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ORIGINAL ARTICLE

A geotechnical approach to compare different slope stabilization techniques for failed slope in the Darjeeling hills, India

Amit Chawla[1] · **Kripamoy Sarkar**[2] · **Rahul Abhishek**[1] · **Sowmiya Chawla**[1] · **Srinivas Pasupuleti**[1] · **Swapnil Mishra**[3]

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Abstract
Landslides are one of the extensive and destructive natural hazards in the mountainous areas and can cause loss of life and infrastructure. Slope stabilization methods can be adopted to minimize the losses due to landslides. The aim of this study is to investigate the failed slope due to landslides and suggest the site-specific ground improvement solutions capable to increase the factor of safety and reduce the displacement. In this study, a slope on a National Highway connecting the ridge to the foot hills in the Darjeeling Himalayas India is selected as the study site due to occurrence of landslides. The study site is investigated and the slope stability analyses are carried out by two-dimensional finite-element analyses. Comparisons of four different slope stabilization methods are introduced with the understanding of behavior of support system. Different slope stabilization methods along with or without ground improvement techniques like benching, retaining wall, soil nails, micropiles, shotcrete, and geogrid are attempted. Factors of safety along with displacements are computed for all the different combinations with and without rainfall effect. Parametric study is also carried out to investigate the optimum configuration for the suggested slope stabilization technique. After comparing and assessing different ground improvement techniques, the results suggest that the combination of soil nails with shotcrete and geogrid on stepped cut slope face along with retaining walls supported by micropiles and soil nails at the bottom has performed well and satisfies the stability conditions for the selected slope. The suggested combination provides an optimal solution and remediation option for stabilizing the slope.

Keywords Landslides; Slope stability analyses · Finite-element analyses · Slope stabilization methods

Introduction

Landslides happen to be the most common natural hazard in the mountain regions (Mandal and Mandal 2016; Tiranti and Cremonini 2019). Landslides and slope stability problems constitute a greater threat to the life and infrastructure of the entire mountainous region of the world (Highland and Bobrowsky 2008; Althuwaynee and Pradhan 2017; NDMA 2019; Kainthola et al. 2021). As per World Disasters Report, nearly 173 significant landslide calamities were reported worldwide between 2004 and 2013, ending 8739 lives and disturbing and influencing nearly 3.2 million people lives (IFRC 2014). Landslides constitute 4.89% of the natural disasters that happened worldwide through 1990–2005 (http://www.em-dat.net). For the period between 1990 and 2015, 54% of the landslides happened in Asia only (Guha-Sapir et al. 2018). Landslide causes death of 264 Indians in 2019 and more than 65% of these deaths happened in the Himalayas (NCRB 2020). However, the number of reported deaths does not represent the true impact of the landslide

✉ Sowmiya Chawla
sowmiya@iitism.ac.in

Amit Chawla
amit.2015dr1018@cve.iitism.ac.in

Kripamoy Sarkar
kripamoy@iitism.ac.in

Rahul Abhishek
rahul.20dr0179@cve.iitism.ac.in

Srinivas Pasupuleti
srinivas@iitism.ac.in

Swapnil Mishra
swapnil@iitism.ac.in

[1] Department of Civil Engineering, Indian Institute of Technology (ISM), Dhanbad, India

[2] Department of Applied Geology, Indian Institute of Technology (ISM), Dhanbad, India

[3] Department of Mining Engineering, Indian Institute of Technology (ISM), Dhanbad, India

on that particular area. High intensity of rainfall, high seismicity, rugged mountains, and unstable steep slopes made the Himalayan belt contribute to fatal landslides in India. The global database suggests that India contributes 16% of all rainfall-induced landslide occurrences globally and 77% of these happened throughout the monsoon, whereas India alone also contributes 30% of the globally reported landslide events in the category of landslides triggered by construction works occurred on road and during the study period of January 2004–December 2016, India also contributes maximum of landslides (12%) activated by mining activities (Froude and Petley 2018). Landslide Susceptibility Zonation maps can also be helpful in identifying the landslide prone areas in advance and shall help the planners in making decisions for the future development and disaster mitigation measures (Chawla et al. 2017, 2019a, b).

Assessment of slope stability problems and identification of suitable stabilization methods is an effective tool in minimizing the losses due to landslides and to cease the soil movement. Slope failures shall also be caused by strength reduction at transition zones of layers, heavy rainfall, toe cutting of slopes, dynamic traffic load, high-intensity earthquake, etc. (Ercanoglu 2005). Regions such as Darjeeling hills, India are mainly at risk for landslides due to highly weathered rocks, steep slopes, heavy rainfall, and unplanned construction and haphazard urbanization at places. The oldest reported landslide in Darjeeling hills was happened on 24th September 1899, when a destructive landslide in Darjeeling town and adjacent regions caused 72 casualties along with the loss of key infrastructure. Darjeeling hills have a history of catastrophic landslides and this fragile Himalayan terrain experienced various significant landslides in the past. Hence, evaluation of the slope stability problems and identification of effective stabilization methods were the key issues. To prevent the landslide hazard, various slope stabilization methods are also introduced, such as benching, soil nailing, and drainage system (Abramson et al. 2002).

Due to haphazard urbanization in hilly regions, there is rapid increase in demand of rail-road transport which resulted in new slope structures of cut and fill. Slope stability analysis becomes a challenging assignment as there are various numbers of factors affecting the behavior and shall result in variety of failure mechanisms. These complex problems can also be evaluated with the aid of finite-element methods (FEM). Various researchers have utilized numerical simulation for studying the behavior of slope. Griffiths and Lane (1999) advocated the FEM for slope stability analysis, as a powerful approach. This study outlines various examples of FE slope stability analysis while comparing with other methods and also discussed that FEM for slope stability analysis is generally a better alternative than limit equilibrium analysis methods**.** 2D finite-element analysis shall be considered to be efficient when the cross-sectional slope profile does not show much variation with the length. Onyango and Zhang (2019) in their study highlighted the benefits of using 2D finite-element analysis over the traditional methods. They discussed that this method can simulate the interaction between the soil and the supports, such as pile and anchors. Onyango and Zhang (2019) using 2D finite-element analysis predicted the failure surface in slip zone and demonstrate that piles embedded in the bedrock were the suitable reinforcement method to contain the failure in that case. Abramson et al. 2002 discussed various slope stabilization instruments like piles, anchors, drainage system, etc. to prevent the potential hazards. Jayanandan and Chandrakaran (2015) discuss a study on nailed soil structures with the help of 2D software. Results suggest that slope stability was improved after the application of nails and the lateral deformation was reduced by about 41% and factor of safety increases by approximately 1.2 times that of without nail slopes. Rawat and Gupta (2016), studied 2D Finite-Element Method-based slope stability analysis on two different soil slope angles, which were reinforced along with nails. The results suggest that, with 60° slope angle, FEM model observed an increment of nail forces. Usluogullari et al. 2016, examined a vulnerable slope of Turkey. The slope was investigated at three profiles and 3D FEM slope stability analyses were performed. Factor of Safety (FOS) and soil movements were predicted. Behavior of piles with and without lateral support was studied. Remedial options and solutions for mitigation of vulnerable slopes have been proposed on the basis of FEM analyses results. Azzmi et al. 2011 investigate about the remedial techniques of slope protection. Bathini and Krishna (2022) discuss about the application and advantages of soil nailing as a ground improvement technique for slope stabilization.

