2.6.2 GIS BASED LANDSLIDES HAZARD MAPPING

Geographic Information Systems (GIS), is a computer-based system for data capture, input, manipulation, transformation, visualization, combination, query, analysis, modeling and output, with its excellent spatial data processing capacity, has attracted great attention in natural disaster assessment (Carrara, 1983).

GIS uses three major methods for the landslides hazards mapping

1. Analytical Hierarchy Process(AHP)
2. Weighted Overlay Combination(WLC)
3. Spatial Multi criteria Evaluation Approach(SMCE)

2.6.2.1 Analytical Hierarchy Process(AHP)

AHP is a best GIS based tool for the analysis of complex problems mainly of site selections, urban arrangement, and landslides vulnerability assessment. In this method a hierarchic order and numerical values are given to different factors and are arranged based on relative importance. These factors are analyzed, and every factor is assigned according to its importance. The weight of every factor taken from matrix weighting factor is multiplied by its weight class. High local representation by the factors are used as the results of susceptibility mapping. The representations are based on multiple parameters including man-made features (roads and other engineering structures), natural (distance to faults and lithology), causal (aspect, slope) and triggering (seismicity, precipitation) factors.

2.6.2.1 Weighted Overlay Combination(WLC)

(WLC) is derived from both qualitative and quantitative approaches. This is a popular method which is used in different GIS and is best adoptable for flexible comparison and combination of different maps. Two types of weights are used a) Primary level weights b) Secondary level weights. The primary level weights are rule based in which the ratings are given to every class of the parameter is dependent on separate criteria. In this method, the density of landslides is a ratio between area of pixels of landslide present inside a category of a pertaining factor divided by total area of that pertaining category. Then the results of the criterion are transformed into percentages. The secondary level determines the degree of interchange of one parameter versus the other parameter based upon opinion. Primary and secondary parameters weights are incorporate to evaluate landslide susceptibility in the area.

2.6.2.2 Spatial Multi criteria Evaluation Approach(SMCE)

Spatial multi-criteria evaluation (SMCE) application allows to perform multi-criteria evaluation in spatial mode. In SMCE, the alternatives are locations in the form of points, lines, areas, and grid cells. The outputs are in the form of maps. It converts both spatial and non-spatial inputs based on the multi criteria evaluation (MCE) and spatial GIS analysis for the generation of output decisions.

The output of SMCE shows the extent up to which criteria are met or not in various areas, results are displayed in form of composite index maps that makes the process more decision making.

The theoretical background of SMCE uses the method of multi-criteria evaluation of AHP. Map generation, standardization, tree analysis, weighting are the different steps for the processing of SMCE. To standardize the criteria, criteria tree is generated with the help of related maps and attribute tables and all other related criteria. SMCE use Boolean, numerical and qualitative methods to standardize the input maps. The methods have the capability to standardize the maps of different units like some map units are in percentages some are in meters, and units of classes in land cover maps.

For landslides hazard mapping we have used SMCE method and different parameters such as slope, aspect, drainage network, flow direction, Strahler network, TWI, SPI, Landcover and rainfall data are for the evaluation of landslides susceptible areas along KKH.

2.7 LANDSLIDES INVENTORY MAPPING

Landslides inventories are further classified based on types of mapping as following:

2.7.1 Archive inventory

Based on the information from literature review or other archive references.

2.7.2 Geomorphological inventories

The geomorphological inventory has the cumulative effects of past occurred landslides events of the region. These inventories are further classified as seasonal, event, historical or multi-temporal inventories.

2.7.2.1 Historical inventory

Based on the age of landslides or in relative terms. Like recently occurred, very old or old. The landslides inventory of Susa Valley, Italy is based on the past events of landslides in the region (Nora Tassetti, Annamaria Bernardini, Eva Savina Malinverni, 2008). This inventory shows the past landslides data on the bases on landslides types.

2.7.2.2 Event inventory

Based on the triggering factor of landslides like earthquake, snow melt, erosion, rainfall. The event inventory also relates the date of occurrence of landslides along with the triggering factor.

2.7.2.3 Seasonal inventory

The landslides occurred in a specific season by single or multiple triggering factors. Multi temporal inventories shows the landslides triggered by different events in over a long time. In multi-temporal and seasonal inventories maps are compile based on landslides date of triggering, date of imagery and the field survey. Indian Space Research Organization geoportal on landslides shows the landslides information of different region on seasonal bases.

To visualize and understand the pattern of landslides along KKH, seasonal and event-based inventories will be made. These inventories will show the frequency, volume and the triggering factor of landslides that will help the user to better analyze the dynamics of landslides along the highway.

2.8 GEOPORTAL

Geoportal is a website having an entry point that display the geographic information on web or a web site where spatial and geographic information can be discovered (Tait, 2005).

Geoportals are used by geographic information users, including commercial sources and government agencies to publish descriptions like geospatial metadata of their geographic information. Geoportals are also used by geographic information consumers, professionals and decision makers to search and access the information they require. In this manner geoportals serve an inexorably vital part in the sharing of geographic data and can keep away from copied endeavors, irregularities, postponements, inconsistencies, and wasted resources.

Several countries have developed certain geoportals that provides ease in search to user for what they are looking for. Like Group on Earth Observations System of Systems (GEOSS) portal allows the users to search for any aspect about earth. This portal provides the information in form of satellite imagery/maps and the details in downloadable form as well (http://www.geoportal.org/)

Likewise, Siri lanka has also made geoportal for the forest monitoring system named as Reducing Emissions from Deforestation and forest Degradation (REDD+). This geoportal allows the user to search for specific contents that are available on the user interface of portal (http://www.nfms.lk/)

More specifically Indian Space Research Organization has developed a geoportal on landslides which is studied for the development of karakoram highway landslides geoportal (http://bhuvan-noeda.nrsc.gov.in/disaster/disaster/disaster.php?id=landslide).

Geoportal is a source of visualizing landslides hazards maps that includes the past events as well as the susceptible maps. Multiple techniques based on the study area, satellite imagery, available data, the scale, the purpose of inventory and the skills of investigator are used for the mapping (Guzzetti et al, 2000; Westen et al, 2006).

For safe future development and success of CPEC there is a need to know about the natural disasters along the KKH. Landslides are the most devastating phenomenon observed damaging the highway in recent years. To overcome and better understand this issue a web-based geoportal is best solution. The geoportal will provide information about the past occurred landslides events and mark the susceptible areas along the highway using advance Remote Sensing and GIS techniques. Through using geoportal user will know and analyze the vulnerability of landslides in form of multiple parameters like recent imagery/satellite imagery, date of occurrence of event, type of event etc. In a nutshell geo-portal will provide central GIS framework to accomplish the overall research objectives and will facilitate the management, integration and analysis dissemination of qualitative and quantitative data of landslides along KKH.

2.9 Knowledge Gaps

1. Why there is a need for the development of landslide inventory database?
2. What is the frequency, distribution and pattern of landslides along KKH?
3. How the geoportal is useful for the local communities and prosperity of CPEC?

These are the knowledge gaps based on which detailed study was carried out to know the dynamics of the study area. Landslides inventory was developed on event, seasonal and volumetric bases to know the frequency, distribution and pattern of landslides in the region. This will help us to know the response of different areas under different conditions like weak geology, high seismicity etc.

Developed geoportal will sever as the planning and mitigation of vulnerable areas of the region. Research based on multiple contributing factors towards landslides will be available as an open source from where decision makers and engineers can plan the safe future development strategies.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 STUDY AREA

The study is along 840 km Karakoram Highway(KKH), N35 passing through the mountainous terrain of karakoram and Hindukush ranges. Karakoram Highway is the world highest altitude cross country road where the study having minimum elevation of 342m to 7669m over a horizontal extent of 15km on both sides of road. The highway starts from Hassan Abadal passing through Mansehra, Pattan, Chilas, Gilgit, Hunza Valley and ends at Kunjerab pass with highest elevation 4,714m at 36°51′00″N to 75°25′40″E. Total study area coverage is 21142 Km^2, most of which is natural terrain mainly formed of mountains and glaciers. The highway is situated in seismic zones 2B,3,4 with peak ground accelerations of 0.16 to 0.24g, 0.24 to 0.32g, >.32g respectively. Major fault lines encountered by study area are Main Karakoram Trust (MKT) and the Main Mantle Thrust (MMT). The study area exhibits high climate variability having an average rainfall of 150mm to 1500mm/year and the temperature fluctuates between -10^o C to 46^o C with snow covered mountains all over the year. The region contains naturally formed debris-flow fans, debris covered slopes, rock slopes, alluvial fans, scree, moraines and, river terraces. Slope angles for rock formations vary from 40^o in highly fractured slates to sub vertical slopes depending upon the discontinuity patterns and lithology while debris flows consist of material from silt to boulders with slopes of low angles ranges from 7^o to 20^o. Major drainage paths are Gilgit and Hunza rivers that fall into the main tributary of Indus river. Minapin, Passu, Ghulkin, Gulmit, Batura and Khunjerab are the major glaciers along the highway.The complex geological setting, high seismicity along with complicate climate makes the study area more susceptible towards landslides. Fig. 3.1 shows the study area along the karakoram highway with marked past occurred landslides.

