DESIGN, NUMERICAL MODELING, KINEMATIC ANALYSIS, SLOPE STABILITY & PROTECTION WORKS INCLUDING SLOPE HEALTH MONITORING

FOR

QUARRY SITE OF SUNNI DAM, SJVNL, DISTRICT SHIMLA, HIMANCHAL PRADESH

INDIAN INSTITUTE OF TECHNOLOGY (ISM)
DHANBAD

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1 INTRODUCTION

1.1 General

Indian hydropower producer Satluj Jal Vidyut Nigam (SJVN), a joint venture of the Government of India and the Government of Himachal Pradesh has proposed construction of Sunni Dam in Himanchal Pradesh. The dam is an extended part of Project Luhri on the river Satluj. The construction of dam is stipulating the need of construction materials in the vicinity of the dam site. For this purpose one possible location has been identified on the right side of bank of River Satluj, near Khaira Village, District Shimla. This site will be utilized for extracting materials and will require planned excavation. As the site is on the hilly regions belonging to Lesser Himalayas, there is a necessity for slope stability analysis and further designing of slopes to prevent any possible hazard with the aid of latest monitoring techniques and remedial measures.

1.2 The Client

The Satluj Jal Vidyut Nigam Limited (Satluj Jal Vidyut) is an electricity producing company. The company is a joint venture entity between the Government of India (GOI) and the Government of Himachal Pradesh (GOHP). Currently, the company is engaged in designing, planning, developing, examining, organizing, executing, operating, as well as maintaining hydroelectric power projects. The company principally operates in Himachal Pradesh and Uttarakhand in India and in Nepal. The company is headquartered in Shimla, Himachal Pradesh, India. After the commissioning of the largest underground 1500 MW Hydro Electric Power Station, the Corporation has expanded its base from a single project to a Multi Project and thereafter became a National Corporation.

Figure 1 Location of general area of Quarry Site

1.3 The Project: Sunni Hydro Electric Power Project

Sunni Dam is a run of the river scheme utilizing the discharge of Satluj River between operational stage Koldam on the downstream and under investigation stage Luhri Stage-II HE Project on the upstream. Some features of Sunni Dam Project are as following:

- Concrete gravity dam 95 m high above deepest foundation level and 178 m long,
- Two level spillways consisting of 6 bays of 8.5 m x 15 m (H) sluice and 1 no. of 8.5 m x 3 m (H) surface spillway; intake on right bank;
- 3 Nos of pressure shaft bifurcating to six units of underground powerhouse.
- The proposed installed capacity of this Project is 382 MW and design energy is 1382 MU.

To meet the demand of stone, bajri and sand for construction of Hydro Electric Project, the Project Authorities applied for grant of mining lease which falls in village Khaira, Tahsil Seoni, District Shimla. The quarry area is a part of hill side on the right bank of the River Saltuj about 13 kilometers from Seoni, via MDR 22. It is at about 58 Km from Shimla.

Figure 2 View of Sunni Hydroelectric Power Project

1.4 Scope of Work

The client has proposed 10.3264-hectare area for the purpose of quarry for the extraction of aggregates to be consumed for the construction of Sunni HEP (382 MW) project on Satluj river. As the area lies in the Himalayan geology, the stability of the slope raises concern amongst the Government and Local officials. The scope of work under this report is to design, analyse the stability of the site and provide solutions for the concern, a brief of scope is as below:

1. Review of geological studies for slope including the documents like available geological studies and reports, data from sources like GSI, SOI etc.
2. Numerical Modeling / Analysis of slopes of Unstable zones: Preparation of Detailed Project Report for the kinematic and slope stability study of the slopes in the quarry area including analysis, design methodology for kinematic analysis and slope stability analysis including planar failure, wedge failure, toppling and global slope failures.
3. Hydrology: The hydrogeology of the area is to be studied for the slope stability along with water content. Water content is dependent on soil properties such as grain size, which can impact infiltration rate, runoff, and water retention.
4. Mitigation Measures: Analyze suggested mitigation measures in report and suggest additional one.
5. Slope monitoring recommendations during construction: Slope monitoring solutions during construction to avoid slope failure and provide early warning to prevent environmental and safety hazard.

1.5 Location of the Site

The project site is located at 58 km from Shimla and can be reached from state highway 13 or main district road 22 via Khaira, nearest village to the site which is 13 km from Seoni, tehsil of Shimla District. The area of the site is 10.3264-hectare on the hillside of right bank of river Satluj. The site extends from an elevation of EL 798 m near the river bank, to EL 912 m towards the hilltop.

Figure 3 General Area of Quarry Site along right bank of River Satluj

For detailed approach longitudes and latitudes of quarry site are given in table and marked up on Google Earth along with elevations. Figure displays clear locations and approach road to the site.

Table 1 Latitude and Longitude of the Area

S. No.	Points	Latitude	Longitude
1	A	31°14’55.6” N	77°12’47.0”
2	B	31°14’54.9” N	77°12’49.0”
3	C	31°14’49.8” N	77°12’54.1”
4	D	31°14’44.6” N	77°12’55.6”
5	E	31°14’46.8” N	77°12’37.6”
6	F	31°14’48.1” N	77°12’35.6”

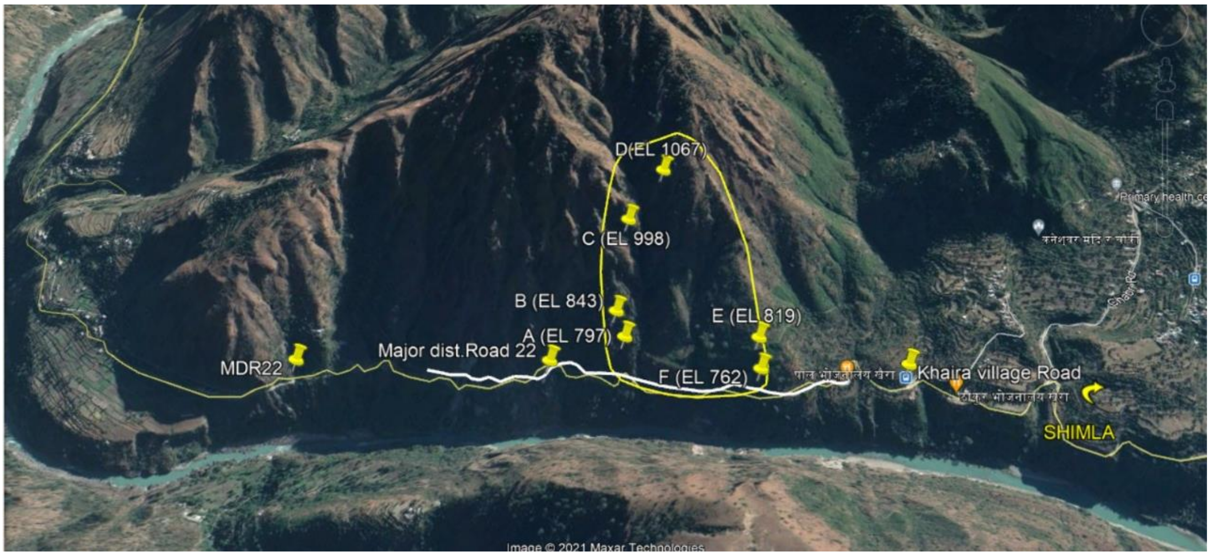


Figure 4 Quarry Site with boundaries on Google Earth Pro

2 GEOMORPHOLOGY OF REGION

The area is part of Lesser Himalaya or Sivaliks, stretching from western India to north eastern part of India, including states like Himanchal Pradesh is the west, Uttar Pradesh and Sikkim in the central and Arunachal Pradesh in the north east, ranging from 1,500 to 5,000 metres in height.

a. Climate

The state of Himanchal Pradesh lies in the lower belt of Himalayas and the typical climatic conditions are described in the figure. The quarry area lies in Shimla district and experiences sub-tropical monsoon with mild and dry winter and moderate summer. The weather is pleasant throughout the year, even so due to changes in altitude the area is prone to sudden rise and fall in temperature.

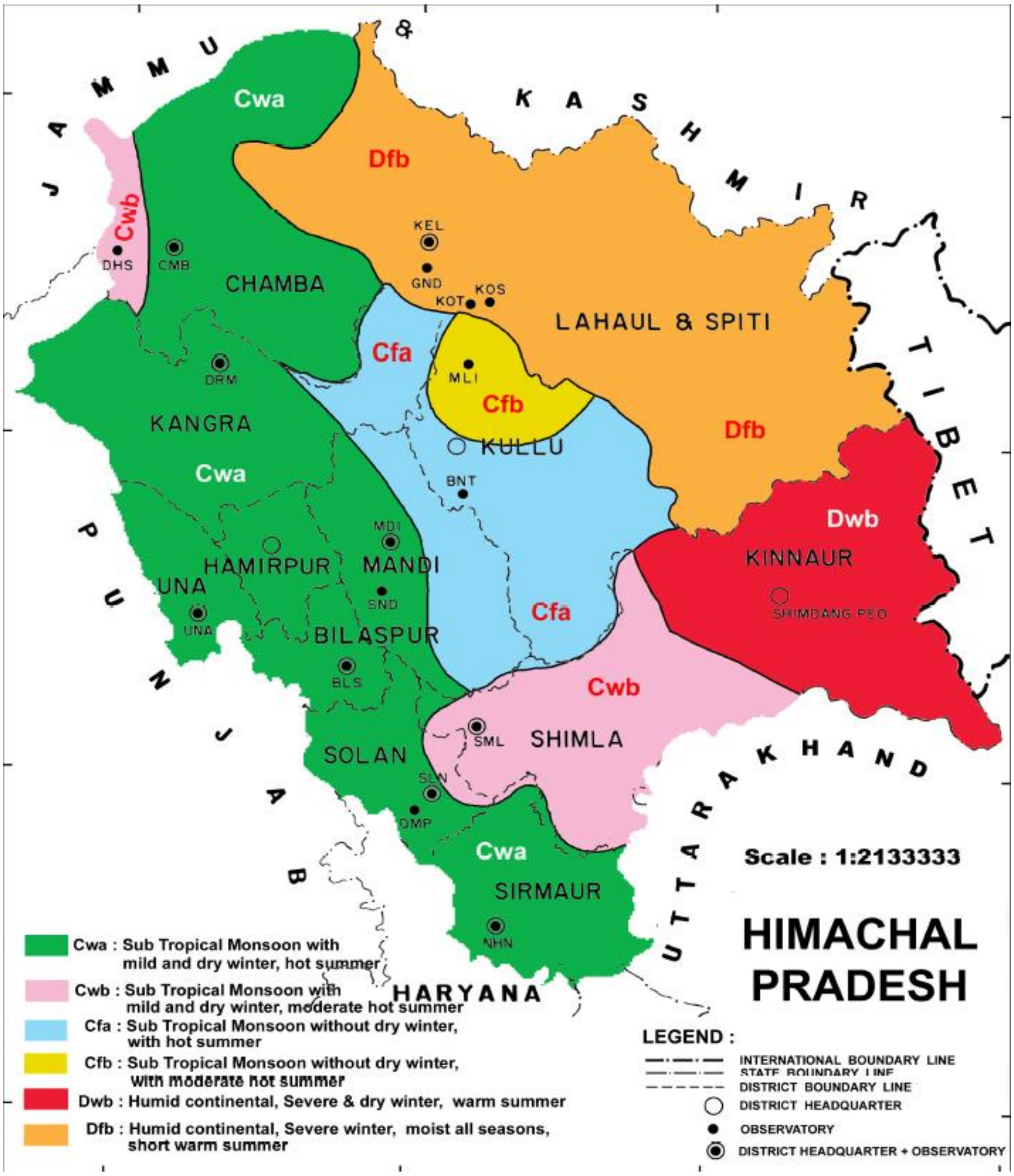


Figure 5 Climatic Conditions across Himanchal Pradesh

b. Altitude

As per the contour maps of interval 2 m, the highest and lowest marks of the Quarry area is respectively 920 m and 754m above MSL. Points D and F in figure below showing highest and lowest contour levels of the Quarry area, respectively.

Figure 6 Highest and Lowest Elevation Points of Site on Google Earth Pro

c. Rainfall

Rainfall in districts of Himanchal Pradesh varies from deficit to heavy rainfall. The monsoon in the Shimla district lasts from the month of June to September. As per the rainfall data of Indian Metrological Department, amount of rainfall is moderate in the district, shown below in figure. The temperature of the region during monsoons drops and ranges from 15º - 35º Celsius.

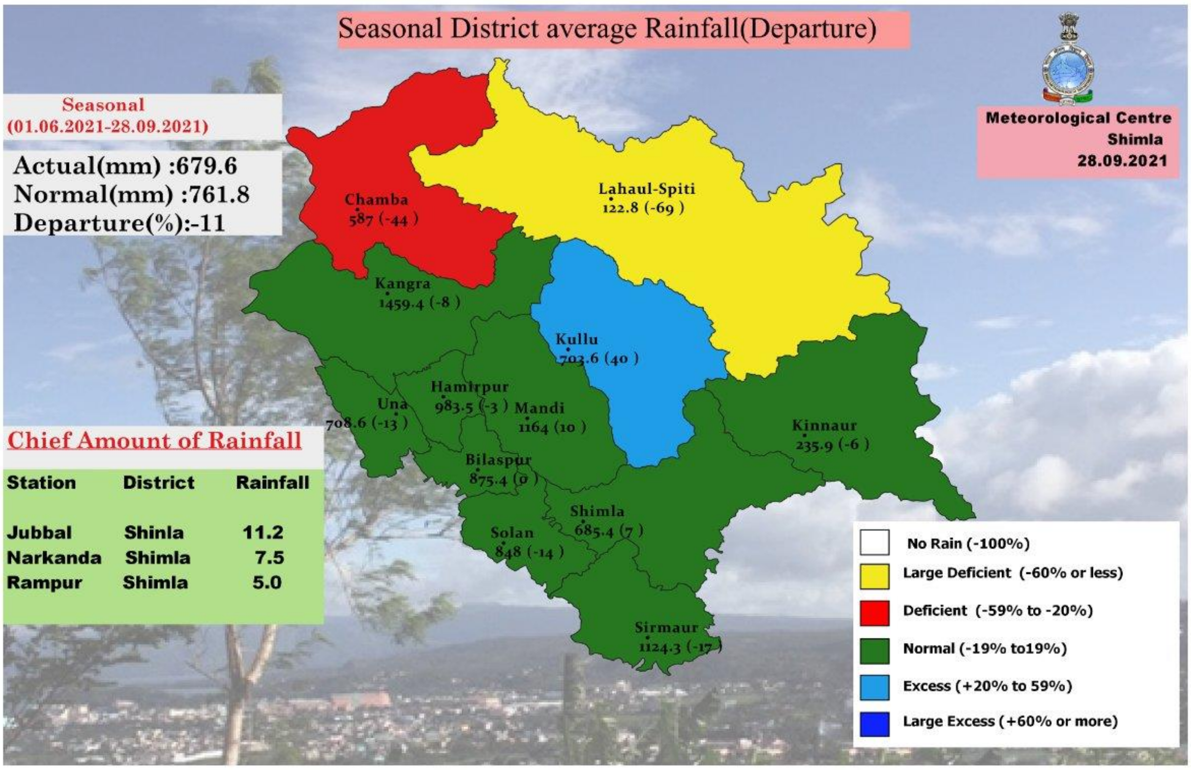


Figure 7 Average Rainfall of Himanchal Pradesh

The catchment areas of state of Himanchal Pradesh are divided into six parts according to the rivers. The site falls in catchment of river satluj with annual rainfall of 1191.9 mm. table displays the amount of rainfall in the catchment area along the satluj river, passing through Luhri, to Project Site, to Bhakra Dam.

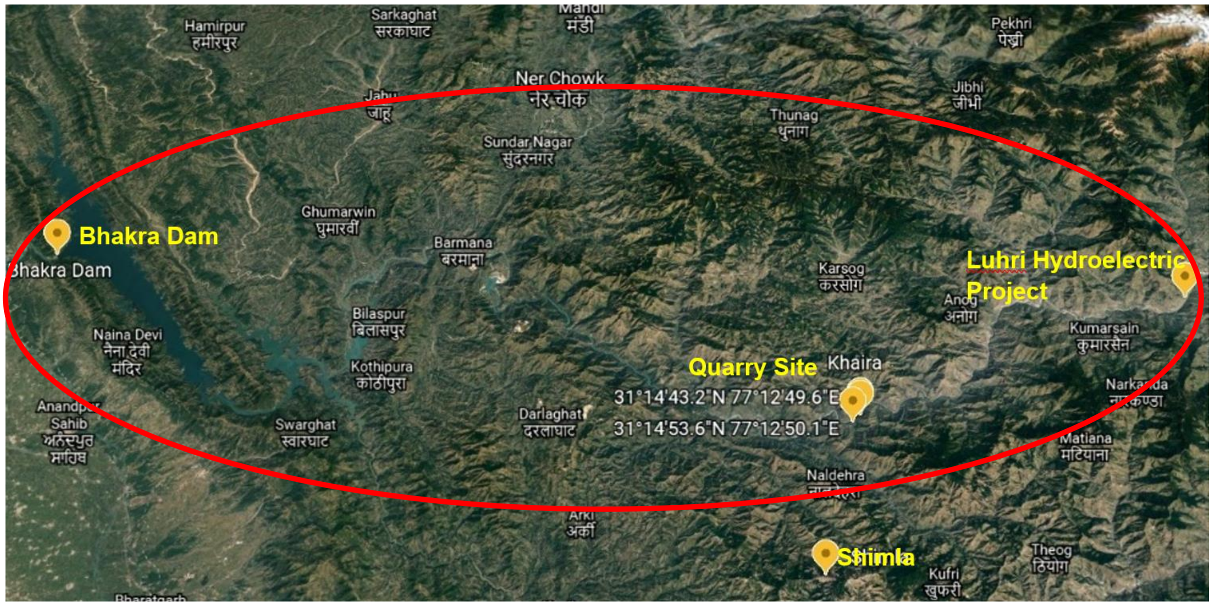


Figure 8 Catchment Area of River Satluj Near Site

Table 2 Mean Rainfall (mm) over River Catchment

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
River Satluj Upto Bhakra Dam Site Districts/parts within this catchment: Shimla, Solan, Kinnaur, Mandi, Bilaspur												
93.5	86.1	89.1	53.3	63.0	99.8	256.6	231.6	120.6	38.7	15.4	44.2	1191.9

d. Slope Angle

The slope angle of the quarry area is moderate towards northwest. The quarry area is part of a hill where dam is located but more towards upstream. As majority of the quarry area is on the upstream of the dam axis, its effect shall be minimal on the dam. The adequate distance between the two sites further assists this philosophy.

e. Drainage pattern

The river and other water channels follow the slope of the terrain, hence forming Dendritic drainage pattern. Two water channels pass across the quarry area. They have boulders and gravels in its bed. Figure shows the drainage pattern of the channels.

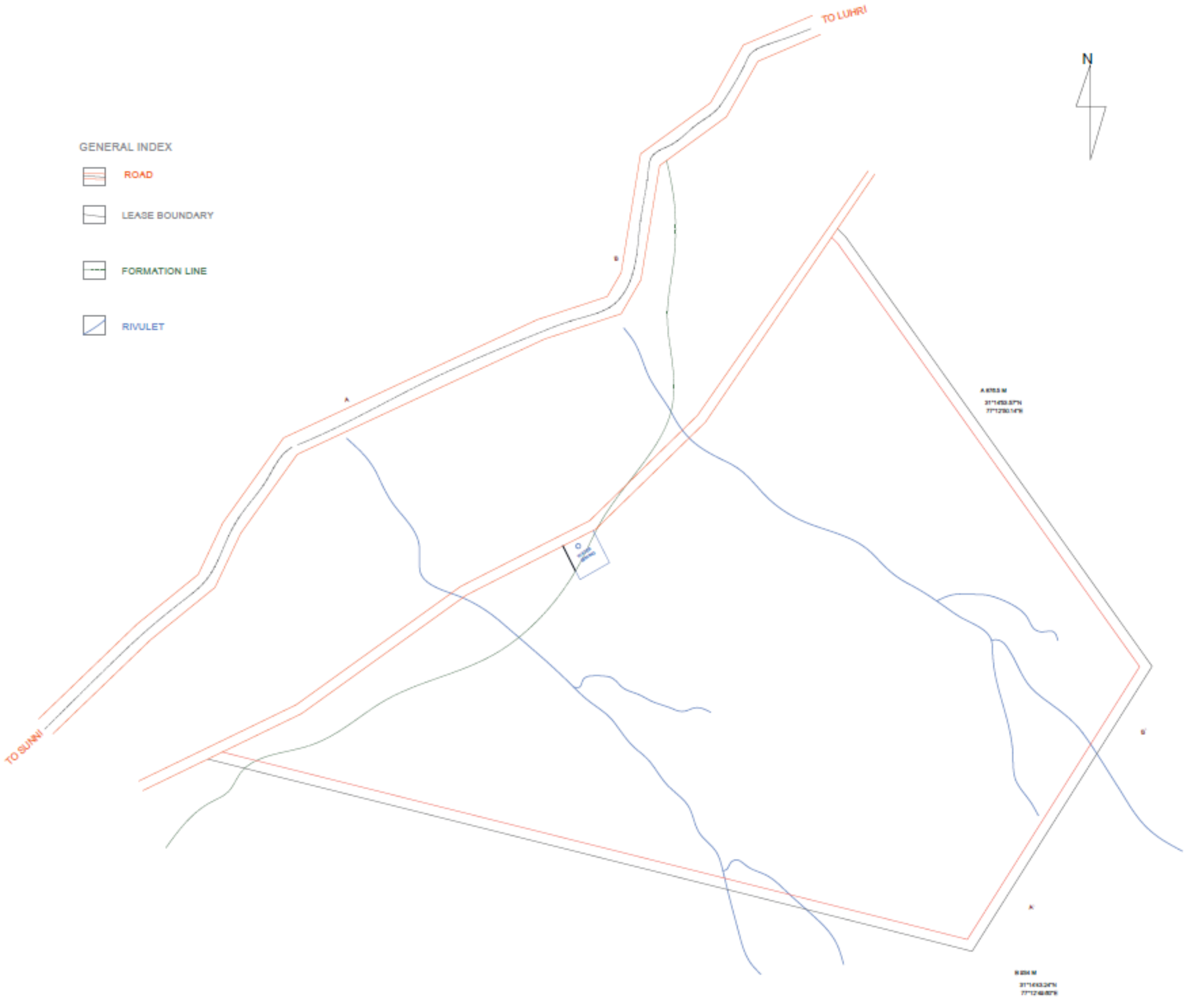


Figure 9 Dendritic Drainage Pattern

3 LANDSLIDE AND SEISMIC EVENTS

3.1 Landslide

Himanchal Pradesh is situated on the Lower Himalayan Ranges, due to which some regions are prone to landslides. Figure shows the landslide events occurred in the state. The number of events occurred in Shimla district are lesser than the events occurred in other districts. Also, the quarry area marked on the map does not display any landslide event in the vicinity of site for more than 15- 20 kilometers.

This was confirmed during visit to the site area for detailed studies for this report. It confirms that the slopes in this general area are stable inspite of the excavations carried out for connecting the road in this remote location. It also brings out the fact that the rock composition in this general area is much stable and stronger. vis-a-vis the general perception of the geology of Himalayan region.

