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Mineralogical Evolution and Geo-mechanical Characterization of Weathering Profiles Along the Central Expressway (CEP 3), Sri Lanka

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Abstract : This research investigates the mineralogical and geo-mechanical factors influencing slope stability along Section 3 of the Central Expressway Project (CEP 3), Sri Lanka. Through a combination of borehole logging, petrographic analysis, and X-ray diffraction (XRD), a comprehensive weathering profile was established. Results delineate a transition from stable, fresh metamorphic gneissic rocks to highly unstable residual soils (SM and ML types). Petrographic data reveal the progressive alteration of primary minerals, specifically Feldspar, Biotite, and Hornblende, into secondary Clay phases. XRD analysis identified the presence of Smectite and Kaolinite, with the former presenting significant risks for moisture-induced volume changes and rotational slides in high-cut sections. The study concludes that the thickness and stability of the residual mantle are directly governed by the modal mineralogy of the metamorphic parent rock, providing a critical framework for geotechnical risk mitigation in hilly terrains.

Keywords : Mineralogical Transformation, Residual Soils, Weathering Profile.

1. Introduction

The Sri Lankan landmass is predominantly composed (approx. 90%) of Precambrian high-grade metamorphic rocks, ranging from granulite to upper amphibolite facies. These lithologies, with ages spanning 610 to 550 million years ago, underwent extensive deformation and recrystallization during the Pan-African orogeny and are locally associated with igneous intrusions such as pegmatite bodies [1].

The crystalline basement is traditionally subdivided into four major lithotectonic units: the Wanni, Highland, Vijayan, and Kadugannawa Complexes [2]. The study area is situated within the Wanni Complex, which is characterized by metamorphic rocks derived from sedimentary protoliths (Figure 1). These metamorphic parent rocks exhibit distinct gneissic foliation, defined by alternating leucocratic (quartzofeldspathic) and melanocratic (ferromagnesian) bands, and are characterized by multiple systematic joint sets.

Under tropical conditions, these metamorphic parent rocks have undergone varying degrees of physical, chemical, and biological weathering, resulting in complex weathering profiles. These profiles consist of residual formations, specifically saprolites and lateritic soils that vary significantly in thickness and morphology based on the degree of alteration of the metamorphic rock [3].

The spatial distribution and physical characteristics of these residual formations are governed by the interplay between the metamorphic lithology, its primary mineral constituents, and the prevailing tropical climatic regime [4]. Consequently, these formations exhibit heterogeneous weathering profiles characterized by varying degrees of chemical and physical alteration, which directly influence the geo-mechanical stability of the high-cut slopes along the CEP 3 trace.

The heterogeneity mentioned is often manifested as structural remnants embedded within the softer, decomposed saprolitic matrix. In the context of the Wanni Complex and the CEP 3 trace, these remnants are critical because they create a highly unpredictable subsurface environment.

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These remnants typically appear in the following forms:

Boudinage Structures: Competent lithological units with high resistance to chemical weathering frequently persist as unweathered, lenticular segments within the softer residual soil (Figure 2). These boudinage structures represent tensional features formed during the high-grade metamorphic deformation of the parent rock [3].

Relict Features: In contrast, sections of the parent rock that have undergone advanced decomposition may still preserve relict discontinuities, such as inherited joint systems and foliation planes (Figure 3). In meta-sedimentary sequences, these relict joints play a geotechnically significant role, as they maintain the structural orientation of the parent rock even after the mineralogical matrix has transitioned into a soil-like state [3].

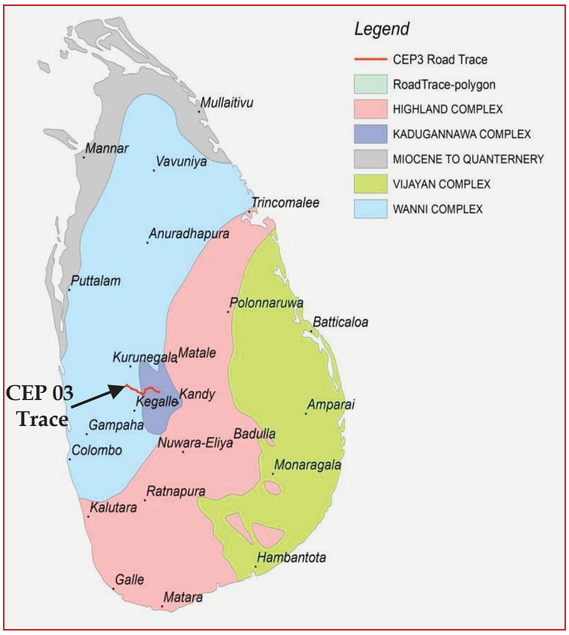


Figure 1 - Central Expressway Project 3 Trace

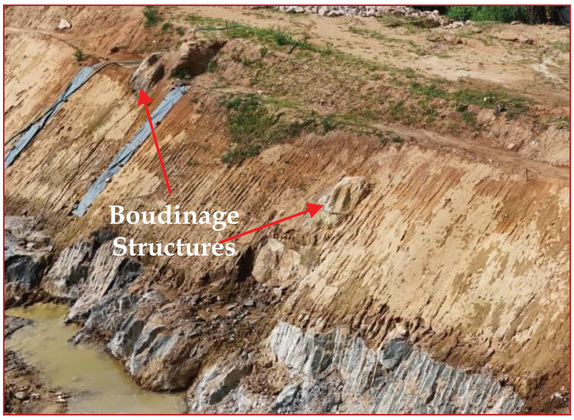


Figure 2 - Residual Formations at Central Expressway Project (CEP 3) Cutting Location

Figure 3 - Highly Jointed Meta-sedimentary Rocks at CEP 3 Cutting Location

The mineralogical heterogeneity inherent in these profiles creates zones of contrasting shear strength, erodibility, and permeability. The alteration of primary minerals such as feldspar and biotite into secondary clays establishes the rock-soil interface as a critical plane of weakness [5].

