Mitigation and management of rainfall induced rockslides along the national highways of Himalayan region, India

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ABSTRACT
The research focuses on slope stability analysis and stabilization measures of Dhalli landslide, Himachal Pradesh. Kinematic analysis reveals joints J1 and J2 dip towards the bedding plane causes a wedge failure. Field investigation of the rock slope was conducted using Slope Mass Rating method (SMR) which assess the stability of slopes using a rating schemes of (0–100). The results revealed an SMR value of 45 indicating the slope is partially stable. The strength of the rock materials was estimated using ten core samples through point load test indicating an average failure load of 5.4 MPa revealing rocks are weak to moderately strong in nature. Based on the results from the field investigation and landslide morphometry slope stability of the rockslide has been calculated based on the Mohr–Coulomb failure criterion using Rocscience software. J1 and J2 has a combined wedge area of 1884 sq. m with an FOS value of 0.9 indicating that the slope is partially stable. A suitable stabilization method was proposed using reinforced wired net mesh with a grid spacing of 15 × 15 cm and shotcrete of 30 cm thickness with as FOS of 1.6 indicating the stability of the slope post-stabilization measure.

1. Introduction

Landslide occurs due to various natural and anthropogenic factors that includes cloudburst, thunderstorms, antecedent rainfall, building and roadways construction. Landslides are mostly restricted to hilly terrains due to their rugged topography, steep slopes, soil content etc. Among other Geohazards landslide occur more frequently in occurrences due to the complex morphodynamic process of the Himalayan region (Martha et al. 2013). On a global scale landslide is one of the major disasters worldwide that contributes higher rate of causalities and economical losses (Bhardwaj et al. 2019; Tanyas et al. 2019). On frequency scale landslide has caused more social and economic loss compared to other natural hazards (Sarkar et al. 2016; Prakasam et al. 2021). The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

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According to the report submitted by ‘International Association of Engineering Geology (IAEG)’ on worldwide landslide events (1971–1975) to the UNESCO they have reported that landslide accounts for about 14% causalities from natural hazards (Froude and Petley 2018). In a report given by International Disaster Database (EM-DAT) the landslide event occurred between 1990 and 2015 covers about 4.9% of the all the disasters that occurred in Asia.

In India, landslide prone areas comprise about 0.42 million sq km of area which includes North Western and North Eastern Himalaya and the Western and Eastern Ghats (Singh et al. 2013; Vakhshoori and Zare 2016). Himalaya being one of the youngest mountains on the earth surface undergoes complex slope movements due to tectonic and erosional activities leading to geomorphic denudation (Avşar et al. 2015). Landslides of various types Shallow, Deep, Complex, pose severe threat to social and economic activities in the Himalayan region, where climate being the ultimate control in the process of initiation of landslides (Jiang et al. 2021; Silhan 2021). Even though landslide and mass movement initiation are mainly due to natural hazards such as earthquakes and monsoon rainfall, anthropogenic activities also contribute to the slope failure such as building construction, manual excavation of rock slopes for transportation corridor, forest plantation and hydro power projects etc. (Iverson 2000; Chandrasekaran et al. 2013; Gupta et al. 2019). Compared with other natural hazards, such as floods and earthquakes, soil erosion and monsoon rainfall plays a major role as landslide triggering factor (Singh et al. 2010; Du et al. 2020; Gobinath et al. 2020; Ngo et al. 2020; Prasad et al. 2020; Prasad and Siddique 2020; Meena et al. 2021). Most of the landslides in the Himalayas occur along the major lineaments and unstable slopes especially along the national highways (Sahoo et al. 1998). Based on the data obtained from the regional meteorological centre, Shimla most of the landslides occurs during the monsoon. Also, the post-monsoon season suggests that the fragile nature of soil and rocks coupled with the monsoon plays an important role in mass movements along the Himalayan region (Rawat et al. 2012; Pareek et al. 2015). The landslides result in impacting the socio-economic aspects of the day to day life and also blockage of transportation corridors etc. (Roback et al. 2018; Yan et al. 2019). Rainfall Induced landslides are mainly controlled by two major factors namely intensity and duration of the rainfall event (Rawat et al. 2012; Pradhan et al. 2006). Most often deep seated failures are caused due to prolonged rainfall while shallow debris and rock slides occur due to short outburst of rains (Rahardjo et al. 1995; Singh et al. 2016). Increased ground vibrations along the unstable road cut slopes due to heavy traffic movement is also of major factor for the reduced slope strength of the rock material. Research specifically focusing on slope stability analysis along the National Highways and various settlement areas have been carried out all over the world (Panikkar and Subramanyan 1996; Ghosh et al. 2012; Sarkar et al. 2012; Bhambrí et al. 2015; Kumar et al. 2019). In terms of landslide research the studies are mainly focused on evaluating the landslide susceptibility at regional level or at monitoring individual landslides. One or more studies focuses on certain aspects of the landslide in terms of geology, geo-technical or geospatial modelling of the landslides. An overall assessment of the individual landslides determining its morphometry, geological and geotechnical investigation, possible slope stabilization
measures and cost estimation is required for its potential practical application of the research work in order to be implemented by the concerned authorities.

