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GEOLOGICAL AND GEOTECHNICAL INVESTIGATIONS OF ARTISANAL MINING SUBSIDENCE AROUND KURU AND GURATOPP AREAS WITHIN THE JOS PLATEAU TIN FIELDS, NORTH-CENTRAL NIGERIA

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ABSTRACT

Artisanal tin mining activities on the Jos Plateau tin field is currently characterized by incessant mine subsidence amongst the many other environmental degradations associated with the mine activities. Geological/geophysical and geotechnical tin field techniques have been applied in the case study of the mine subsidence. Geological studies revealed the tin mining fields are characterized by variable thickness of alluvium hosting the tin minerals with little or no rock outcrops. Geo-electrical resistivity soundings across the mining sites revealed variable thickness (3-27m) geo-electrical layers/lithological units of: (1) top lateritic soil, (2) sand/sandy clays, (3) weathered granite, and (4) slightly weathered to fresh granite.

Laboratory test of sub-base soil samples for geotechnical parameters of: moisture content, atterberg limits, specific gravity, shear triaxial test and allowable bearing pressures were carried out. The results showed that moisture content is highest at 56% and lowest at 25%. Similarly, highest plastic limit (PL) is 43% and lowest is 19%; plastic index (PI) at highest value is 13% with lowest at 6%. These values indicate moderate expanse and shrinkage of the fine grained soil which contribute moderately to the mine shaft collapse. Allowable bearing pressure test results in KN/$_{m}^{2}$ range between 86 and 279 KN/$_{m}^{2}$ with an average of 135KN/$_{m}^{2}$. There is wide pressure variation with highest at 279KN/$_{m}^{2}$ and lowest at 22KN/$_{m}^{2}$ and these values are not consistent and can cause the collapse of the mine pits and tunnels.

From particle size analysis; coefficient of uniformity (Cc) of Kuru Jenta mine shows that Cc=0, Cu=12, 21 and that of Guratopp shows Cc=0, Cu=6. The particle size distribution curves show narrow ranges of soil particle sizes and suggest a gap graded/poorly graded soil with poor compaction hence weak in stability and leading to mine shafts and tunnels collapse. The tin bearing alluvial materials has a wide range of particle sizes which are gap graded, poorly compacted, weak and hence leads to roof flow collapse in the cause of shafting and tunneling. The artisanal underground mining using shaft and tunneling techniques in the thick alluvial deposits must ensure intensive support and the dewatering to prevent collapse and navigate weak ground.

Keywords: Artisanal Mining, Jos Plateau Tin Fields, Geological/geophysical/geotechnical investigations, Mine Subsidence.

1.0 Introduction

Artisanal mining is a typical mining method that utilize minimal mechanization and automotive systems involving individuals or small groups and most times informal and unregulated [1, 2]. Artisanal and small scale mining activities thrive mainly because of the immediate impact on the livelihood that impacts by reduction in poverty and economic renewal though development of non-agricultural businesses [3]. The economic impact of artisanal mining constitutes about 70-90% of the mining activities in Nigeria [3, 2]. Generally, mining activities all over the world have its attendant environmental degradational impact and one amongst many is mine subsidence [4]. Hazards caused by mine subsidence usually include: damage to man, topography, infrastructure, mine inundation and mine fires [5,6].

Mine subsidence occur as a result of the ground above the mine collapses or shift after the rock roof failure, pillar crushing or failure of ground beneath the mine workings [7, 8, 6, 9]. Mine subsidence could occur as a result of active or non-active underground mining [5,6]. Mine subsidence can be classified into two types based on their nature and causes. The two main types of mine subsidence are Pit (continuous) and Sag (discontinuous) subsidence [10].

Tin mining activities on the Jos Plateau started in the early 1900s and have left immense consequences on the environment [11]. Recently, there is uncertain artisanal mining activities as a result of the economic challenges and these activities have increased further damages to the land [12]. The most glaring environmental effects of the Jos Plateau tin mining activities include: drowning of people and animals in the abandoned mine ponds and pits, radioactive radiations to pollution of water in mine-out areas by heavy metals etc [13, 11, 14], soil erosion and mine subsidence [15] (https://www.jotscroll.com/forums/3/posts/155/tin-mining-in-jos-plateau.html; [13,11]. The artisanal and small scale tin mining activities are carried out by vertical shafting and/or by tunneling. The excavation of the ground mass by subsurface "lotto" can cause loss of balance leading to change in stress around the open pit which can result in failure of earth material [16]. Generally, the mine-out pits are left open with their attendant hazards. In 2017 around Zawan community within the Bukuru tin mining field, an inactive mining pit collapsed and killed over 50 people who were prospecting in the pit (https://r4d.org). The increasing number of lives lost daily as a result of mine subsidence from artisanal mining activities calls for this study to determine the geological, geophysical and geotechnical factors causing the mine subsidence and proffer scientific solution where possible.

2.0 Location and Physiography

Kuru Jenta and artisanal tin fields lies between latitude 9.695 and 9.698°N and longitude 8.883° and 8.8885°E (Figure. 1) while Guratopp tin mining fields lies between latitude 9.831° and 9°.834°N and longitude 8°.911° and 8.9145°E (Figure. 1 and 2). The Kuru Jenta and Guratopp mining fields are characterized by river/stream drainages flowing northwest-southeast and north-south directions respectively. The streams are generally semi-perennial to perennial in character with small flow-discharges. Most times the flow of the rivers are impeded by mining activities along the river channels.

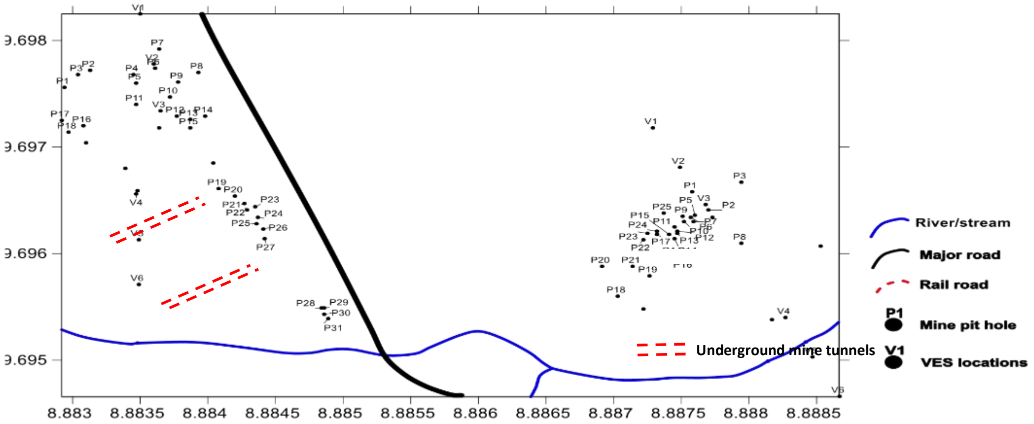


Figure 1. Location Map of Kuru-Jenta Mines (Site1 and 2) showing the VES locations and Mine pit holes