The present study discusses about the failed slope due to initial landslide in Darjeeling hills. The agencies were working to stabilize this slope; although the scope of this paper is to assess the stability of slope and identify an alternative optimal slope stabilization method to strengthen the failed slope. This initial landslide causes the devastating loss of infrastructure like damage of walls of UNESCO world heritage Darjeeling Himalayan Railway (DHR) locomotive workshop, damage, and washed away the portion of National Highway-110, and DHR track, and also obstructs the traffic flow (both road and rail). Post these initial landslide, a sequence of slope failures triggered by intense rainfall has also occurred, which has further impacted the important infrastructures. For stabilizing the susceptible slope and to minimize the loss of life and infrastructure, the selected landslide site was investigated. Based on the collected information, a detailed 2D finite-element analysis by strength reduction method is studied for analyzing the factor of safety, displacements, and pre- and post-failure conditions. Numerical analysis with different combinations of slope stabilization methods and ground improvement techniques were carried out and compared to understand various merits and demerits associated with them. Positive effect of the incorporation of soil nails, micropiles, shotcrete, geogrid, retaining wall, and their potential combinations are presented. For determining the optimal slope stabilization method, factor of safety and displacement of slope were computed. Comparisons of all the four slope stabilization methods are introduced with the understanding of behavior of support system. The results of the FE analysis were used to suggest the appropriate slope stabilization methods capable to increase the factor of safety and reduce the displacement.

Study area

The study site is a landslide located in Tindhari, which falls under the Kurseong subdivision of the Darjeeling district, West Bengal, India (Fig. 1) and lies at latitude 26°51′14.55″ N and longitude 88°20′13.12″ E. The study site landslide is somewhat triangular in shape with its maximum width toward the top (130 m), a length (crown of the slided slope to the toe of the slided slope) of about 280 m, and a distinct debris run out distance of about 350–400 m, and covers a geographical area of around 20,000 Sq. m (Fig. 2). National Highway-110 passes along

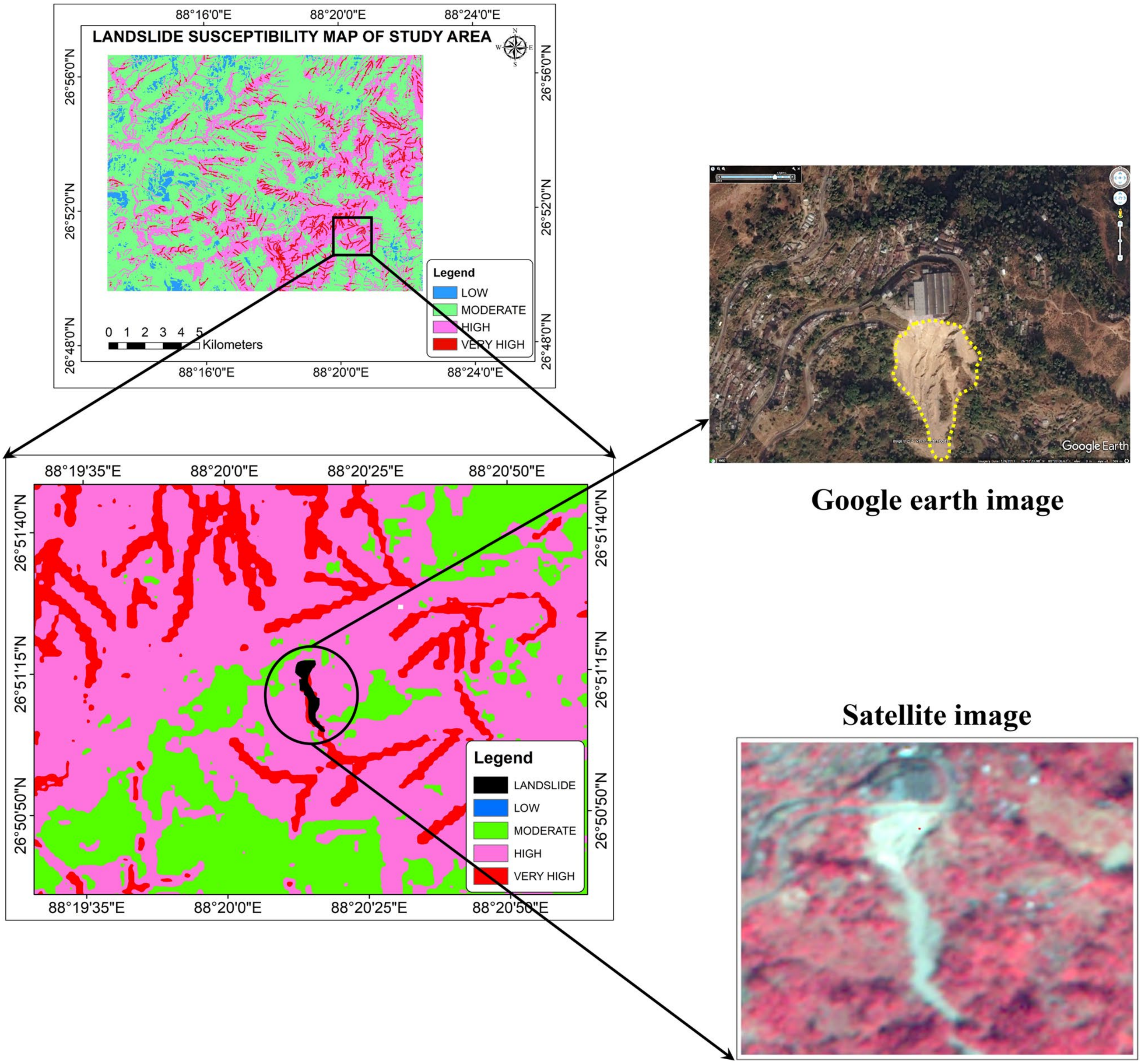


Fig. 1 Representation of the study site

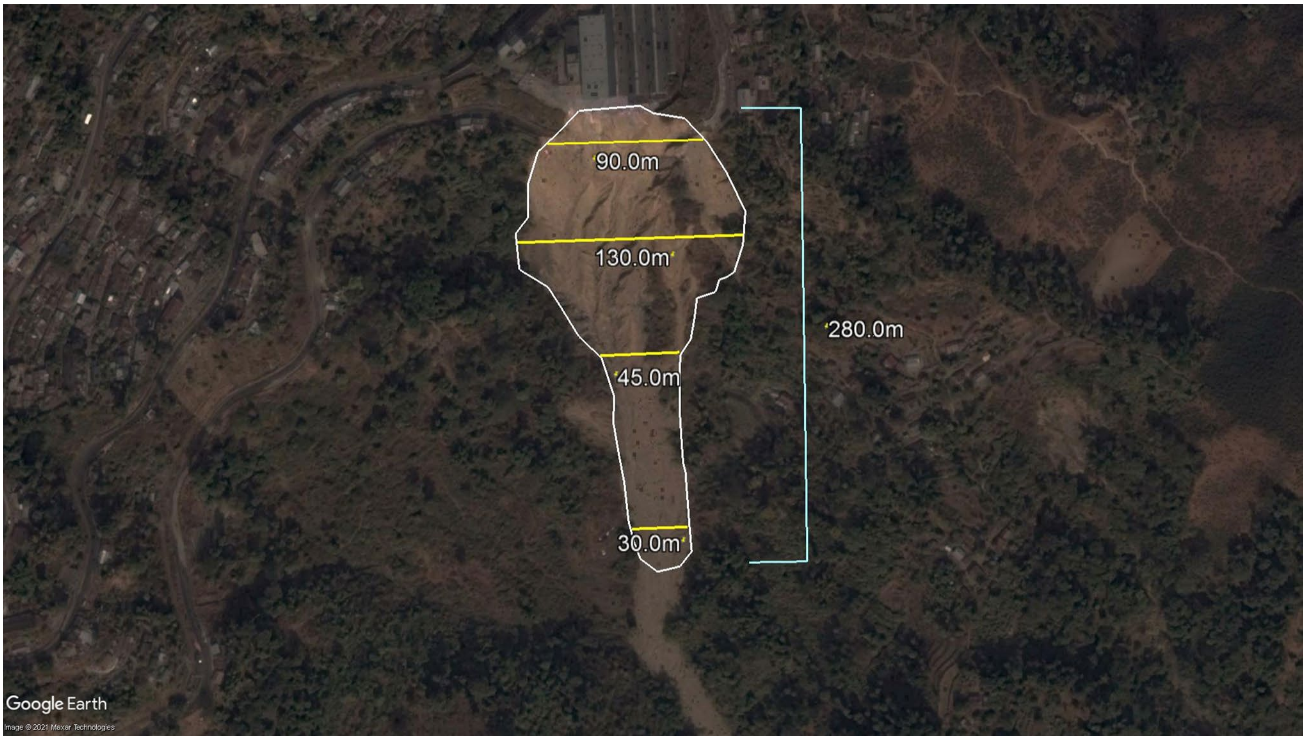


Fig. 2 Morphometric parameters of the study site

steep mountain slopes of the study site. In addition, the UNESCO World Heritage Darjeeling Himalayan Railways run along NH-110. The study site lies at the margin of uplifting mountains in the zone of monsoonal heavy rains; active tectonic features and the substratum lithology comprising rocks of low-to-medium strength.