The current research is focused on evaluating the stability of the rainfall induced rock slide through various Geological and Geotechnical Investigation such as Kinematic analysis, Slope mass rating (SMR), Statistical analysis on the frequency of joint sets and calculating the FOS through Mohr–Columb failure criterion. Rainfall intensity estimation for both annual and seasonal rainfall analysis have been carried out to study the relationship between landslide and rainfall intensity. Reinforced wired net mesh shotcrete has been suggested as a suitable remedial measure for slope stabilization.

2. Background of the study area

Heavy monsoon triggered massive rockslide (reactivated) on the 2nd September, 2017 situated along the National Highway (NH-5A) in Dhalli area, Shimla town, Himachal Pradesh connecting Shimla to other major regions of the country (Figure 1). The study area extends between 31°05′46″ to 31°06′24″ latitude and 77°11′55″ to 77°12′40″ longitude with a total geographical area of 85 ha. The total height of the landslide from crown to runout distance extends for about 76.7 m and the width of the landslide extends for about 18.6 m (Figures 2 and 3). Due to the rockslide, few parked vehicles were damaged nearby Settlements along the downhill, National

Figure 1. Dhalli study area.
Figure 2. Settlements damaged along the landslide runout area.

Figure 3. Damaged vehicles and buildings due to landslide.
Highway (NH-5A) (Figure 3). Average rainfall of the area is about 999, were most of them occurring during rainfall season.

Slate and Silt are the major geological features of Dhalli landslide present in the study area. These rocks range weak to moderately strong in nature with number of joints sets proving to be an essential parameter for the rockslide. Slate and Fine loamy type of rock and soil particles have been identified along the landslide site which played a major role in mass movement initiation due to inadequate toe

Figure 4. (a) Annual rainfall – Dhalli (1971–2018). (b) Seasonal rainfall (June to September) – Dhalli (1971–2019). (c) Research methodology.
support and drainage system. Grain size distribution reveals that the soil particles range from 4 cm to 0.075 m along the top surface of the landslide. The soil particles are poorly sorted and arranged as huge pore paces through which rainfall water percolates causing slope instability. Geology was interpreted from the maps retrieved from the Soil and Landuse survey of India (SLUSI). Major rock types present in the slate. Slate ranges moderately strong rock in the Geological Strength Index. The joint sets along the landslide are heavily jointed and the gaps between joint sets has soft infillings and rain water infiltrating is one of the major factor for slope failure. Geomorphologically the area is mostly undifferentiated hill side and mountain side slope. LULC was prepared using Worldview-2 data.