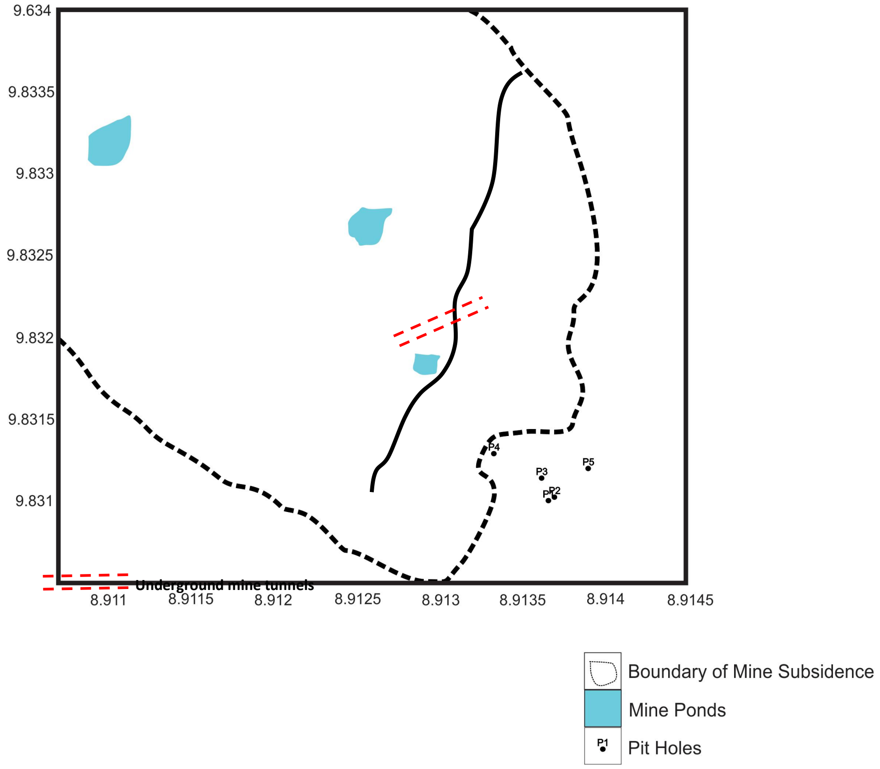


Figure 2. Location Map of Guratopp Mining Site Showing the Mine Subsidence Area, Pit holes and Geo-electrical Resistivity Sounding.

3.0 Regional Geology of the Jos Plateau

The regional geology of the Jos Plateau (Fig.3) is dominated by three major rock types which include: Pre-Cambrian/basement rocks, Jurassic Younger Granites, and Tertiary-Quaternary volcanic rocks including basalt flows and volcanic cones (https://en.m.wikipedia.org/wiki/Jos-Plateau) [17]. The Jos-Bukuru Younger Granite Complex consists of about four major rock units. The units comprises of the Jos Biotite Granite, Ngell Biotite Granite, Delimi Biotite Granite, Rayfield-Gona Biotite Granite and lateritic covering Older Basalts (Fluvio-volcanics). Generally, the study area are low lying and the rocks are poorly exposed. The valley areas rises gradually or sharply into the surrounding granitic hills. The areas are drained by streams and rivers dominated by alluvial deposits along their channels.

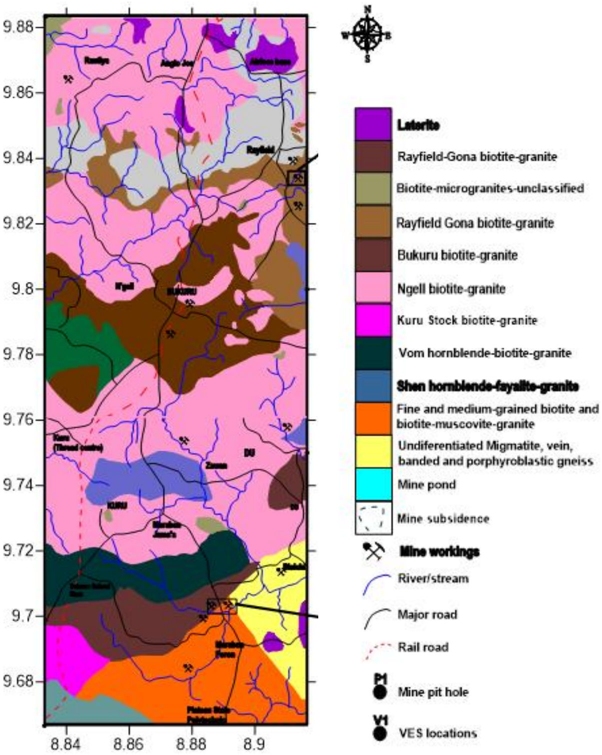


Figure 3. Regional Geologic Map of Parts of Jos Plateau: Modified after [17]

3.0 Materials and Methods

3.1 Geological Mapping

The study areas were mapped to identify and delineate the various rock types underlying the different mine-out pits, ponds and areas where subsidence have occurred as a result of the tin mining activities.

3.2 Geophysical Investigation

The geo-electrical resistivity soundings employing the schlumbeger array was used to determine the geo-electric layering/lithologic sequences down to the basement. In this technique, the current (AB/2) and potential (MN/2) electrodes spreads from 1.5 to 215m and 0.5, 3.5 and 14m respectively with depth penetration compatibility of 71m. The soundings were carried out in strategic profiles cutting across the mine-out tin field (Figure 2 and 3). A total of 15 VES were carried out: 12 and 3 VES in Kuru Jenta and Guratopp mines respectively. The field data was interpreted using linear filter theories of direct current method [18, 19] and software using Win resist version 1.0 [20]. The software uses an iteration technique to model the VES field curve and an eventual segmentation of the geo-electric layers. The VES location coordinates was determined in the field using the GPS Garmin-12 channel type.

3.3 Geotechnical Investigations

Disturbed soil samples from mine- out pits and collapsed mine faces were sampled sequentially layer by layer from top to bottom. The depths and static water levels of the mine pits and ponds were measured using water level indicators in the field.

