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Effects of Geological and Geotechnical Characteristics on Cut-Slope Stability of Residual Formations in the Hilly Terrain of Sri Lanka
A Case Study from Central Expressway (Section 3)

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Abstract: Residual formations consist of residual soils and parent rocks of different levels of weathering due to physical, chemical and biological processes. Existence of residual soils on the hilly slope surface and weathering of parent rocks of the residual formations can cause slope instability problems. Cutting on the hilly slopes during development projects have aggravated the problems. Sri Lankan residual soil formations are formed by weathering of the metamorphic rock and have inherited significant abrupt variations in engineering characteristics. Basic characteristics of these residual formations such as unsaturated shear strength (geotechnical) and variation of geological features (geological) are essential parameters in slope stability analyses. Therefore, a study for effects of geological and geotechnical characteristics on cut slope stability of residual formation was done by selecting major cutting sections on hilly terrain in Central Expressway Project (CEP 03) trace where degree of weathering of the parent rock units, their petrography, physical, mechanical properties and various structural features as well as series of index properties, engineering properties and strength tests on residual soils were performed.

This paper highlights the need for detailed experimental studies and presents preliminary studies that have been conducted to establish the geological and geotechnical characteristics of unsaturated Sri Lankan residual formation. The results indicate that the variation in geotechnical as well as geological characteristics of the residual formation are related to cut slope stability in hilly terrain.

Keywords: Geological description, Geotechnical property, Residual soil

1. Introduction

Soils can be basically described according to the method of formation as residual and transported soils. At least half of earth's surface is covered by residual soils [1]. Residual soil is defined as a soil material which lies at the location of the parent rock, usually found in tropical climates with relatively high temperatures and rainfall [2]. Transported soils are those materials that have been moved from their place of origin by gravity, wind, water or glaciers [3].

Engineering behaviour of residual soils is more complex than transported soils due to effects of mineralogical structure of parent rocks, presence of relict features (joints) and different levels of weathering (very significant in Metamorphic rocks) [4].

Residual formations consist of residual soils and parent rocks of different levels of weathering due to physical, chemical and biological processes [5]. The occurrence and distribution of residual formations in nature vary from location to location depending on the rock type, its mineral constituents and the climatic regime of the area [6].

Existence of residual soils on a hilly slope surface of the residual formations can cause slope instability problems, especially related to the strength [7]. Also, hilly slope of the residual formations originally consisted of hard and strong parent rocks; their stability have been impaired by weathering, heavy rainfall and seepage flows [8].

Therefore, frequent catastrophic failures i.e., landslides, and cuttings on the residual hilly slopes during development projects, have aggravated the problem.

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Residual formations have materials of different levels of weathering due to changes in the mineralogical structure of the parent rock and weathering under tropical conditions. It results in zones of different shear strength, erodability and permeability [9].

Some parent rocks in residual formations having high resistance to weathering remain as un-weathered sections (as shown in Figure 1) and are known as Boudins. Also, some parent rocks in residual formations show high weathering units (as shown in Figure 2) and remain as relict features (joints) in formations that are very significant in Metamorphic rocks [10].

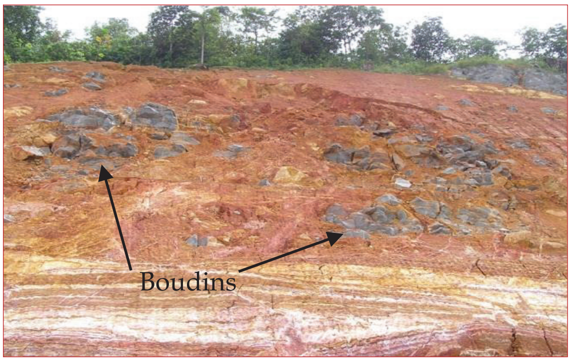

Figure 1 - Residual Formations at Southern Transport Development Project (STDP) Area

Figure 2 - Highly Jointed Metamorphic Rocks at STDP

Strength of residual soils in hilly residual formations is uniquely related to matric suction and water content [11]. Slope failures occur due to loss of matric suction on saturated state with two phases system (i.e. solid and water) that is caused by infiltration of rainwater (rainfall) as a main triggering factor. In the absence of any rainfall, these residual soils are in unsaturated state with four phases, i.e., solid, water, air and contractile skin interface. As a result, a pressure difference is created between air and water. This difference is termed as matric suction or capillary pressure and it enhances the shear strength. Therefore, matric suction (unsaturated behaviour) can give additional safety to residual soils due to capacity of the soil matrix to hold onto water in the absence of solute in the water [12].

Therefore, geological characteristics on parent rocks and geotechnical characteristics on residual soils can affect the slope stability of cutting sections in residual formations.

2. Study Area

Central Expressway is one of the expressways identified in the National Road Master Plan of Sri Lanka. Geographically, Central Expressway Project Section 03 (CEP 03) trace traverses Pothuhera to Galagedara (32.5 km) along hilly terrain (as shown in Figure 3). Many sections of CEP 03 Corridor is covered by residual formations comprising residual soils and parent rocks of different levels of weathering.

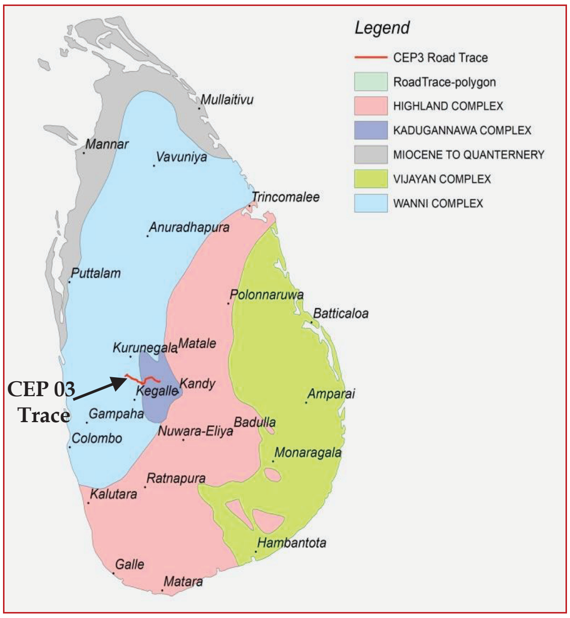

Figure 3 - Central Expressway Project 03 Trace

Major cutting section from Ch.9+500 to Ch. 10+300 (as shown in Figures 4 & 5) in this hilly terrain of the project trace was selected as a study area.

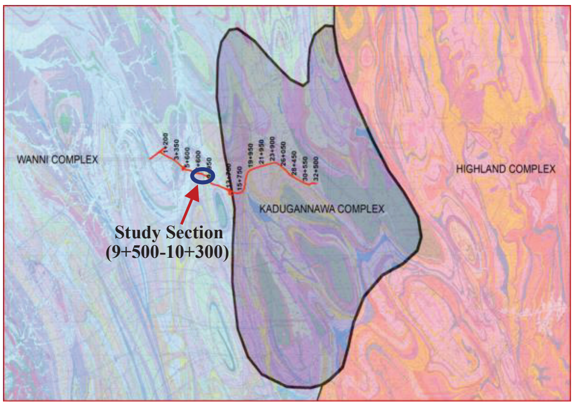

Figure 4 - Location Map of Study Area

Figure 5 - Study Area (Ch: 9+500 - Ch: 10+300)

Study area is almost covered by residual formations as a result of weathering of the Wanni complex rocks which are Metamorphic, such as Chanockitic Biotite Gneiss rocks, according to Geological map of Sri Lanka [13] as shown in Figure 6, where weathering units and relict features (joints) are very significant.

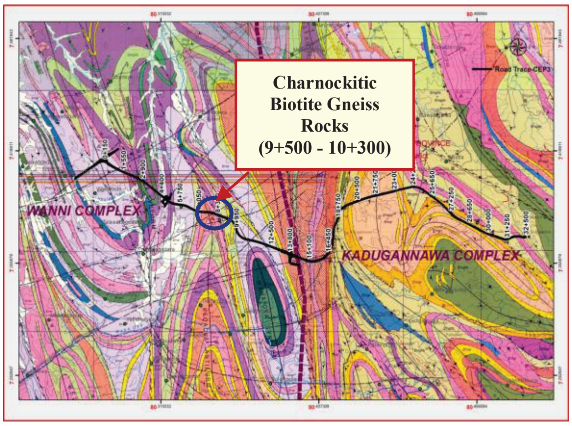

Figure 6 - Geological Map of Study Area

3. Methodology

Understanding the geological and geotechnical characteristics in a region is of vital importance in handling problems associated with slopes and slope development in unsaturated residual formations. This research is an experimental study to establish geology and geotechnical characteristics of unsaturated residual formations in the hilly terrain of Sri Lanka by considering two model studies, viz.,

- Structural Model and
- Soil/Rock Mass Model

In the structural model, identification of parent rocks, identification of relict structures / discontinuities, measurement of relative position and orientations of structural features, classification of weathering grades of rocks, mapping/drawing of 2D view of cross sections of area with software and kinematic analysis for designed rock cut slope were included.

In soil/rock mass model, determination of the index properties of residual soils, classification of residual soils and parent rocks, determination of the strength parameters of residual soils and geo-mechanical properties of parent rocks using laboratory tests, analysis of geo-mechanical properties of parent rocks with depth and slope stability analysis for designed residual soil cut slope were included.

3.1 Field Investigation

Field visits to study the section were made and information on individual rock types, their physical properties, mode of occurrence, various structural features, weathering, as well as samples of individual rock units, were collected by adopting different manual tools. Brunton compass and clinometer were used for measurement of dip and strike within foliations and joints.

3.2 Laboratory Investigation

3.2.1 Sample Collection

Before doing tests related to different models, sample collection and preparation work were commenced carefully. Undisturbed residual soil samples from study area at depths between 1-2m and rock samples from each boreholes were collected (as marked in Figure 7).

3.2.2 Sample Preparation

Uni-axial compressive strength test, Aggregate impact value, Specific gravity test and Water absorption test were done using collected individual rock units. Undisturbed residual soils as box samples for direct shear tests and disturbed residual soil samples for moisture content and index tests were collected.