The study site is located in Tindharia faced landslides triggered by the 18th September 2011 Sikkim earthquake of $M_w = 6.9$ and its epicenter was at Taplejung (27°21′0″ N-87°40′0″ E) Nepal and overall more than 111 people were killed by the effects of this earthquake. Post these landslides at the study site, a sequence of slope failures triggered by intense rainfall also happens on 27th and 28th September 2011. This landslide has impacted the important infrastructure like damage and washed away the portion of National Highway (NH) 110, damage and washed away the portion of railway track of World Heritage Darjeeling Himalayan Railway and also provide damages to the walls of DHR heritage locomotive workshop which happens to be located at crown of this landslide. Essential services were also disrupted for several days due to this landslide. At the study site, the landslides again happen in the subsequent intense monsoonal rainfall on 19th July 2012 and from there continue to trigger in monsoon seasons which resulted in causing different type of losses. Due to the landslides at the study site, most of the houses on and around the study site were vacated and relocated. Stretch of NH-110 and vehicular movement (i.e., on and around the study site) was affected by the slides mostly in the monsoon season. Darjeeling Himalayan Railway was also affected by these slides, as the railway track is located parallel to the National Highway. NH-110 links Siliguri to Darjeeling town and passes through Kurseong and the importance of this route is; it connects the plains to the hills.

Selection of the study site

Consequential to the geo-morphic features of the study site, the area enfolds many characteristics that impart high vulnerability to landsliding. Slope steepness of the study site is in the range of $40° - 45°$, which imparts high sliding force. The internal factors provide favorable conditions for the operation of external factors in the causation of landslides. Darjeeling hills receive intense rainfall (3000–4000 mm) and also have a history of earthquakes. According to the seismic zonation map of India, the study site falls under Zone IV, i.e., severe intensity seismic zone, and is considered as the high damage risk zone. In addition, undercutting of the slope toe was also observed. With the overarching impact of the landslide inducing factors, the study site assumes high vulnerability to landsliding.

Identification and selection of the study site, i.e., the vulnerable site to landslide was adopted on the basis of the parameters like: from the Landslide Susceptible Zonation map (Chawla et al. 2018) of the part of Darjeeling district, the study site landslide is falling in very high susceptibility zone (Fig. 1), settlements on and around the landslide in large numbers, landslide impacting important infrastructure like damage of National Highway, damage of railway track of World Heritage Darjeeling Himalayan Railway and damage to UNESCO recognized Darjeeling Himalayan Railway heritage locomotive workshop walls, history of significant and active landslides which causes damage to life and infrastructure, and crossing of key infrastructure like important institutions, National Highways, State Highways, and railway line passing through. These parameters emphasize the importance of this study. By considering all of these key factors into consideration, the study site was selected and detailed exploration about the study site has been carried out. The objective is to identify and select the vulnerable landslide site, which will be studied for treatment and proposal of alternative landslide remedial solutions and safer design.

Geological and geotechnical properties of the investigated area

The landslide site selected is studied for stabilizing the susceptible slope. Accordingly, for proposing the alternative landslide remedial solutions for the study site, a database of the material characterization and sub-surface information is required for the simulation of the study site through finite-element analysis. For the present study, the study site was investigated and a total of 11 borelogs data relevant to this site were adopted from the study of Kundu 2019 for the sub-surface detailing for finite-element modeling and analysis. Location of boreholes at study site is presented in Fig. 3. In the present study for generating the existing slope profile for the study site, the contour information was utilized from Kundu 2019. The contours were digitized and the same were utilized for the generation of TIN surface by utilizing the TIN tool in the GIS environment (Fig. 4a). The TIN surface was utilized for the generation of DEM by utilizing the conversion tool in the GIS environment (Fig. 4b). DEM has been utilized for generating the existing slope profile of the study site in the GIS environment. Survey of India (SOI) toposheet no. 78 B/5 has also been utilized to check the ground profile existed at that time (i.e., before slide). Slope steepness of the study site observed is in the range of 40°–45°, which also imparts high sliding force.

The geological profile of the study site showing general sub-surface stratification has been prepared using the existing slope profile and bore log data (Fig. 5). As per borelog data, overburden soils consisting of colluviums and residual soils were found at all the locations with varying thicknesses of up to 16.0 m. Immediately below the overburden, completely to highly weathered rock was encountered up to an average depth varying from 17.0 to 21.0 m and this highly weathered rock can be crumble with very little pressure.