In highway engineering, these variations compromise the stability of high-cut slopes. Slopes where relict joints or mineralogically weak zones daylight are highly susceptible to failure, dictating the adoption of specialized stabilization designs based on site-specific mineralogical profiles [6].

2. Objectives

Understanding regional mineralogy is vital for managing slope stability [7]. This research investigates mineralogical transformations in residual formations and their metamorphic parent rocks within Sri Lanka's hilly terrain. The primary objective is to characterize weathering grades and mineralogical alterations along the CEP 3 corridor, evaluating their specific roles in driving slope instability.

3. Study Area

Central Expressway Project Section 3 (CEP 3) is a 32.5 km trace from Pothuhera to Galagedara, traversing the topographically rugged terrain of Sri Lanka's National Road Master Plan. The corridor is characterized by extensive residual formations and metamorphic parent rocks exhibiting varied weathering grades. A critical cut-slope section from Ch. 9+500 km to Ch. 10+290 km (Figures 4 & 5) was selected for this study. This site provides a representative, highly variable geo-mechanical profile, featuring deep saprolitic horizons and diverse mineralogical transitions.

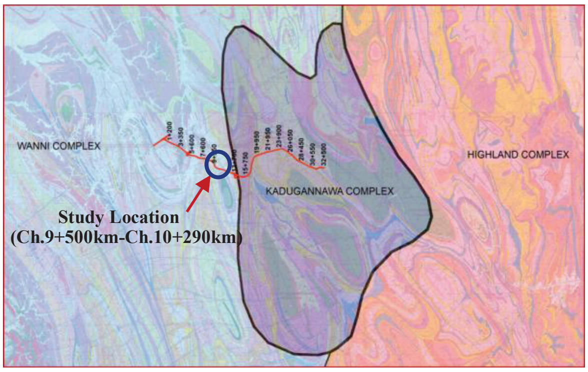


Figure 4 - Map of Study Location

Figure 5 - Study Location (Ch: 9+500 km - Ch: 10+290 km)

For systematic data collection and lithological classification, the study location was subdivided into three distinct geological sections based on observed rock types and weathering profiles:

- Section 1: From 9+500 km to 9+670 km
- Section 2: From 9+670 km to 9+830 km
- Section 3: From 9+830 km to 10+290 km.

The study area is predominantly mantled by residual formations derived from the intense weathering of the Wanni Complex metasedimentary sequence. According to the Geological Map of Sri Lanka [2], the underlying basement lithology consists of Charnockitic Biotite Gneiss (Figure 6).

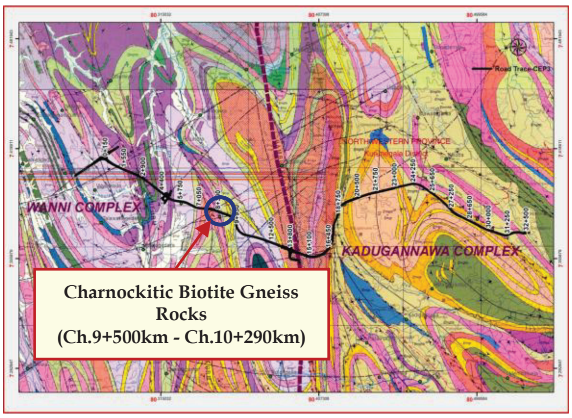


Figure 6 - Geological Map of Study Locations

4. Methodology

The study integrated field mapping and laboratory analysis to characterize the mineralogical and geomechanical properties of the site. Investigations included petrographic analysis, X-ray diffraction (XRD), and physical/mechanical testing of rock and soil units.

4.1 Field Investigation

Systematic site visits were conducted across three sections of the CEP 3 study area. Fieldwork focused on identifying weathering grades and assessing the physical properties of both metamorphic parent rocks and residual formations. Representative samples were collected using manual sampling techniques.

4.2 Laboratory Investigation

4.2.1 Sample collection

Undisturbed residual soil samples were retrieved from depths of 0-2.5m. Complementary rock samples were obtained from boreholes and exposed cut-slope sections to capture a complete weathering profile (Figure 7).

4.2.2 Sample preparation

Petrography: Selected rock units were prepared as polished thin sections for microscopic analysis of mineral textures and alteration (Figure 8).

XRD Analysis: Disturbed soil samples were oven-dried and pulverized to a fine, homogeneous powder (particle size <10 µm or 200-mesh) for crystalline phase identification (Figure 9).

4.2.3 Sample testing

Standardized testing protocols were applied to the prepared specimens (Table 1) to determine the index properties, mineralogical composition, and mechanical strength of the material.

