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STABILITY ANALYSIS AND CONTROL MEASURES OF A DEBRI LANDSLIDE – A STUDY ALONG NATIONAL HIGHWAY OF HIMALAYAN REGION

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ABSTRACT

This study focused on the slope stability evaluation and providing suitable slope stabilization measures for the Kotropi landslide, that occurred on 13th Aug 2017 along NH 154 of the Padhar Tehsil, Mandi district, Himachal Pradesh. The landslide mechanism was complex and involved translational and rotational movement. The length and width of the landslide were 1155 and 190 m, respectively. Five soil samples were collected using the random sampling method for evaluating slope stability controlling properties such as direct shear strength, Atterberg limit, and particle size distribution. Soil classification revealed large quantities of pebbles and fine-grained particles (lean clay and silt). The results from particle size distribution revealed that soil size ranged from 4.75 to 2 mm and 0.42 to 0.15 µm in diameter and on an average comprised 44.5% of the soil sample. The 2D limit equilibrium model (LEM) was used for the slope stability assessment. the Factor of safety (FOS) was estimated to be 0.83, which proved the slope to be unstable even post-failure. Since the Kotropi landslide is located in the seismic zone IV, stability measures were checked under the influence of seismic loading in addition to rainfall conditions. Based on the Janbu simplified method, the FOS of the slopes reduced to 0.72 under the rainfall and seismic loading conditions which is well below the accepted limit indicating that the slopes are vulnerable post landslides. The proposed stabilization measure involves benching of slopes and reinforcing them with end anchorage techniques. Reinforced bench slope with end anchorage techniques have been suggested as the cost effective measure for post stabilization. A FOS values of 1.2 and 1.0 were achieved for rainfall and rainfall as well as seismic conditions proving that the proposed stabilization technique made the slope stable under both conditions.

KEYWORDS: Kotropi Landslide; Limit Equilibrium; Spencer Method; Morgan - GLE Method; Landslide Morphometry; Stabilization Measures; End Anchorage Technique

INTRODUCTION

An earthquake, torrential rainfall, overburden, or other external forces can cause a land slide, which involves the downward movement of soil or debris materials, including rock particles. As a result of these external forces, rock and soil particles slide, causing mass movements [1-3]. [4-6] stated that the different types of landslide movements such as topples, creeps, slide and flow falls within the landslide category. Landslides of different types in the form of velocity, mode of failure, type of failure and type of material involved [7]. Landslides are more frequent in the hill region and leads to destruction and damage of buildings and agriculture land than any other natural disasters. Especially in the NW Himalayas landslide caused more destruction to the roadways, buildings and farm lands compared to others [8-10]. Torrential and antecedent rainfall, soil erosion, unstable slopes with less or no tree tops and increased pore pressure during monsoon and post monsoon time are major causes of the landslides in these region [11-12]. The Himalayan region and the Western and Eastern Ghats are susceptible to landslide activities. The “Building Promotion and Technology Council” Gov. of India have categorized the Himalayan region as class IV vulnerable zone for landslides.

Landslides are more frequent along the roadways and vulnerable slope regions due to soil and/or geological formation coupled with no tree covers leaving the soil exposed during monsoon times in the Himalayan region [11-13]. The social and economic losses due to landslides have increased in the last few years during the monsoon and winter rains [14-16]. The loss of built-up areas, agricultural lands, damage to roadways, communication lines, economic losses, and civilian causalities are prime examples of damage caused by landslides [17-19]. The Himalayan Mountain region is young and comprises of porous soil and rock formation [20]. These parameters coupled with anthropogenic activities and dynamic local climate patterns are the main reasons for landslide occurrences [21-23]. In their report entitled “State Disaster Management Plan (SDMP) Himachal Pradesh, deforestation, unscientific road construction, terracing, and water-intensive agricultural practices and encroachment have resulted in the increased intensity and frequency of landslides” [24]. Since Landslide are sudden and fast, it limits the time to inform and evacuate the citizens leading to increased mortality rate [25]. According to [26] “landslides are responsible for significant life loss, injuries to people, loss of livestock, and agricultural lands in the Himalayan region”. Therefore, studies on critical aspects of landslides, including slope stability and stabilization measures are crucial in controlling and negating future occurrences of landslides [27], Landslide occurrences have exhibited an increasing trend not only in the Himalayas but also in the mountainous regions across the world due to global climate change, migration and unpredictable rainfall seasons, and increased urban development and population, leading to overexploitation of resources”. 2D limit equilibrium model helps to find out the type and mode of failure before assuming FOS [30-31]. The model is accurate and produces reliable results in a short span of time to address the post mitigation measures and strategies. Research on various gaps addressing the landslide issue have been studied from remote sensing perspective on various scales of mitigation and modelling such as 2D, 3D modelling and monitoring of landslide using drones and high-resolution photographs, stability analysis and mitigation measures etc. This study was conducted to assess the failed slope through the field and laboratory-based investigations of various geological and geotechnical parameters post-landslide stability and suitable stabilization measures have been proposed

BACKGROUND OF THE STUDY AREA

Geographically, the Kotropi landslide occurred at the Padhar Tehsil of Mandi district, Himachal Pradesh (Figure 1). The district is located between 31°13′ 0” to 32°04′ 01” N and 76°37′ 45” to 77°23′ 21” E with a total geographical area of 3,950 km^2. Based on Hungr’s system for classification of landslides [29] the Kotropi landslide has been categorized under Debrislide with Rotational and translational movement. According to the 2011 Census of India, the district has a population of 9,99,777 inhabitants. The region is drained by two major rivers, Sutlej and Beas. Water from the rivers forms a crucial part of the agriculture and step cultivation along the riverbanks, and numerous macro and micro-hydroelectric power plants are located along these rivers for electricity production. According to Central Ground Water Board (CGWB), geologically, the area is in a thrusted contact (main boundary thrust) between the Siwaliks and the Shali Group of rocks mainly comprising dolomites, brick red shale, micaceous sandstones, purple clay, and mudstones. The Mandi district experiences varied climates in different parts of the region depending upon whether the regions are valleys (subtropical) or hilltops (temperate). The district receives rainfall during the northeast monsoon season between mid-July to September with an annual rainfall of 1331.5 mm. Kotropi landslide that occurred along the NH 154 is a deep seated landslide extending in the N-S direction with an runout length of 1.3 kms with the crown, main body and toe part of the landslide located along the uphill section of the slope (Figure 2).

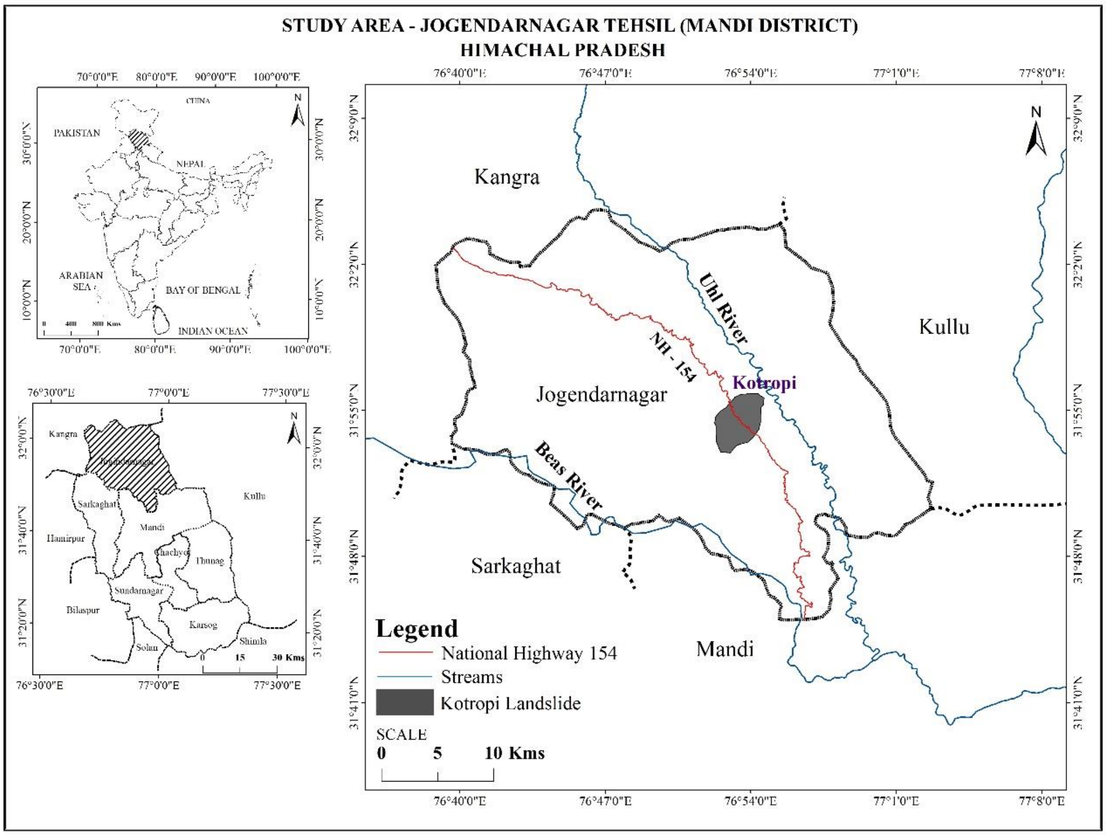

Fig. 1 Kotropi Landslide (Mandi, Himachal Pradesh)