Table 1. Datasets.

| Sl. no. | Data                      | Source                        | Year   | Resolution |
|--------|----------------------------|-------------------------------|--------|------------|
| 1      | Toposheets (53E/04)        | Survey of India               | 1974   | 1:50,000   |
| 2      | Large scale mapping        | Worldview                     | 2017   | 0.4mts     |
| 3      | Geology                    | SLUSI                         | –      | 1:50,000   |
| 4      | Geomorphology              | SLUSI                         | –      | 1:50,000   |
| 5      | Soil texture               | SLUSI                         | –      | 1:50,000   |
| 6      | Geo-technical Investigation| Field survey and lab analysis| –      | –          |
| 7      | Rainfall                   | Regional Meteorological Centre, Shimla | 2011–2017 | 1 day     |
Dhalli study area has four major seasons, the winter rain, pre-monsoon, monsoon and post-monsoon. The study area receives most of its rainfall from the month of June to September and also during the winter rain.

Figure 5. (a) Landuse landcover (Dhalli). (b) Landslide morphometry.

Dhalli study area has four major seasons, the winter rain, pre-monsoon, monsoon and post-monsoon. The study area receives most of its rainfall from the month of June to September and also during the winter rain.
In the recent years (after 2010) Dhalli area has been receiving an annual rainfall of 1250 mm to 1630 mm (Figure 4a) among which most of the rainfall has been received during the Monsoon season (June–September) and Winter Rain (Figure 4b). The severe rainfall intensity causes high infiltration rate along the soil surface leading to the increased pore water pressure and soil burden causing slope instability. Water infiltration along the fractured rock surface and joint beds and the repeated freeze & thawing of the rocks leads to rupturing of rock slopes leading to mass movements.

3. Materials and methods

The base map and study area boundary was extracted from Survey of India Toposheet (53E/04). Large scale Landuse Landcover mapping was prepared using

Table 2. Landuse and landcover (area coverage).

| Class           | Area (ha) | Percent |
|-----------------|-----------|---------|
| Barren land     | 10.61     | 12.38   |
| Built-up land   | 13.03     | 15.21   |
| Roadways        | 3.01      | 3.52    |
| Shrub forest    | 32.67     | 38.12   |
| Shrub land      | 26.36     | 30.77   |
| Total           | 85        | 100.00  |

Figure 6. (a) Exposed joint sets along the surface of the landslide, (b) bedding plane and exposed joint surface along the study area; (c) field Investigation collecting various results on geotechnical parameters.
Figure 7. Collection of various joint sets from study area.

Figure 8. (a) Stereonet with all joint planes plotted; (b) wedge failure, and (c) direct toppling failure.
Table 3. Various joint sets.

| Sl. no | Joints      | Dip amount | Dip direction |
|--------|-------------|------------|---------------|
| 1      | J0          | 33°        | 230°          |
| 2      | J1          | 68°        | 2°            |
| 3      | J2          | 71°        | 127°          |
| 4      | J3          | 77°        | 80°           |
| 5      | Slope face  | 81°        | 116°          |

Figure 9. (a) and (c) Collection of core samples; (b) represents fractured core samples.

Figure 10. (a) Core samples being tested using point load machine; (b) core samples fractured at critical failure.
Worldview-2 and Total station data obtained from NRSC and field investigations. The features were manually digitized in the GIS environment based NRSC level 2 classification of LULC. Thematic information of Soil, Geology and Geomorphology were retrieved from maps obtained from Soil and Landuse Survey of India (SLUSI). Geological and geo-technical investigation of the landslide sites and also results retrieved from the field investigations and lab tests (Table 1).

The research has been carried out to assess the stability of the rock slide through various geological and geotechnical investigation namely Stereonet analysis, Slope Mass rating and stability measure using joint conditions and landslide morphometry. Large scale mapping and morphometry of the study area have been conducted using Worldview-2A and field investigation. Morphometry analysis and slope geometry was obtained through total station.