Table 1 - Sampling and Testing Program

Test Procedure	Material Type and Sampling Source
Index Tests	Residual Soil, Representative samples from critical slope locations
X-Ray Diffraction (XRD)	Residual Soil, Representative samples from critical slope locations
Petrographic Analysis	Parent Rock (Bedrock), Core samples extracted from Boreholes

Index Property Testing: To determine the geotechnical characteristics of residual soils, particle size analysis, Specific Gravity, and Atterberg Limits tests were conducted in accordance with BS 1377:1990 (Part 2).

Petrographic Analysis: Fresh and weathered metamorphic parent rock units were examined via optical microscopy to quantify modal mineralogy, assess micro-textures, and document weathering-induced alterations.

X-Ray Diffraction (XRD): Crystalline phases within the residual soils were identified using XRD to determine the presence of secondary minerals (e.g., clay minerals and inorganic compounds) resulting from chemical weathering [8].

Residual soil   Highly/Moderately Weathered rock   Slightly Weathered/Fresh rock

Figure 7 – Sample Collected Points at Study Sections of Location (Ch: 9+500 km - Ch: 10+100 km)

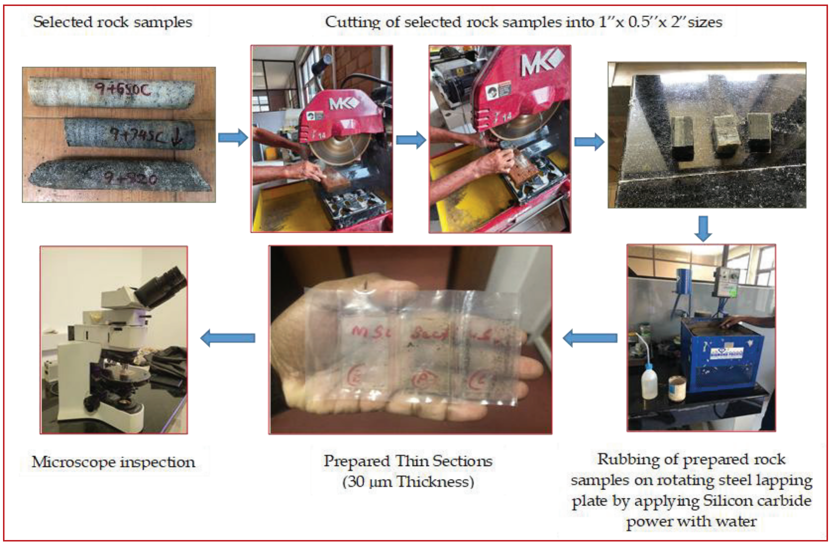


Figure 8 - Thin Sections Preparation for Petrographic Study

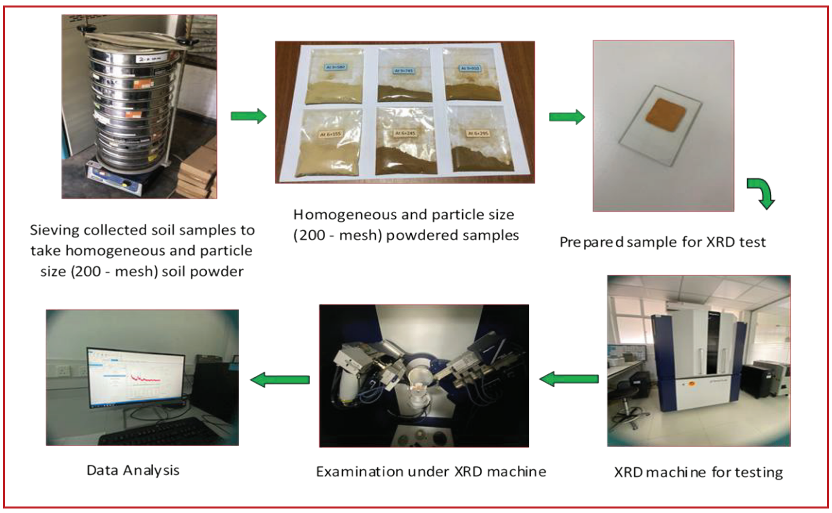


Figure 9 - Finely Ground Homogeneous Sample on X-Ray Diffraction (XRD) Test

5. Results

5.1 RMR Classification for Weathering Grades of Parent Rocks

The Rock Mass Rating (RMR) system, also known as the Geo-mechanics Classification, serves as a fundamental framework in rock engineering for quantifying the quality of a rock mass and to predict its behavior during and after excavation. To determine the RMR score, five primary parameters such as the Unconfined Compressive Strength (UCS) of the rock, Rock Quality Designation (RQD), spacing of discontinuities, condition of those discontinuities, and groundwater conditions, are assigned individual ratings and summed to a maximum value of 100. A sixth parameter, the orientation of joints relative to the engineering structure (such as the strike and dip of a slope face), is then applied as a negative adjustment ranging from 0 to -60. In this specific study, the vertical borehole investigation is crucial because it allows for the direct calculation of the RQD by measuring the percentage of intact core pieces longer than 10 cm, while specimens cut from core boxes and subjected to UCS testing provide the necessary rock material strength values. By carefully investigating discontinuity properties such as roughness, weathering, infilling, aperture, and water condition, these field data points are combined with laboratory results to provide a final score (0 to 100) that categorizes the rock into classes ranging from Very Good (Class I) to Very Poor (Class V). Based on the standard correlation between the ISRM (International Society for Rock Mechanics) Weathering Grade and the resulting RMR classification, the values typically align as shown in Table 2. Accordingly, weathering profiles of sections at study location was classified [9].

