

# Integrated Geotechnical Stability Assessment and Real-Time Porewater Monitoring of a Tailings Storage Facility in the Rokel-Kasila Belt, Sierra Leone

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## ABSTRACT

The long-term geotechnical integrity of Tailings Storage Facilities (TSFs) in tropical environments is a critical challenge for sustainable mining, requiring a transition from static safety assessments to dynamic, data-driven monitoring. This study presents a comprehensive geotechnical evaluation of the TSF at Marampa Mines Limited (MML), situated within the Rokel-Kasila Belt of Sierra Leone. The research integrates three core components: a detailed subsurface investigation using Standard Penetration Tests (SPT) and Cone Penetration Tests (CPTu), numerical slope stability modeling via GEO-5 software, and the implementation of a real-time monitoring network using Vibrating Wire Piezometers (VWPs). Initial field characterization identified the prevalence of "clayey gravel with sand and silty sand" strata, providing the baseline parameters for stability analysis. Numerical results confirmed a robust Factor of Safety (FoS) of 2.08 for the facility's northern wall. To validate these findings under fluctuating climatic conditions, a network of five VWPs was strategically installed to monitor dynamic porewater pressures. This paper details the rigorous data processing methodologies employed, including temperature and barometric corrections using both linear and second-order polynomial equations. By correlating in-situ shear strength with real-time pressure readings, the study demonstrates how proactive monitoring verifies the operational safety thresholds established during the design phase. This integrated approach provides a replicable framework for the management of critical mining infrastructure in similar tropical geological contexts, ensuring ongoing vigilance and structural integrity throughout the facility's service life.

**Keywords:** Tailings Storage Facilities (TSFs), Geotechnical Instrumentation, Slope Stability, Vibrating Wire Piezometer (VWP), Rokel-Kasila Belt, Site Investigation, Porewater Pressure.

## INTRODUCTION

The long-term geotechnical integrity of Tailings Storage Facilities (TSFs) in tropical environments poses a significant challenge for sustainable mining operations. Ensuring the structural stability of these critical facilities in climatically difficult conditions is paramount to responsible practice. Marampa Mines Limited (MML) operates a TSF within the Marampa district of Sierra Leone, a region characterized by complex geological settings.

The project area is located within the Rokel-Kasila Belt, an approximately 100-km wide, NNW-SSE trending belt of Archean to Neoproterozoic age rocks. The underlying stratigraphy is highly deformed, featuring principal lithologies such as Quartz-Mica Schist (QMS), Specularite Schist (SQS), Piemontite Schist (PMS), and Gneiss. Field investigations revealed the local subsurface strata primarily consist of "clayey gravel with sand and silty sand" characterized by medium density and moderate plasticity. This paper presents a comprehensive, integrated geotechnical evaluation and real-time monitoring program conducted on the northbound section of the existing

MML TSF embankment, synthesizing findings from subsurface investigations, laboratory characterization, and numerical analysis.

## METHODOLOGY

The geotechnical investigation and subsequent monitoring program were executed in strict compliance with applicable geotechnical engineering and ASTM standards (ASTM D5778-12, 2012).

### Subsurface Investigation

A comprehensive drilling program involved three boreholes drilled to a maximum depth of 15 meters using a GY-150 percussion drilling rig. Standard Penetration Tests (SPT) were performed at 1.0-meter intervals to obtain N-values and disturbed soil samples, following established procedures for sampling and overburden pressure effects (Skempton, 1986). (pp. 2, 6) Five Cone Penetration Tests with porewater pressure measurement (CPTu) were also conducted to a maximum depth of 25 meters, recording cone tip resistance ( $Q_c$ ) sleeve friction ( $F_s$ ), and porewater pressure ( $U_2$ ) at 0.1-meter intervals. The acquired data were processed using CPeT-IT software.