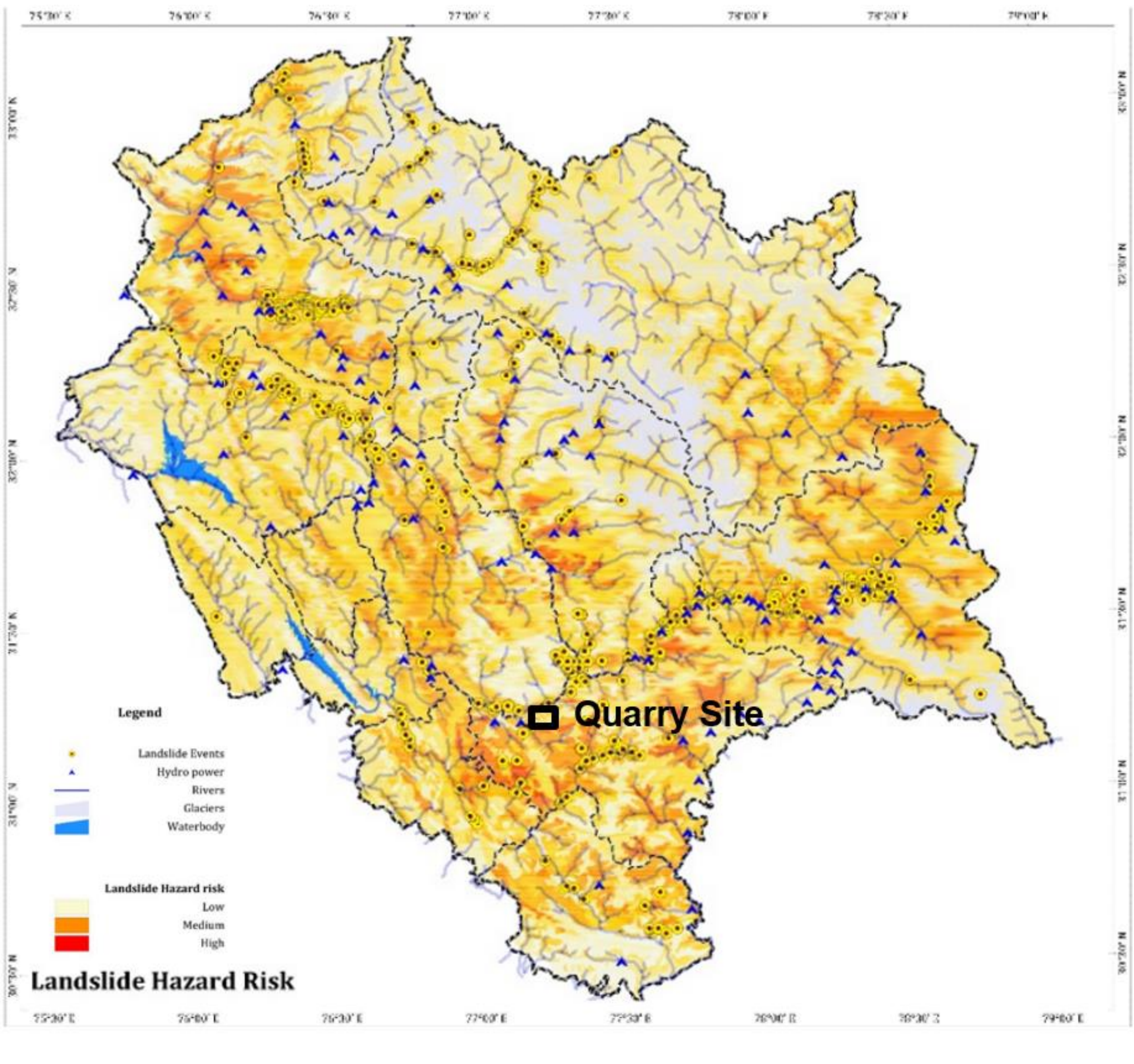


Figure 10 Himanchal Pradesh Landslide vulnerability zonation

The various in-situ tests carried out by SJVNL in detail show that the joints of rock in the east of quarry area dip into hill side, therefore, are least susceptible to slide. Even so, the mining plan includes that no excavation works during the monsoon season when the wet rock is most susceptible to slide.

Figure 11 Absence of Landslide Event in the vicinity of Quarry Site

3.2 Seismic Activities

The Himalaya are among the most seismically active regions in the world, the result of an ongoing collision between two continental plates: the Indian and the Eurasian. The presence of Himanchal Pradesh in the Himalayan Range brings vulnerability towards seismic events. As shown in figure the area encircled falls under zone V of seismic activities, and area outside that region falls under seismic zone IV.

District Shimla also falls in seismic zone 4, the effect of earthquake on slope cannot be neglected. The project site under Shimla district falls under high vulnerability zone, as the whole region is part of lesser Himalayas. Although there has been no seismic events in the area in the past, complete possibility cannot be neglected. The requisite inputs and parameters for earthquake zone IV have been considered in analysis of slope stability. This shall ensure the safety and any sudden movements even during earthquake.

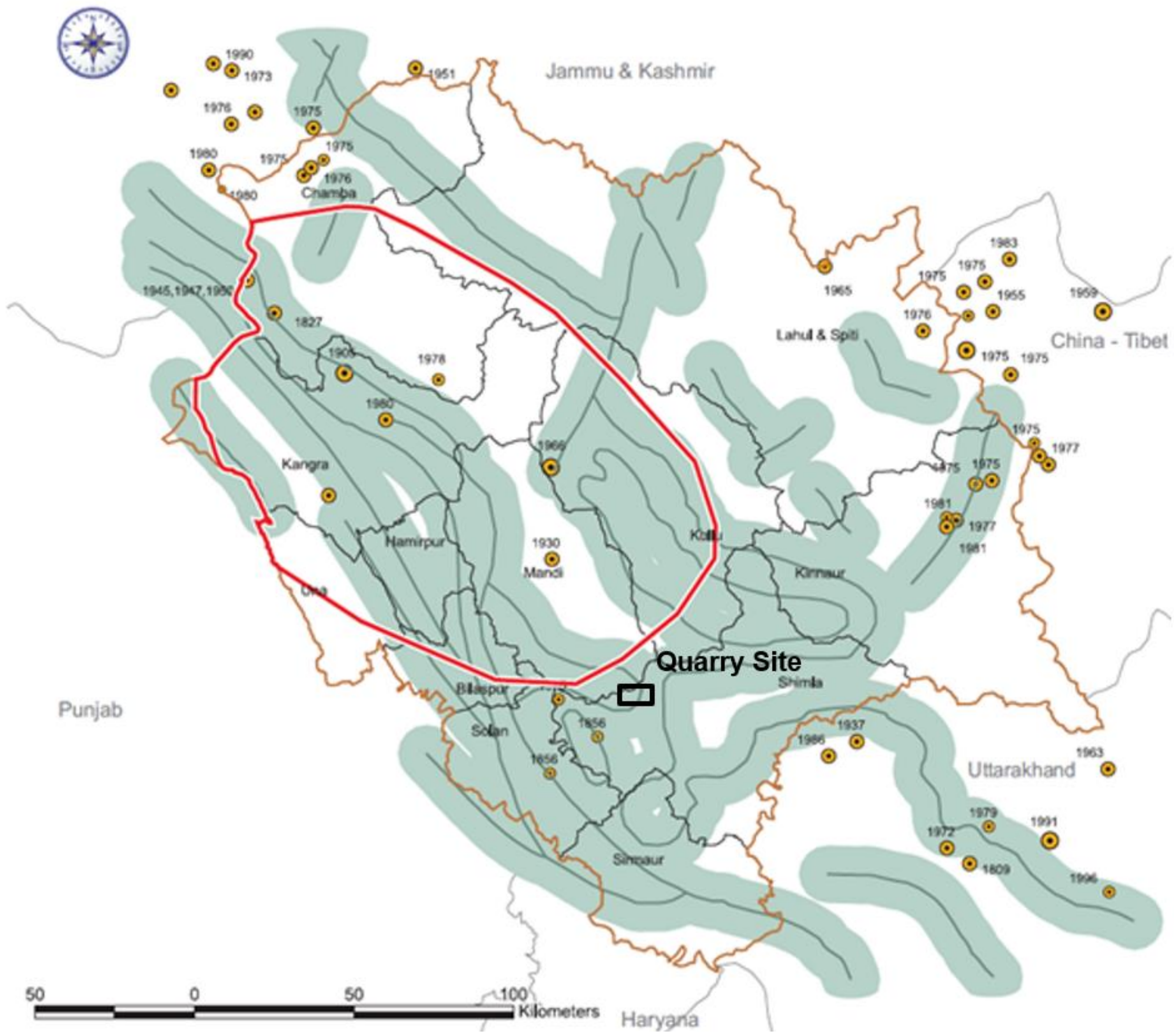


Figure 12 Earthquake Hazard Map of Himanchal Pradesh

4 GEOLOGY OF THE REGION

4.1 Rock Type

Himachal Pradesh has been divided into two contrasting tectogens with their own distinctive geological history viz. the Lesser Himalayan Tectogen in the south and Tethys Himalayan Tectogen in the north as shown in figure . These two tectogens has been separated by a major tectonic discontinuity called as Main Central Thrust (MCT) and on the either side of this thrust the tectogens display contrasting stratigraphic and tectonic features indicating convergence of two alien blocks.

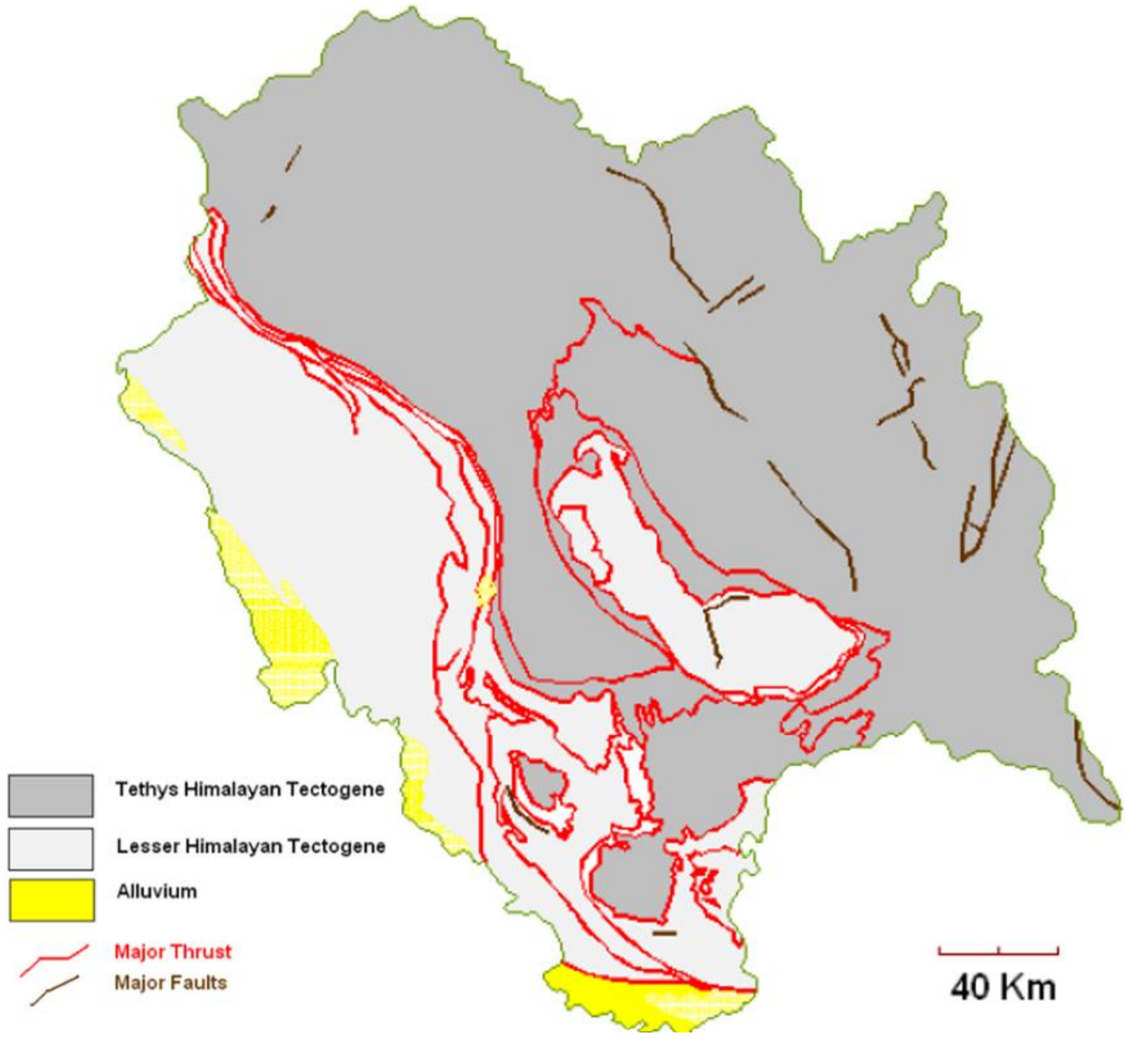


Figure 13 Geological Division of the Himachal Pradesh

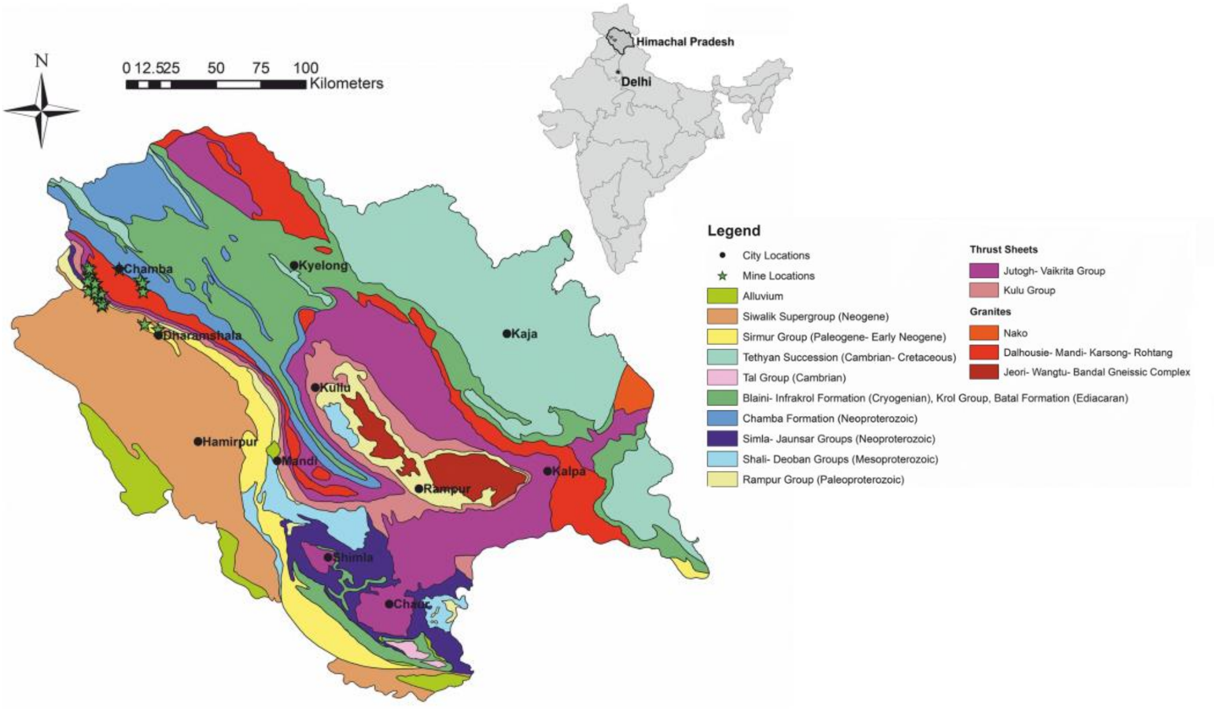


Figure 14 Geological Formation in the state of Himanchal Pradesh

Within these formations, the project site has presence of Shali group all across the area. The shali group further has various rock formations out of which: Ropri, Khaira, Khatpul, Sorgharwari, Tattapani, Makri, Parnali, Bandala formations are present in the region of Shimla district. Only the Khaira and Khatpul are exposed in the quarry portion and, Sorghawari and Tattapani Formations of the Shali Group are exposed around the site. The formations in the quarry site are from the Neoproterozoic period.

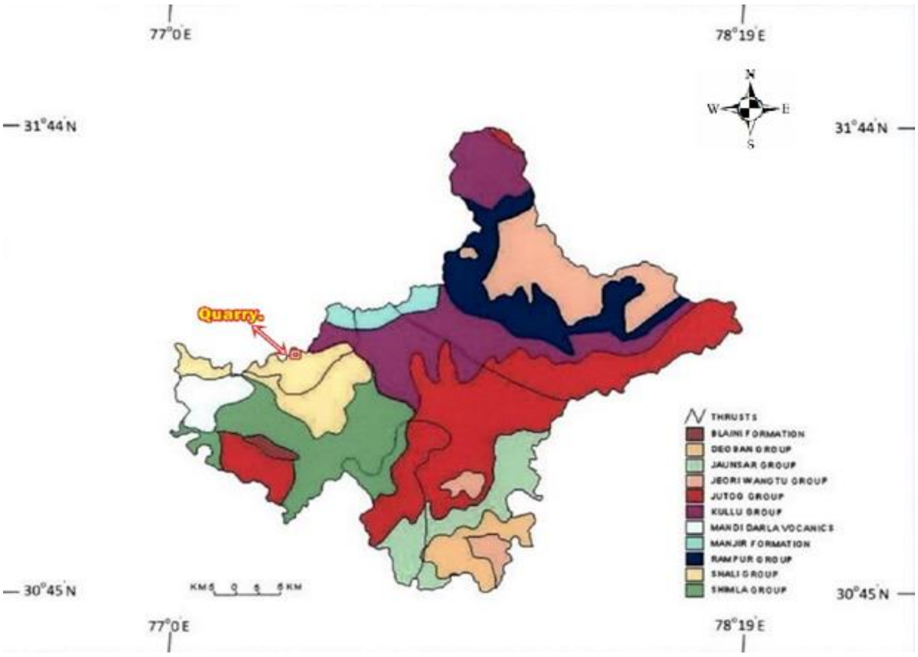


Figure 15 Geological Map of Shimla DIstrict

Litohological description of these formations is given below:

Table 3 Litho-Stratigraphy of locally exposed Shali Group

S. No.	Formation	Thickness (m)	Lithology
1	Khaira	380	Mainly pink and purple, also white quartzarenite.
2	Khatpul	300	Massive dolomite with sporadic quartzite, and a thin red shale band at the base.
3	Sorgharwari	400	Pink and grey cream textured limestone with shale partings.
4	Tattapani	610	Cherty dolomite, grey and pink in colour with grey phyllitesed shales.

4.2 Major Formations in Project Area

Khaira Formation: The Khaira Formation comprises red to gray medium to fine grained, locally coarse-grained quartzarenite/quartzite. Locally thin red shale bands are present in the quartzarenite/quartzite. The bedding features include cross bedding, ripple marks and syneresis mud cracks. The Khaira Formation represents a beach environment of deposition, possible a sand barrier island in a warm and arid climate.

Khatpul Formation: It is made up of grayish blue dolostone, cherty at places with thin but persistent red shale bed at its base. Locally red coloured dolostone bands are also present. The basal part of the dolostone is contains siliceous oolites, obviously as replacement of the calcareous oolites. Also present are gray dolomitic limestone, dolomitic breccias. Stromatolites are exclusively developed in the Khatpul Formation.

Figure 16 Stable Khaira and Khatpul Formations at quarry site

Sorgharwari Formation: The Sorgharwari Formation comprise of pink, grey and cream coloured limestone. This formation achieves maximum thickness of 300 metres in the area. The limestone bed has two distinct sequences:

a. The lower, pink to purple limestone

b. The upper, grey limestone

The pink to purple limestone is very fine textured, creamy, well laminated, banded and bedded. It is also fine grained, dense homogeneous and exihibit concoidal or subconcoidal fractures.

The Sorgharwari Formation was deposited in deeper marine environment where little sunlight penetrated to permit prolific development of stromatolites.

Tattapani Formation: This formation is exposed near Tattapani area, along the river bank of satluj and has has three following litho-units:

a. Black to dark gray fissile and splintery, locally phosphatic shale with thin beds of dolostone and limestone.

b. Massive structureless grayish-blue, locally bedded dolostone at the base.

c. Well-bedded gray locally pyritous dolostone weathering to yellow. It interbedded with gray shale and rare 4-5 cm sandstone beds.

4.3 Geology of Quarry Site

The area belongs to the Lesser Himalayan Zone representing steep valleys and irregular denudated ridges with varying altitudes from 700 m above the mean sea level in the Sutluj Valley to 2867 m the Shali Hill top. The rock exposed in the dam and powerhouse area is mainly pink to grey colour Quartzite/Quartzaranite of the Khaira formation and Dolomite of Khatpul formation belonging to Shali Group. In the reservoir area mainly three rock formations are found: Khaira, Khatpul and Sorgharwari formation of Shali Group.

The geological studies and in-situ tests conducted by SJVNL for the quarry area shows that among the four major geological formations in the region, the geology of area consist of Khaira Formation and Khatpul formation. The Khaira formation shows presence of quartzite and Khatpul formation of Dolomite. The two rock formations Khaira and Khatpul, are joining in the quarry area as shown in figure .

Khaira formation of Shali group is of thickness 380 m displaying Mainly pink and purple color and also white quartzarenite. Khaira formation at base of the hill on the right bank of river Satluj is displaying pink color rock formation. Whereas Khatpul formation of the shali group is of 300m thickness with Massive dolomite with sporadic quartzite. Khatpul formation is observed near the hilltop of site area.

Figure 17 Presence of Khatpul Formation

The khaira formation is present below the formation contact upto the river-bank. Only Khatpul formation is present above the formation contact in the quarry site. The khatpul formations can be seen from the 798 m elevation on the right side of the quarry area and from 758 m elevation on the left side of quarry area.

As seen in the figure below, The major part of the quarry consist of stable khatpul formations consisting of dolomite. At the lower portion of the plan view and more towards the center and western side, there is presence of stable khaira formation consisting of quartzite. the khaira formation is present below the formation contact upto the river-bank, whereas above the formation contact only khatpul formation is present. This concludes that major portion of the site is having khatpul formation.

Both the formations consist of strong to moderately strong rocks having compressive strength of around 50 MPa. The rock patterns having similar compressive strength ensures the uniform homogeneity of formations on the slope, inspite of two different formations.

The quarry site is interspersed with two seasonal drains at approximately at a distance of one-third in the plan view. There were no signs of water in the channels during the visit. A detailed study of the area also did not show any presence of flow of water in the vicinity of quarry area, including below the road level upto the river. Based on this it can be presumed that these channels only contain seasonal rainfall water for draining. However, as water assists landslides, a provision of detailed instrumentation has been advised in this report.

The quarry area has a gentle slope varying from 30-40degrees. The quarry site, based on the slope can be broadly divided into three major portions. The initial one-third area from the top of the quarry area is comparatively gradual slope as the contour lines are spaced apart comparing to the center portion. The central part of the quarry area is having comparatively steeper slope as the contours are at much closer spacing. The last one-third portion closer to the road is again having a gentle slope as compared to the centre portion. This moderate slope on the top and bottom portion of the quarry acts as a natural stability factor to the slope. as per the mining plan, the bottom portion of the leased area is not planned to be disturbed. It shall help to continue providing the natural support to this slope.