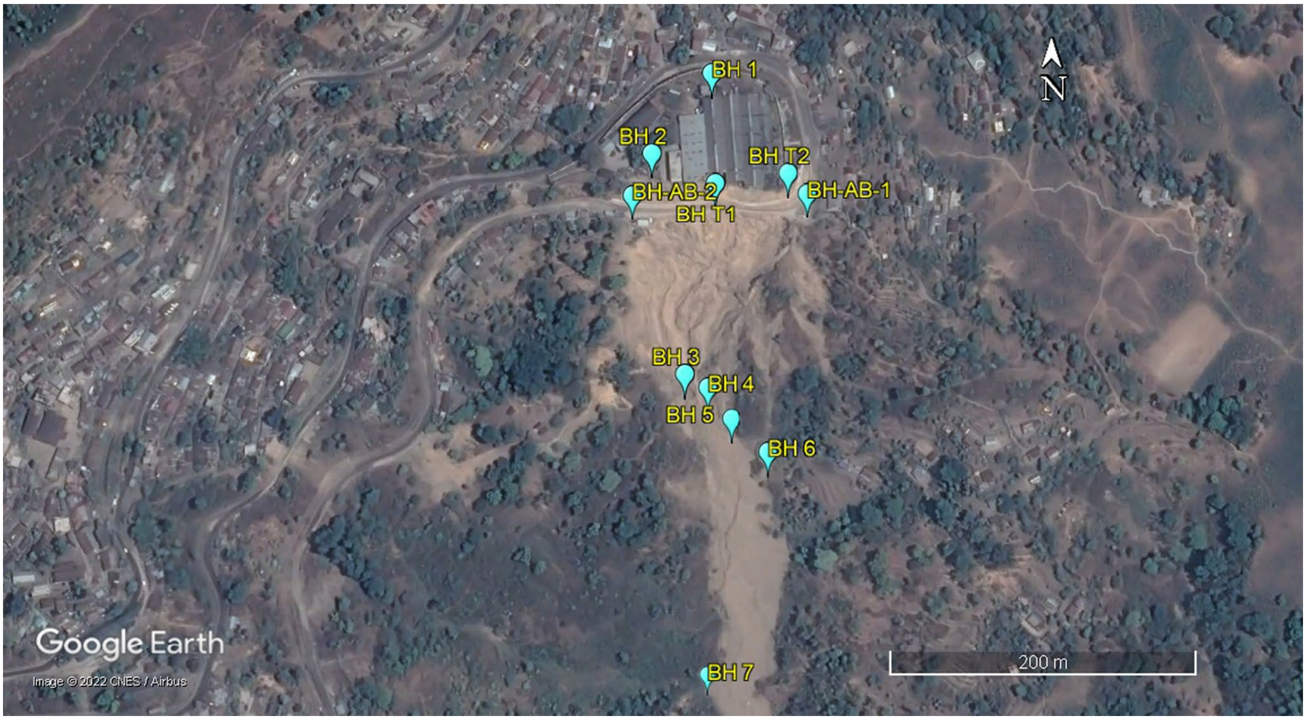


Fig. 3 Borehole location map of the study site

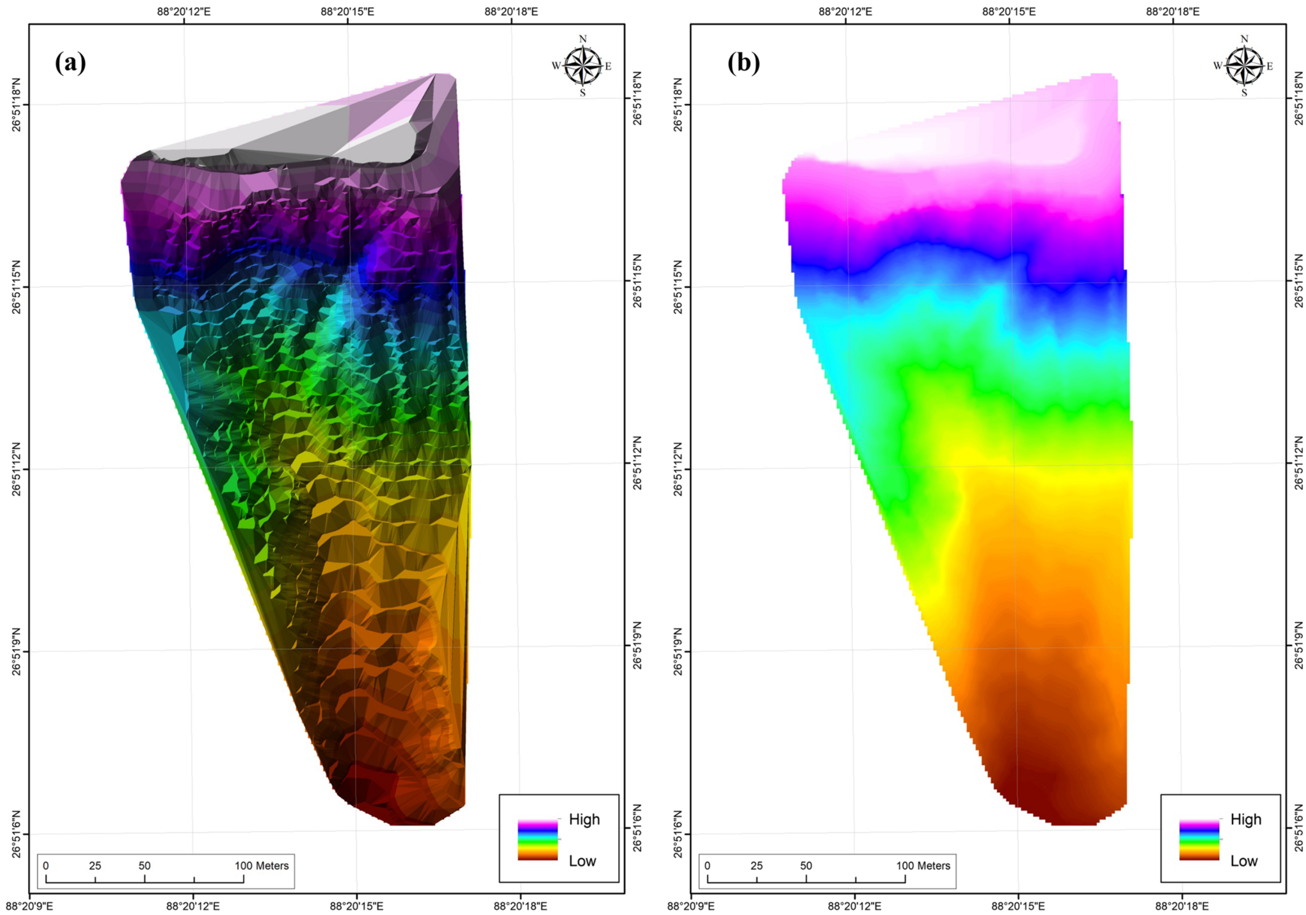
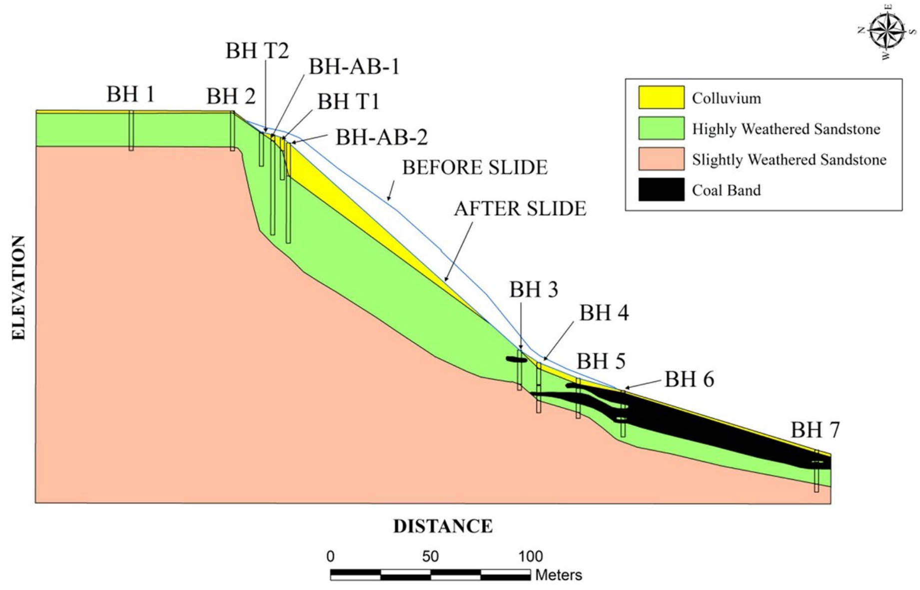


Fig. 4 **a** TIN surface generated by the contours and **b** DEM generated by the TIN surface of the study site

Fig. 5 Slope information of the study site



Immediately below the highly weathered rock, the slightly weathered rock was observed in all the boreholes, but not on surface. However, exposure was found in the slided zone. A coal band outcrop was observed just below the steep upper part of the slope failure area. The coal band lies in the lower area of the slope failure.

The visits were conducted to the study site, where the samples were collected for further analyses. Three samples were collected from three different locations of the study site and the average range of particles obtained for overburden was 71% sand, 28% silt, and 1% clay, whereas average range of particles obtained for completely weathered rock was 20% gravel, 49% sand, and 31% silt. The laboratory tests were performed to augment the data. For material characterization study, grain size distribution test for the classification of the material, direct shear test for the determination of shear strength parameters (cohesion, c', angle of internal friction, ϕ'), measurement of moisture content for providing an indication of engineering properties, and permeability test for calculating the coefficient of permeability were carried out for the collected samples. The results obtained from the laboratory experiments were utilized as an input parameter for the finite-element analysis of the study site. Overburden and completely weathered rock samples have been classified as well graded as per grain size analysis. The scree and overburden material are mostly sandy in nature with silt and negligible amount of clay constituents and are highly permeable. The shallow overburden comprising of loose colluvium were highly erodible, under the condition of intense rainfall.