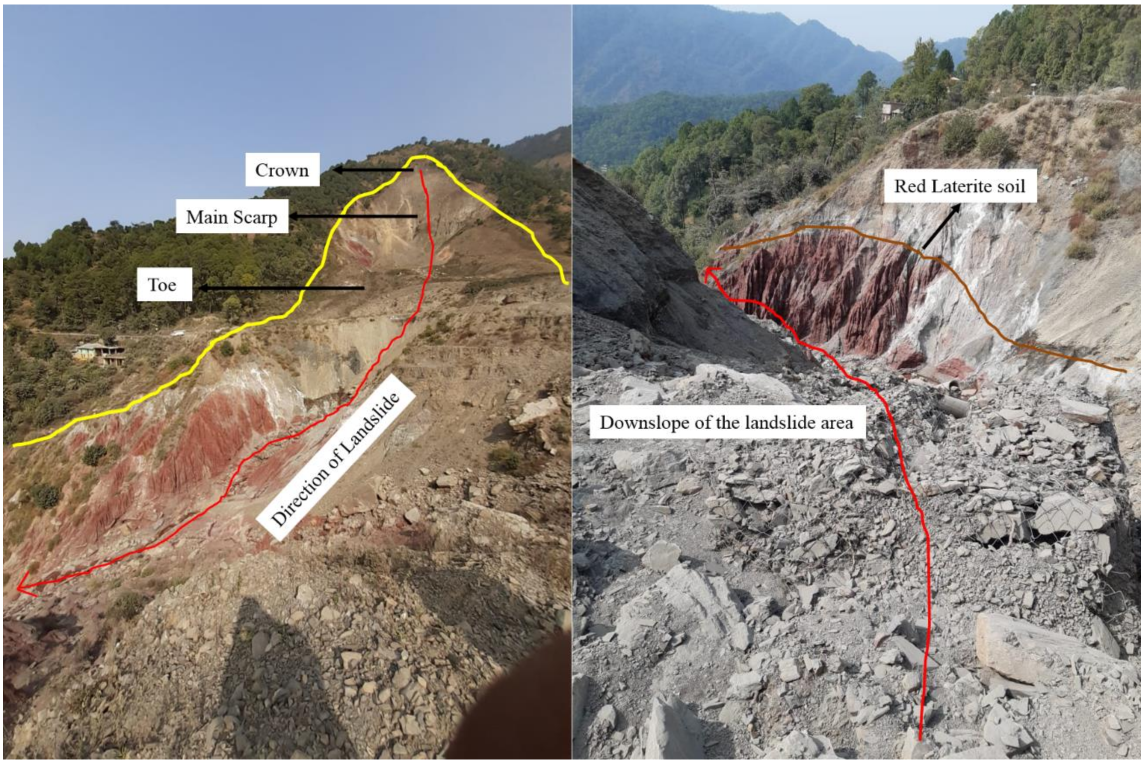

Fig. 2 Demarcation of upslope and downslope of the landslide area with varying soil types along the downslope region

1 Regional Setting

It is primarily dominated by mountainous and sub-mountainous soils. In the Mandi district, the Seraj and Karsog blocks are dominated by sub-mountainous soils, whereas the remaining blocks are dominated by mountainous soils. Temperate stone fruits and vegetables grow well in sub-mountainous soils, where phosphate levels are low and organic carbon levels are high. Additionally, mountainous soil contains low levels of phosphorous and medium levels of potassium, and nitrogen. The soil texture in the Mandi district is loamy to sandy loam. The main boundary thrust runs perpendicular to the direction of landslide occurance, and the Kotropi landslide occurs right along its edge. Also, according to a recent study, it has been summarized that 55% of the overall earthquake occurred in the study area between 1970 to 2019 have been shallow earthquakes with a depth of 10 to 20 kms [31]. The steady vibrations created by the earthquakes coupled with the regional monsoon and exposed surface with no to less tree cover poses a threat of slope failure along these regions. As a result of geomorphology, scarped slopes are abundant, usually dipping in a southwest-northeast direction. In addition, the district is home to many intermountain valleys, the Bahl valley being the most prominent. Its slopes dip NNE and is located at 790 m above the mean sea level (MSL). Alluvial plains dominate this region, which is highly undulating. Alluvial deposits are mainly found along the riverbanks of Beas and Sutlej rivers.

Multi-temporal Landslide Landcover (LULC) mapping was used to estimate the effects of the Kotropi landslide. A maximum likelihood method (Figure 3) was used to calculate the changes in landcover through supervised classification of Sentinel–2A satellite images for 2017. For morphometry mapping of the landslides, Google earth images were combined with satellite data sets. The LULC analysis determined that shrublands constitute approximately 75.4% of the total study area, whereas landslides and plantations account for a combined 10% of the total study area. Built-up land and barren lands, however, are present only in small quantities (Table 1).

Table 1: LULC – Kotropi landslide, Himachal Pradesh

Sl. No.	Class	Area (hectares)	Percent (%)
1	Barren Land	3.91	2.62%
2	Built-up Land	0.83	0.56%
3	Plantation	16.34	10.96%
4	Landslide Area	15.60	10.46%
5	Shrub Land	112.4	75.40%
	Total	149.08	100.00

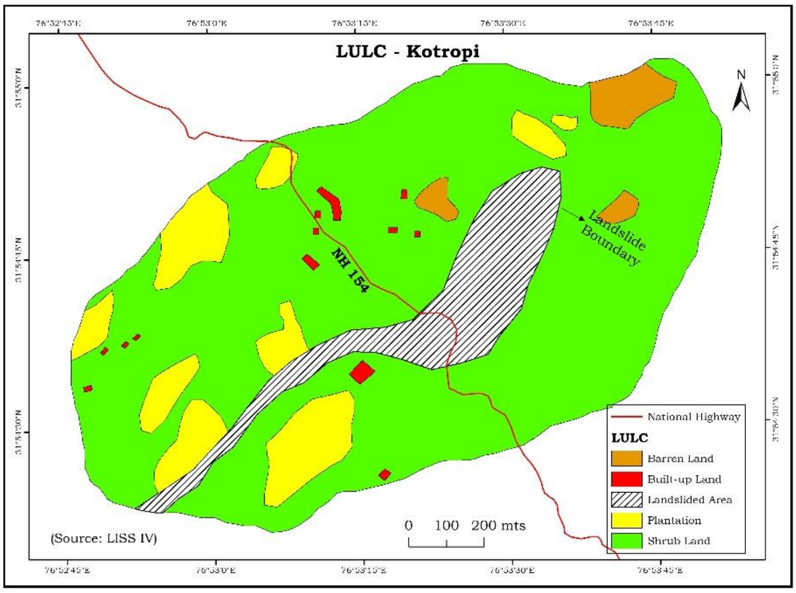

Fig. 3 Landuse Landcover map

Groundwater is the primary source of water scheme for agriculture and irrigation in the Mandi district. According to the CGWB report, the groundwater table is accessed through a series of borewells in the Padhar tehsil for agriculture and irrigational purposes. The water table lies at a depth of 120 to 150 m below the surface. Proper recharge and runoffs of rainfall are necessary to minimize the pore water pressure and soil burden to prevent slope failure. A basis of the soil tests was conducted under saturated conditions to account for the soil–water interaction during failure.

2 Land Susceptibility – Kotropi (Complex Slide)

Landslide susceptibility maps were developed for the Kotropi area by using various physical and anthropogenic factors such as geology, soil, geomorphology, and LULC. The factors were rated using numerical modelling on a scale of 1–5 ranging from significantly low to significantly high. The final landslide susceptibility map was analyzed and processed in the GIS environment by using the weighted overlay method. The results revealed that 43.5% of the total area is covered in a moderate vulnerable zone, 42.5% area falls under high vulnerable zone, and 14% area falls under very high vulnerable zone (Table 2). The crown, main scarp, and toe of the landslide fall under high vulnerable area.

Table 2: Landslide Susceptibility assessment – Kotropi

S.no	Vulnerable category	Percent (%)
1	Moderate	43.5
2	High	42.5
3	Very High	14

3 Rainfall Characteristics

Data for the Mandi rain gauge station from 1981 to 2018 were obtained from the Indian Meteorological Department, Pune (IMD, Pune), the Government of India. The results show that the area receives 867 mm of rainfall on average every year (Figure 4). Slope characteristics are highly influenced by hydrologic characteristics in this area. Due to the inaccessible of potentiometers, triggering rainfall and antecedent rainfall datasets have been used as indirect parameter to establish relation between slope failure and rainfall activity. Based on the data collected from (IMD, Pune), prior to 17th August 2017 a total of 292.38 mm of rainfall has been recorded between 05 to 13th August 2017 and 99.38 mm post landslide event. The rocks and soil along the upslope & downslope are highly crushed and weathered along the landslide area. This high rainfall intensity within a short span of time would have allowed water to percolate along the soil pore spaces, thus increasing the pore water pressure since there was no proper drainage system for the rainwater to drain through. It is evident from (Figure 5) that slope failure is mainly due to high intensity rainfall during the last five years during the monsoon season.