3.1. Large scale mapping and morphometry analysis

Large scale mapping of the Dhalli Landslide was conducted to study the various features that are prone to the landslide along the Upslope and Downslope of the study area. High resolution mapping of the landslide and study area was done though Worldview-2, Google Earth data and Field work. The Landuse and Landcover maps were prepared based on NRSC Level 2 Landuse Landcover classification. The maps prepared have been used to study detailed morphometry of the landslides and potential features at risk due to landslides like roadways, settlements along the downslopes and religious centres. Landslide Morphometry was conducted based on the data collected from field photographs and survey of the landslide. The morphometry was done to study the various parts of the rockslide.
3.2. Geotechnical investigation of the landslide

Geo-technical assessment was done to estimate the stability of slopes and propose suitable stabilization measures. The field work involves in estimating studying parameters such as Kinematic analysis, statistical assessment on the frequency of joint sets, slope mass rating (Basu et al. 2017) to estimate the stability of slopes. Field analysis for measuring rock properties have been carried out during field investigation such as RQD, joint spacing, joint conditions, etc. (Mani et al. 2017; Banerjee et al. 2018; Mondal et al. 2018). Preliminary investigation of the stability of slopes was conducted through slope mass rating (SMR) method. The slope mass rating method (SMR) proposed by Romana (1993) is a modified version of RMR that adds adjustment factors into RMR depending on the joint–slope relationship and mode of excavation (Kainthola et al. 2015; Singh et al. 2017). Kinematic analysis and point load strength have been studied to estimate the mode of failure of the rock surfaces, major joint sets involved in the rock failure. Through kinematics analysis rock core samples are collected for point load test to estimate the shear strength of the rock samples. The results retrieved from field and lab-based investigation has been used to study rock slope stability through Mohr–Columb failure criterion. Based on the factor of safety (FOS) critical value proper slope stabilization measure has been recommended.

The methodology adopted in the study uses results retrieved from the joint intersection and rock parameters as key values to evaluate this particular form of rock slide. Both field and lab studies were conducted to assess the stability of the slopes and provide suitable stabilization measures such as concrete wall, net mesh, to negate the further occurrences of landslides.

This methodology helps in providing accurate results of stability analysis and stabilization measures through Mohr–Columb failure criterion. Future analysis of this study includes high resolution 3D mapping using Drone imageries and subsidence monitoring.
4. Results

4.1. Large scale mapping and morphometry analysis

LULC was prepared using data retrieved from Worldview-2 and Total station in GIS environment to delineate the various features. The area is covered by Shrub Forest, Shrub Land, Settlements and Barren land (Figure 5a). Shrub forest and shrub land cover about 38.6 and 24.3 ha which constitute a total of 70% of the study area. The remaining area is composed of Barren land (10.6 ha), settlements (10.3 ha) and National Highway (2.0 ha) (Table 2).

Morphometry of the Dhalli landslide was conducted through field investigation and Total station. The total height of the landslide is 24.3 m, and the width is 18.6 m. The total runout length of the landslide is estimated at 76.7 m from the crown of the landslide (Figure 5b). The runout debris has damaged the National Highway connecting Shimla to Rampur, Parked vehicles, few settlements and temple located along the downslope of the landslide.

4.2. Geo-technical investigation of Dhalli landslide

4.2.1. Stereonet analysis of Dhalli landslide

The Geological field investigation was conducted at the landslide area. Stereonet analysis has been used to determine the type of landslide failure. Kinematic analysis emphasizes the use of Intersection of various joints and rock surfaces to estimate their potential weak zones and mode of failure (Figure 6a–c). Wedge mode of failure was observed along the rock slide with two joint sets plunging along the same direction as that of slope angle (Figure 7).

Based on the field data collected Stereonet analysis was performed to determine the mode of failure for Dhalli landslide. Stereonet uses Circular graphs to represent the orientation of the Joint faces in terms of Dip direction and Dip amount.

The joint set J0 runs parallel to the bedding plane. Four different types of joint intersections were found as shown in the (Figure 8a; Table 3).