3.3.1 *Laboratory analysis*

The soil samples were analyzed at Rock Material Laboratory of Mecon Geology and Engineering Services Ltd Jos. The geotechnical parameters analyzed include: moisture content, wet sieve analysis, specific gravity, triaxial compression test, bearing capacity, water table in dry and wet season, bulk density, consolidation and direct shear test using the appropriate methodologies [21]

4.0 Results

4.1 Local Geology

Kuru-Jenta and Guratopp (Rayfield) Mining Areas

Kuru-Jenta is underlain by mostly the Bukuru biotite granite, fine medium grained biotite and biotite-muscovite-granite and the undifferentiated migmatite, vein, banded and porphyroblastic gneiss (Figure. 4a) [17]. The Guratopp mining areas are underlain mainly by Rayfield Gona biotite granites (Figure.4b). The study areas are generally low lying with little or no exposure of rock outcrops. The soil cover all characterized thick lateritic core. Rock outcrops of Younger Granite rises instantly and forming the highly trends sometimes in ring forms. The low lying areas are characterized by streams/river/valleys weathering from the Younger Granite which contain casiterite and associated minerals.

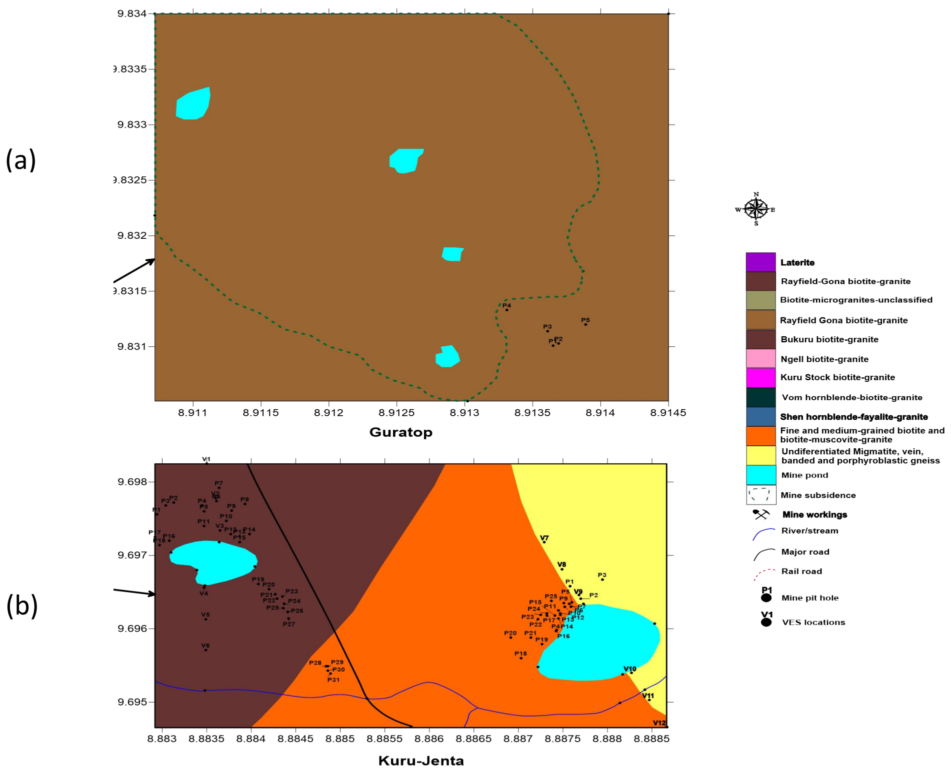


Figure 4. Local Geology of the Guratopp and Kuru-Jenta Artisanal Tin Mining Sites

4.2 Geo-electric Sounding Interpretations

The geo-electrical resistivity sounding interpretation for Kuru and Guratopp showing depth to various geo-electric layers are shown in Table 1. The characterized curve types obtained in the study areas are H, QH, HA and QKH with 40%, 26, 13% and 6% respectively. Generally, the resistivity values are characteristics of the mineralogic constituent of the rock types and general geology of the areas. The major geo-electric layering/sequence and resistivity ranges around the Kuru Jenta are: Top lateritic layer (258-5,289ohm-m), weathered layer (40-771ohm-m), slightly weathered layer and fresh granite (149-∞ ohm-m). However, the Guratopp area have more of QH type curves with higher resistivity values: Top lateritic soil (5,508-14, 4114 ohm-m), weathered layer (129-750 ohm-m), slightly weathered-fresh granite (57-539 ohm-m).

Table 1: Summary of VES Qualitative and Quantitative Interpretations

Location	VES No.	Depth (m) d_1/d_2 ……dn^{-1}	Resistivity (ohm-m) p_1/p_2 ……pn	Curve Type
Kuru Jenta Mine Sites I & II	P1	0.6/3.8/17.6/∞	1398.5/315.4/280.8/215.4	Q
	P2	0.9/8.9/31.0/∞	1576.2/227.3/149.6/359.5	QH
	P3	0.9/17.0/∞	924.3/124.9/312.8	HA
	P4	1.1/9.7/44/∞	1062.4/258.5/76.7/277.2	QH

	P5	0.7/11.1/34.4/∞	972.6/346.1/49.3/679.3	H
	P6	0.6/4.9/47.1/∞	5289.2/771.1/84.3/423.7	HA
	P7	4.2/22.4/∞	290.3/158.8/551.8	A
	P8	2.4/18.4/22.4/∞	383.1/55.6/551.8	H
	P9	1.4/13.0/∞	258.8/40.1/449.7	H
	P10	1.4/12.0/∞	471.1/115.2/1071.2	H
	P11	1.1/13.6/∞	625.9/218.9/923.7	H
	P12	1.3/13.1/∞	529.8/176.4/818.6	H
Guratopp Mine Areas	P13	0.7/7.1/19.2/47.6∞	1147-14114/129/87/128.8	QKH
	P14	0.7/4.8/27.5/69.8∞	5508/715/257/56/539	QH
	P15	1.0/6.8/21.8/38.7∞	1668/320/92/57/213	QH

4.2.1 Geo electric Sections

The geo-electric section for Kuru Jenta mining site in NW-SE and N-S duration revealed 3 to 4 geo-electric sequences/lithological units consisting of: Lateritic topsoil (0-3.8m), weathered granite consisting of sand and sandy clays (0.6-28m), slightly weathered granite (4.2-m) and characterized by average resistivity values of 1062 to 5289ohm-m, 49 to 316ohm-m, and 277 to 677 ohm-m respectively.