In this study, all the four layers were assumed to be isotropic in nature. Mohr–Coulomb constitutive model has been used to simulate the colluvium layer. The strength characteristics of rock and coal materials highly depend on the degree of weathering they are subjected during their life. Hoek and Brown (1980) suggested the equivalent continuum concept to define the stress decrease phenomenon in the jointed rock mass failure. This method defines the uniaxial compressive strength that could not be considered in the existing Mohr–Coulomb method and allows accurate and simple representation of rock behavior, making it a widely used analysis method (Hoek and Brown 1980; Midas 2016). Coal, highly weathered and slightly weathered rock layers were modeled as generalized Hoek and Brown model. The model required weathering parameters, such as Geological Strength Index (GSI) (Hoek et al. 2013), intact rock parameter, disturbance factor, and uniaxial compressive strength (Karakas 2008). The GSI for these three layers were selected based on the rock mass structure and surface condition. The structure of the coal was observed to be highly disintegrated having poor-to-very poor surface conditions. In addition to the coal, other inherent materials were also modeled as generalized Hoek and Brown materials, where slightly weathered sandstone showed interlocked and partially disturbed structure and highly weathered sandstone showed blocky and disturbed structure, respectively. The highly weathered sandstone present at the site had a large number of closely spaced heavily jointed rock mass, whereas the slightly weathered sandstone base could be characterized as partially disturbed rock mass. Owing to the above inferences, the value of GSI was adopted (Hoek et al. 2013) for coal, highly weathered and slightly weathered sandstone layers, respectively. Sandstones belongs to the category of clastic sedimentary rocks, whereas coal is an organic non-clastic sedimentary material. The above facts were used to determine the intact rock parameter value (mi). The mi value was adopted (Karakas 2008) based on its material composition for coal, slightly weathered sandstone and highly weathered sandstone, respectively. The disturbance factor was considered (Karakas 2008) for both coal and highly weathered sandstone by assuming small-scale blasting at the study site, whereas the slightly weathered sandstone which lies well below the coal seam shall be comparatively less affected. All the three materials were considered similar to weak rocks; therefore, the UCS value for the coal was adopted in the

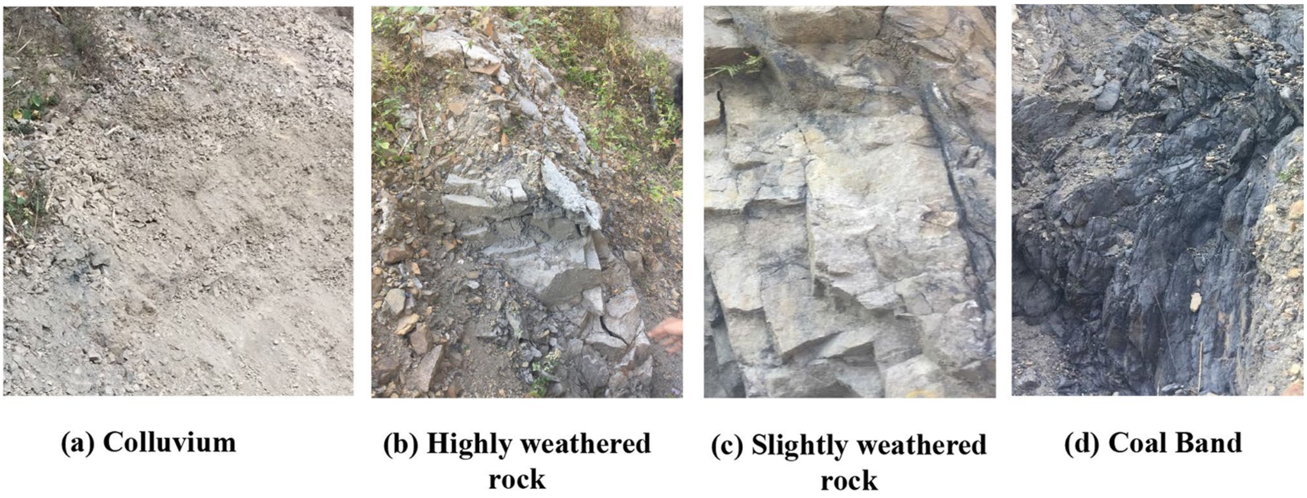


Fig. 6 Different inherent soil and rock materials of the studied slope

Table 1 Material properties of the study site

Material properties	Colluvium	Highly weathered rock	Slightly weathered rock	Coal	Source
Material model	Isotropic-Mohr–Coulomb	Isotropic-Generalized Hoek–Brown	Isotropic-Generalized Hoek–Brown	Isotropic-Generalized Hoek–Brown	
Coefficient of permeability, k_s (m/s)	1×10^{-5}	–	–	–	–
Cohesion, c (kN/m^2)	1	–	–	–	–
Friction angle, ϕ (°)	38°	–	–	–	–
Intact rock parameter (mi)	–	17	19	7	–
Geological Strength Index (GSI)	–	40	50	20	–
Disturbance factor (D)	–	0.7	0.5	0.7	–
Uniaxial compressive strength, σ_{ci} (kN/m^2)	–	10,000	25,000	5000	–
Coefficient of permeability, k_s (m/sec)	–	1.23×10^{-10}	1.23×10^{-10}	1×10^{-8}	Pino and Diaz (1998), Newman et al. (2016)
Modulus of elasticity, E (kN/m^2)	3,000,000	1,500,000	3,000,000	1,500,000	Kundu (2019)
Poisson's ratio	0.3	0.3	0.3	0.3	Kundu (2019)
Bulk unit weight, γ_b (kN/m^3)	18	25	26	18	Kundu (2019)
Saturated unit weight, γ_{sat} (kN/m^3)	20	26	26	20	Kundu (2019)

lowest range of weak rocks. Similarly, the UCS value for the highly and slightly weathered sandstone was considered (Karakas 2008) with relatively higher compressive strength compared to coal. The different inherent soil and rock materials of the studied slope are shown in Fig. 6 and their material properties are summarized in Table 1.

Slope stability analysis

In this study, slope stability analysis for the selected study site has been carried out using 2D finite-element method. Different methods along with or without ground improvement techniques like benching, retaining wall, soil nails, micropiles, shotcrete, and geogrid were attempted in this study for stabilizing the slope for the study site. Midas GTS NX 2016 commercial software has been utilized for carrying out the FEM analysis. Mesh sensitivity analysis was carried out for the study site to check the convergence of the FE analysis results. The Strength Reduction Method (SRM) analysis for the study site slope model before failure was carried out using a total of 11 different mesh sizes. Same mesh size was considered for all the material layers. The resulting factor of safety (FOS) was evaluated corresponding to each mesh size. The meshed geometry has different mesh sizes ranging from 1 to 20 m. The FOS value decreases from 1.03 to 1 as the mesh moved from a coarse size of 20 m to a fine size of 6 m. Beyond 6 m, the decrease in mesh size did not significantly influence the FOS values. As a result, mesh size of 5 m has been considered for all the analysis purpose to develop a balance between the accuracy and the computation time. Self-weight was considered as the destabilizing force acting on the slope.

The Strength Reduction Method is a way of carrying finite-element analysis of slopes to check their stability against failure (Chen 2017; Dyson and Tolooiyan 2018). This method is similar to other finite-element techniques, which depends on the numbers of iterations. With each iteration satisfying the stability criteria, the strength reduction parameters (c, ϕ) were gradually reduced until the slope failure takes place. The factor of safety and maximum horizontal displacement is considered to determine the stability of the slope.

Effect of rainfall on landslides

The study area belonging to the Darjeeling hill region receives abundant monsoonal rainfall averaging annually around 3000–4000 mm (NATMO 2015; Hait 2022), which also contributes in initiating the rainfall-induced landslides. The slides are generally shallow, confined within top overburden materials comprising of gravels and boulders in sandy matrix. Rainfall generally affects the landslides in two ways; (a) increases the shear stress (τ_d) due to increase in density and (b) decreases the shear strength due to rise in pore water pressure. Majority of the rainfall-induced landslides in the Himalayan region are shallow and involves failure of overburden materials comprising of colluviums and residual soils.

To understand the failure mechanism of the study site under intense precipitation conditions, an SRM-based slope stability analysis by incorporating the rainfall data for the study site was attempted. The intensity of rainfall data for the period of 10-Aug-2018 to 7-Sep-2018 (Kundu 2019) has been considered in this study for slope stability analysis. The rainfall data were simulated as varying nodal heads with respect to time in days on the sloping surface. The drainage of the nodal heads specified depends on the coefficient of permeability value of the inherent materials. The coefficient of permeability in all the directions was considered to be the same.