Two joint sets J1 and J2 dipping towards the slope face indicates a wedge failure along the study area (Figure 8b). The area indicated by the pink colour represents the wedge failure conditions and unstable region for wedge failure. Point A represents

| Parameter                      | Site 1 Results | Corresponding RMR values |
|--------------------------------|----------------|--------------------------|
| Uniaxial compressive strength  | 42.4 Mpa       | 7                        |
| Rock quality designation       | 23.15%         | 8                        |
| Spacing of discontinuity       | 200 – 600 mm   | 10                       |
| Persistence                    | 3 – 10 mts     | 2                        |
| Separation                     | 1 – 5 mm       | 1                        |
| Roughness                      | Very rough     | 6                        |
| Infilling                      | Soft infilling | 2                        |
| Weathering                     | Slightly weathered | 5                       |
| Groundwater                    | Dripping       | 4                        |

Total rating value 45

Table 6. Corresponding RMR values for Dhalli landslide.
Table 7. Corresponding SMR values for Dhalli landslide.

| SMR factors | Site 1 Results | Corresponding SMR values |
|-------------|----------------|-------------------------|
| F1          | 117°           | 0.15                    |
| F2          | 35°            | 1                       |
| F3          | 35°            | 0                       |
| F4          | Mechanical excavation | 0                      |

Source: Author’s calculation.

Figure 12. (a) 3D view of the Dhalli Rock slope. (b) Top, front and side view of the Dhalli Rock slide. (c) Grey part indicating reinforced wire mesh with shotcrete.
the intersection of J1 and J2 and lies in more unstable region, compared to the intersection of J2 and J3 (Figure 8c).

4.2.2. Point load test of Dhalli landslide rock materials

The point load test is used to test the strength classification of rock materials. Point load strength index of a rock specimens and strength Anisotropy Index is calculated using point load index to minimum and maximum values’ (Ansari et al. 2014; Gupta et al. 2016). Further the point load test is also used to calculate the Uniaxial compressive strength of the rock materials. Rock samples were collected from the site and found to be heavily jointed slate rock material which is a moderately strong rock. The discontinuity along the joint beds was mapped and the rocks samples were collected from joint beds running parallel to the bedding plane. The rock samples were then transported to the National Geotechnical Facility in Dehradun for the calculation of UCS test.

A total of 10 core samples were extracted to perform the analysis based on the method suggested by ASTM (1995) (Figure 10a). The width and the diameter of the core samples were estimated before analysis. Then the core samples were fed to the point loading machine to perform the analysis. The analysis was performed for both perpendicular and parallel to the plane of weakness (Figure 10b).

\[ I_s = \frac{P}{D_e^2} \text{ (MPa)} \]

where
Table 8. Cost estimation for Dhalli landslide stabilization measure.

| Material cost estimation | Sl. no | Type of material | Required Amount | Per kg cost | Total cost |
|--------------------------|--------|------------------|-----------------|------------|------------|
|                          | 1      | Concrete (dry sand + cement + Aggregate (Fine)) | 144 Cu.mts | 4300 rupees/Cu.m | 4300 × 144 = 6,19,200 |
|                          | 2      | Reinforced wire mesh = thickness (5 mm) + mesh size = 10 × 10 cm grid | 500 sq. ft | Rs 14/sq.ft | 5000 × 14 = 70,000 |

| Labour cost estimation | Sl. no | Type of work | Required amount | Cost per head | Total cost |
|------------------------|--------|--------------|-----------------|---------------|------------|
|                        | 1      | Junior Engineer | 2               | 460           | 460 × 12 = 5,520 |
|                        | 2      | Mason Grade IV | 1               | 371           | 371 × 12 = 4,452 |
|                        | 3      | Driver        | 1               | 305           | 305 × 12 = 3,660 |
|                        | 4      | Sprayman      | 2               | 250           | 250 × 12 = 3,000 |
|                        | 5      | Unskilled labour | 5               | 250           | 250 × 12 = 3,000 |
|                        | 6      | Miscellaneous labour | 3               | 250           | 250 × 12 = 3,000 |
|                        | Total  |              |                 |               | 22,632 (INR) |