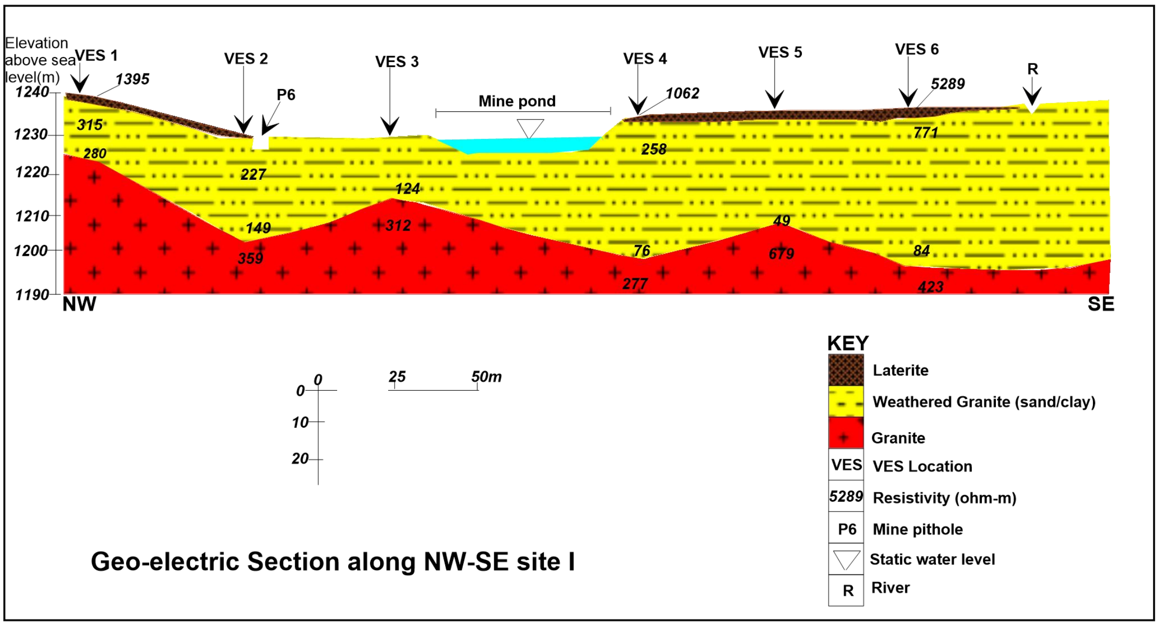


Figure 5. Geo-electric Section of Kuru Jenta Site 2 along NW-SE Direction

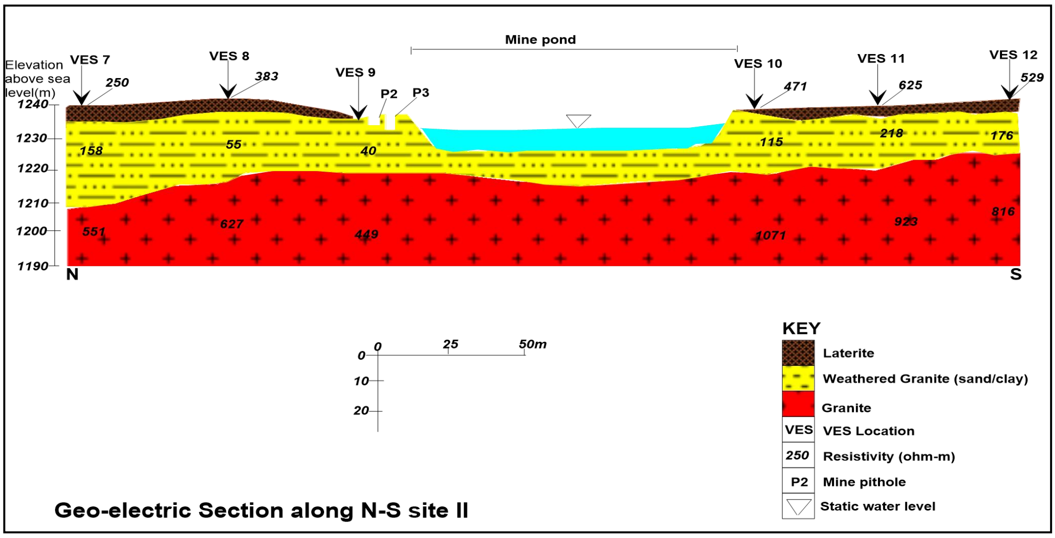


Figure 6. Geo-electric Section of Kuru Jenta Mine Site along N-S Direction.

In the Guratopp mining site, the geo-electric section around revealed a similar geo-electric sequence/lithological variation of: Top lateritic soil (0.7 to 7.1m), weathered granite consisting of sands/sandy clays (7 to 27.5m), slightly weathered/fractured granite (>19 to ∞) and characterised by resistivity values of 147 to 14 ohm-mm, 87 to 716 ohm-m and 129 to 539 ohm-m respectively.

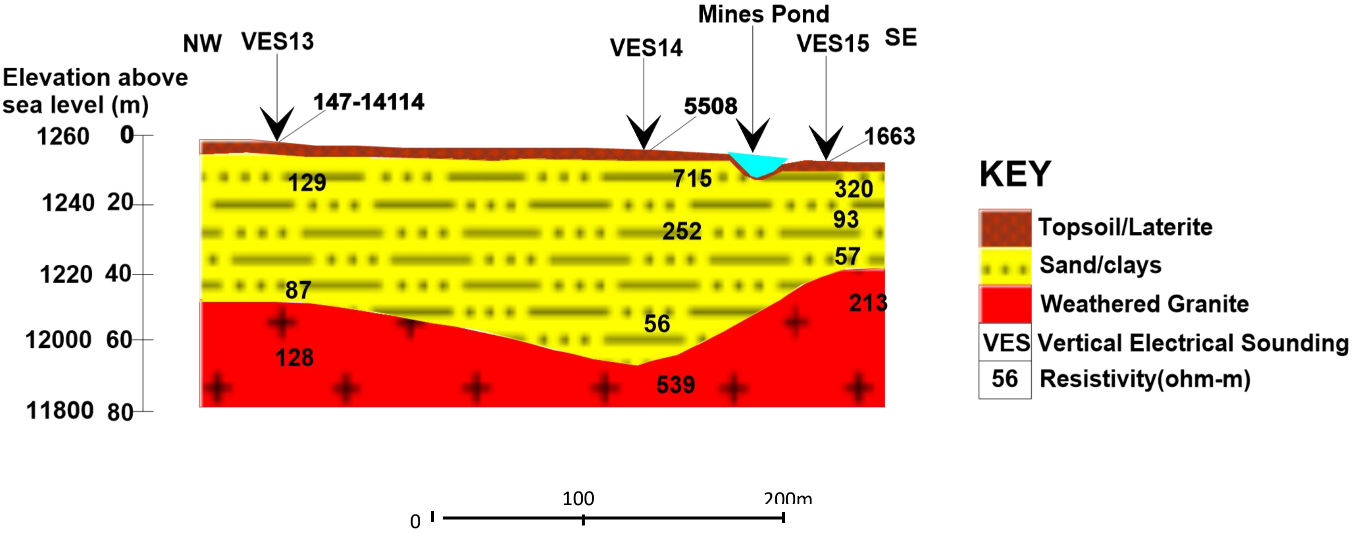


Figure 7. Geo-electric Section: Guratopp Mine Site in Northwest-Southeast Direction

4.3 Geotechnical Investigation

4.3.1 Lithostragraphy: Kuru Jenta and Guratopp mine sites

The Lithostragraphic profile of the mine-out pits around the Kuru-Jenta and Guratopp mining fields revealed a sequence of : Highly Lateralized Topsoil, Sand/sandy clays, gravelly sands from 0.4 to 4.4m, 0.4 to 4.5m and 4.5 to >5m depth respectively.