5.1.1 Characterization of weathering profile

Weathering grades of the metamorphic parent rock were classified as a function of depth for each study section. The classification was based on the RMR system [9] to delineate the weathering profile, as summarized in Table 3.

Table 2 - ISRM Weathering Grade and the resulting Rock Mass Rating (RMR) Classification

Weathering Grade	Description	Typical RMR Range	Rock Class
W1	Fresh	81 – 100	I (Very Good)
W2	Slightly Weathered	61 – 80	II (Good)
W3	Moderately Weathered	41 – 60	III (Fair)
W4	Highly Weathered	21 – 40	IV (Poor)
W5	Completely Weathered	< 21	V (Very Poor)
W6	Residual Soil	N/A	VI

Table 3 - Classification of Weathering Profile at Study Location According to RMR Classification

Study Section	RQD (%)	CR (%)	Weathering Grade	Depth (m)
Study Section 1 (at 9+580)	0	0	Residual soil	0.00 - 0.45
	0	0	Completely weathered rock	0.45 - 0.55
	43	88	Moderately weathered rock	0.55 - 3.30
	100	100	Fresh rock	3.30 - 4.80
	76	96	Slightly weathered rock	4.80 - 7.80
	100	100	Fresh rock	7.80 to advance
Study Section 2 (at 9+745)	0	0	Residual soil	0.00 - 1.35
	0	0	Completely weathered rock	1.35 - 3.00
	40	83	Moderately weathered rock	3.00 - 4.50
	65	98	Slightly weathered rock	4.50 - 7.30
	100	100	Fresh rock	7.30 to advance
Study Section 3 (at 9+910)	0	0	Residual soil	0.00 - 2.50
	0	0	Completely weathered rock	2.50 - 3.00
	48	81	Moderately weathered rock	3.00 - 4.50
	70	100	Slightly weathered rock	4.50 - 7.50
	97	100	Fresh rock	7.50 to advance

5.2. Results of Residual Soil Tests

5.2.1 Index tests

To characterize the physical behavior of the residual soils, natural moisture content, specific gravity, particle size distribution, and Atterberg limits were determined. For the particle size distribution, sieve analysis was performed to determine gravel and sand percentages, while hydrometer analysis was utilized to determine the fine percentages of clay and silt.

with the crystal lattices of the constituent minerals. The resulting diffraction angles and intensities produce a unique pattern, or "fingerprint," characteristic of specific mineral phases. This technique provides critical data regarding mineralogical composition, crystalline structure, and degree of crystallinity, enabling the identification of both primary and secondary (clay) minerals within the residual formations [10].

Table 4 - Results of Index Tests at Study Location

Study Section	Thickness of Residual Soil (m)	Sampling Depth (m)	Natural Moisture Content (%)	Specific Gravity (Gs)	Grain Size Distribution				Atterberg Limits			SPT Value	Soil Type (USCS)
					Gravel (> 4.75 mm) (%)	Sand (4.75 mm - 0.075 mm) (%)	Silt (0.075 mm - 0.002 mm) (%)	Clay (< 0.002mm) (%)	LL (%)	PL (%)	PI (%)		
Section 1 (at 9+580)	0.45	0.00 - 0.50	24	2.54	12	47	27	14	35	25	10	09	SM
Section 2 (at 9+745)	1.35	0.50 - 1.00	28	2.50	5	31	32	32	38	26	12	11	ML
Section 3 (at 9+910)	2.50	1.00 - 1.50	32	2.48	10	35	30	25	48	33	15	13	ML

***LL-Liquid Limit, PL-Plastic Limit, PI-Plasticity Index**

Additionally, SPT values were obtained during borehole investigations. These parameters were utilized to classify the soil units according to the Unified Soil Classification System (USCS). Based on the USCS, the residual soils at the study site consist primarily of two types such as Silty Sand (SM) and Low Plasticity Silt (ML). The summarized geotechnical properties for these units are presented in Table 4.

5.2.2 X-Ray Diffraction (XRD) test

The mineralogical composition of the residual soils was determined via X-ray diffraction (XRD), with diffraction patterns presented in Figures 10-12. During analysis, finely powdered samples were exposed to X-rays, which interact

