Evaluation and Remedial Measures for Unstable Slopes at Gagangir Sonmarg, J&K: A Case Study

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1 Introduction

Uncertainties in geotechnical Engineering are inevitable, often we see considerable variability in soil properties within a short-range thereby complicating analysis and design of structures like dams, buildings, etc. [1]. Slopes are an important part of geotechnical studies owing to their relation to human life and property. There are many methods available for analysis of failure susceptible slopes; however, the precision of analysis, mechanism of failure, and slip surface profile typically depend on the selection of the method for slope stability evaluation [2]. The factor of safety is used as a principal index for determining the failure vulnerability of a slope. Limit equilibrium methods and finite element methods are most popular methods for analysis each having advantages and disadvantages [3].

Limit equilibrium (LE) methods use Mohr–Coulomb failure criterion for evaluation of shear strength along a sliding surface and under this criterion failure does not occur due to normal stress or shear stress alone but due to a combination of both [3]. In limit equilibrium method, after working out slope geometry and soil properties, a comparison is made between forces resisting failure and forces causing failure to calculate Factor of Safety (FOS) or in other words, the FOS is calculated as the ratio of shear strength of the soil and mobilized shear strength of soil [3–5]. In LE method, slip surfaces (Circular or Non-circular) are divided into vertical slices, and then static equilibrium conditions (Force and Moment equilibrium) are used to calculate stresses and FOS on each slice [6, 7]. As of now, we have many LE methods available and these include Fellinius, Bishop, Sarma, Janbu, Morgenstern-Price method, etc., with each one having a distinct set of properties.

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In this study, advanced Bishop's method has been used through GEO-5 software for slope stability analysis.

The principal factors on which the instability of terrain depend are geologic, geomorphologic, drainage, usage of the land, anthropogenic activity, and climatic conditions, some of these factors like drainage, slope geometry, etc., can be determined rather easily, however, greater uncertainty is associated with factors like rainfall and earthquake anticipation [8, 9]. The above-mentioned factors don't act in isolation rather a combination of some factors cause failure [10]. Instability of natural and built-in slopes has been a serious geotechnical challenge, particularly in the Sonmarg area of the mountainous Kashmir region, where a large number of landslides and slip surface failures are experienced every year. The area exhibits undulating and rugged topography with highly mountainous terrain having little vegetation, the mountains are composed of sedimentary and igneous rocks that are being subjected to severe cold weathering and the altitude varies between 2500 and 3800 m above MSL [11]. Hill faces are made up of high-rocky escarpments, steep slopes, and moderate–Gentle slopes made up of slid debris. A good comprehension of analytical methods, tools of investigation, and that of stabilization techniques are important for solving slope instability issues [3]. A quantitative, as well as qualitative assessment of the safety factor, is important when decisions are made. It can be said that the primary aim of slope stability analysis is to work out the safe and economic design of excavations, embankments, and earth dams.

2 Scope and Site Location

Like other mountainous regions, Jammu & Kashmir has large variations in its topography. The high Himalayas on the periphery, the gentle to steep mountains in the middle, and the flat land on the interior have provided both opportunities and challenges [11]. Kashmir valley is connected to the Ladakh region through national Highway-1 through Srinagar-Sonmarg-Gumri road and this road remains closed for traffic for around 6-months per year owing to frequent blockades due to landslides. Alam et al. [12] prepared a landslide susceptibility zonation map of this area and from that it can be inferred that this particular road stretch is susceptible to moderate to high landslides. To ensure all-weather connectivity of the Ladakh region with Kashmir valley, the government started a project couple of years back which includes the construction of several tunnels and new roads through this mountainous terrain. One such under-construction road connects Z-Morh tunnel with the existing national highway and this road for the tunnel portal takes off from chainage km 69 + 00 of NH-1D Srinagar-Leh road to the western portal and makes a total length of 3.75 km. During my first site visit, cutting of slopes was completed for the initial kilometre and final kilometre of the proposed 3.75 km approach road of the Z-Morh tunnel. Soil samples were collected from two sites located at chainage 600, i.e., 600 m from the start point (Fig. 1) and chainage 700 (Fig. 2), i.e., 700 m from the start point of the road as these two points seemed very much susceptible to failure.

Fig. 1 Slope profile at Chainage-600

The scope of this study involves understanding the influence of factors impacting slope stability and how they govern the design of various stabilization methods. It also helps us in understanding the economic perspective and practical feasibility of different slope stabilization measures. This project started with a field visit to the site, i.e., Gagangir, Sonmarg for the collection of soil samples both disturbed as well as undisturbed and also for the collection of relevant data like the height of slope, slope angle, water table, geologic, and hydrologic data about the location. The research methodology adopted for this project was multi-phased, and in the initial phase laboratory, tests were conducted as per the Indian-Standard Codes for the evaluation of basic soil properties especially cohesion, angle of internal friction, unit weight, etc. Then, the next phase involved the usage of these properties as basic input parameters in the GEO-5 software for analysis of slopes. It's imperative to mention here that GEO-5 uses limit equilibrium for analysis and is easy to use the software. In the final stage, various slope models were analysed by using different

Fig. 2 Slope profile at Chainage-700

stabilization techniques for these unstable slopes and the factor of safety for all these configurations was evaluated. After considering the feasibility, practicality, and economy of all these measures, suggestions regarding the stabilization measures were made to the executing agency in the final report.

3 Laboratory Investigations

After collecting disturbed and undisturbed samples from the site, exhaustive laboratory testing was done for the evaluation of basic soil properties following the procedures mentioned in Indian standard Codes [16]. All the collected samples were oven-dried for 24 h at 105–110 °C temperature. Then Particle Size distribution [IS-2720-4(1985)] as shown in Fig. 3, Specific Gravity (IS-2720-3-1), Plastic & Liquid limit (IS-2720-5), Direct Shear test (IS-2720-13), and Triaxial test (IS-2720-11) were conducted to determine specific gravity, unit weight, moisture content, cohesion, and angle of internal friction, all of which are important for slope stability analysis. All these parameters are the basic input factors for the GEO-5 software to complete the analysis. These parameters have been tabulated in Table 1.

