Geoenvironmental and geotechnical assessment of soil slopes in the vicinity of Atal tunnel in Himachal Pradesh, India

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ABSTRACT
In this work, geological, mineralogical, geotechnical and stability analysis using limit equilibrium method (LEM) was carried out around the vicinity of Atal tunnel in Himachal Pradesh, India to access the slope instability. Four representative unstable soil slopes along the Palchan road to the South portal of Atal tunnel were identified. The study area is located in the north-west Himalayas near South portal (S-1, S-2 and S-3) and one slope (S-4) near North portal (NP) of Atal tunnel. It is the only road connecting the city to the tunnel and therefore, the stability assessment of road cut slopes is imperative for safe transportation. South portal is mainly composed of clayey sand and NP consists of poorly graded sand (SP) as thick overburden. Laboratory investigation showed that the soil slopes are sandy and non-cohesive and high dynamic conductivity. Shear strength parameters (c and \( \phi \)) were also found to be low (Cohesion < 33 KPa and friction angle less than < 25\(^{\circ}\)). Stability assessment of all the four soil slopes was carried out using LEM; however, the detailed analysis was carried out for soil slopes S-3. Factor of safety (FoS) of 0.75 was obtained and reliability index \( \text{RI (ve)} \) for soil slope S-3 without reinforcement while FoS got increased to 1.19 and RI (3.61) for reinforced soil condition with nail spacing between 2.5 to 2.75 m. A sensitivity analysis has been performed on geomechanical parameters like cohesion and angle of internal friction for determining the distribution of FoS.

Abbreviation List: AST M: American Society for Testing Materials; BS: Bishop Simplified; FE-SEM: Field Emission Scanning Electron Microscope; FoS: Factor of Safety; IS: Indian Standard; LEM: Limit Equilibrium Method; MSL: Mean Sea Level; NMC: Natural Moisture Content; OMC: Optimum Moisture Content; P F: Probability of Failure; RI: Reliability Index; SDA: Self- Drilled Anchors; SEM: Scanning Electron Microscope; SP: South Portal; XRD: X-Ray Diffraction
1. Introduction

The term landslide incorporates rockfall, topple and debris flow, etc., under the effect of gravity (Varnes 1984). Determination of susceptibility is not an easy task as the slope stability is governed by several factors, such as geomorphological features (Hoek and Bray 1981), geotechnical rainfall/groundwater (Jaswal et al. 2020) freeze-thaw (Sardana et al. 2020), seismic activities (Valagussa et al. 2014) and vegetation. Geotechnical and geodynamic behaviour of the slopes in the Himalayan region are responsible for the frequent landslides (Chandel and Brar 2010). Himalayan region contributes about 30% of the total losses due to landslides and related destruction (Dahal et al. 2009) in India. Due to rapid climatic change, an increase in the frequency and intensity of rainfall has caused dislodging of the bulk of weathered material from its original location which flowed down the hills. Several slope failures in the Himalayan region showed the interweaved relationship between tectonic and erosional processes that led to the geomorphic denudation (Bartarya and Valdiya 1989). Climatic conditions have a crucial control on topographical development (Brozovic et al. 1997) and also accountable for various types of landslides in the Indian Himalayan Region (Dikshit et al. 2020; Sardana, Verma, Singh, Laldinpuia, et al. 2019; Sardana, Verma, Verma, Singh, et al. 2019; Verma et al. 2021).

During the construction of the geotechnical structure in hilly region, there may be chances that the slopes in the proposed project area are unstable (Ahmad et al. 2015). Therefore, geotechnical characterization of slope material is necessary to evaluate its’ behaviour. During the development of infrastructure projects, such as bridges, tunnels, roads, dams, etc., geotechnical engineers have faced several problems caused by the physico-mechanical behaviour of soils. Hence, detailed characterization is necessary to mitigate these problems (Sharma et al. 2017). The soil properties, such as grain size, pore volume and porosity distribution of the soil greatly influencing the stability of slopes. Therefore, slope stability analysis for both probabilistic and deterministic is important to be carried out for stability assessment (El-Ramly et al. 2002). In the probabilistic method, each geo-mechanical parameter is provided with a range that indicates uncertainties involved in the soil properties. In recent few decades, concepts and principles of probabilistic analysis have been well established (Khajehzadeh et al. 2010; Leynaud and Sultan 2010; Christian et al. 1994; Vanmarcke 1980).