Results and discussion

Slope stabilization methods

This section discusses about the potential slope stabilization methods which were simulated along with the current slope profile to study their effect on the FOS of the study site. The initial FOS from SRM analysis for before landslide case was computed as 1, which also indicates that the initial slope is bound to fail at some point of time. Further after incorporating the rainfall effect in the analysis, the FOS for before landslide case was reduced far below 1. The failure surface obtained in the present study was also found in close agreement with the actual slip surface along which the landslide took place. For the post-landslide case, the FOS from SRM analysis for unreinforced case was 1.25. By including the rainfall analysis in post-landslide case, the FOS again reduced to 1.13, thus highlighting the immediate need to implement the suitable ground improvement (GI) techniques for suggesting the remedial measures and stabilizing the study site. Accordingly, four slope stabilization methods with different combinations are attempted in this study to understand the behavior of the support system.

Stepped cut

The bench slope profile is a technique in which the overall slope is divided into multiple small slopes. It reduces the driving forces above the failure surface by reducing the weight of the slope (Alfat et al. 2019; Mekonnen 2021). In this study, initially, the stepped cuts were considered for stabilizing the slope surface by modifying its geometry. The steps or benches were considered in such a way that minimum excavation or filling activities and transportation of fill materials from outside shall be required and the colluvium layer was divided into four steps. The FOS from SRM analysis with the considered configuration of stepped cuts was computed as 1.31, and when the rainfall effect was included in the analysis with the considered configuration of stepped cuts, the FOS was reduced to 1.2. Generally, a slope is designed for a minimum factor of safety not less than 1.5 (Duncan and Wright 2005; Ranjan and Rao 2007). Hence, to stabilize the study site slope, other slope stabilization combinations are attempted.

Stepped cut and retaining wall at bottom

The stepped cut increases the FOS value only by a relatively small amount for both with and without rainfall analysis cases. Thus, to further improve the FOS and reduce the displacements, a gravity retaining wall was included near the end of the colluvium layer along with stepped cuts. The retaining wall with the dimensions of 12 m height and 8.4 m wide base of footing was assumed to be made of concrete. Concrete was considered as an isotropic-elastic material and the material properties adopted in this study like modulus of elasticity, Poisson's ratio, and unit weight of concrete used for retaining wall were reported in the literature (Usluogullari et al. 2016).

The FOS was expected to rise considerably with the inclusion of retaining wall along with stepped cuts. However, the change observed was insignificant as the FOS increases from 1.31 to 1.35 (Fig. 7) for without rainfall and from 1.20 to 1.23 for with rainfall cases. These results can be attributed as the entire base of the gravity wall was lying on the colluvium layer and thus can slip or overturn along with the material or because of the upward shift in the potential failure surface toward the stepped cuts. Therefore, other combinations are also attempted.

Stepped cut and retaining wall at bottom supported by micropiles and soil nails

Micropiles are small diameter piles that are used for foundation underpinning and new construction. Micropiles are generally used in tension and compression as load-bearing tendons. Effectiveness of micropiles as a ground improvement technique was also evaluated and discussed by Gupta and Chawla 2022. Instead, soil nails are typically used in steep slope or wall stabilization where the nails are installed beyond the soils' failure plane (angle of internal friction). Hence, micropiles and soil nails have advantages but difference in their applications. An attempt was made with the stepped cuts and gravity retaining wall along with concrete micropiles provided at the base of the retaining wall and soil nails provided to support the wall portion, to prevent

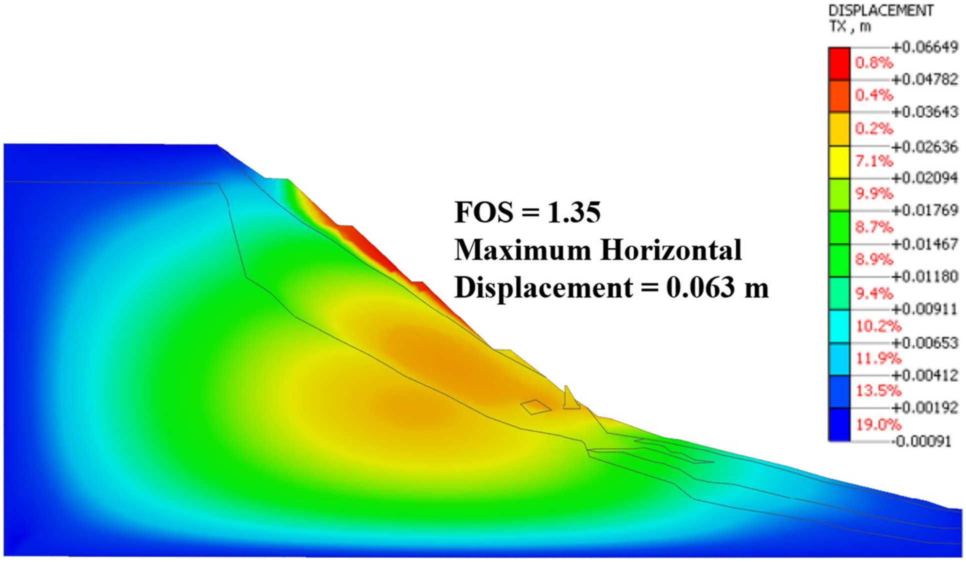


Fig. 7 FEM results for slope stabilization technique—(option 2) stepped cuts along with retaining wall

the retaining wall from slipping downwards along with the colluvium layer.

Ten micropiles were considered having an equal spacing of 0.8 m. Micropiles were assumed as 1 D beam element having a solid round section with a diameter of 0.25 m and length of 30 m, to ensure that the micropiles should cross the highly weathered rock and have anchorage of hard strata. These dimensions also satisfy the permissible limits of Federal Highway Administration (FHWA Micropiles Design and Construction, Publication No. FHWA NHI-05-039, December 2005). Eleven soil nails of 28 mm diameter with 0.9 m soil nail spacing were considered to provide support to the wall portion. The soil nails were inclined at an angle of 10° with the horizontal axis and was assumed as 1 D truss element made of isotropic-elastic steel material. The material properties adopted in this study like modulus of elasticity, Poisson's ratio, and unit weight of steel used for soil nails were reported in the literature (Qureshi and Salim 2018). Despite the application of soil nails and micropiles in retaining wall, the FOS remains 1.35 and 1.23 for without and with rainfall cases. This also indicates that for further improvement in factor of safety, upper stepped region shall also require reinforcement. However, a reduction in retaining wall displacement value was observed due to the extra reinforcement provisions (Fig. 8).

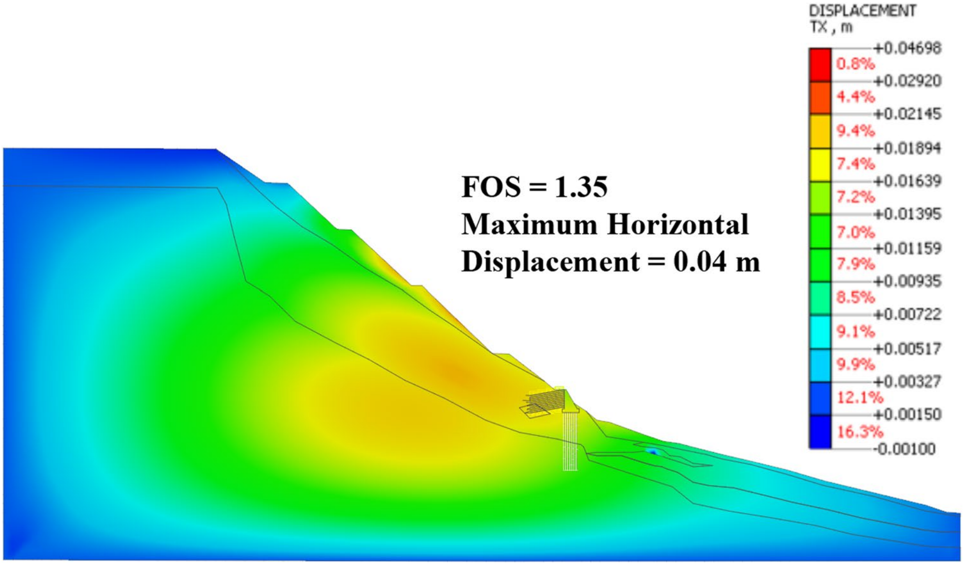


Fig. 8 FEM results for slope stabilization technique—(option 3) stepped cut and retaining wall at bottom supported by micropiles and soil nails