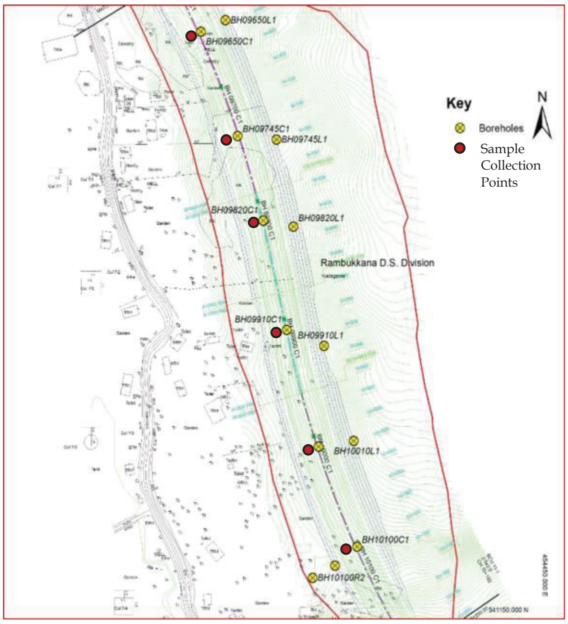

Figure 7 - Boreholes and Sample Collection Points at Study Area

3.2.3 Sample Testing

After careful collection and correct specimen preparation of samples as above, standard tests mentioned in Table 1 were carried out for residual soil and parent rock samples separately.

Index property tests were used to identify basic engineering properties of residual soils. Particle size analysis, Specific gravity, Density and Atterberg limit tests were the main index property tests performed in accordance with ASTM D 7012-04 and BS 1377:1990 (part2) codes. Uniaxial compressive strength tests were carried out to find compressive strength of rock units.

In addition, Aggregate Impact Value (AIV), Specific gravity and Water absorption tests were carried out as per the relevant ASTM code of practice to interpret the physical and mechanical properties of the parent rock units.

Direct shear tests under unsaturated conditions (suction values between 10-20 kPa) were performed under shearing rate 0.5 mm/min with $15kN/m^2$, $20kN/m^2$ and $30kN/m^2$ normal stresses respectively to determine the shear strength parameters of residual soils. Three tests on three box samples from each location were performed on consolidated and drained condition. Normal stresses were selected based on loading capacity of equipment available at laboratory [eg: according to area of tested samples, high load (more than 900 kg) must be loaded to achieve more than 100 kN/m^2 of normal stress, but it was impossible].

Table 1 - Standard Tests

Test	What was carried out
Index tests	Residual soil samples collected from above mentioned points
Uniaxial compressive strength test	Parent/bed rock samples collected from bore holes
AIV, Specific gravity and Water absorption tests	Parent/bed rock samples collected from above mentioned points
Direct shear test	Prepared undisturbed residual soil box samples

4. Results

4.1 Structural Model

Structural model was done according to results of field observations and tests as described below.

4.1.1 Results of Field Observations and Tests

Based on field observations and tests, rock structural features, weathering profiles and their physical properties were identified.

4.1.1.1 Identification of Rock Structural Features

Structural features such as dip and strike within foliations and joints were visually identified at study area before excavation and their orientations and relative positions measured. Details of measured structural features are shown in Table 2. Those exposed geological features and details of borehole investigation were used to predict expected thicknesses of residual soils and types of parent rocks. Mapping of those is presented in Figure 8.

Table 2 – Details of Measured Structural Features at Study Area

No	X Coordinate	Y Coordinate	FOLIATION		DICONTINUITIES(Fractures and Joints)							
			Fl_ Strike	Fl_Dip Angle	Fr_ Strike	Fr_Dip Angle	J1_ Strike	J1_Dip Angle	J2_ Strike	J2_Dip Angle	J3_ Strike	J3_Dip Angle
1	454145.87	541692.00			313	85						
2	454097.58	541598.53	345	13			275	85	011	83	325	10
3	454266.19	541595.11	325	10			290	80				
4	454160.45	541488.74	330	5			075	70	304	83		
5	454262.43	541458.56	346	18			273	80				
6	454259.28	541398.69	335	16			285	90	020	60		
7	454304.66	541315.18	320	16			090	90	010	86	335	90
8	454285.88	541332.75			002	52						
9	454266.47	541316.34	354	25			070	37	347	84	320	74
10	454352.82	541239.61			290	46						
11	454324.32	541225.95	335	10			273	82	335	84		
12	454311.67	541158.18	330	12			300	90	070	90		

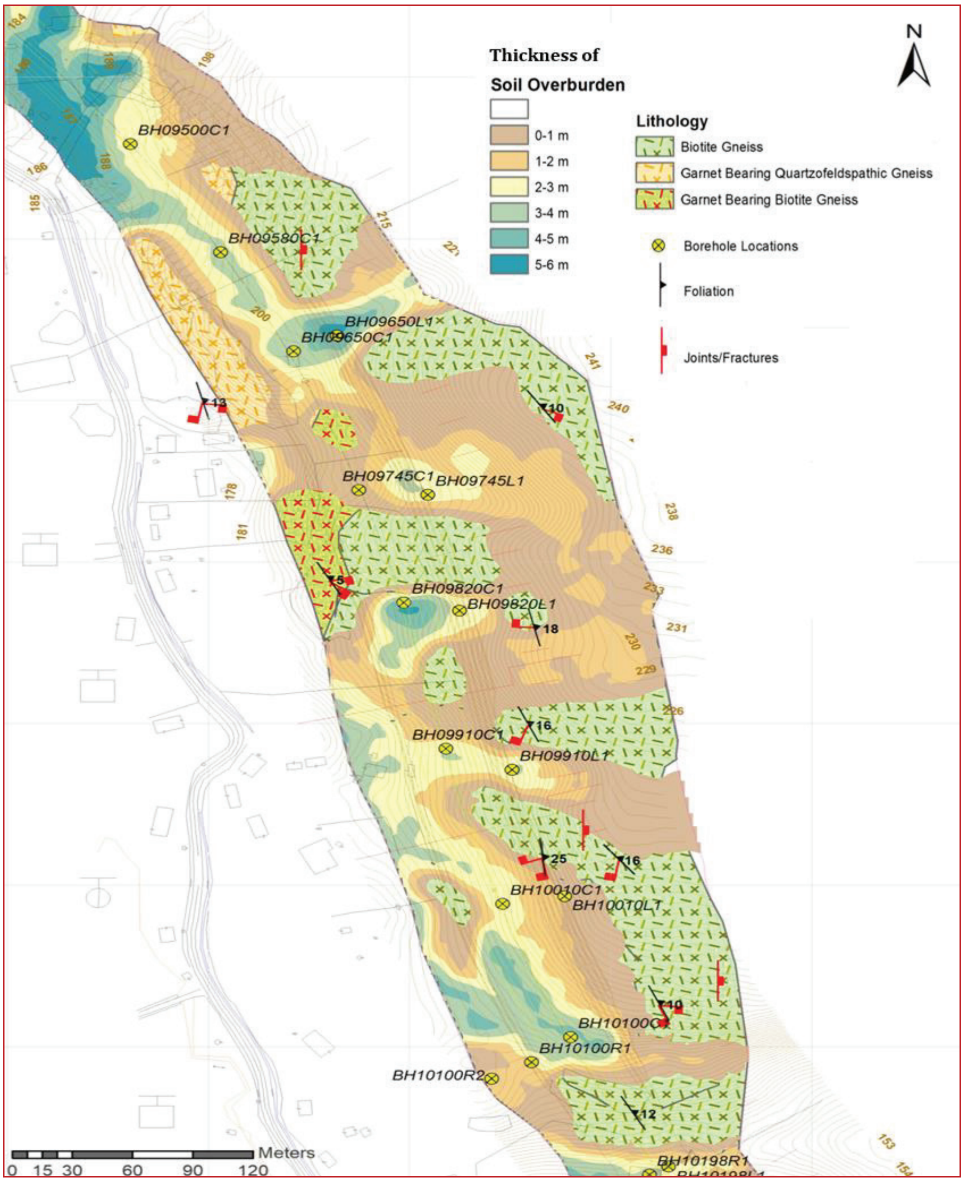

Figure 8 - Mapping of Exposed Geological Features at Study Area

4.1.1.2 Identification of Parent Rocks and Their Physical Properties

Most minerals within rocks can be characterized and classified by their unique physical properties [14]. Where physical properties of parent rocks such as colour and type were measured from borehole investigation, samples were collected between 4m-6m depth and results are shown in Table 3.

Table 3 - Physical Properties of Parent Rocks at Study Area

Study Point	Parent Rock Type	Physical Properties
9+580 C & 9+650 C	Garnet Bearing Quartzo Feldspathic Gneiss	Moderately strong, Greyish white, Metasedimentary
9+745 C	Garnet Bearing Biotite Gneiss	Slightly strong, White with grey, Metasedimentary
9+820 C, 9+910 C & 10+010 C	Biotite Gneiss	Strong, Blackish grey with Pinkish white Metasedimentary

4.1.1.3 Characterization of Weathering Profile

Classification of weathering grades of parent rocks with depth at the study area was done according to Rock Mass Rating (RMR) classification [15] with found Rock Quality Designation (RQD) and Core Recovery (CR) values. Results are shown in Table 4.

4.2 Soil/Rock Mass Model

Soil/Rock mass model was done according to results of residual soil and parent rock tests as follows.

4.2.1 Results of Residual Soil Tests

4.2.1.1 Index Tests

Natural moisture content, Specific gravity, Particle size analysis and Atterberg limits tests were performed to find the main index properties of residual soils for USCS soil classification. Results of index tests are shown in Table 5.

Table 4 - Classification of Weathering Profile at Study Area According to RMR Classification [15]

Study Point	Parent Rock Type	RQD (%)	CR (%)	Weathering Grade	Depth (m)
9+580 C	Garnet Bearing Quartzo Feldspathic Gneiss	-	-	Completely weathered rock	0.00 - 3.00
		65	83	Slightly weathered rock	3.00 - 4.50
		100	100	Fresh rock	4.50 - 21.30
		40	98	Slightly weathered rock	21.30 to advance
9+650 C	Garnet Bearing Quartzo Feldspathic Gneiss	-	-	Completely weathered rock	0.00 - 5.50
		85	100	Slightly weathered rock	5.50 - 17.00
		100	100	Fresh rock	17.00 to advance
9+745 C	Garnet Bearing Biotite Gneiss	-	-	Completely weathered rock	0.00 - 2.55
		68	98	Slightly weathered rock	2.55 - 5.25
		94	100	Fresh rock	5.25 to advance
9+820 C	Biotite Gneiss	-	-	Completely weathered rock	0.00 - 5.00
		98	100	Slightly weathered rock	5.00 - 11.10
		91	100	Fresh rock	11.10 -20.10
		54	100	Slightly weathered rock	20.10 - 24.60
9+910 C	Biotite Gneiss	-	-	Completely weathered rock	0.00 - 3.00
		11	98	Moderately weathered rock	3.00 - 9.25
		63	100	Slightly weathered rock	9.25 - 19.50
		97	100	Fresh rock	19.50 to advance
10+010 C	Biotite Gneiss	-	-	Completely weathered rock	0.00 - 2.70
		-	30	Highly weathered rock	2.70 - 4.00
		48	64	Slightly weathered rock	4.00 - 5.50
		100	100	Fresh rock	5.50 to advance

Table 5 - Results of Index Tests at Study Area

Study Point	Thickness of Residual Soil (m)	Sampling Depth (m)	Natural Moisture Content (%)	Specific Gravity	Grain Size Distribution				Atterberg Limits		
					Gravel (%)	Sand (%)	Silt (%)	Clay (%)	LL (%)	PL (%)	PI (%)
9+580 C	0.00 - 1.35	1.0 -1.5	10	2.53	5.7	67.3	15.0	12.0	35	22	13
9+650 C	0.00 - 2.00	1.0 -1.5	10	2.55	5.0	49.5	30.5	15.0	42	27	15
9+745 C	0.00 - 1.55	1.0 -1.5	12	2.54	0.8	56.0	20.2	23.0	42	25	17
9+820 C	1.00 - 2.80	1.0 -1.5	12	2.60	5.8	44.4	26.0	13.8	37	24	13
9+910 C	1.00 - 2.50	1.0 -1.5	10	2.61	2.5	44.1	36.0	17.4	48	33	15
10+010 C	0.00 - 2.00	1.0 -1.5	14	2.60	4.2	75.1	12.0	8.7	49	35	13

4.2.1.2 Direct Shear Test

Direct shear tests under unsaturated conditions were performed with 15kN/m², 20kN/m² and 30kN/m² normal stresses on residual soil samples. Results are shown graphically in Figure 9.