### Laboratory Testing

A thorough laboratory testing program was undertaken on both disturbed and undisturbed soil samples to determine material properties and obtain essential input parameters for stability analysis (Peck et al., 1974). Tests performed included natural moisture content, plasticity and liquid limits, particle size distribution (PSD), consolidated undrained (CU) triaxial tests, and permeability tests. These tests allowed the classification of soils according to the Unified Soil Classification System (USCS).

### Stability Analysis and Monitoring

Slope stability analysis was performed using two parallel approaches: numerical modeling with GEO-5 software (employing the Bishop Optimization method) and analysis of data obtained from field instrumentation. A network of five VWPs was strategically installed within potential failure planes to monitor dynamic porewater pressures. The data acquisition process involved the use of an RST VW2106 Readout Unit. The raw data underwent temperature and barometric pressure corrections. The corrected pressure was calculated using either a linear or second-order polynomial equation:

#### Linear Equation:

$$P = C(L_0 - L) - T_k(T_0 - T) + (S_0 - S) \dots\dots\dots 1$$

#### Second-Order Polynomial Equation:

$$P = L^2 + BL + C - T_k(T_0 - T) + (S_0 - S) \dots\dots\dots 2$$

Where

$$C = (L_0)^2 + BL_0 \dots\dots\dots 3$$

$L$  is the current B-unit reading,  $L_0$  is the initial reading,  $T$  is temperature,  $S$  is barometric pressure,  $CF$  is the calibration factor, and  $T_k$  is the temperature correction factor.

## RESULTS AND ANALYSIS

The field investigation yielded substantial factual data that informed the detailed analysis of the TSF embankment. Subsurface exploration was completed in August 2022. (p. 3)

### Field and Laboratory Results

Variations in SPT N-values observed across the site generally increased with depth as expected, but with fluctuations attributed to geological interruptions like weak seams (see Figure 1). Field N-values were corrected for hammer efficiency (55%), borehole diameter, and rod length to obtain  $N_{60}$  and  $N_{1(60)}$  values, which were used to estimate in-situ densities (see Table 1) and allowable bearing (see Table 2 Table 3, Table 4, and Table 5).

CPTu testing provided continuous data profiles of cone tip resistance, sleeve friction, and porewater pressure at 0.1 m intervals. CPeT-IT software was used to interpret this data using normalized soil behavior type charts ( $SBT_n$ ), which classified the soil into various zones (Robertson et al., 1986; Robertson, 1990). Laboratory tests performed on collected samples confirmed the general presence of clayey gravel with sand and silty sand layers. Key parameters were determined through Consolidated Undrained (CU) Triaxial Tests and permeability tests, which provided the necessary input for subsequent stability calculations.