Combination of soil nails with shotcrete and geogrid on stepped cut slope face and retaining wall supported by micropiles and soil nails at the bottom

To further improve the FOS and reduce the displacement, soil nails with the same configuration as before were provided on the sloping surface of the stepped cuts along with micropiles and soil nails at the bottom of retaining wall. In addition, the soil nails on stepped cut were provided along with shotcrete and geogrid layers on the sloping face. The benefits of geosynthetics reinforcement have also been discussed by various researchers like Alston (1991), Sowmiya (2013), Chawla and Shahu (2016a, b), Patil et al. (2016), Banerjee et al. (2018, 2020a, 2023; b), Chawla et al. (2019a, b, 2021), Zhang et al. (2020), Suresh and Chawla (2022), Vadavadagi and Chawla (2023). The material properties adopted in this study like modulus of elasticity, Poisson's ratio, and unit weight of shotcrete were reported in the literature (Palassi and Asadollahi 2004), whereas the properties adopted in this study like modulus of elasticity and shear modulus of geogrid were reported by Chawla and Shahu 2016b. Figure 9 depicts the line diagram, constructed faces, meshed geometry, applied auto-boundary condition, and self-weight, respectively.

With this combination, the FOS has been increased drastically to 1.6 and 1.85 for with and without rainfall cases and the displacement has also been reduced significantly. Hence, the slope can be considered as stable with the application of combination of soil nails with shotcrete and geogrid on the stepped cut slope faces and retaining wall supported by micropiles and soil nails at the bottom (Fig. 10).

Parametric study

Parametric study was carried out to investigate the influence that some key parameters of the model shall have on the quality of the results and to identify the optimum configuration of the suggested slope stabilization techniques. Therefore, four parameters have been varied and their influence on the FOS has been studied.

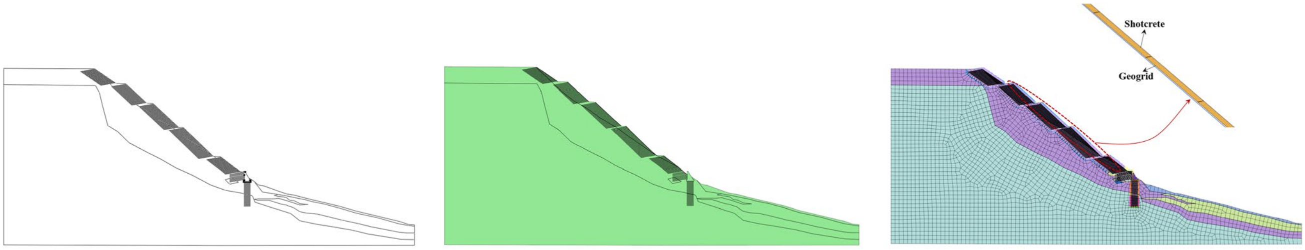
i. Soil nail diameter.
ii. Micropile diameter.
iii. Soil nail length.
iv. Soil nail spacing.

Soil nail diameter variation

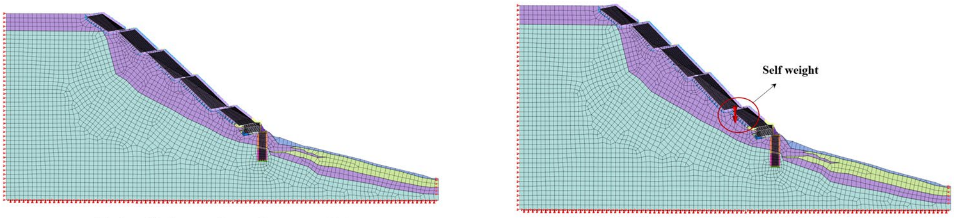
Soil nail diameter was varied from 8 to 32 mm considering an interval of 2 mm. The FOS increases with the increase in soil nail diameter up to 28 mm. Beyond 28 mm diameter, a decrease in FOS was observed, thus suggesting the optimum soil nail diameter of 28 mm for the present study (Fig. 11).

Micropile diameter variation

Micropile diameter was varied from 125 to 250 mm considering an interval of 25 mm. The FOS increases continuously with the increase in micropile diameter up to the maximum permissible value of 250 mm (Fig. 12). Thus, suggesting the optimum micropile diameter of 250 mm for the present study.



(a) Line diagram (b) Face diagram (c) Meshed geometry with Shotcrete and geogrid



(d) Applied auto boundary condition (e) Self weight

Fig. 9 FEM results for slope stabilization technique: **a** line diagram, **b** face diagram, (**c**) meshed geometry with shotcrete and geogrid, **d** applied auto-boundary condition, and **e** self-weight

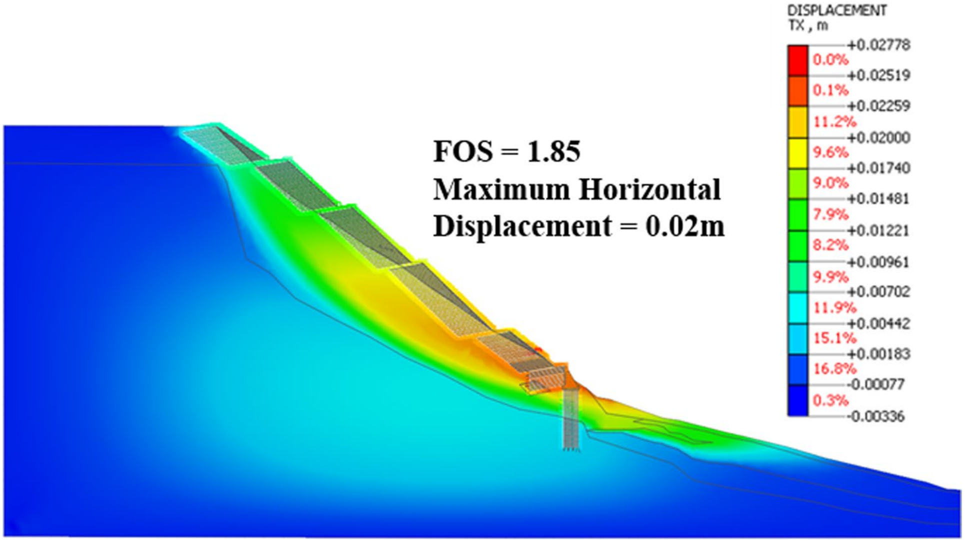


Fig. 10 FEM results for slope stabilization technique—(option 4) combination of soil nails with shotcrete and geogrid on stepped cut slope faces and retaining walls supported by micropiles and soil nails at the bottom

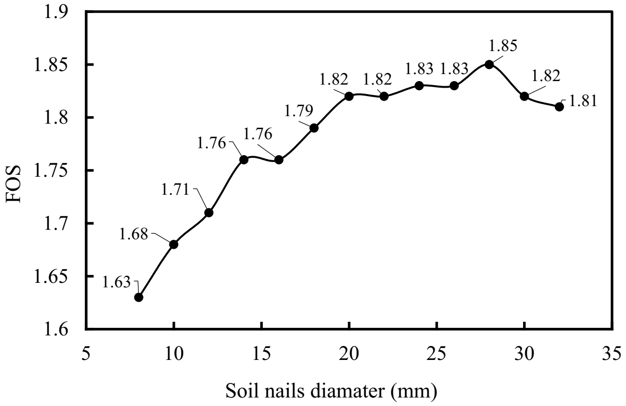


Fig. 11 Parametric analysis illustrating the variation of FOS with soil nails diameter