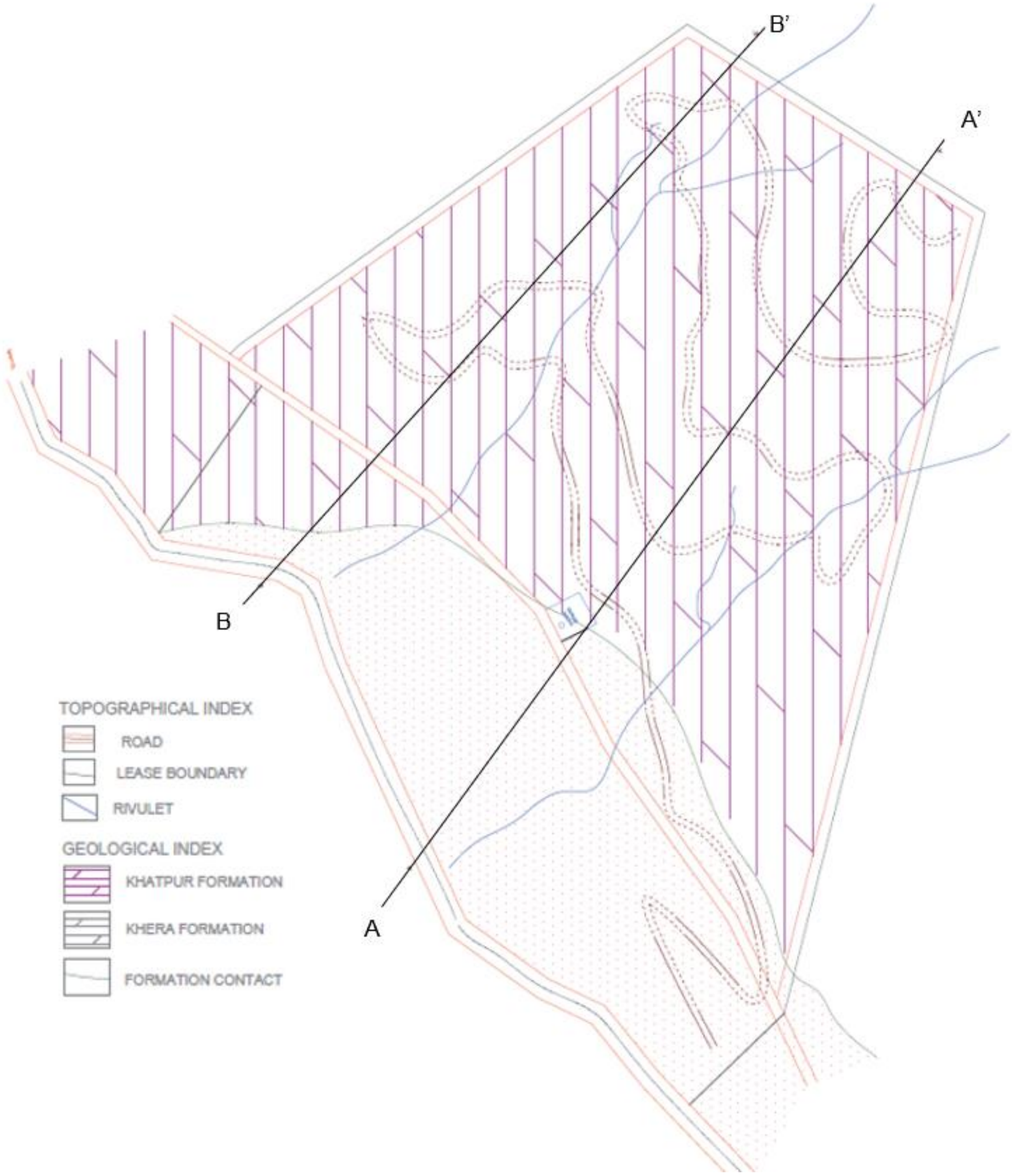
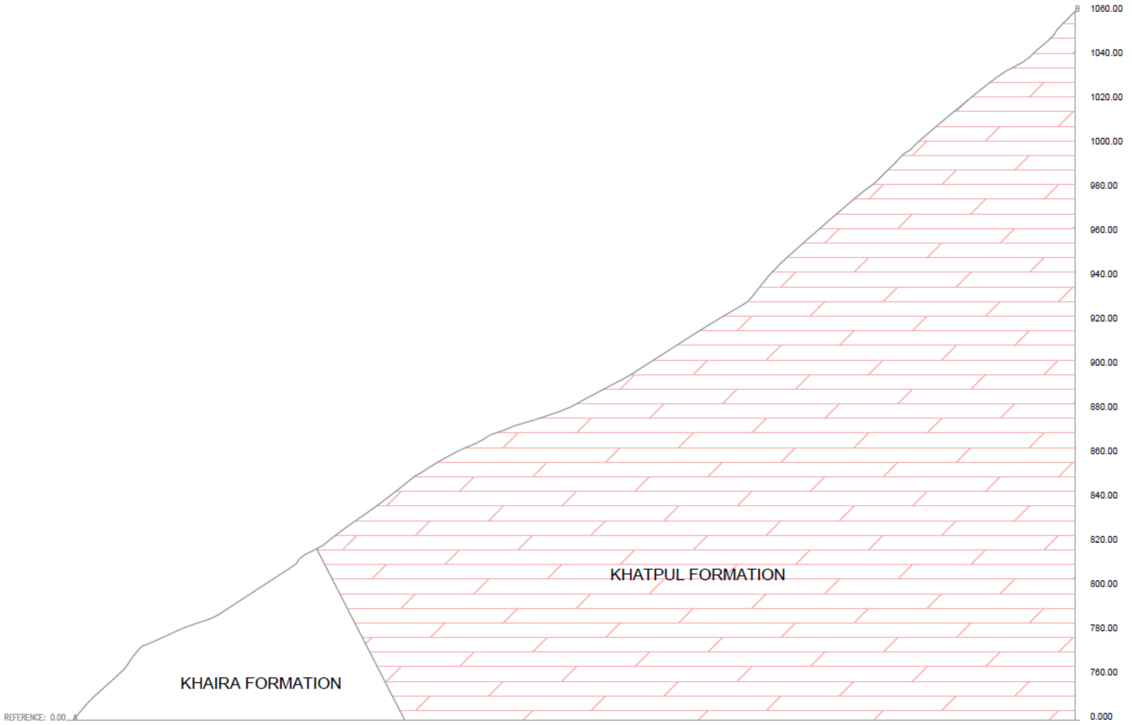
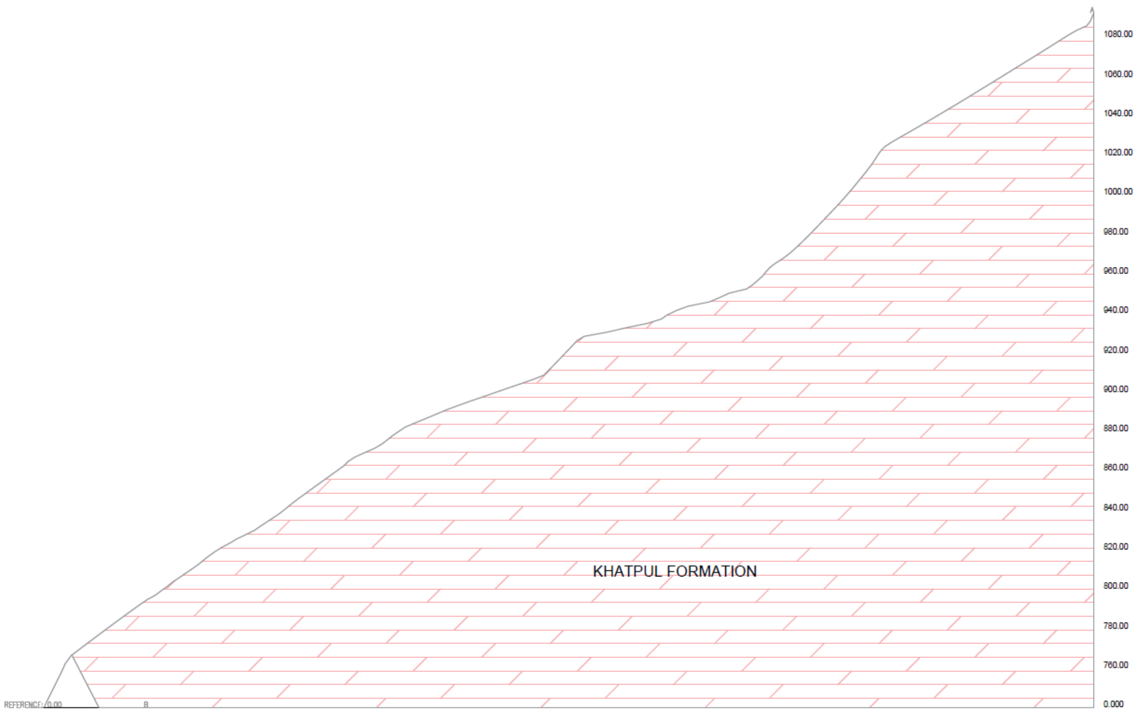


Figure 18 Topography of Quarry Area

The profile of the site shows the elevations and formation joint for khaira and khatpul formations.



a. Profile Along A-A’



b. Profile Along B-B’

Figure 19 Geological Plan and Section of Site

The whole quarry area has composition of Khaira and Khatpul formations which is having average strength of approximately 53 MPa and 49 MPa. As the strength of rock is good and there is no large overburden, In spite of having slope varying from 30-40 degrees, the slopes are very stable. This can also be visualized while travelling through the area where no landslide being seen.

The slope at the top and bottom portion of the site is flatter, while it is slightly steeper at the middle section. The flatter portion of the site slope will assist in stability, as during excavation of site, the overburn is less so the chances of turning or sliding is reduced.

Figure 20 Soil and Vegetation Cover near Site

During site visit it was observed that the soil and vegetation cover in the region is minimal and mostly covered in bushes. This will save the amount of wastage and less harm to the regional environment will happen. Large portions of the site are exposed with khatpul formation, which means that the excavated material can be used to the maximum and less wastage will occur.

The cohesion parameter (c) and angle of internal friction (phi) of the rock formations is described in the table below. The geological strength index for khaira and khatpul formations is 40 and 38 respectively from project geological and in-situ test reports. The geological properties shows that the strength and quality of rock is good, and the area is present with stable rock formations.

S. No.	Rock Formation	C' (MPa)	Phi' (MPa)
1	Khaira	0.94	39
2	Quartz Arenite	0.91	41
3	Khatpul	1.7	42

The site is on the right bank of the river Satluj, starting at an elevation of 798m upto 912m. There is absence of any major tributaries of river, however there are two water channels flowing across the site from contour levels 896m and 906m, also seen in the plan view of site in figure 19.

The client has conducted in-situ tests for shear strength, and excavated drift. A drift excavated of approximately 55m length.

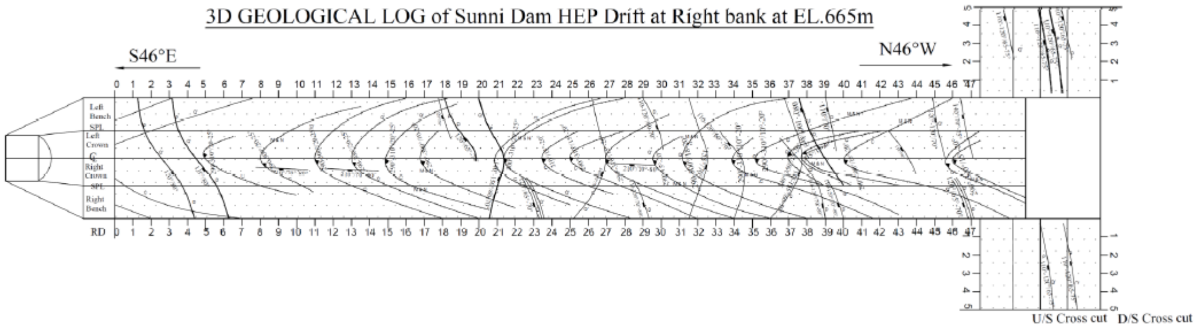


Figure 21 3D Geological Log of Sunni DAM HEP Drift at Right Bank

The in-situ tests conducted on the drift along the right bank of river near dam site. The khatpul formation is not completely foliated and the joints in the formation are at adequate spacing of 10 m in some locations. this shows that the geology of the area is good and stable.

The drift confirms the geological formations throughout the area are consisting of quartzites and dolomite. As the lower part of the quarry where quartzites were anticipated, the same has been seen during excavation of drift. This also confirms that the rock formation is substantially deep in the hills. Hence a partial quarrying of the slope does not endanger the stability of the hill as whole.

5 HYDROGEOLOGY

Hydrogeology deals with the relationships between geological materials and its processes with water. The expertise is important in connection with all construction activities, such as slope cuts and carvings, tunnels, mines, landfills, and excavations for larger structures. During the construction activities, hydrogeology is important for assessment of structural stability.

The Geology of the quarry area encounters massive dolomite, local quartz arenite, thin red shale at base of Khatpul formation and pink, purple, locally grey/ white quartzarenite of Khaira formation. Majority of the quarry cut is in Khatpul formation (Dolomite). The cut also encounters a formation contact along South-West to Northern side and 2 major water channels. These water channels in the slope and the major part of slope is located on the upstream part of dam axis.

The physical characters of rocks, including mineralogical and chemical composition, grain size, their sorting and packing and the primary structures that makes up the overall lithology have hydro-geological significance in the study area. Unconsolidated granular materials like gravels, cobbles, pebbles and sand deposits are potential aquifers and geological structures like synclinal folds, faults, joints and stratified rocks are potential zones for the movement and storage of ground water. The ground water potential of an area is dependent upon the intrinsic characters of the rocks and soil, surface hydrology, depositional and structural features are a direct consequence of the surface geomorphology. Highly inclined alternate layers of rock formations allow runoff in the undulating hilly terrain.

Groundwater represents an important parameter in the geotechnical engineering. The groundwater level has a major influence on material behaviour (drained-undrained), and changes in groundwater level can result in settlements and damage to structures and infrastructure.

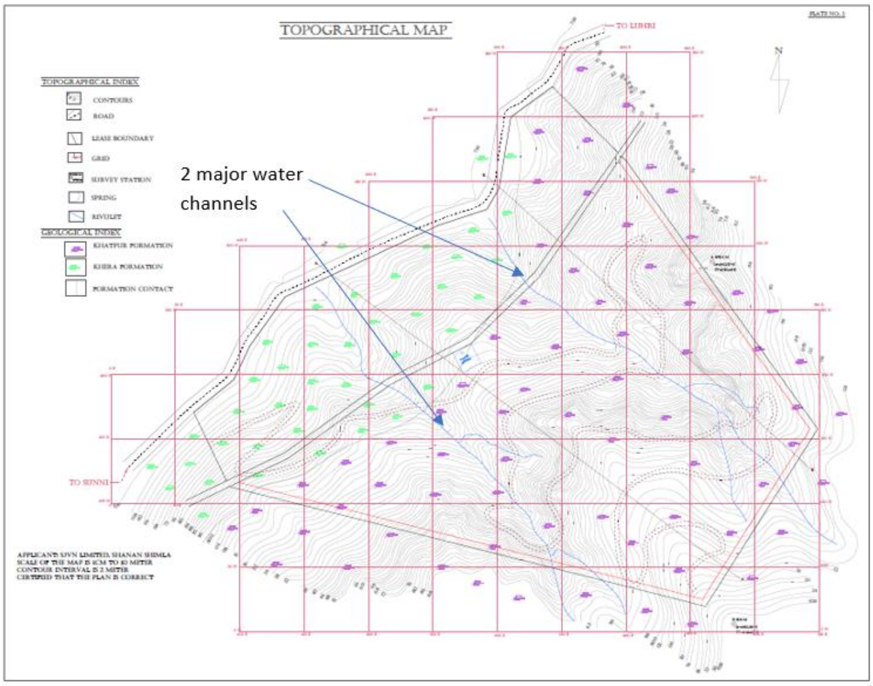
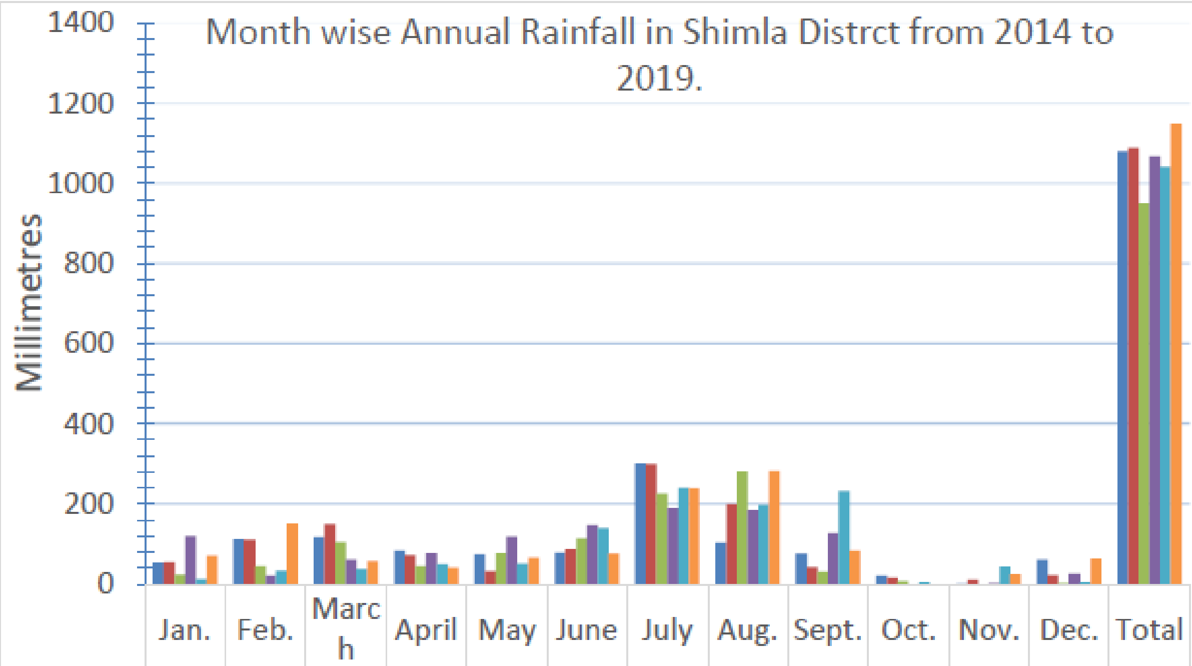


Figure 22 Quarry Map showing Water Channels

5.1 Hydrology of the area

The natural slope observed in the lease area is almost at 45° which makes the rainwater from the catchment area runoff quickly to Satluj River below the hill.

The catchment area is around 0.3 Sq Km and the approximate discharge as per preliminary calculation comes out as approximately 5 cum/s. However, detailed hydrological studies are required to further estimate the discharge precisely.



	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
2014	53.3	112	117	83.6	74.3	78.7	301	103	75.7	21.1	0.6	60.7	1081
2015	54.4	110	149	70.5	30.6	87.3	299	199	41.3	15.1	11.1	21.4	1089
2016	22.6	44	104	43.8	77.6	114	225	281	29.5	6.5	0	2.8	950
2017	120	19.9	59.7	77.5	119	146	189	183	127	0	2.4	24.8	1068
2018	12	32.7	37.6	48.8	50.5	139	239	197	232	3.8	43.4	4.8	1041
2019	70	151	56.2	40.9	64.6	76.8	239	281	83.3	0	23.8	63.1	1149

Figure 23 Monthly average rainfall data of the area

5.2 Catchment area and Quarry site

For the preliminary hydrological design, the reports available on geology and hydrology are considered. No springs are found in the catchment area or near the quarry site. The area is free of snowfall. The expected source of water is thus limited only to rainfall. The area is experiencing mild rainfall with a maximum of 301mm of rain during monsoon in 2014. The slopes are around 25° to 35° on North – West direction. This slope makes the water runoff easier and reduces the effect of permeability and porosity on dolomite. The natural water channels drain the whole water in the catchment area to the river below. The chances of water penetrating to the rock is less in this case. The interaction of water with dolomite is less and the complexities arising due to this can be ignored. However, to have a stable slope, proper drainage design is recommended to make the rainwater run off to the river.

Figure 24 Catchment area and Quarry site

There are 2 natural drains in the catchment area which takes the rainwater to the river below. The steep slopes make it easy for the water to drain easily. The proposed quarry will cut both the drains thus disturbing the natural flow. The concepts and failure mechanisms that underlie slope stability analysis hold on both natural slopes and man-made slopes. This can be lessened with the introduction of catchwater drain networks with proper slope. Details design of the drain shall be carried out and the same should ensure the runoff quickly. The lack of presence of springs in the area makes it suitable for quarry.

Figure 25 The natural drains on the Quarry slopes

5.3 Drainage requirements

There are some significant differences between the analysis of soil slopes and the analysis of slopes in rock. As the area are primarily of dolomite rock, the effect of groundwater conditions on Slope Stability in Rock is only considered in the design. The estimated soil cover is less and will be removed during cutting of slopes. Any water flowing from the top of the quarry shall be collected with smaller drains to the main central drains running parallel to the natural drains. Drains along the benches will collect the water flowing over the slopes and will be delivered to the main drains.

The runoff water is calculated as 5 cum/s overall. Considering size and slope of the natural channels it is estimated that 3 cum/s will be flowing through the left drain and 2 cum/s will be taken by the right channel. Assuming a min velocity of 2m/s, the approximate maximum area requirement of the drain comes out to be 1.5 sqm. The approximate size of the RCC drains can be kept as 1.5m x 1m depth. To collect the water falling from the cut slopes and to deliver to the main drains, suitable drains of size 500m x 500m is proposed. All these are based on the data available. Detailed design shall be done for accurate calculation and results.

The excavation area cuts 2 major water channels. These natural drainages shall be reinstated after the mining. To minimise the contact of water with rock formation, the drains shall be made of concrete across the slopes and flushing with the gabion walls according to the slope design. Any blockage to the natural drain must be avoided. Proper maintenance is to be ensured for the drains to remove the debris and rocks falling in the drain. The drain is designed to have the same slope as the cut section and at the foot of the cut area, a minimum slope of 2% shall be provided to drain the water to the river. Proper mitigation measures shall be adopted to avoid debris and rock falls to the drain from the top of the cut section.

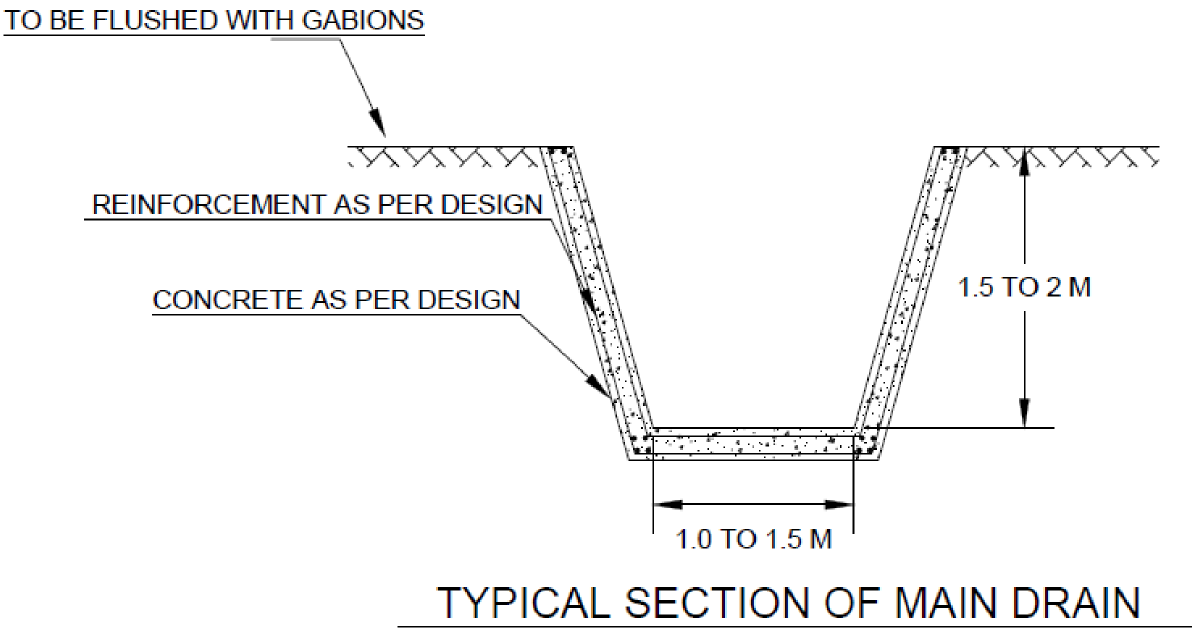


Figure 26 Typical Section of Main Drain

6 SLOPE STABILITY

6.1 Factors that Influence Slope Stability

6.1.1 Gravity

The overburden on a slope is critical for the slope stability analysis. The main force responsible for movement of overburden mass is gravity. If the slope contains of huge boulders it needs to remove or should be stabilized with proper measures. The slope angle of the formation and the excavation planned is also a critical factor to be considered.

Gravity is the force that acts everywhere on the Earth's surface, pulling everything in a direction toward the center of the Earth. On a flat surface the force of gravity acts downward. So long as the material remains on the flat surface it will not move under the force of gravity.

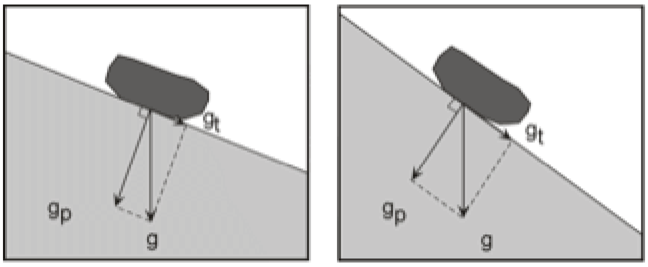


Figure 27 Effect of Gravity

On a slope however, the force of gravity acts different and can be resolved into two components: a component acting perpendicular to the slope and a component acting tangential to the slope.

- The perpendicular component of gravity, g_p, helps to hold the boulders on the slope. The tangential component of gravity, g_t, causes a shear stress parallel to the slope that pulls the boulder in the down-slope direction parallel to the slope.
- The forces resisting movement down the slope are grouped under the term shear strength which includes frictional resistance and cohesion of the formation.
- When the shear stress becomes greater than the combination of forces holding the overburden material on the slope, the slope will fail.
- Alternatively, if the overburden consists of a collection of materials like soil, clay, sand, etc., if the shear stress becomes greater than the cohesive forces holding the particles together, the particles will separate and move or flow down-slope.

Thus, down-slope movement is favored by steeper slope angles which increase the shear stress, and anything that reduces the shear strength, such as lowering the cohesion among the particles or lowering the frictional resistance. This is often expressed as the safety factor, Fs, the ratio of shear strength to shear stress.

$$F_s = \text{Shear Strength / Shear Stress}$$

Shear strength consists of the forces holding the material on the slope and could include friction, and the cohesive forces that hold the rock or soil together. If the safety factor becomes less than 1.0, slope failure is expected.

The slope on which the quarry is proposed is having a gentle slope and no presence of boulders were observed during the initial reconnaissance. The geology of the area is expected to be of moderately strong to strong dolomite rocks of Khatpul formation. The effect of slope angle, excavation proposed on the slope is analyzed below using finite element analysis. The gravitational force is considered in the form self-weight of the materials and by considering the body forces as a parameter during analysis.

6.1.2 Ground Water and Runoff

The topography of the proposed quarry area is such that it has two valleys encountering it. During rain there will be runoff through these valleys and a chance of water seeping through the joints of the rock outcrops into the slopes. A drain provision shall be proposed to tackle the runoff water approaching the excavated quarry area and to avoid future slope stability issues.

Although water may not always directly be involved in slope failure, it does play an important role. Water becomes important for several reasons

- Addition of water from rainfall or snow melt adds weight to the slope. Water can seep into the soil or rock and replace the air in the pore space or fractures. Since water is heavier than air, this increases the weight of the soil. Weight is force, and force is stress divided by area, so the stress increases, and this can lead to slope instability.
- Water can change the angle of repose (the slope angle which is the stable angle for the slope)
- Water can dissolve the mineral cements that hold grains together. If the cement is made of calcite, gypsum, or halite, all of which are very soluble in water, water entering the soil can dissolve this cement and thus reduce the cohesion between the mineral grains.
- Liquefaction of soil may occur because of ground shaking, as we discussed during our exploration of earthquakes, or can occur as water is added as a result of heavy rainfall or melting of ice or snow. It can also occur gradually by slow infiltration of water into loose sediments and soils.
- Groundwater exists nearly everywhere beneath the surface of the earth. The water table is the surface that separates the saturated zone below, wherein all pore space is filled with water from the unsaturated zone above. Changes in the level of the water table occur due changes in rainfall. The water table tends to rise during wet seasons when more water infiltrates into the system and falls during dry seasons when less water infiltrates. Such changes in the level of the water table can have effects on the factors of geology as discussed above.

