



# Stability analysis of road cut slope near Devprayag in Lesser Himalaya, India

TARIQ ANWAR ANSARI<sup>1,\*</sup>, K H SINGH<sup>1</sup>, T N SINGH<sup>1</sup> and JAYANT NATH TRIPATHI<sup>2</sup>

<sup>1</sup>*Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai 400 076, India.*

<sup>2</sup>*Department of Earth and Planetary Sciences, University of Allahabad, Allahabad 211 002, India.*

\*Corresponding author. e-mail: 22tariq@gmail.com

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The slope instability issues in Himalayan terrain is drastically increasing due to variety of anthropogenic activity and rapid urbanization. Road and highway networks in mountainous regions are the main source in remote parts of hilly terrain for the transportation as well as all sorts of socio-economic features. The study of slope stability in these hilly regions along the highways and roads are major concern, where slope instability caused transportation problems, death and injury of human, loss of their properties and also environmental degradation. Present article exposed the slope instability analysis for the two typical slopes along National Highway (NH-7), between Devprayag and Mulyagao in Uttarakhand, where the Highway goes up to the holy shrine of Kedarnath and Badrinath. The vulnerable slopes are numerically simulated using limit equilibrium method (LEM) and finite element method (FEM) for dry and saturated condition. The comparative analysis of factor of safety for LEM and FEM results show good correlation, i.e., 1.6–2.4% variance in dry condition and in saturated condition the LEM and FEM results show 11–13% variance. The finite element simulation has also assessed the principal stresses and displacement vector, which gives more understanding to identify and reveal the slope stability issues in analogous morphology. The result shows that both the slopes are in critical condition and prone to failure in rainy season due to exertion of water in intensely fractured rocks.

**Keywords.** Lesser Himalaya; slope stability; LEM; FEM.

## 1. Introduction

Slope instability is a devastating geo-hazard in hilly terrain commonly in the Himalayan region mainly triggered due to rainfall, road expansion and seismic activity. Kumaun Garhwal and the Lesser Himalayan region are diversely affected due to neo-tectonics and structural deformation along the Main Boundary thrust (Valdiya and Bartariya 1989; Valdiya 2001, 2003) that caused more relevant slope failures. In recent years, rapid urbanization and various anthropogenic activity mostly along Highways has increased that caused more slope instability

issues in the hilly terrain of Himalayas. Transportation and communication in the hilly regions are mainly followed through road networks, so the failure of slopes along the roads in this region is a matter of concern. The poor blasting and fluky excavation of various slopes also caused more instability and failures. Major and minor landslide always happened in hilly region especially in rainy season. As the study area is highly jointed, the slope failure occurred not only in rainy season, but also happened in dry season. The study area belongs to Lesser Himalayas, which possessed various rock types that are inherently heterogeneous and fractured, followed by various

geological processes. Discontinuities could happen in any form as fissures, joints, faults, bedding, etc. These discontinuities also played a vital role for rock slope failure. Slope stability is a complex phenomenon as many factors influenced it. Generally, slope instability occurred due to one or combination of factors like slope geometry, strength, geo-hydrological condition, structural discontinuity, slope forming material, tectonic forces, lithological changes, weathering and heavy rainfall (Singh and Singh 1992; Umrao *et al.* 2011; Ahmad *et al.* 2013; Singh *et al.* 2014).

Recently the slope stability issues have been broadly discussed by Singh *et al.* (2016), Antinoro *et al.* (2017), Sharma *et al.* (2017), and Subramanian *et al.* (2017), using novel methods of conventional, continuum and discontinuum methods. In recent years, several numerical methods have been developed to reveal the slope failure mechanism and to support the unstable slopes. The numerical and conventional methods mainly consist of finite element method (FEM), limit equilibrium method (LEM), finite difference method (FDM), GIS and fuzzy logic and neural networks, which has been discussed by various authors in recent years (Chen and Shao 1988; Coggan *et al.* 1998; Jing and Hudson 2002; Zhu *et al.* 2003; Pradhan and Saied 2010; Alavi and Gandomi 2012; Singh *et al.* 2012, 2013, 2014; Ahmad *et al.* 2013; Gupte *et al.* 2013; Kainthola *et al.* 2013; Ramakrishnan *et al.* 2011).

The present study discusses the instability of the road cut slopes along NH-7 between Devprayag and Mulyagao, in the Garhwal region of Uttarakhand state, India (figure 1). The representative data for numerical simulation of two vulnerable locations were collected with their slope geometry, geomaterials, failure history and degree of weathering cautiously. The representative samples were tested in the laboratory to find out the input parameters for numerical simulation. Then two vulnerable locations were simulated by the LEM (Slide v.6 software) with the simplified Bishop method and FEM (Phase<sup>2</sup> software) method. The factor of safety, strain variation and displacement vector with their failure direction were evaluated by dynamic programming of LEM and FEM models.

## 2. Description of the study area

The study area belongs to Devprayag and Srinagar region, which is located in the Lesser Himalayan Zone and characterized as structurally complex

part (Valdiya 1983; Srivastava and Mitra 1994). The Srinagar area is characterized as thrust sheet, as it divided the Lesser Himalayas into an inner and outer sequence (Ahmad *et al.* 2013). The North Almora Thrust (NAT) cuts the area in NE part which trend NW–SE, whose dip is 40°–50° towards SE. The folds, faults, thrusts and associated shear zones can be ascribed to the effects of sequential stresses and the genesis of all these structures are interrelated (Shekhar *et al.* 2006). At many places, much steeper dips and variation in the strike for thrust sheet are recorded (Shekhar *et al.* 2006). The slope and aspect map of the area have been shown in figures 2 and 3, respectively, which illustrate the large slope variation with very less ground surface mostly in and around fluvial tributaries.