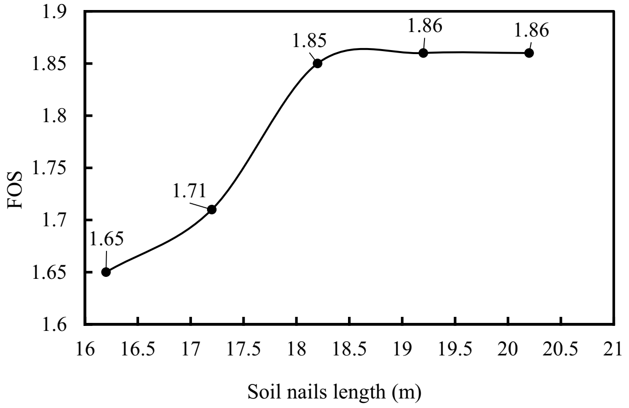


Fig. 13 Parametric analysis illustrating the variation of FOS with soil nails length

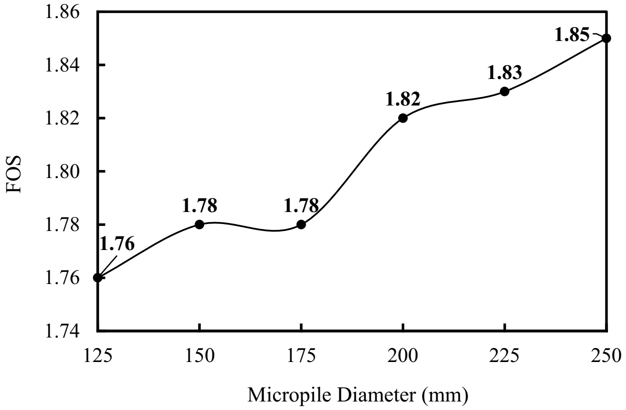


Fig. 12 Parametric analysis illustrating the variation of FOS with micropile diameter

Soil nail length variation

Soil nail length was varied from 16.0 m to 20.0 m considering an interval of 1 m. The FOS increases continuously with the increase in soil nail length up to 19.0 m. Beyond 19.0 m, the change in FOS was negligible (Fig. 13). Thus, suggesting the optimum length of 19.0 m for soil nails in the present study.

Soil nail spacing variation

Three soil nail spacings 0.7, 0.9, and 1.1 m were considered for the parametric study, as the stability of slope decreases proportionately with the increase in spacing. The FOS

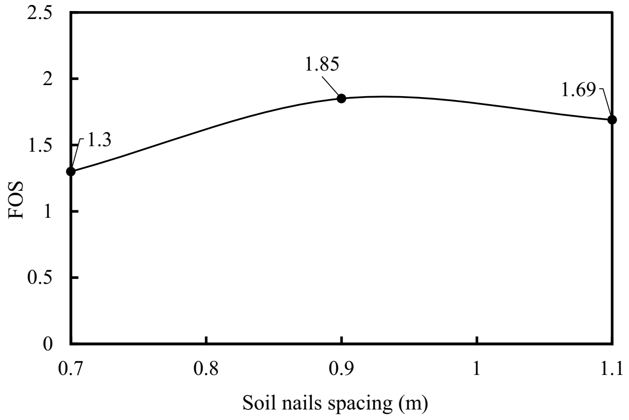


Fig. 14 Parametric analysis illustrating the variation of FOS with soil nails spacing

increases till the spacing of soil nails was increased up to 0.9 m, but decreases afterward (Fig. 14). Accordingly, the maximum FOS value was obtained at a spacing of 0.9 m. Thus, suggesting the optimum spacing of 0.9 m for soil nails in the present study.

Conclusions

In this study, slope stabilization analysis was performed and the results are summarized in Table 2, which presents a comparison of all the four combinations factor of safety and maximum horizontal displacement corresponding to with and without rainfall case scenarios. The FOS changes with the incorporation of different combination of ground improvement and reinforcement techniques. The suggested ground improvement technique increases the study site slope FOS from 1.13 to 1.6 for the rainfall scenario and from 1.25 to 1.85 for the scenario without rainfall. In addition, the maximum horizontal displacement value was also reduced from 0.13 m to 0.02 m.

Based on the results of the FEM analysis, the following conclusions are drawn:

- The study site which has witnessed catastrophic landslides in the past was vulnerable to slope failure. The strength and safety of the slope was also under doubt and uncertainty exists. Accordingly, for minimizing the losses, detailed study of the study site has been undertaken for proposing the alternative landslide remedial solutions and safer design.
- For the selected landslide site, the initial FOS analyzed for before landslide unreinforced case was 1.0 and it was observed that the initial slope was bound to fail at some point of time. Further, the FOS reduced to far below 1, when the rainfall effect was included in the analysis. The failure surface obtained in the present study is also in close agreement with the actual slip surface along which landslide took place. Post-landslide unreinforced case, the FOS from SRM analysis was obtained as 1.25. By including the rainfall analysis, again, the FOS reduced to 1.13, thus emphasizing the urgent need to implement some suitable ground improvement technique for stabilizing the study site.
- Comparison of all the four slope stabilization methods was introduced with the understanding of behavior of support system. Stabilizing the slope by modifying its geometry with the application of benching was attempted and the FOS value was analyzed as 1.31. With the application of rainfall effect in SRM analysis, the FOS further reduces to 1.2. Hence, other slope stabilization combinations were, therefore, attempted in an effort to stabilize the slope.
- The FE analysis also highlights that individual use of gravity retaining wall is inefficient. However, retaining wall supported with soil nails and micropiles can be provided at the end of colluvium layer, to partially retain the debris which may fall from the top as a result of toppling failure of the slope.

Table 2 FOS and maximum horizontal displacement values for different cases

Analysis case	FOS (without rain, with rain)	Maximum horizontal displacement (m)
Unreinforced—before landslide	1.00, < 1.00	0.15
Unreinforced—after landslide	1.25, 1.13	0.13
Stepped cuts	1.31, 1.20	0.09
Stepped cut and retaining wall at bottom	1.35, 1.23	0.06
Stepped cut and retaining wall at bottom supported by micropiles and soil nails	1.35, 1.23	0.04
Combination of soil nails with shotcrete and geogrid on stepped cut slope faces and retaining walls supported by micropiles and soil nails at the bottom	1.85, 1.6	0.02

- For stabilizing the slope, the FOS value analyzed for most of the individual ground improvement techniques like stepped cut and retaining wall with and without soil nails and micropiles at bottom was below 1.5, thus making them unsuitable for implementation. With the application of rainfall effect in SRM analysis, the FOS reduces further, thus making the individual reinforcement measure inefficient in improving the FOS.
- Furthermore, results of the parametric study suggests that soil nails of length 19.0 m, diameter 28 mm, and spacing 0.9 m were the most optimum configuration which can be used in the given scenario for the study site. The parametric study also suggests that micropiles of diameter 250 mm can be considered for providing the support to the gravity retaining wall, which lies on top of the colluvium layer. Advantages of the incorporation of soil nails, micropiles, shotcrete, geogrid, retaining wall, and their potential combinations are also discussed.
- For the study site, the combination of soil nails with shotcrete and geogrid on stepped cut slope faces and retaining walls supported by micropiles and soil nails at the bottom can be considered as the most effective alternative slope stabilization measure which can safeguard the slope in both with and without rainfall case scenarios. By adopting this combination, higher factor of safety for with and without rainfall case and lower displacement was achieved.
- In the present study, only the self-weight along with the triggering factor like rainfall have been considered as the destabilizing forces acting on the study site. For the future research work, the factors like earthquake, railroad traffic, etc. can also be incorporated and analyzed.
- Laboratory scaled model tests can also be conducted in the future studies to study the application of various ground improvement techniques for the study site to enhance and validate the proposed design procedure developed through the FEM analysis of this study. Slope stability analysis method considering the non-uniform characteristics of soil and rocks can also be analyzed in the future studies.

Author contributions All authors contributed to the study. AC, RA, SC and KS contributed in writing the manuscript. SM helped in data collection. SP helped in English writing. All authors read and approved the final manuscript.

Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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