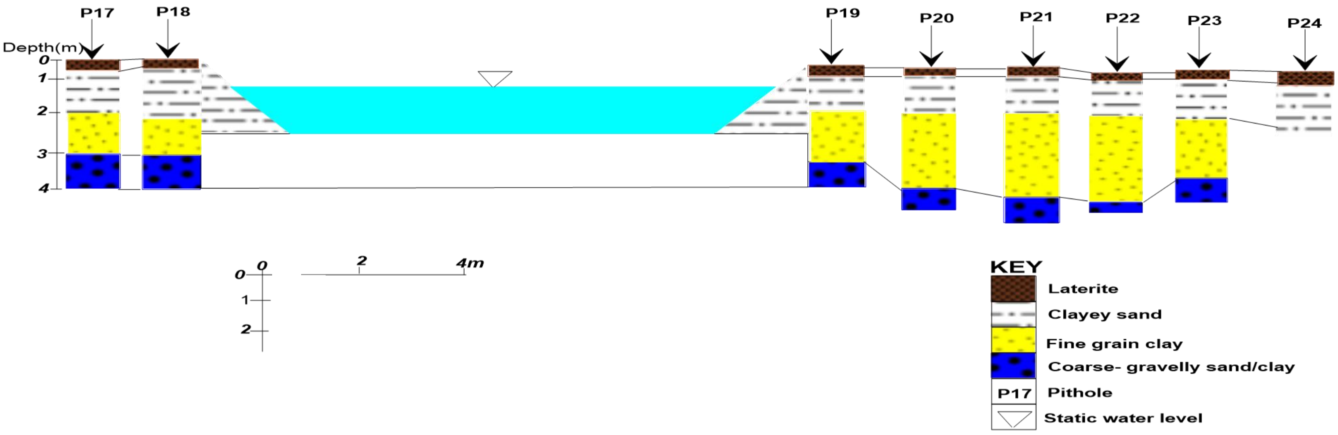


Figure 8. Lithostragraphic Section of Kuru-Jenta Mine pits and Subsided Mine Pond

The Guratopp mine site along the exposed mine (Figure.9) face from top to bottom revealed a slightly different lithological variation with lateritic topsoil, clays with fine grained sands, clays with medium grained sands, fine grained sands, medium grained sands with clays, coarse-gravelly sands at depth of 0 to 0.3m, 0.3 to 1.2m, 1.2 to 2m, 20 to 3.7, 3.7 to 4m and 4 to 5m respectively.

Figure 9. Lithological Section of Mine-out Pit at Guratopp Mine Site.

4.4 Guratopp Mine Subsidence

Figure 11 shows the typical artisanal mining by piting and tunneling to access the mineralized tin layers. The multiple or closed clustering of the horizontal tunnels characterized by high groundwater level, most times, generates the mine subsidence. Some of the tunnels go up to 100m or more (Figure. 9 & 10).

Figure 10. Guratopp Mine Sites Showing the Mining Tunnels

Figure 11. Guratopp Mine Site- Typical Mine Rooftop Collapse along the Mine Tunnels

4.5 Test Results for Sub-Base Investigation of Kuru-Jenta and Guratopp Soil

4.5.1 Soil Moisture Content

The moisture content analysis for the Kuru Jenta and Guratopp mine soils from mined out pits are as shown in Table 2

Table 2: Moisture Content Tests for Kuru-Jenta and Guratopp Mine Sites

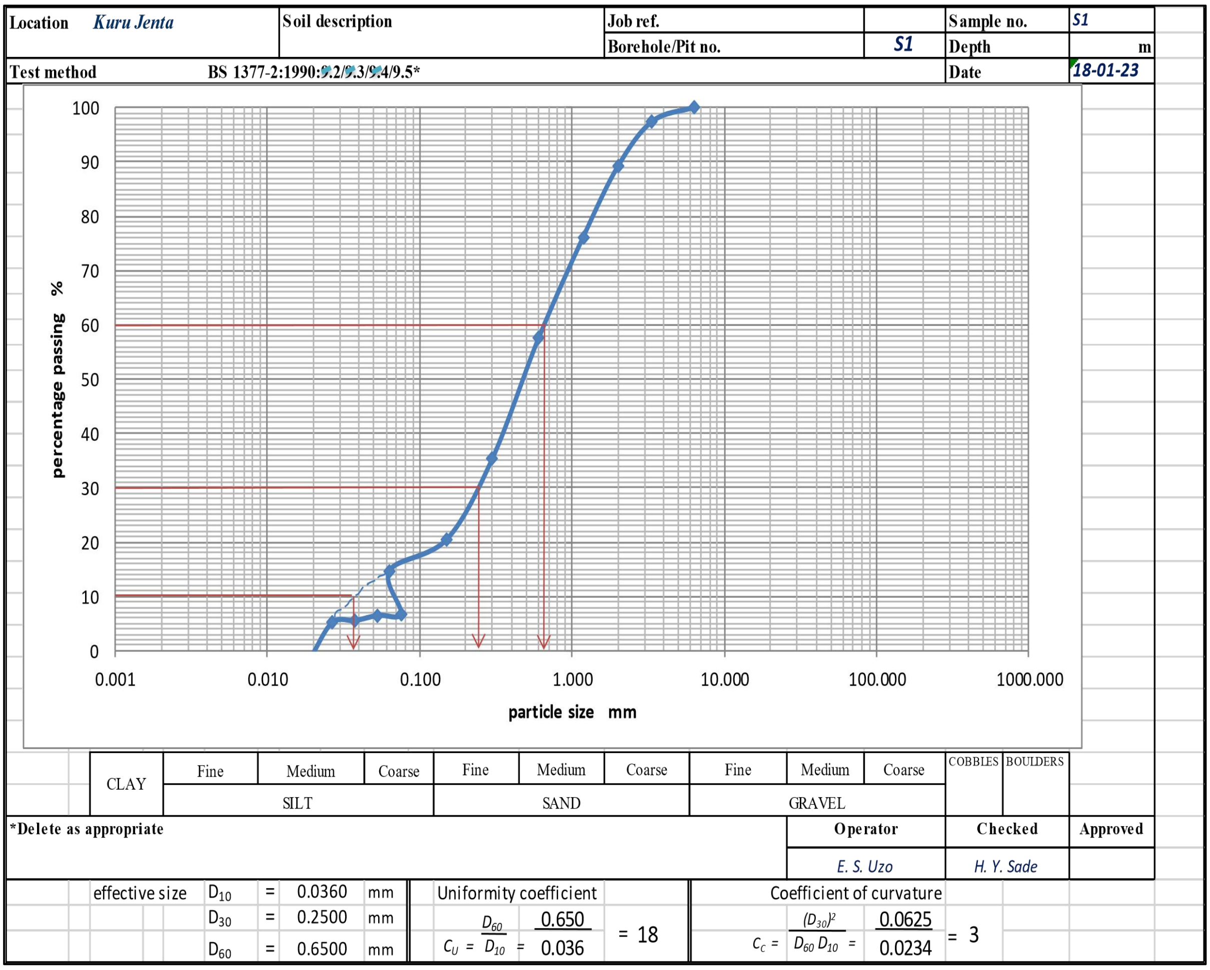
Location	Sample Pit No.	Average Moisture Content
Kuru-Jenta Site 1	Sample 1 - (Stream (S1)	5.68%
	Sample 2 – Pit (2m) 1m	8.33%
Kuru-Jenta Site 2	Pit 2 (2m)	2.01%
	Pit 1 (3m)	12.8%