Devprayag and Srinagar area belongs to Jaunsar Group, which comprises the Mandhali, Chandpur and Naghat formations of the Neo-Proterozoic age (Auden 1934). The Chandpur Formation is mainly consisted of olive green and gray phyllites with subordinate slate, interbedded with quartzite met siltstone and fine-grained wackes (Shekhar *et al.* 2006). Quartzite is very extensively found in the whole Lesser Himalayas extending as a linear belt below the Krol Group of rocks (Kumar *et al.* 1974; Kumar and Aggarwal 1975). The study area is witnessed of phyllites and quartzites with some metavolcanics between Devprayag and Mulyagao.

## 3. Geomorphology and climatology of the area

Devprayag and Srinagar area comprises the Lesser Himalayan zone, which is bounded by Main Central Thrust and Main Boundary Thrust (Gansser 1964; Yin 2006) with mature topography and less rugged mountains. Physiography of the lesser Himalayan zone is characterized by geomorphological features such as cliffs, dendritic and trellis drainage pattern, rocky slopes, debris avalanche, waterfalls, major and minor ridges and numerous fluvial geomorphic features such as meandering scars, point bar, natural levees, terraces, quaternary deposits in Alkananda valley and its tributaries (Khan *et al.* 1982; Dhingra and Chakrapani 2004; Shekhar *et al.* 2006; Sati *et al.* 2007; Sundriyal *et al.* 2007; Ray and Srivastava 2010). In Devprayag, Alkananda river meets Bhagirathi river, where it forms Ganga River. The whole area has gentle to steep slopes, somewhere covered with landslide debris with inversion of relief in

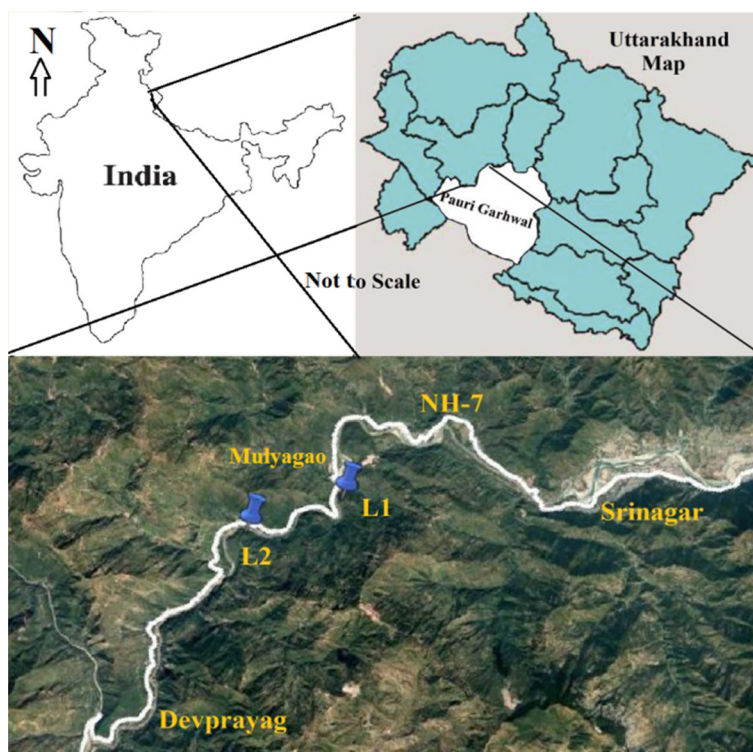


Figure 1. Location map of the study area.

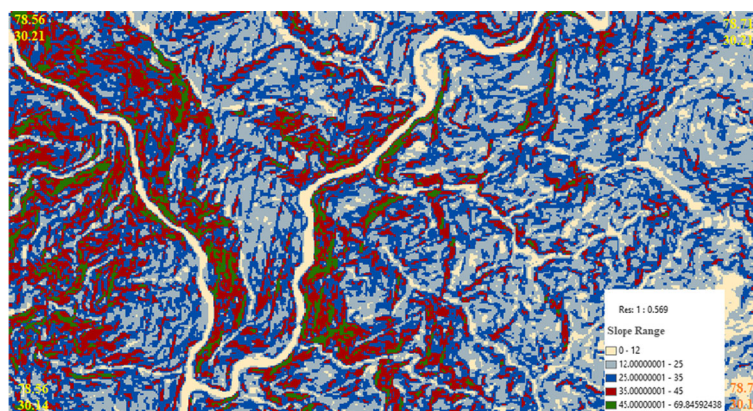


Figure 2. Slope map of the area.

metamorphic rocks. At many places, rocks are going to be weathered due to tectonic upliftment, fluvial and glacial activity.

The Garhwal Himalayan region is mostly followed by temperate climate zone. The study area (Devprayag and Srinagar) belongs to Pauri Garhwal and Tehri Garhwal districts of Uttarakhand state. The area received moderate snowfall during December–February on higher altitudes. Average annual temperature of the Garhwal region ranges between 25 and 30°C and maximum temperature is recorded in the month of June, i.e.,

45°C. Most of the rainfall is during mid-June till mid-September, where 90% of rainfall occurred during the monsoon period. Thomas and Christoph (2005) have reported that heavy rainfall events from past 30 yrs had dramatic changes, which bound to increase the warming global environment. High rainfall is a reason for increment of erosion rates in Himalayan terrain (Nagle *et al.* 1999), where the regional erosion rate has been discussed by various authors (Curry and Moor 1971: 0.7 mm yr<sup>-1</sup>; Menard 1961: 1.0 mm yr<sup>-1</sup>). The rainfall data from 1966 to 2016 of the Garhwal region has been