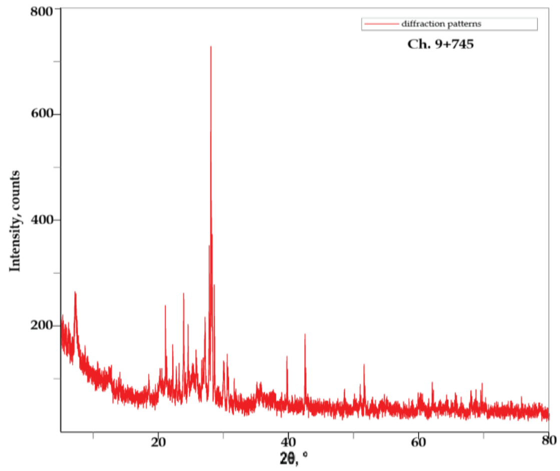


Figure 11 – Measured XRD Test Pattern of Soil at 9+745

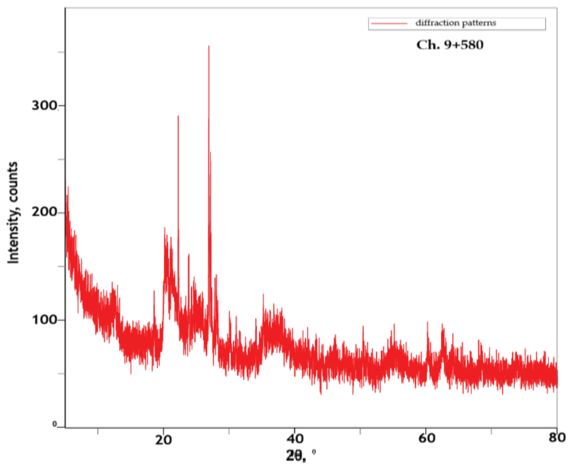


Figure 10 – Measured XRD Test Pattern of Soil at 9+580

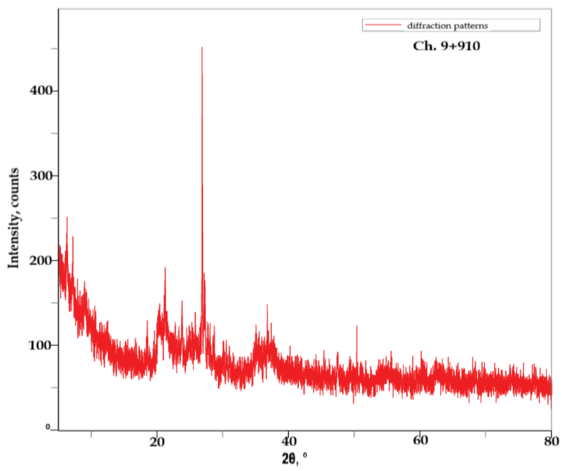


Figure 12 – Measured XRD Test Pattern of Soil at 9+910

5.2.2.1 Mineral constituents within residual soils

Deciding on the types and percentages of minerals within residual soils from XRD results involves a two-step transition from raw electromagnetic data to mineralogical identification and quantification. In the context of the study area, this process is what allowed for the identification of specific clay minerals, like Kaolinite and Smectite, which are critical to understanding the stability of the slopes.

The "type" of mineral is determined by matching the diffraction pattern (the positions of the peaks) against a known database, such as the ICDD (International Centre for Diffraction Data). Once the minerals are identified, their relative percentages are calculated using the intensity (height and area) of the peaks [7]. Types of minerals and calculated mineral percentages for the study site are summarized in Table 5.

5.3 Results of Sightly Weathered/Fresh Parent Rock Tests

5.3.1 Identification of parent rocks and their physical properties

Rock-forming minerals are classified by their physical properties [11]. In this study, the metamorphic parent rocks were logged via boreholes, recording color and lithology, with identities confirmed by petrographic analysis (Table 6). Rock strength was categorized using visual observation, hammer blow tests, and UCS laboratory analysis. Rock mass quality was further quantified through RQD and, in weathered zones, SPT values.

5.3.2 Petrographic analysis test

Photomicrographs of the metamorphic parent rocks (fresh to slightly weathered) are presented in Figures 13–15, captured under both plane-polarized light (PPL), 'a', and cross-polarized light (XPL), 'b'. These images facilitate the identification of mineral textures, grain boundaries, and alteration features. Based on these petrographic observations, the primary mineral assemblages and modal compositions of the parent rocks were determined. The identified mineral contents for each study section are summarized in Table 7.

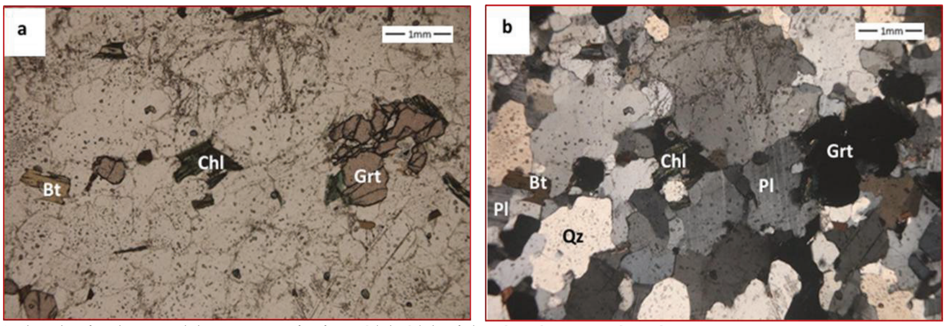
Identifying minerals and estimating their percentages from photographic images (a method often called Digital Image Analysis or Petrographic Image Processing) involves analyzing the visual characteristics of the rock at a macroscopic or microscopic level. While XRD provides the chemical fingerprint, photographic analysis provides the spatial distribution. The "type" of mineral in a photograph is decided by identifying diagnostic physical properties that remain visible in the image. The percentage is estimated through Point Counting or Area-Based Image Segmentation.