It is noteworthy to mention that Direct Shear tests on the remolded soil samples were initially performed to work out the cohesion and angle of internal friction as in

Table 1 Soil properties at two locations

Soil properties		Soil 1 (Chainage-600)	Soil 2 (Chainage-700)
Specific gravity		2.71	2.67
Moisture content (%)		19.4	16.2
Unit weight (kN/m^2)		19.00	18.3
Liquid limit (%)		36.5	33.1
Plastic limit (%)		24.7	23.8
Cohesion (kPa)	DST (Direct shear test)	27	23.5
	Triaxial	20	17
Angle of friction	DST (Direct shear test)	36.3	41.2
	Triaxial	28.4	33.5

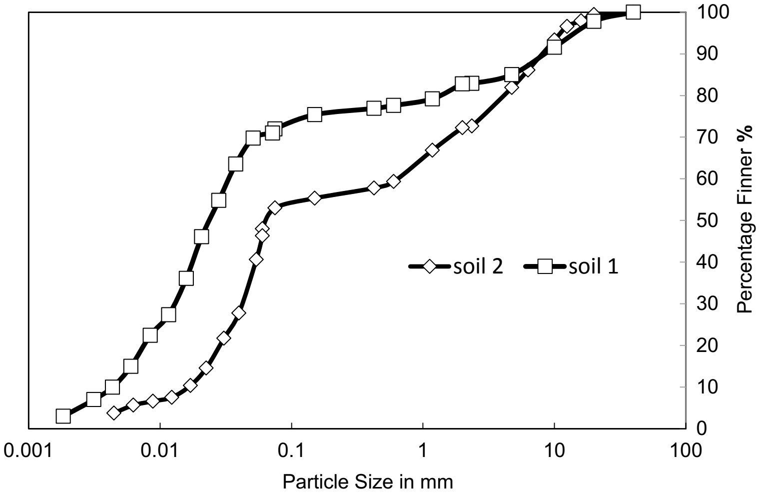


Fig. 3 Grain size distribution of soil samples

Fig. 4; however, the values of these two parameters were on the higher side quite contrary to the stability of the slopes, therefore, Triaxial tests were carried out under consolidated-undrained conditions to get more precise values of cohesion and angle of friction as shown in Fig. 5, and later these values were used for the slope stability analysis purposes. Also, Fig. 6 shows the specimen shape after shearing in the Triaxial test. The graphs corresponding to the above-mentioned investigations and the resulting parameters have been provided below.

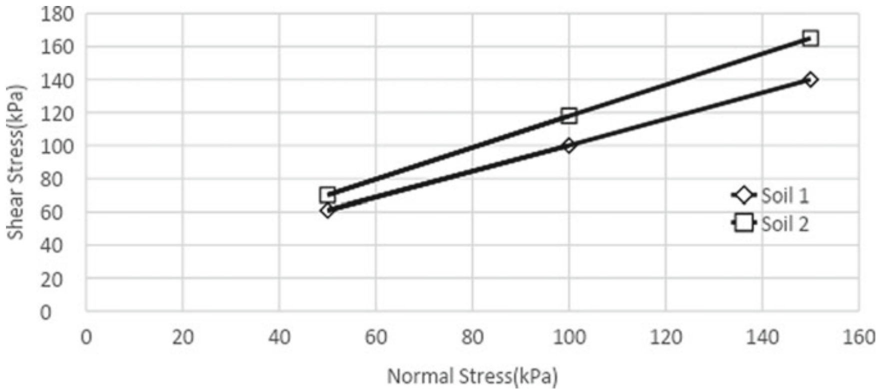


Fig. 4 Plot for direct shear test of soil samples

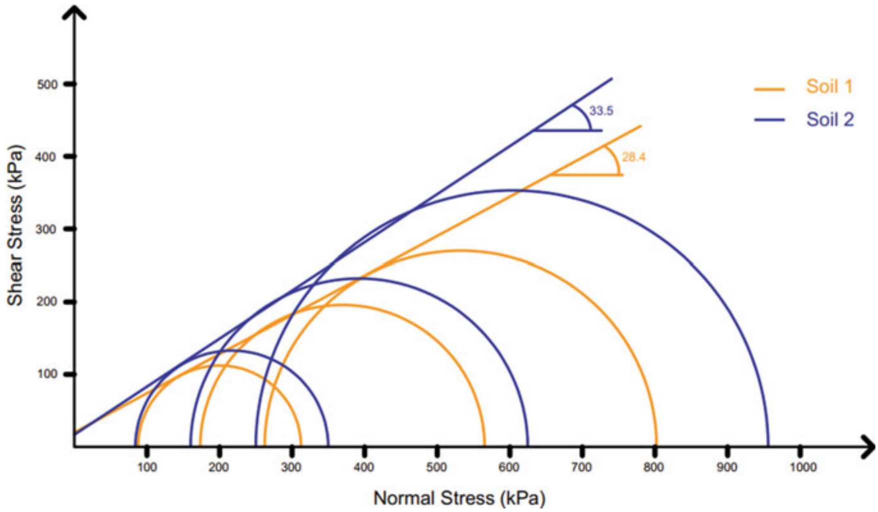


Fig. 5 Mohr circles of soil samples (Triaxial test)