The quarry area is located well above the Satluj river and on a higher slope of the mountain. Influence of ground water is less likely on the excavated slope. However, the effect of water table is considered in the analysis by taking the saturated unit weight of rock formations. The reports provided on the quarry area points out the presence of strong to moderately strong rock presence. On considering the seepage of runoff through the joints, adequate draining facilities for ground water shall be assured for preventing the development of pore pressure. The development of pore pressure may lead to slope failure. These simple measures throughout the excavated slope will see the complication due to the ground water and seepage water solved to an extent.

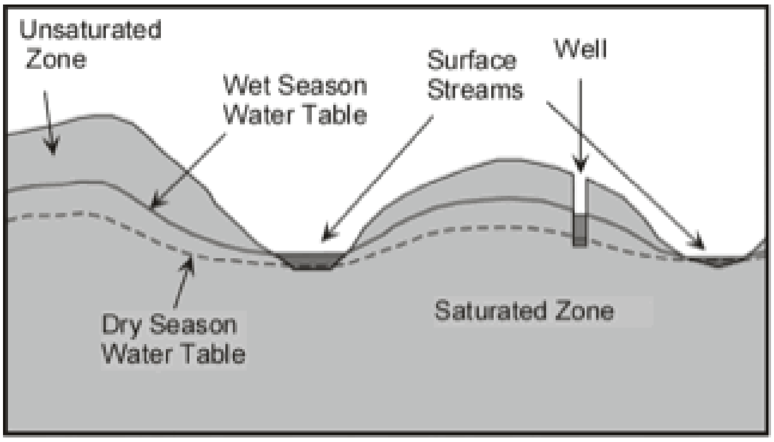


Figure 28 Effect of Groundwater

6.1.3 Triggering Events

A mass movement event can occur any time a slope when it becomes unstable. Sometimes, as in the case of creep or solifluction, the slope is unstable all the time, but the process is continuous. However, sometimes, triggering events can occur that cause a sudden instability to occur. A sudden shock, such as an earthquake may trigger slope instability. Minor shocks like heavy trucks rambling down the road, trees blowing in the wind, or human made explosions can also trigger mass movement event. Hence, doing a slope stability analysis and kinematic analysis in the case of a quarry is important to ensure the stability of the slope.

The analysis suggested in the report shall also consider the earthquake forces in determining the global stability of the excavated slope. This analysis can ensure stability slope against failure to an extent against the vibrations caused due to earthquake forces, other forces from excavation, vehicle movement etc.

6.2 Methodology for Design of Slopes

In general, slope stability analysis is carried out by considering the two failure modes, circular failure to check global stability, failure against sliding of wedge along the discontinuities (planar and wedge). Kinematic analysis of the wedge formations is checked by discontinuity analysis using Dips. Wedge stability is checked by using software SWEDGE, planar sliding is checked using software RocPlane to find FOS for potentially unstable wedges and global stability is checked by Phase 2 model. Adopted factors of safety for different failure modes are tabulated in Table.

Table 4 Adopted FOS for Possible Loading Conditions

Load Cases	Description	Minimum Factor of Safety Required
Dead Load + Water	Normal Operating condition	1.5
Dead Load + Water + Earthquake load	Extreme Condition	1

6.2.1 Load Combinations/ FOS for Possible Loading Conditions

Following load combinations are considered for the analysis:

1. Self-weight of rockmass (saturated unit weight) is considered.
2. Earthquake Loads: Since the area falls in Zone IV of seismic map of India. As per IS 1893, the basic seismic coefficient for zone IV is 0.24, the importance factor is 1.5 for these slopes R = 3 for conservative value and Sa/g =2.5. Hence the horizontal Seismic Coefficient will be (0.24/2)*(1.5/3)*2.5=0.15 (Response Spectrum Method) and Vertical Seismic Coefficient equal to 0.10 (2/3rd of Horizontal Coefficient) will be considered.

6.3 Assumptions for Designing Slopes Support System

- Structural features are described as weakness planes along which slope failure may take place.
- Representative models have been developed based on available structural discontinuities with conservative joint strength parameters.
- Failure plane will be a single plane or a combination of planes.
- The shear parameters for the rock mass considered in the analysis are estimated based on available geological data, geotechnical investigation and testing data, surface geological mapping report.

6.4 Support/Reinforcement Properties

The geology of the quarry area is expected to be stable, since a gentle slope is planned for excavation on a moderate to strong dolomite rock formation. The supports are proposed to stabilize the fracture patches of rocks if encountered and to tackle the possibilities of failure due to joint sets. Support measures shall be adopted alongside the proposed drain for stability of the benches nearby as per site conditions.

The proposed support system to stabilize the probable weak area is gabion walls. Gabions walls shall be adopted at the bottom most slope of the proposed benches, where the chance of failure is highest and possibility of rolling stone from above. The technical specification for gabion walls is provided in the section below.

6.4.1 Gabion Walls

6.4.1.1 Stone

Stones used for filling for gabion boxes shall be clean, hard, sound, unweathered and angular rock fragments or boulders. The smallest dimension of any stone shall be at least twice that of the longer dimension of the mesh of the crate. The mesh spacing shall be decide after detail design along with the minimum strength of stone filling. A representative sample of the filling rock sample proposed to use in the gabions shall be approved by concerned authority. Further representative samples shall be submitted for approval each time whenever there is a change in the type or strength of the rock.

6.4.1.2 Gabion Crates

Gabions shall consist of steel wire mesh crates. The steel wire shall be mild steel wire complying with IS 280-197. All wire used in the manufacture of the crates and for use as diaphragms, binding and connecting wire shall be galvanised with an extra heavy coating of zinc by an electrolytic galvanising process. The weight of deposition of zinc shall be in accordance with IS 4826-1979. Zinc coating shall be uniform and shall be able to withstand a minimum number of dips and adhesion test specified as per IS 4826-1979. Tolerance on diameter of wire shall be 2.5 percent and the diameter of the wire shall be fixed after detail design of gabion wall. The tensile strength shall be between 300 to 550 N/mm2 or design specific. The wire shall be mechanical woven into a hexagonal mesh of standard size with tolerance of +16 and -4. The tightness of the twisted joints shall be such that a force of 7 KN is required to pull on one wire to separate it from the other wire provided that each wire is prevented from turning and the whole process is done in one plane. All edges of the crates shall be finished with a selvedge wire. Gabions shall be manufactured in the standard sizes shown in the following table. A typical section of gabion wall is provided with the report.

Table 5 Standard sizes of Gabions

Sl. No.	Dimensions (m)	Diaphragm (No)	Dimensions of Diaphragms (m)	Volume of Crate (m3)
1	1x1x1	1	1x1	1
2	1.5x1x1	1	1x1	1.5
3	2x1x1	1	1X1	2
4	3x1x1	2	1x1	3
5	2x1x0.5	1	1x0.5	1

Diaphragms shall be manufactured of the same materials as the parent gabion and shall have selvedge wire throughout their perimeter. The number and size of diaphragms to be provided with each crate shall be as in the above table. All crates shall be supplied with binding and connecting wire.

6.4.2 Geotechnical Properties

The geotechnical properties of the rock formations are of primary importance for carrying out the slope stability analysis. The strength parameters of rock formations on the right bank of the dam are found out by conducting various in situ tests in the drift and laboratory tests on the samples are provided. Two failure criterions, Hoek and Brown and Mohr Coulomb properties are also provided from these test results.

The major geological formation of mining area is Khatpul and Khaira formation which belongs to Shali group. The major rock formation observed in Khaira formation is Quartzite and Khatpul formation consists majorly of Dolomite rock. The failre criterions for dolomite and quartzite rocks of Khatpul and Khaira formations respectively are defined below:

6.4.2.1 Hoek and brown parameters

The Hoek and Brown criteria defines the strength parameters of the rock formations by considering various factors like joint spacing, joint roughness, UCS value etc. This criterion defines the Geological Strength Index (GSI) of the formation along with other factors like m_i value, 'a' value and 's' value. The parameters for the rocks Quartzite, Quartz Arenite and Dolomite formations as provided in the reports are explained in the following sections.

Quartzite

- The GSI value by considering the factors from site and tests is provided to be - GSI – 40
- As per the failure criterion, for GSI > 25, a = 0.5
- By adopting various values for 's' analyses is carried out for finding m_i values.

Analysis I: Adopting s = 1, 0

Analysis II: when mi and s are purely evaluated from triaxial data,

mi = 65 and s = 0.60

Analysis III: mi recommended by Hoek and Brown for Quartzite

mi = 24 for s = 1

After considering the following analyses and GSI values the recommendation for m_i is provided as:

As per the Generalized Hoek and Brown Criterion, in the absence of triaxial data, for quartzite rock mi can be considered as 24, which in the particular case is far lower than that of triaxial data. So, in view of the foregoing, a conservative value 35 can be adopted as mi for the Quartzite.

Quartz Arenite

- The GSI value by considering the factors from site and tests is provided to be - GSI – 40
- As per the failure criterion, for GSI > 25, a = 0.5
- By adopting various values for 's' analyses is carried out for finding m_i values.

Analysis I: Adopting s = 1,

mi is ranging from 24 to 48 and most of the values are hovering around 40.

Analysis II: when mi and s are purely evaluated from triaxial data,

mi = 44 and s = 0.79

Analysis III: mi recommended by Hoek and Brown for Quartz Arenite

Not mentioned

After considering the following analyses and GSI values the recommendation for m_i is provided as:

In view of the foregoing, a conservative value 25 can be adopted as mi for the Quartz Arenite.

Dolomite

According to the provided results obtained from the investigations performed on the Dolomite rock cores, are having wide scatter and infers that the rock is having high inherent variability.

- The GSI value by considering the factors from site and tests is provided to be GSI – 38
- As per the failure criterion, for GSI > 25, a = 0.5
- By adopting various values for 's' analyses is carried out for finding m_i values.

Analysis I: Adopting s = 1,

mi is ranging from 18 to 60 and most of the values are in between 20 to 40.

Analysis II: when mi and s are purely evaluated from triaxial data,

mi = 24 and s = 0.57

Analysis III: mi recommended by Hoek and Brown for Dolomite

Not mentioned

After considering the following analyses and GSI values the recommendation for m_i is provided as:

In view of the foregoing, a conservative value 15 can be adopted as mi for the Dolomite.

6.4.2.2 Mohr Coulomb criteria

The shear strength of a formation is defined by C and Phi properties obtained from various tests. These parameters is adopted for the global stability check by considering the Mohr coulomb criteria of the excavated slope of quarry area. Angle of Friction and Cohesion properties as provided for the formations in the quarry area is given in the table below:

Table 6 Shear Strength Parameters

Sl. No.	Rock Type	E (MPa)	C' (MPa)	Phi' (MPa)
1	Quartzite	25000	0.94	39
2	Quartz Arenite	27000	0.91	41
3	Dolomite	35000	1.7	42

6.4.2.3 Characteristics of Discontinuity

The discontinuity characteristics are obtained from the field observations of the formations. The joint data provided for the quarry area are tabulated below for Dolomite and Quartzite separately. Joint sets and its characteristics have a huge significance in kinematic analysis of the slope.

Quartzite

The joint data for Quartzite is obtained from the 3D geological log of drift provided for the right bank of dam. The formation of quartzite on the slope is expected to be more or less same as it is observed in the drift. Table below is listing the joints.

Table 7 Joint Details of Quartzite

Joint Set	Dip angle	Dip direction
J1	80	110
J2	80	110
J3	85	210
J4	70	120
J5	65	155
J6	60	165
J7	70	155
J8	15	290
J9	60	165
J10	80	95
J11	70	110
J12	70	125
J13	70	140
J14	65	120

Dolomite

The joints set for the dolomite formation on the right bank is provided and is listed below by considering the data.

Table 8 Joint Details of Dolomite

Joint Set	Dip angle	Dip direction
J1	15°-22°	305°-310°
J2	30°-75°	120°-160°
J3	75°-85°	210°-230°
J4	80°-90°	275°-300°

6.5 Analysis & Design of Slope

The conventional method for analysis and design of slope in geotechnical design is to apply a factor of safety using different methods. Such factor of safety can be computed from **Equation** below

$$FS = \frac{R}{S} \geq 1$$

where R is the load resistance limit and S is the load effect. In the analysis shear strength reduction method is considered for global stability analysis using Phase 2 and kinematic analysis is carried out for planar and wedge failure of slope using Dips.

Section of existing ground surface is obtained from the contours and modeled in Phase 2 for checking the stability of the natural slope. The natural slope consists of two geological formations, Khaira and Khatpul formations. Quarry area is proposed is majorly in Khatpul formations in which the rock formation is of dolomite. Whereas the lower slopes majorly consist of Quartzite of Khaira formation. Stability of the natural slope is analyzed and compared with the slope formed after proposed excavation for a better understanding of the influence of excavation.

Kinematic analysis of the slopes after excavation are carried out using Dips. The joint data provided in table above for the right bank of dam area is used for this analysis. 3D geological log provided for the right bank of dam axis and the joint details provided for the right bank geology are considered for the data. A stereo net is produced using the data and is been checked for planar, wedge, and toppling failure.

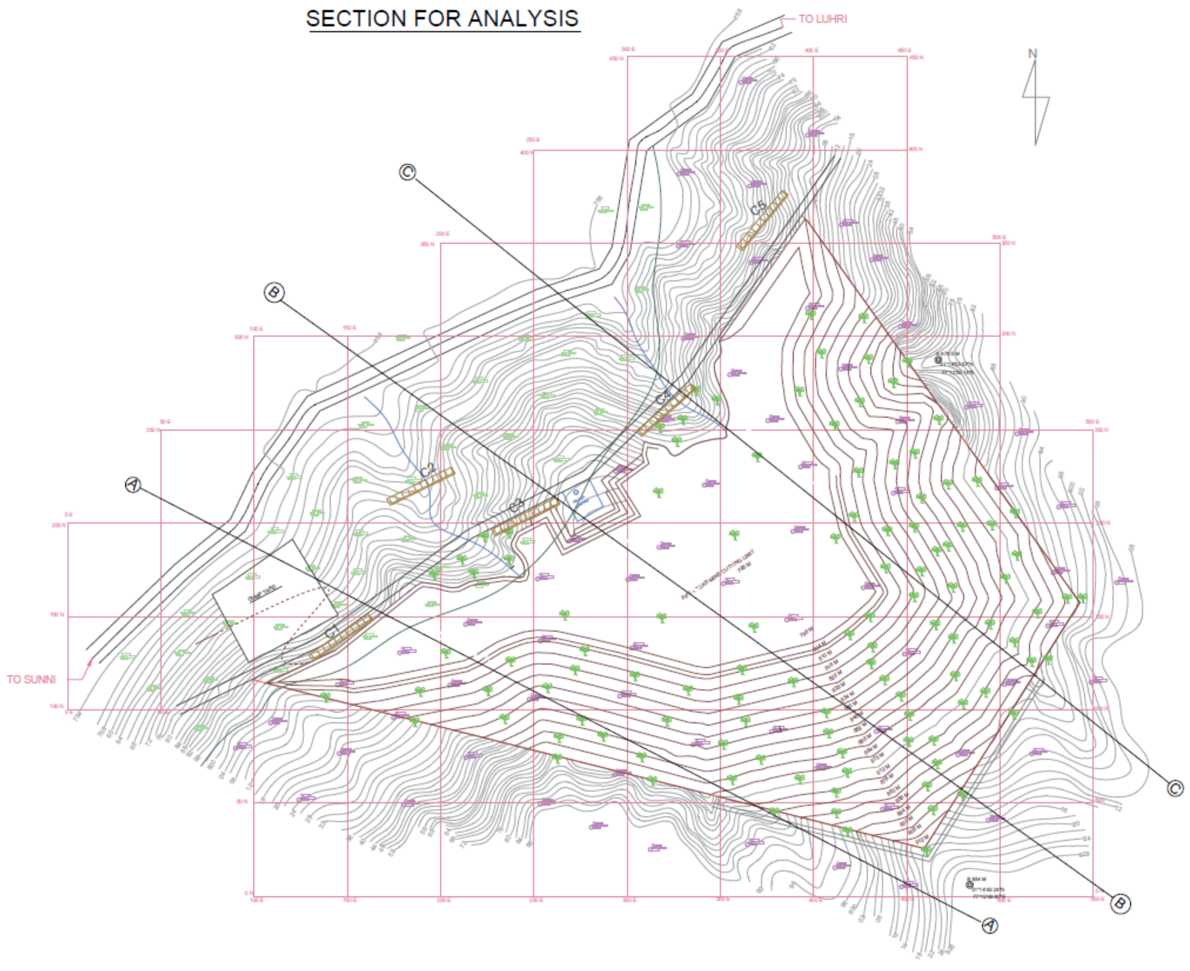


Figure 29 Sections for Phase 2 Analysis

Three Sections (section A-A, section B-B, section C-C as shown in figure above) were considered from the quarry area for analysis. The section is selected according to the criticalities of the locations. Model 1 is selected randomly on the quarry area where the section A-A is encountering both dolomite of Khatpul formation and Quartzite of Khaira formation. Model 2 is the same section that of Model 1 in which the natural slope is been excavated. This section which is having both Khaira and Khatpul formation will be critical for slope stability since two different formations are encountering. Whereas the section B-B adopted in model 3 is having only dolomite rocks of Khatpul formation.

The proposed quarry area is also having two valleys and will be critical to analyze the section along the valley. Section C-C is selected on the valley area of the quarry where the formation encountered is dolomite.

The slope below the proposed quarry area is also considered in the analysis since, the excavation may have some influence on the slope below. It consists of quartzite of Khaira formation and considered in the model 1 in global stability check. The joint sets of the slope is considered in kinematic analysis using Dips. The slope below the quarry area is also of prime importance and necessary measures needs to be taken for its stability.

6.5.1 Global Stability Check for Slope Using Phase 2/RS2

The global stability analysis for the slope is carried out in three different critical sections (section on valley, section on ridge, section with both Khaira and Khatpul formations). The results of the analysis are expressed as a factor of safety which is defined as the ratio of available shear strength to the shear stresses developed on the sliding plane.

6.5.1.1 phi-C Reduction Method

The traditional approach to decide the safety factor is to increase the load incrementally until failure so that the difference between failure load and actual load is studied. But sometimes in practical work, strength reduction methods will be applied as alternatives. One procedure is called φ − c reduction method. The strength parameters (c, phi) are gradually reduced until failure while keeping load constant instead of changing it. In some finite element programs like Phase2, the Mohr-Coulomb failure surface is lowered incrementally and the cohesion a is kept constant until large deformations appear. A new form of safety factor, multiplier for safety factor MSF, is then defined as the ratio between actual strength and reduced strength. As shown in **Figure** below and **Equation**, the calculation will be continued until it reaches a well-developed plastic failure and a well-defined safety factor.

$$MSF = FS = \frac{tan\varphi}{tan\rho}$$

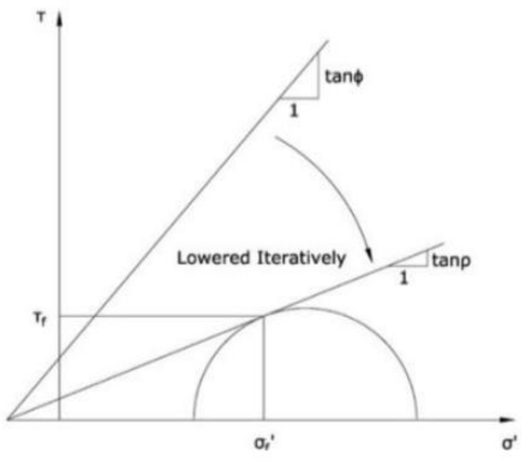


Figure 30 phi-C Reduction

6.5.2 Analysis

6.5.2.1 Model 1 - Existing Slope

The existing natural slope is modeled in phase 2 to compare its stability with the excavated slope. The section is obtained from the provided contour of the mining area. There are two different formations Khatpul and Khaira encountered in the mining area which consists of Dolomite and Quartzite respectively. Both the formations is modelled in the software for global stability analysis.

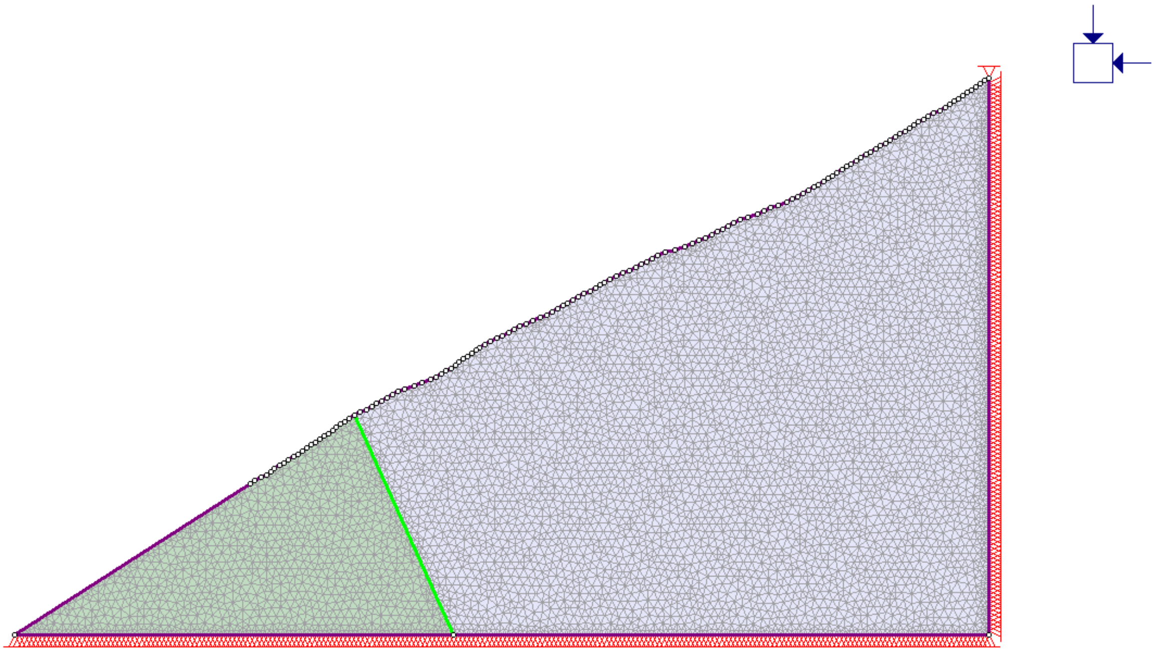


Figure 31 Model 1 - Phase 2 Model for natural Slope

Mohr Coulomb failure criteria is adopted for checking the stability of the slope. Material for dolomite and quartzite is modeled as plastic elements by providing peak and residual values for C and Phi parameters. Automatic meshing of the model is adopted using 6 noded triangular elements. The bottom and right side boundary of the modeled slope where the ground will continue is supported against X and Y direction. The boundary of ground surface of the model is kept free for taking the body force into account during analysis.

Result

The result shows the natural slope is having factor of safety of 1.66 which is more than 1.5 and the slope is stable. The analysis also shows the failure pattern developed after the 1.66 FOS is due to the global failure of the whole existing slope. This value of factor of safety may increase if the whole mountain slope is modeled in Phase2, which may simulate a better natural condition for the slope.