Material cost estimation | 6,89,200 (INR)
Labour cost estimation | 22,632 (INR)
Final amount | 7,11,832 (INR)

\[ P = \text{failure load (N)}, \quad D_e = \text{equivalent core diameter} = D \quad \text{for diametral tests}, \quad m, \quad D_e^2 = D_s^2 \quad \text{for cores, mm}^2, \quad \text{or} \quad D_e^2 = 4A/\pi \quad \text{for axial, block, and lump tests, mm}^2, \quad A = WD \quad \text{minimum cross-sectional area of a plane through the platen contact points}\]

In Table 4, the parameters are represented as follows:

- \( \text{Is} = \) Uncorrected point load strength; \( P = \) Point load strength observed from core samples in lab; \( D = \) Thick of the specimen; \( W = \) length of the specimen.

Compressive strength of the core samples was calculated along the perpendicular direction to the plane of weakness. The compressive strength of the rock samples retrieved from the parent rock material ranges between 3.82 and 6.41 MPa with an average value of 5.4 MPa (Table 4). The analysis reveals that the slate type of rock material present in the study area is weak to moderately strong rock. These slate rocks are heavily jointed, where the major joint sets J1 and J2 are dipping towards the slope direction. Water percolation along these joint spaces causes freeze and thawing of the rock leading to joint failure and causing landslide.

4.2.3. Statistical analysis on frequency of joint sets for Dhalli landslide

In order to study more comprehensively about the joints sets the frequency of total number of joint sets have been studied at a particular interval. Along the landslide study area, the total number of joint sets for a particular unit length have been calculated. An interval of one meter has been chosen to study the frequency of joint sets within a one-meter unit length. A total of 5 samples (Joint sets within an one meter interval) has been taken into analysis for frequency studies. The joint sets were
counted and recorded in the field using tape measurements and visual interpretation. A total of five sample locations were chosen to study the frequency of joint sets (Table 5).

The results retrieved suggests that the joints sets along the study area are high in frequency and are heavily jointed. A minimum of 73 joint sets for 1 sq mt unit and a maximum of 79 joint sets for 1 sq mt has been observed along the exposed rock surface (Figure 11). The heavily jointed rock surface indicates that the exposed rock surfaces are highly prone to rock failure. Plants growing along the gaps between the joint sets reveal about soft infilling along the cracks and water dripping along the joint sets will increases the probability of the failure.

4.3. Slope mass rating

4.3.1. Uniaxial compressive strength

The uniaxial compressive strength (UCS) is the ability of a rock material to withstand maximum compressive strength at stress. The UCS is normally conducted by collecting bore hole samples from the intact rock material. Since our study area has weak to moderately strong rock the core samples fractured during the drilling process, UCS has been estimated by pounding various rock samples at the site using Geological Hammer and also through point load test. The types of rock present in the study area is slate material. Five rock samples were tested in the field for the compressive strength and the rock samples cracked with one or two firm blows to it indicating the rock is weak to moderately strong in nature. Based on the results from the field test and Point load test conducted at the lab the SMR rating of 7 was assigned for the UCS parameter (Table 5).

4.3.2. Rock quality designation

Rock Quality Designation (RQD) represents the quality of the rock core taken from the bore hole sample. It signifies the degree of jointing or fracture in the rock mass measured as percentage. RQD of 75% denotes good quality hard rocks whereas, a quality of 25% denotes low quality weathered rocks. RQD is mainly done thorough collecting bore hole samples. In our study we followed the method of volumetric joint count (International Society for Rock Mechanics). ‘The RQD can also be estimated using the correlation between RQD and volumetric discontinuity frequency’.

\[
RQD = 115 - 3\lambda v
\]