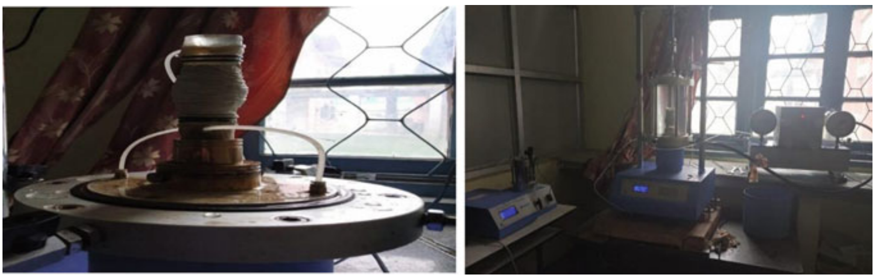


Fig. 6 Specimen shape after shearing in the Triaxial test

4 Analysis and Discussions

Analysis of slopes has traditionally been carried out by limit equilibrium-based Bishop's method which in principle depends on the static equilibrium of forces and moments [17]. After evaluating the basic properties of soil at a chosen location GEO-5 software was used for analysis purposes and also for the design of slope stabilization techniques [13]. The factor of safety was evaluated for multiple stages. The factor of safety (FOS) was evaluated for the existing condition as shown in figure, then the slope was varied by changing the cutting angle from 90° to 50° and subsequently, FOS was checked for each variation using GEO5, and also the cutting volume was calculated in AUTOCAD. Finally, either retaining wall/soil nailing or both were used as stabilizing measures, and the consequent increase in FOS was evaluated. Results of all these stages for two locations have been provided as follows.

4.1 Evaluation of Slope at Chainage 600 (Soil-1)

The existing slope profile at this location as shown in Fig. 7 has been created in AutoCAD wherein the height, width, slope angle, and other details are visible. The soil properties used as input parameters for GEO-5 analysis have been mentioned in the laboratory investigations section preceding this part.

4.1.1 Variation of FOS Due to Change of Cutting Angle

After varying the angle of cutting from 90° to 50° and calculating the cutting volume, it was found that FOS increases from 0.80 to 1.17. Considering the economic and safety perspective, it was found that a cutting angle of 60° will be

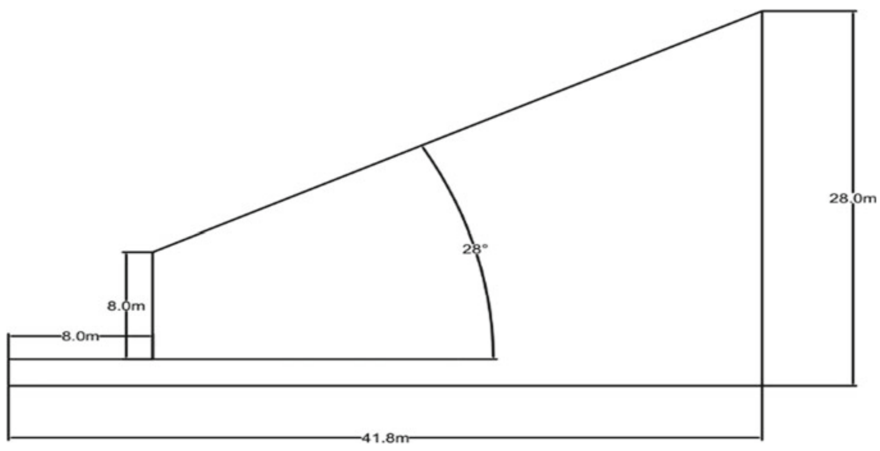


Fig. 7 Existing slope profile

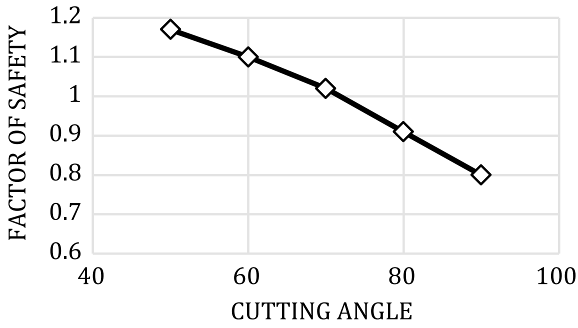


Fig. 8 FOS versus cutting angle

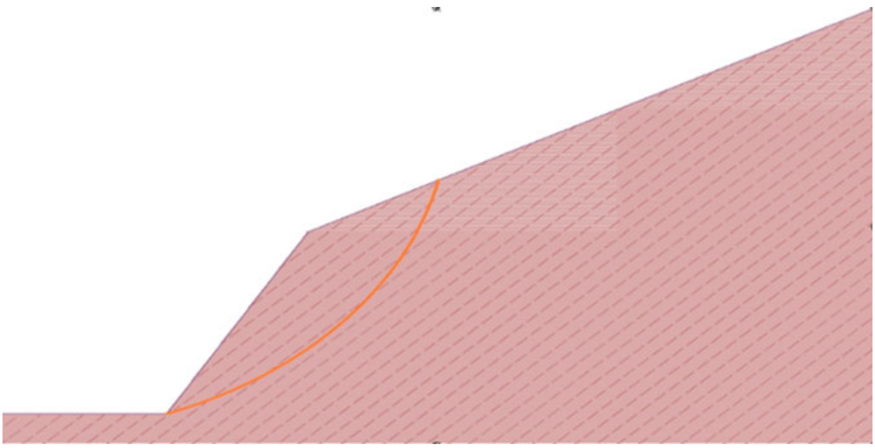


Fig. 9 GEO-5 profile of slip surface at 60° angle

adopted to have significant FOS (**1.10**) and lesser cutting volume. The following graphical plots show the AutoCAD layout (Fig. 10) of the slope, a variation of FOS with cutting angle (Fig. 8), and GEO-5 critical slip surface profile (Fig. 9).

4.1.2 Variation of FOS Due to the Placement of a Retaining Wall

After fixing the angle at 60°, the concrete retaining wall with a unit weight of 24 kN/m^3 was provided at the base and the same was modeled in GEO 5. During the modeling in GEO-5, the height and unit weight of retaining wall (RW) was varied [14], and a corresponding change in FOS was noted accordingly. Figure 11 shows the AutoCAD layout of a slope with RW, a variation of FOS with Height of retaining Wall (Fig. 12), and GEO-5 critical slip surface profile (Fig. 13).