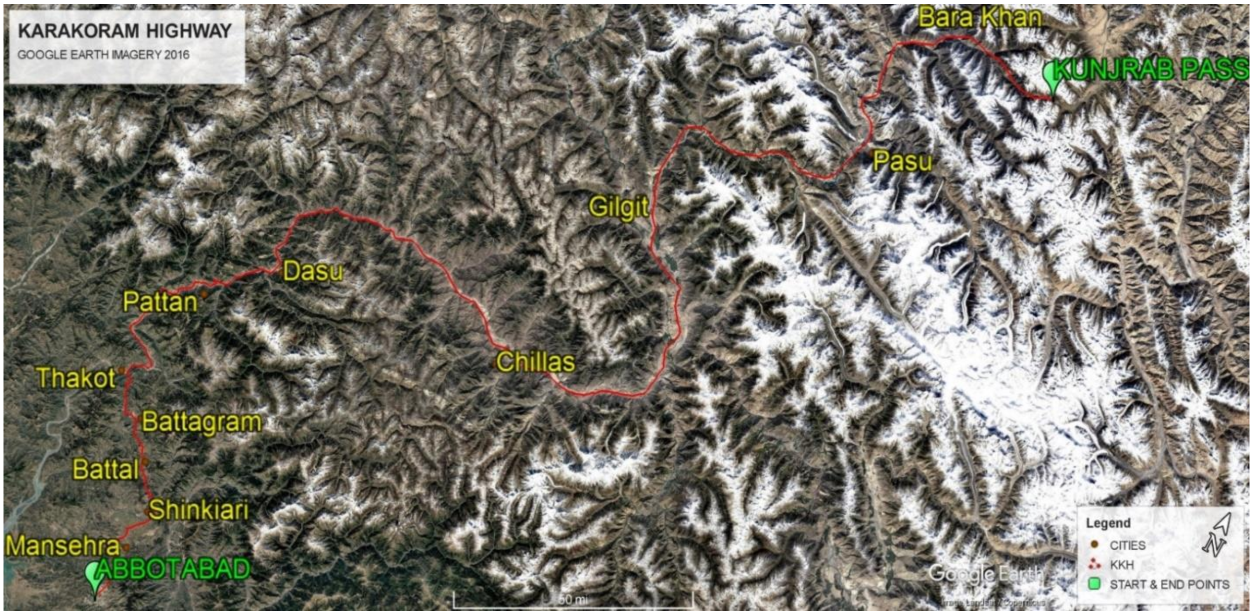

Fig 3.1 Study area Map

3.2 DATA UTILIZATION

For the susceptibility mapping and future prediction of landslides, the data layers of environmental factors that affect the landslides occurrence can be utilized (Cees J. van Westen, Castellanos, and Kuriakose 2008). There are no principle international standards for the selection of these parameters (Ali Yalcin 2008). Based on literature review, previous knowledge about landslides and the data availability, 12 factors are selected for the assessment of landslides. Data type, source of factors, processing method and description of the data set is summarized in the following Table 3.1

CAUSATIVE FACTORS		DATA		
		TYPE	RESOLUTION	SOURCE
TOPOGRAPHY	Elevation	ASTER GDEM	30m GRID	USGS
	Slope			
	Aspect			
	Plane Curvature			
HYDROLOGY	Drainage Network	Satellite Based TRMM	10m GRID	USGS
	Rainfall			
	Stream Power Index (SPI)			
	Topographical Wetness Index(TWI)			
	Strahler Order Network			
LANDCOVER	NDVI	LANDSAT 8 Image	30m GRID	USGS
GEOLOGY	Lithology	Geological Map	scale 1:250,000 Polygon	GSP
	Fault Lines	Seismotectonic Map	TIFF	

Table 3.1 Causative factors of landslides

3.2.1 TOPOGRAPHY

3.2.1.1 Elevation

Advanced Space-borne Thermal Emission and Reflected Radiometer (ASTER) Global Digital Elevation Model (GDEM) dataset was utilized with the spatial resolution of 30m. Digital elevation model is used to extract the elevations of study area and 3D visualization of terrain using ArcGIS 10.3.1 software. For accuracy of dataset, DEM was further pre-processed to identify the sinks and then fill operation was applied that help to remove the errors for terrain-based analysis. ArcGIS Ver 10.3.1 was used of the purpose. The study area shows the minimum elevation of 342m and highest of 7669m.

Fig 3.2 Digital Elevation Model of study area

3.2.1.2 Slope

Slope is an important factor for the evaluation of landslides occurrence. Areas with higher slope angles are more susceptible to landslides as compare to gentle slopes. Usually the areas with low slope angles have less shear stress as compared to high slopes or vice versa. Study area map shows the slope angles varying from 0^o to 89.4226^o. 30m resolution digital elevation model with first derivative of elevation gives the slope. From the study area it is observed that more than 40% of the area have slopes greater than 30^o.

Fig 3.3 Slope map of study area

3.2.1.3 Aspect

Slope stability is greatly affected by metrological factors such as pattern of rainfalls, direction of sunshine and the morphological formation of region as well (Mohammadi 2008). Stability of slopes depends on saturation and rate of infiltration in terms of pore water pressure, slopes receiving more rainfall saturates faster however infiltration is controlled by certain factors like soil type, porosity, organic content, permeability etc.

Studies shows that direction of seasonal monsoon rainfall is south west to south east that effects the slopes confronting south to north west (Rashid 2004; Ahmed et al. 2014). This shows that slopes confronting northwest and southwest are more vulnerable towards landslides. Aspect map of study area shows higher values of southwest and northwest which makes the region more vulnerable to landslides. In ArcGIS software, aspect is classified according to the angles, i.e. Flat (-1), North (0°-22.5°, 337.5°-260°), Northeast (22.5°-67.5°), East (67.5°-112.5°), Southeast (112.5°-157.5°), South (157.5°-202.5°), Southwest (202.5°-247.5°), West (247.5°-292.5°) and Northwest (292.5°-337.5°). Fig 3.4 shows the distribution matrix of aspect used in ArcGIS.

Fig. 3.4 Shows Aspect values

Fig. 3.5 Shows Aspect values

3.2.1.4 Plane Curvature

Curvature is the rate of change of slope over the entire area. The study area shows the curvature values from -1183.11 to 1183.11 which are further classified in terms of concave and convex slopes. After precipitation concave slopes have more ability to retain the water for longer time that increases the chances of landslides. The erosion of slopes also depends on the convergence and divergence pattern of water flow, that makes the parameter important for the study of landslides. The concavity, convexity and the flat surfaces are shown in Fig 3.6 exhibiting positive values for concave curvature slopes and positive for negative curvature.

Fig 3.6 Plane Curvature map of study area

3.2.2 HYDROLOGY

3.2.2.1 Drainage Network:

ASTER GDEM with 30m spatial resolution using HMS module was used for the extraction of drainage. Drainage path causes the material saturation and erosion of lower parts of slopes that adversely effects the stability of slopes (Gokceoglu and Aksoy 1996). Study areas contain three minor drainage paths Gilgit, Hunza and the khunjerab Rivers that falls into the major stream of Indus River. Mountains are covered with snow all over the year, in summer the melting of glaciers causes the glacial erosion and high-water flow making the region more susceptible towards landslides.

Fig 3.7 Drainage pattern map of study area

3.2.2.2 Rainfall

Tropical Rainfall Measuring Mission (TRMM) is a combined mission of the American space agency NASA and the Japanese counterpart JAXA. The rainfall data of study is extracted through TRMM. The map generated through the TRMM data shows the average rainfall of 155mm to 1080mm/year of the study area. Rainfall contributes the instability of slopes by increasing the crest loading due to the penetration of water into slopes. Water presence in the soils/rocks causes the increase in pore water pressure due to which shear strength reduces and become a source for slope failures. In study area although the precipitation rate is low at higher elevation, but rainfall is the contributing factor for the slopes instability.