Accordingly, shear strength parameters at above mentioned points of study area were taken and these are shown in Table 6.

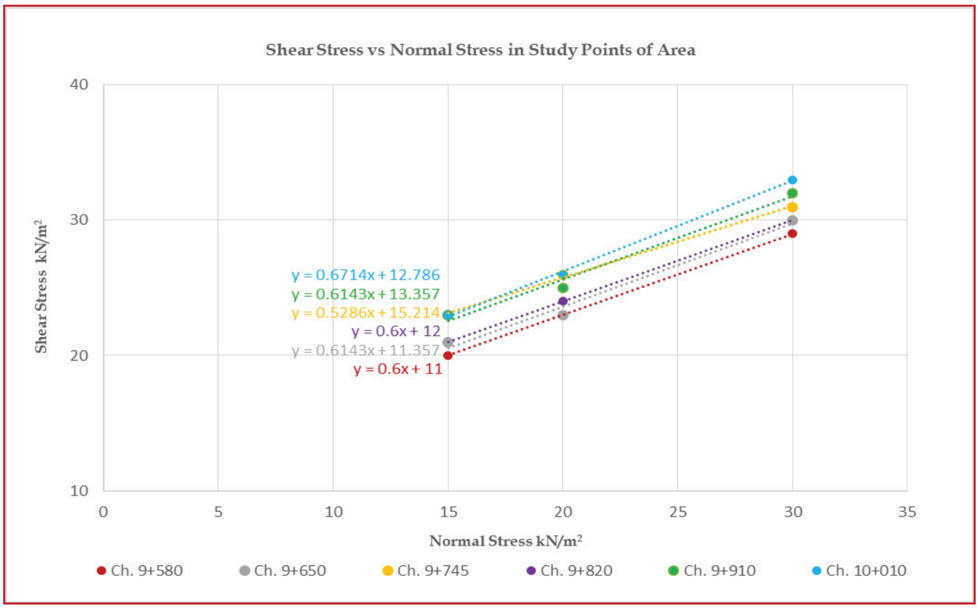

Figure 9 – Shear Stress Vs Normal Stress Relationship in Study Points of Area

Table 6 - Shear Strength Parameters of Residual Soils at Study Points of Area

Study Point	Residual Soil Type according to USCS	Thickness of Residual Soil (m)	Sampling Depth (m)	Degree of Saturation (%)	In-situ Unit Weight (kN/m³)	Vertical Deformation (mm)	Cohesion (kN/m²)	Friction Angle
9+580 C	SM	0.00 - 1.35	1.0 -1.5	47.7	17.9	-0.5 to +4.5	11	31^0
9+650 C	SM	0.00 - 2.00	1.0 -1.5	49.0	18.1	-0.5 to +4.5	11	31^0
9+745 C	SC	0.00 - 1.55	1.0 -1.5	56.4	18.1	-0.5 to +5.0	15	28^0
9+820 C	SM	1.00 - 2.80	1.0 -1.5	54.7	18.2	-0.5 to +3.5	12	31^0
9+910 C	ML	1.00 - 2.50	1.0 -1.5	45.0	17.8	-0.5 to +3.5	13	32^0
10+010 C	SM	0.00 - 2.00	1.0 -1.5	60.7	18.2	-0.5 to +3.0	12	34^0

4.2.2 Results of Parent Rock Tests

4.2.2.1 Aggregate Impact Value, Specific Gravity and Water Absorption Tests

Results of Aggregate Impact Value (AIV), Specific Gravity and Water Absorption tests of parent rocks at study area are shown in Table 7.

Table 7 - Results of AIV, Specific Gravity and Water Absorption Tests of Parent Rocks

Study Point	Parent Rock Type	AIV Value (%)	Specific Gravity (%)	Water Absorption (%)
9+580 C & 9+650 C	Garnet Bearing Quartzo Feldspathic Gneiss	29.67	2.54	1.24
9+745 C	Garnet Bearing Biotite Gneiss	28.45	2.55	1.18
9+820 C, 9+910 C & 10+010 C	Biotite Gneiss	27.72	2.61	0.92

4.2.2.2 Uniaxial Compressive Strength Tests

Rock core samples collected from boreholes at different depths were used to find compressive strength of parent rock samples based on ASTM D 7012 - 04 test method. Results are shown in Tables 8-10.

Table 8 - Results of Compressive Strength Test of Parent Rocks with Different Depths at Ch. 9+745 Point in Study Area

UCS Value (N/mm²)	Garnet Biotite Gneiss Rock, Depth (m)
	at Ch: 9+745
66.7	5.20
29.3	11.15
48.0	15.50
57.1	20.15
54.8	23.10

Table 9 - Results of Compressive Strength test of Parent Rocks with Different Depths at Ch. 9+580 and Ch. 9+650 Points in Study Area

UCS Value (N/mm²)	Garnet Bearing Quartzo Feldspathic Gneiss Rock, Depth (m)	
	at CH: 9+580	at CH: 9+650
52.6	4.20	
42.6	6.10	
35.7	14.80	
35.0	22.35	
81.1		4.85
81.8		7.90
44.1		10.30
40.6		14.10

Table 10 - Results of Compressive Strength Test of Parent Rocks with Different Depths at Ch. 9+820, Ch. 9+910 and Ch. 10+010 Points in Study Area

UCS Value (N/mm²)	Biotite Gneiss Rock, Depth (m)		
	at Ch: 9+820	at Ch: 9+910	at Ch: 10+010
58.2	6.20		
53.6	9.45		
40.0	12.40		
32.8	18.45		
50.2		5.90	
30.7		8.90	
54.4		12.10	
59.5		14.90	
62.2			5.10
33.6			9.00
39.2			13.10
61.7			18.90

5. Analysis

5.1 Structural Model

Analysis of structural model was done based on results of kinematic analysis and weathering profiles as described below.

5.1.1 Kinematic Analysis for Designed Rock Cut Slope at Study Area

Using the attributes of bed rock discontinuities obtained at the surface level (as mentioned in Table 2), kinematic analysis was performed for designed cut slope by dividing study area into three zones as shown in Figure 10 based on the availability and persistence of bedrock discontinuities, as well as the designed slope orientation. Images of kinematic analysis were presented in the Annexure (Figures A1 to A24).

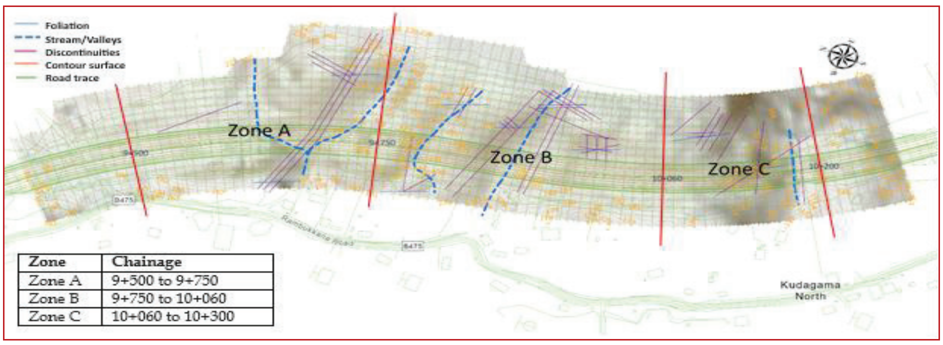

Figure 10 – Three Zones for Kinematic Analysis at Study Area

5.1.2 Analysis of Weathering Profiles

Data from all boreholes logs were combined to produce the generalized weathering profile characteristics of the study area. RMR classification [15] was used to produce the weathering profile of the study area. Weathering profile characteristics are shown in Table 4. According to RMR classification for bed rocks, different weathering grades can be seen from top to bottom of profiles and it can be seen that high level of weathering decreases gradually with depth. Also, at some locations such as 9+580 and 9+820, in-situ boulder nature can be seen.

Predicted cross sectional profiles of study area were analysed according to weathering profile characteristics. Surfer Software was used for 2D mapping of cross-sectional profiles perpendicular to trace of the road stretch at study points of area and results are shown in Figure 11.