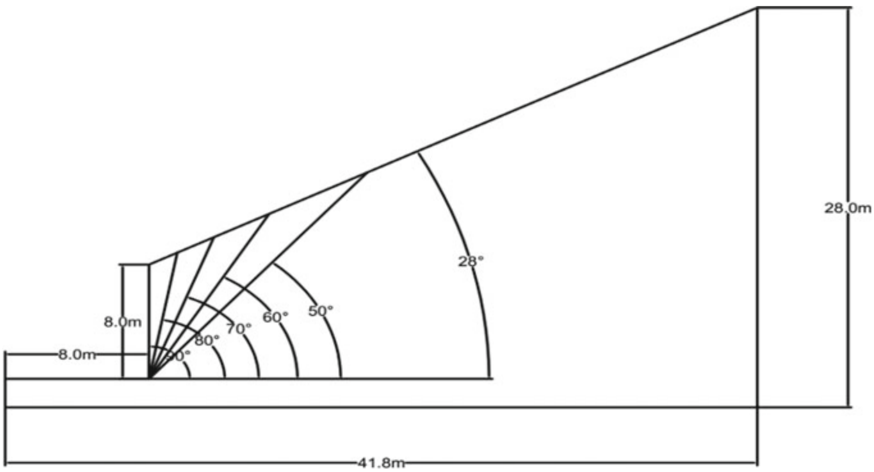


Fig. 10 Proposed geometric profile of slope at Ch-600

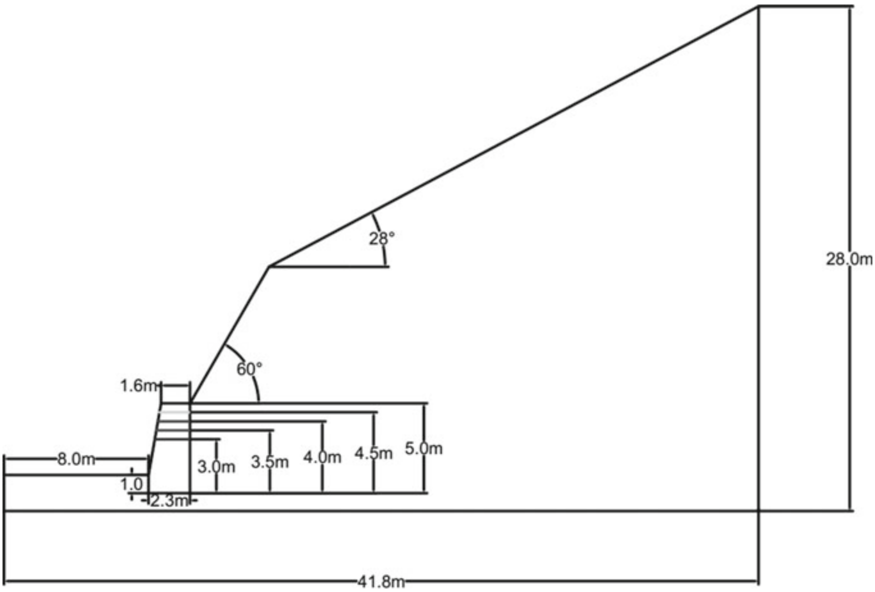


Fig. 11 Slope profile with retaining wall at 60^o angle

4.1.3 Increase in Slope Stability Due to Soil Nailing

As is evident from the above results that the increase in factor of safety due to construction of retaining wall is 1.36 which is less than 1.50 and is insufficient considering the stability of the slope, thereby necessitating additional stabilization

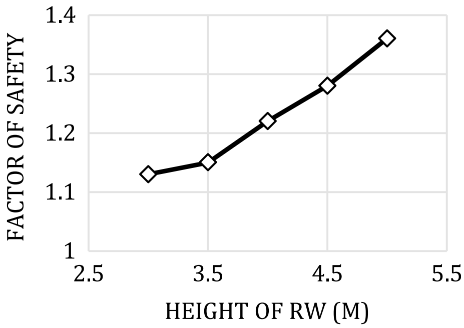


Fig. 12 FOS versus Height of RW

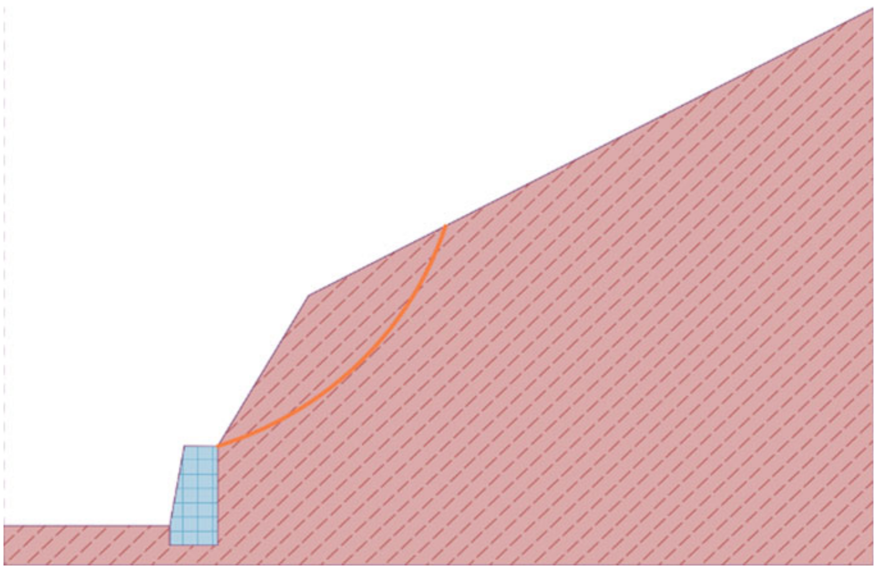


Fig. 13 GEO-5 profile of slip surface with RW

measures like soil nailing, anchoring, etc. However, after evaluating multiple measures based on economy, suitability, stability, ease of construction, etc., at the site, it was found that soil nailing is the only realistic option available which covers all these parameters, i.e., soil nailing apart from being economical also provides for increased safety and ease of construction. The design of soil nailing herein includes optimization of length, strength, inclination, and diameter of soil nails following the codal provisions [15]. Figure 14 shows the AutoCAD layout of a stabilized slope profile and GEO-5 slope profile (Fig. 15). The FOS increased to 1.60 well greater than 1.50 after soil nailing, soil nails with following specifications have been provided after optimization:

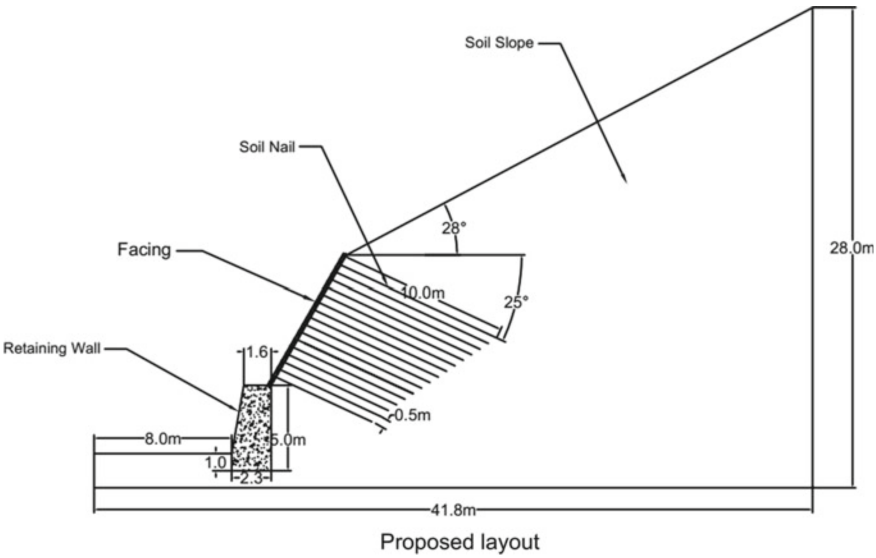


Fig. 14 Final proposed profile of stabilized soil slope at Ch-600

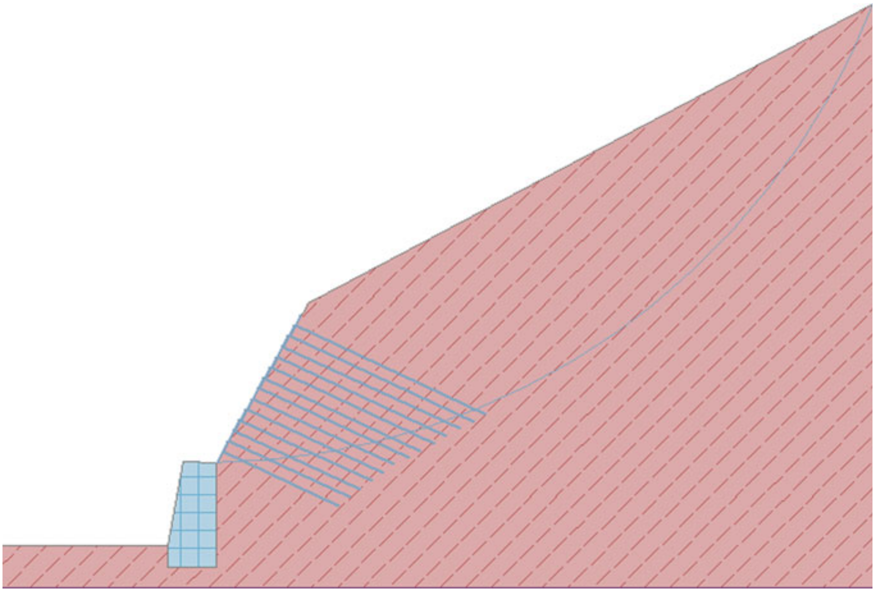


Fig. 15 GEO-5 profile of slip surface of slope with RW and soil nailing

Diameter = 20 mm, Angle of Inclination = 15°, Type of Steel = Fe-415 bars, Spacing = 0.5 m, Length varies from 10 m at top to 6.10 m at bottom, Total bars in 2-D plane = 13.

After analysing the FOS values for different cutting angles, a cutting angle of 60° was provided which led to an increase in overall FOS up to 1.10, however, any further cutting would have been uneconomical. Therefore, a retaining wall of 5-m height was provided which increased FOS to 1.36, still below a safe value of 1.5. Finally, soil nailing was done on the above the retaining wall for further stabilization of slope, and after optimization, soil nailing increased FOS to 1.60 well above the safe value of 1.5.

4.1.4 Impact of Earthquake on Slope Stability

For all the above-mentioned stages of slope stabilization, the pseudo-static analysis was done to check for the impact of the earthquake on stability because the site is located in an earthquake-prone area and comes under zone 4 of classification. The coefficients of acceleration in the horizontal direction are taken as 0.11 and that in vertical direction 0.08, respectively. The results from the analysis are given below, it can be inferred that slope cut at 60° has FOS less than 1.00 hence is unstable in case an earthquake strikes, whereas for slopes with retaining wall and soil nails FOS is well above 1.00 making these slopes quite stable, and the variation of FOS of slope under different earthquake conditions has been given in Table 2.

4.2 Evaluation of Slope at Chainage 700 (Soil-2)

The existing slope profile at this location as shown in Fig. 16 has been created in AutoCAD wherein the height, width, slope angle, and other details are visible. The soil properties used as input parameters for GEO-5 analysis have been mentioned in the laboratory investigations section preceding this part.