Guratopp	Sample 1	0.48%

The average moisture content for Kuru-Jenta Site I and II ranges from 2.01 to 8.33% within pit depth ranges of 1-3m while that of Guratopp sites has an average of 0.48%.

4.5.2 Wet sieve analysis: Particle size distribution

The wet sieve analysis of the Kuru-Jenta Site I and Site II and Guratopp mine sites shows that the particle size distribution ranges from 0.02 to 6.5mm in site I, 0.015 to 10mm site II and 0.015 to 10mm for Guratopp (Figure 3). The calculated coefficient of uniformity Cu, and coefficient of curvature (Cc) for the soils are as shown in Table 3. A well graded soil has adequate contribution of all sizes in a particular soil sample and may be represented by the following combination: Sand – 40%, Silt – 40% and Clay – 20%. However, for the sample for Kuru-Jenta sites I and II and Guratopp, the distribution of soil sizes are poor and gap graded (Table 4).



Location *Kuru Jenta*	**Soil description**	**Job ref.**		**Sample no.**	*S1*
		Borehole/Pit no.	*S1*	**Depth**	m
Test method BS 1377-2:1990:9.2/9.3/9.4/9.5*				**Date**	*18-01-23*

CLAY	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	COBBLES	BOULDERS
	SILT			SAND			GRAVEL				

***Delete as appropriate**

Operator	**Checked**	**Approved**
E. S. Uzo	*H. Y. Sade*	

effective size D_{10} = 0.0360 mm

D_{30} = 0.2500 mm

D_{60} = 0.6500 mm

Uniformity coefficient

$$C_U = \frac{D_{60}}{D_{10}} = \frac{0.650}{0.036} = 18$$

Coefficient of curvature

$$C_C = \frac{(D_{30})^2}{D_{60}\,D_{10}} = \frac{0.0625}{0.0234} = 3$$

Figure 12. Particle Size Distribution for Kuru Jenta Mining Site

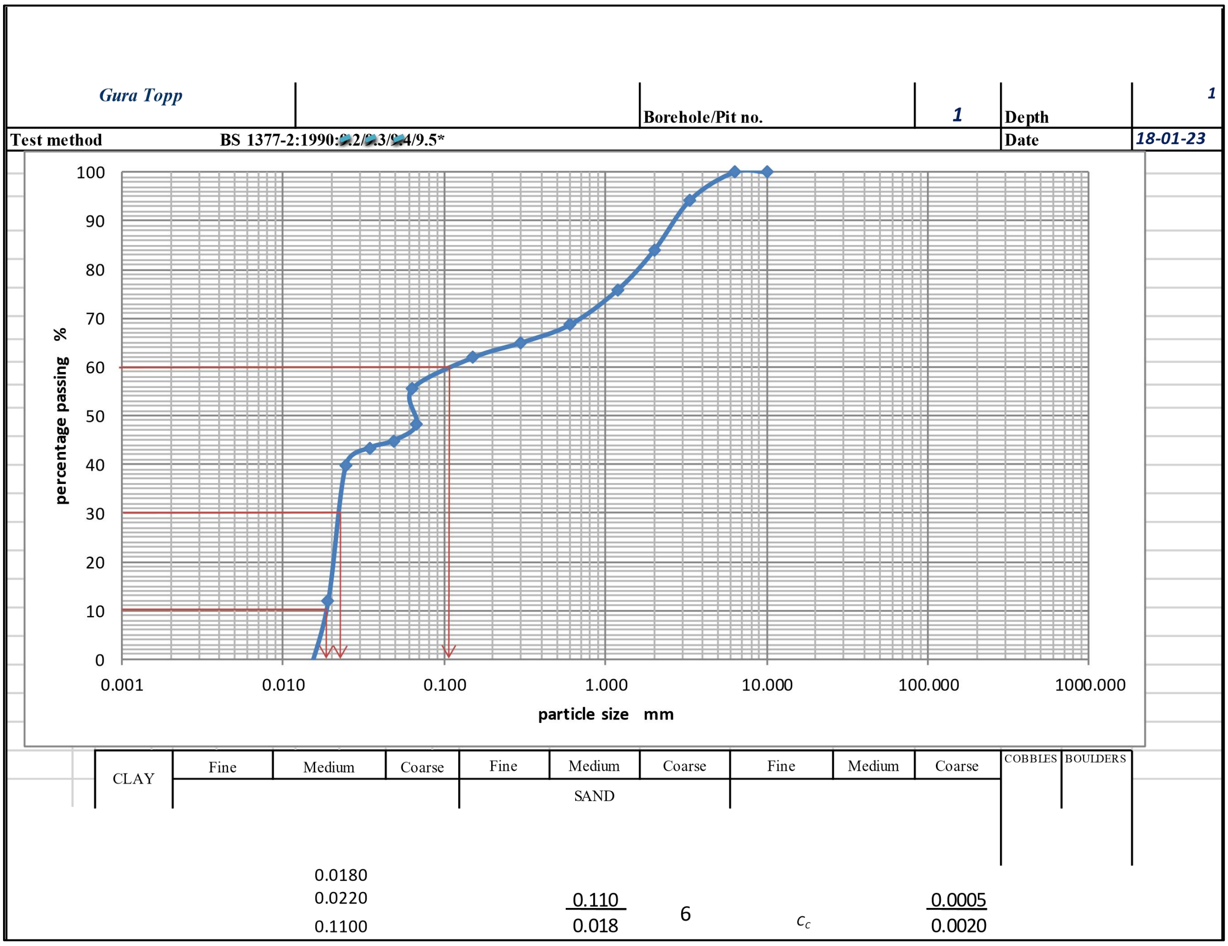


Figure 13. Particle Size Distribution for Guratopp Mining Site

Table 3: Sieve Analysis Test for Kuru-Jenta and Guratopp Mine Sites

Location		Coefficient of uniformity Cu=$\frac{D60}{D10}$	Coefficient of curvature Cc= $\frac{(D30)^2}{D60 \times D10}$	Remarks
Kuru-Jenta Streams	Site1:	18		Cu>4 soil is well graded, Cc=3 lies between 1 and 3-soil is well graded.
Pit 2 (1m)		3	1	Poorly graded
Kuru-Jenta Pit1(3m)	Site2:	12	0	Gap graded
		21	0	Soil is gap graded
Pit2 (2m)				

4.5.3 Specific Gravity (S.G)

The specific gravity of the various soils from the two mine fields are as shown in Table 5 and 6. The specific gravity (SG) values for Kuru mines and Guratopp falls within the range of 2.54-2.64. In general, soils with SG values of 2.65 to 2.80 are good and has a fair distribution of fine-coarse grained soils. Generally, specific gravity of a soil helps to determine the soil porosity or the voids it contains.