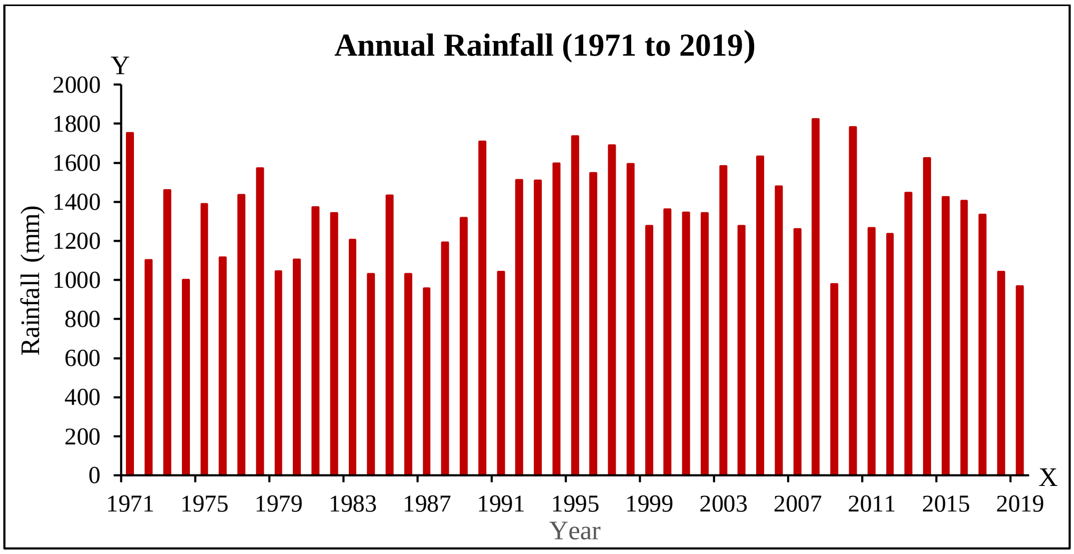

Fig. 4 Annual rainfall precipitation - Kotropi (1971 to 2019)

An Average value of 1,137.47 mm monsoon rainfall over the last eight years (2011-2017) has occured in the region (Figure 5). The high intensity of rainfall during the monsoon season causes an increased water infiltration, especially in areas with unstable slopes. Water infiltration, combined with poor or no drainage networks, lead to soil overload, which ultimately lead to slope failures.

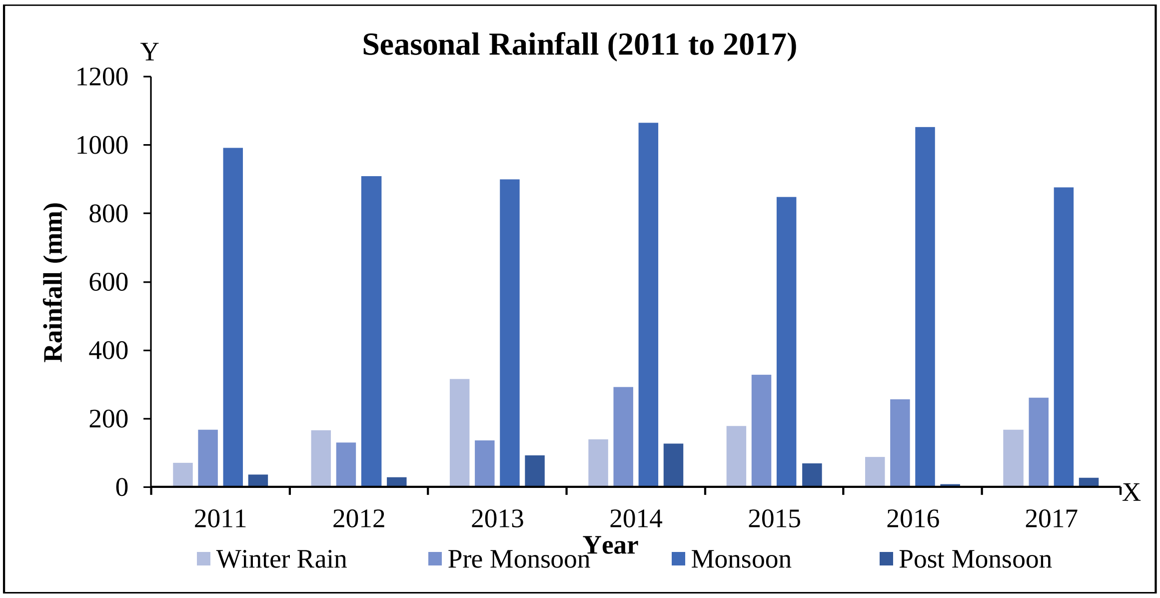

Fig. 5 Seasonal rainfall precipitation – Kotropi (2011 to 2017)

DATA USED AND METHODS

A site-specific landslide investigation involves large-scale mapping of the individual landslide and field-based studies for stability analysis and stabilization measurement (Table 3). The topographical map obtained from the Survey of India (53A/13) was used for base map preparation. Large-scale mapping was performed using LISS IV satellite images and the NRSC level-2 classification system. Lithology, soil, and geomorphology information was obtained from maps retrieved from the Mining wing, Shimla, Himachal Pradesh. The morphometric analysis of the landslide was conducted using the local stations and PALSAR DEM data. For assessing and analyzing the slope stability, field-based soil sample collection and morphometry analysis of the landslides were conducted.

Table 3: Datasets used

Sl. No.	Data	Source	Year	Resolution
1	Toposheets	"Survey of India" (53A/13)	1974	1:50,000
2	Geology	Mining wing, Shimla, Himachal Pradesh	1985	1:50,000
3	Landuse Landcover	LISS IV	06/10/2018	5.8 mts
4	Geomorphology	Mining wing, Shimla, Himachal Pradesh	1985	1:50,000
5	Soil	Mining wing, Shimla, Himachal Pradesh	1985	30 mts
6	Geotechnical Results	Field data collection	2020	-

Stability investigation was a two-stage analysis. Large-scale mapping and morphometry analyses involved collecting base slope parameters, such as the runout length, slope inclination, and width. High-resolution contours were mapped through a total station survey and PALSAR DEM. Because the Kotropi landslide involves complex landslide mechanisms (mud and debris slide), soil samples were collected from landslide areas through random sampling. Lab investigation established various physical parameters, such as liquid limit and grain size. Direct shear test analysis was used to predict the cohesion and shear strength parameters. Slope stability analysis was performed through 2D LEM by using the Janbu simplified method to estimate FOS post-landslide failure and provided suitable stabilization measurements (Figure 6).