Limit equilibrium methods are prime methods used for decades in geotechnical engineering to determine the factor of safety (FoS). LEM is considered quite simplistic and versatile compared to other numerical methods due to its cost-effectiveness and less time-consuming approaches (Song and Cui 2016; Cheng et al. 2007; Abramson et al. 2002). Engineers and researchers of the scientific community prefer LEM to perform slope stability analysis as there are certain limitations in the practical application of numerical modelling techniques in certain cases, whereas the LEM remains capable of producing accurate and reliable results for most homogenous materials. Numerical methods, such as the strength reduction-finite element method generally yield unique failure surfaces and other possible failure surfaces may not be simply defined. However, LEM can determine two or more critical failure surfaces having very close FoS values that should be considered in stabilization measures.
(Singh et al. 2018). Hence, numerical methods may suggest a less important local slip surface while a more vulnerable failure surface may get overlooked (Cheng et al. 2007). Thus, in this regard, the LEM serves as a better tool for soil slope stability analysis. However, LEM also has its limitations, such as its inability to calculate strains and deformations.

Himachal Pradesh in India is inherently very prone to natural disasters, as it is a part of young Himalaya which is the world’s most tectonically dynamic mountain chain. Historically, many natural disasters like landslide, earthquake, lake burst and flood have occurred with variable intensities which have hampered the development of infrastructure in Himachal Pradesh, India (Planning Commission 2005). According to Dikshit et al. (Dikshit et al. 2020) 13% of rainfall-induced landslide studies belong to Himachal Pradesh when compared to the rest part of India. In this scenario, Solang Valley road is one important road in India, as it connects the Solang valley to the Atal tunnel (previously known as Rohtang tunnel) that provides all-weather connectivity. Approximately, 5000 vehicles daily pass through the Atal tunnel since its opening in October 2020. The study area has witnessed many unreported slides. In 2016, an earthquake occurred which acted as a triggering event in the monsoon season that led to slope failure along this roadway and large tension cracks were developed all along the road. The road was not accessible for civilians until October 2020. However, since the opening of Atal tunnel, the road is mostly used by travellers and Army and Government officials. Therefore, based on the importance of the road and the absence of previous studies in this area, a geotechnical and slope stability assessment study is necessary for safety of the people in this area. A detailed investigation was carried out in this study followed by a laboratory investigation. The stability assessment was performed to identify the vulnerable slopes and further protection measures were recommended to stabilize the slope for safe travelling in the area.

2. Materials and method

2.1. Location of the area

The study area is located in the vicinity of the Rohtang Tunnel, now popularly known as Atal Tunnel in Himachal Pradesh, India, located above an altitude of 10,000 feet (3048 m). There have been frequent slides along this route. Hence the tunnel will provide an alternative route to the Manali-Leh highway for safe transportation. The tunnel has two portals: South Portal (SP) 32.36459°N; 77.13328°E and North Portal (NP) 32.43951°N; 77.16323°E. NP of tunnel is about 28.4 km from Lahul and Spiti, whereas SP is about 24.3 km from Manali. Palchan, is a tri-point junction for Manali, Solang Valley and Rohtang pass. Since the opening of the Atal tunnel, the highway along Solang valley has become an alternative route to Leh/Lahul and Spiti from Manali providing the all-weather connectivity. This study includes four slopes along the highway near the Atal tunnel, out of which three slopes (S-1–S-3) are located near SP and the remaining one slope (S-4) is located near NP (Figure 1). The geographic details of all four soil slopes are provided in Table 1.
2.2. Geology and stratigraphy of the studied area

The study area comes under the northwest part of the Himalayas, with an elevation of 2600–3000 above MSL. The geological information shows that there are six major tectono-stratigraphic units around the Mandi-Rohtang area (Misra and Tewari 1988) (Table 2). The studied area falls under two major stratigraphic units, namely Vaikrita Group and Jutogh Group (Figure 2). Rohtang tunnel project is located within the Vaikrita group of central crystalline Himalayas having anticlinely folded structure that trends roughly along the axis of the Great Himalayan Range, extending from East to West. Tunnel alignment towards SP passes through the Salkhala Group, which is mainly comprised Quartz-schist. Slopes near the NP (Koksr), comprised gneissic rocks of the Rohtang Complex which mainly contains migmatites with intense schistosity and frequent mica banding. Localized landslides along this road have been frequently encountered during rainy season.