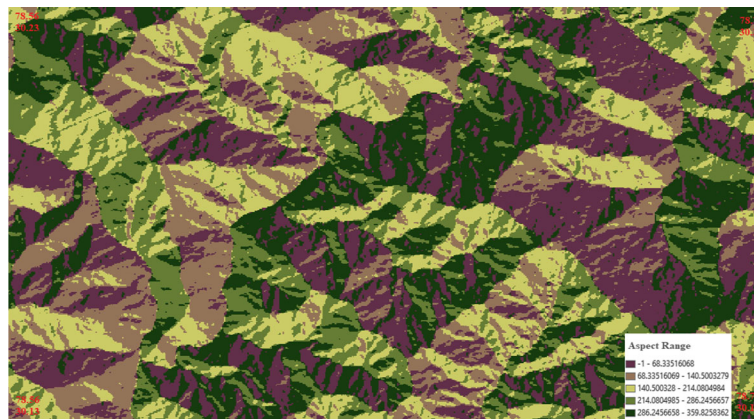
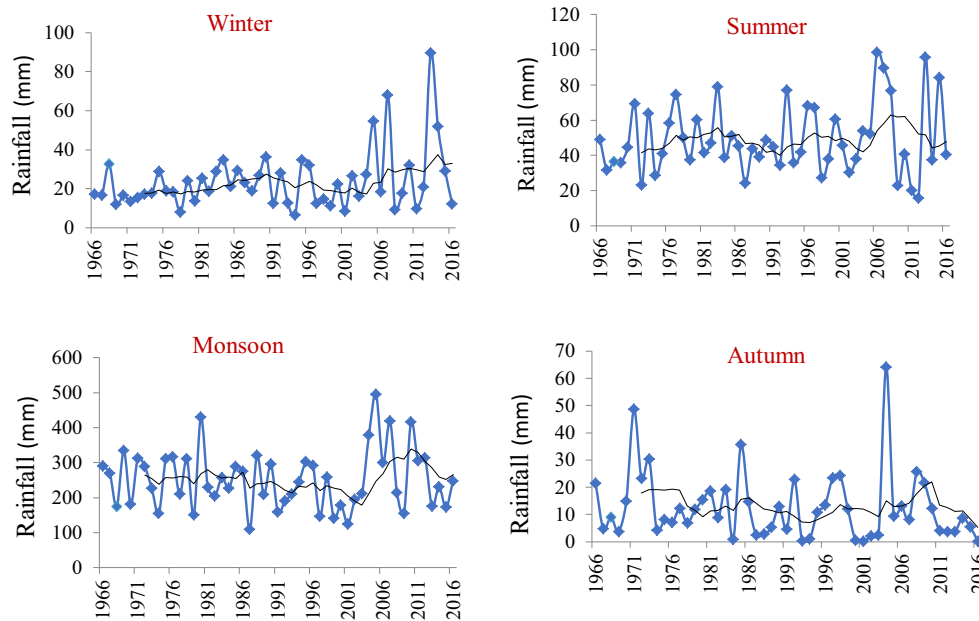


Figure 3. Aspect map of the area.

Figure 4. Seasonal rainfall for the Garhwal region of the study area (1966–2016), data from Indian Meteorological Department and Ministry Department (<http://www.imd.gov.in> and <https://data.gov.in>).

pre-meditated as four main seasons; the winter (December–February); the summer (March–June); monsoon or rainy season (July–September) and autumn or post-monsoon period (October–November) as shown in figure 4.

The graph shows a small increase in the trend of rainfall for the winter season (December–February) and summer season (March–June). The graph of monsoon period (June–September) also pointed the increasing trend in rainfall. In the autumn season (October–November), there is no increasing trend of rainfall from 1966 to 2016. The result shows the overall yearly increment in rainfall of the area, which has drastic effect as discussed above.

#### 4. Numerical analysis technique

Several advanced numerical techniques (continuum, discontinuum and hybrid methods) are available and being widely used in rock slope stability analysis (Griffiths and Lane 1999; Zheng *et al.* 2005; Cheng *et al.* 2007; Sharma *et al.* 2017). The present study exposed, limit equilibrium method (Simplified Bishop Method) and continuum method (Finite element analysis) for slope stability analysis. The numerical simulation effort has been carried out using SLIDE 6.0 and PHASE<sup>2</sup> 7.0 software and a comparative analysis has been done to predict and reveal the failure mechanism. The input parameters

for numerical simulation have been evolved as per ISRM (1978, 1979, 1981) standards.

#### 4.1 Rock-mass properties

The experimentally investigated intact rock parameters are used for rock mass parameters, which are calculated using Roclab software (Rocscience Inc 2010; Kainthola *et al.* 2013). Roclab is a developed software based on the generalized Hoek–Brown failure criterion to determine the rock mass parameters and to find out the equivalent Mohr–Coulomb parameters from the Hoek–Brown failure envelope. The generalized Hoek–Brown failure criterion (Hoek *et al.* 2002) has been used to evaluate the rock mass parameters, which is expressed as:

$$\sigma'_1 = \sigma'_3 + \sigma_{ci} \left( mb \frac{\sigma'_3}{\sigma_{ci}} + s \right)^a \quad (1)$$

Here,  $m_b$  is a reduced value of the material constant  $m_i$ ,  $s$  and  $a$  are constants for the rock mass and given by

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right), \quad (2)$$

$$s = e^{\left(\frac{GSI-100}{9-3D}\right)} \quad \text{and} \quad a = \frac{1}{2} + \frac{1}{6} \left( e^{\frac{-GSI}{13}} - e^{\frac{-20}{3}} \right). \quad (3)$$

The  $D$  factor depends upon the degree of disturbance, where the rock mass has been subjected by blast damage and stress relaxation. The value 0 is for undisturbed *in-situ* rock masses and 1 for very disturbed rock masses.