Table 5 – Percentage of Mineral Constituents within Residual Soils at Study Location

Study Section	Residual Soil Type	Mineral	Percentage (%)
At 9+580	SM	Quartz	25 - 27
		Feldspar	23 - 25
		Kaolinite	17 - 20
		Fe-oxide	14 - 16
		Smectite	11 - 13
		Illite	07 - 09
		Chlorite	02 - 03
At 9+745	ML	Kaolinite	30 - 32
		Quartz	15 - 17
		Feldspar	14 - 16
		Illite	14 -16
		Fe-oxide	13 - 15
		Vermiculite	08 - 10
		Chlorite	03 - 04
		Hornblende	02 - 03
At 9+910	ML	Kaolinite	36 - 38
		Quartz	17 - 20
		Feldspar	12 - 15
		Fe-oxide	11 - 13
		Illite	10 - 12
		Vermiculite	07 - 09
		Chlorite	05 - 07
		Biotite	02 - 03

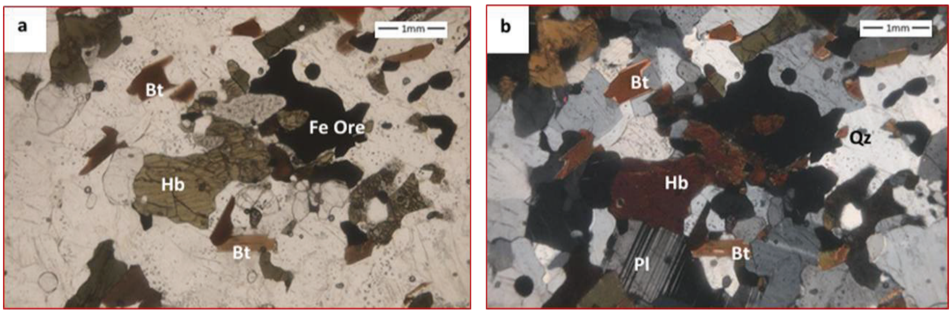
Table 6 - Physical Properties of Parent Rocks at Study Location

Study Section	Parent Rock Type	Physical Properties
Study Section 1 (at 9+580)	Quartzo Feldspathic Gneiss	Moderately strong, Greyish white with Pinkish white, Metasedimentary
Study Section 2 (at 9+745)	Biotite Hornblende Gneiss	Slightly strong, White with grey, Metasedimentary
Study Section 3 (at 9+910)	Biotite Gneiss	Strong, Blackish grey Metasedimentary



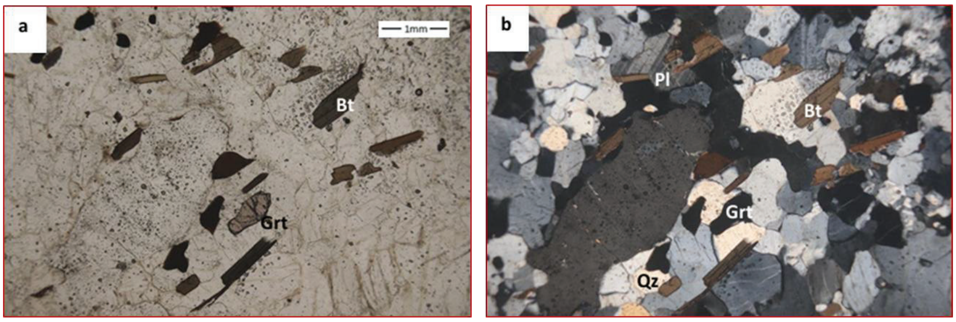
*Pl- Plagioclase Feldspar, Bt-Biotite, Chl-Chloride, Qz-Quartz, Grt-Garnet

Figure 13 – Photomicrographs of thin Section at 9+580



*Pl- Plagioclase Feldspar, Bt-Biotite, Hb-Hornblende, Qz-Quartz

Figure 14 – Photomicrographs of thin Section at 9+745



*Pl- Plagioclase Feldspar, Bt-Biotite, Qz-Quartz, Grt-Garnet

Figure 15 – Photomicrographs of thin Section at 9+910

Table 7 – Mineral Constituents of Parent Rocks (Slightly Weathered/Fresh) at Study Location

Study Section	Parent Rock Type (Lithology)	Minerals	Percentage (%)
Study Section 1 (at 9+580)	Quartzo Feldspathic Gneiss	Quartz	38 - 42
		Alkali Feldspar	20 - 25
		Plagioclase Feldspar	15 - 20
		Fe-Oxide	08 - 10
		Biotite	05 - 06
		Garnet	01 - 02
Study Section 2 (at 9+745)	Biotite Hornblende Gneiss	Alkali Feldspar	28 - 30
		Quartz	23 - 25
		Plagioclase Feldspar	18 - 20
		Hornblende	15 - 18
		Biotite	05 - 07
		Fe-Oxide	03 - 04
Study Section 3 (at 9+910)	Biotite Gneiss	Alkali Feldspar	33 - 38
		Quartz	25 - 30
		Plagioclase Feldspar	20 - 25
		Biotite	09 - 12
		Fe-Oxide	03 - 05
		Garnet	01 - 02

6. Analysis

6.1 Analysis of Weathering Profiles

Borehole logs were synthesized to establish a generalized weathering profile for the study area. Utilizing the RMR system [9], the profile illustrates a transition of weathering grades from the surface to the basement lithology. The data, summarized in Table 2, demonstrate that weathering intensity decreases progressively with depth, as the rock mass transitions from highly decomposed residual soil to the fresh metamorphic parent rock.

The observation that weathering intensity decreases progressively with depth is primarily derived from the vertical variation of the RQD and the UCS values observed in the borehole data.

In the upper sections of the profile, chemical weathering is most intense, causing the decomposition of primary minerals into secondary clays and weakening the rock structure; this results in highly fractured cores with low RQD values and rock material with low UCS. As the borehole progresses deeper, the rock mass is less exposed to surface-driven weathering agents, leading to more "massive" and intact core recoveries (>75% RQD) and higher intact strength measurements from the laboratory [9].