The study is carried out for three slopes (S-1–S-3) along Palchan-Solang valley road and rest one slope (S-4) along Palchan-NP road. Quartz-Schist and phyllites observed along the road are highly weathered and found as soil. Beas river flows along the valley side of road. There have been instances of toe cutting of the slopes along the valley side. The slopes around the area are moderately steep, ranging from 45° to 65°. Also, the slopes are curvilinear in nature at some places but straight in many places.

Table 1. Detailed location of soil slopes.

| Slope | Coordinates | Elevation (m) | Distance from tunnel portal (m) | Landmark | Sample collection spots |
|-------|-------------|---------------|-------------------------------|----------|-------------------------|
| S-1   | 32° 21’ 47.00” N, 77° 07’ 59.10” E | 3079 | 200 from SP | Near South Portal | 03 (70–75 kg) |
| S-2   | 32° 21’ 21.10” N, 77° 07’ 45.90” E | 2915 | 2900 from SP | Near Tunnel Site Office | 03 (70–75 kg) |
| S-3   | 32° 21’ 02.70” N, 77° 07’ 54.80” E | 2831 | 4600 from SP | Near Dhundi Bridge | 03 (70–75 kg) |
| S-4   | 32° 25’ 47.31” N, 77° 12’ 32.50” E | 3138 | 3900 from NP | Between North Portal and Rohtang Pass | 03 (70–75 kg) |

Figure 1. Google Satellite image showing the location of four slopes around Atal tunnel.
2.3. Methodology

During the field investigations, four representative slopes have been considered based on (i) slopes that have recurring failure in nature, (ii) slopes that show failure (local or global) or surficial instability, (iii) slopes adjacent or near to the tunnel that can damage the portal of the tunnel and (iv) the importance of the roadway, as it only links between the SP of Atal tunnel and Solang valley. The soil samples were collected at a depth of about 1.0–1.5 m from the surface for experimental investigation, including mineralogical and geotechnical properties as per IS Standard and American Society for Testing Materials (ASTM) standards. Further, these values

Table 2. Stratigraphy of Vaikrita and Jutogh Group near Atal tunnel (Bhargava and Srikantia 2014).

| Age Group | Formation | Lithology |
|-----------|-----------|-----------|
| Undifferentiated Proterozoic<sup>a</sup> | Vaikrita Chamba | Phyllite and slate |
| | Shaisu | Quartzite and schist band |
| | Morang | Schist and quartzite |
| | Kharo-Rohtang Gneissic complex | Sillimanite, kyanite-boitite schist, quartzite, gneiss and migmatite |
| | Jaknoti | Schist, gneiss, amphibolite and marble |
| | Chirgaon | Quartzite, schist and amphibolite |
| | Rohru | Schist and quartzite |
| | Badrol | Quartzite and quartz schist |
| | Naura | Schist, quartzite, gneiss, marble and amphibolite |
| | Kanda | Quartzite and quartz schist |
| | Taradevi | Quartz schist, carb.phyllite, marmorized limestone and amphibolite |
| | Khirki | Quartzite |
| | Bhotli | Slate, phyllite and quartzite |
| | Manali | Quartzite and carbonaceous phyllite |
| | Panjerli | Carbonaceous phyllite, schist, carbonaceous limestone and quartzite |

<sup>a</sup>Era without affirmed age.

Figure 2. Geological map of the studied area in Himachal Pradesh after (Misra and Tewari 1988).
were used in the probabilistic and reliability analysis of the instable slopes. The methodology of this study has been explained in terms of a flowchart as shown in Figure 3.