#### 4.2 Limit equilibrium method and finite element method

Simplified Bishop Method has been utilized in limit equilibrium analysis for the two vulnerable slopes, where Mohr Coulomb criteria have been used as the failure criteria by Slide v.6 software (Slide 2010). In Slide software, the geomaterials above the slope is divided into various vertical slices and slices are dependent to profile of geomaterials and slope geometry. In Bishop Simplified method (Bishop 1955), factor of safety is the ratio between the shear strength of the surface and the shear stress acting on the surface used for Mohr Coulomb strength material for both dry as well as saturated conditions. In Bishop simplified, slope failure is

expected to happen with the rotation of a mass of rock/soil on a circular slip surface, centered on a common point. The forces on the side of each slice is considered as horizontal, where there is no shear stress between slices (Bishop 1955). The factor of safety computed by Bishop’s simplified method and the shear strength reduction factor commonly favours about 5% (Wright *et al.* 1973). The finite element method (FEM) is extensively used for slope stability analysis and most popular techniques using strength reduction parameter (SRF) approach with fewer assumptions (Griffiths and Lane 1999). Continuum methods are suitable methods, which have been used for the analysis of soil/rock slopes, and most continuum codes are comprised with distinct features like bedding plane and faults (Hammah *et al.* 2004; Singh *et al.* 2008; Monjezi *et al.* 2011; Sarkar *et al.* 2012). In FEM, the shear strength of material is reduced with SRF by a factor of safety, and simulated the FEM models of the slope, till deformations too large and a solution is not converged for the slope. Slope is generally discretized by six nodes triangular mesh and the stress reduction factor (SRF) value is systemically determined, when the slope has gone to converge for the failure. In FEM and LEM, the Mohr–Coulomb model was processed like linear elastic but perfectly plastic model. Commonly six input parameters such as unit weight, friction angle, cohesion, Poisson’s ratio, dilation angle and deformation modulus (Young’s modulus) are required to simulate the Mohr–Coulomb model, where dilation angle is considered as 0, supposing a non-associated flow rule (Griffiths and Lane 1999).

### 5. Slope description and engineering parameters

Two vulnerable slope locations were selected through rigorous field study along NH-7 between Devprayag and Mulyagao in Uttarakhand. The field study included collection of geo-materials, geotechnical data with different structural information. Both locations have phyllitic characteristics, which are highly fractured. Location 1 consists of three sets of joints, whereas location 2 has two sets of joints only. As the slopes are structurally controlled, the rock mass parameters are required for numerical simulation. The rock mass rating (RMR) and geological strength index (GSI) values were calculated for both discontinuous slopes as

followed by Bieniawski (1989) and Sometz and Ulusay (1999, 2002), respectively (table 1).

5.1 Location 1

The field investigation of location 1 is mostly structurally controlled, where mechanical and geometrical parameters showed wedge type of failure. The rock mass has phyllitic characteristics, which is highly fractured and has three sets of joints with high persistency. The field photograph and slope geometry for location 1 has been shown in figure 5. The slope has typically the height of 40 m above the road, where overall slope angle is 79° with variance at different points. The input parameters (rock mass) required for numerical simulations were also calculated using Roclab software for both dry and saturated conditions as in table 2.

5.2 Location 2

The location 2 is also an extremely fractured rock cut slope, where toppling of slope failures occurred due to joints orientation and geometrical properties. The rock mass has phyllitic characteristic, where two sets of joints cut each other. The slope geometry and field photograph for location 2 has been shown in figure 6. The slope height for location 2 was measured as 25 m above the road, where slope angle varied at some points and average slope angle is measured as 64°. The rock mass parameters for numerical simulation of location 2 were calculated using Roclab software, for which GSI value has been presented in table 1. The intended rock mass parameters (used in LEM and FEM models) for dry and saturated conditions are given in table 3.

6. Result and discussion

The road cut slope instability in the phyllitic rocks of study zone is a serious concern due to its inherent properties and intensely fractured characteristics. The phyllitic rocks have generally foliation planes with tabular and elongated minerals, along which rocks can be easily broken into sheets. The petrographical analysis of phyllitic rocks of the studied slopes shows mainly the quartz, feldspar, mica and chlorotic minerals, where clay minerals are mostly settled in a preferred orientation (figure 7). The clay materials in these phyllites

Table 1. Quantified GSI, RMR and GSI value.

Location no.	UCS value (MPa)	UCS Rating	RQD	RQD Rating	Rating of spacing	Rating joint condition	Rating G.W. condition	Jn Rating	Jr Rating	Ja Rating	SRFa	SRFb	SRFc	SRF	Jwice	RMR	GSI
1	24.89	2	92.26	20	9.3	12.5	15	3	3	1	5	4	2	3.67	0.5	58	40
2	20.21	2	74.58	13	9	12.5	15	4	1	1	5	3.5	4	4.17	0.1	49	33

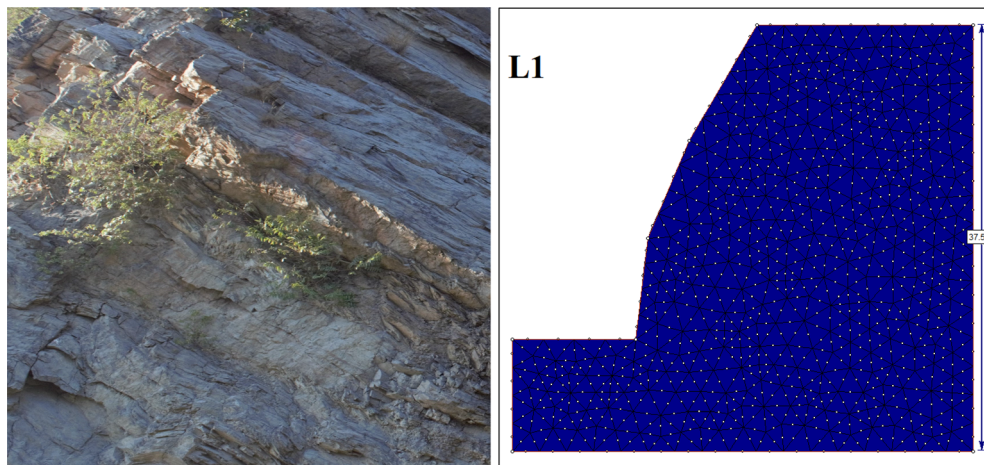


Figure 5. Field photo and slope geometry for location 1.

