Slope Stability Analysis for an Airport Runway in North-East India

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Abstract. The development of infrastructure in hilly regions requires cutting of slopes and applying slope stabilization techniques to prevent landslides. In this paper, the results of slope stability analysis are presented for a newly constructed airport in north-east India. This study was conducted on an upcoming airport runway in a hilly region. The slope stability analyses for the retaining structures on the side of the runway are performed using computer simulation. These simulations are used to analyse static and pseudo-static stability of slopes. The stability of slopes is checked using Morgenstern-Price method, which is based on limit equilibrium. An RCC cladding wall supports the cut slopes. Cable anchors and rock bolts support this wall. Further, self-drilling anchors (SDAs) are used on the open ground slopes to resist local failures. At some places, cable anchors are used in combination with self-drilling anchors to support steep slopes. The study shows that long anchors with shear reinforcement are the best solution to stabilise steep ground slopes.

Keywords: Slope stabilization; GeoStudio; Reinforcement; Slope/W; Morgenstern Price method; Hilly Terrain; Airport; Runway

1 Introduction

The world is rapidly growing and getting smaller day by day. Transportation is a necessity for a fast-growing population. Travel by air is the fastest way to travel as it is also getting cheaper by the day. Airport construction facilitates the need for transportation, but it has its hurdles. From environmental regulations to noise pollution, airport authorities face a daunting task before constructing an airport.

In this study, one such case is taken where the airport is being built at the foothills of Himalaya mountains. The primary concern for designing this kind of airport is slope stability. Cutting natural slopes to make way for a runway and landing requires meticulous analysis. Figure 1 shows a specific section of a proposed airport site and the part to be excavated. The stabilisation is needed to be done in the land boundary of Airport Authority of India (AAI).

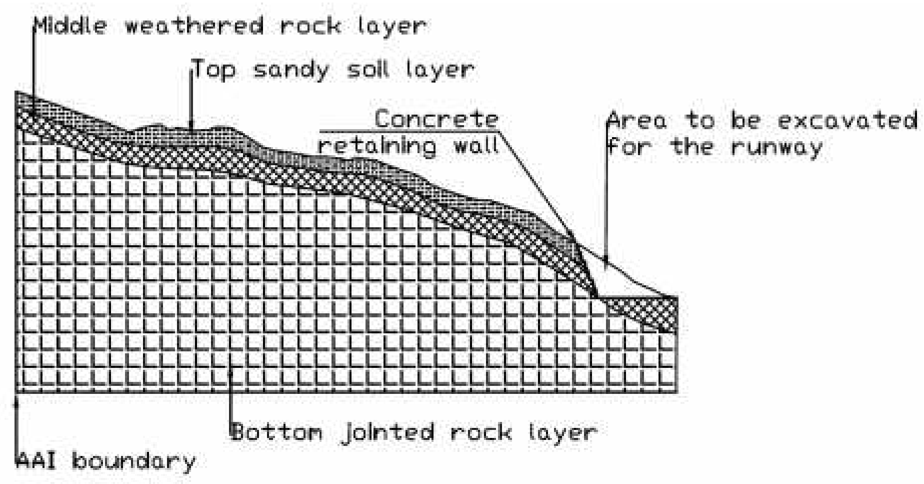

Fig. 1. Schematic diagram of hill slope to be stabilised

In this paper, SLOPE/W (A part of GeoSlope software package) is used to analyse the factor of safety (FoS) of 18 sections of cut slopes running parallel to the airport runway.

2 Methodology

Morgenstern-Price method in GeoSlope (Slope/W) considers both normal and shear inter-slice forces and satisfies both force and moment equilibrium. This method allows for a variable relationship between the inter-slice shear and normal forces. Limit equilibrium method allows calculating the FoS by the ratio of average shear strength along a critical shear surface to the average equilibrium shear stress mobilised along the same surface. GeoSlope enables users to regulate soil properties, pore-water pressure conditions, loading conditions as well as slip surface profiles to generate the desired output. The aim is to determine reinforcement requirements of all slope sections economically and feasibly to attain global slope stability. In this paper, an attempt is made to provide stability solutions to 18 slope sections achieving a minimum FoS for static and pseudo-static analysis as per standard codes with the help of Slope/W.