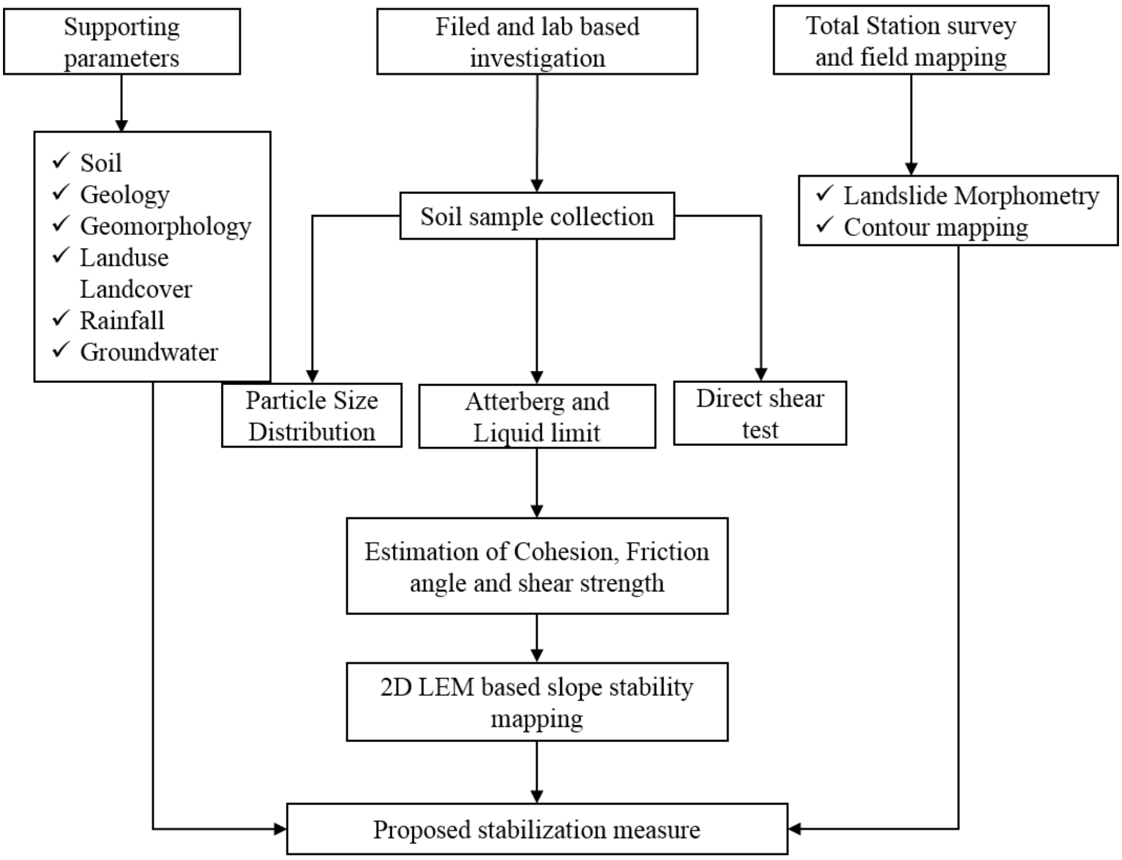

Fig. 6 Research Methodology

RESULTS AND DISCUSSION

1 Large Scale Mapping and Morphometry Analysis

The Kotropi landslide occurred because of the torrential rainfall caused by the northeast monsoon winds on 13th August 2017. The landslide occurred along the national highway (NH 154) connecting the Mandi–Pathankot to other parts of the region. Based on the total station survey and high-resolution satellite images, the total runout length of the landslide was 1290 m, and the width of the main scarp of the landslide was 190 m. The estimated runout length of the slope material along the downslope of the landslide was 551 m. Through field investigation, the landslide was identified as a deep rotational failure in which complex movements, such as translational and rotational mode of failure, were observed. The slope materials included a mixture of mud and debris-forming materials, with mud being a dominant soil particle in the landslide area. Soil overburden and pore water pressure due to monsoon rainfall are the major causes of landslides. In addition to step cultivations, few hamlets have been identified along the uphill section of the landslide through multi-temporal satellite images. These hamlets minimize cohesion between soil particles, further contributing to landslide initiation. Dolomite, mudstones, and brick red shales are the main rock types commonly occurring along the Mandi district. Red laterite and coarse loamy soils constituted the major portion along the landslide region. LULC changes revealed step cultivation and the presence of few hamlets along the uphill and downhill of the landslide area. The landslide destroyed local agricultural lands and built-up lands and resulted in numerous civilian casualties. Google Earth images revealed the existence of old landslide scarps along with the landslide site, which proved the existence of past landslide occurrences induced by unstable slopes. A road cut slope without a drainage system, increased monsoon rainfall, and soil overburden due to increased pore water pressure and soil holes were observed as the main causes of the landslide. Post-landslide, gabion walls, and drainage support are constructed along the toe of the landslide to minimize the soil burden during rainfall seasons. These support structures were destroyed during the recent monsoon season (Figure 7).

Fig. 7 Temporary construction of gabion walls and drainage system destroyed during the recent monsoon season

Mapping the study area at a large scale was conducted through both total station and dual frequency GPS device. The landslide site lies in the Survey of India Toposheet No 53E/11. Nearby benchmarks and the contour lines were recorded through the local station and GPS. Contour data sets were obtained using the local station as individual point data sets. Because the landslide had a large length and breadth, the control points were established at various locations to collect contour points throughout the study area. Both the prism and non-prism modes were employed in the collection of control points. Elevation data were collected at 1-m contour interval to develop a contour map of 2 m. The data sets obtained were processed in the GIS environment to develop an accurate 2D model of the Kotropi landslide (Figure 8). The landslide site lies in the Survey of India Toposheet No 53A/13. The total mapping revealed that the crown of the landslide is situated at a height of 1544 m MSL, and the toe of the runout debris is located at an elevation of 1188 m. The slope is dipping in the north to south direction at an angle of 55° post-landslide failure. The contour mapping of the landslide site revealed that the contour lines are closely packed along the crown part of the landslide, indicating a steeper slope failure than that of the main scarp and the toe part of the study area. The angle of inclination was determined to be 55° along the main scarp of the landslide. The field investigation of the landslide revealed that the point of failure of the landslide is >10 m below the ground surface, which indicated a deep-seated failure. The landslide is not observed for the time but old scarps are identified through old multi-temporal satellite images. Forest plantations and settlements along the uphill of the landslide at an altitude between 1380 and 1320 m were completely buried in the landslide runoff materials.

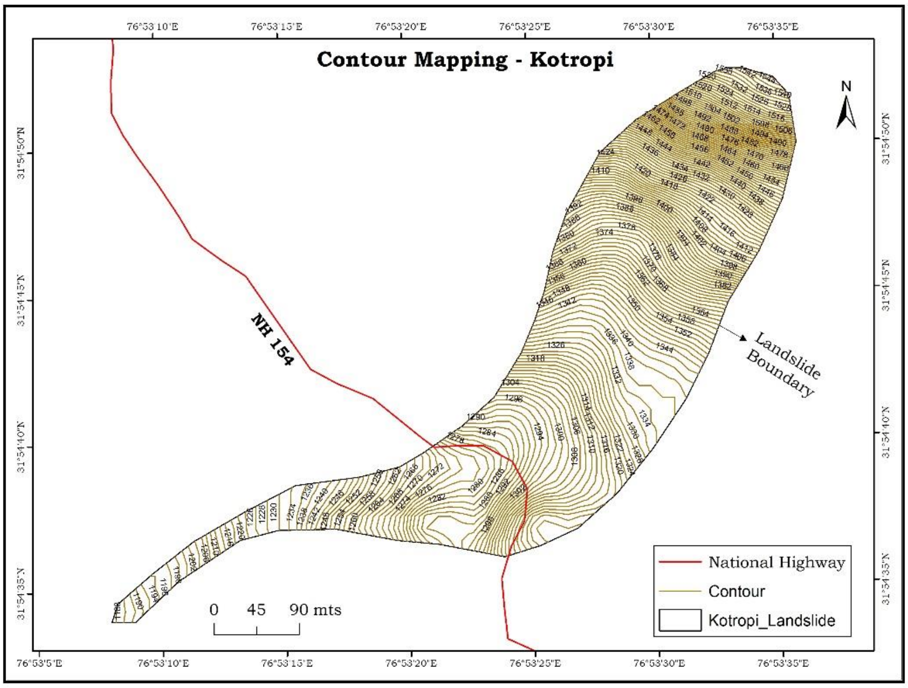

Fig. 8 Contour mapping

2 Geological and Geotechnical Investigation

The Kotropi landslide is a deep-seated landslide, which involves complex slope movements (translational and rotational failure). The majority of the soil particles are debris and mud, with mud being the dominant proportion. Because the landslide involves soil materials, disturbed core samples were collected using the BIS method through random surveying from five locations (Table 4). Based on the soil samples collected, required information such as the angle of friction, cohesion, and shear strength was calculated by conducting grain size distribution, direct shear, Atterberg, and liquid limit tests. The results were used to derive the post-landslide FOS value of slope stability and provide proper mitigation measures.

Table 4: Geo-location of Kotropi landslide soil samples

Sl. No.	Soil Sample	Latitude	Longitude
1	1	31°29'11''	77°41'37''
2	2	31°29'9''	77°41'40''
3	3	31°28'55''	77°41'40''
4	4	31°28'57''	77°41'39''
5	5	31°28'59''	77°41'38''

The grain size analysis of the soil samples (five) retrieved from the fieldwork was performed through the random sampling method. The soil samples subjected to particle size distribution through the sieve method were classified using the Bureau of Indian Standards and revealed that most of the soil consisted of pebbles and fine-grained particles (lean clay and silt) that were present in large quantities. Particle size distribution revealed the soil ranges are inconsistent. The particle size considerably varies in texture and consistency. Grain size distribution revealed that the particle size ranges from 4.75 to 2 mm and 0.42 µm to 0.15 µm in diameter. On average, it accounts for approximately 44.5% of the total soil content (Figure 9). The soil size of <0.425 µm accounts for approximately 50% of the total soil content (Table 5). The soil is characterized through non-uniform gradation. The grain size distribution curve for the soil procured in Kotropi landslide area has also been depicted (Figure 10). This type of soil allows water to percolate and increases the soil burden and pore pressure capacity to a considerable extent, leading to slope failure and initiation of mass movement.