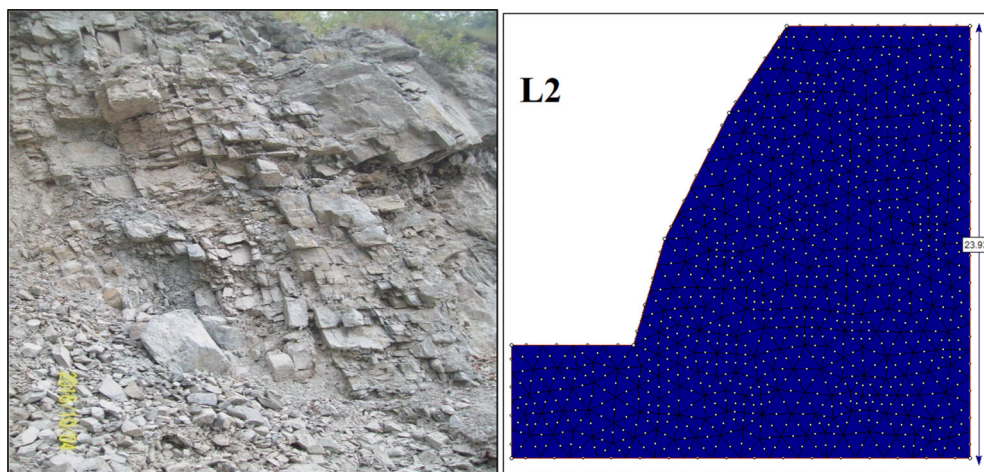


Figure 6. Field photo and slope geometry for location 2.

Table 2. Input parameters for dry and saturated conditions.

Sl. no.	Parameters	Unsaturated/dry	Saturated
1	Unit weight (kN/m <sup>3</sup> )	27.3	28
2	Cohesion (KPa)	95.0	90
3	Friction angle (°)	21	18
4	Young's modulus (KPa)	52300e3	53700e3
5	Poisson's ratio	0.25	0.25
6	Tensile strength (KPa)	80	74

have specific property of water holding capacity and the percolating water through foliation and jointed planes caused more weathering and instability issues.

The numerical simulation for highly fractured and foliated rocks were evaluated to know the stability of road cut slopes. The simplified Bishop method

(using Slide V.6 software), was used in LEM model to calculate the safety factor in dry and saturated conditions. Further same slope locations are simulated by FEM technique using Phase<sup>2</sup> 7.0 software, where six nodes triangular mesh has been discretized under gravitational loading for dry and saturated conditions. The base and the right

Table 3. Input parameters of rock mass for dry and saturated condition.

Sl. no.	Parameters	Unsaturated (dry)	Saturated
1	Unit weight ( $\text{kN/m}^3$ )	27.8	28.5
2	Cohesion (KPa)	56	52
3	Friction angle ( $^\circ$ )	21	18
4	Young's modulus (KPa)	52000e3	53900e3
5	Poisson's ratio	0.25	0.25
6	Tensile strength (KPa)	11.23	9.5

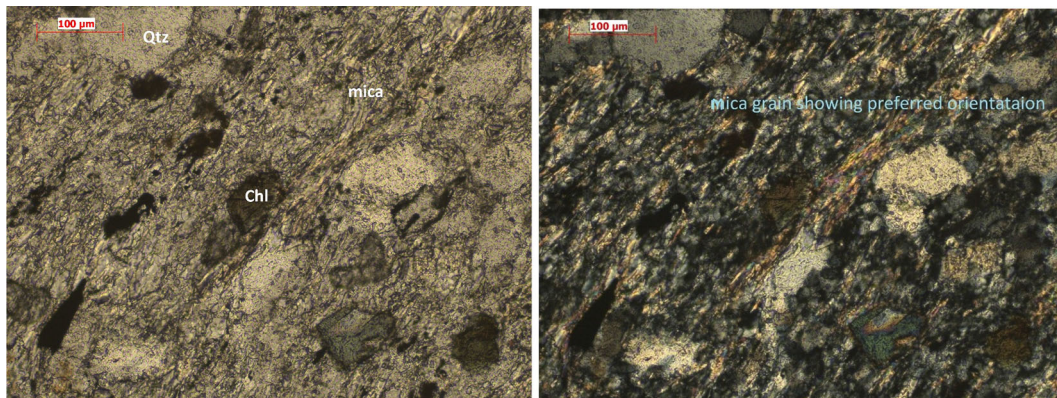


Figure 7. Petrography of phyllitic rock.

boundary have been restrained in both X and Y directions and the slope face towards the road has been kept free according to the boundary condition. The colour code simulated in LEM/FEM model represents the factor of safety variance along the slip surfaces. Total displacement contour pattern has been generated from FEM modelling results to check the extent of possible damage zone (i.e., the zone of failure) which also depicts deformation intensity in various portion of the slope. The maximum shear strain contour pattern of each slope is extracted from FEM results to assess their distribution and behaviour across the slope. It helps to predict probable mode of slope failure, its mechanism and other secondary/minor detachment.