Hence, the result of the simulation is approached specifically to the excavated slope area from the strain diagrams obtained after the analysis

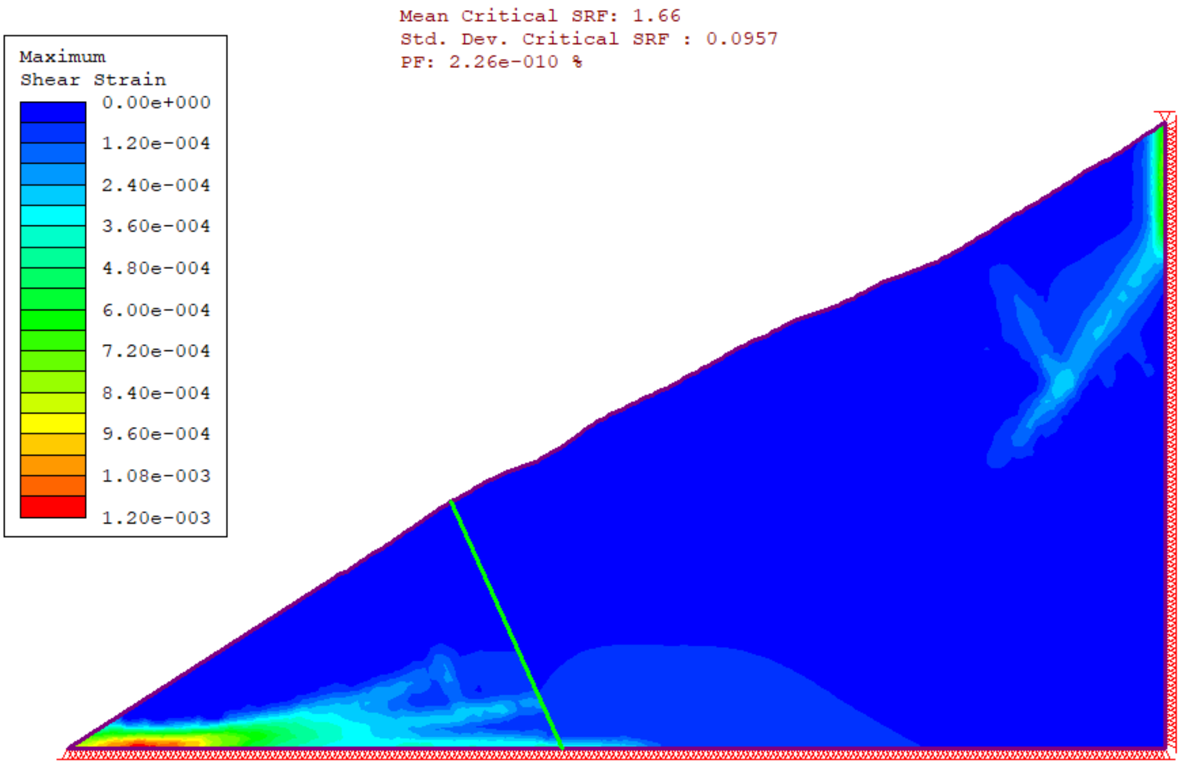


Figure 32 Results of Model 1 for natural Slope

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6.5.2.2 Model 2 - Section with Khatpul (Dolomite) and Khaira (Quartzite) formations

Model 2 represents the completely excavated natural slope which formed after the execution of five-year mining plan. Similar to model 1 both dolomite and quartzite rocks are being encountered in model 2 also. The section of the quarry area for global stability check is modeled in Phase 2 for analysis as shown below. After simulation both the models will be compared for their factor of safety. to consider Mohr Coulomb failure criterion of slope. Automatic meshing of the model is adopted using 6 noded triangular elements. The bottom and right side boundary of the modeled slope where the ground will continue is supported against X and Y direction. The boundary of ground surface of the model is kept free for taking the body force into account during analysis.

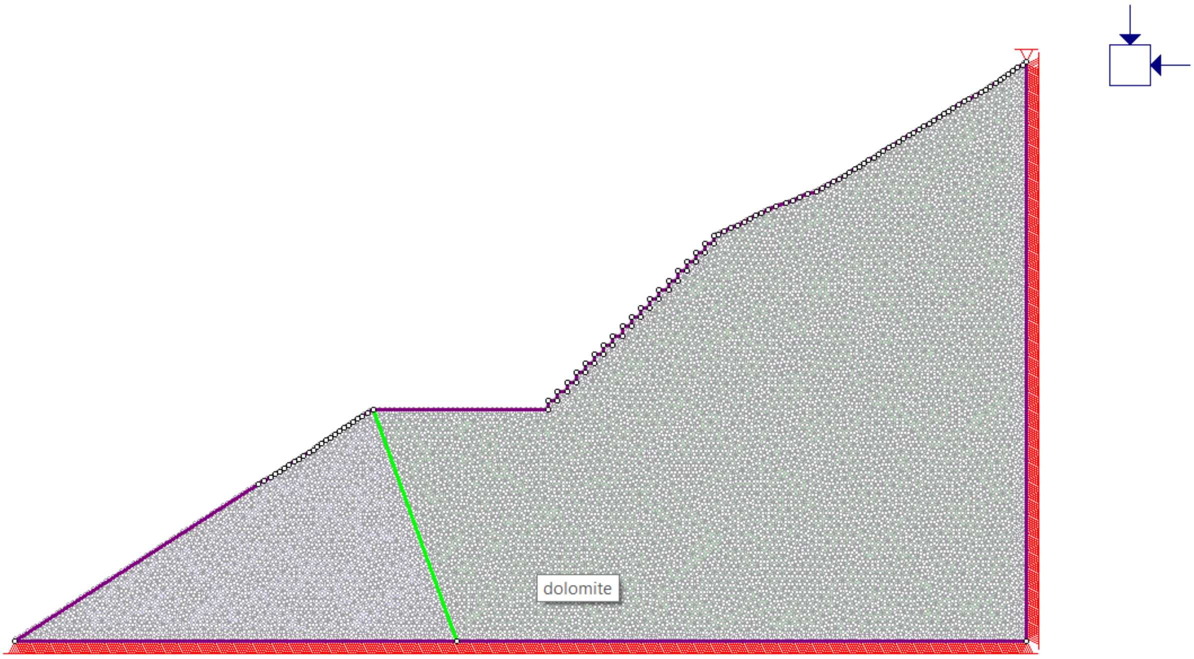


Figure 33 Model 2 - Phase 2 Model for excavated Slope of Section A-A

The model is also analyzed for earthquake loading by considering a maximum ground acceleration of 0.24g since the quarry area falls in Zone IV. The horizontal seismic coefficient and vertical seismic coefficient is calculated according to IS 1893 and given input as a factor in Phase 2 for analysis.

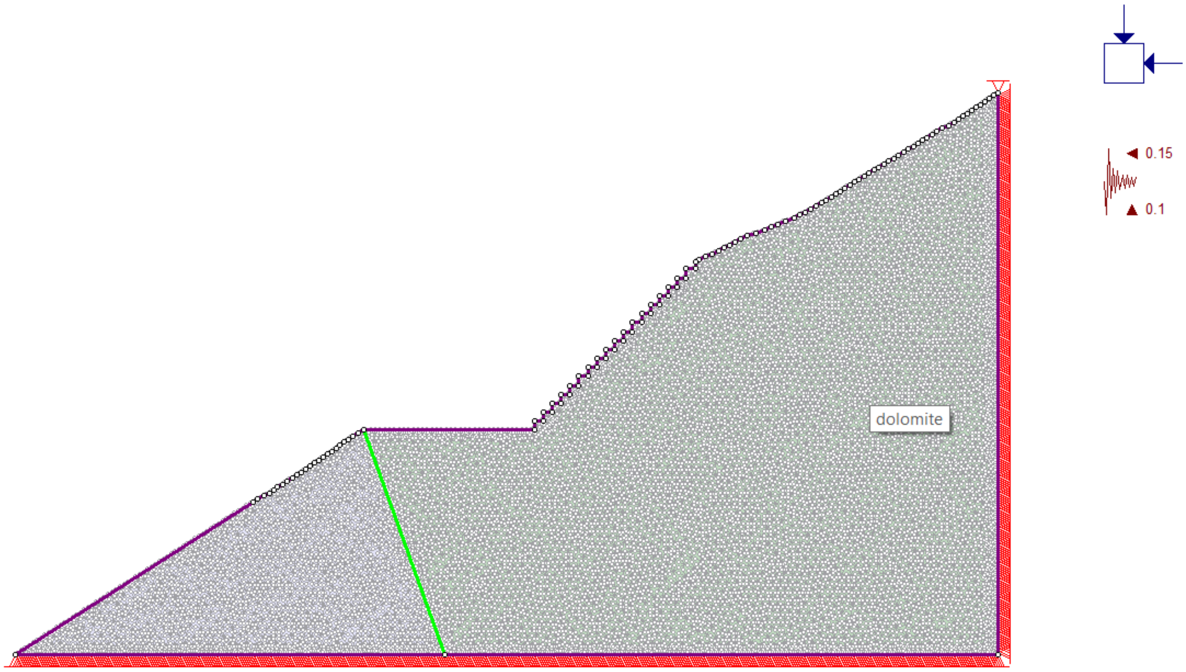


Figure 34 Model 2 - Phase 2 Model for excavated Slope of Section A-A

(Earthquake force is considered)

Result

The result of simulation is showing an increase in FOS after the excavation of natural slope as expected. This is because, the excavation decreased the self-weight of the slope and lead to shift in center of gravity of probable slip circle further down. It will increase the stability of the slope. The results obtained with a higher factor of safety is also simultaneously validating our model.

From the maximum shear strain diagram obtained from the analysis it is visible that the quarry area is not having any critical zone. This ensures the global stability of the excavated slope.

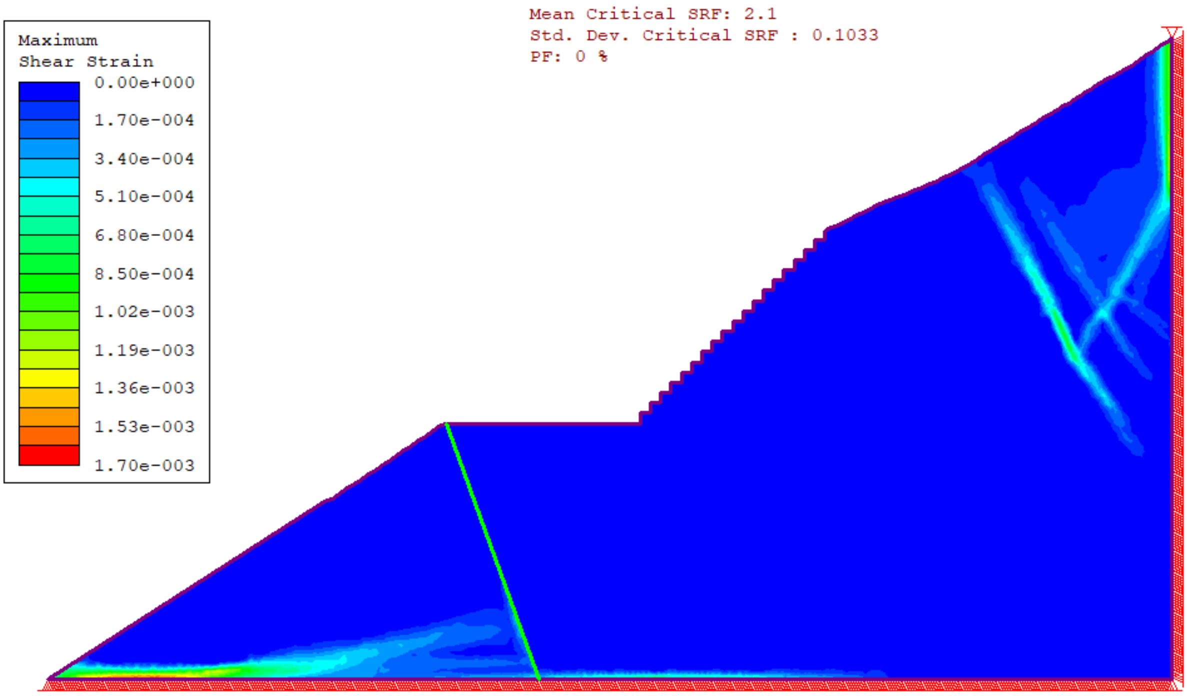


Figure 35 Result of Model 2 for excavated Slope of Section A-A

After considering earthquake force in the analysis the factor of safety decreases to 1.51 from initial factor of safety of 2.1. The limiting critical factor of safety when exceptional loading is taken into account is 1.0. Hence, we can conclude our slope is stable to the satisfiable limit against the occurrence of unusual vibrations.

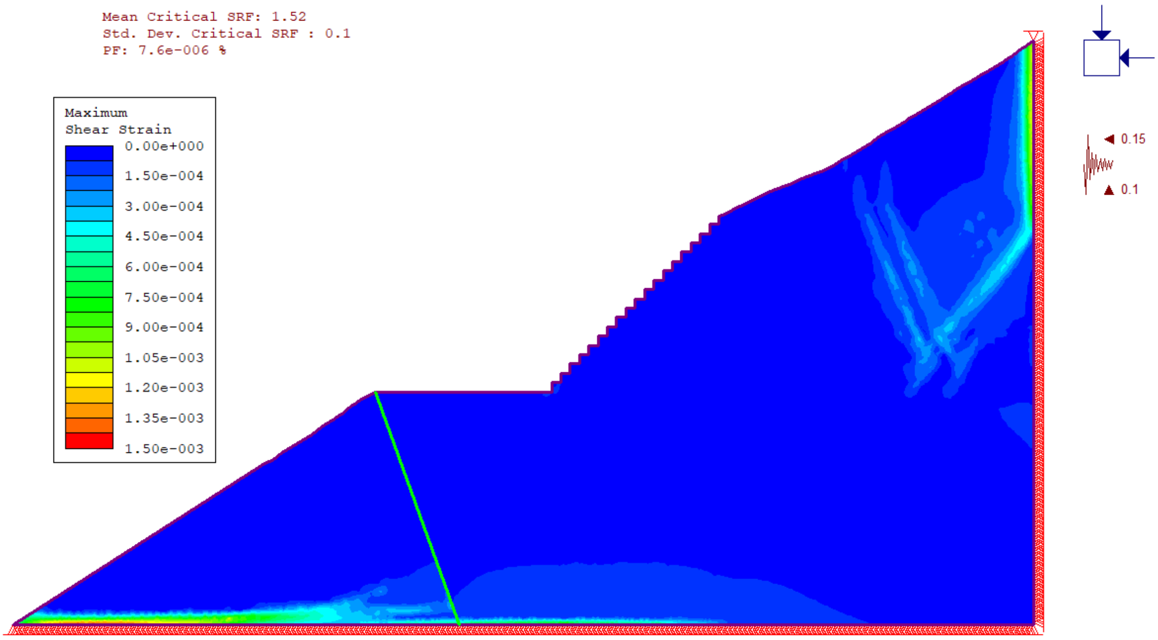


Figure 36 Result of Model 2 for excavated Slope of Section A-A

(Earthquake force is considered)

6.5.2.3 Model 3 – Section with Khatpul formation (Dolomite)

Model 3 represent a section of the completely excavated mining area where only dolomite of Khatpul formation is encountering. It is modeled by adopting similar material properties which was adopted for dolomites in the previous models. The input parameters for Phase 2 like failure criterion and shear strength reduction method is also similar to that of other models. The model after meshing is shown in the figure below.

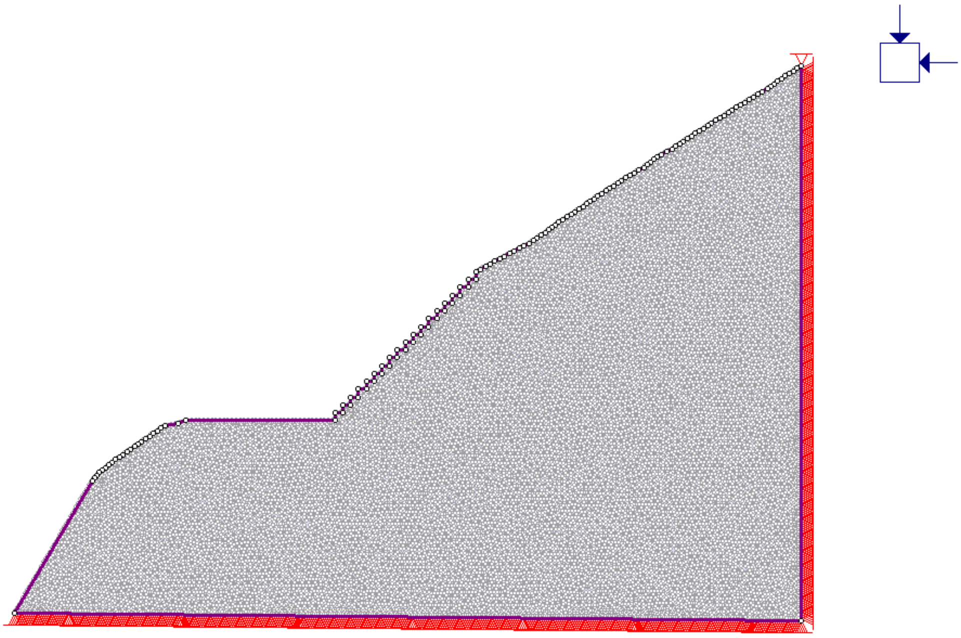


Figure 37 Model 3 - Phase 2 Model for excavated Slope of Section B-B

Results

The slope is having a factor of safety of 1.6 which is greater than 1.5 and is stable slope. The model 3 is having steeper slope hence a reduction in FOS is observed from 2.1 to 1.6 when compared to model 2. The failure in this case also initiated for the whole natural slope and no significant shear strain is observed near the excavated slope of quarry area.

Similar to model 2 this also signifies a higher factor of safety for the excavated slope and negligible chances of global failure of the slope.

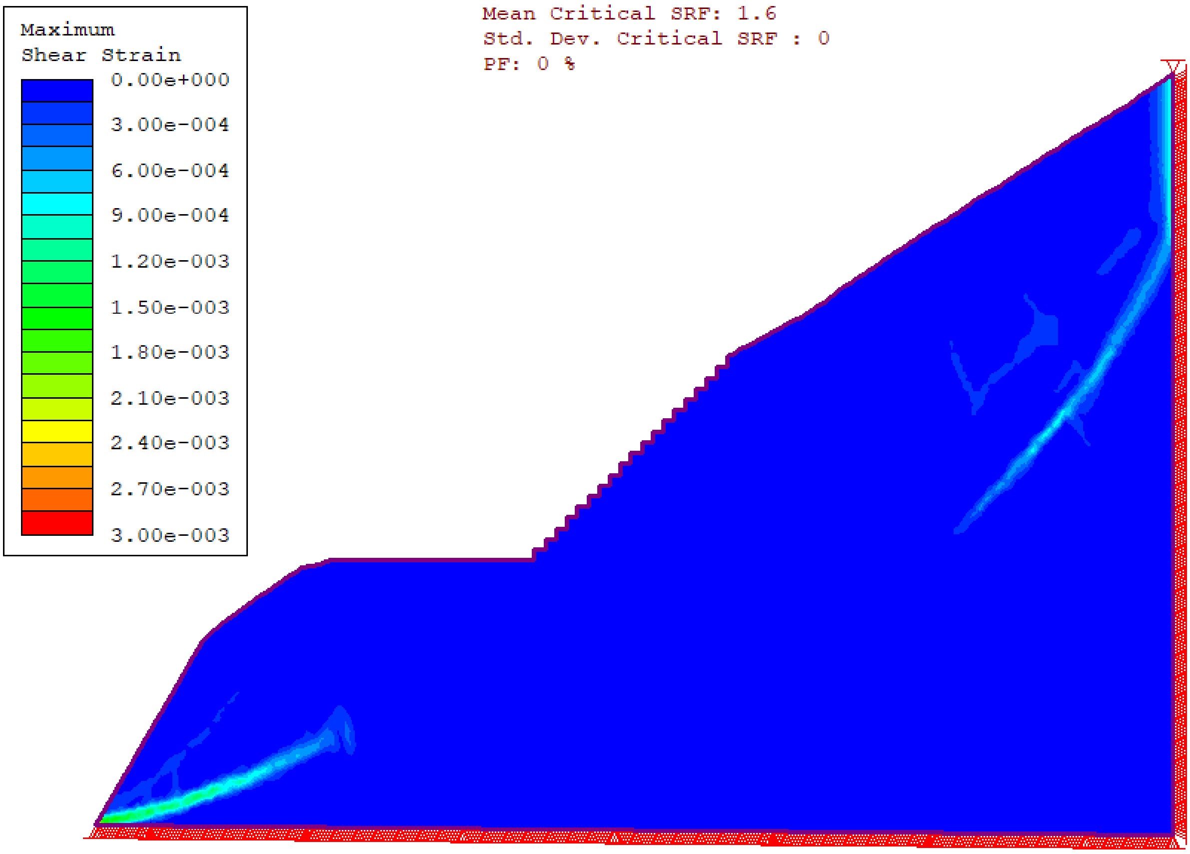


Figure 38 Result of Model 3 for excavated Slope of Section B-B

6.5.2.4 Model 4 – Section with Khatpul formation (Dolomite)

Model 4 is a section of a valley portion in the quarry area where a steeper slope is observed. Dolomite of Khatpul formation is encountered throughout the slope section of slope. It is modeled by adopting similar material properties which was adopted for dolomites in the previous models. The input parameters for Phase 2 like failure criterion and shear strength reduction method is also similar to that of other models. The model after meshing is shown in the figure below.

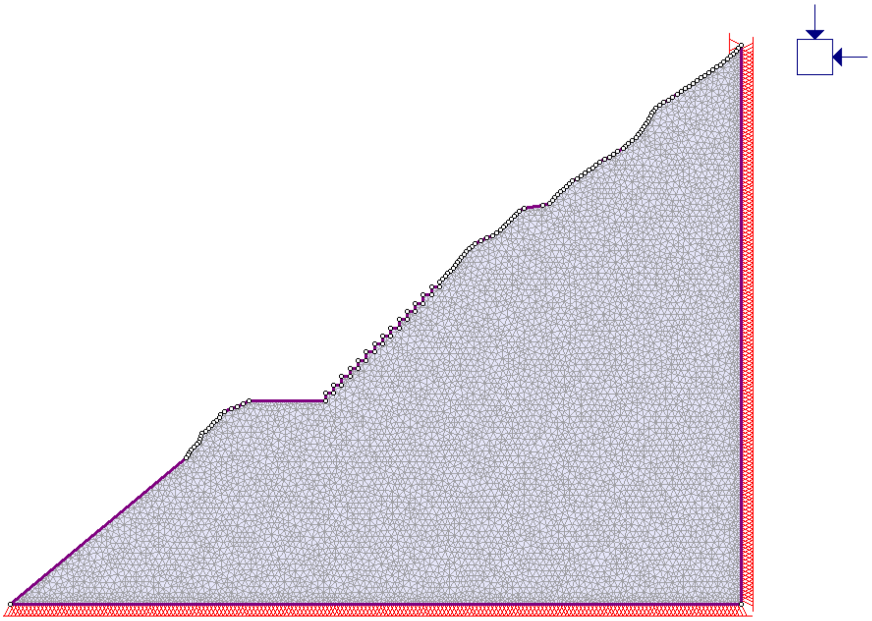


Figure 39 Model 4 - Phase 2 Model for excavated Slope of Section C-C

Results

The FOS observed for the model after analysis is 1.7 which is more than 1.5 which shows the slope is stable. Similar to ither models this section also not showing much deformation in the excavated face.

The analysis of the third section ensures the excavated slope is globally safe.

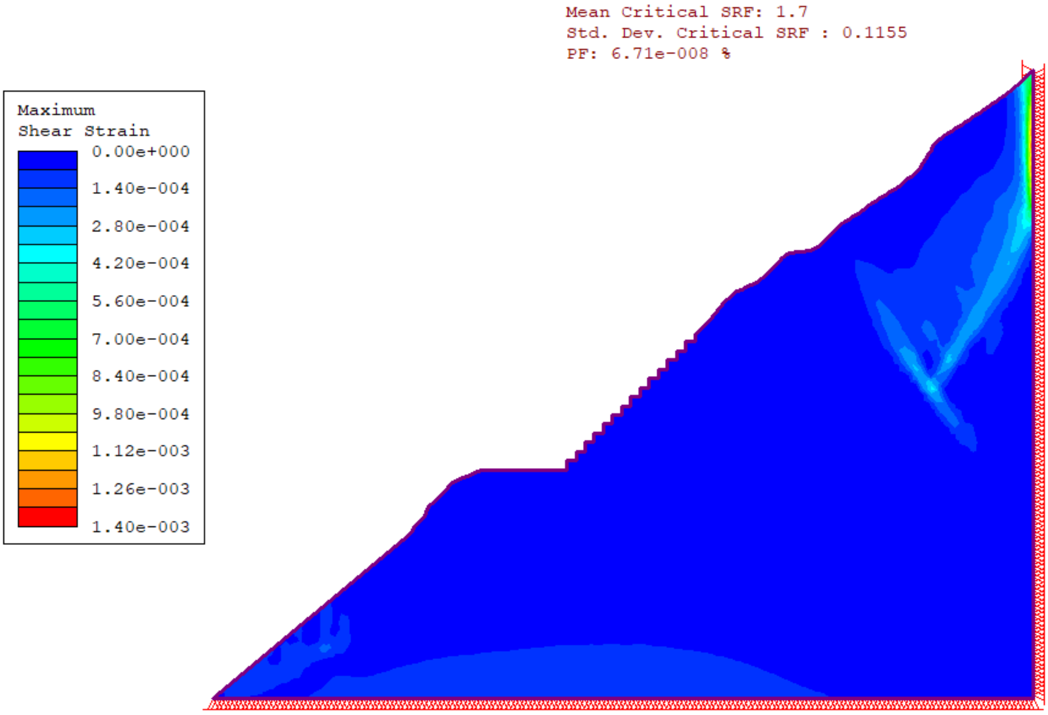


Figure 40 Result of Model 4 for excavated Slope of Section C-C

6.5.3 *Kinematic Analysis using Dips*

The quarry area proposed on the right hand side slope of the Satluj river and is having a north west direction. A 3D geological model of a drift excavated on this side of slope is provided in existing geotechnical studies of the area. This drift is providing joint data for Khaira formation in which the major rock formation is of Quartzite. The quarry area proposed is on further upper side of the slope in which the formation is Khatpul formation which consists of dolomite majorly. The joints of both these formations are provided by conducting various investigations and is listed in section characteristics of discontinuities.