2.3.1. Slope stability

In this study, slope (S-3) has been analysed using LEM based Slide version 7.0 program (Rocscience, Toronto, Canada), as it has a history of frequent instabilities in the past two decades to assess the potential risk. Geometry of the slope has been divided into three portions, namely upper portion, lower portion and valley. The slope dip of the slope is varying between 60 and 75\degree for upper to lower portion and the slope angle for the valley portion is about 64\degree. The material properties used in the slope stability analysis are tabulated in Table 4. The cohesion and angle of internal friction determined through the triaxial test are 33.4 KPa and 26\degree, respectively. FoS, is computed using the interslice horizontal forces in Bishop Simplified (BS) method. Though the force-equilibrium is not satisfied, overall moment-equilibrium is satisfied.

These methods are broadly classified under two categories – mass procedure and method of slices. This mass procedure method is restricted to analysis of homogeneous and isotropic slopes. The mass of the material above the trial slip surface is considered as a single unit as well as total stress is assumed to analyse the stability of slope. Slip surface can be defined as the assumed surface where sliding or rupture may take place.

However, the method of slices estimates the FoS without knowing initial condition; however, these methods do not consider the stress–strain relationship of material model. To locate the critical failure surface, LEM call for trial failure surfaces and optimization analysis (Abramson et al. 2002). In this study, BS method was adopted for the computation of FoS.

3. Field investigations

A detailed field investigation has been carried out on the four soil slopes in the vicinity of the portals of the Rohtang tunnel. The slopes of the studied road-cuts were found to
be trending towards NE-SW. The height and width of the slopes in the region varied from approximately 12 to 50 m and 20 to 200 m, respectively. The road width along these slopes varied from 7 to 8 m throughout the stretch. Further, the valley depth varied from 10 to 30 m in the region. The slopes are mostly comprised soil-boulder mixture strata in the region. The slopes are observed to be vertical to sub-vertical. Dense vegetation has been observed on the upper part of slopes. Most of the slopes show a local failure of surficial instability. The max height range of slopes S-1 through S-4 was about 12–15, 15–20, 45–50 and 18–23 m, respectively, with a stretch length of 90, 70, 190 and 110, respectively. Slope S-1 and S-2 comprised approximately 30–40% of small to medium-sized boulder with soil. However, S-4 shows medium-large-sized boulders and S-3 shows small to large-sized boulders mixed with soil.

The field photographs of the studied slopes are shown in Figure 4(a–f). Loose materials of glacial deposits combined with quartz schist were mostly found along this road. Small-sized rock fragments to big boulders were embedded within the soil slopes. Surface runoff has been observed all along the four studied slopes field. Debris material was found to have high moisture content, showing signs of water seepage. This has also resulted in rockfall actively in the area. It is observed that the slope angle with thick overburden and significant erosion is responsible for the slides for all four slopes.

During the site investigations, approximately 300 kg, i.e. 70–75 kg of soil samples from each location were collected during the site investigation. The soil samples were collected from the three spots (near upper portion, middle portion and near toe of the slope; Figure 5(a)) for each location.

The Solang valley area receives the rainfall when the south-western monsoon passes through the northwest region of the country. The rainfall data of the year

| Specimen No. | Confining stress (KPa) | Deviator stress (KPa) | Cohesion (KPa) | Friction angle (°) |
|--------------|------------------------|-----------------------|---------------|-------------------|
| S-1          | 1                      | 49.03                 | 88.35         | 25.1              | 12                |
|              | 2                      | 98.07                 | 112.7         |                   |                   |
|              | 3                      | 147.10                | 142.36        |                   |                   |
| S-2          | 1                      | 49.03                 | 91.16         | 27.1              | 11                |
|              | 2                      | 98.07                 | 112.48        |                   |                   |
|              | 3                      | 147.10                | 140.72        |                   |                   |
| S-3          | 1                      | 49.03                 | 184.19        | 33.4              | 26                |
|              | 2                      | 98.07                 | 241.78        |                   |                   |
|              | 3                      | 147.10                | 337.97        |                   |                   |
| S-4          | 1                      | 49.03                 | 176.44        | 33.5              | 25                |
|              | 2                      | 98.07                 | 246.97        |                   |                   |
|              | 3                      | 147.10                | 319.27        |                   |                   |