Fig 3.8 Rainfall map of study area

3.4.2.3 Stream Power Index (SPI)

SPI is the erosive power effect of water that plays important role in the stability of area. High SPI represent, rough steep and straight slopes while lower SPI values shows the floodplains and alluvial flats. The water coming from low slope areas and velocity of water flow increases as catchment area and gradient of area increases making the SPI higher in that area (Moore et al. 1991). SPI is defined as

$$SPI = CAtan\beta$$

CA represents the specific catchment area in m^2 whereas β is the value of slope gradient in degrees (Poudyal et al. 2010). The SPI values of study area vary from -13.8155 to 16.5285 that is further classified into three groups Low, Moderate, High with values ranges from -13.8 to -4.1, -4.17 to 1.41 and 1.41 to 16.5 respectively.

Fig 3.9 Stream Power index map of study area

3.4.2.4 Topographic Wetness Index (TWI)

Landslides occurrence is largely related to hydrological factors. The influence of those factors is determined by the Topographic Wetness Index (TWI). TWI is the logarithmic ratio of the local upslope area draining through a certain point per contour length (α) to the tangent of the local slope of the area (tanβ). TWI is defined as

$$TWI = \ln(\frac{\alpha}{tan\beta})$$

TWI is directly related to catchment area and the slope, it increases as the slope angle decreases and catchment area increases (Hengl & Reuter 2008). TWI ranges from 2.9 to 26.8 which is further classified into High, Moderate, Low with values range 2.9 to 4.8, 4.8

to 8.86 and 8.86 to 26.8 respectively. The areas with high TWI are more susceptible towards landslides (Lee & Min 2001; Gorsevski et al. 2006; Hengl & Reuter 2008)

Fig 3.10 Topographical wetness index map of study area.

3.4.2.5 Strahler Order Network

Strahler order network gives the formation of main drainage path originating from the small tributaries. Strahler order is a technique for assigning the numeric values to the stream network. This order help to identify and classify the different types of steams based on their tributaries. Numeric value 1 refers to first tributary and as the number increases the streams of same order intersect. The study area is assigned from 1 to 6 showing the emergence of small tributaries to the main drainage path respectively.

Fig 3.11 Strahler order network of study area

3.2.3 LANDCOVER

3.2.3.1 Normalized Difference Vegetation Index (NDVI)

Vegetation cover provides root retaining strength and ability to control rainfall runoff movement gives both mechanical and hydrological factors that are beneficial for slope stability. Conversely fallow areas and barren lands are the factors for slopes destabilization (Chauhan et al. 2010). Landsat 8 multi-spectral imagery with the spatial resolution of 30m used to extract the vegetation cover. ERDAS IMAGINE software to process the imagery for layer stacking and mosaicking. NDVI was calculated using formula

$$NDVI = \frac{NIR - RED}{NIR + RED} = \frac{ETM + \ BAND\ 4 - ETM + BAND\ 3}{ETM + BAND\ 4 + ETM + \ BAND\ 3}$$

Values of NDVI ranges from -1 to 1, values from -1 to 0 are the barren lands, rocks while the values from 0 onwards show the vegetation that become dense at value of 1.

Fig 3.12 Normalized Difference Vegetation Index map of study area

3.2.4 GEOLOGY

3.2.4.1 Lithology

It is broadly recognized that lithology applies major control on landforms (C. F. Lee et al. 2001). It plays an important role in slope stability analysis and correlates material properties forming the slope like rock mass strength (S. B. Bai et al. 2014). Hard copy of geological map of scale 1:250,000 was obtained from Geological Survey of Pakistan.

Fig 3.13 Geological map Islamabad to Chilas section

Fig 3.14 Geological map Chilas to kunjerab pass section

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Fig 3.13 and Fig 3.14 shows the two sections of geological map. The map was scanned to make it useful. Then map was geo-refed using ArcMap and both sections were joined using coordinates correction and a complete map .tiff file was created for the digitization of map. A shape file of polygons was created based on the symbology of the map. Fig 3.17 shows the results of digitized map, symbology of the digitized map was assigned as the symbology was provided on the map by GSP. For the better visualization and understanding of geology again the digitized map was spilt into four zones at zoomed extent. There are three major categories of lithology existing in the study area with further 56 different groups of rock formation. Four zones are as following:

A) islamabad to Jijal

B) Jijal to Tatapani

Fig 3.15 Zone A and B of geological map

C)Tatapani to Sust

D) Sust to kunjrab pass

Fig 3.16 Zone C and D of geological map

In zone A mainly alluvium formation, but in Abbotabad section different types of rocks are present including basal conglomerate, limestone, dolomite, with cherty bands, at places dolomitic limestone, sandstone, shale. In Mansehra section main composition is of granite. In Jijal section the formation is of Garnet pyroxenite, Dunite and serpentinite which is a very weak geology as seen from the landslides data that this part is most inclined towards landslides.

In zone B major formation is of Chilas complex mainly formed of sheared gabbronite, gabbrom and diorite. In areas of sazin and barseen the formation is of Kamila amphibolite Garnet-bearing amphibolites (massive and sheared). Again, the area is highly susceptible to landslides as previously seen that major volume of past occurred landslides was in tata pani area.

In zone C Kohistan Batholith is the main formation mainly composed of granite, pegmatite, aplite, Diorite, Orthogneiss passing through the areas of Gilgit, Hassanabad, Murtazabad upto the areas of Sust.

In zone D Mishgar Slates is the main formation mostly formed of slates with minor quartzite and limestone. This region is also inclined to landslides mainly is spring and summer seasons due to the melting of glaciers.

Fig 3.17 Complete digitized geological map

3.4.2.2 Seisomo tectonics

Seismotectonics is the study of response of active tectonics, earthquakes, and individual faults of the region. A paper map of seismotectonics is acquired from Geological Survey of Pakistan as shown in Fig 3.18

Fig 3.18 Seismotectonic map of Pakistan

The map was scanned, and geo refed in ArcMap to make it useful. After geo referencing the map two shape files were created one in line format for seismic lines i.e faults and the other in points format for earth quake epicenter. After the map processing it is seen that study area is encountering with 30 earthquakes hotspots with magnitude of 3 - 5 and depth 0-50Kms, 8 earthquake hotspots with magnitude of 5 - 7 and depth 0-50Kms and 3 hotspots with magnitude of 3 - 5 and depth 101 - 200Kms as shown in Fig 3.19.

Fig 3.19 Earthquake epicenters map of study area

From the lines shape file faults map was generate as shown in Fig 3.20. The actives fault lines of Main Karakoram Thrust(MKT) and Main Mantle Thrust (MMT) are near to Jijal, Tatapani, Chilas, Hassanabad, Sust increasing the seismicity region. While Islamabad to Abbotabad section the presence of undifferenced faults and traces of probable recent faults were observed.

Fig 3.20 Fault map of study area

3.4.2.2.1 Faults

Faults are the planar surfaces due to displacements in the rocks because of mass movements, plate tectonic forces are the reason behind the faults formation. The study area traverses through two main fault lines the Main Karakoram Trust (MKT) and the Main

Mantle Thrust (MMT), that increases the seismicity of region. Distance from faults is further divided into three class 0-500m, 500-1000m and >1000m. Fault lines are created from the fault map of Pakistan produced by Geological Survey of Pakistan(GSP), after that buffer zones are derived from fault lines using ArcGIS.

Fig 3.21 Fault map of study area

3.4.2.2.2 Seismology

In mountain regions landslides and rockfalls have significant hazard. Seismology is the study of earthquake and purpose of seismological study along KKH to see the effect of earthquake on landslides and rockfalls. Seismic detection of natural events like debris flows, rock falls can be used to provides early warning to populace so that the associated risks can be reduced. To study seismological behavior of study area, seismological map was extracted from Building Code of Pakistan as shown in fig 3.22. The map was geo refed and shape file of seismic zones falling in the study area was created using Arc map.

Fig 3.22 Seismic map of Pakistan

From the map Fig 3.22 most of the study area fall in seismic zone 3 with peak ground acceleration of 0.24 to 0.32g. While at higher elevation its falls in seismic zone 2B with ground peak acceleration of 0.16 to 0.24g. The landslides, debris flows and rockfall in these regions along the highway can be caused by seismicity of the region.