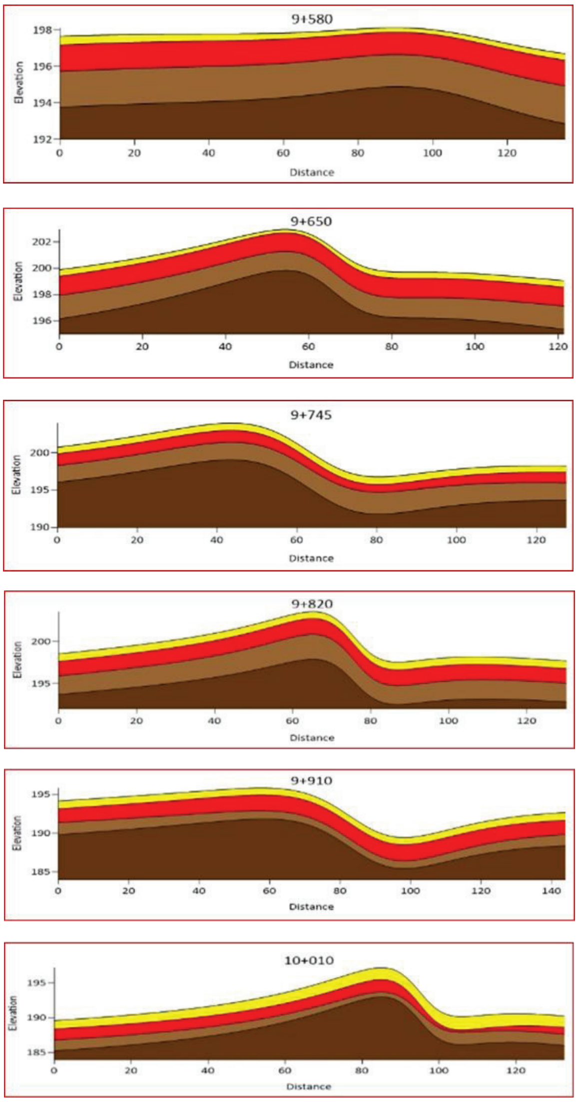

Figure 11 - Cross-sectional Profiles Perpendicular to Trace of the Road Stretch at Study Points of Area

Residual Soil
Completely to Highly Weathered Rock
Highly to Slightly Weathered Rock
Slightly to Fresh Weathered Rock

5.2 Soil and Rock Mass Model

5.2.1 Classification of Residual Soils

According to Unified Soil Classification System (USCS), residual soils found at study points of area showed three main types, silty sand, clayey sand and low plasticity silt. The grain sizes of residual soils varied from fine to coarse. Those details are presented in Table 11.

Table 11 - Details of Classified Residual Soils at Study Area

Study Point	Residual Soil Type (USCS)	Description
9+580 C	SM	Medium dense to loose, reddish brown with light brown, SILTY fine to medium SAND.
9+650 C	SM	Medium dense, light yellowish brown, SILTY angular fine to coarse SAND.
9+745 C	SC	Firm, reddish brown, CLAYEY angular fine to coarse SAND.
9+820 C	SM	Medium dense to loose, dark and yellowish brown, SILTY fine to medium SAND.
9+910 C	ML	Medium dense, yellowish brown, LOW PLACITITY SILT with fine to medium Sand.
10+010 C	SM	Medium dense, dark brown with light brown, SILTY fine to medium SAND.

5.2.2 Slope Stability Analysis for Designed Residual Soil Cut Slope at Study area using Strength Parameters

According to values of vertical deformation and degree of saturation (as mentioned in Table 6), residual soils at study points of area were over-consolidated nature and unsaturated condition. By considering these conditions and strength parameters of residual soils at study points of area (taken lowest values as c=10kPa and $Ø=30^0$), slope stability analysis was performed with Geo Studio SLOPE/W Software for critical designed residual soil cut slopes such as 9+510, 9+900 and 10+160 within three study zones (A, B and C) of study area as similar to kinematic analysis (see Figures 12, 13 and 14, respectively).

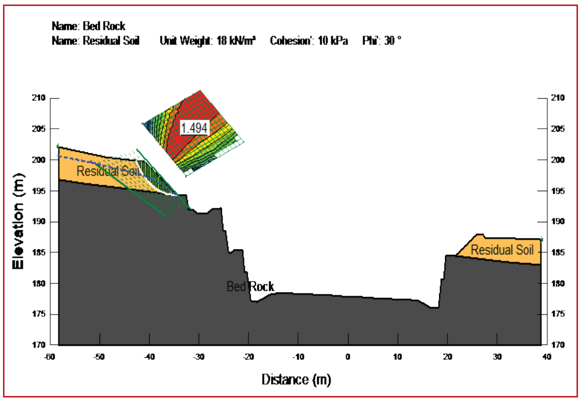

Figure 12 - Slope Stability Analysis for Critical Designed Residual Soil Cut Slope at 9+510 (Only LHS) within Zone A (9+500 to 9+750)

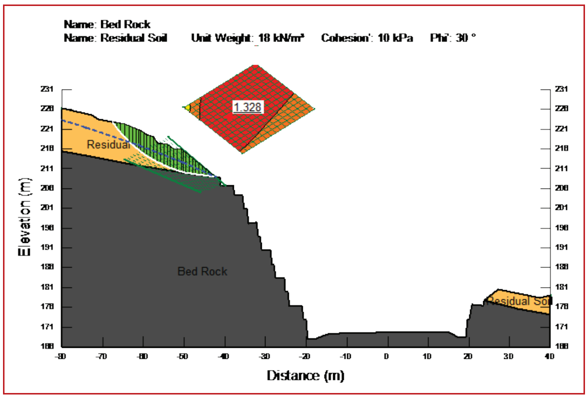

Figure 13 - Slope Stability Analysis for Critical Designed Residual Soil Cut Slope at 9+900 (Only LHS) within Zone B (9+750 to 10+060)

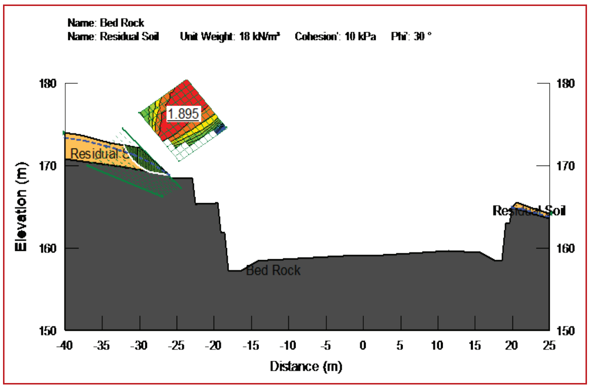

Figure 14 - Slope Stability Analysis for Critical Designed Residual Soil Cut Slope at 10+160 (Only LHS) within Zone C (10+160 to 10+300)

5.2.3 Visual Identification of Parent Rocks

Rocks have no formal classification equivalent to soils. The rock types should always be determined in assembling data for the appraisal of residual formation. In general, rock units found at study area showed three main parent rock types such as Garnet Bearing Quartzo Feldspathic Gneiss, Garnet Bearing Biotite Gneiss and Biotite Gneiss with colours of black, grey, white and pink. The grain sizes of the rocks varied from fine to coarse and they showed gneissose structure. The mineral grains occurred as Subhedral to Anhedral.

5.2.4 Uniaxial Compressive Strength of Parent Rocks

Different parent rock types showed different compressive strength values (Geo-mechanical) with depth indicating non-relationship between them. Therefore, compressive strength values of different types of parent rocks with same weathering grade (slightly weathered) and RQD and CR values were considered to find the relationship between them. Findings from analysis are shown in Table 12.

Accordingly, Garnet Bearing Biotite Gneiss parent rock showed higher compressive strength value and inversely Garnet Bearing Quartzo Feldspathic Gneiss rock showed lower compressive strength value.

Table 12 - Uniaxial Compressive Strength Values (Slightly Weathered Grade) with RQD and CR Values at Study Area

Study Point	Parent Rock Type	Average UCS Value (N/mm^2)	RQD Value (%)	CR Value (%)
9+580 C	Garnet Bearing Quartzo Feldspathic Gneiss	52.6	83	65
9+650 C		55.5	100	85
9+745 C	Garnet Bearing Biotite Gneiss	66.7	98	68
9+820 C	Biotite Gneiss	55.9	100	98
9+910 C		56.9	100	63
10+010 C		62.2	64	48

5.2.5 AIV, Specific Gravity and Water Absorption of Parent Rocks

From Table 7, it can be noted that the specific gravity of parent rocks varied from 2.54 to 2.61. The value of water absorption of the parent rocks of study area varied from 0.92% to 1.24%. The aggregate impact value of parent rock units of study area varied from 27.72% to 29.67%. Garnet Bearing Quartzo Feldspathic Gneiss rocks showed lower overall physical strength due to low value of specific gravity and high values of water absorption and impact resistance. Also, Biotite Gneiss rocks showed higher overall physical strength due to high value of specific gravity and low values of water absorption and impact resistance.

6. Discussion

Effects of geological and geotechnical characteristics of major cutting area on hilly terrain in CEP 03 trace was undertaken focussing on degree of weathering of the rock units, their petrography, physical, mechanical properties and various structural features as well as series of index properties, engineering properties and strength tests on residual soils in order to determine the causes of the slope instability. Accordingly, analysed results of three zones (A, B and C) in study area can be discussed as follows.

From 9+500 to 9+750(Zone A)

Garnet Bearing Quartzo Feldspathic Gneiss rock was found at RHS of this zone and showed lower physical and compressive strength. Biotite Gneiss parent rock was found at LHS of this zone and showed higher physical and compressive strength.

Foliation planes and joints with varied attitude were readily observed in all the rock types of the zone. According to designed cut slope orientation, parent rock slope failures (both RHS and LHS) of zone cannot be expected due to planar and wedge sliding, but toppling failure can be expected only on RHS of zone of the area due to failure along joints/fractures and foliation planes. Therefore, slope instability can be expected during excavation on RHS of zone and slope stabilization techniques must be adopted for slope protection of parent rocks. But, at some point, in zones such as 9+580, in-situ boulder nature can be observed according to weathering profile analysis, therefore slope failure vulnerability can be expected during excavation work.

Residual soils found at RHS and LHS of this zone were mostly the weathered products of Quartzo Feldspathic Gneiss and Biotite gneiss rocks, respectively. Slope stability analysis for critical designed cut slope (9+510) at LHS of zone showed safe stability (factor of safety was more than 1.3) under unsaturated condition. Therefore slope stabilization techniques are not necessary for slope protection of residual soils.

From 9+750 to 10+060(Zone B)

Garnet Bearing Biotite Gneiss rock was found at RHS of this zone and showed lower physical and compressive strength. Biotite Gneiss parent rock was found at LHS of this zone and showed higher physical and compressive strength.

Although, weak structural features observed in all the rock types of area similar to zone A, parent rock slope failures (both RHS and LHS) cannot be expected due to planar sliding according to designed cut slope direction. But, wedge sliding and toppling failures can be expected only on RHS of this zone due to failure along joints/fractures. Therefore slope stabilization techniques must be required for slope protection of parent rocks in this zone. However some points in this zone such as 9+820, in-situ boulder nature can be observed by indicating high risk on slope failure during excavation work in such points.

Slope stability analysis for critical designed soil cut slope (9+900) at LHS of zone B showed safe stability (factor of safety was more than 1.3) under unsaturated condition. Therefore slope stabilization techniques are not required.

From 10+060 to 10+300(Zone C)

Only Biotite Gneiss parent rock was found at this zone (both RHS and LHS) and showed higher physical and compressive strength.

Structural features observed in this zone and expected slope failures along weak planes were similar to Zone B. Therefore slope stabilization techniques similar to Zone B must be adopted for slope protection of parent rocks. Also, in-situ boulder nature cannot be observed in this zone, indicating no risk on slope failure during excavation work.

In addition, critical designed soil cut slope (10+160) at LHS of this zone showed safe stability (factor of safety was more than 1.3) under unsaturated condition by showing needlessness of slope stabilization techniques.