4.2.1 Variation of FOS Due to Change of Cutting Angle

After varying the angle of cutting from 90° to 50° and calculating the cutting volume, it was found that FOS increases from 0.86 to 1.25. Considering economic and safety perspective, it was found that a cutting angle of 65° will be adopted to

Table 2 FOS variation of slope systems during earthquake at Ch-600

No	Condition of slope	Factor of safety	Safety
1	Slope cut at 60° angle	0.95	Unsafe
2	Slope cut at 60° with a retaining wall	1.17	Safe
3	Slope cut at 60° with retaining wall and soil nails	1.38	Safe

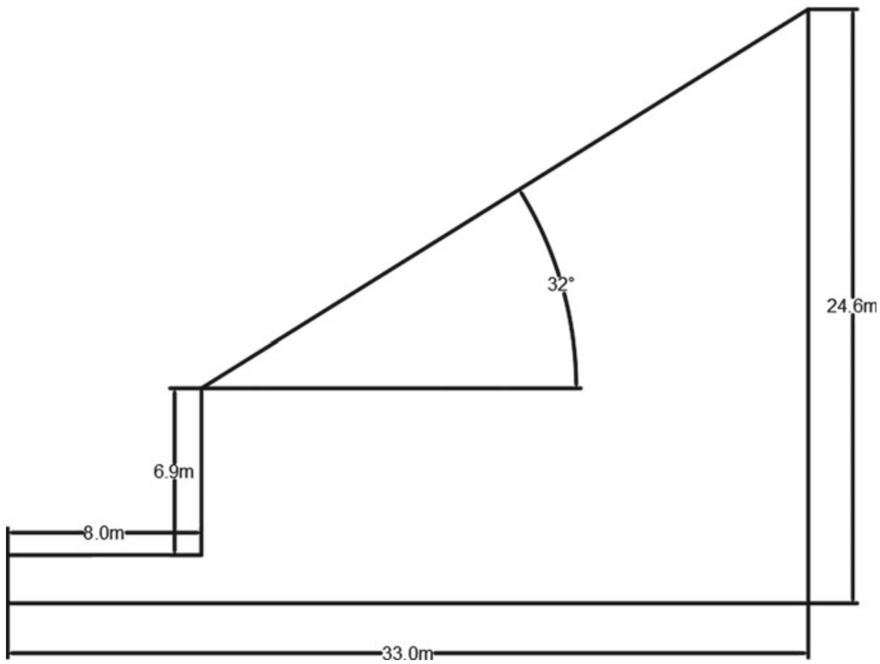


Fig. 16 Existing slope profile

have significant FOS (1.15) and lesser cutting volume. Following graphical plot in Fig. 17 shows AutoCAD layout of a slope, a variation of FOS with cutting angle (Fig. 18) and GEO-5 critical slip surface (Fig. 19).

4.2.2 Variation of FOS Due to the Placement of a Retaining Wall

After fixing the angle at 65°, a concrete retaining wall (RW) with a unit weight of 24 kN/m^3 was provided at the base and the same was modeled in GEO 5. During the modelling in GEO-5, the height and unit weight of retaining wall were varied and the corresponding change in FOS was noted accordingly. Figure 20 shows the variation of FOS with the height of RW, and, whereas GEO-5 profile of critical slip surface with RW is shown in Fig. 21. The AutoCAD layout of the slope is shown in Fig. 22.

After analysing the FOS values for different cutting angles, a cutting angle of 65° was provided which led to an increase in overall FOS up to 1.15, however, any further cutting would have been uneconomical. Therefore, a retaining wall of 4.5-m height above ground was provided which increased FOS to 1.53, well above the safe value of 1.5. Figure 23 shows the final proposed final AutoCAD layout of the slope.

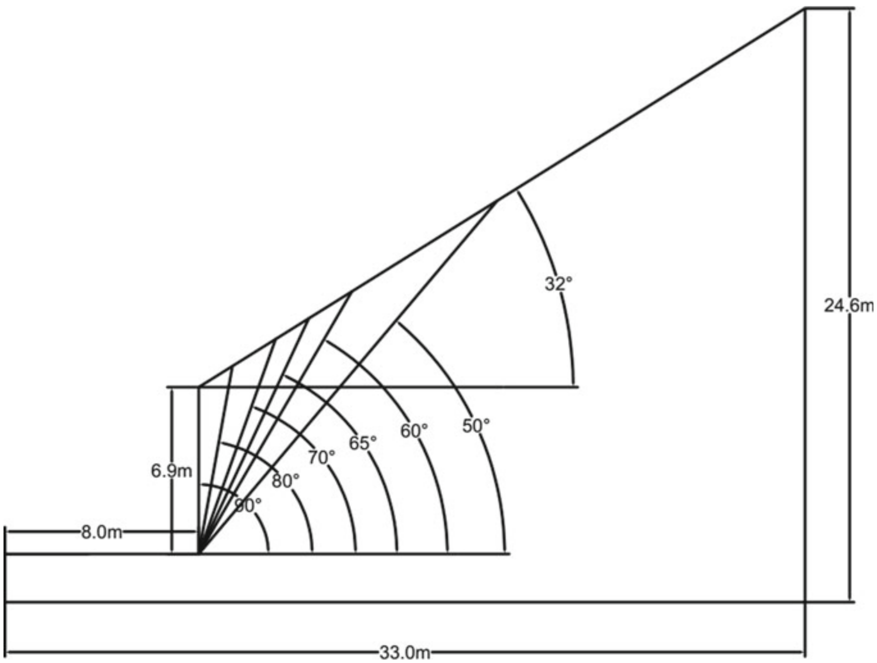
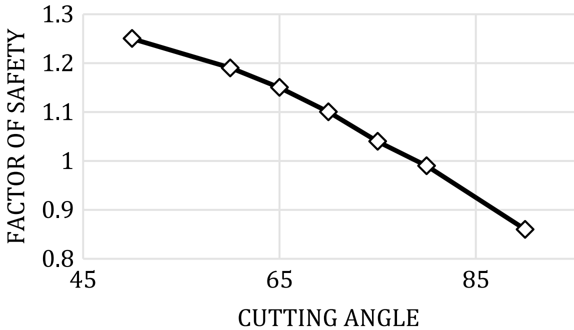