LEM analysis for location 1 shows critical condition for dry condition, where it is unstable for saturated condition as shown in figure 8. The simulated result for location 1 from FEM analysis show critical condition for dry, and unstable for saturated condition (figure 9). The LEM and FEM simulation for dry condition of location 2 were also accomplished, which explain critical state in dry situation, whereas for saturated condition the slope is going to fail (figures 10 and 11). The LEM

and FEM analysis for dry condition of both the locations exposed <5% variance in factor of safety (table 4). The variance in dry and saturated conditions in factor of safety for both locations in LEM model predicted 11–12.68%, whereas in FEM model 12.14–13.73%, respectively (table 4). The simulated factor of safety for dry to saturated conditions in both the models exposed more variance, which may be due to highly discontinuous absorbent geomaterials. The LEM and FEM analysis for locations 1 and 2 illustrate that failure direction is from top to toe. The maximum shear strain for dry and saturated conditions is accumulated near toe portion as well as top right of the slope in locations 1 and 2 as from FEM analysis. The total maximum displacement along the free face computed from FEM analysis for locations 1 and 2, exposed less value of displacement (between 0.77 and 3.50 mm) in dry and saturated conditions. The less value may be due to intensely fractured, less cohesive geomaterials and shallow damage zone (figures 12 and 13). The displacement contour for both locations displays maximum damage zone near toe (hanging portion or half tunnel structure) of cut slope and their distribution like curvo-planer pattern suggest shallower damage zone confined in



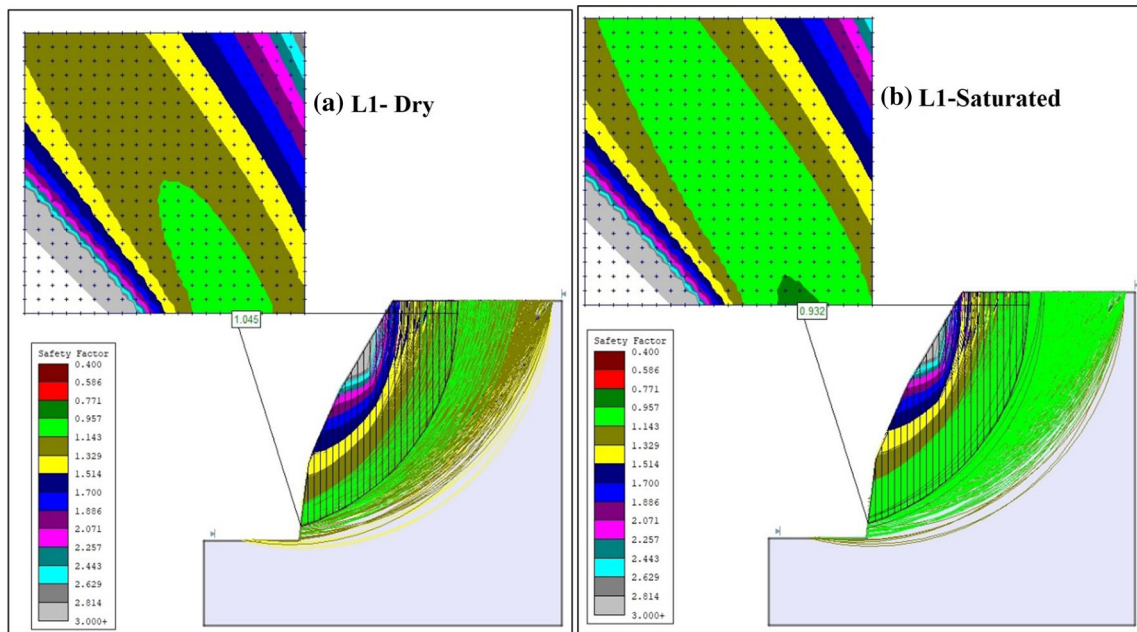


Figure 8. Results of grid search: (a) dry condition and (b) saturated condition.

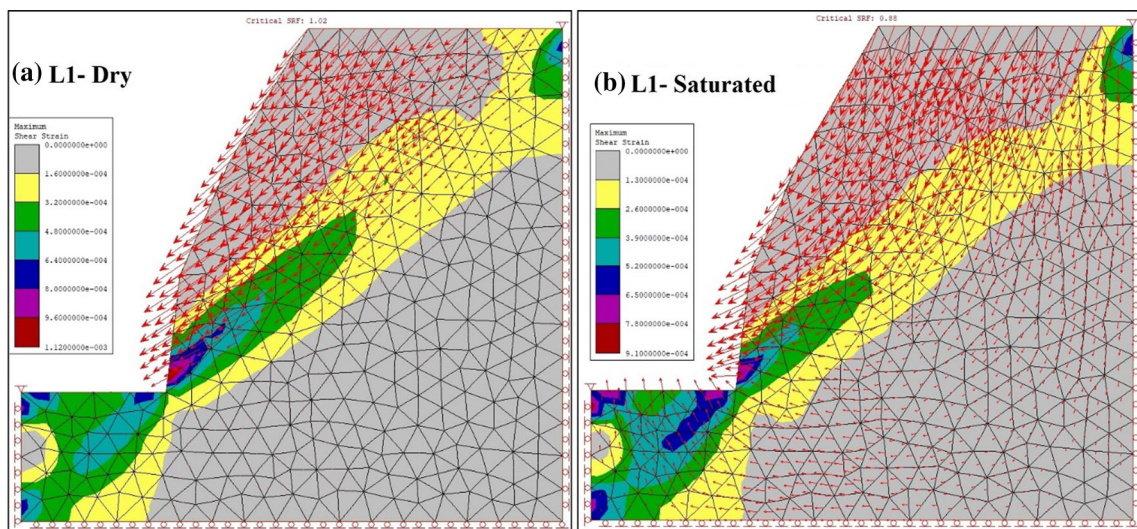


Figure 9. Maximum shear strain with deformation vectors: (a) dry condition and (b) saturated condition.

free face of cut slope. This is also confirmed during field visit by presence of thinly foliated hanging rock which may initiate slope failure on small scale, likely to create problem for commuters (figures 5 and 6). Steepness of slope is also greater than sliding plane and bedding joint dipping towards the free face of slope in same direction as slope does, hence sliding plane may daylight in the slope face. The free face is highly fractured, comprised of displaced, and detached fragile rock block that are stuck on slope face, that dip more or less outward

from slope face tend to fail any time without prior indication. The steepness of slope, orientation of discontinuities aligned in such a way that failure involves sliding on discontinuity plane and shearing through the rock mass at the toe of the slope clearly affects the alignment of the road. The loose material on the edge of road is subsiding gradually into valley. Also the cohesion between rock mass planes is reduced sufficiently by dry clay and ferrous material, hence there will be gradual loss of load-bearing capacity of entire slope. The