Table 3. Geotechnical properties with standard deviation for the soil specimens estimated in the laboratory.

| Geotechnical property | Unit | Slope S-1 | Slope S-2 | Slope S-3 | Slope S-4 |
|-----------------------|------|-----------|-----------|-----------|-----------|
| Natural moisture content | %    | 9.3 (±0.89) | 10.7 (±0.72) | 8.1 (±0.85) | 7.6 (±0.57) |
| Specific gravity | – | 2.55 (±0.15) | 2.63 (±0.19) | 2.66 (±0.20) | 2.59 (±0.18) |
| Gravel % | 30.4 (±7.15) | 24.4 (±2.640) | 30.1 (±2.56) | 29.1 (±3.1) |
| Sand % | 58.1 (±7.76) | 58.0 (±2.01) | 55.0 (±1.63) | 66.5 (±2.89) |
| Silt % | 11.5 (±1.59) | 17.7 (±0.66) | 14.9 (±1.08) | 4.4 (±0.4) |
| Liquid limit | % | 43.4 | 34.6 | 37.7 | 39.6 |
| Plastic index | % | 20.9 | 7.8 | 19.8 | 14.9 |
| Dry density g/cm³ | 1.83 | 1.82 | 2.0 | 1.95 |

Table 4. Shear strength parameters of the slope forming material at four locations.
1998–2017 suggested that the highest amount of rainfall (approx. 200–250 mm) occurred from June to September in the summer and January to March during the winter season (Figure 5(b)). Hence, the high-intensity rainfall in this region reduces the slopes’ stability factor for a long time.

As mentioned earlier, the slopes in the studied region mostly comprise soil-boulder mixture strata. However, the rock slopes were also observed for a few hundred meters on the stretch. The study area had witnessed many shallow/large landslides and rock-fall events caused by numerous factors. Hoek and Bray (Hoek and Bray 1981) define various failures such as Planar, Wedge, Topple and Circular failures in slopes. The
region’s slopes have generally shown wedge, topple and circular failures during the investigations. The study area comprised few rock slopes and mostly of soil slopes. Verma et al. (Verma et al. 2018) observed multiple wedge failures and toppling for rock slopes in the studied area. However, the slopes comprising soil-boulder mix strata show either local failure, surficial instability and/or the circular failure. The site photographs of location S-3 show a large circular failure whereas the surficial instability was observed in the remaining slopes.

A barren nature of the soil on a particular section on the slope could be the reason for landslide reactivation. The recurring failure of slope S3 can be understood by the Google satellite imagery from the last decade (Figure 6(a–c)). Figure 6(a) shows failure of the slope S3 on November 2010. Figure 6(b) shows the increase in the failed area on the slope in the span of four years till October 2014. Figure 6(c) indicates the mass failure on the two sections of the slope and debris flows in the valley, including washed-off the roadway on September 2019.

4. Results and discussion

Representative soil samples were collected from the four locations around Atal Tunnel based on the field conditions and degree of weathering. Laboratory investigations on these collected soil samples were carried out for characterizing their physio-mechanical properties. Slope stability analysis has been carried out using these properties for further analysis as described below.

4.1. Mineralogical and microscopic analysis

The mineralogical analysis of slope forming material has been performed using the X-ray diffraction (XRD) method and scanning electron microscope (SEM). XRD was carried out using the Philips PW-1710 diffractometer under CuKα radiation (\(\lambda = 1.5405 \, \text{Å} \)) on the fresh powdered soil samples. Minerals identified in the XRD analysis were quartz, albite, clinochlore (Mg rich chlorite) and zeolite (Figure 7(a–c)). SEM analysis has been carried out using Field Emission Scanning Electron Microscope (FE-SEM) using FE-SEM SUPRA 55, Carl Zeiss, Germany. SEM images
showed weathering of the mineral particles (Figure 8(a–c)). XRD and SEM images indicate the hexagonal nature of weathered quartz grain, weathered flakes of phyllosilicate minerals and triclinic nature of weathered albite respectively. According to Collettini et al. (Collettini et al. 2009), the presence of phyllosilicate grains in slope material facilitates slope instability. Also, the presence of albite indicates that feldspar is sodium bearing which gets weathered quickly leading to soil erosion.