This physical transition is further supported by the Condition of Discontinuities parameter, which typically shows a shift from wide, clay-filled joints (Grade IV–V) near the surface to tight, fresh joint surfaces (Grade I–II) at depth. When these parameters are aggregated into the RMR score, the numerical result increases with depth, providing a quantitative validation that the rock mass quality improves as it approaches the fresh metamorphic parent rock [9].

6.2 Analysis of Mineral Constituents within Weathered Parent Rocks

Petrographic analysis and XRD results were integrated to characterize the mineralogical evolution from the weathered metamorphic parent rock to the residual soil. This transition highlights the chemical breakdown of primary minerals and the subsequent formation of secondary clays. The comprehensive mineralogical changes observed across the weathering profiles are summarized in Tables 8-10.

Table 8 – Mineral Changes within Weathered Profile of Garnet Biotite Gneiss Rock at Ch. 9+580

Mineral Constituent (%)	Garnet Biotite Gneiss Rock at Ch. 9+580		
	Slightly Weathered /Fresh	**Highly/ Moderately Weathered**	**Residual Soils**
Quartz	38 - 42	35 - 37	25 - 27
Alkali Feldspar	20 - 25	18 - 20	23 - 25
Plagioclase Feldspar	15 - 20	12 - 15	
Fe oxide minerals	08 - 10	10 - 12	14 - 16
Garnet	01 - 02	00	00
Biotite	05 - 06	02 - 03	00
Kaolinite	00	09 - 11	17 - 20
Illite	00	03 - 06	07 - 09
Smectite	00	00	11 - 13
Chlorite	00	06 - 08	02 - 03

Table 9 – Mineral Changes within Weathered Profile of Biotite Hornblende Gneiss Rock at Ch. 9+745

Mineral Constituent (%)	Biotite Hornblende Gneiss Rock at Ch. 9+745		
	Slightly Weathered /Fresh	**Highly/ Moderately Weathered**	**Residual Soils**
Quartz	23 - 25	20 - 22	15 - 17
Alkali Feldspar	28 - 30	18 - 20	14 - 16
Plagioclase Feldspar	18 - 20	12 - 14	
Hornblende	15 - 18	07 - 08	02 - 03
Biotite	05 - 07	01 - 02	00
Fe oxide minerals	03 - 04	11 - 13	13 - 15
Kaolinite	00	15 - 17	30 - 32
Illite	00	05 - 07	14 - 16
Vermiculite	00	00	08 - 10
Chlorite	00	07 - 09	03 - 04

Table 10 – Mineral Changes within Weathered Profile of Biotite Gneiss Rock at Ch. 9+910

Mineral Constituent (%)	Biotite Gneiss Rock at Ch. 9+910		
	Slightly Weathered /Fresh	Highly/ Moderately Weathered	Residual Soils
Quartz	25 - 30	20 - 22	17 - 20
Alkali Feldspar	33 - 38	19 - 21	12 - 15
Plagioclase Feldspar	20 - 25	10 - 12	
Biotite	09 - 12	03 - 05	02 - 03
Fe oxide minerals	03 - 05	14 - 16	11 - 13
Kaolinite	00	18 - 20	36 - 38
Illite	00	06 - 08	10 - 12
Vermiculite	00	00	07 - 09
Chlorite	00	08 - 10	05 - 07

7. Discussion

This study investigated the impact of mineralogical characteristics on the stability of high-cut slopes along the CEP 3 trace.

<u>Mineralogical and Geo-mechanical Zonation</u>

Mineralogical and geo-mechanical zonation established in this study provides a direct roadmap for slope design and risk mitigation. By integrating the RMR classification with weathering grades, the following applications are identified:

1. Foundation and Support Design (W4–W6)

In the Upper Zone, the presence of Grade W6 (Residual Soil) and W5 (Completely Weathered) material corresponds to a "Very Poor" Rock Class. Because RMR values drop below 21 in these zones, the material behaves as a soil mass rather than a rock mass.

Application: Traditional rock bolts are useless here as there is no "competent" rock to anchor into. Instead, engineers must use soil nailing and heavy-duty shotcrete with wire mesh to create a reinforced "gravity wall" effect. The focus is on preventing rotational slides by increasing the overall shear resistance of the soil matrix [12].

2. Structural Stabilization and Kinematic Control (W3–W4)

The Central Zone, characterized by W3 (Moderately Weathered) and W4 (Highly Weathered) rock, falls into the "Fair" to "Poor" rock classes (RMR 21–60). Here, the rock still retains its crystalline structure, but it is heavily intersected by joints and fractures.

Application: This is the most critical zone for kinematic analysis. Because failure occurs along relict joints, engineers must apply patterned rock bolting. These bolts must be long enough to pass through the weathered "loose" blocks and anchor into the more competent rock of the zone below. Drainage is also vital here; weep holes must be drilled into the shotcrete to prevent buildup of hydrostatic pressure behind the slope face, which is a common trigger for rockfalls [12].

3. Optimized Excavation and Slope Geometry (W1–W2)

The Bottom Zone consists of W1 (Fresh) and W2 (Slightly Weathered) rock, representing "Good" to "Very Good" rock classes (RMR 61–100), respectively.