The joint sets defined in the material property is plotted in a stereo net using Rocscience dips and kinematic analysis shall be carried out for both Khaira and Khatpul formations.

6.5.3.1 *Quartzite*

The joint details provided were plotted in stereo net by defining dip angle and dip directions. From theses joints, four major joint sets were observed and plotted in the stereo net as shown below in the model. Each of this joint set have a mean vector for which a mean plane is defined as shown below. This stereo net model developed is used for the planar, wedge and topple analysis of these joint sets.

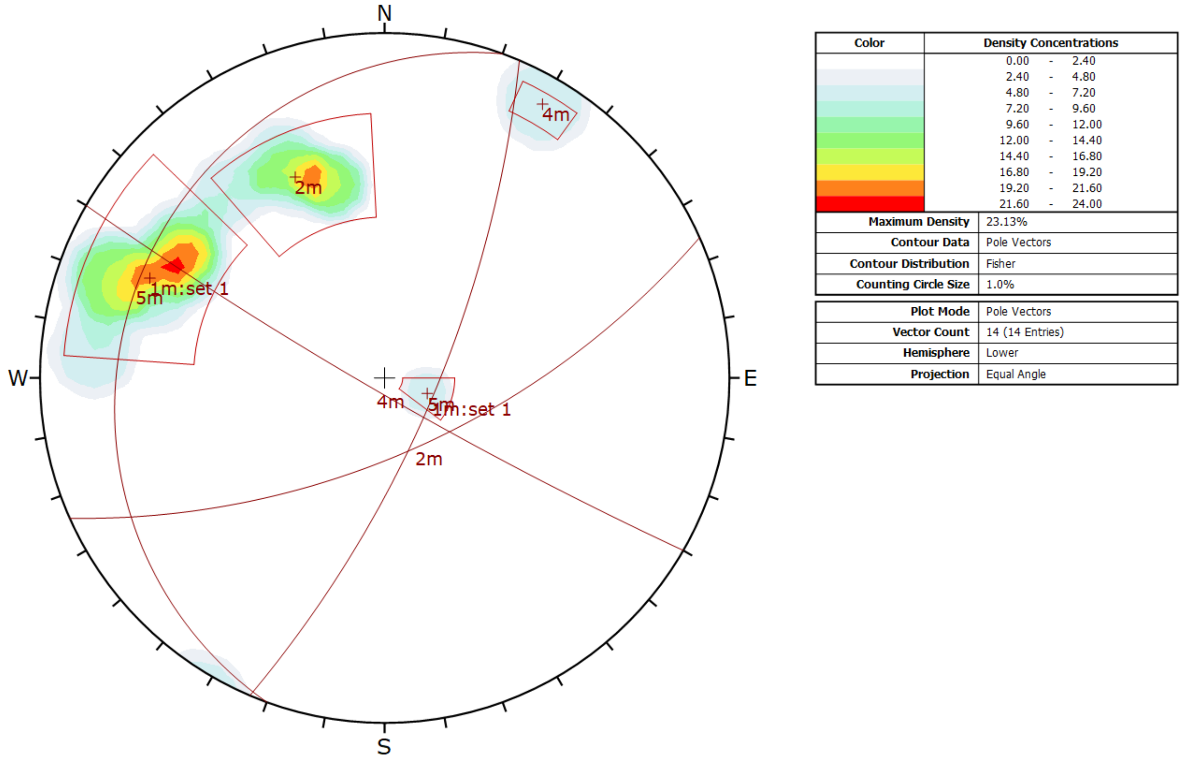


Figure 41 Stereonet for quartzite

6.5.3.2 *Dolomite*

In the details provided four joint sets were defined for the dolomite of Khatpul formation. These four different joint sets considered as mean vector and respective four planes were defined in the stereo net as shown below. This stereo net plotted using dips is further used for kinematic analysis of dolomite rock formation.

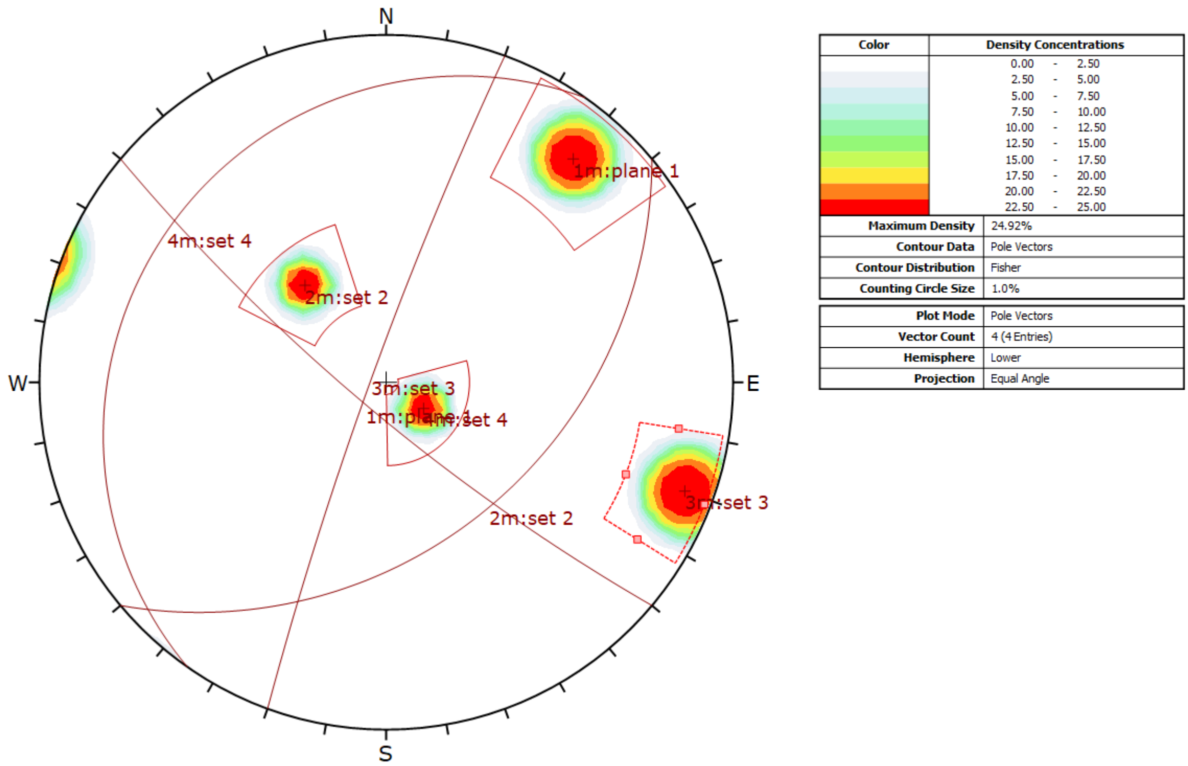


Figure 42 Stereonet for dolomite

6.5.4 Planar Failure

In order for this type of failure to occur, the following geometrical conditions must be satisfied in field:

a) The plane on which sliding occurs must strike parallel or nearly parallel (within approximately ± 20º) to the slope face.

b) The sliding plane must “daylight” in the slope face, which means that the dip of the plane must be less than the dip of the slope face, that is, $\psi p < \psi f$.

c) The dip of the sliding plane must be greater than the angle of friction of this plane, i.e. $\psi p > \varphi$.

d) The upper end of the sliding surface either intersects the upper slope or terminates in a tension crack.

e) Release surfaces that provide negligible resistance to sliding must be present in the rock mass to define the lateral boundaries of the slide. Alternatively, failure can occur on a sliding plane passing through the convex “nose” of a slope

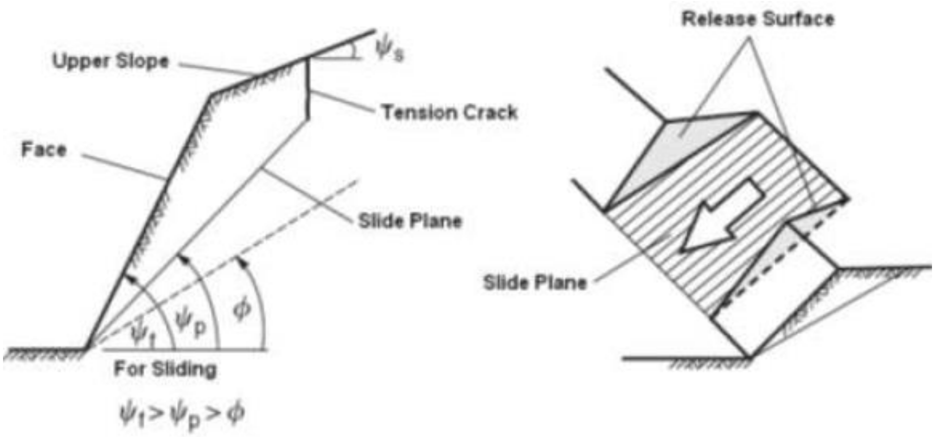
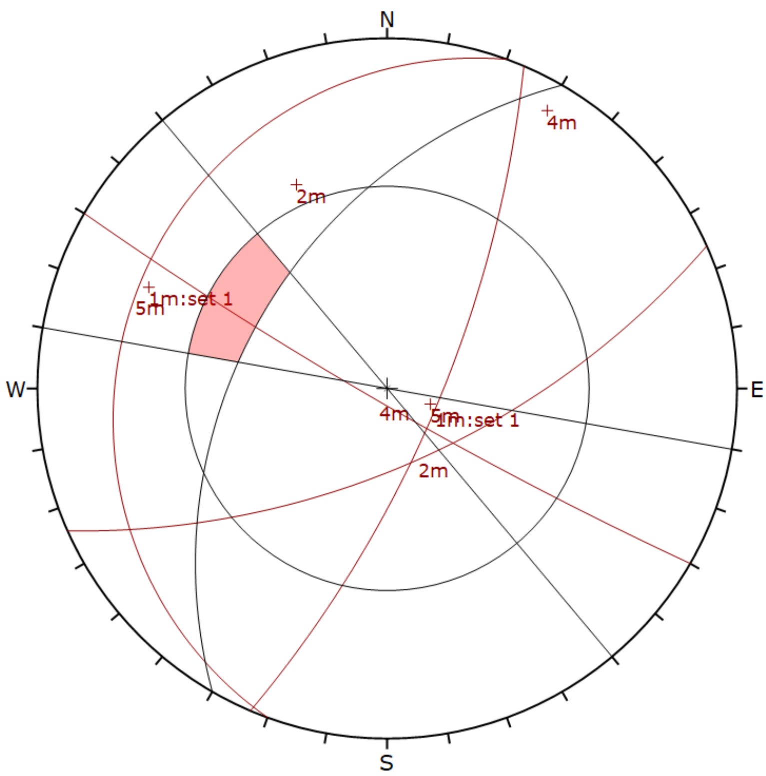


Figure 43 Geometric conditions of planar failure

6.5.4.1 Quartzite

Quartzite rock formation is observed on the lower slopes of quarry area at several locations. The quarry slope is aligned in NW direction and the slope is assumed approximately at an angle of 45^0 to the horizontal. The angle of friction for intact quartzite formation is approximately 40^0 as provided, hence the angle of friction for joints of quartzite is assumed as 30^0.



Kinematic Analysis	Planar Sliding
Slope Dip	45
Slope Dip Direction	300
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Planar Sliding (All)	0	14	0.00%

	Color	Trend	Plunge	Label
Mean Set Planes				
1m	■	293	17	set 1
2m	■	336	25	
4m	■	30	5	
5m	■	110	75	

Plot Mode	Dip Vectors
Vector Count	14 (14 Entries)
Hemisphere	Lower
Projection	Equal Angle

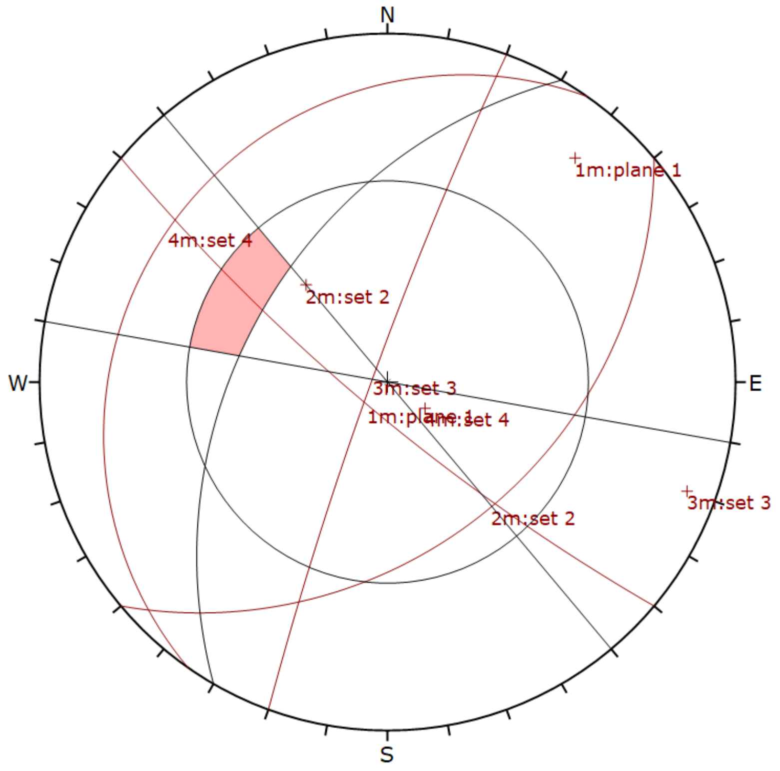
Figure 44 Planar failure analysis for quartzite slope

Kinematic analysis for planar failure is carried out by inputting all the necessary parameters explained above. The joint sets fall in the critical area of stereo net is nil after analysis, hence the quartzite formation is having a negligible chance of planar failure.

6.5.4.2 *Dolomite*

Dolomite rock formation is observed on the proposed quarry area covering a major area and entire excavated slope. The quarry slope is aligned in NW direction and the slope is assumed approximately at an angle of 45^0 to the horizontal. The dolomite is expected to be strong to moderately strong in the quarry area with less joint sets.

The angle of friction for intact dolomite formation is approximately 41^0 as provided, hence the angle of friction at the joints of dolomite is assumed as 30^0 for kinematic analysis.



Kinematic Analysis	Planar Sliding			
Slope Dip	45			
Slope Dip Direction	300			
Friction Angle	30°			
Lateral Limits	20°			
		Critical	**Total**	**%**
	Planar Sliding (All)	0	4	0.00%

	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m	■	80	220	plane 1
2m	■	40	140	set 2
3m	■	85	290	set 3
4m	■	15	305	set 4

Plot Mode	Dip Vectors
Vector Count	4 (4 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure 45 Planar failure analysis for dolomite slope

Kinematic analysis for planar failure is carried out by inputting all the necessary parameters explained above. The joint sets fall in the critical area of stereo net is nill after analysis, hence the dolomite formation is having a negligible chance of planar failure.

6.5.5 *Wedge Failure*

This failure occurs when slopes containing discontinuities striking obliquely to the slope face and sliding of a wedge of rock takes place along the line of intersection of two such planes. The geometry of the wedge for analysing the basic mechanics of sliding is defined in **Error! Reference source not found.**.

Based on this geometry, the general conditions for wedge failure are, as follows:

a) Two planes will always intersect in a line. On the stereo net, the line of intersection is

represented by the point where the two great circles of the planes intersect, and the orientation of the line is defined by its trend (αi) and its plunge (ψi).

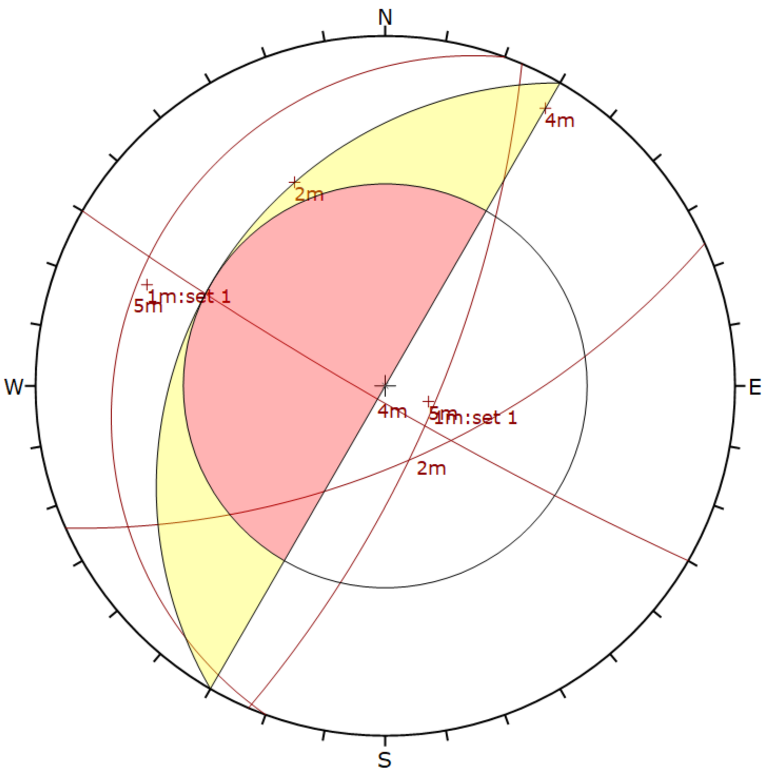
b) The plunge of the lb line of intersection must be flatter than the dip of the face, and steeper than the average friction angle of the two slide planes, that is ψfi > ψi > φ. The inclination of the slope face ψfi is measured in the view at right angles to the line of intersection.

(Note: ψfi would only be the same as ψf, the true dip of the slope face, if the dip direction

of the line of intersection were the same as the dip direction of the slope face). The line of intersection must dip in a direction out of the face for sliding to be feasible; the possible range in the trend of the line of intersection is between αi and αi'.

6.5.5.1 Quartzite

Wedge failure is expected to occur locally at different benches of the quarry area, hence it is to be analyzed for a vertical plane. Hence, the angle of slope considered in kinematic analysis of wedge failure is 90^0. The excavation slope's direction is NW and is approximately at an angle of 300^0 from north.



Symbol	Feature
■	Critical Intersection

Kinematic Analysis	Wedge Sliding		
Slope Dip	90		
Slope Dip Direction	300		
Friction Angle	30°		
	Critical	Total	%
Wedge Sliding	0	6	0.00%

	Color	Trend	Plunge	Label
Mean Set Planes				
1m	■	293	17	set 1
2m	■	336	25	
4m	■	30	5	
5m	■	110	75	

Plot Mode	Dip Vectors
Vector Count	14 (14 Entries)
Intersection Mode	Mean Set Planes
Intersections Count	6
Hemisphere	Lower
Projection	Equal Angle

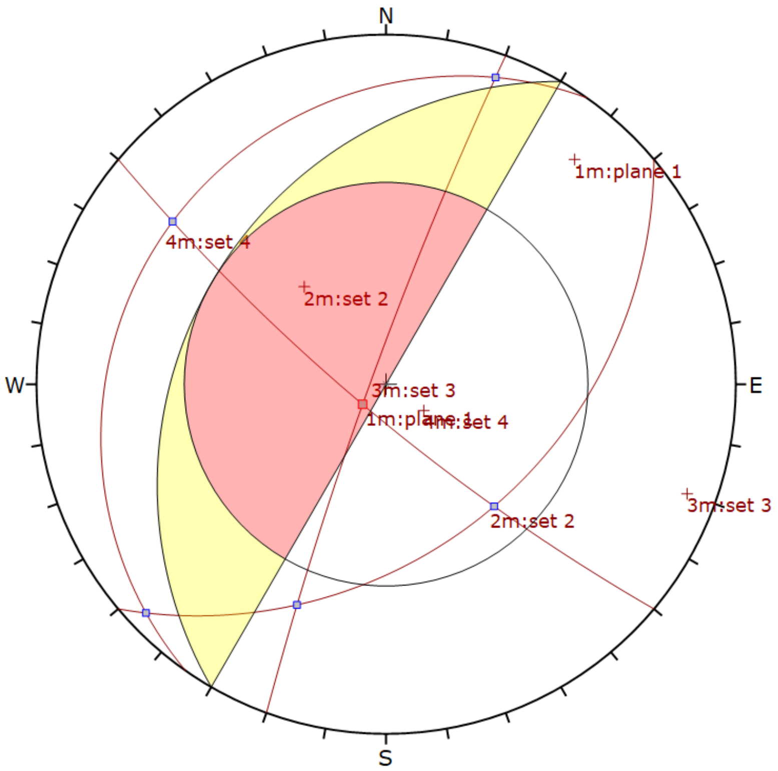
Figure 46 Wedge failure analysis for quartzite slope

Kinematic analysis result of quartzite formation shows no mean plane falls in the critical area of stereo net and the probability of wedge failure is negligible for the current set of joints in the formation. The slope is safe from wedge failure.

6.5.5.2 Dolomite

Dolomite formation is majorly present in the quarry area and is critical for wedge analysis. Wedge failure is expected to occur locally at different benches of the quarry area, hence it is to be analyzed for a vertical plane. Hence, the angle of slope considered in kinematic analysis of wedge failure is 90^0. The excavation slope's direction is NW and is approximately at an angle of 300^0 from north.

Kinematic analysis result of quartzite formation shows no mean plane falls in the critical area of stereo net and the probability of wedge failure is negligible for the current set of joints in the formation. The slope is safe from wedge failure.



Symbol	Feature
■ (red)	Critical Intersection
■ (blue)	Intersection

Kinematic Analysis	Wedge Sliding
Slope Dip	90
Slope Dip Direction	300
Friction Angle	30°

	Critical	Total	%
Wedge Sliding	1	6	16.67%

	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m	■	80	220	plane 1
2m	■	40	140	set 2
3m	■	85	290	set 3
4m	■	15	305	set 4

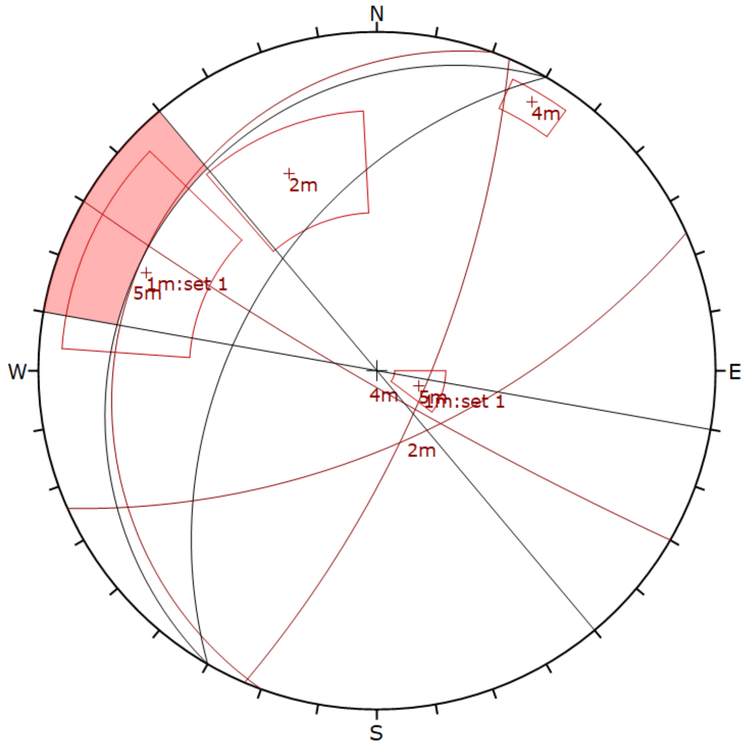
Plot Mode	Dip Vectors
Vector Count	4 (4 Entries)
Intersection Mode	Mean Set Planes
Intersections Count	6
Hemisphere	Lower
Projection	Equal Angle

Figure 47 Wedge failure analysis for dolomite slope

Kinematic analysis for wedge failure for dolomite formation shows 1 of the mean plane out of 6 falls in the critical area of stereo net. The probability of wedge failure is 16.67 % which is negligible for the current set of joints in the formation. The slope can be considered safe from wedge failure.

6.5.6 Flexural Topple

The excavated slope and joint properties considered for flexural topple analysis of quartzite and dolomite formation is similar to that of planar failure. The analyses results are shown in figures below.