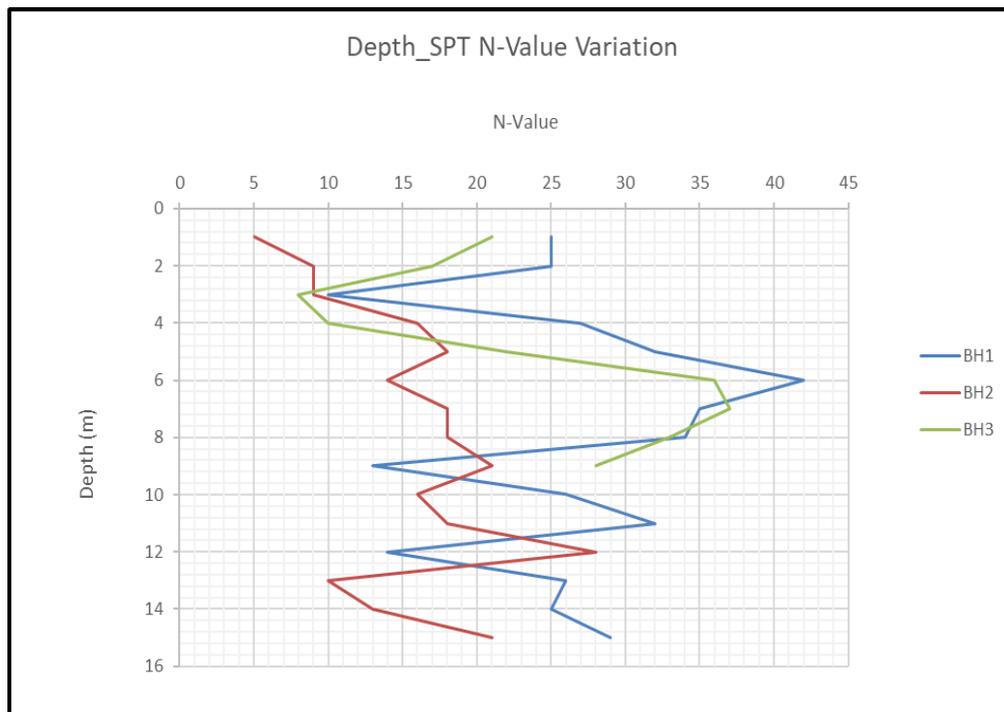


Figure 1: Variation of SPT N-Values with Depth

Table 1: Estimated Density Values from SPT-N Values

Depth	Density (KN/m <sup>3</sup> )		
	BH1	BH2	BH3
1	18.80	15.00	20.20
2	18.80	15.40	18.80
3	15.40	15.40	16.70
4	19.02	15.40	17.20
5	19.5	15.40	20.60
6	20.1	15.40	22.20

7	19.6	18.40	22.40
8	19.3	17.90	20.80
9	16.0	17.60	19.50
10	18.5	17.90	
11	19.1	18.40	
12	16.0	18.40	
13	18.5	15.40	
14	18.5	15.60	
15	19.0	17.50	

Table 2: Computed Bearing Capacity for BH-1

Dep th (m)	Soil Descripti on(s)	BOREHOLE - ID: BH-01										
		Ns pt	Unit weig ht of soil (KN/ m3)	Tota l stres s (Kp a)	Grou nd water Not Water @11. 2m	Porewa ter Pressur e (Kpa)	Effecti ve stress (Kpa)	Overburd en correctio n factor (CN)	Combin ed ST correcti on factor	N 60	(N1) 60	<b>Bearin g Capaci ty Qa(KP a)</b>
1	Clayey Gravel with Sand	25	18.80	19	0	0.00	19	2.000	0.7875	20	39	<b>417</b>
2	Clayey Gravel	25	18.80	38	0	0.00	38	1.631	0.7875	20	32	<b>340</b>
3	clayey gravel with sand	10	15.40	53	0	0.00	53	1.374	0.7875	8	11	<b>115</b>
4	clayey gravel with sand	27	19.02	72	0	0.00	72	1.178	0.8925	24	28	<b>301</b>
5	Clayey gravel with sand	32	19.5	92	0	0.00	92	1.045	0.8925	29	30	<b>316</b>
6	Silty Sand	42	20.1	112	0	0.00	112	0.947	0.8925	37	35	<b>376</b>
7	Silty Sand	35	19.6	131	0	0.00	131	0.873	0.9975	35	30	<b>323</b>
8	Silty Sand	34	19.3	151	0	0.00	151	0.815	0.9975	34	28	<b>293</b>

9	Silty Sand	13	16.0	167	0	0.00	167	0.775	0.9975	13	10	<b>107</b>
10	Silty Sand	26	18.5	185	0	0.00	185	0.735	0.9975	26	19	<b>202</b>
11	Silty Sand	32	19.1	204	0	0.00	204	0.700	0.9975	32	22	<b>237</b>
12	Silty Sand	14	16.0	220	0.8	7.85	212	0.686	0.9975	14	10	<b>102</b>
13	Silty Sand	26	18.5	239	1.8	17.66	221	0.673	0.9975	26	17	<b>185</b>
14	clayey gravel with sand	25	18.5	257	2.8	27.47	230	0.660	0.9975	25	16	<b>174</b>
15	clayey gravel with sand	29	19.0	276	3.8	37.28	239	0.647	0.9975	29	19	<b>198</b>