Application: This zone is the most economically advantageous. Due to high shear strength and minimal fracturing, engineers can design steeper slope angles at the base (e.g., 70° to 80°) without compromising safety. This "steepening" at the bottom reduces the total volume of earthwork required at the top of the cut, significantly lowering project costs. Furthermore, this zone serves as a reliable foundation for heavy structures or bridge abutments along the trace.

By applying these mineralogical insights, the CEP 3 project can transition from a "one-size-fits-all" slope design to a **zonation-based approach**. This ensures that high-risk areas receive maximum reinforcement while stable zones remain cost-effective, ultimately enhancing the long-term safety of the infrastructure [13].

<u>Petrographic and Mineralogical Evolution</u>

The petrographic and mineralogical evolution of the gneissic parent rock along the CEP 3 trace provides a fundamental explanation for the varying stability levels observed across the slope profiles.

In the Moderately Weathered (Grade III/IV) zones, the preservation of the parent rock texture is deceptive; while the rock appears competent, petrographic analysis reveals the initial chemical breakdown of biotite, garnet, and hornblende into chlorite and iron oxides. These secondary minerals often coat joint surfaces, significantly reducing the shear strength of discontinuities and facilitating structural failures even in relatively solid rock.

As weathering advances to Grade VI (Residual Soil), XRD analysis confirms a complete mineralogical shift that dictates the soil's physical behavior. Silty Sand (SM) derived from Garnet Biotite Gneiss retains high quartz content but is plagued by the presence of Smectite, an expansive clay mineral that introduces a high risk of volume change and instability during seasonal moisture fluctuations. Conversely, the Sandy Silt (ML) derived from Biotite Hornblende Gneiss exhibits a higher clay fraction but contains Vermiculite, which can actually enhance drainage and soil structure.

This mineralogical differentiation is critical for engineering, as it determines whether stabilization should focus on moisture-proofing expansive soils or installing advanced subsurface drainage to prevent the internal erosion of silty layers.

Impact on Geotechnical Stability

The mineralogical composition of the slope material along the CEP 3 trace acts as the primary driver for its geotechnical performance, influencing everything from surface durability to deep-seated shear strength. Quartz serves as the structural backbone of the soil matrix, offering high resistance to mechanical erosion and enhancing overall stability due to its chemically inert nature. In contrast, high concentrations of Feldspar represent a long-term liability; because feldspar is highly susceptible to hydrolysis, its presence indicates a material that will continue to weaken over the project's lifespan as it further decomposes into clay [13].

The specific type of clay mineral present further refines the stability profile. While Kaolinite tends to act as a stabilizer by providing a relatively low-plasticity framework, and Illite enhances the soil's cohesion, the localized presence of Smectite introduces significant risk. Smectite's high swelling capacity means that even minor moisture fluctuations can trigger volumetric changes, leading to a rapid loss of shear strength and potential slope failure [13]. Consequently, in smectite-rich zones, the engineering focus must shift toward rigorous drainage control and moisture barriers. Finally, the presence of Iron oxides (Fe-oxides) plays a dual role; beyond influencing the distinct reddish-brown coloration of the tropical terrain, these minerals can contribute to natural particle cementation, slightly increasing the "apparent cohesion" of the soil and providing a marginal boost to the slope's factor of safety [14].

Site-Specific Variations

The spatial distribution of weathering intensity along the CEP 3 trace establishes a clear correlation between residual soil thickness and mineralogical maturity, creating distinct geotechnical risk profiles for different project segments.

In Study Sections 2 and 3, the presence of high soil thickness alongside depleted primary minerals (quartz and feldspar) and high clay concentrations signifies a mature weathering profile. This advanced state of decomposition implies that the metamorphic parent rock's structural integrity has been almost entirely replaced by a fine-grained, low-strength overburden, resulting in a high susceptibility to deep-seated slides and creep.

Conversely, Section 1 is characterized by an immature weathering profile, featuring low soil thickness and a boulder-rich landscape that retains significant percentages of primary minerals. While this section benefits from higher material strength and lower clay content, the engineering challenge shifts from mass stability to the management of localized boulder roll-outs.

These site-specific variations necessitate a differentiated design approach, where mature sections require extensive mass stabilization and deep drainage, while immature zones focus on structural anchoring and rockfall protection.

8. Conclusion

The investigation of the CEP 3 corridor demonstrates that slope stability is fundamentally controlled by the mineralogical evolution of the gneissic parent rock. The study yielded the following key conclusions:

Weathering Control: The RMR-based weathering profile successfully delineated three geo-mechanical zones. Stability risks transition from rotational slides in the upper residual soils

(Grade VI) to structural rockfalls in the fractured central horizons (Grade IV/V), while the fresh metamorphic basement remains stable.

Mineralogical Transformation: Petrographic and XRD analyses confirmed that the breakdown of feldspar, biotite, and hornblende within the gneiss into secondary clay minerals is the primary driver of soil formation. This transition from primary minerals to clays correlates directly with increased plasticity and reduced shear strength.

Mineral-Specific Risks: The presence of Smectite in Silty Sand (SM) soils at specific chainages represents a critical risk factor due to its high swelling potential. Conversely, the presence of kaolinite and Fe-oxides provides a degree of structural stability through cohesion and cementation.

Geological Heterogeneity: Significant variations in residual soil thickness (highest in Sections 2 and 3) are tied to the specific mineral composition of the gneissic parent rock. Higher clay-to-quartz ratios in these sections indicate advanced weathering maturity, requiring specialized engineering interventions.

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