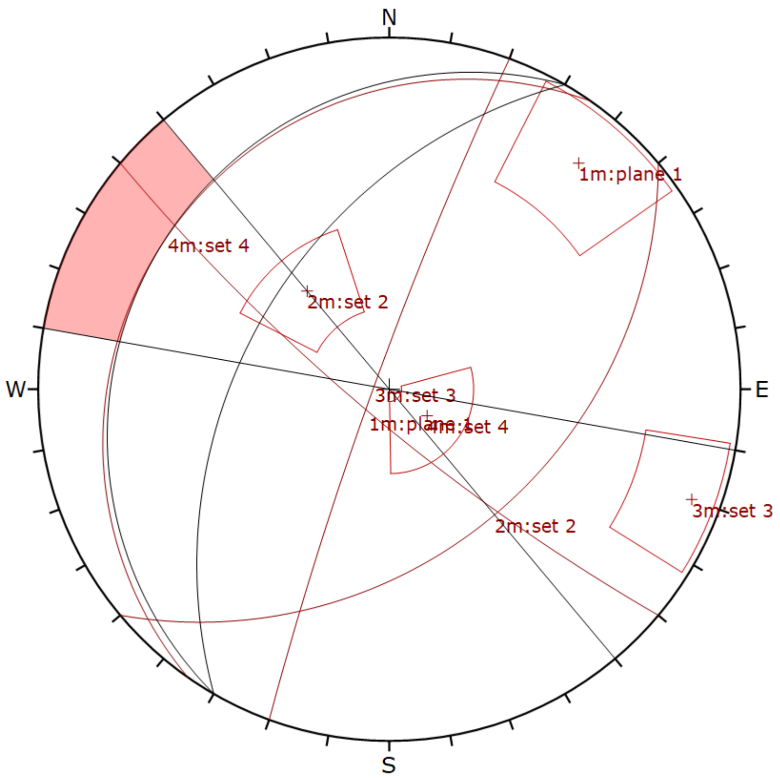


Kinematic Analysis	Flexural Toppling		
Slope Dip	45		
Slope Dip Direction	300		
Friction Angle	30°		
Lateral Limits	20°		
	Critical	Total	%
Flexural Toppling (All)	2	14	14.29%
Flexural Toppling (Set 1)	2	7	28.57%

	Color	Trend	Plunge	Label
Mean Set Planes				
1m	■	293	17	set 1
2m	■	336	25	
4m	■	30	5	
5m	■	110	75	

Plot Mode	Pole Vectors
Vector Count	14 (14 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure 48 Flexural topple for quartzite



Kinematic Analysis	Flexural Toppling		
Slope Dip	45		
Slope Dip Direction	300		
Friction Angle	30°		
Lateral Limits	20°		
	Critical	Total	%
Flexural Toppling (All)	0	4	0.00%

	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m	■	80	220	plane 1
2m	■	40	140	set 2
3m	■	85	290	set 3
4m	■	15	305	set 4

Plot Mode	Pole Vectors
Vector Count	4 (4 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure 49 Flexural topple for dolomitez

Kinematic analysis for flexural topple failure shows that both Quartzite and dolomite formations falls on critical region of stereo net and are having a negligible probability of failure. Hence, the slopes are stable from flexural topple failure.

6.6 Conclusions from the analysis

The major geological formation of mining area is Khatpul and Khaira formation which belongs to Shali group. The major rock formation observed in Khaira formation is Quartzite and Khatpul formation consists majorly of Dolomite rock. The quarry area proposed encounters moderately strong to strong dolomite rock formation which is generally stable.

The analysis considered three sections on the proposed quarry area. Section A-A is modelled as natural slope prior to excavation in model 1 and the same section is excavated as per the mining plan in model 2 and analyzed. In model 2 after excavation a significant amount of overburden is removed which lead to the stability of the section and is observed in analysis. The model 1 had a factor of safety of 1.6 and after excavation the factor of safety of the section in model 2 increased to 2.1 which validates the model conceptually. The other two sections considered is also satisfying the criteria of factor of safety of more than 1.5 as presented above.

Kinematic analysis is carried out for both dolomite and quartzite rock formations encountering the excavated slope of the quarry area. The joint details for these two formations provided in reports were used to plot stereo net as explained in the analysis section. The results of kinematic analysis for planar failure obtained showed there is negligible probability of planar failure to occur. Similarly, the probability of flexural toppling is also observed to be negligible.

In case of wedge analysis carried out locally for the joint sets of dolomite formation, about 16% failure probability were observed. This type of failure along with small patches of weak formations can be expected in the quarry area which shall be mitigated with adequate measures. It is proposed to provide gabion walls to mitigate this condition. The dimension of gabion walls shall be decided after detail design, however a typical section of gabion wall for a height of 6m is attached with the report. It is also suggested to provide gabion wall along the whole length of two bottom most slopes of the proposed mining area.

The quarry area is also encountering two valleys through which runoff is expected and shall be taken out using a properly designed drain. This will avoid the chances of failure of excavated slope due to runoff, seepage and change in ground water table. It is also recommended to support the slope near the drain with properly designed gabion walls.

The points observed from the analysis are summarized below:

1. Natural slope in the quarry area is stable against global failure as no failure is observed in the analysis and no symptoms of history of failure are seen in the site.
2. After excavation of the natural slope of quarry area in to steps the stability of slope is further increased. (Factor of safety increased)
3. It is advised to make gabion walls on two bottom most benches of final year mining plan to enhance the stability of the slope and to enhance the environmental aspects.
4. Kinematic analysis carried out on the slopes for quartzite and dolomite formation is stable against planar failure, wedge failure and flexural toppling.

5. There is a small probability for wedge failure to occur for dolomite formations which shall be mitigated by constructing gabion walls.
6. Drains needs to be provided along the perimeter of the quarry area, at the bottom of the benches and across the mining area as provided in conceptual drain plan. This will ensure proper drainage of runoff water and decreases the seepage.

7 RISKS AND MITIGATION MEASURES

The site is part of hill slope, prone to some risk hazards but no major risk hazard is associated. The possible scenarios for this site are as below:

- Earthquakes
- Landslide
- Accidents (during mining or vehicular movement)

Landslide

The geological formations in the site consist of jointed Quartzite and Dolomite therefore, to avoid the sliding of pit walls during mining, the bench height is to be maintained to six metres. As per mining plan the mining work will not be carried out during monsoon season when the wet rock is most susceptible to slide.

Earthquakes

The area falls in seismic High hazard zone. The mining operations are open cast pit mining. The mining pits will be only of six metre depth. There won't be any structure in the area likely to cause risk to worker. The workers rest sheds, store building and toilets will be constructed of lightweight wood and tin sheets.

Accidents

Possibility of occurrence of accidents can be due to two reasons: interference due to mining or movement of vehicles. Although the likelihood of these situation is low and can be taken care by minimal medical care, yet the possibility is not zero, hence precautions should be taken into account.

7.1 Stabilizing Approaches

The site is in hillside on the right side of bank of river Satluj, although the site is stable and the slopes of the mining quarry are secured, precautionary measures can be taken to completely negate any probable incident of instability at the slopes.

Table 9 Different methods to stabilize slope

S. No.	Method	Types	S. No.	Method	Types
1	Surface Erosion Protection	-	4	Column Supported Embankments	-
2	Increase resisting force	•Change geometry •Lower groundwater •Increase shear strength of soil mass	5	Earth retaining systems	•MSE walls •Gravity walls •Soldier beams and lagging •Soldier beams and shotcrete

					• Tangent pile walls • Secant pile walls
3	Soil Improvement	•Densification •Dynamic Compaction •Stone columns •Vibrocompaction •Consolidation •Soil reinforcement •Physicochemical Changes	6	Decrease driving force	•Change geometry •Lower groundwater

7.2 Preventive Measures

Some of the preventive measures are provided readily in the mining plan by SJVNL. However, it can be monitored by incorporation of latest monitoring techniques such as instrumentation and health monitoring of slopes, which is described in detail in the next section.

Preventive Measures against Sliding:

The site is present on the Himalayan region having high altitudes and overburden. The area is also vulnerable to seismic activities. The Shimla district where the quarry site is located, did not show any sliding events in the past, and the geology and design analysis show that the slopes are stable. Precautionary measures are to be taken in order to prevent any instability caused due to surface or subsurface drainages, instability due to reduced internal strength or any external force. Table suggests various measures against landslides.

Table 10 Preventive measures against landslide

S. No.	Category	Procedure
2	Reduce driving forces	Drain surface
		Drain sub-surface
		Reduce weight
3	Increase resisting forces apply external force	Use buttress and counterweight fills; toe berms
		Use structural systems
		Install anchors
4	Increase internal strength	Drain subsurface
		Use reinforced backfill
		Install in situ reinforcement
		Use biotechnical stabilization

		Treat chemically
		Use electroosmosis
		Treat thermally

To stabilize the slope two systems are present, it can be externally or internally. The suggested systems include retention using in-situ walls, gravity walls for external stabilization, and reinforced soil, in situ reinforcement of soil for stabilizing the slope internally. The figure shows different options available for slope retention.

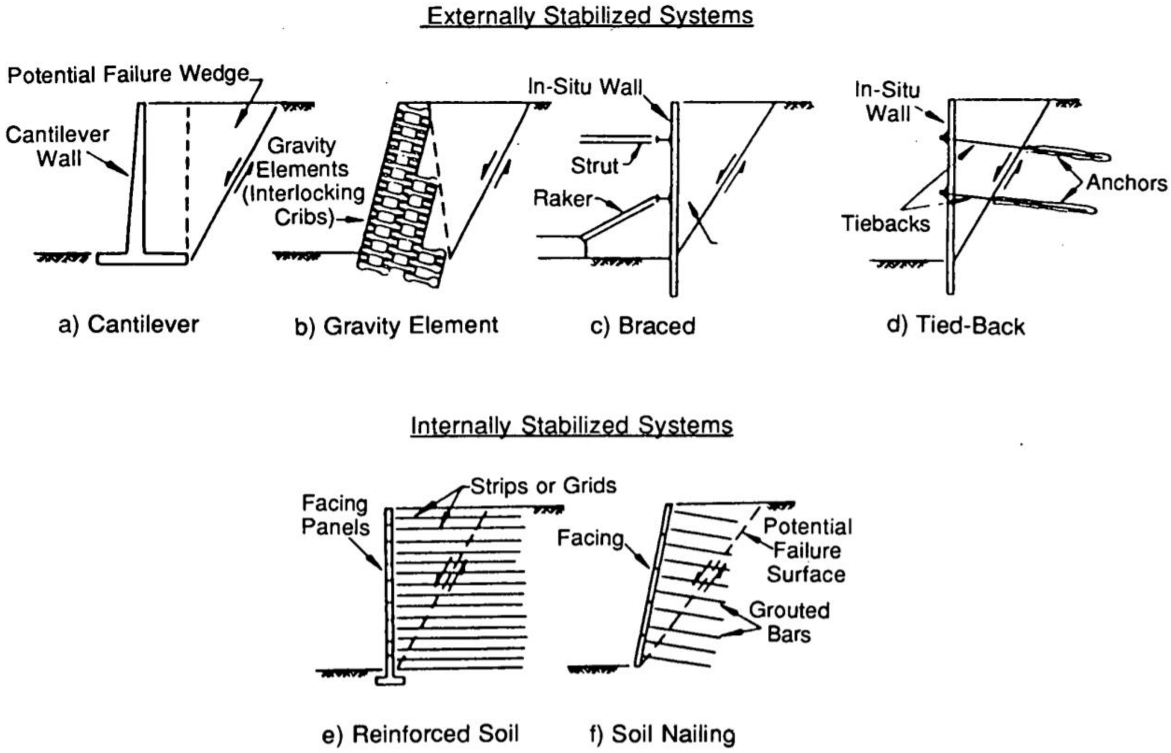


Figure 50 External and Internal Stabilization System

The measures in the mining plan are as below:

Measures to prevent Inundation/Flooding/drowning

Being on hill slope of quartzite & dolomite rock there would be no mining operation during monsoons or rainy days, as the wet loosed rocks are prone to uncontrolled slide.

• Height of benches would be constrained to four metres, cannot be further reduced.

Measures to Prevent Accidents during Loading

• The truck should be brought to a lower level so that the loading operation suits to the ergonomic condition of the workers.

• The loading should be done from one side of the truck only.

• The workers should be provided with gloves and safety shoes during loading.

• Opening of the side covers would be done carefully and with warning to prevent injury to the loaders.

• Operations during daylight only.

Measures to Prevent Accidents during Transportation

• Vehicles will be periodically checked and maintained in good condition.
• Overloading will not be permitted.
• To avoid danger of accident roads and approach to the mining pit/bench would be properly maintained.
• The truck would be covered and maintained to prevent any spillage;
• The maximum permissible speed limit of 20 kms would be ensured;
• The experienced truck drivers with proper driving license would only be employed.

Measures to Prevent Accidents during Earthquakes

Occasional drills to create awareness for safety measures during mining operations and specially the measures to be adopted during earthquakes etc will be undertaken in consultation with experts.

Proposed Measures

There are several approaches to provide stability to the slopes as shown in table and figure,` however since the site fairly stable, apart from the measures provided in the mining plan of SJVNL, following are the additionally measures suggested:

a. Gabion Walls

The gabion walls are provided as gravity retaining walls which use their own weight to resist the lateral earth pressures. The filling must have compressive strength and durability to resist the loading, as well as the effects of water and weathering. Anchor Mesh must be joined securely to the gabion wall facing with spirals or tie wire at the specified elevations as layers of backfill are placed and compacted.

In order to provide additional stability to slopes of site, gabion walls are proposed with ribs at 6m intervals at the base of slope for the entire length, opposite to the river bank to provide protective area to MDR 22. Typical gabion wall section has been attached with the report.

Figure 51 Typical Gabion Wall

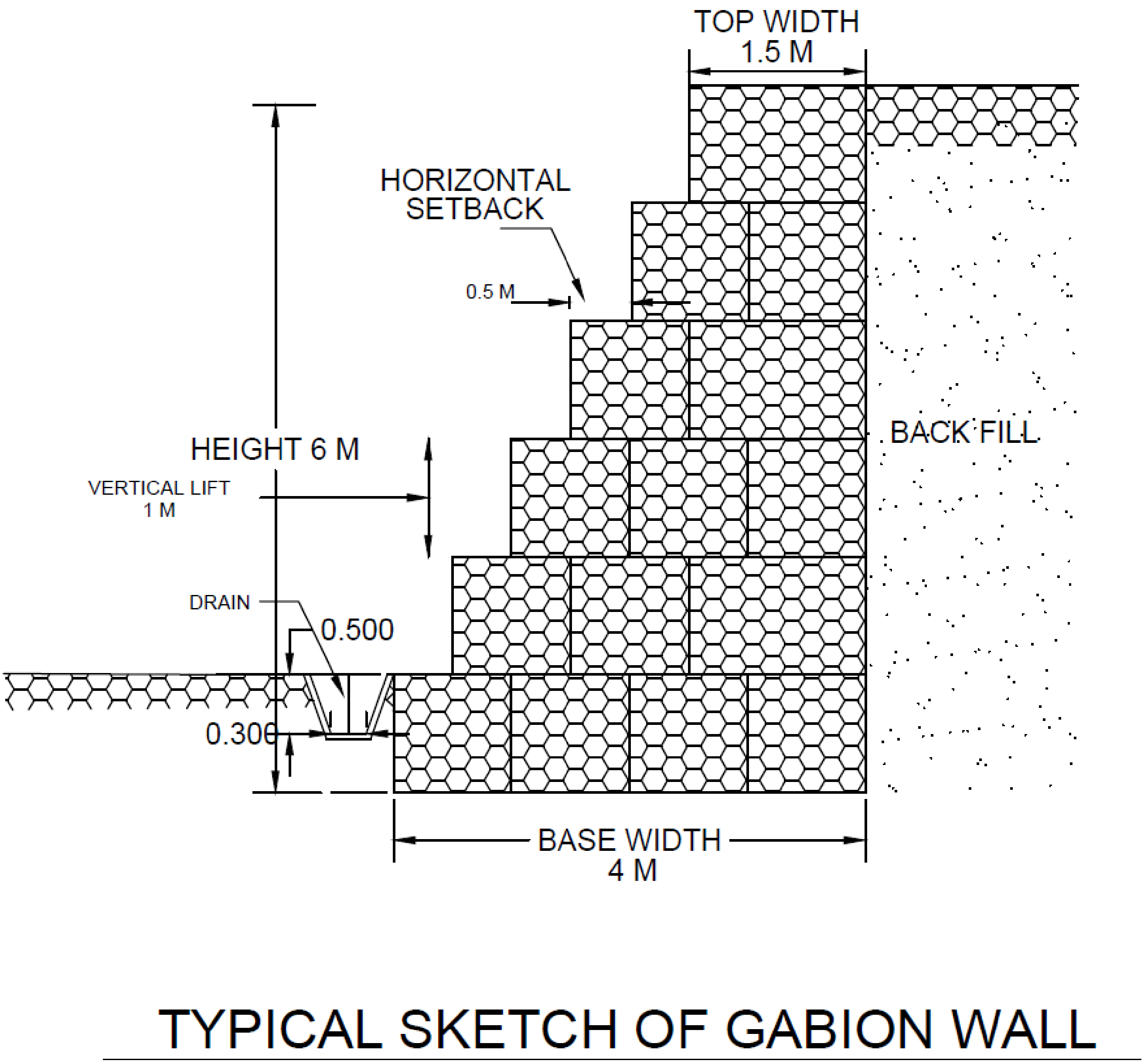


Figure 52 Typical Cross-section of Gabion Wall

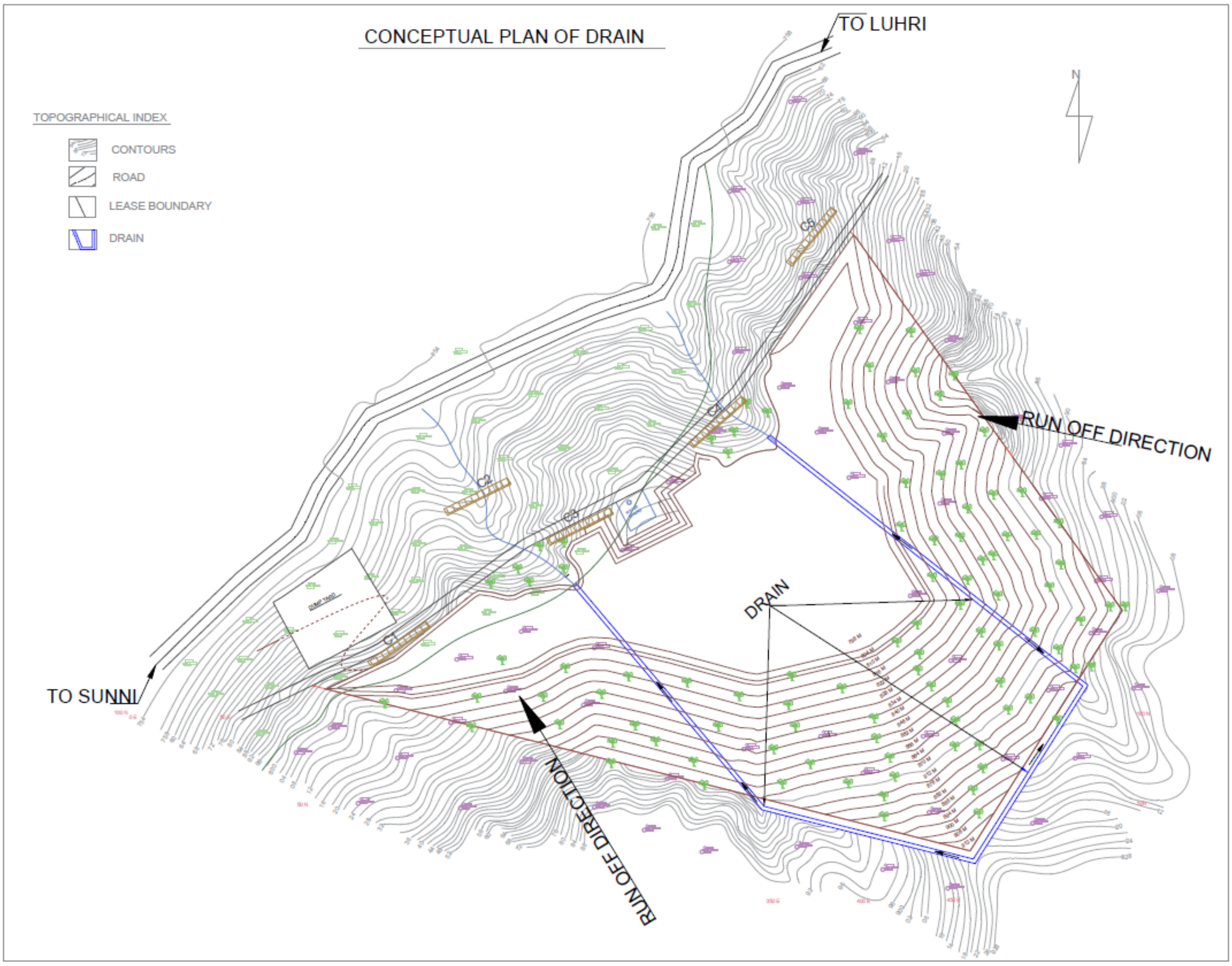


Figure 53 Drainage Plan

b. Drainage Systems

The rainfall data from IMD for the site shows that the rainfall in the quarry location is moderate, also there are no major tributaries with high amount of discharge. However, two minor valleys are observed in the quarry location. As these water channels are seasonal, during rain, run-off is expected through these valleys. It is critical to drain out the water systematically to ensure stability of the excavation slope made. Any seepages and any sub surface discharge may reduce the structural integrity of dolomitic formations, therefore it is important provide drainage system after detailed design. However, there is a conceptual drainage plan attached with the report. A typical section of main drainage is shown in figure.

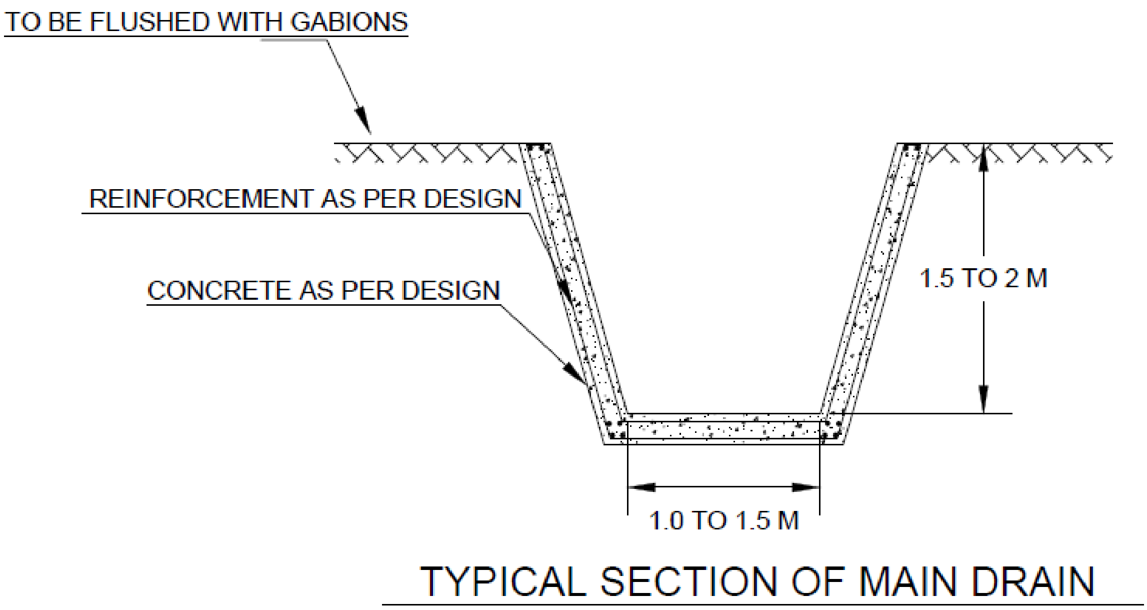


Figure 54 Typical Section of Main Drainage System

c. Slope Monitoring

Geotechnical instrumentation plays an important role in the investigation of deformation, water etc such that all the parameters which affects the stability of slope, can be monitored. As per the geology, folds, faults, joints, and stratified rocks are potential zones for the movement and storage of ground water. The groundwater level has a major influence on material behaviour (drained-undrained), and changes in groundwater level can result in settlements and damage to structures and infrastructure.

As per the quarrying plan, while excavation is being done the settlement of rocks should be monitored form the initial excavation itself. This shall assist in analysing the slopes and movements thereof if any. The quarry had a joint between the dolomites and quartzite rock that are to be encountered while quarrying. It is advisable to monitor the movement at this joint with respect to each other. Probe inclinometers, “in-place” inclinometers, tiltmeters, extensometers, and TDR can be used alone or in combination to monitor slope movements. A detailed concept of monitoring the slope with the help of instrumentation has been covered as a separate chapter in the report.

8 INSTRUMENTATION

Slope failures occur due to geological factors such as faults, dykes etc. inherent in host rock. Their adverse effects can be amplified by mining activity. Knowledge of when slope failure is likely to happen by predicting the event is the answer to mitigating the risk. This knowledge of slope failure is achieved by monitoring areas of the mine that have a risk of failure and understanding the behaviour of the rock mass.

As the area is being mined for quarry material stability of slope can be monitored using Instrumentations which become an essential tool for monitoring safety and stability of the slopes. It can provide valuable data on a variety of engineering parameters such as horizontal and vertical deformations, pore water pressure, rainfall, rock displacement etc. This information can be applied to understand the movements of the slopes and plan the remedial measures.

Slope stability and landslide monitoring involves selecting certain parameters and observing how they change with time. The two most important parameters are groundwater levels and displacement. Slope displacement can be characterized by depth of failure plane(s), direction, magnitude, and rate. One or all these variables can be monitored.