7. Conclusion

Evaluation of slope stability on residual formations is an interdisciplinary endeavour requiring knowledge and concepts from engineering geology, soil mechanics and rock mechanics. Awareness of geological and geotechnical characteristics is necessary for appropriate idealization of ground conditions and the subsequent development of realistic slope stability models [16].

Although the hilly slope of the study area consisted of hard and strong rocks, their stability had been impaired by weathering and structural conditions of rocks, morphology and the amount of water that access underground.

Due to the presence of foliations, weak planes have been formed facilitating weathering and percolation of water. The most abundant structural features observed were the joints. Their distribution and orientation were found to be the chief cause of slope instability. Therefore slope instability can be expected during excavation of rocks in study area and slope stabilization techniques must be adopted for slope protection of parent rocks.

However, residual soils in study area showed safe slope stability with designed residual soil cut slope orientation under unsaturated condition. Therefore, it is recommended to keep residual soils in study area in unsaturated condition by maintaining proper drainage facilities.

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Annexure

Kinematic Analysis for Designed Cut Slope (both LHS & RHS) at Zone A (9+500 to 9+750)

Figure A1 - Planar Sliding Analysis at Zone A (LHS) in Study Area

Figure A2 - Planar Sliding Analysis at Zone A (RHS) in Study Area

Figure A3 - Wedge Sliding Analysis at Zone A (LHS) in Study Area

Figure A4 - Wedge Sliding Analysis at Zone A (RHS) in Study Area

Figure A5 - Direct Toppling Analysis at Zone A (LHS) in Study Area

Figure A6 - Direct Toppling Analysis at Zone A (RHS) in Study Area

Figure A7 - Flexural Toppling Analysis at Zone A (LHS) in Study Area

Figure A8 - Flexural Toppling Analysis at Zone A (RHS) in Study Area

Kinematic Analysis for Designed Cut Slope (both LHS & RHS) at Zone B (9+750 to 10+060)

Figure A9 - Planar Sliding Analysis at Zone B (LHS) in Study Area

Figure A10 - Planar Sliding Analysis at Zone B (RHS) in Study Area

Figure A11 - Wedge Sliding Analysis at Zone B (LHS) in Study Area

Figure A12 - Wedge Sliding Analysis at Zone B (RHS) in Study Area

Figure A13 - Direct Toppling Analysis at Zone B (LHS) in Study Area

Figure A14 - Direct Toppling Analysis at Zone B (RHS) in Study Area

Figure A15 - Flexural Toppling Analysis at Zone B (LHS) in Study Area

Figure A16 - Flexural Toppling Analysis at Zone B (RHS) in Study Area

Kinematic Analysis for Designed Cut Slope (both LHS & RHS) at Zone C (10+060 to 10+300)

Figure A17 - Planar Sliding Analysis at Zone C (LHS) in Study Area

Figure A18 - Planar Sliding Analysis at Zone C (RHS) in Study Area

Figure A19 - Wedge Sliding Analysis at Zone C (LHS) in Study Area

Figure A20 - Wedge Sliding Analysis at Zone C (RHS) in Study Area

Figure A21 - Direct Toppling Analysis at Zone C (LHS) in Study Area

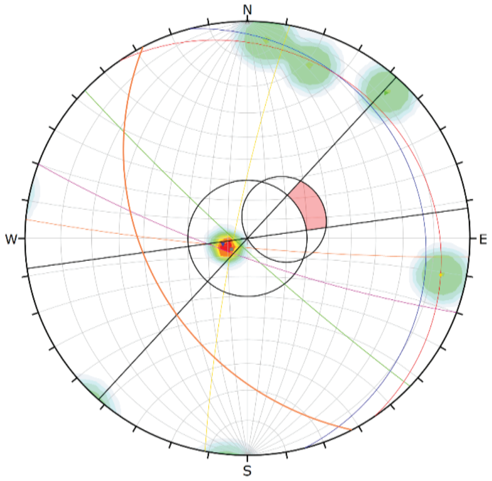
Figure A22 - Direct Toppling Analysis at Zone C (RHS) in Study Area

Figure A23 - Flexural Toppling Analysis at Zone C (LHS) in Study Area

Figure A24 - Flexural Toppling Analysis at Zone C (RHS) in Study Area

Kinematic Analysis for Designed Cut Slope (both LHS & RHS) at Zone A (9+500 to 9+750)

Planar Sliding – No planer sliding present



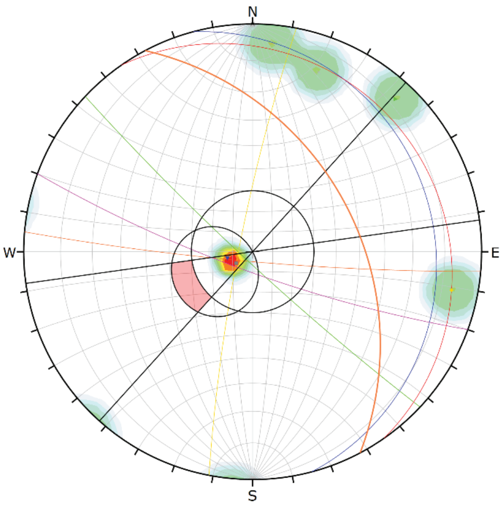
Symbol	NAME	Quantity
	F 055/10	1
	F 075/13	1
	Fr 223/85	1
	J1 185/85	1
	J1 200/80	1
	J2 281/83	1

Kinematic Analysis	Planar Sliding		
Slope Dip	41		
Slope Dip Direction	242		
Friction Angle	30°		
Lateral Limits	20°		
	Critical	Total	%
Planar Sliding (All)	0	6	0.00%

Plot Mode	Pole Vectors
Vector Count	6 (6 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A1 - Planar Sliding Analysis at Zone A (LHS) in Study Area

Planar Sliding – No planer sliding present



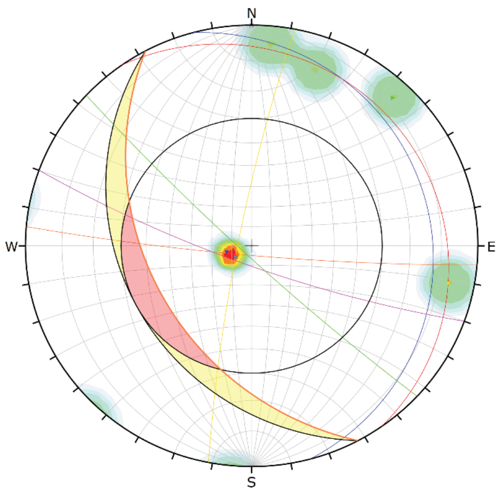
Symbol	NAME	Quantity
	F 055/10	1
	F 075/13	1
	Fr 223/85	1
	J1 185/85	1
	J1 200/80	1
	J2 281/83	1

Kinematic Analysis	Planar Sliding		
Slope Dip	41		
Slope Dip Direction	62		
Friction Angle	30°		
Lateral Limits	20°		
	Critical	Total	%
Planar Sliding (All)	0	6	0.00%

Plot Mode	Pole Vectors
Vector Count	6 (6 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A2 - Planar Sliding Analysis at Zone A (RHS) in Study Area

Wedge Sliding - No wedge sliding present



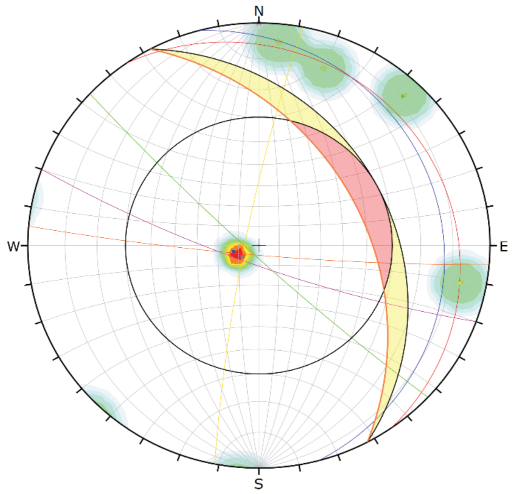
Symbol	NAME	Quantity
	F 055/10	1
	F 075/13	1
	Fr 223/85	1
	J1 185/85	1
	J1 200/80	1
	J2 281/83	1
Symbol	Feature	
	Critical Intersection	

Kinematic Analysis	Wedge Sliding		
Slope Dip	41		
Slope Dip Direction	242		
Friction Angle	30°		
	Critical	Total	%
Wedge Sliding	0	15	0.00%

Plot Mode	Pole Vectors
Vector Count	6 (6 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	15
Hemisphere	Lower
Projection	Equal Angle

Figure A3 - Wedge Sliding Analysis at Zone A (LHS) in Study Area

Wedge Sliding - No wedge sliding present



Symbol	NAME	Quantity
■	F 055/10	1
▼	F 075/13	1
▸	Fr 223/85	1
-	J1 185/85	1
×	J1 200/80	1
•	J2 281/83	1
Symbol	**Feature**	
▪	Critical Intersection	

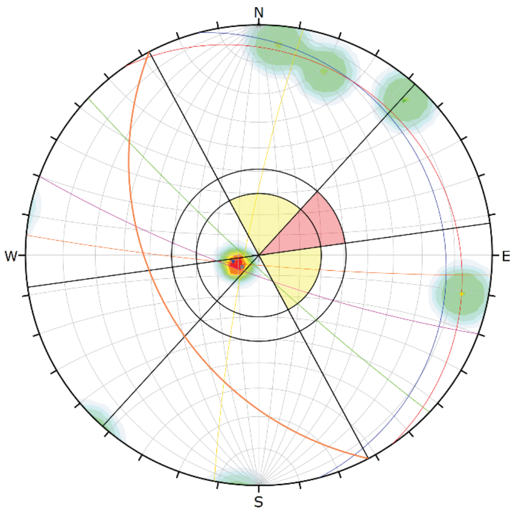
Kinematic Analysis	Wedge Sliding
Slope Dip	41
Slope Dip Direction	62
Friction Angle	30°

	Critical	Total	%
Wedge Sliding	0	15	0.00%

Plot Mode	Pole Vectors
Vector Count	6 (6 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	15
Hemisphere	Lower
Projection	Equal Angle

Figure A4 - Wedge Sliding Analysis at Zone A (RHS) in Study Area

Direct Toppling - No direct toppling sliding present



Symbol	NAME	Quantity
■	F 055/10	1
▼	F 075/13	1
▸	Fr 223/85	1
-	J1 185/85	1
×	J1 200/80	1
•	J2 281/83	1
Symbol	**Feature**	
▪	Critical Intersection	