Table 3: Computed Bearing Capacity for BH-2

Dep th (m)	Soil Description(s)	BOREHOLE - ID: BH-02										
		Ns pt	Unit weight of soil (KN/m <sup>3</sup> )	Total stress (Kpa)	Groundwater Encountered @13.4m	Porewater Pressure (Kpa)	Effective stress (Kpa)	Overburden correction factor (CN)	Combined SPT correction factor	N 60	(N1) 60	Bearing Capacity Qa(KPa)
1	Clayey Gravel with Sand	5	15.00	15	0	0	15	2.0000	0.7875	4	8	<b>83</b>
2	Clayey Gravel with Sand	9	15.40	30.4	0	0	30	1.8137	0.7875	7	13	<b>136</b>
3	Sandy silt	9	15.40	45.8	0	0	46	1.4776	0.7875	7	10	<b>111</b>
4	Silty Sand	16	15.40	61.2	0	0	61	1.2783	0.8925	14	18	<b>193</b>
5	Silty Sand	18	15.40	76.6	0	0	77	1.1426	0.8925	16	18	<b>195</b>
6	Silty Sand	14	15.40	92	0	0	92	1.0426	0.8925	12	13	<b>138</b>
7	Silty Sand	18	18.40	110.4	0	0	110	0.9517	0.9975	18	17	<b>181</b>
8	Silty sand	18	17.90	128.3	0	0	128	0.8828	0.9975	18	16	<b>168</b>
9	Silty sand	21	17.60	145.9	0	0	146	0.8279	0.9975	21	17	<b>184</b>
10	Silty sand	16	17.90	163.8	0	0	164	0.7813	1.0500	17	13	<b>139</b>
11	Silty sand	18	18.40	182.2	0	0	182	0.7408	1.0500	19	14	<b>148</b>
12	Silty sand	28	18.40	200.6	0	0	201	0.7060	1.0500	29	21	<b>220</b>

13	Clayey Gravel	10	15.40	216	0	0	216	0.6804	1.0500	11	7	<b>76</b>
14	Clayey Gravel	13	15.60	231.6	0.6	6	226	0.6656	1.0500	14	9	<b>96</b>
15	Clayey Gravel	21	17.50	249.1	1.6	16	233	0.6546	1.0500	22	14	<b>153</b>

Table 4: Computed Bearing Capacity for BH-3

Depth (m)	Soil Description(s)	BOREHOLE - ID: BH-03										
		Nspt	Unit weight of soil (KN/m3)	Total stress (Kpa)	Groundwater Encountered @2.3m	Porewater Pressure (Kpa)	Effective stress (Kpa)	Overburden correction factor (CN)	Combined SPT correction factor	N60	(N1)60	Bearing Capacity Qa(KPa)
1	Clayey gravel	21	20.20	20.2	0	0	20	2.0000	0.7875	17	33	<b>351</b>
2	Clayey gravel	17	18.80	39	0	0	39	1.6013	0.7875	13	21	<b>227</b>
3	Clayey gravel	8	16.70	55.7	0.7	7	49	1.4310	0.7875	6	9	<b>96</b>
4	Clayey gravel with Sand	10	17.20	72.9	1.7	17	56	1.3337	0.8925	9	12	<b>126</b>
5	Clayey Sand with Gravel	22	20.60	93.5	2.7	26	67	1.2216	0.8925	20	24	<b>254</b>
6	Clayey Sand with Gravel	36	22.20	115.7	3.7	36	79	1.1222	0.8925	32	36	<b>382</b>
7	Clayey Sand with Gravel	37	22.40	138.1	4.7	46	92	1.0426	0.9975	37	38	<b>408</b>
8	Clayey Sand with Gravel	33	20.80	158.9	5.7	56	103	0.9854	0.9975	33	32	<b>344</b>
9	Clayey Sand with Gravel	28	19.50	178.4	6.7	66	113	0.9421	0.9975	28	26	<b>279</b>