Fig 3.23 Seismic map of study area

3.3 LANDSLIDE INVENTORY

To develop a relationship between conditioning factors and landslides the key and essential step is the preparation of landslides inventory.

Fig 3.24 Methodology for Landslide inventory

The historic landslides data from 2014 to 2018 was obtained from Frontier Work Organization(FWO). A field visit was conducted to obtain the latest information of landslides along the highway. First, “Landslides Inspection Proforma” was designed including different parameters of landslides like location, GPS Coordinates, type, remediation and geometry of landslide. Due to extreme climate conditions and complex topography field visit was conducted into five zones as shown in fig 3.25.

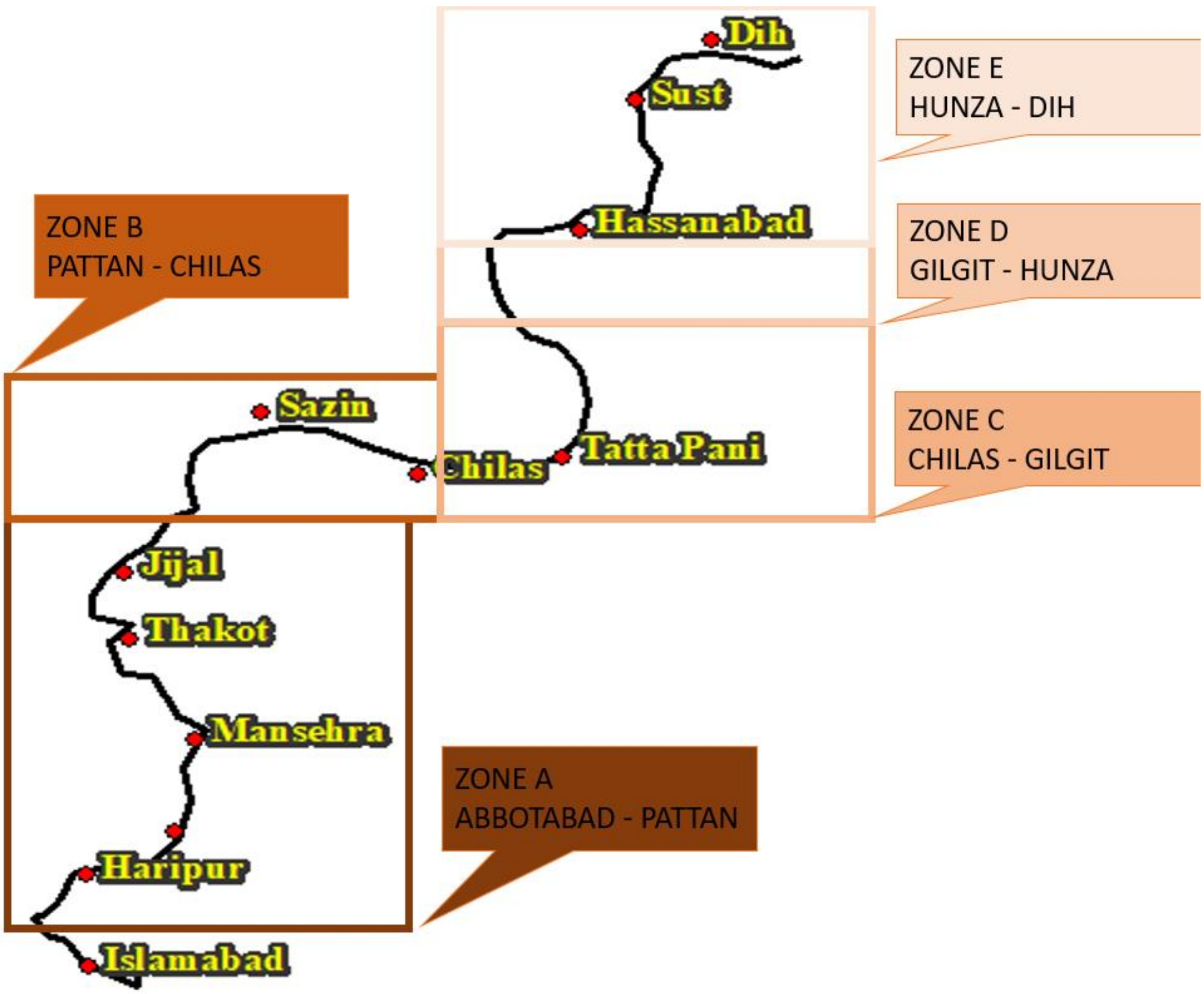


Fig 3.25 KKH Zones division for field survey

During the visit drone imagery along with GPS coordinates of mostly triggered landslides was collected. To know the strength and geology of rocks, samples of rocks and mud flows were also collected. From field collected data and data from FWO it is recorded that total number of 778 landslides occurred since 2014 to March 2018. To evaluate the results of data, it is classified to different basis like date of failure, season, year, type of landslide etc. To know the frequency distribution, pattern and occurrence of landslides along the karakoram highway multiple inventories were prepared.

3.3.1 Season based landslides inventory

To check the seasonal variation effect on landslides season-based landslide inventory map was generated. Based on months data was converted into four seasons

a) Winter — Dec, Jan, Feb
b) Spring — March, April, May
c) Summer — June, July, August
d) Autumn — Sep, Oct, Nov

3.3.2 Volume-based landslides inventory

Similarly, volumetric based inventory was developed to figure out the damaging effect a and major landslides prone areas. Volume is categorized into three parts a) 0-10000m^3 b) 10000-60000m^3 c) 60000-225000m^3.

3.3.4 Event based landslides inventory:

Event based inventory was also prepared that will help to configure the type of landslides with specific area. This also relates the landslides occurrence with the geology. Mostly KKH is suffering from boulders and mud flows. Even the precipitation rate is low at higher elevation but due to faults lines and high seismicity region is highly vulnerable towards landslides.

3.3.5 Spatio-temporal landslides inventory:

A spatio- multi temporal inventory was also developed that shows the past occurred landslides on yearly bases.

3.4 SUSCEPTIBILITY MAPPING

Landslide susceptibility mapping is an important step prior to landslide assessment planning, management and disaster mitigation (Fell et al. 2008).

Fig 3.26 Susceptibility Mapping Methodology

The choice of method for susceptibility mapping not only dependent on the study area size, but also the conditions of the data availability. A qualitative index based heuristic approach in GIS environment was applied to assess the landslide susceptibility in the region which assumes that the causative factors triggering future landslides will be the same factors that have influenced landslides in the past. Twelve thematic layers were selected for spatial mapping of landslide susceptibility in the study area. Analytical hierarchy process (AHP) was used to evaluate the weights of all parameters based on the previous studies, nature and physical properties of each parameter and subjective expert's opinions (Ahmed et al. 2014: Pachauri et al. 1998; El Khattabi & Carlier 2004; Calligaris et al. 2013: Rashid 2004; Feizizadeh & Blaschke 2011; Marjanovic 2013; Daneshvar 2014; Wu et al. 2016: Basharat et al. 2016; Kumar & Anbalagan 2016). Every parameter was subdivided into number of classes and rating value between 1 and 9, 1 being least susceptible and 9 most susceptible to landslides, is assigned to each class based on their potential to cause slope instability. The AHP method is used in this study to systematically assign preferences based on numerical scale proposed by Saaty, given in Table 3.6. All these elements were compared against each other in a pair wise comparison matrix (PCM) which allows for an independent evaluation of each factor contribution and redundancy thereby reduces the measurement error as well as produces a measure of consistency of the judgments comparison, called consistency index (CI), is defined as follows:

$$CI = \frac{\lambda_{Max} - n}{n - 1}$$

where λ_{Max} = maximum eigenvalue of the matrix;

n = number of participating parameters

Table 3.2. Fundamental scale of Saaty for pair wise comparisons (Saaty 2000)

Saaty randomly generated reciprocal matrixes using scales 1/9, 1/8…,, 1,…, 8, 9 to evaluate a socalled random consistency index (RI) (Saaty 2000), as given in Table 3.6.1. Consistency ratio (CR) is determined as:

$$CR = \frac{CI}{RI}$$

Scale	**Degree of Preference**
1	Equally importance
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Extremely high importance
Reciprocal	2, 4, 6, 8 Intermediate values Opposite

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.9	0.12	1.24	1.32	1.41	1.45	1.49

Table 3.3 Random consistency index up to n =10.