4.2. Geotechnical characterization

The following geotechnical properties of soil, namely natural moisture content (NMC), specific gravity, grain size analysis, dry-density, liquid and plastic limit, cohesion and friction angle for the four locations have been investigated in the laboratory in accordance with the Indian Standard codes (IS) and their values are summarized in Table 3. The experimental setup used for geotechnical characterization is shown in Figure 9.
Figure 7. (a–c) X-ray diffraction patterns of collected soil samples.
It is observed in the field that the topsoil has a NMC, which varies from 7.5 to 10.7% for all the four slopes. Higher moisture content, at slope S-2, shows the soil with higher void ratio. Values of specific gravity varied from 2.55 to 2.65 for all the four studied slopes. It indicates that the soil particles for all the four slopes have a similar type of soil compactness, as specific gravity values are approximately uniform. Based on consistency limits, the topsoil of all the four slopes shows low to intermediate plasticity.

The particle size distribution analysis plays a crucial role to estimate the strength parameters. The friction value of soil material is a function of particle size distribution, particle shape and surface roughness, specific gravity of individual particles, state of packing and applied stress. The soil packing density and soil porosity may also be estimated through particle analysis (Koner and Chakravarty 2016). The friction angle reduces with decreasing particle size (Williams 2000). The testing has been performed as per IS: 1498–1970. The trend shows it is well-graded sand. However, i.e. uniformity coefficient (Cu) and coefficient of curvature (Cc) do not fulfill the criteria, i.e. Cu greater than 6 and Cc between 1 and 3. Presently, for all four slopes, the value of Cu is higher than 6 (i.e. 44.1, 37.5, 47.5 and 18.8, respectively); however Cc is less than 1 (i.e. 0.87, 0.38, 0.38 and 0.22, respectively). The soil sample of S-4 has fine content less than 5% which passes on 75-micron IS sieve. Therefore, it falls under poorly graded sand (SP) since it did not meet all the gradation requirements for SW (well-graded sand) and the remaining three slopes S-1–S-3 show clayey sand (Figure 10(a)).
The peak of the curves shown in Figure 10(b) is considered as maximum dry density on the abscissa and optimum moisture content (OMC) on the ordinate. The range of maximum dry density and OMC varied from 1.82 to 2.0% and 11 to 14%, respectively. Although the values of NMC are less than OMC for the slope forming material, NMC values have been found to close to the OMC values during the rainy season. All the geotechnical properties of slope forming material from all the four slopes have been tabulated in Table 4.

Triaxial compression test was performed under three different sets of confining stresses, i.e. 0.5, 1.0 and 1.5 kg/cm² to determine shear strength parameters. Cohesion...
and friction angle values have been estimated by plotting Mohr-Coulomb failure circles (Figure 11). Range of shear strength parameters, i.e. cohesion and friction angle, has been estimated to be 25.1–33.5 KPa and 11–26\(^\circ\), respectively (Table 4). Lower cohesion has been observed for slope forming material at slope S-1, whereas a lower friction angle has been observed at slope S-2.

4.3. Stability assessment

Probabilistic analysis and deterministic analysis have been carried out to incorporate possible variations in the soil properties and its effect on slope stability. The outcome of the stability analysis has been represented in terms of deterministic and
probabilistic distribution of FoS, probability of failure (PF) and reliability index (RI). RI is a probabilistic measure of safety and it can be mathematically represented using Eq. (1) for normally distributed safety factors. RI of 0 indicates unsafe structure FoS = 1 and its negative value represents unsafe design, i.e. mean FoS < 1. RI higher than 3 is good for safety assurance.

$$\beta = \frac{\mu - 1}{\sigma}$$  

where $\beta$ : RI, $\mu$ :mean FoS, $\sigma$ :standard deviation of FoS.