Table 5: Particle size of Kotropi landslide soil samples

Sl. No.	Grain Size (mm)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
1	4.75	45.80%	14.30%	22.60%	15.10%	15.40%
2	2	18.50%	21.90%	23.10%	22.80%	25.70%
3	1.18	4.40%	5.40%	5.80%	5.90%	5.70%
4	0.425	14.40%	21.10%	18.50%	19.50%	18.50%
5	0.3	1.60%	3.40%	2.80%	3.20%	3.70%
6	0.15	4.80%	15.10%	12.10%	13.30%	12.40%
7	0.075	3.30%	8.90%	9.20%	9.40%	9.00%
8	0.004	7.20%	9.90%	5.90%	10.80%	9.60%

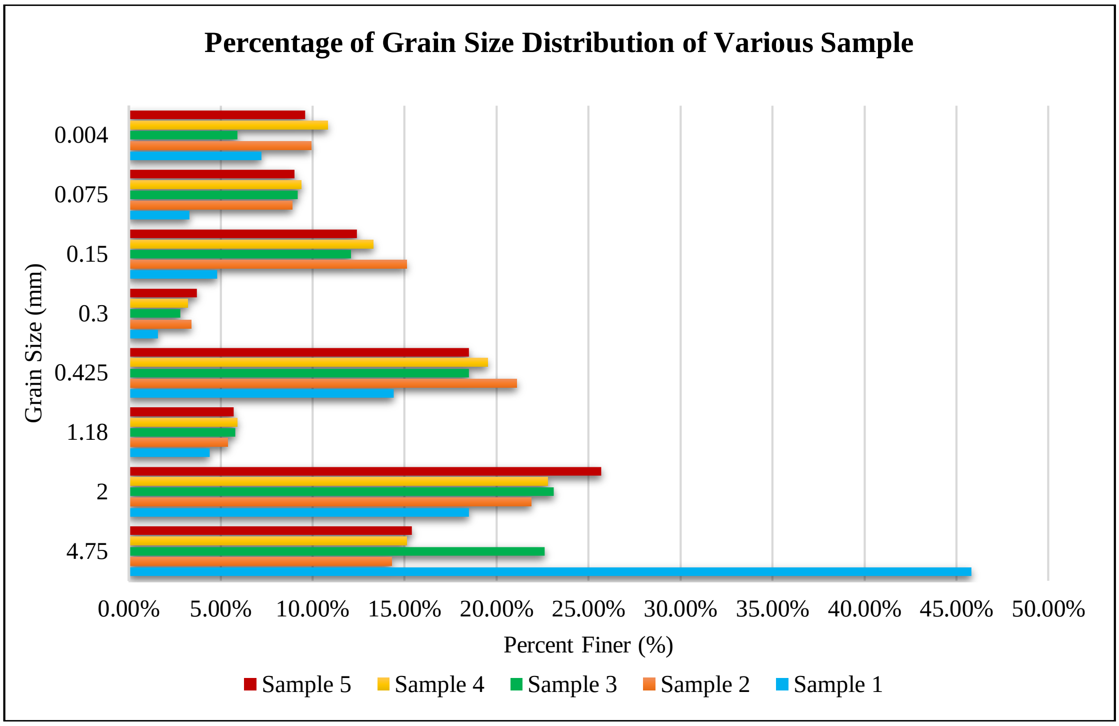

Fig. 9 Percentage of Grain Size Distribution of Various Sample

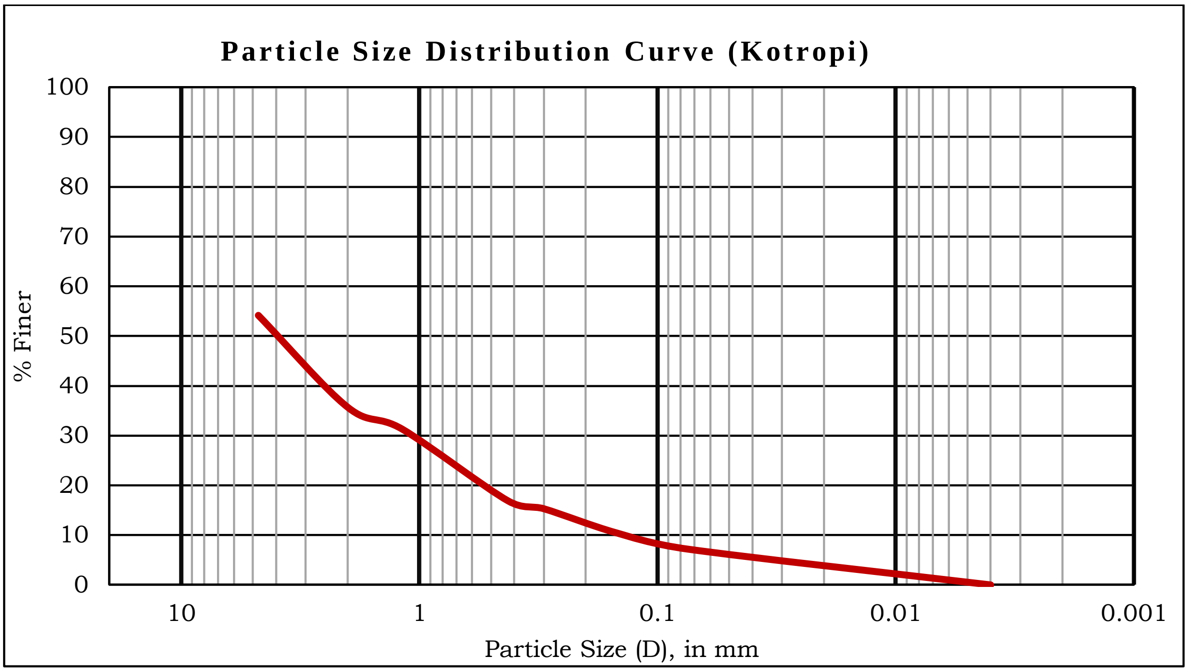

Fig. 10 Grain size distribution chart - Kotropi Landslide

Atterberg limit test is carried out to determine the cohesiveness of the soil content. The point at which the soil turns from liquid to plastic state. As the moisture content of the soil decreased, the number of blows increased. Using the results of this study, it can be concluded that the soil particles in the Kotropi area are classified as plastic to moderate inorganic clays. The blows vary between 18 and 21 at natural moisture content (Figure 11). Water percolating through such soils leads to moisture accumulation during rainfall seasons, which reduces the soil's cohesiveness and leaves it vulnerable to landslides. The tabulated results are given in (Table 6).

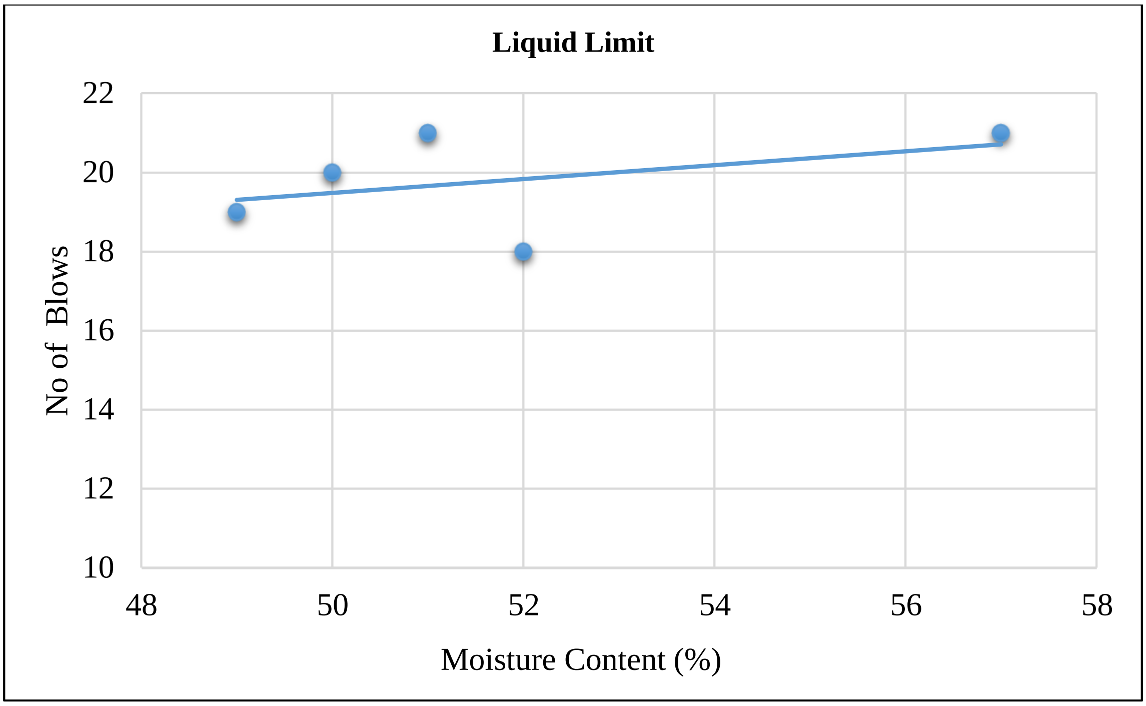

Fig. 11 Liquid Limits obtained from the soil samples

Table 6: Atterberg limit – Kotropi Landslide

Determination Number	1	2	3	4	5
Container number	1	2	3	4	5
Weight of container	177.2	197.4	177.4	197.5	218.5
Weight of container + wet soil	377.2	399.4	385.4	398.5	421.5
Weight of container + dry soil	327.2	347.4	327.4	347.5	368.5
Weight of water	50	52	58	51	53
Weight of dry soil	29	28	28	29	30
Weight of wet soil	35	34	35	35	35
Moisture content (%)	**49**	**51**	**57**	**50**	**52**
No. of blows	**19**	**21**	**21**	**20**	**18**

The results of the lower and upper limit for liquid limit test were observed between 18 to 21 for the soil samples collected and plastic limit to be 16.6. Due to the presence of small percent of silt in the soil, consolidate drained test has been employed to study the slope failure under drained conditions.