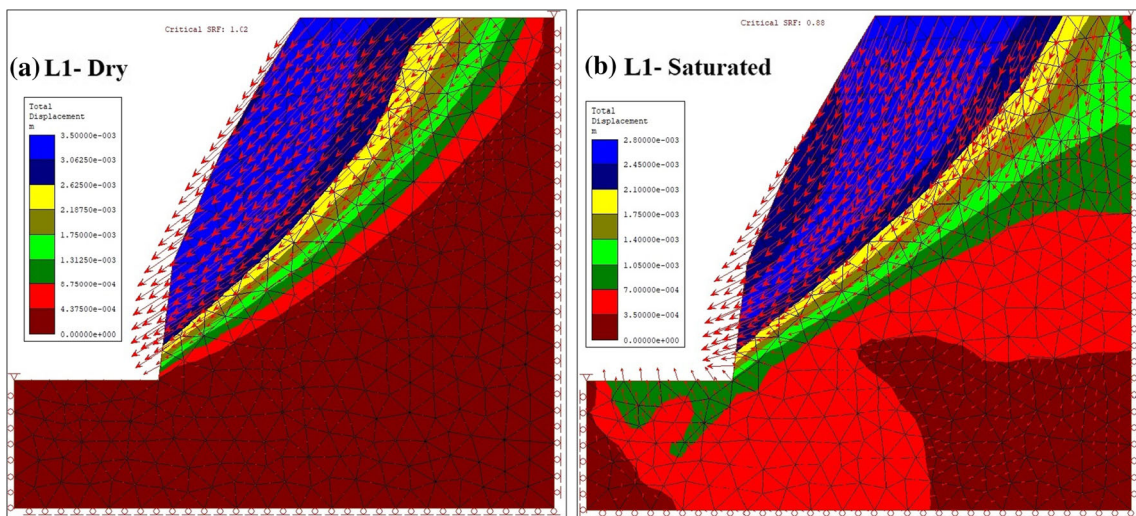


Figure 10. Maximum displacement: (a) dry condition and (b) saturated condition.

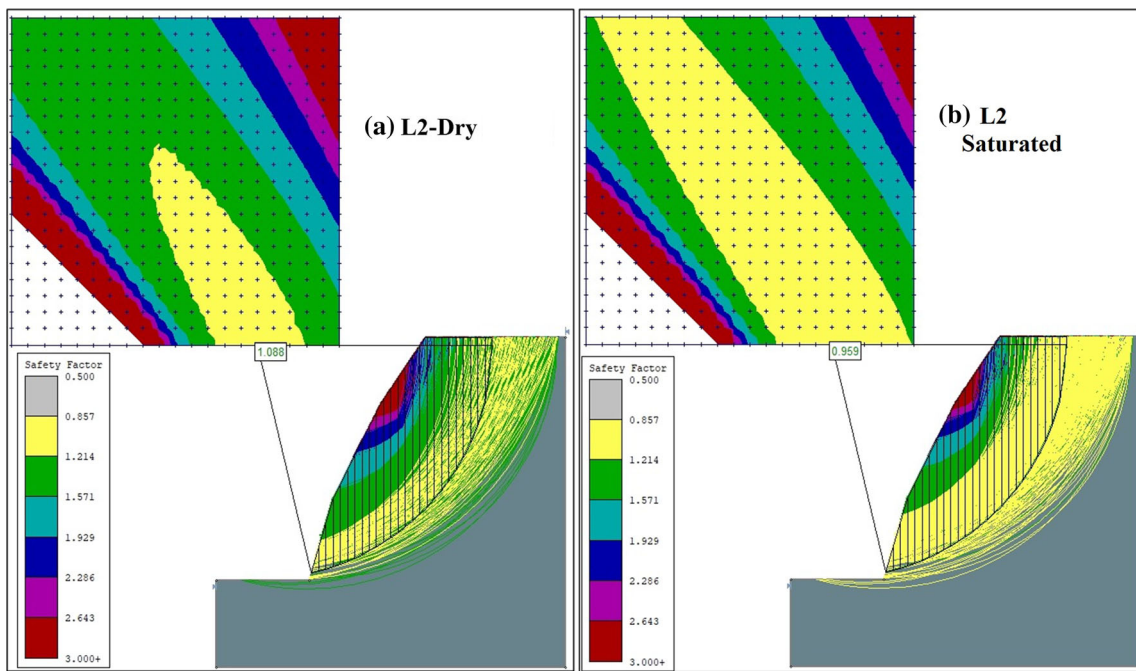


Figure 11. Results of grid search: (a) dry condition and (b) saturated condition.

Table 4. Variation in FOS in different situation of dry and saturated condition.

LEM (dry)	LEM (sat.)	LEM (sat.) and LEM (dry), (%)	FEM (dry)	LEM (dry) and FEM (dry), (%)	FEM (sat.)	FEM (dry) and FEM (sat.), (%)
1.045	0.93	11.00	1.02	2.40	0.88	13.73
1.088	0.95	12.68	1.07	1.65	0.94	12.14

dislodged chunks of rock mass are seen to stuck in loose altered material and angular block hanging on the free face of slope along the road side. The material that gradually failed at the toe of the slope

and along the bank of road causes disturbances in ongoing traffic. Mix type of failure was seen on the slide zone, where the width of road is gradually decreasing due to heap of loose materials.