8.1 Factors of Slope Failure

Slope stability and landslide monitoring involves selecting certain parameters and observing how they change with time. The two most important parameters are ground water levels and displacement. Slope displacement can be characterized by depth of failure plane(s), direction, magnitude, and rate. One or all these variables may be monitored. Conventional slope monitoring utilizes a single method or a combination of methods. Piezometers allow the determination of water levels; surveying fixed surface monuments, extensometers, inclinometers, and tiltmeters allow determination of direction and rate of slope movement and depth and areal extent of the failure plane; extensometers provide an indication of displacement magnitude. Manually operated probe inclinometers are the most common means of long-term monitoring of slopes.

The two most common factor require to be monitored in the present site are Water and Displacement.

8.1.1 Water

The present site has two natural seasonal water drains crossing the quarry area. Engineering solutions for the same have being provided to ensure the natural flow of the water even after the quarrying of the site is done. However, water can add to some movements of the faults depending on the seepage possibilities of the ground. Water factors such as Increase in pore water pressure, drop in water level and Water pressure in fractures can lead to slope instability. Hence it is pertinent to measure the water pressure near the joints as well as it is recommended to measure the water pressure as per the proposed plan, after the excavation has started. A figure below gives an outlook of pore pressure that can be encountered on a slope.

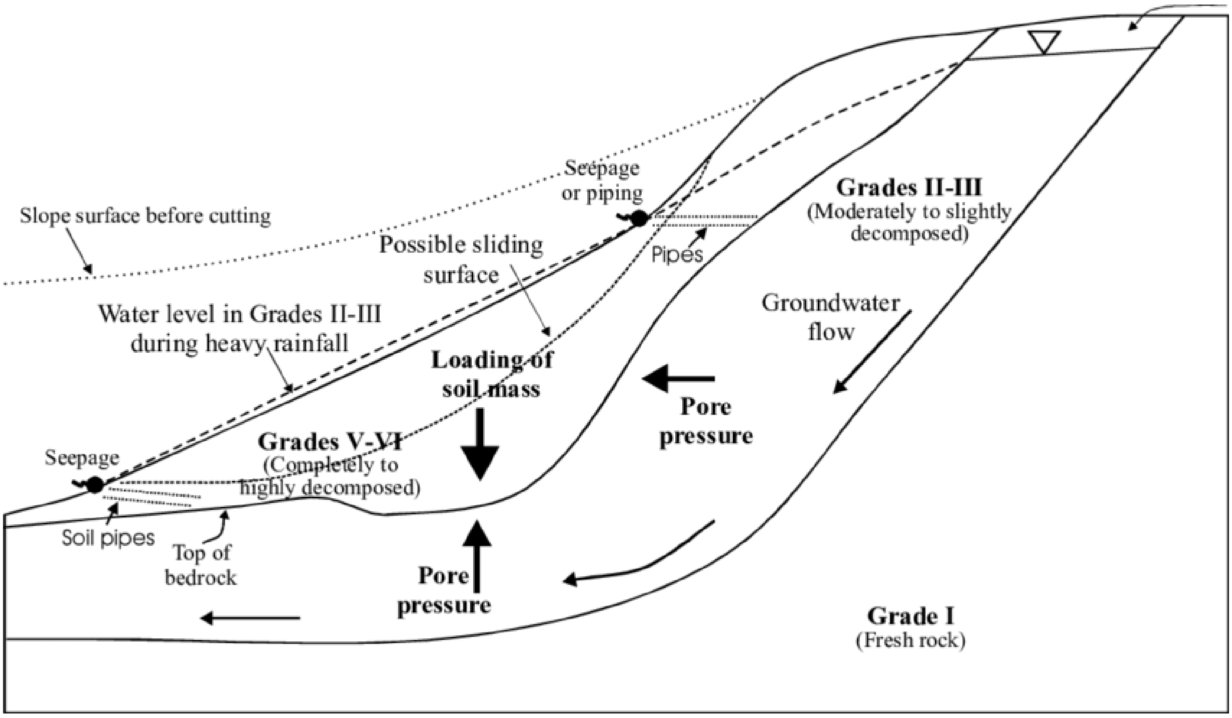


Figure 55 Effect of Pore pressure on slope

The simplest method of monitoring water pressure in a slope is using vibrating wire piezometers. These piezometers can be installed at different locations on different elevation after the excavation of benches is done in different phases of excavation plan.

8.1.2 Displacements movements due to Excavation

While excavations are being done the natural equilibrium of the site gets disturbed and there is shift in balance of loads. For an eco-sensitive area, it is advisable to monitors the displacements that can occur due to movements of the slopes. As per the quarrying plan, while excavation is being done the settlement of rocks should be monitored form the initial excavation itself. This shall assist in analysing the slopes and movements thereof if any. The quarry had a joint between the dolomites and quartzite rock that are to be encountered while quarrying. It is advisable to monitor the movement at this joint with respect to each other. Probe inclinometers, “in-place” inclinometers, tiltmeters, extensometers, and TDR can be used alone or in combination to monitor slope movements. Though there is no activity below the road level but still it is advisable to monitor as it forms toe of the slope above using geotechnical instruments such as piezometers, MPBX, Inclinometers etc., which shall assist to understand the impact of excavation at higher elevation. To monitor the lateral and longitudinal deformation, Multipoint borehole extensometer as well as Inclinometers are recommended to install immediately after the excavation of that bench which is proposed in the instrumentation plan. The figure below gives a general understanding of movements that have been discussed above.

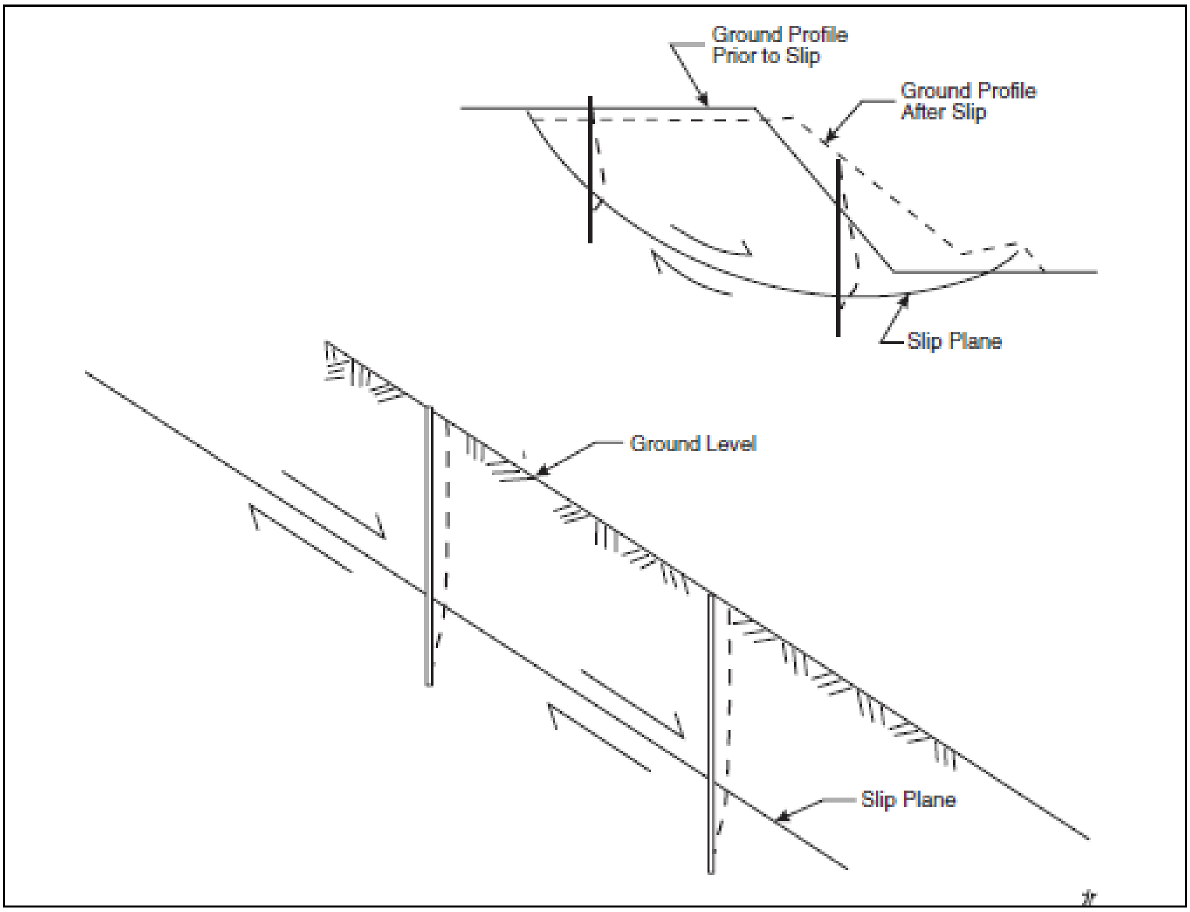


Figure 56 Displacement Movement due to excavation

8.2 Instrumentation for Slope Monitoring

The critical data that are required from a slope monitoring program are the water level(s) in the slope and the depth and rate of movement.

8.2.1 Piezometers

The Standpipe Piezometer (also known as a Casagrande Piezometer) is used to monitor piezometric water levels in vertical boreholes. The Standpipe Piezometer typically comprises two parts: at its lowest point is a porous piezometer tip; connected to the tip is a riser pipe which continues upwards out of the top of the borehole. To measure the borehole water level, the filter tip zone is packed with sand and then backfilled above. To isolate pore water pressure at the filter tip, a bentonite seal is required between the sand filter zone and the backfill. Alternative filter tip types may be driven or pushed into soft soil, and different tip designs are available to suit various types of ground.

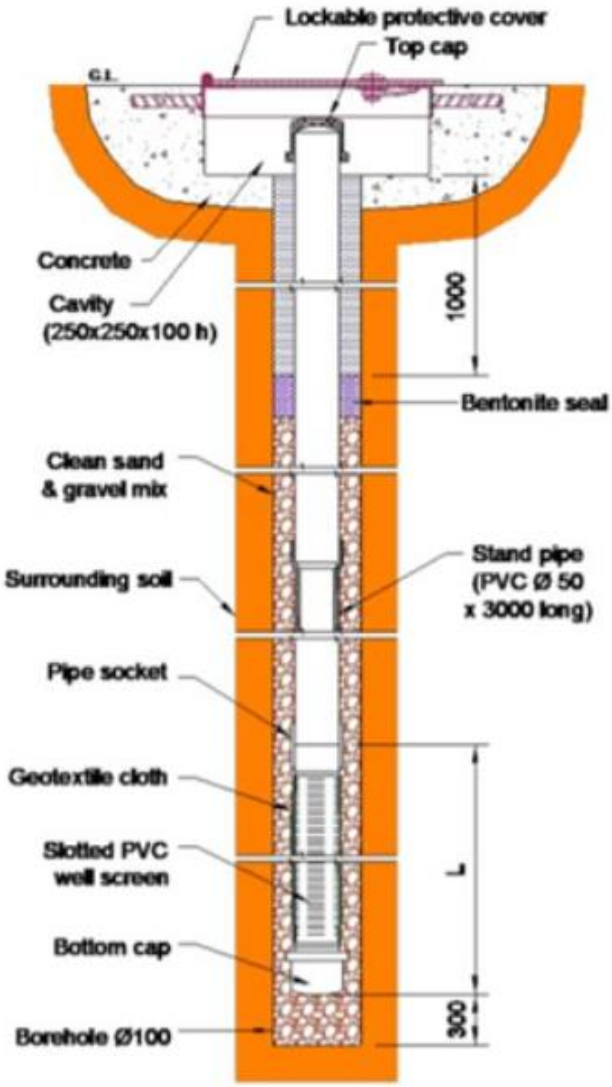


Figure 57 Standpipe Piezometer

8.2.2 Multipoint Borehole Extensometer

A borehole extensometer is a type of geotechnical instrument that is used to measure the stability, movement and behaviour of rock masses and soil within and adjacent to mines. Basically, they work by measuring the position of an internal rod relative to a reference/anchor point (or “head”). This information is then read electronically, using data loggers. A **multi-point borehole extensometer** is so named because it can simultaneously monitor multiple reference points. This makes for more accurate and useful readings.

The depth of the anchors is determined mainly by geological factors and the size and geometry of the mass being instrumented. It is useful to have one of the anchors located in stable ground so that it can serve as a reference for movements of the other anchors.

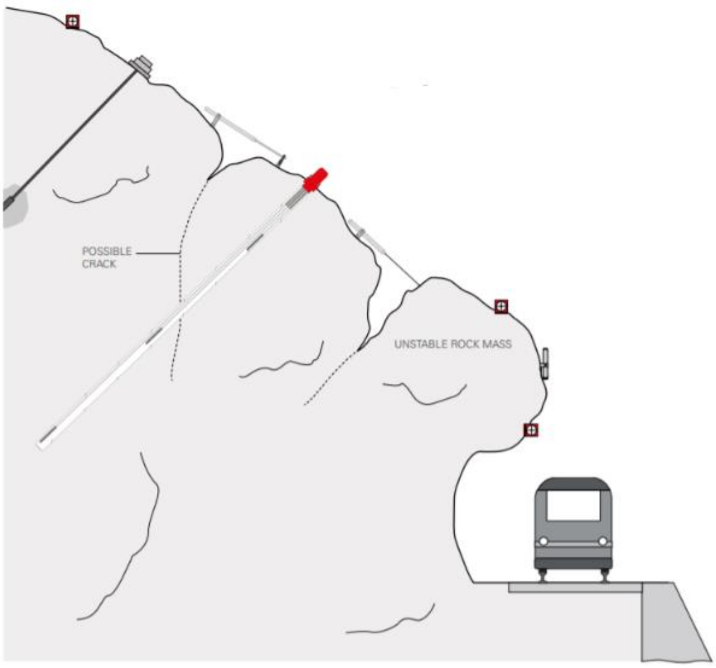


Figure 58 MPBX Installation Example

8.2.3 Geodetics

Optical 3D displacement monitoring is a geodetic measuring method, which defines the absolute, spatial position of strategically placed targets, which are firmly connected to the structure to be monitored. By repeated measurements of the 3D measuring points, time dependent diagrams can be produced, which describe the deformation behaviour of the structure measuring points with precision. The method was developed for geotechnical measurements of rock behaviour.

8.2.4 Inclinometers

The primary instrument for monitoring lateral, subsurface deformations is the inclinometer. There are two types of inclinometer systems: the portable, traversing probe system and the dedicated, in-place sensor system. Both systems require the use of inclinometer casing. This special-purpose, grooved pipe is installed in a borehole that passes through suspected zones of movement.

Inclinometers are probes that are typically used to monitor the lateral ground movement that occurs during landslides. They operate by traveling up and down specialty grooved casing that is installed a minimum of 10' into bedrock or 20' into stable ground below the suspected failure surface. The inclinometer system (Figure 1) consists of the probe, casing, graduated electrical cable and a readout unit. A pulley assembly should also be used to obtain consistent readings. The probe houses two force-balanced servo-accelerometers which measure the angle of inclination of the casing at a given depth. Trigonometry is then used to convert the measurement into a value for lateral deviation from vertical. Readings are taken every 2' from the bottom to the top of the casing and a profile of lateral earth movement is developed based on the casing being deformed as earth movements take place above the fixed bottom portion of the casing. The first set of readings is used as a baseline. Readings are then taken periodically and compared with the first set to observe the movement over time. The goal of utilizing inclinometers is to determine the depth of the failure surface, magnitude of movement, rate of movement and direction of movement.

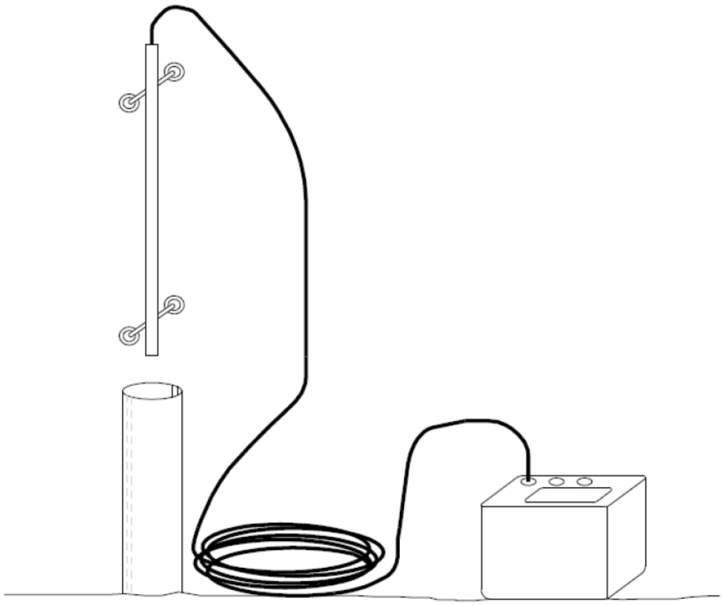


Figure 59 Schematic Sketch of Inclinometer

8.3 Instrumentation concept to be Implemented

Geotechnical instrumentation plays an important role in the investigation of deformation, water etc such that all the parameters which affects the stability of slope, can be monitored. Quarry excavation is planned in 5 phases, where the completion of each phase is planned per year. Excavation will be started from top where benches of 6m height, will be excavated. As per the geology, folds, faults, joints, and stratified rocks are potential zones for the movement and storage of ground water. The groundwater level has a major influence on material behaviour (drained-undrained), and changes in groundwater level can result in settlements and damage to structures and infrastructure. therefore, tentative instrumentation plan is designed in such a way that surface deformation of each bench will be monitored using bi-reflex targets and theodolite as well as MPBX and Inclinometers are proposed in each phase of work plan to monitor the rock settlement because of joints in the proposed lease area. piezometers will be used in each phase of work to monitor pore pressure and joint water pressure. Fixed plan for no. of instruments and the exact location for their installation, shall be generated after performing geotechnical investigations and consultation with geologist.

The excavation plan has been adequately covered in the mining report. The following concept is proposed to be implemented for proper monitoring of the slope.

First Year Plan

As the highest elevation of leased out area is 920m above MSL. The quarry cut under first year plan, will start from the elevation of 920m upto 876m which area falls in Khatpul formation (Dolomite). Dolomite rocks make up some of the best aquifers. There are frequently large fissures and openings in the rock, through which lots of groundwater can move quickly. So just after the excavation piezometers as well as inclinometers will have to be installed on benches which are equally distributed at two locations in the proposed tentative plan, and corners of each excavated bench will have to be monitored using bi-reflex targets for surface deformation. MPBX will be installed on the slope perpendicularly for obtaining normal deformation.

Second Year Plan

In second year, excavation work will start from where it was left at 876 m MSL, and the excavation will happen up to the elevation of 852m. Height of the benches through out the complete plan will remain uniform of 6m. While coming down for the excavation, the area of benches will increase therefore location of proposed instruments will also increase to produce 79the accurate analytics of slope stability. This area also comes in Khatpul formation therefore all the critical parameters which is to be measured will remain similar as discussed in first year plan.

Third Year Plan

This whole area comes under the Khatpul formation, and the start of excavation will be from 852m MSL up to 834m MSL. The cut also encounters a formation contact along south-west to north side direction at an approximate level of 790m to 810m. Since the third-year plan is approaching joints, it is to be monitored. As the elevation will decrease then area of benches will increase therefore tentatively proposed location of the instruments will increase on the benches.

Fourth Year Plan

As most of the mining plan comes under Khatpul formation, area for the fourth-year plan also covers the same geology. In fourth year, excavation will start from 834m-816m. In this area also joints will be encountered and tentatively those will have to be monitored using joint meters. As the elevation will decrease, the area of benches will increase therefore tentatively proposed location of the instruments will increase on the benches.

Fifth Year Plan

In the fifth-year plan excavation will be from the elevation of 816m up to 798m where the height of benches will be uniform as earlier in previous plans. Area under fifth year plan shall encounter joints of Khaira and Khatpul formations so it will have to be monitored using proposed instruments so that their relative deformation analytics can be produced which will help to identify the factor of deformation using the analytics of installed instruments in earlier phase. Therefore, monitoring in each phase is recommended which will mitigate the risk of slope failure.

A conceptual plan for installation of various instruments as following:

1. Geodetic Targets:

   Geodetic 3D targets should be installed all along the boundaries of the quarrying area and at each 1/3rd of both length and breadth. In addition the 3D targets should be installed at adequate spacing in yearly plan of excavation on benches being excavated. This shall help in understanding the movements of the quarrying area as whole as well as local movements of each year excavational area if any. This inputs will also help to understand if any additional supports are required at later stages. The present analysis however do not indicate such requirements.

2. Multipoint Borehole extensometer:

   Multipoint borehole extensometers should be installed during each year excavation in the benches. This shall assist in understanding the movement of each layers. Along with placing the extensometers at regular interval it should ensured to place this instruments along the two prominent seasonal water channels in the quarry area. Movements in joint between the two formation must be ensured.

3. Peizometers:

   Piezometers should be planned in the area near the water channel as well along with few interspersed in area to get understand water seepage in the area of faults. Focus must be laid to access the water movement between the dolomites and quartzites.

4. Inclinometer:

   Inclinometers must be planned on the slopes to get tilts of the movements

Apart from mining area instrumentation is recommended for slope below the road level as excavation will have some effect on that and dam is also proposed on the same slope. This area would have to monitor from initial when excavation is started. Total Instrument plan is listed below in the table which consist of all varieties of instrument to monitor the slope failure factors.

After installation, monitoring is the key aspect to assess the health of any structure. So, after the installation of the instrument readings will be taken more frequently which can be reduced after a month if no deviation in instrument's reading is found. If any of the instrument is showing any pattern and with time if it increases, frequency of monitoring will have to be increased.

Being on hill slope of quartzite & dolomite rock there would be no mining operation during monsoons or rainy days, as the wet loosed rocks are prone to uncontrolled slide. This will be the perfect time of monitoring the geological impacts on structure.

9 CONCLUSION & RECOMMENDATIONS

9.1 Geology

- The area of quarry is selected and located in stable geology consisting of Khira formation consisting of Quartzite rock and Khatpul formation of Dolmite rock. These rock types have reasonable average compressive strength of around 50Mpa.
- There are no tell-tale signs of landslides in the vicinity of general area of quarry for a distance of 15 to 20 kilometers. During the site visit the same was observed in the general study of the quarry site while traveling on this road. The area selected for quarry hence seems to be most feasible.
- The quarry site is placed at an adequate distance and elevation from the road as well as the riverbed. The quarry area has comparatively moderate slopes on the upper and lower side of the proposed quarry area. These moderate slopes act as a natural stability factor for the slopes. As per the quarrying plan sufficient toe of the quarry area has been left undisturbed, which shall provide further stability to the slope.
- The quarry site less soil cover. Beneath the soil cover formation consisting of Dolomite and Quartzite are available. The rock formations are generally at a dip between 30^0 to 60^0 to which is favorable for quarrying and from safety aspect.
- As per the Geotechnical test conducted the strength of Dolomites and Quartzite is 50 MPa. Higher to moderate strength of rock mass indicates the stability of the area and reduces the chances of failure and landslides. As both the formations have similar strength, this shall ensure the homogeneity of the rock mass on the slope and add to the stability of the area.
- A prominent joint is expected between the quartzite and Dolomites. Although the rocks have higher degree of strength and stability it has been advised to monitor the slopes with instrumentation. This additional measure shall assist in understanding the behavior of the slopes and assist to incorporate solutions required if any in the ecologically sensitive area. Instrumentation shall act as a further layer of safety and will be able to anticipate solutions for any unforeseen conditions, although the same are not expected as per the studies and analysis carried out.
- Various drifts have been excavated in the area on slopes across the quarry site as well as below the quarry site. The rock encountered in the drift area is quartzite and matches with the subsurface geological studies and investigations. The drifts have been made up to a distance of approximately 55 m and it confirms the presence of stable base under the quarry site.

9.2 Quarrying Method

- The quarry mining plan proposes no blasting for quarrying at the quarry site. The absence of blasting by explosive will drastically reduce the effect of vibration in the area. This method of quarrying without blasting shall reduce the impact of failure due to vibrations. A stable slope is also envisaged in earthquake analysis of the report.

- Quarrying without blasting will assist in reduction of noise pollution and reduced dust propagation in the area.
- Quarrying without blasting is favorable as the slips and joints of the rocks will not be disturbed and this shall ensure the natural balance which has been arrived by the rock mass over the years.

9.3 Design

- The slope is analyzed using phase 2 software for global stability of the slope and for the earthquake forces. The analysis has found the slope stable with adequate factor of safety as per the prevalent engineering standards.
- Kinematic analysis for both Quartzite and Dolomite rock formations is carried out to check the stability against planar failure, wedge failure and flexural toppling. The results did not show probability for failure of slope.
- The slopes are stable and further reduction in overburden will further enhance the safety of the slope, However, as the rock encountered is jointed fractured Gabion walls are recommended as an additional safety measures.
- Although the slope is stable, along with geological formations of the area however as a additional measures of safety drains and gabion walls are suggested. The same has been covered in detail in the report. However, as the same is related civil engineering aspects further inputs if required can be provided separately.

9.4 Instrumentation and additional Safety measures.

- Even though the slopes are stable as an additional safety measure it is recommended to install instrumentation as given in the report. This shall assist in monitoring the behavioural aspects of the slope and shall assist if any additional precautionary measures are required.

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