Direct Shear Test Analysis

To rapidly asses the FOS of the slope, direct shear test has been employed as both the Consolidated drained and undrained takes a very little time and pore pressure dissipates quickly due to small portion of the soil sample. The soil samples of <0.425 µm were used to evaluate the soil shear strength cohesion and angle of internal friction through direct shear tests. Because the monsoon rainfall is a critical factor in the control and initiation of landslides, the test was conducted under drained, saturated conditions to calculate the maximum shear stress at which the soil fails. The experiment was conducted at five normal stress loads (0.1, 0.25, 0.5, 1, and 1.5 kg) to study the shear stress limit. The readings were noted at intervals of 25 under prescribed normal loads. Based on the results, the cohesion of the soil material was calculated to be 26.5 kPa, which suggests the soil is moderately strong. The angle of internal friction was evaluated at 40.1°

as the maximum angle at which the soil can fail (Table 7). The slope angle of the Kotropi landslide was estimated at 64°, well above the tolerated level retrieved through the lab tests (Figure 12).

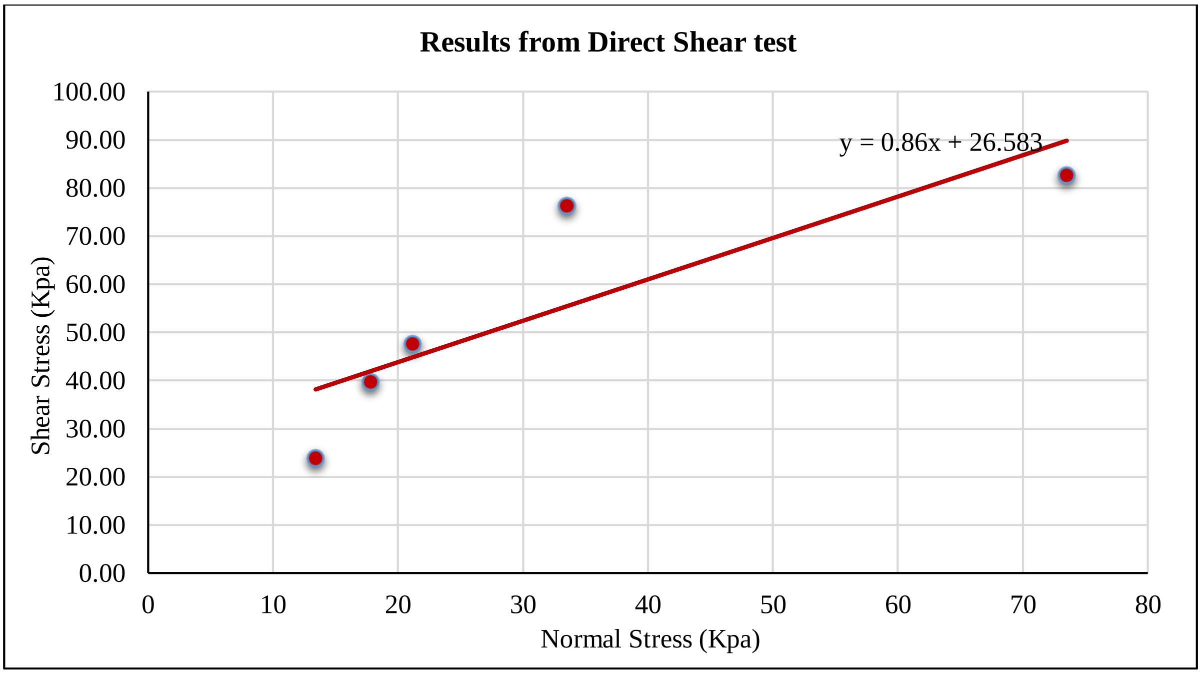

Fig. 12 Direct Shear test - Kotropi Landslide

Table 7: Normal and Shear Stress – Kotropi landslide

Normal Stress(kg/cm^2)	Normal Stress (kPa)	Shear Stress At failure (kPa)	Slope Stability Factor	C (kPa)	Slope (m)	Slope Angle
0.1	13.4	23.80	0.56	26.5	0.86	40.1
0.25	17.8	39.70	0.44			
0.5	21.2	47.60	0.44			
1	33.5	76.30	0.43			
1.5	73.5	82.60	0.88			

3 Slope Stability Assessment and Stabilization Measures under Rainfall Conditions and Pseudo – Static Seismic Loading

3.1 LEM Based Slope Stability Assessment and Stabilization Measures for Kotropi Landslide

“The LEM is a commonly used method by researchers across various fields for the 2D slope stability analysis due to its simplicity”. It is stated that the “numerical model is time-consuming and has some restrictions to a certain extent compared with the LEM model that can produce accurate and reliable results within a short period for homogenous materials. In the 2D LEM model, stability analysis was derived using the trial slip surface and optimization techniques’. The FOS for current research was estimated based on two models, namely the Janbu simplified and Morgan–Pierce methods. The Kotropi landslide had a height of 283.5 m, extending from the road surface between the crown and toe part of the landslide. After -landslide failure, the slope angle was 55°. The cohesion, friction angle and unit weight were estimated to be 26.5 kN/m^2, 40.1°, and 14.2 kN/m^3, respectively. Through Janbu's simplified method, the FOS was estimated to be 0.83, which proved the slope to be unstable even after failure (Figure 13). The stability analysis indicated that the Kotropi landslide is a deep-seated landslide movement with the origin of failure lying 33.93 m below the landslide surface. The resultant FOS value indicated the lack of slope stability post-landslide occurrences.

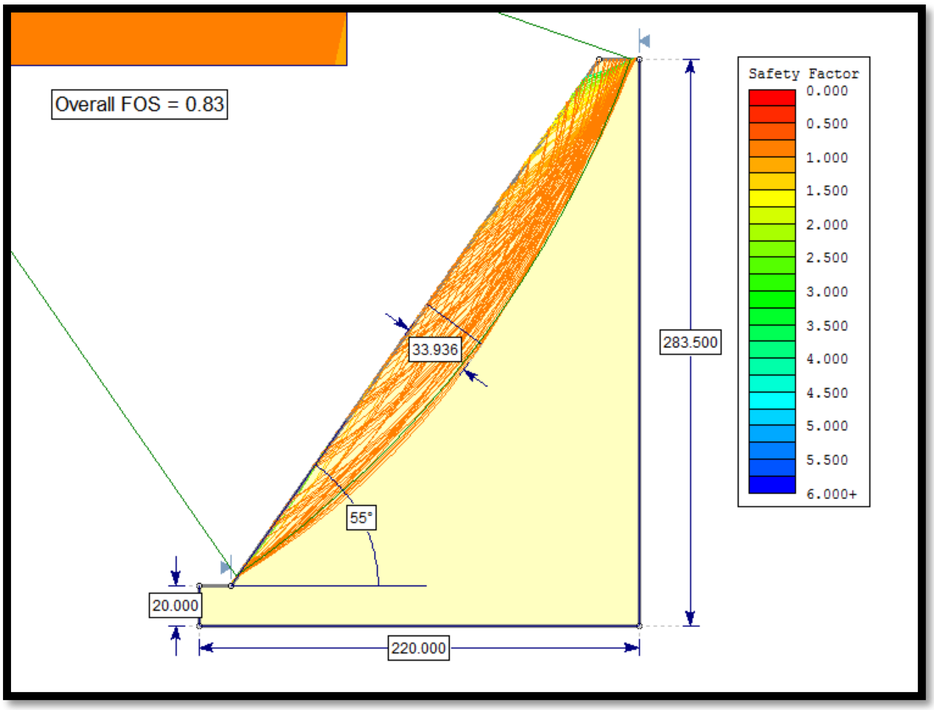

Fig. 13 FOS of the slope under consolidated drained conditions (without seismic factor)

3.2 Pseudo static seismic analysis along the landslide area

In conjunction with slope stability analysis performed under rainfall conditions, the analysis was also performed under Pseudo-static loading. Materials properties having been given with respect to the scenario of post-landslide failure and physical soil parameters such as friction angle, cohesion and unit weight were estimated to be 40.1°, 26.5 kN/m^2, and 14.2 kN/m^3 respectively through the direct shear test. Spencer and GLE / Morgenstern prince method has been adopted for stability analysis under seismic loading conditions. Since the Landslide area is located in the seismic vulnerable zone 4, pseudo-static coefficient of 0.12 (i.e., Half of the peak ground acceleration expected in seismic zone 4) has been adopted to represent horizontal seismic load.