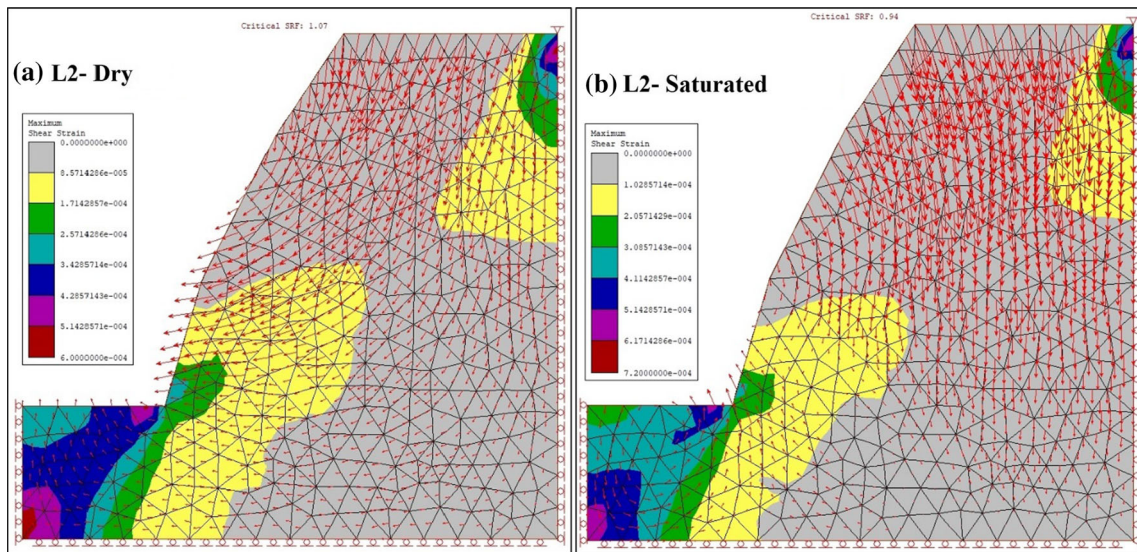


Figure 12. Maximum shear strain with deformation vectors: (a) dry condition and (b) saturated condition.

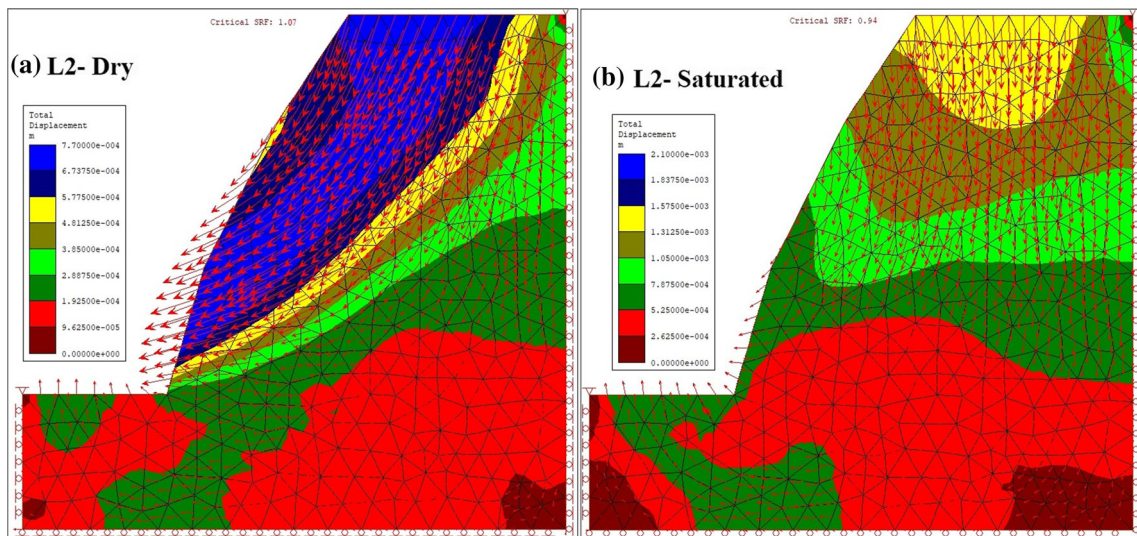


Figure 13. Maximum displacement: (a) dry condition and (b) saturated condition.

## 7. Conclusion

The rocks of the study region are highly deformed and distorted as the area is seismically active and weathering effects are more due to increasing trend of rainfall. The road cut slope analysis in the phyllitic rock of the study zone is a serious concern due to rock inherent properties. The petrographical study of foliated rocks (phyllite) revealed quartz, feldspar, mica and chlorite, etc., where the foliated rocks are more easily broken into sheets due to weathered and intensely fractured rocks. The clay contained of phyllitic rocks in the intensely fractured slopes has water holding capacity that

creates more instability. The numerical simulation of two phyllitic rock road cut slopes were evaluated using most adaptive LEM (Slide V.6 software) and FEM (Phase 2.0 software) models along NH-7 between Devprayag and Mulyagao in Uttarakhand. The numerical analysis from LEM and FEM revealed that both the locations were in critical condition in dry state, while in saturated condition both the locations went to unstable. The FOS from both the methods exposed good agreement with <5% variance. While the FOS in dry and saturated conditions showed more variance, i.e., almost 11–13%, which might be due to water holding capacity of clay materials in the phyllitic

rocks. Maximum shear strain has more concentration near top portion of slope, discretely distributed, gradually decreases towards toe of the slope. The maximum displacement vector in FEM analysis along the slope face also pertained less value (0.77–3.5 mm), which could be due to intensely fractured, less cohesive geomaterials and shallow damage zone. The steepness of slope, intensely fractured rock, orientation of discontinuities, clay and ferruginous material between open discontinuities and poor way of blasting to the road cut slopes are the key factors for the instability of slopes. The area asserts religious connotation and connected to religious corridor (Shri Kedarnath and Badrinath temples) in Uttarakhand state. To protect these slope locations from failures, it is recommended to apply rock bolting with net fencing, viz., in an appropriate way to prevent further failures.

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