If the value of the CR is smaller or equal to 0.1, the inconsistency is acceptable, but if the CR is greater than 0.1, the subjective judgment needs to be revised (Saaty 1977). In this way, based on AHP and through normalization of AHP-PCM, different weights were assigned to each input parameter with respect to their anticipated landslide susceptibility level. This is a systematic way to generate weights for heuristic weighted overlay method and avoid inconsistencies in the weights.

Table 3.7.2 PCM

CONTROLLING FACTORS	ASPECT	ELEVATION	DISTANCE FROM FAULT	LITHOLOGY	LANDCOVER	DISTANCE FROM DRINAGE	RAINFALL INTENSITY	SLOPE	CURVATURE	SEISMICITY
ASPECT										
ELEVATION										
DISTANCE FROM FAULT										
LITHOLOGY										
LANDCOVER										
DISTANCE FROM DRINAGE										
RAINFALL INTENSITY										
SLOPE										
CURVATURE										
SEISMICITY										

3.5 KKH LANDSLIDES GEOPORTAL

This application is developed to provide a better understanding of the extent, rate and drivers for landslides on the Korakoram highway, and to provide information for planning to reduce risk to population and infrastructure from landslide hazards. The design of this Web-GIS application aims to create a user-friendly Web interface for the public to stay informed about the landslide situation at Korakoram Highway.

3.5.1 Features

3.5.1.1 Landslide Hazard

This data, organized as map layers consists of information about topography, hydrology, seismotectonics and drainage network of the area. It includes maps of aspect, curvature, faults, flow direction, digital elevation model (DEM), lithology, rainfall, slope, stahler network, stream power index, topographic wetness index, faults, curvature, rainfall and vegetation of the Korakoram Highway. In addition, basic and administrative layers including district and country boundaries are available for analysis. Users can turn on and off different map layers, navigate around the area, search and retrieve data.

Fig 3.27 Landslide Hazard layers and layer controls

Figure 3.28 Popups with attribute information

3.5.1.2 Landslide Incidents

Includes map of all the landslide incidents occurred at Korakoram highway. Users can find information about the date, location, volume, season, and type of landslide occurred. Landslide incidents tab also includes live weather forecast. There's an option to search weather situation in any desired district.

Figure 1.29: KKH Landslide Incidents map

Figure 3.30: Measure Distance and Area Tool

Figure 3.31: Calculated Area and Distance

Figure 3.32: Search District Wise Weather Forecast

3.5.1.3 Early Warning

Crowd sourcing is enabled to provide the users an up-to date information about the landslide situation at Korakoram highway. The system geo-locates user latitude and longitude, and stores against the information provided. This information is later displayed on the map as volunteered geographic information (VGI).

Figure 3.33 User credentials for crowd sourcing

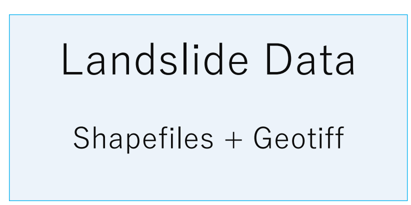
3.5.2 Tools and Technologies

3.5.2.1 Web mapping libraries

Openlayers and leaflet are used to publish raster and vector data as dynamic web maps. These are open-source JavaScript libraries for interactive web maps. The data is published in Geojson format. No server-side program is required.

3.5.2.2 Interfacing

The structure of interface is established using HTML/CSS and Bootstrap elements. CSS describes how HTML elements are to be displayed on screen. The JavaScript maps are called in HTML script and layer toggle properties are enabled.



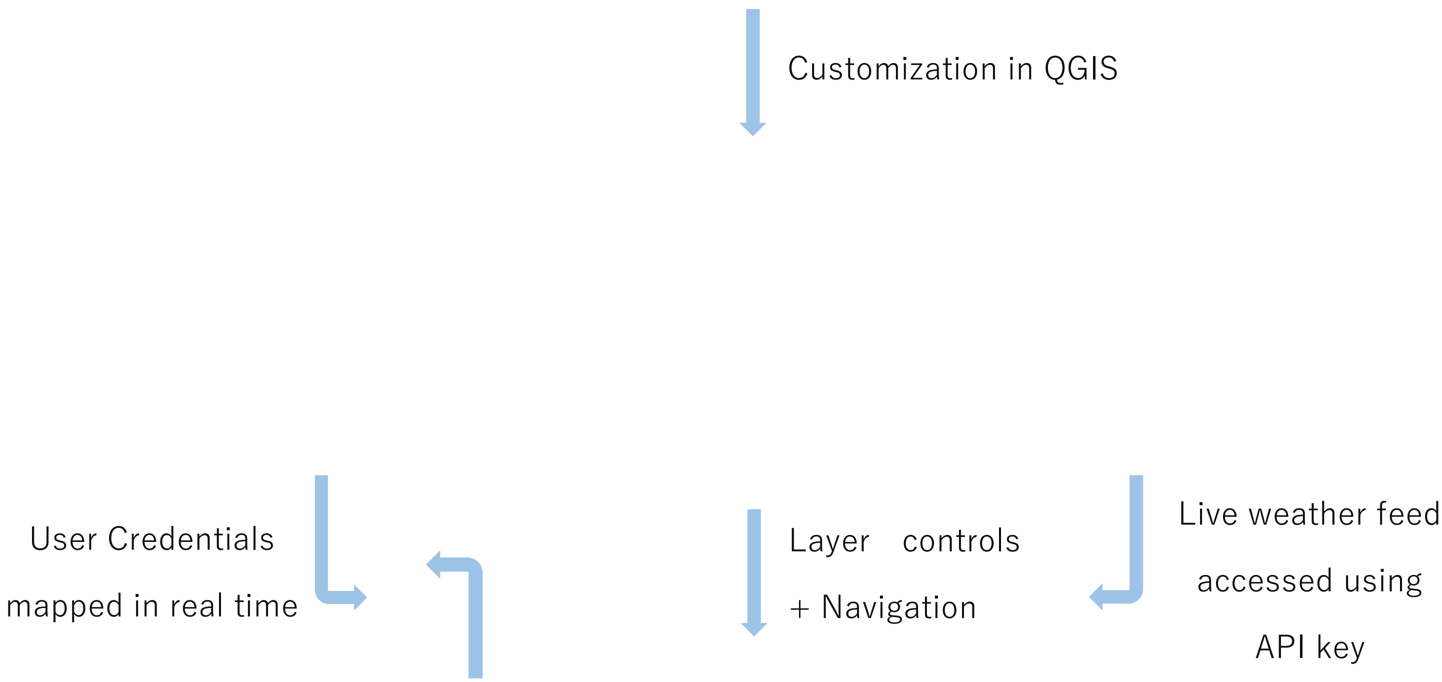


Fig 3.34 Flow Chart of Web Architecture

```
var overlayPopup = new ol.Overlay({
    element: container
});

var expandedAttribution = new ol.control.Attribution({
    collapsible: false
});

var map = new ol.Map({
    controls: ol.control.defaults({attribution:false}).extend([
        expandedAttribution
    ]),
    target: document.getElementById('map'),
    renderer: 'canvas',
    overlays: [overlayPopup],
    layers: layersList,
    view: new ol.View({
        maxZoom: 28, minZoom: 1
    })
});
map.getView().fit([7928994.533906, 3943002.264802, 8560510.207659, 4449774.949679], map.getSize());
```

Figure3.35: Setting up web map using Open layers API

```
    <div class="col-md-2">
        <img class="logo" src="images/nust_logo.png" />
    </div>
    <div class="col-md-8">
        <h1>  KKH Landslide Geoportal</h1>
    </div>
    <div class="col-md-2">
        <img class="logo" src="images/kui.png" />
    </div>

</div>
<div class="search col-md-4">

    <div class="col-md-6">
        <select class="form-control">
            <option value="1">--Select District--</option>
        </select>
    </div>

    <div class="col-md-6">
        <select class="form-control">
            <option value="1">--Select Settlement--</option>
```

Figure 3.36 User interface styled using html/css

CHAPTER 4

RESULTS

4.1 Landslides Distribution Characteristics

To obtain the landslides susceptible areas along the Karakorum highway frequency ratio method is utilized. This method uses quantitative approach to detect the areas which are more likely probable towards landslides. If the frequency ratio is greater than 1, the higher centrality of relationship amongst landslide and the specific variables, range or attribute. If the frequency ratio is less than 1, the lower centrality of relationship amongst landslide and the specific variables, range or attribute. The relationships between the causative factors and the spatial ranges are described below. It shows that for all intents and purposes all chosen causative factors are factually huge in controlling the landslide events.