Fig. 17 Proposed geometric profile of slope at Ch-700

Fig. 18 FOS versus cutting angle



4.2.3 Impact of Earthquake on Slope Stability

The pseudo-static analysis was done for evaluating the impact of an earthquake on FOS of a slope. The coefficients of acceleration in the horizontal direction are taken as 0.11 and that in vertical direction 0.08, respectively. From the results, it can be inferred that slope cut at 65° has FOS greater than 1.00 hence is stable in case an earthquake strikes and also for the slope with retaining wall FOS is well above 1.00 making the slope quite stable, and the variation of FOS of slope under different earthquake conditions has been given in Table 3.

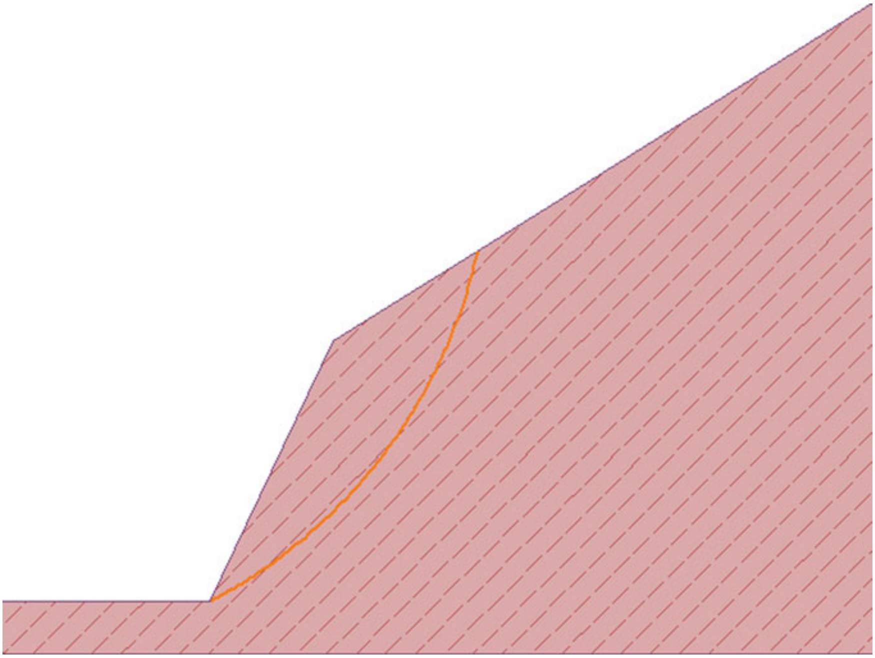


Fig. 19 GEO-5 profile of slip surface at 65° angle

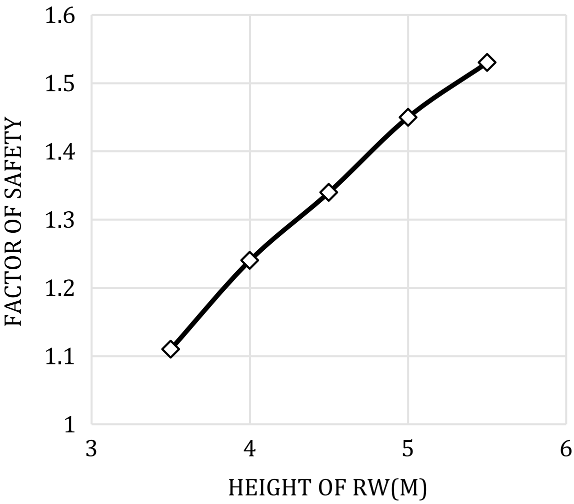


Fig. 20 FOS versus Height of RW

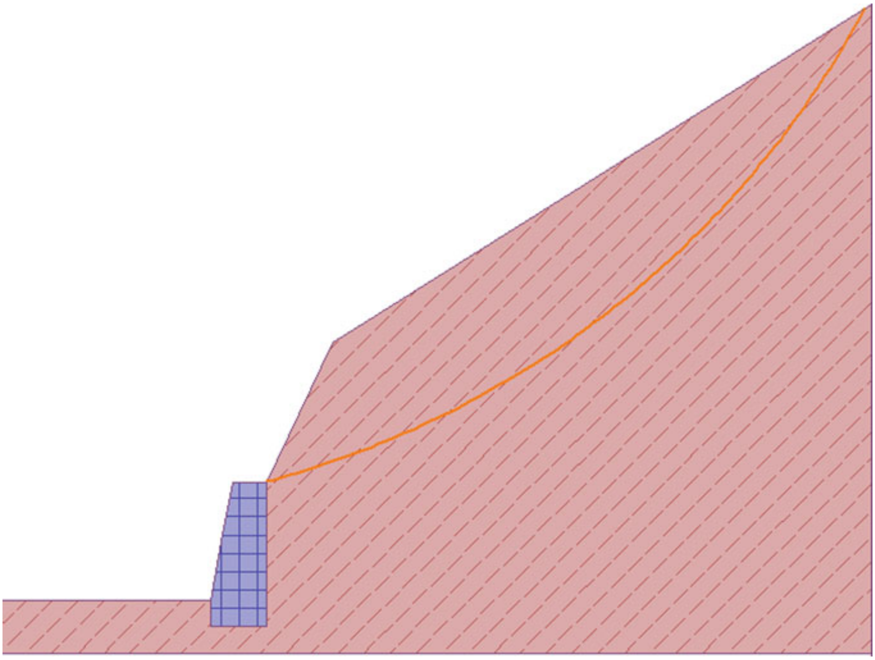


Fig. 21 GEO-5 profile of slip surface with RW

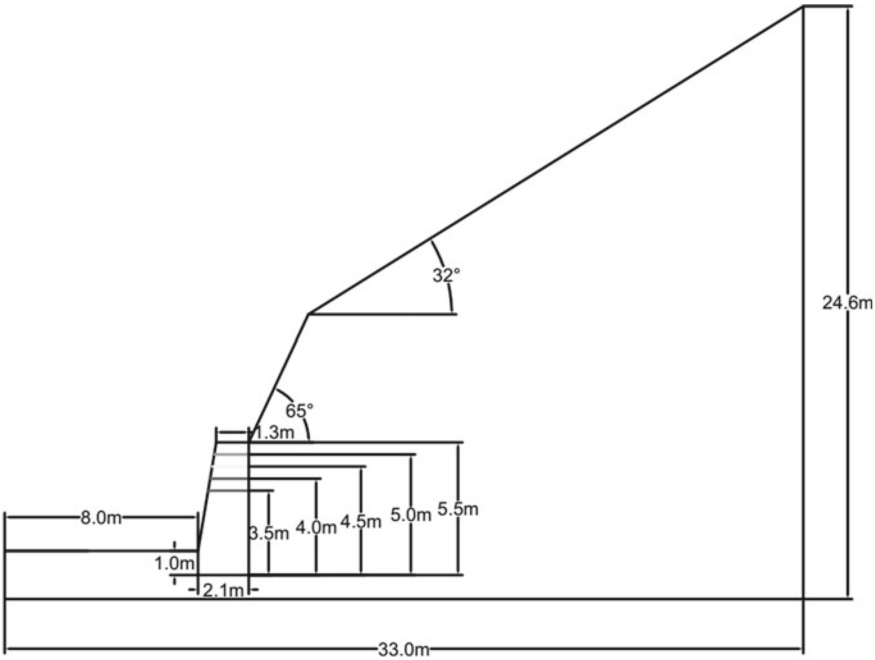


Fig. 22 Slope profile with retaining wall at Ch-700

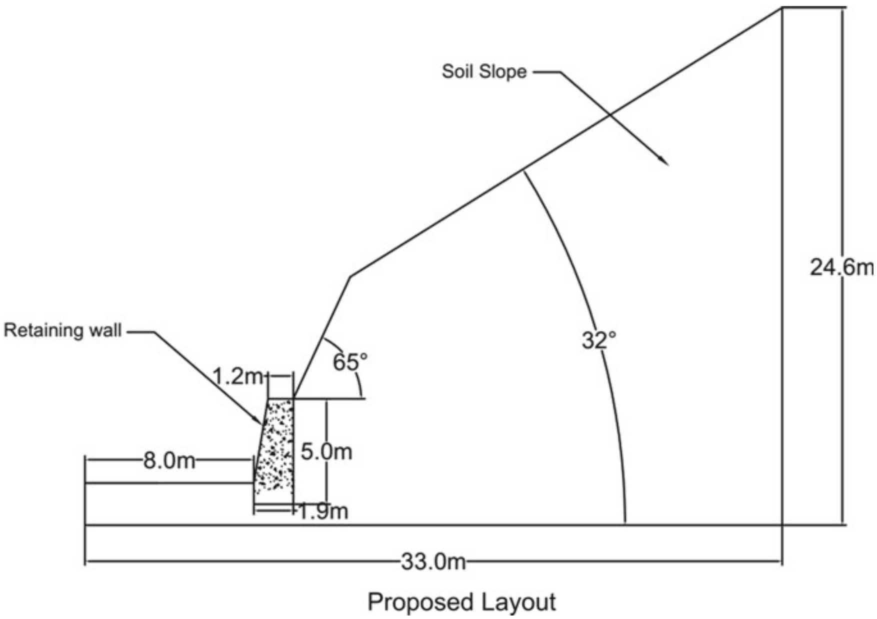


Fig. 23 Final proposed layout for slope at chainage 700

Table 3 FOS variation of slope systems during earthquake at Ch-700

No	Condition of slope	Factor of safety	Safety
1	Slope cut at 65° angle	1.05	Safe
2	Slope cut at 65° with a retaining wall	1.29	Safe

5 Conclusions

The research described in this thesis has achieved the objectives which can be summarized as follows:

- Gained a better understanding of factors that cause slope instability and their importance in the geotechnical analysis.
- Influence of shear strength parameters and other soil properties on slope stability.
- Evaluation of the stability of slopes at Gagangir Sonmarg along approach road of Z-Morh tunnel.