‘where the volumetric discontinuity frequency (\(\lambda v\)) is the sum of the number of discontinuities per unit length for all discontinuity sets, which can be determined from the discontinuity set spacing within a volume of rock mass.’ ‘Due to the vertical nature of the slope RQD was estimated using the total station for evaluating the discontinuity along the joint surface.’ A unit length of 12.85 m was taken to study the RQD. A total of 30 joint planes have been recorded with a length of more than 10 cm. The final output with the value 23.15 suggests that the rock is very poor in quality and an SMR value of 8 (Table 5) has been assigned.
4.3.3. Spacing of discontinuities
Spacing of discontinuity is measured for a unit length along the general direction of a particular joint set at a specific location. The spacing between various joint sets have been recorded during field investigation. The spacing has been recorded by counting the distance between successive discontinuity along a fixed length. The spacing recorded between various joint sets ranges an average between 2.3 and 5.8 cm per discontinuity.

4.3.4. Condition of discontinuity
Condition of discontinuity relates various of the particular masses its roughness, degree of weathering, separation and infilling material, etc. These datasets have also been collected through field-based investigation.

The condition of discontinuity has been recorded through visual interpretation of the landslide. The rock surface was rough, with soft infillings found in between them with plant growths. The ground water conditions have been noted based on the water dripping along the pre-existing cracks on the joint surfaces.

Based on the results retrieved from the field investigation, the values were tabulated and RMR rating was found to be 45 (Table 6)

Adjusting factors for slope mass rating (Table 7)

Dip direction of joint = 2° Dip of joint = 68°
Dip direction of slope = 116° Dip of slope = 81°

\[
\text{SMR} = \text{RMR} + (F1 \times F2 \times F3) + F4
\]
\[
= 45 + (0.15 \times 1 \times 0) + 0
\]
\[
= 45
\]

4.4. Rock slope stability assessment and stabilization measures for Dhalli landslide
Dhalli landslide that occurred along the NH-5A near Dhalli Town, Shimla is structurally controlled without toe support. Various joint sets running through the rock surface made it prone for Shallow translational wedge failure. SWEDGE module from Rocscience software is used for the stability analysis based on the data collected from field and lab investigations (Figure 12a). The joint sets are plotted using deterministic analysis of Mohr–Coulomb failure criterion. ‘The Mohr–Coulomb (MC) failure criterion is a set of linear equations in principal stress space describing the conditions for which an isotropic material will fail, with any effect from the intermediate principal stress being neglected’. The Equation is represented as

\[
\tau f = C_i + \sigma'\tan \theta
\]

where \(\tau f\) = shear strength of intact rock, \(C_i\) = cohesion of the rock material, \(\sigma' n\) = effective normal stress, \(\theta\) = internal friction of the angle.
The joint sets are plotted using deterministic analysis of Mohr–Coulomb failure criterion. Based on the results it has been estimated that J1 and J2 has a total wedge area of 297.33 and 1587.52 sq m. The FOS is estimated to be 0.9 which is less than the required value of 1 suggesting the slope is unstable. Based on the nature of slope we applied reinforced wire mesh with Shotcrete type of stabilization measure.

The width of the shotcrete can be kept between 0.2 and 0.3 m providing an increased stability up to an FOS value of 1.63 (Figure 12c). For slope stability analysis and FOS computation of Mohr–Coulomb criterion method have been adopted in the current study. The geometry of the slope obtained from field Observations and readings taken through total station has been used in stability analysis with its determined material properties.

4.5. Cost–benefit analysis of stabilization measures for Dhalli landslide

Stabilization measures suggested for any given landslide should also be cost effective in terms of construction activities. A possible cost benefit analysis for the Dhalli stabilization measure has been conducted (Table 8). To estimate the construction materials and general Labour work force needed we consulted local vendors and standard govt rates for the material and Labour cost. Based on the input of various sources we have estimated that we would need two separate cost analysis such as material cost estimation and Labour cost estimation. Material costs included the Concrete (Dry sand, Aggregate and Cement) and Reinforced Wire Mesh. Labour cost includes daily wages for Junior Engineer, Mason Grade, Driver and Sprayman, etc. A total cost of 7.11 lakhs has been proposed for the stability measurement.