2.1 Material Properties

Properties of materials are identified by laboratory testing of data [4]. Bore logs and SPT data collected from the site divides it into three distinct layers. The top layer is a sandy soil, the middle one is a weathered rock layer, and the last layer is a jointed rock mass. Geotechnical properties of soil for a section is taken from the borehole data nearest to the section.

Table 1(a) and 1(b) shows the properties of soil layers required for software input.

Table 1(a). Geotechnical properties of layers

Layer	**Material Model**	**Angle of internal friction (ϕ, degrees)**	**Cohesion (kPa)**	**Unit Weight (kN/m³)**
Overburden Undrained	Bilinear	Refer to Table 1(b).		18
Highly Weathered Saturated Rock	Bilinear			24
Jointed Rock	Mohr-Coulomb	36	44	28
Side Wall Concrete	Mohr-Coulomb	0	3000	25

Table 1(b). Geotechnical properties of layers

Top soil σ-τ data (large direct shear test)		**Weathered rock σ-τ data**	
Normal Stress (kg/cm2)	**Shear Stress (kg/cm2)**	**Normal Stress (kg/cm2)**	**Shear Stress (kg/cm2)**
0	0	0	0
0.77	0.598	1.2	1.048099
1.5	1.077	2.4	1.522851
2.256	1.42	3.6	1.894832

2.2 Reinforcement Properties

The following types of reinforcement systems are allowed to be installed for the global stability of slope sections.

1. Self-drilling anchors (SDAs): Long/medium nails which are bolted into loose soils to stabilize them [6-7].
2. Rock bolts: These are smaller in length and diameter from SDAs. These are used to transfer the loads from weak to strong stratum [6-7].
3. Cable anchors: This is long, complex cables, more flexible than nails and generally used as a post-tension member, unlike nails, which are pretensioned [6].

The properties given in Table 2 are used in slope stability analysis for these three types of reinforcements.

Table 2. Design material parameters of systems for global stability analysis

Parameter	**Self-drilling anchors**	**Cable anchor**	**Rock bolts**
Length (m)	3 to 8	Bonded = 7 Overall = 20, 25 and 30	4
Out of the plane spacing (m)	2.5 or/and 3.0	3	1.5
Bond diameter (mm)	100	125	25
Pullout resistance (kPa)	60	490	60
Tensile strength (kN)	220	900	415
Shear strength (kN)	110	0	207

The pullout resistance of SDAs and rock bolts are taken as 60kPa based on a previously performed material testing by the supplier. Pullout resistance of reinforcement is the function of friction between soil and the outer layer of the reinforcement. Field pullout tests performed on the reinforcement members render the values given in Table 2.

3 Numerical Analysis in Slope/W

Material properties are given in Table 1 (a) and 1(b) are assigned to the layers, as shown in Figure 1 using Mohr-coulomb and bilinear material model available in Slope/W interface. All the other properties, such as suction are kept as default in the property definition.

Reinforcements are applied using reinforcement loads module of Slope/W. Cable anchors [6] are modelled using anchor configuration as it asks for a development/bond length. Rock bolts and SDAs are modelled using nails module [6, 7] as it considers the complete length to be bonded. Properties of the above reinforcements are defined as shown in Table 2 [5, 11].

A total of 18 slope sections are stabilised for 1 km long airport runway. AutoCAD cross-section of these slope section was made available by a classified consulting firm. These sections are preprocessed and imported into Slope/W.

To incorporate the effect of the groundwater table, the ratio of pore water pressure to vertical pressure (R_u) is specified in Slope/W. R_u of 0.25 for the top two layers are used to assimilate the effect of groundwater table in the analysis.