- Suggestions regarding stabilization measures for unstable slopes.
- Assessing the accuracy of locating the most critical slip surface and the associated factor of safety considering the type of searching technique.

In this study, two slopes along approach road of Z-Morh were analyzed for stability with the help of GEO-5 software which is a limit equilibrium-based software, and measures were suggested for increasing stability and for prevention of failure. For location-1 (Chainage-600), the slope was found to be unstable under natural conditions with FOS less than unity; therefore, remedial measures like construction of retaining wall and soil nails were suggested after evaluation and optimization with the help of GEO-5 software which consequently increased the FOS value up to 1.60, well above the safe value of 1.50. Similarly, for slope at location-2 (Chainage-700), the slope was unstable under natural conditions and had FOS value below the safe FOS value of 1.50, the construction of retaining wall increased FOS to 1.53, thereby making slope safe. Some of the inferences that can be made out of this study are as follows:

- The precision of analysis, mechanism of failure, and slip surface profile typically depend on the selection of the method of slope stability evaluation.
- GEO-5 has a very user-friendly interface, is easy to learn and is more precise as compared to other software available in market
- Optimization of slip surfaces is an important function of GEO-5 because it helps in identifying critical slip surface having maximum chances of failure
- Cohesion, angle of friction, the height of slope, slope angle, and unit weight of soil are the factors that govern the stability of the slope.

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