4.1.1 Elevation

Topographical data like elevation, slope, curvature and aspect are derived from ASTER GDEM with a resolution of 30m. According to table 4.1 and Fig.4.2 0-1000m and 1000-2000m elevation classes have 47.34% and 36.84% of historic landslides distribution. 0-1000m class has the highest frequency ratio value of 2.51, after that frequency ratio decreases as the elevation increases. After elevation of 4000m landslides become insignificant due to the presence of stiff rocky material and the thin coverage of soil.

Fig 4.1 Digital elevation model based on classes

Table 4.1 Landslide Percentage and Frequency Distribution According to Elevation Classes

Fig 4.2 Landslide Percentage and Frequency Distribution According to Elevation Classes

4.1.2 Slope

From Table 4.2 and Fig 4.3 the frequency ratio of class 15^o-30^o is highest (2.29) and approximately 50 % occurrence of landslides with slope greater than 25^o. Slope angel less the 15^o have the frequency ratio of 0.48 which indicates the less chances of landslides occurrence. Due to lower shear stresses the frequency ratio of gentle slopes is low while slopes with greater angle are not prone to landslides due to hard bedrock (Mohammady, Pourghasemi, and Pradhan 2012). There is no specific classification system for slopes. Slopes are categorized as 5^o -15^o as gentle slopes, 15^o -30^o as steep slopes, 30^o -40^o as very steep slopes, >45^o as escarpments.

	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
ELEVATION (m)	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						

Fig 4.3 Slope map based on classes

	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
SLOPE (Degree)	1						
	2						
	3						
	4						

Table 4.2 Landslide Percentage and Frequency Distribution According to Slope Classes

Fig 4.4 Landslide Percentage and Frequency Distribution According to slope Classes

4.1.3 Aspect

In slope aspect case from Table 4.3 and Fig 4.5 it is seen that south and south east facing slopes are most susceptible towards landslides. The frequency ratio of south east facing slope is maximum (1.32). Major landslides distribution occurred in the study region fall in the east and southeast slopes while lower in other classes this can be the consequence of southeast to southwest monsoon high rainfalls during summer season.

	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
ASPECT	North	0°-22.5°					
	North-East	22.5°-67.5°					
	East	67.5°-112.5°					
	South-East	112.5°-157.5°					
	South	157.5°-202.5°					
	South-West	202.5°-247.5°					
	West	247.5°-292.5°					
	North-West	292.5°-337.5°					

Table 4.3 Landslide Percentage and Frequency Distribution According to Aspect Classes

Fig 4.5 Landslide Percentage and Frequency Distribution According to Aspect Classes

4.1.4 Plane Curvature

The frequency ratio and landslides distribution percentage from Table 4.4 and Fig 4.7 shows that convex curvature has more proportion of past occurred landslides in the region. Landslides probability increases as the values of curvature become more positive or negative. The reason behind is that after heavy rain fall more concave slopes tends to retain water for longer time while in convex slopes the runoff rate is more which make the slopes less to more susceptible towards landslides (J. Choi et al. 2012). In case of concave slopes, after rainfall the concentration of debris and water increases making more chances of occurrence of landslides.

Fig 4.6 Plane curvature map based on classes

PLANE CURVATURE	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
	Convex						
	Concave						

Table 4.4 Landslide Percentage and Frequency Distribution According to Curvature Classes

Fig 4.7 Landslide Percentage and Frequency Distribution According to Curvature Classes

4.1.5 Distance from Drainage

An important factor for the susceptibility mapping is that how much slopes are closer to drainage. Slopes may adversely have affected by the erosion power of streams. From Table 4.5 class 1 with 0-50m distance from drainage has the maximum frequency that shows occurrence possibility of landslides is more near drainage. From Fig 4.9 the distribution of landslides is more as the drainage distance increases. The causal factor behind these landslides can be rainfall or some other triggering mechanism.

Fig 4.8 Drainage map based on classes

DISTANCE FROM DRINAGE(m)	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
	1						
	2						
	3						

Table 4.5 Landslide Percentage and Frequency Distribution According to Drainage Classes

Fig 4.9 Landslide Percentage and Frequency Distribution According to Drainage Classes

4.1.6 Rainfall

In study area amount of rainfall decreases as the elevation increases. From Table 4.6 and Fig.4.11 class 3 with 529mm-786mm precipitation has maximum frequency ratio (1.83) while the landslides percentage is maximum in areas with less rainfall. That means areas with higher elevation and low rainfall are highly vulnerable towards landslides. At higher elevation triggering factor for landslides may be the glacial erosion due to glacial coverage all over the year. There are also chances of earthquake induced landslides. It is seen that areas with high rainfall don't have the landslides, because these are geological stable, populated and developed now.

Fig 4.10 Rainfall map based on classes

	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
RAINFALL (mm)	1						
	2						
	3						

Table 4.6 Landslide Percentage and Frequency Distribution According to Rainfall Classes

Fig 4.11 Landslide Percentage and Frequency Distribution According to Rainfall Classes

Stream Power Index (SPI)	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
	Low						
	Moderate						
	High						

4.1.7 Stream Power Index (SPI)

Stream power index indicates the erosion power of area due to water flow. SPI is an important factor for the evaluation of landslides susceptible area. From Table 4.7 and Fig 4.13 it is clearly seen that most of the past occurred landslides (54.99%) fall in the region of "HIGH" SPI class, the frequency ratio of the class is 1.32 while others have lower. These results are significantly caused by the drainage pattern of study area. In our case we have major as well as minor tributaries of water flows in whole area. Glacial erosion along with high rain fall make the water flow more making the higher SPI contributing towards more number of landslides.

Fig 4.12 Stream power index map based on classes

Table 4.7 Landslide Percentage and Frequency Distribution According to SPI Classes

Fig 4.13 Landslide Percentage and Frequency Distribution According to SPI Classes

4.1.8 Topographic Wetness Index (TWI)

Topographic wetness index is one of the important causative factors for the determination of susceptibility areas as it relates the hydrology with slope. From Table 4.8and Fig 4.15 it is clearly seen that most of the past occurred landslides (59.53%) fall in the region of "HIGH" TWI class, the frequency ratio of the class is 13.31 while others have lower. These results are significantly caused by the drainage pattern of study area and the slope angle. Most of the landslides along KKH are "Mudslides/Debris flows", the results from TWI shows that at higher class the water amount is more, and slope angle is less that also validates slope results. The landslides distribution is higher in less slope category. So low slope angle along with high rate of water flow makes the higher TWI as seen in results.

Fig 4.14 TWI map based on classes

	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
Topographical Wetness index (TWI)	High						
	Moderate						
	Low						

Table 4.8 Landslide Percentage and Frequency Distribution According to TWI Classes

Fig 4.15 Landslide Percentage and Frequency Distribution According to TWI Classes

4.1.9 Lithology

Lithology is the most important factor that contributes the occurrence of landslides. Table 4.9 shows the landslides distribution and frequency ratio based upon 22 classes of the lithology categories. The class Dunite (Jjd) is the most significant slope instability class with frequency ratio of 18.35. Over all the cretaceous to Jurrasic category has the highest frequency ratio. After that Jurrasic is the most susceptible category with frequency ratio of 4.94, this category has further five different class of lithologies. Both categories fall in the Jijal Complex and Kamila Amphibolite, mainly class formation of Garnet pyroxenite(Jjgpy) with highest frequency ratio of 8.57.

	Category	Group	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	% Category a	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	% Category b	FREQUENCY DISTRIBUTION (b/a)	Category b/a
[illegible]	CAMBRIAN	Єmgr	58284771	0.83	0.83	6	0.78	0.78	0.95	0.95

ccording to Lithology Classes

Fig 4.16 Landslide Percentage and Frequency Distribution According to Lithology Classes

4.1.10 Normalized Difference Vegetation Index (NDVI)

NDVI is an important factor for slope stability that encounters the effects of hydrological and mechanical factors also. NDVI is further classified into five classes based on NDVI values, 0 is as barren land, 1 is as degraded vegetation, 2 sparse vegetation, 3 grassland, 4 as dense vegetation and 5 as forest cover. Table4.10 and Fig 4.18shows the highest frequency ratio (1.740) and landslides percentage in the no vegetation areas. Then the frequency ratio of class 3 with grass land is high that's due the presence of faults in the areas causing the slopes destabilization continuously.