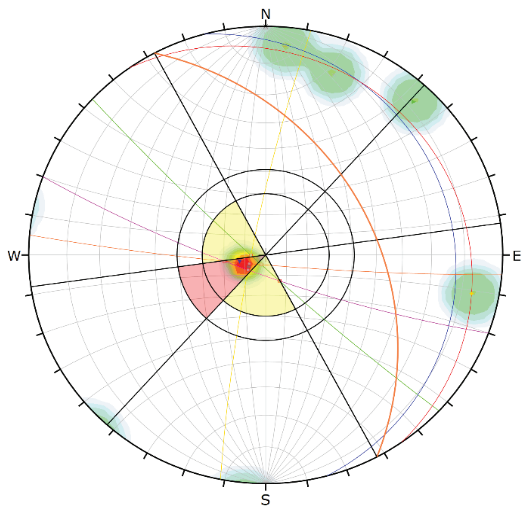
Kinematic Analysis	Direct Toppling
Slope Dip	41
Slope Dip Direction	242
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Direct Toppling (Intersection)	0	15	0.00%
Oblique Toppling (Intersection)	0	15	0.00%
Base Plane (All)	0	6	0.00%

Plot Mode	Pole Vectors
Vector Count	6 (6 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	15
Hemisphere	Lower
Projection	Equal Angle

Figure A5 - Direct Toppling Analysis at Zone A (LHS) in Study Area

Direct Toppling – Direct Toppling failure present along joint/fracture and foliation planes



Symbol	NAME	Quantity
■	F 055/10	1
▼	F 075/13	1
▸	Fr 223/85	1
-	J1 185/85	1
×	J1 200/80	1
•	J2 281/83	1
Symbol	**Feature**	
▪	Critical Intersection	

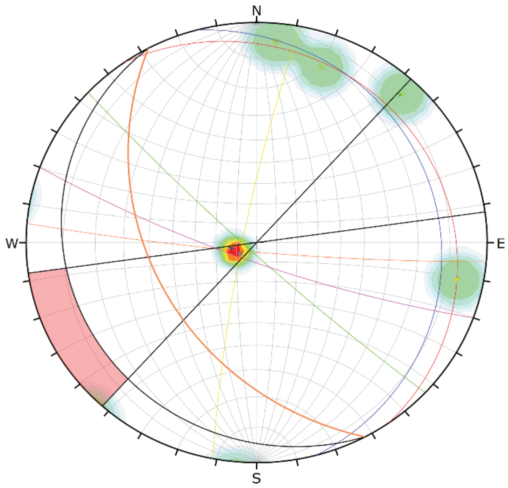
Kinematic Analysis	Direct Toppling
Slope Dip	41
Slope Dip Direction	62
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Direct Toppling (Intersection)	3	15	20.00%
Oblique Toppling (Intersection)	3	15	20.00%
Base Plane (All)	2	6	33.33%

Plot Mode	Pole Vectors
Vector Count	6 (6 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	15
Hemisphere	Lower
Projection	Equal Angle

Figure A6 - Direct Toppling Analysis at Zone A (RHS) in Study Area

Flexural Toppling - No flexural toppling sliding present



Symbol	NAME	Quantity
	F 055/10	1
	F 075/13	1
	Fr 223/85	1
	J1 185/85	1
	J1 200/80	1
	J2 281/83	1

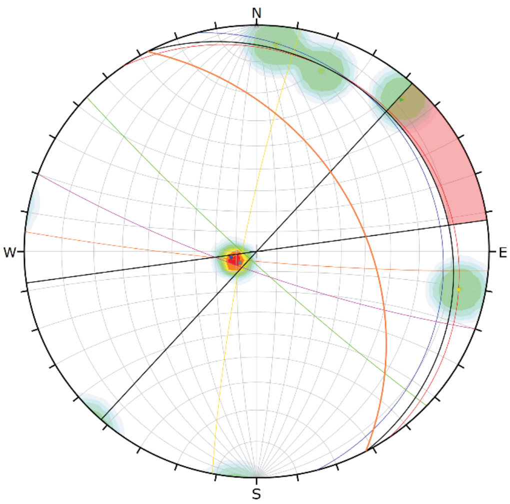
Kinematic Analysis	Flexural Toppling
Slope Dip	41
Slope Dip Direction	242
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Flexural Toppling (All)	0	6	0.00%

Plot Mode	Pole Vectors
Vector Count	6 (6 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A7 - Flexural Toppling Analysis at Zone A (LHS) in Study Area

Flexural Toppling - Flexural toppling sliding present alone joint planes



Symbol	NAME	Quantity
	F 055/10	1
	F 075/13	1
	Fr 223/85	1
	J1 185/85	1
	J1 200/80	1
	J2 281/83	1

Kinematic Analysis	Flexural Toppling
Slope Dip	41
Slope Dip Direction	62
Friction Angle	30°
Lateral Limits	20°

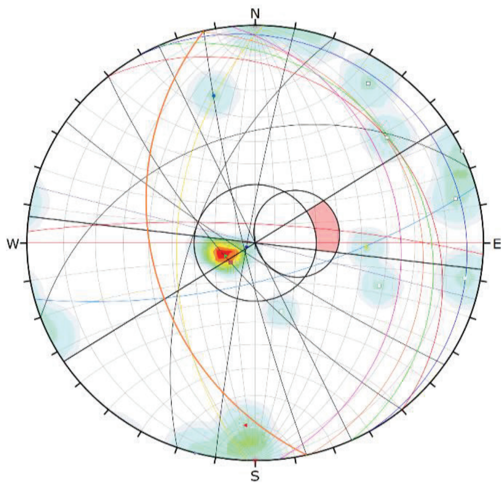
	Critical	Total	%
Flexural Toppling (All)	1	6	16.67%

Plot Mode	Pole Vectors
Vector Count	6 (6 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A8 - Flexural Toppling Analysis at Zone A (RHS) in Study Area

Kinematic Analysis for Designed Cut Slope (both LHS & RHS) at Zone B (9+750 to 10+060)

Planar Sliding – No planer sliding present



Symbol	NAME	Quantity
	F 050/16	1
	F 060/05	1
	F 065/16	1
	F 076/18	1
	F 084/25	1
	Fr 272/52	1
	J1 000/90	1
	J1 003/80	1
	J1 015/90	1
	J1 165/70	1
	Others	7

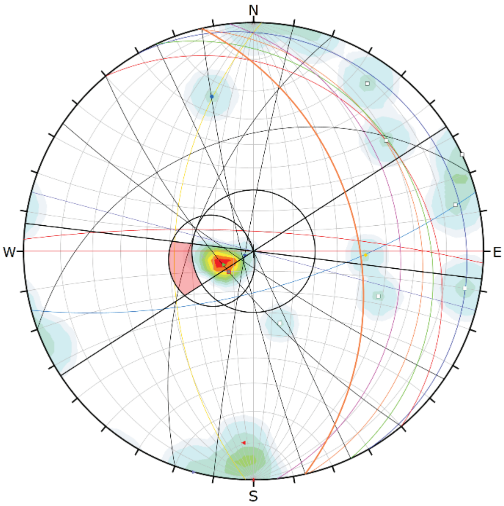
Kinematic Analysis	Planar Sliding
Slope Dip	41
Slope Dip Direction	257
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Planar Sliding (All)	0	17	0.00%

Plot Mode	Pole Vectors
Vector Count	17 (17 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A9 - Planar Sliding Analysis at Zone B (LHS) in Study Area

Planar Sliding – No planer sliding present



Symbol	NAME	Quantity
	F 050/16	1
	F 060/05	1
	F 065/16	1
	F 076/18	1
	F 084/25	1
	Fr 272/52	1
	J1 000/90	1
	J1 003/80	1
	J1 015/90	1
	J1 165/70	1
	Others	7

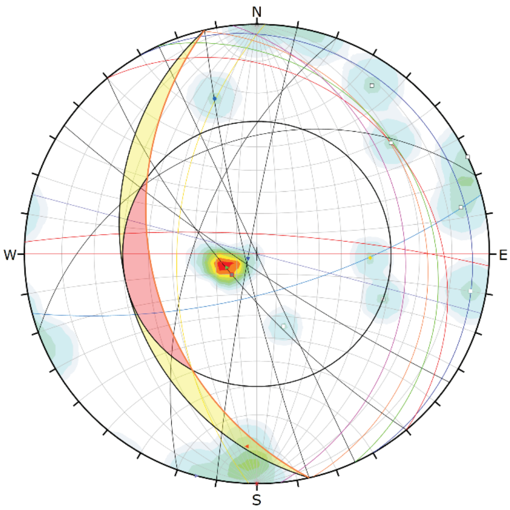
Kinematic Analysis	Planar Sliding
Slope Dip	41
Slope Dip Direction	77
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Planar Sliding (All)	0	17	0.00%

Plot Mode	Pole Vectors
Vector Count	17 (17 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A10 - Planar Sliding Analysis at Zone B (RHS) in Study Area

Wedge Sliding - No wedge sliding present



Symbol	NAME	Quantity
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	F 060/05	1
	F 065/16	1
	F 076/18	1
	F 084/25	1
	Fr 272/52	1
	J1 000/90	1
	J1 003/80	1
	J1 015/90	1
	J1 165/70	1
	Others	7
Symbol	**Feature**	
	Critical Intersection	

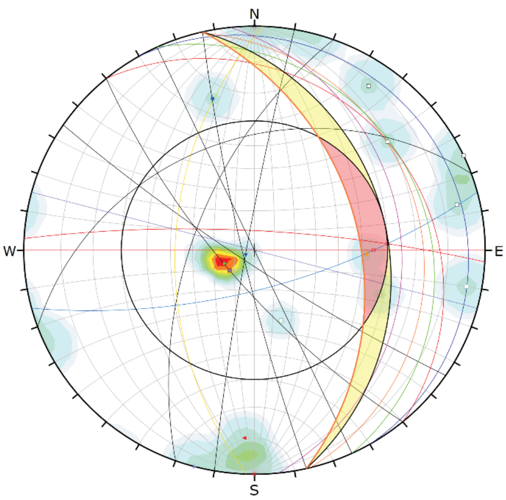
Kinematic Analysis	Wedge Sliding
Slope Dip	41
Slope Dip Direction	257
Friction Angle	30°

	Critical	Total	%
Wedge Sliding	0	136	0.00%

Plot Mode	Pole Vectors
Vector Count	17 (17 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	136
Hemisphere	Lower
Projection	Equal Angle

Figure A11 - Wedge Sliding Analysis at Zone B (LHS) in Study Area

Wedge Sliding – Wedge sliding present alone joint planes



Symbol	NAME	Quantity
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	F 060/05	1
	F 065/16	1
	F 076/18	1
	F 084/25	1
	Fr 272/52	1
	J1 000/90	1
	J1 003/80	1
	J1 015/90	1
	J1 165/70	1
	Others	7
Symbol	**Feature**	
	Critical Intersection	