Table 5: Computed Bearing Capacity for Rock Encountered @BH-3

Bore hole ID	Depth to rock (m)	Rock diameter (mm)	Length of rock core sample (m)	Total length of pieces greater than rock Diameter (m)	Total length of pieces greater than 100mm (m)	Core run (mm)	Rock type	Total core recovery (TCR) %	Solid core recovery (SCR) %	Rock quality designation (RQD) %	Unconfined compression strength (MPa)	Allowable bearing capacity (MPa)
BH-3	9.8	55	0.84	0.84	0.84	15	Gabbroic rock	0.56	0.56	56	103	10.77

## Stability Analysis and Monitoring Outcomes

The slope stability analysis was conducted using two distinct approaches: the GEO-5 numerical analysis and the VWP data analysis.

**GEO-5 Analysis:** It utilises the Bishop Optimization technique, compared total restoring moments to sliding moments along a critical failure plane. The analysis, based on current site conditions, definitively determined the investigated section of the TSF for it to be stable.

**VWP Data Analysis:** Five VWPs were installed at critical sections of the investigation area. The data processing methods using linear and polynomial equations allowed for the continuous monitoring of porewater pressure fluctuations. This data was directly integrated into the stability assessment by accounting for its impact on soil shear strength in the field.

Both approaches provided a consistent assessment of the TSF's condition. As shown in Table 1, the calculated Factor of Safety (FoS) of 2.08 significantly exceeds both the minimum safety requirements and recognized international benchmarks for long-term TSF stability.

Table 1. Comparison of Calculated FoS against International Safety Benchmarks

Stability Condition	Minimum Required FoS	MML TSF Result (Northern Wall)	Compliance Status
Static (Long-Term)	1.5	<b>2.08</b>	<b>Exceeds</b>
Operational (Steady-State)	1.3	2.08	Exceed
Stability Limit	1.0	2.08	Well Above

The northern wall boasts a static Factor of Safety (FoS) of 2.08, significantly exceeding the minimum safety requirement of 1.0. The GWT-based analysis also affirmed that the TSF is not susceptible to failure caused by groundwater levels, as all derived FoS values remained above. The continuous VWP monitoring is instrumental in validating these findings against real-time subsurface changes, ensuring ongoing vigilance throughout the facility's service life.

## CONCLUSIONS

The comprehensive geotechnical investigation and integrated monitoring program at the Marampa Mines TSF successfully characterized the subsurface conditions. The assessment integrated data from extensive field testing (SPT and CPTu), laboratory analysis, numerical modeling, and real-time instrumentation. The key findings confirm the robust stability of the TSF's northern wall, which exhibits a static Factor of Safety (FoS) of 2.08 under current operating conditions. All stability analyses conducted based on various groundwater table scenarios consistently produced FoS values greater than 1.0, indicating low susceptibility to failure from typical GWT fluctuations.

Furthermore, this framework aligns with the Global Industry Standard for Tailings Management (GISTM), as the static FoS of 2.08 exceeds the 1.5 requirement for long-term stability. The implementation of a continuous monitoring system using VWPs is instrumental in maintaining ongoing vigilance over the stability of the slope throughout its operational service life. The correlation of site-specific field investigation results with continuous monitoring data provides a valuable framework for effective management strategies for TSFs in similar tropical geological contexts.

## RECOMMENDATIONS

Based on the findings, the following are recommended for continued safe management:

- **Continuous Monitoring:** The current VWP monitoring system should be maintained without interruption for promptly identifying shifts in subsurface conditions.
- **Data Analysis:** The established methodology for VWP data processing, incorporating temperature and barometric corrections, should be consistently applied.
- **Routine Review:** Monitoring data should be routinely reviewed and compared against the established stability parameters (e.g., minimum FoS of 1.0).
- **Integrated Management Plan:** Insights gained from this integrated approach should be formally incorporated into the site's overall TSF management plan.

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