Table 4: Summary of Soil Test: Geotechnical Parameters

Test Pit No.	Depth (m)	n.m.c. (%)	Atterberg Limits			Specific Gravity	Particle Size Analysis				Shear Box / Triaxial		Consolidation		Unit Weight γ_b kN/m3	USCS Classification	
			LL (%)	PI (%)	LS (%)		Sieve No. 4 _ 4.75mm	Sieve No. 10 _ 2.00mm	Sieve No.40 _ 425μm	Sieve No. 200 _ 75μm	Cu (kN/m²)	Φu (°)	c_v m²/year	m_v m²/MN		Group Symbol	Group Name
Kuru-Jenta Stream 1	*1*	*5.7*	*34*	*-*	*0*	*2.64*	*99.1*	*89.3*	*46*	*16*	*0*	*33*	—	—	*21.06*	*SM*	*Silty Sand*
Gura Topp Sample 1	*1*	*0.5*	*56*	*13*	*6*	*2.54*	*98.3*	*84*	*66.3*	*57.5*	*15*	*16.7*	*>100*	*0.244*	*16.45*	*MH*	*Silty clay*
Kuru-Jenta Pit 2	*2*	*8.3*	*36*	*12*	*5*	*2.63*	*100*	*98.9*	*87*	*66.5*	*18*	*19.4*	*>100*	*0.279*	*17.19*	*CL*	*Clay*
Pit 1	*3*	*12.5*	*28*	*9*	*4*	*2.64*	*99*	*92*	*69.5*	*50.5*	*2*	*22*	*>100*	*0.271*	*17.11*	*CL*	*Clay*
Pit 2	*1*	*2.01*	*25*	*6*	*3*	*2.62*	*98*	*88.1*	*66.5*	*48.2*	*0*	*15*	*>100*	*0.168*	*18.13*	*SM-SC*	*Silty Sand and Clay*

The values of specific gravity in all the soil samples fall short of the range of fine soils which is 2.65 – 2.80 which shows a lot of porosity in the soil mass, hence there was ground water movement in the soil in the given depths. Water flows from points of higher potential energy to points of lower potential energy in horizontal direction hence, the horizontal hole (shaft) or "lotto" caused vertical flow from the upper layer of soil into the horizontal shaft thus washing off fine grains out of the coarse grains/gravels, causing the collapse of the soil above the shaft (horizontal) and also the caving-in of the sides of the well.

4.5.4 Atterberg Limits-Cone Test

The Atterberg Limits-Cone test is a plot of the moisture content (%) vs cone penetration in (mm) and results is as presented in Table 4. The Liquid Limits (LL), Plastic Limits (PL) and Plasticity Index (PI) are indicated and summarized in Table 5. Generally, LL, PL and PI for the mine sites range from 25 to 56, 19 to 43, and 6 to 13 respectively. It is observed that PL and PI for the stream sample for the Kuru-Jenta mine sites is calculated to be 0. Atterberg limits can be used as a guide indicating how much soil is likely to settle or consolidate under load in the field. If the field moisture is near the liquid limit, a lot of settlement is likely, if the field moisture is near or below the plastic limit, there will be minimal acceptable settlement (vertical soil movement) under loads. Atterberg limits of soils are very important in construction/tunneling in mining.

4.5.5 Allowable Bearing Pressures: Triaxial Compression Test

The results of the triaxial compression test and other geotechnical parameters of the mine fields are as shown in Table 4. The allowable bearing pressure (Table 6) for the two mine sites vary from 64kN/m^2 to 837kN/m^2; these values used for engineering and geotechnical purposes would be lower than values of the test results. Allowable bearing pressure is the load a soil can take safely without causing the failure of the soil when a load is applied on it.

The angle of internal friction of a soil is the angle on the graph (morh's circle) on the shear stress and normal stress at which shear failure occurs.

Angle of internal friction between soil particles depend upon the shape, size, roughness, grading and packaging of particles. The allowable bearing pressures from the result shows that the minimum is 15° and the maximum is 22°. If it were for buildings, designs will be based on the applied safety factors, but in the case of artisanal mining walls and horizontal shafts, the soil above the horizontal shaft forms a horizontal beam without reinforcement. The soil mass above the shaft forms the beam with all its weight. Once the soil becomes saturated at the peak of the rainy season, the soil above the shaft will undergo subsidence while the sides of the wall caves in , that is what happened in the cases of these multiple subsidence in the sites at Kuru-Jenta and Guratopp.

Table 5: Summary of Allowable Bearing Pressures of the Mine Site

S/N	Mining Pit No.	Depth (m)	c kN/m^2	Φ (°)	γ_b kN/m^3	N_q	N_c	(Hansen) N_γ	q_f kN/m^2	q_{nf} kN/m^2	FOS		q_{al} kN/m^2
1	Pit 1 (3m)	3.00	2	22	17.11	7.50	16.42	4.62	457	406	3		135
2	Pit 2 (1m)	1.00	0	15	18.13	3.90	10.91	1.39	83	65	3		22
3	Gura Topp Sample 2	1.00	15	17	16.45	4.64	12.12	1.96	274	258	3		86
4	Pit 2 (2m)	2.00	18	19	17.19	6.03	14.29	3.19	492	458	3		153
5	Kuru-Jenta Stream 1	1.00	0	33	21.06	26.09	38.64	29.33	858	837	3		279

5.0 Discussion

5.1 Geological Mapping

There is little or no rock outcrops seen along the Kuru Jenta area except along the NW-SE flowing stream channels. Mine-out pit lithology of Kuru Jenta site I and site II have variable depth of 1 to >10m with a lithological sequence of Top lateritic soils, Clay/Sandy soils, and coarse to gravels/sands. This lithological sequence is similar to the general lithological sequence of the Jos alluvial tin fields [11].

Artisanal mining activities around the two mine fields revealed mine-out pits average depths of 3-15m and consists more of lateritic topsoil, clay/sandy clays, coarse-gravelly sands etc. Most of the mine-out pits did not reach the underlying basement. The alluvial sediment hosting the tin deposit on the Jos Plateau tin fields could go up from 30-40m depth or thickness in many places [11, 22].