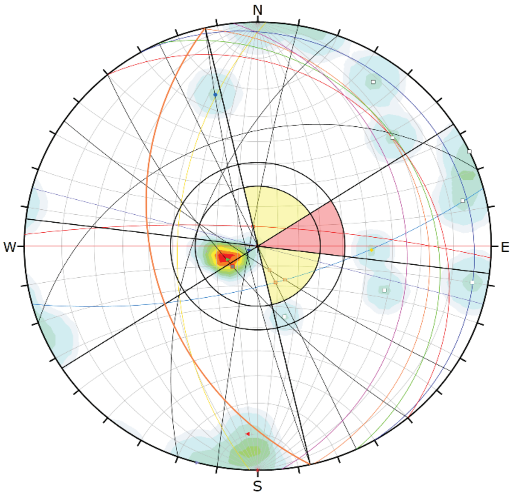
Kinematic Analysis	Wedge Sliding
Slope Dip	41
Slope Dip Direction	77
Friction Angle	30°

	Critical	Total	%
Wedge Sliding	2	136	1.47%

Plot Mode	Pole Vectors
Vector Count	17 (17 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	136
Hemisphere	Lower
Projection	Equal Angle

Figure A12 - Wedge Sliding Analysis at Zone B (RHS) in Study Area

Direct Toppling - No direct toppling sliding present



Symbol	NAME	Quantity
■	F 050/16	1
▼	F 060/05	1
▶	F 065/16	1
+	F 076/18	1
×	F 084/25	1
●	Fr 272/52	1
×	J1 000/90	1
◀	J1 003/80	1
▶	J1 015/90	1
●	J1 165/70	1
□	Others	7

Symbol	Feature
■	Critical Intersection

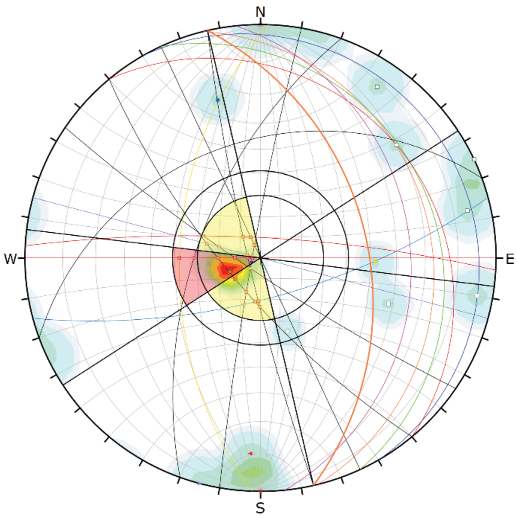
Kinematic Analysis	Direct Toppling
Slope Dip	41
Slope Dip Direction	257
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Direct Toppling (Intersection)	0	136	0.00%
Oblique Toppling (Intersection)	6	136	4.41%
Base Plane (All)	0	17	0.00%

Plot Mode	Pole Vectors
Vector Count	17 (17 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	136

Figure A13 - Direct Toppling Analysis at Zone B (LHS) in Study Area

Direct Toppling - Direct Toppling failure present along joint/fracture and foliation planes



Symbol	NAME	Quantity
■	F 050/16	1
▼	F 060/05	1
▶	F 065/16	1
+	F 076/18	1
×	F 084/25	1
●	Fr 272/52	1
×	J1 000/90	1
◀	J1 003/80	1
▶	J1 015/90	1
●	J1 165/70	1
□	Others	7

Symbol	Feature
■	Critical Intersection

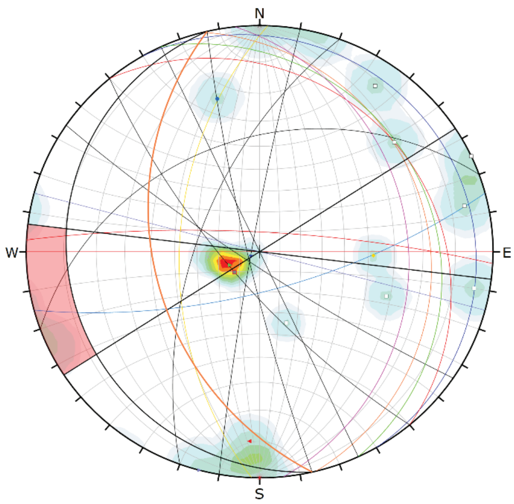
Kinematic Analysis	Direct Toppling
Slope Dip	41
Slope Dip Direction	77
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Direct Toppling (Intersection)	6	136	4.41%
Oblique Toppling (Intersection)	18	136	13.24%
Base Plane (All)	5	17	29.41%

Plot Mode	Pole Vectors
Vector Count	17 (17 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	136

Figure A14 - Direct Toppling Analysis at Zone B (RHS) in Study Area

Flexural Toppling - No flexural toppling sliding present



Symbol	NAME	Quantity
■	F 050/16	1
▼	F 060/05	1
▶	F 065/16	1
+	F 076/18	1
×	F 084/25	1
●	Fr 272/52	1
×	J1 000/90	1
◀	J1 003/80	1
▶	J1 015/90	1
●	J1 165/70	1
□	Others	7

Kinematic Analysis	Flexural Toppling
Slope Dip	41
Slope Dip Direction	257
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Flexural Toppling (All)	0	17	0.00%

Plot Mode	Pole Vectors
Vector Count	17 (17 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A15 - Flexural Toppling Analysis at Zone B (LHS) in Study Area

Flexural Toppling - Flexural toppling sliding present alone joint planes

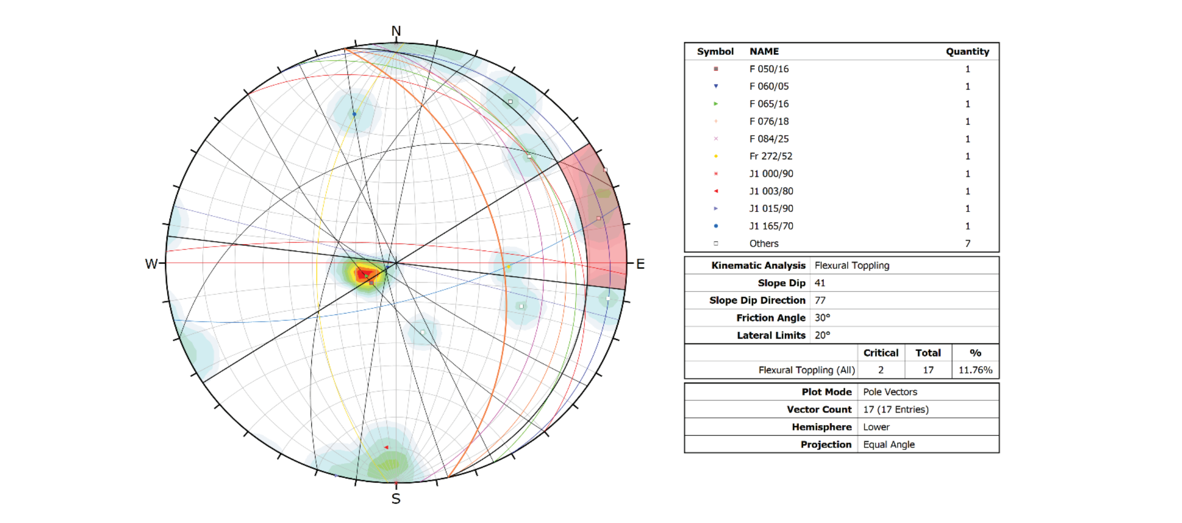


Figure A16 - Flexural Toppling Analysis at Zone B (RHS) in Study Area

Kinematic Analysis for Designed Cut Slope (both LHS & RHS) at Zone C (10+060 to 10+300)