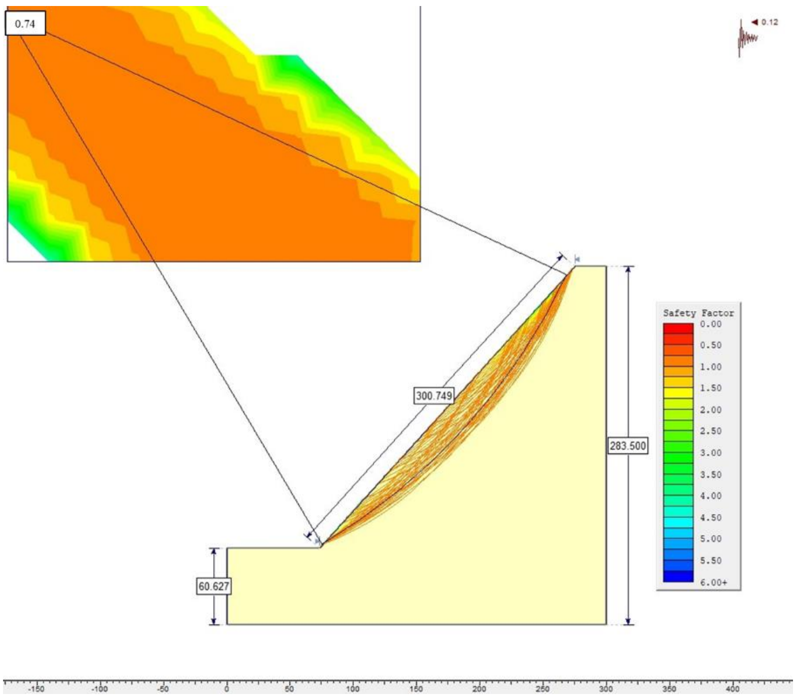

Fig. 14 Slope stability under earthquake loading using a pseudo-static coefficient of 0.12

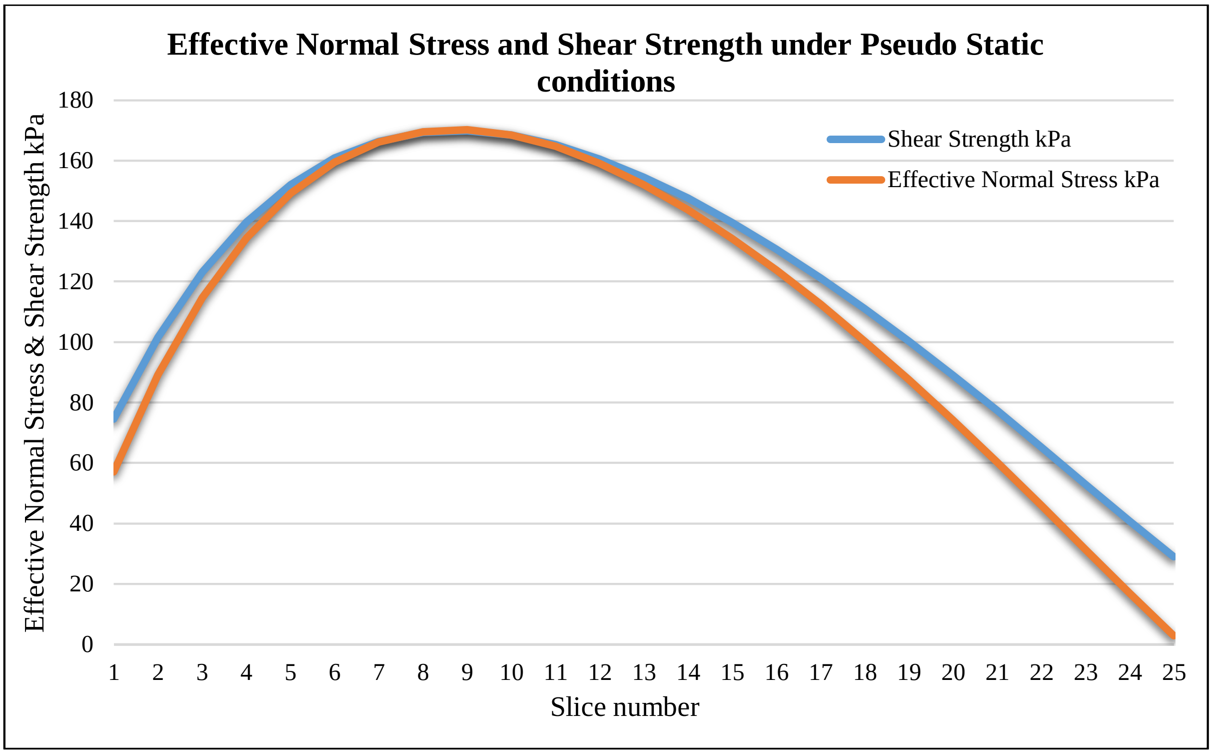

Fig. 15 Effective stress vs shear strength of Kotropi landslide under consolidated drained condition

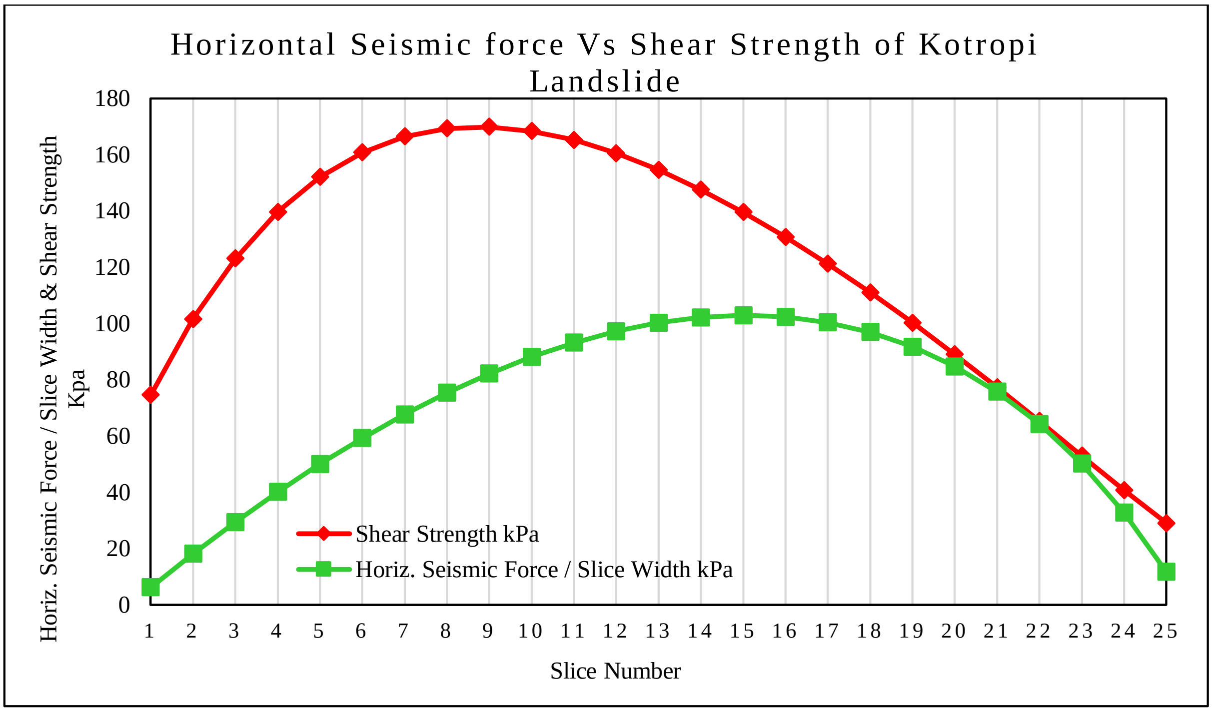

Fig. 16 Horizontal seismic force vs shear strength (under pseudo seismic loading of 0.12)

The factor of safety (FS) is calculated to be 0.74 (Figure 14) under the seismic load of 0.12 which is below than the average required stability margin that the slope would fail under this condition. The maximum shear strength exhibited under the spencer and Morgenstern price method were 163 kPa and 172 kPa respectively (Figures 15 and 16). Post these limits and under suitable conditions during monsoon seasons have a higher chances of slope failure.

3.3 Slope Stabilization Measures

Even though the earthquakes are primary factor of slope failure, rainfall and monsoon season are the primary factors for landslide initiation. Landslide cannot be controlled under every circumstance especially during the time of earthquakes. Hence the stability measures have been developed considering two key parameters i.e., seismic and monsoon activity. As monsoon being the primary causative factor, suitable slope stabilization measure was proposed to prevent future landslide occurrences. The proposed stabilization measurement involves benching the slope and reinforcing them with end anchorage techniques. Compared to the existing soil nailing, helical soil nailing has been proposed as suitable structure for stabilization due to its easy installation. These soil nailing does not require grouting which is installed at the toe of the landslide. The stability is provided by the friction of the surrounding soil and bearing capacity of the soil nailing itself. Since the slope is cut into number bench slopes, theoretically, the soil nailing has to be inserted at an angle less than 25° to achieve stability.