Fig 4.17 NDVI map based on classes

	CLASSES	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
Normalizes difference vegetation						

Table 4.10 Landslide Percentage and Frequency Distribution According to NDVI Classes

Fig 4.18 Landslide Percentage and Frequency Distribution According to NDVI Classes

4.1.11 Distance from Faults

Fig 4.20 shows the low probability of landslides as the distance from line increases. The frequency ratio of class 500-1000m is highest (1.73), that shows the more probable chances of landslides within 1km distance from fault line making the are high susceptible. Fault lines also affects the formation of material structures and slope instability specially caused by the permeability of terrain. From Table 4.11 and Fig 4.20 it is clearly seen as the probability of landslides decreases with the increment of distance from fault lines. Weathering phenomenon and the fracturing of rock mass increases as the distance from fault lines decreases that causes the slope failure.

Fig 4.19 Fault map based on classes

	CLASSES	VALUE RANGE	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
FAULT (m)	1						
	2						
	3						

Table 4.11 Landslide Percentage and Frequency Distribution According to Fault Classes

Fig 4.20 Landslide Percentage and Frequency Distribution According to Fault Classes

4.2 SUSCEPTIBILITY RESULTS

Landslides susceptibility map was generated using analytical hierarchy process. Fig 4.21 shows the results as the map was classified into 4 categories based on susceptibility level 1) low susceptible 2) Moderate susceptible 3) high susceptible 4) very high susceptible. From results it has been seen that 36% of the area fall in high susceptible zone while 16% falls in very high susceptible zone.

Fig 4.21 Susceptibility map based on four classes of study area

Fig 4.22 Susceptibility map based on nine classes of study area

7% and 20% of the highway fall into low and moderate susceptibility areas. Due to lucidity and space reasons susceptibility map was further divided into five parts.

Section 1 Islamabad to Mansehra including Thakot areas as well. Although this section suffers from high rain fall and presence of probable past faults but falls in the low susceptibility zone due to the stable geology, broad valleys and gentle slopes covered by vegetation.

Section 2 Thakot to Sazin, this section passes through the highly susceptible areas of Jijal due to the presence of active faults mainly Main Mantle Thrust and poor rock quality. The areas of Pattan and Sazin are falls in the high susceptible region due to the weak geology. The multiple shear zones (KJS) crosses highway between Pattan and Dassu and the surroundings of Sazin fall into the reach of Kamila strike slip fault (KSF) and the active HSZ as shown in (Fig. 4.23). Two main drainage streams of Samar and Harbon Nallah are also responsible for the mudflows in the areas of Sazin.

Section 3 Sazin to Tatapani, in this section Chilas areas fall is moderate susceptible zones while Tatapani is the biggest hotspot for landslides along the KKH. Due the Main Mantle Trust and very weak geology of Tatapani it falls in the highly susceptible zone.

Section 4 Tatapni to Hassanabad this area is also highly susceptible because it lies directly over the the Main Mantle Trust and active Raikot fault(RF). This area become more aggravate due to steep slopes and slopes toe erosion by the drainage network of Indus river.

Section 5 Hassanabad to Kunjerab Pass, glacial erosion, snow melting in summer and steep slopes are responsible for the susceptibility of area. Hassanabad and surroundings areas falls in highly susceptible zones because of very steep slopes and Main Karakoram Fault.

Fig 4.23 Shear zones map. MMT-Main Mantle Thrust, KJS-Kamila Jal Shear zone, MKT Main Karakoram Thrust, KF- Karakoram Fault, KSF-Kamila Strike slip fault, IKSZ-Indus Kohistan Seismic zone, HSZ Harman Seismic Zone, RSSZ-Raikot Sassi Seismic zone, YSZ-Yasin Seismic Zone. (compiled from: Khan and Jan, 1991; Derbyshire et al., 2001; DiPietro and Pogue, 2004; DiPietro et al., 2000; Hewitt et al., 2011, USGS Earthquake Catalog 2017).

4.3 RESULTS VALIDATION

It was recorded that total 778 landslides occurred from 2014 to 2018 along the highway for the validation of susceptibility results two data sets were prepared one for training and the other for validation. From Table 4.12 and Fig 4.24, 580 (75%) landslides from 2014 to 2018 were chosen for the training dataset while randomly selected 198 (25%) landslides occurred during the whole-time series is used for the validation of model. Frequency ratio model was developed for the analysis of results. The prescient power of the model can be assessed that how much landslides occurred from 2014 to 2018 are effectively predicted by the model as by the training dataset of other landslides.

Fig 4.24 Study Area Map for results validation

	Training Dataset	Validating dataset
Percentage		
Occurrence year		
Landslides Count		

Table 4.12 Landslides Record for temporal verification

VARIABLE	CLASSES	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
TRAINING DATASET						

Table 4.13 Pixels in domain and landslides Percentage According to Training data set

	CLASSES	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
VALIDATION DATASET						

Fig 4.25 Pixels in domain and landslides Percentage According to Training data set

Table 4.14 Pixels in domain and landslides Percentage According to Validation data set

Fig 4.26 Pixels in domain and landslides Percentage According to Validation data set

For the analysis of results of susceptible maps frequency ratio method was used. Two data sets were prepared, and the results were compared from both. Table 4.13 of training dataset shows the highest frequency ratio (1.62) of class four which is of highly susceptible zone. Almost same results were seen from the validation data set. Overall class three of high susceptible zone has the highest landslides percentage, and the results were validated on the same percentages of both datasets.

The validation results for susceptibility maps of nine classes are as following:

	CLASSES	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
TRAINING DATASET	1					
	2					
	3					
	4					
	5					
	6					
	7					
	8					
	9					

Table 4.15 Pixels in domain and landslides Percentage According to training data set (nine classes)

Fig 4.27 Pixels in domain and landslides Percentage According to Training data set(nine classes)

	CLASSES	PIXELS IN DOMAIN	% PIXEL IN DOMAIN (a)	LANDSLIDES DISTRIBUTION	% LANDSLIDES DISTRIBUTION (b)	FREQUENCY DISTRIBUTION (b/a)
VALIDATION DATASET	1					
	2					
	3					
	4					
	5					
	6					
	7					

	8					
	9					

Table 4.16 Pixels in domain and landslides Percentage According to Validation data set(nine classes)

Fig 4.28 Pixels in domain and landslides Percentage According to Validation data set (nine classes)

In this study, validations of the mapping results were performed by calculating receiver operating characteristics (ROC). It has been commonly used in medical decision making, and in recent years has been increasingly applied in machine learning and data mining research (Fawcett 2006). The graphs are useful for organizing classifiers and visualizing the modeling performance. In this method, the susceptibility value of all cells is sorted in a descending order and divided into 10 classes of accumulated area ratio percentage according to the landslide susceptibility value (Figure 4.29). Finally, the area under the ROC curve (AUC) values, are used to evaluate the accuracy (i.e ‘prediction rate’) of the models. The AUC value ranges from 0.5 (random prediction, represented by the diagonal reference line) to 1 (perfect prediction). In the study area, the area ratio for AHP model was 0.84, which implies that the prediction accuracy of the model is 84%. Using the area under curve (AUC) of the receiver operator characteristic (ROC) curve, the validation results show that AHP model is capable of predicting the susceptibility of landslides and more reliable in as much as the model best corresponded to the subsequent actual ground truth.

Fig 4.29 ROC plot for the susceptibility results of AHP Mode

CHAPTER 5

CONCLUSIONS

In natural disasters landslides are the most hazardous. Complex geology, intense rainfall, dynamic seismicity, glacial erosion and the mountainous terrain makes Karakorum highway makes it unique as most vulnerable to the hazards of landslides. For the landslides hazards assessment along KKH landslides susceptibility mapping provides fundamental information. The direct geomorphological approach to the landslides hazards is virtually not possible in the mountainous terrain. Remote sensing techniques provides effective and powerful alternatives for the identification, detection, and monitoring of landslides. With the help of GIS and remote sensing techniques, this research is expected to not only produce a map but also create suitable strategies for the landslides susceptibility mapping.

With the passage of time landslides occurrence is increasing along the highway, mud flows and rock falls being the most observed events during recent years. Frequent and large volume of landslides occurred in spring season especially in Jijal and Tatapani areas.