For pseudo-static loading, K_h (horizontal coefficient for seismic acceleration) is taken as 0.15 as the site of construction comes under seismic zone 4 [3]. K_v is taken as 0.10, i.e., two-thirds of the K_h value.

The wall is inclined at 12° from the vertical, as shown in Figure 2. Figure 2 also indicates that the cable anchors and rock bolts applied on the wall are perpendicular to the wall hence inclined at 12° from horizontal. The SDAs and cable anchors used on the ground slope are inclined at 40° from the vertical, as shown in Figure 2 [9, 10].

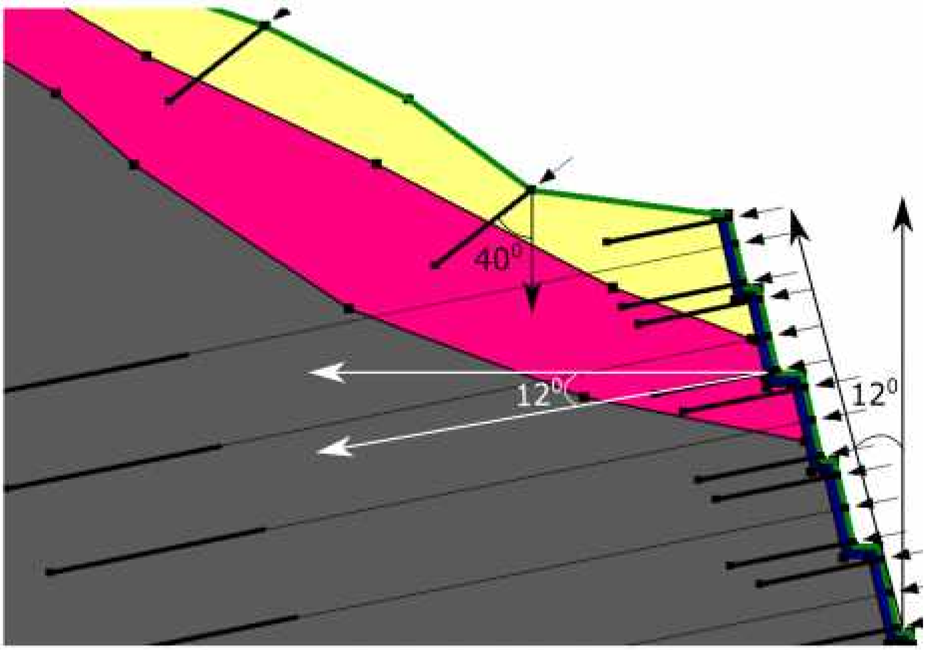

Fig. 2. Schematic diagram of a reinforced hill slope in Slope/W

The following features are incorporated to check global slope stability in the software:

1. Modelling of slope profiles for detailed stability analysis (Geometry and property assignment for slope layers and reinforcements).
2. Analysis under both static and pseudo-static conditions to achieve safe design (Incorporating K_h and K_v).
3. Modelling of groundwater table according to available borehole data from field testing (Incorporating R_u).
4. Optimizing the quantity and quality of reinforcements to accomplish required minimum FoS.

3.1 Grid Convergence Study

For Slope/W analysis, grid and radius approach is chosen. In this approach, a grid is drawn, which represents the centre of cutting circle. The radius is then taken from the drawn radius domain. The iterations are then run for each cut to check the factor of safety. To select a grid and radius mesh, three combinations are tried keeping the same area of interest. For these grid-radius combinations, the minimum factor of safety and time of analysis is recorded. Grid of 30 by 30 and radius increments of 30 are chosen for which the analysis time and FoS are optimal.

Table 3. FoS for different grid-radius configuration

Mesh size (grid, radius)	**Computational time (sec)**	**Minimum FoS**
15,15	11.88	1.710
30,30	70.28	1.734
50,50	312.07	1.697

4 Results

Consideration of site-specific conditions like high disturbances of the rock mass, heavy rainfall in the area and the importance of the project play a major role in determining the stability criterion of slopes. Table 3 describes the stability criterion for this particular case of slopes [1, 2, 8].