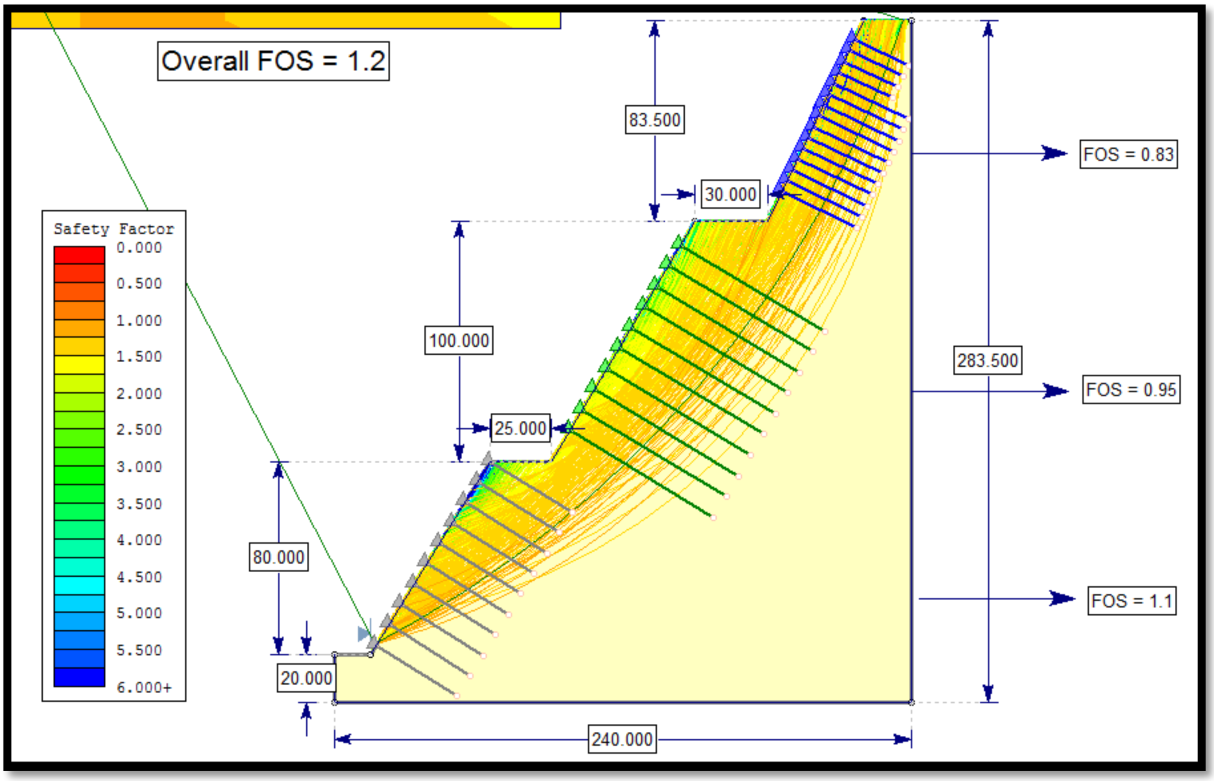

Fig. 17 Reinforced Bench slope with End anchorages consolidated drained conditions

The slope stabilization measures has been carried out under two different conditions. The performance of slope post stability measures under and under extreme rainfall conditions (Figure 17) and seismic conditions (Figure 18). The analysis reveals a FOS value of 1.2 under consolidated drained condition with the proposed stabilization technique. Under pseudo static conditions, the analysis reveals an FOS value of 1.0, proving that the stabilizations measures will be able to prevent slope failure under seismic condition.

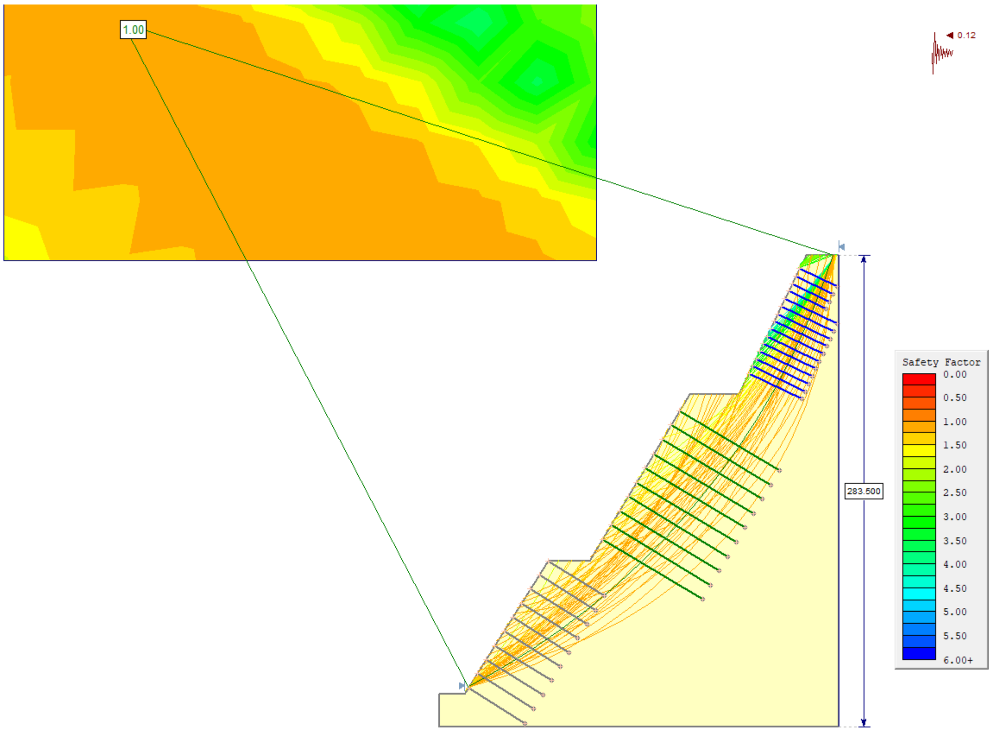

Fig. 18 Reinforced Bench slope with End anchorage technique under Pseudo seismic static conditions value loading of 0.12 conditions

CONCLUSION

The Kotropi landslide occurred due to the torrential rainfall of the northeast monsoon on 13th August 2017. The landslide occurred along the national highway (NH 154) connecting Mandi–Pathankot to other parts of the region. Based on the total station survey and high-resolution satellite images, the total runout length of the landslide was 1290 m, and the width of the main scarp of the landslide was 190 m. The estimated runout length of the slope material along the downslope of the landslide was 551 m. The soil mainly constituted pebbles and fine-grained particles (lean clay and silt), with 44.7% particle size ranging from 4.75 to 2 mm and 0.42 µm to 0.15 µm in diameter. After landslide failure, the slope angle was 55°. Cohesion, friction angle, and unit weight were 26.5 kN/m^2, 40.1°, and 14.2 kN/m^3, respectively. The FOS of 0.83 derived from the Janbu simplified method indicated that the slope was unstable, confirming the field observations. Seismic analysis was also performed with the help of pseudo-static loading of 0.12g, which is taken as half of the expected PGA for seismic zone 4. Under pseudo-static loading condition, a FOS of 0.72 was procured, indicating failure of the slope due to seismic loading. The proposed stabilization measure as adopted in this study involves benching the slopes and reinforcing them with end anchorage techniques. With the stabilization technique as proposed in this study, a FOS of 1.2 pertaining to consolidated drained condition was observed indicating that the slope stabilization measure aided in making the slope stable. Analysis was also performed by incorporating seismic loading to the proposed stabilized slope, where a FOS of 1.0 was procured. The proposed stabilization techniques as adopted in this study were able to make the slope stable for both rainfall and seismic loading conditions, which was indicated by FOS value of 1. The geotechnical and geological aspects of individual landslides in Himachal Pradesh have been studied extensively, but only a few studies have considered the detailed geotechnical and geological aspects of individual landslides and their remedial measures. This study evaluated detailed geotechnical and geological attributes for the slope stability assessment, and suitable stabilization measures were proposed for the Kotropi landslide. The results of this study can be considered as pilots for rapid and accurate assessment of the stability of slopes due to soil slippage and failures. However, proper site-specific studies needed to be performed before adopting the procedure outlined in this article, on other slopes in order to assess their stability. Extensive large-scale studies regarding the morphometry, factors influencing landslides, stability assessment, and stabilization measures were conducted only for a few landslides. High-resolution 3D modelling through drone and aerial photographs will provide accurate assessment on the dimension of the landslides coupled with researches on stability measures using native vegetational species with deep root penetration capabilities and artificial protection measures using passive & active techniques are future aspects of the research.

DECLARATIONS

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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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Ethics approval: The research work conducted is adhered to the strict guidelines of the journal.

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