The findings of susceptibility mapping shows that 36% of the study area fall in high susceptible zone while 16% falls in very high susceptible zone. 7% and 20% of the highway fall into low and moderate susceptibility zones. Jijal, Tatapni, Hassanabad are the most susceptible hotspots along the highway.

The developed geo portal will serve as an open source to the people for the hazard visualization of the landslides along the karakoram highway. By using the susceptibility and related factors maps coupled with latest aerial view of the most susceptible landslides of the area the diversity of the region can be evaluated. KKH geoportal is one of its best kind because it is the first time an open source web will be available to everyone only for the hazards evaluation of the northern areas of Pakistan.

In a nutshell this research will contribute for the safe future sustainable development of the region along the karakoram highway. Without prior knowledge and research, it is not possible to safely move forward in social as well as economical aspect. This research will lead to the proper land use planning, disasters mitigation and the safe development of the region.

RECOMMENDATIONS

It should also be noted that this susceptibility model is intended for use as a screening tool at the regional scale, useful for focusing efforts for more detailed study. Landslide risk assessment or cost of future landslides may also be considered for improve the urban planning strategies, given that detail rainfall data and factors relevant to vulnerability such as buildings and infrastructure. Advances in information technology allow in situ ground and weather data to be transmitted to geospatial computation system so that a warning could be issued in a real time and regional specific manner. Geospatial computing, like many other disciplines of science and engineering, is currently facing a daunting challenge in data management that compels researchers and engineers to address the need for handling voluminous geospatial data with ever-increasing complexity and heterogeneity. For data-intensive geospatial computing like landslide susceptibility and hazard assessment, spatial cloud computing certainly offers an alternative solution for researchers to perform scalable and efficient geospatial data-processing tasks, with no need to maintain complex computer resources. With the aid of geospatial cloud computation, it is also expected to strengthen the effort of avoiding hazards and restricting development in landslide-prone areas, and consequently allow for cloud-enabled early-warning, which starts with the sensor in the field and ending with user-opitmized warning messages and action advice.

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APPENDIEX

Lithology Map Legend

SYMBOL	FORMATION
KOHISTAN ISLAND ARC	
Qal	Alluvium
SYMBOL	**FORMATION**

KARAKORAM-ASIAN PLATE

oint Load Test Results

SR.#	RD	Sample	Load P (KN)	Distance between the Platen in mm D=(mm)	Width of Specimen in mm W(mm)	*Corrected Pont load	**UCS of rock	Avg. qc
1	207+300	1		32	35			
		2		23	46			
		3		22	42.5			
2	209	1		15	40			
		2		30	48			
		3		28	60			
3	216	1		20	47.5			
		2		15	42.5			
		3		33	75			
4	217	1		17	37.5			
		2		27	66			
		3		39	60			
5	220+800	1		30	57.5			
		2		20	92.5			
		3		37	82.5			
6	221+225	1		24	56			
		2		30	42.5			
		3		42	100			
7	234+100	1		27	85			
		2		39	85			
		3		45	85			
8	234+200	1		24	67.5			
		2		49	62.5			
		3		25	75			
9	236+330	1		39	67.5			
		2		34	62.5			
		3		25	57.5			
10	240	1		28	75			
		2		20	65			
		3		42	80			
11	240+900	1		28	62.5			
		2		28	77.5			
		3		23	102.5			
12	250+800	1		25	82.5			
		2		20	87.5			
		3		23	87.5			
13	254+100	1		33	67.5			

		2		42	50			
		3		35	71			
14	256	1		20	60			
		2		28	52.5			
		3		36	60			
15	257+550	1		25	47.5			
		2		51	59.5			
		3		20	95			
16	259	1		44	74			
		2		35	57			
		3		35	62.5			
17	261+300	1		22	62.5			
		2		21	50			
		3		40	52.5			
18	263	1		25	73			
		2		30	66			
		3		43	90			
19	263+100	1		25	105			
		2		34	62.5			
		3		24	35			
20	263+900	1		24	75			
		2		38	42.5			
		3		24	60			
21	265	1		35	55			
		2		25	80			
		3		30	62.5			
22	267+800	1		41	67.5			
		2		36	46.5			
		3		26	47.5			
23	274+600-900	1		22	57.5			
		2		25	60			
		3		39	58			
24	277+500	1		21	70			
		2		16	48.5			
		3		28	67.5			
25	282+100-700	1		23	79			
		2		24	97.5			
		3		34	90			
26	288+340	1		30	56			
		2		49	67.5			
		3		35	52.5			
27	290+292	1		30	57.5			
		2		34	55			
		3		35	62.5			
28	296+630	1		21	57.5			
		2		34	70			
		3		38	42.5			
29	298+100	1		40	70			

		2		22	85			
		3		23	90			
30	301+200	1		28	60			
		2		25	72.5			
		3		31	67.5			
31	305+380	1		31	62.5			
		2		19	65			
		3		30	50			
32	317+300	1		24	45			
		2		19	42.5			
		3		27	70			
33	325	1		26	100.5			
		2		38	77.5			
		3		25	85			
34	327+500	1		36	60			
		2		28	65			
		3		34	77.5			
35	330	1		26	52.5			
		2		28	72.5			
		3		33	80			
36	334	1		31	50			
		2		23	67.5			
		3		20	55			
37	344+200	1		31	42.5			
		2		35	50			
		3		38	47.5			
38	358+500	1		28	35			
		2		30	32.5			
		3		23	40			
39	360+100	1		37	52.5			
		2		34	55			
		3		35	77.5			
40	362	1		32	75			
		2		27	57.5			
		3		37.5	71			
41	386+200-300	1		17.5	80			
		2		17	62.5			
		3		19	77.5			
42	404+100	1		36.5	125			
43	405+200	1		24.5	62.5			
		2		31	85			
44	410+800	1		18	70			
		2		16	55			
		3		19.5	72.5			

45	428+800	1		21.5	70			
		2		34	55			
		3		18.5	35			
46	440+100	1		28	65			
		2		29	70			
		3		33.5	62.5			
47	444+500	1		26.5	57.5			
		2		29	65			
		3		29	60			
48	448-449	1		29.5	57.5			
		2		25	57.5			
		3		23	75			
49	456+200	1		25	37.5			
		2		42	70			
		3		54	72.5			
50	466	1		26	55			
		2		25	87.5			
		3		47	82.5			
51	466+500	1		34	65			
		2		32	67.5			
		3		27	52.5			
52	467	1		26	55			
		2		25	87.5			
		3		47	82.5			
53	473	1		27.5	62.5			
		2		22	52.5			
		3		24	35			
54	491+085	1		21	85			
		2		14	80			
		3		18	50			
55	493	1		34	112.5			
		2		19	80			
		3		44	70			
56	499+360	1		36	57.5			
		2		35	62.5			
		3		18	75			
57	504	1		18	67.5			
		2		30	70			
		3		25	80			
58	506+100	1		16	50			
		2		30	65			
		3		21	75			
59	528+200	1		17	67.5			
		2		31	57.5			
		3		20	90			
60	579+100	1		35	75			
		2		19	65			
		3		24	60			

61	582+500	1		21	70			
		2		24	64			
		3		38	67.5			
62	593	1		13	55			
		2		11	57.5			
		3		24	55			
63	598	1		24	55			
		2		23	55			
		3		27	62.5			
64	600	1		27	52.5			
		2		30	42.5			
		3		38	60			
65	605	1		48	57.5			
		2		29	45			
		3		25	60			
66	606+300	1		10	80			
		2		17	72.5			
		3		14	90			
67	609	1		21	56			
		2		21	80			
		3		27	42.5			
68	614+100	1		13	40			
		2		29	42.5			
		3		25	50			
69	622+500	1		36	45			
		2		39	70			
		3		30	65			
70	623	1		29	47.5			
		2		35	35			
		3		45	42.5			
71	625+200	1		26	72.5			
		2		28	55			
		3		33	47.5			
72	645	1		23	51.5			
		2		22	50			
		3		37	31.5			
73	690	1		30	42.5			
		2		17	57.5			
		3		30	62.5			
74	703	1		16	50			
		2		27	45			
		3		16	57.5			
75	716	1		21	57.5			
		2		18	60			
		3		32	75			
76	723	1		32	42.5			
		2		14	55			
		3		20	42.5			

77	749	1		18	57.5			
		2		21	60			
		3		7	85			

*Corrected Pont load Ii50=(((P*1000)/((D*W)¾*7.07)))Mpa
**qc=15*Is50 (Mpa)