Table 4. Minimum FoS requirements for global stability analysis

Loading Conditions	Minimum Desired Factor of Safety
	Long Term (Undrained Behaviour)
Static Loading	1.4
Seismic loading	1.05

For a better perspective, four critical sections (section 6, 11, 13 and 1) with corrections to stabilize the slope are given in Table 5 and Figure 3, 4 and 5.

Table 5. Initial and final configurations

Initial Configuration				
	Section-9	Section-11	Section-13	Section-1
Rock bolts	14	18	24	8
Cable anchors	5 of 25 m 2 of 20 m total= 7	7 of 25 m 2 of 20 m total= 9	2 of 30 m 8 of 25 m 2 of 20 m total= 12	2 of 25 m 2 of 20 m total= 4
SDAs*	191	191	172	117
Final Configuration				
	Section-9	Section-11	Section-13	Section-1

Rock bolts	14	18	24	8
Cable anchors	2 of 20 m 5 of 25 m 3 of 20 m on slope total= 10	7 of 25 m 2 of 20 m total= 9	2 of 30 m 8 of 25 m 2 of 20 m total= 12	2 of 25 m 2 of 20 m 6 of 20 m on slope total= 10
SDAs*	138 of 6 m 44 of 4 m total= 182	165 of 6 m	113 of 8 m 59 of 4 m total= 172	165 of 8 m (spacing 1.5 m) 117 of 4 m toal= 282

*By default all SDAs are of 4 m with 2.5 m out-of-the-plane spacing

Section 1 was failing due to a steep slope which is out of the AAI boundary. The reinforcements were allowed till the AAI boundary were extended out till the end of the critical steep slope. This increased the number of SDAs drastically with densification at steep part (out-of-the-plane spacing is reduced to 1.5 m for SDAs). Six cable anchors were also added to provide stability to the steep slope. The initial and final configuration is shown in Figure 3.

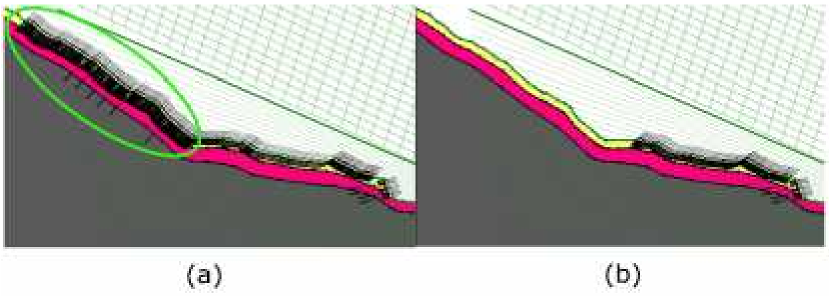

Fig. 3. Section 1 (a) after, (b) before after the required stabilisation

Section 9 was encountering a local failure at a slope transition and after some iterations with 8 meter SDAs and 20 meter cable anchors on the slope, The latter correction was applied for the stabilisation as shown in Figure 4.

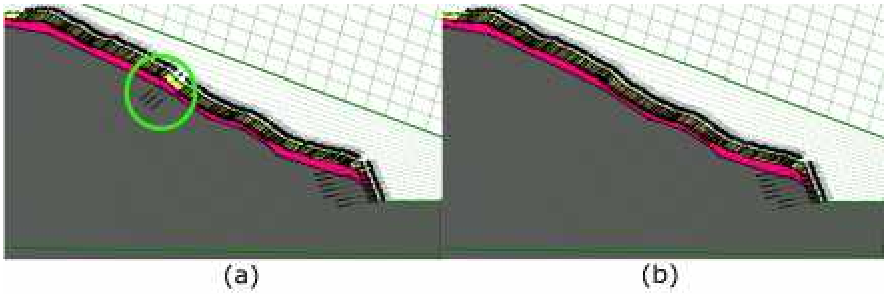

Fig. 4. Section 9 (a) after, (b) before after the required stabilisation

Top layer of the soil was the problematic zone for section 13 as failure surface beginning from there was extending to cause a large failure. Length of SDAs in the steep section was increased to 8 meter to keep the section safe as shown in Figure 5.