Planar Sliding – No planer sliding present

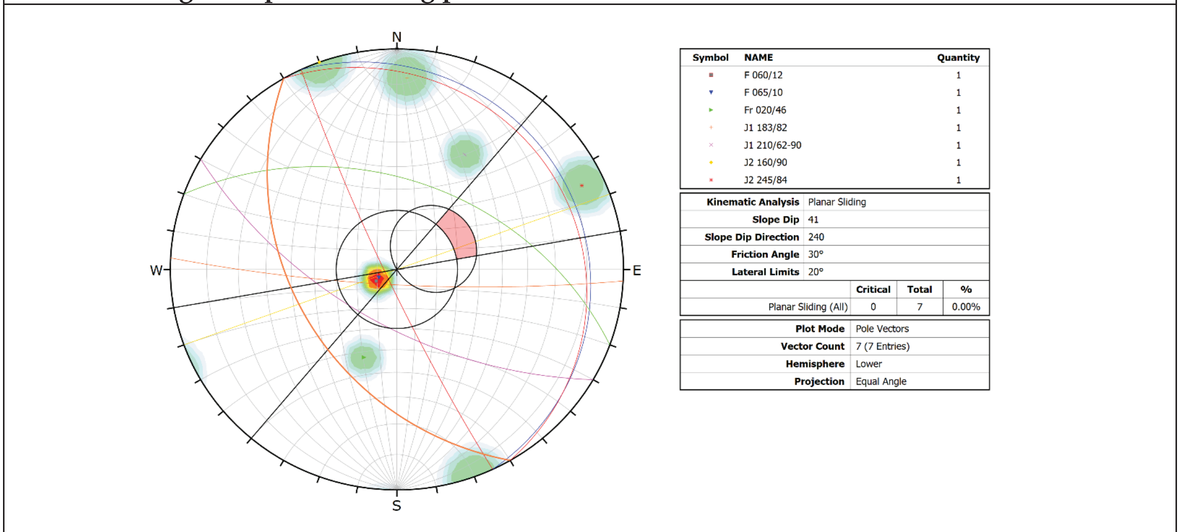


Figure A17 - Planar Sliding Analysis at Zone C (LHS) in Study Area

Planar Sliding – No planer sliding present

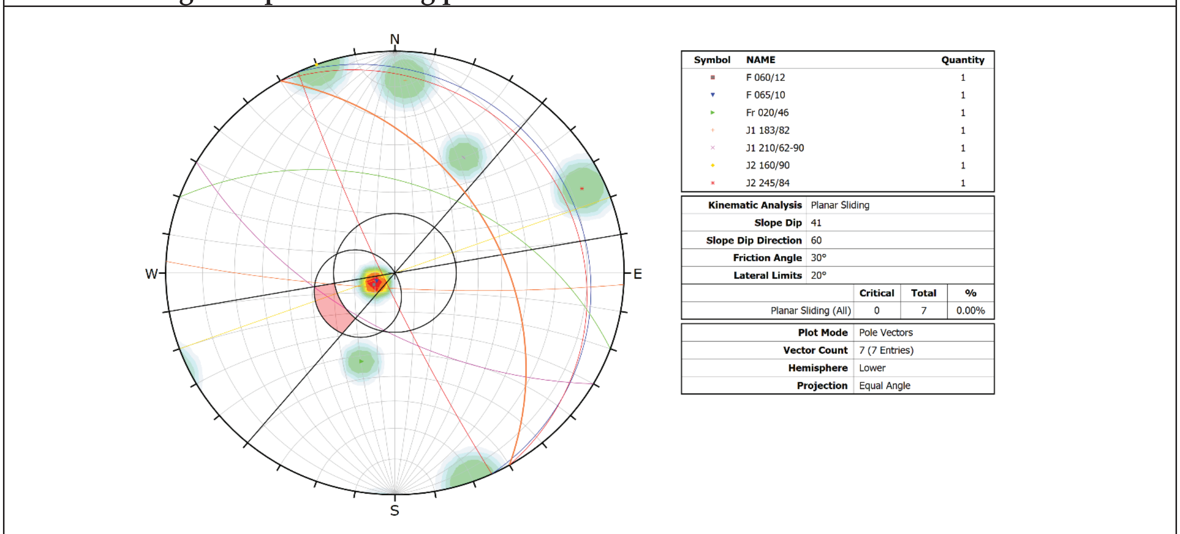


Figure A18 - Planar Sliding Analysis at Zone C (RHS) in Study Area

Wedge Sliding - No wedge sliding present

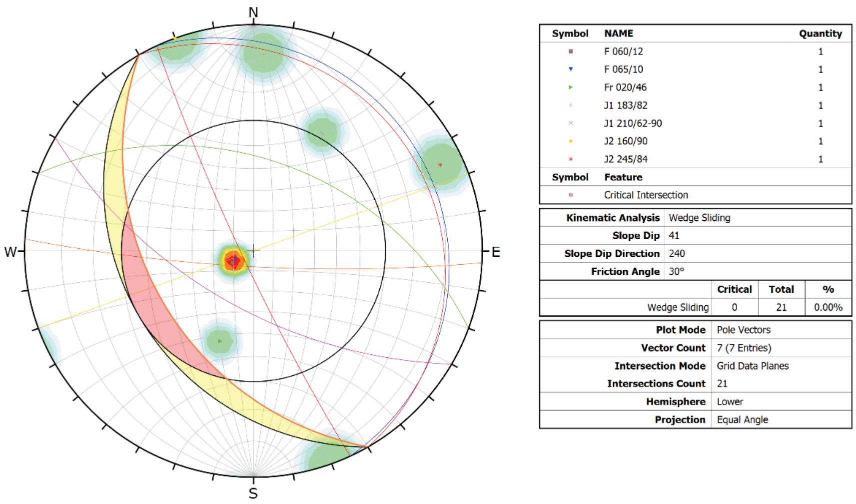


Figure A19 - Wedge Sliding Analysis at Zone C (LHS) in Study Area

Wedge Sliding - Wedge sliding present alone joint planes

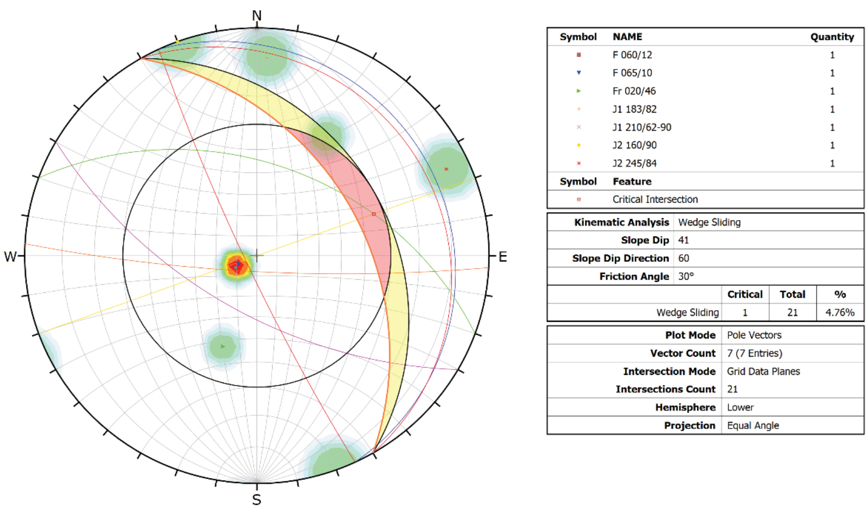


Figure A20 - Wedge Sliding Analysis at Zone C (RHS) in Study Area

Direct Toppling - No direct toppling sliding present

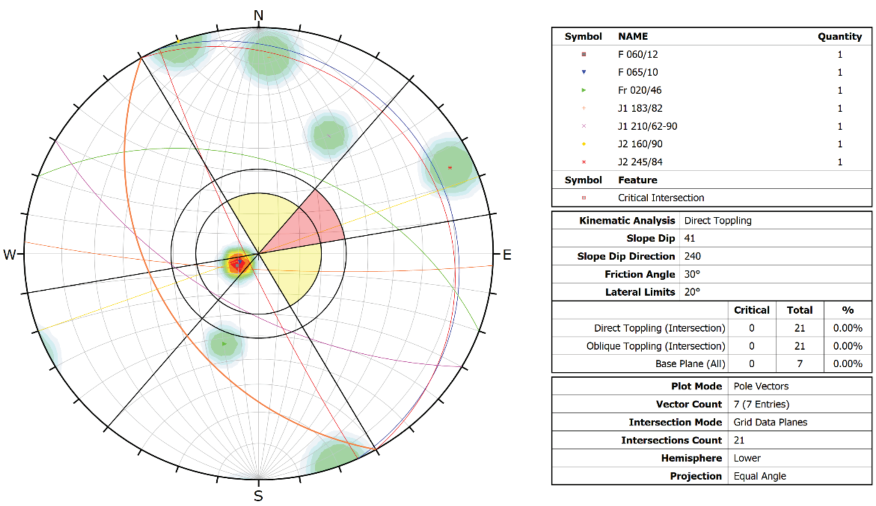
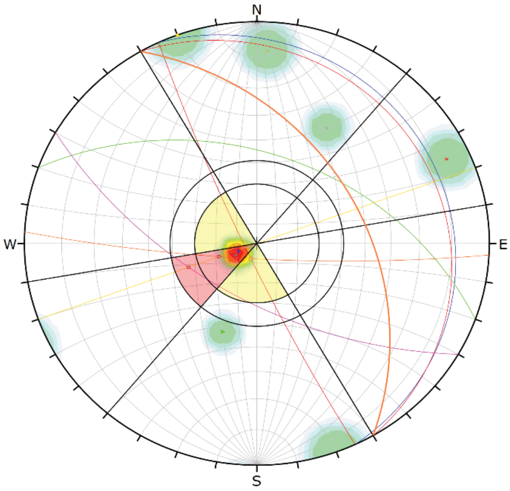


Figure A21 - Direct Toppling Analysis at Zone C (LHS) in Study Area

Direct Toppling - Direct Toppling failure present along joint/fracture and foliation planes



Symbol	NAME	Quantity
■	F 060/12	1
▼	F 065/10	1
▶	Fr 020/46	1
+	J1 183/82	1
×	J1 210/62-90	1
◆	J2 160/90	1
✱	J2 245/84	1
Symbol	**Feature**	
□	Critical Intersection	

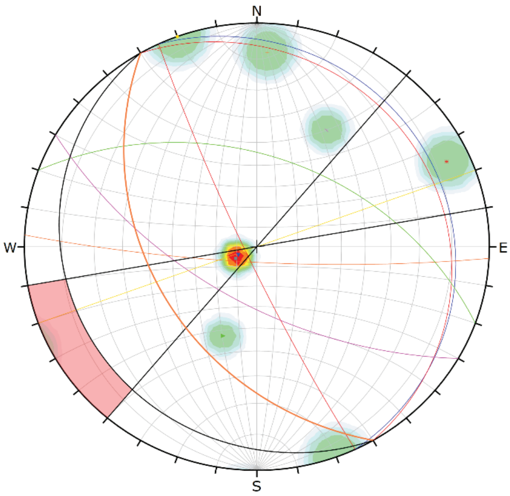
Kinematic Analysis	Direct Toppling
Slope Dip	41
Slope Dip Direction	60
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Direct Toppling (Intersection)	3	21	14.29%
Oblique Toppling (Intersection)	1	21	4.76%
Base Plane (All)	2	7	28.57%

Plot Mode	Pole Vectors
Vector Count	7 (7 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	21
Hemisphere	Lower
Projection	Equal Angle

Figure A22 - Direct Toppling Analysis at Zone C (RHS) in Study Area

Flexural Toppling - No flexural toppling sliding present



Symbol	NAME	Quantity
■	F 060/12	1
▼	F 065/10	1
▶	Fr 020/46	1
+	J1 183/82	1
×	J1 210/62-90	1
◆	J2 160/90	1
✱	J2 245/84	1

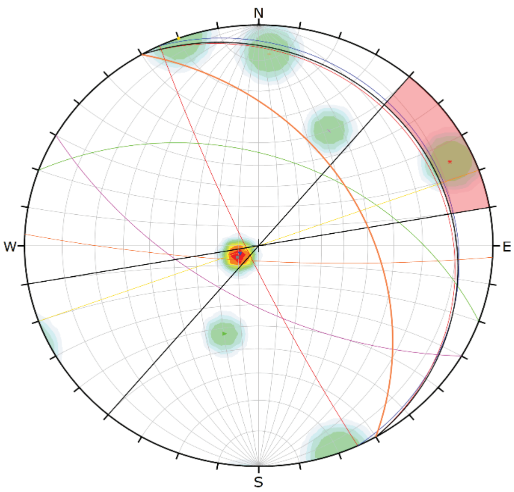
Kinematic Analysis	Flexural Toppling
Slope Dip	41
Slope Dip Direction	240
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Flexural Toppling (All)	0	7	0.00%

Plot Mode	Pole Vectors
Vector Count	7 (7 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A23 - Flexural Toppling Analysis at Zone C (LHS) in Study Area

Flexural Toppling - Flexural toppling sliding present alone joint planes



Symbol	NAME	Quantity
■	F 060/12	1
▼	F 065/10	1
▶	Fr 020/46	1
+	J1 183/82	1
×	J1 210/62-90	1
◆	J2 160/90	1
✱	J2 245/84	1

Kinematic Analysis	Flexural Toppling
Slope Dip	41
Slope Dip Direction	60
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Flexural Toppling (All)	1	7	14.29%

Plot Mode	Pole Vectors
Vector Count	7 (7 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure A24 - Flexural Toppling Analysis at Zone C (RHS) in Study Area