5. Discussion

The landslide is located along one of the major national highway (5A) connecting Chandigarh Shimla and other important towns. The landslide is caused due to anthropogenic and natural causative factors of these region. Overburden due the to the settlements areas along the surface of the hill coupled with partially stable rock slope, heavily jointed rock surfaces and seasonal rainfall are the major factors of the landslide. The large-scale mapping revealed that the landslide areas are located along the escarpment of the mountain region facing east side. Built-up lands, Shrub land and Shrub forest areas are in major areas. Settlements are found along the crown portion of the landslides and also along the downslope regions. The landslide region is a part of an escarpment along the slope section having a National Highway (5A) coursing through the steep slope. The exposed rock surface revealed that the failed section of the landslide region consists of numerous highly jointed rock surfaces. Stereonet analysis of the exposed joint surface conclude a total of four joint sets (J1, J2, J3, J4) among which J1 and J2 are intersecting and dipping towards the same direction as the slope face causing wedge failure in the study area. The severe rainfall intensity causes high infiltration rate along the soil surface leading to the increased pore water pressure and soil burden causing slope instability. Water infiltration along the fractured rock surface and joint beds and the repeated freeze and thawing of the rocks
leads to rupturing of rock slopes leading to mass movements. The type rock feature present are dominated by slate material in the landslide area rated weak to moderately strong in nature. In order to establish the shear strength of the rock materials core samples are collected from the rock blocks and samples are subjected to point load test to evaluate the peak shear strength of the rock materials. The results conclude the rock materials has an average shear strength of 5.4 Mpa demarcating the rock surface are weak to moderately strong in nature. The field based geological and Geotechnical investigation concludes that the rock surface is prone to reinitiation of landslides. A preliminary assessment of the slope stability was performed through SMR method resulting an FOS value of 45. The value suggest that the slope is partially stable in nature. Based on the results retrieved from field and lab investigations slope stability analysis was performed thorough SWEDGE plugin, part of Rocscience software. The results reveal a total wedge area of 1884.85 sq m of the failed slope section between J1 and J2 intersections. Critical FOS value 0.9 suggest that slope is unstable post-failure and hence reinforced wire mesh shotcrete has been suggested as suitable solution for stabilization of the landslide with an FOS value of 1.6 post-stabilization. The methodology used in the research can be applied in monitoring the stability of rock slopes and developing suitable stabilization measures

6. Conclusion

Dhalli landslide is a structurally controlled landslide that occurred along a Road cut slope without proper toe support. Field work of the landslide was conducted to study the stability of the slopes and propose suitable stabilization measures to negate the future occurrences of the landslide. Stereonet analysis revealed a total of four joint sets among which J1 and J2 are dipping towards the slope causing the wedge failure. Statistical assessment on the frequency of joint sets reveals a total of 79 jointed planes along the direction of J1 indicating that the rock slope is highly jointed and prone to failure. SMR rating of 45 indicates that the rock slope is partially stable in nature post-failure. Stability assessment was done through trial and error using various models of necessary shotcrete width and wire net mesh spacing based on the Mohr–Columb failure criterion method using Rocscience software. FOS value of 0.9 reveals the slope is unstable and suitable stabilization measure has been proposed using Reinforced wire mesh shotcrete indicating a FOS value of 1.6 post-stabilization. The findings conclude that the similar category of rock nature and joint properties are found along the various sections of these steep slope in which the landslide has occurred and that the slope along this region is partially stable in nature and are prone to reinitiation of landslides and also occurrences of new landslides in other sections. The proposed research not only helps in addressing the landslide vulnerable regions, but also has the capacity to address the social and economic impacts due the landslide occurrences. With the help of fewer datasets and field-based investigations more reliable results can be derived. The results will in turn be provided to the concerned authorities which will be helpful in performing future investigations and risk management.
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Disclosure statement

The authors do not have any competing interest.

Data availability statement

The data is available with the corresponding author Dr. C. Prakasam and will be provided upon reasonable request.

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