The stability analysis has been performed considering the slope conditions prior to failure using the bishop method of slices. Probabilistic analysis for pre-failure slope reveals FoS of 0.75, negative RI and completely 100% PF (Figure 12(a)). The initiation point of the failure surface is located near the crest of the slope and terminate point is more than above 5 m from road level. A similar kind of failure was observed at the site, as shown in photos (Figure 13). A major landslide occurred on the slope S-3 which damaged the road stretch of up to 900 m in September 2016 (Figure 13(a)).
Width of cracks along the damaged road varied from 30 to 150 cm. The outcome of the limit equilibrium analysis is tabulated in Table 5.

In order to stabilize the representative slope, soil nailing was proposed based on FHWA (FHWA 2015). Self-drilled anchors (SDA) of 32 mm diameter are commonly used to strengthen the soil slope. Their tensile capacity ranges from 230 kN to more than 1000 kN, depending on the increase in diameter. After multiple trials, the soil design was optimized with SDA of 8 m length and 230 kN of tensile strength with 1.5 and 2.5 m centre-to-centre spacing in longitudinal and lateral direction, respectively. Support analysis of reinforced slope shows a mean FoS of 1.19, RI of 3.61 and 0.00% of PF (Figure 12(b)). The spacing of the nails was varied from 1 to 3 m to obtain a suitable optimized FoS and RI. The relationship of nail spacing with FoS and RI reveals that the 2.5–2.75 m of nail spacing is required to achieve the FoS of 1.2 and RI of 3 (Figure 14(a,b)). Closer nail spacing will achieve higher FoS and RI assuring stability; however, it will incur additional cost.

### 4.4. Sensitivity analysis

Geotechnical investigation provides discrete values for each soil parameter. However, in reality and considering the stretch of the slope, variation in parameters can be expected. It is found from laboratory investigation that the strength parameters, such as cohesion and angle of internal friction for all the four slopes vary from 25.1 to 33.5 KPa and 11° to 26°, respectively. Therefore, a sensitivity analysis for the slope has been performed on geomechanical parameter like cohesion and angle of internal friction for determining the distribution of FoS. The analysis is carried out for both failed and reinforced slopes. A correlation coefficient of 0.98 has been observed for both failed and reinforced slopes between FoS and nail

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**Table 5. Outcome of the limit equilibrium analysis for Slope S-3.**

| Slope conditions | Factor of safety | Probability of failure (%) | Reliability index (normal) |
|------------------|------------------|----------------------------|----------------------------|
| Failed           | 0.75             | 100.00                     | -6.084                     |
| Reinforced       | 1.192            | 0.00                       | 3.61                       |

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**Figure 14. Relationship of nail spacing for Slope S3 with (a) factor of safety (b) reliability index.**
spacing while correlation coefficient 0.99 has been found between RI and nail spacing. The steepness of the linear curve for the angle of internal friction is higher than cohesion for both reinforced and pre-failure slope which implies a slight change in angle of internal friction due to external factors will affect the stability of the slope (Figure 15(a,b)).

5. Conclusion

The recurring failure of soil slopes along the Solang valley road makes it critical due to its socio-economic relation. It is the only road that connects the Solang valley to the Rohtang tunnel. This study includes geotechnical investigation and stability assessment to understand the behaviour of representative road cut slopes. The XRD and SEM images have identified the minerals and the analysis reveals the presence of weathered flakes of phyllosilicate, weathered quartz grain and weathered albite. Soil index properties, such as NMC, specific gravity and grain size analysis were determined to classify soils. The soil samples from one slope indicate SP, whereas the remaining three show clayey sand soil (SC). The shear strength parameters estimated in the laboratory varied from 25 to 33 KPa and 11 to 26°. Probabilistic analysis indicates an FoS less than 1, negative RI and a 100% PF for location S-3. The site conditions corroborate the findings of the stability assessment. Further, soil nailing was proposed with 8 m nail length and 230 kN tensile strength to strengthen the slope to achieve the desired FoS. Further increase in nail length or reduction in nail spacing can achieve higher FoS. The solution can be implemented to slopes with similar problems. The limitation of the study is not consideration of seismic analysis in the study.

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Disclosure statement

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