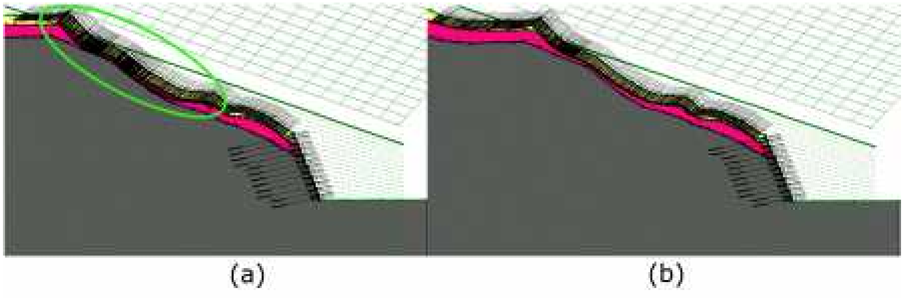

Fig. 5. Section 13 (a) after, (b) before after the required stabilisation

The factor of safety of before and after the application of corrections are shown in Table 5 for sections mentioned above.

Table 5. Minimum static and pseudo-static FoS comparison

Section	**Factor of Safety (Static)**		**Factor of Safety (Pseudo-static)**	
	Initial	**Final**	**Initial**	**Final**
9	1.376	1.519	0.943	1.026
11	1.375	1.533	0.941	1.044
13	1.315	1.444	0.930	1.156
1	0.991	1.465	0.731	1.006

To summarise the analysis of all 18 sections, sections 7, 8, 10, 14, 15 and 16 do not require any reinforcement change as they are good to go with initial configuration suggested by the contractor. In section 4, the initial configuration consisted of cable anchors on overburden and only the spread of the SDAs were changed. Three SDAs were added in section 2 to achieve desired stability in AAI boundary. In section 11 and 17, the total number of SDAs were reduced in the initial configuration, but the length of SDAs in the problematic areas was increased. The number of SDAs and length of some SDAs had to be increased to 6 meter in section 3. Number of SDAs were increased in section 5 to stabilize the slope region. In section 13, the number of SDAs were kept the same but length of some SDAs were increased to 8 meter keeping the rest 4 meter. An economical design was determined for section 18 where the length of SDAs in a major portion was reduced to 3 meter increasing the remaining SDAs to 6 meter. Although, the overall number of SDAs had to be increased but only the difficult portions were reinforced with 6 meter SDAs.

In unstable sections like 1, 9 and 12, cable anchors were additionally introduced on the sloping regions to increase the gripping power along with changes in length and number of SDAs. For the steeper part of section 1, the out-of-the plane nail spacing is reduced by 1 meter to densify the reinforcements, and the length of SDAs were increased up to 8 meter from 4 meter in steep portions.

5 Conclusions

From the results of this study, some significant conclusions can be drawn about soil slope reinforcement in the lower Himalayan region. These conclusions are given below.

1. Local slope failures can be a big problem in weak soils. In this study, top soil is the weakest; hence, the reinforcements should penetrate the top soil and seated in the lower layer to bind it with the relatively stronger lower layer.
2. Shear reinforcement is a significant concern for steeper slopes. SDAs posses shear strength; hence, they can be used in steeper slopes as compared to cable anchors which are grouted for only 7 meters. In critical cases, cable anchors should be used in conjunction with rock bolts and SDAs.
3. From the current study with weak top soil resting on a fractured rock layer, long fully grouted anchors (SDAs longer than the thickness of top soil layer) will be the best solution for slope stability. This conclusion can be generalised for slopes in the lower Himalayan region.

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