5.2 Geophysical Investigation

Geo-electrical resistivity interpretation (Table 2) across the mine fields reveals more of the H and QH type curves and are typical of crystalline environment [23,24]. Geo-electric sections (Figure 5) across the Kuru Jenta and Guratopp tin fields revealed a variable alluvial sediment thickness of 20 to >30m overlying the granitic basement. The alluvial sediments hosting the tin that agrees with other studies weathered overburden thickness/depth are variable over the underlying granitic/basement rocks within the tin fields and could go up to 30-40m and agrees with other previous studies on the Jos Plateau tin fields [25, 11].

5.3 Geotechnical Investigation

The Kuru Jenta and Guratopp artisanal mine sites with mine wells and hand dug tunnels are scattered randomly. On the average, the mine wells do not exceed 10 meters in depth and the tunnels diameter range from 1.2 to 1.5 meters which can go up to 100meters and horizontally underground. An interview with some of the miners shows that the mine tunnels criss-cross the highway deep under the ground (Figure. 1 and 2). The overburden above the mine tunnels ranges from 8.5-8.8 meters with the ventricular contributing to the soil subsidence.

5.4 Impacts of Soil Moisture in Construction and Mine Subsidence

Tunnel failures have occurred worldwide orbiting to a variety of ground conditions.

Furthermore, it is worth nothing that some of the largest and significant consequences of failures occur during tunneling in or close to and or other granular materials which are coleuses soils [26].The tunnels under the highway in Kuru Jenta amount to a collapse only waiting to happen. [27] have posited that the greatest and adverse consequences for third parties such as fatalities, injuries on road or building collapse when tunneling in granular soils. Granular soils is used to describe natural materials that behave largely as uncemented collections of particles that only exhibit apparent cohesion because of unsaturated soil [28].

The sectioning of ground surface by the seepage action of water causes a decrease in the soil strength and an increase in the soft weight of the soil [29].

Increasing moisture content reduces shear strength namely both cohesion and friction angle of collapsing walls making it less stable [30]. This and other factors generally increase collapse risk.

5.5 Why the Mines Shafts and Tunnels Collapsed

5.5.1 Kuru Jenta Mine Field

Moisture content**:** Few samples taken for laboratory testing and analysis shows values of 5.68%, 8.33%, 2.01% and 12.8% giving an average of 7.21%. Normally, when soil dries at low moisture content it shrinks and this way induce cracks are very likely, especially if it is poorly graded [30].

5.5.2 Guratopp Mine Field

Moisture content**:** Guratopp moisture content is 0.48% indicating it's the extreme dry soil type and characterized by lots of visible cracks. Reduced moisture content in the soil create cracks in the overburden over a void certainly led to the collapse of the soil materials.

5.6 Specific Gravity

The Kuru Jenta specific gravity results are 2.62, 2.63 and 2.64 while that of Guratopp is 2.54 (Table 5). These specific gravity values falls short of the range of fine soils of 2.65-2.80 [31] in all the sample in the Kuru and Guratopp mines sites.

5.7 Coefficient of Curvature and Coefficient Uniformity

The Kuru-Jenta samples had coefficient of curvature of zero ($C_{c=0,}$) while coefficient of uniformity $C_{u=12,\ 21}$, while that for Guratopp: $C_{u=0,}$ $C_{u=6.}$

A well graded soil has C_c values as $\{1< C_{c<3}\}$. Any value less than 1 or more than 3 is gap graded or poorly graded ($C_{c<1}$ or >3) [28, 31]. Soil density of gap graded soil is low and porous allowing seepage with less compaction and density [28, 31]. For Guratopp samples, $C_{c=0,}$ $C_{u=6.}$ A $C_{4>6}$ for sand and $C_{4>4}$ for gravels indicate the soil sample has a wide range of particle sizes. $C_{4<6}$ (for sand) and $C_{4<4}$ (for granite) suggest a gap graded/poorly graded/uniformly graded soil where compaction is poor and stability is weak [31, 26].

5.8 Atterberg Limits

Atterberg Limits are critical water contents that deprives the consistency of fine grain soils (clays and silts) as they change from liquid to plastics, semi-solid and solid state [31]. This is where moisture level change behavior of soils [30, 31].

From Table.5 the result shows the highest value is 56% and the lowest 25%. Similarly the highest value of plastic limit of 43% with lowest at 19%. Plastic index at 13% with lowest at 6%. The value indicate moderate expanse and shrinkage of the fine-grained soils which contribute moderate activities to the mine shaft collapse.

5.9 Allowable Bearing Capacities

Allowable bearing pressure is the maximum allowable net loading intensity of the soil in any given case taking consideration of the bearing capacity of the ground recovering the load [28]. From the mine fields (Table 8), values of the test results in KN/$_{m}^{2}$ are 22, 86, 135, 153, 279 with an average of 135KN/$_{m}^{2}$. There is a wide variation of the value with the highest at 279KN/$_{m}^{2}$ and the lowest at 22KN/$_{m}^{2}$. This indicate that the allowable bearing pressure is not consistent and unreliable. Inconsistent allowable pressure in soils may lead to collapse. These with other factors caused the collapse of the mines pits and tunnels. An overburden of about 8m of unreliable bearing pressure worsen in the rainy season on top of the void certainly will cause collapse as the overburden becomes saturated in the rainy season with very low shearing strength.

5.10 Atterberg limits

Atterberg limits are critical water contents that define the consistency of fine-grained soils (clay and soils) as they change from liquid to plastic, semi-solid states [31]. This is where moisture levels change the behaviors of soils. The results above shows the highest value of 28%. Similarly, the highest value of plastic limit is 43% with the lowest at 19%. Plastic index stood at 13% with the lowest at 6%. The values indicate moderate expansion and shrinkage of the fine grained soils which contributed moderate activities to the mines shafts collapse.

In summary, soils lacking diverse particle sizes (gap graded) cannot effectively interlock creating voids that allows internal erosion. Uniform soils allow easy passage of water enhance erosion and destabilizing tunnel walls with collapsing. Note that artisanal mines do not have means of providing support as walls for the tunnels. Rainfall and rising ground water significantly reduce soil strength, triggering collapses in tunnels that might seem stable. The major causes of the collapses are the poorly graded soils around the mines pits and tunnels, the variable allowable bearing pressure of the soil material and the action of rain and ground water.

6.0 CONCLUSION

This study revealed the main causes of mine subsidence using artisanal mining method within the Jos Plateau tin as follows:

I. The alluvial material hosting the tin have short range soil sizes which are poorly or gap graded and allows easy passage of water and enhances erosion, destabilization of tunnel walls and collapsing.
II. There is a wide variation in the values of allowable bearing capacity of the mining pit soils and shows the bearing capacities are not consistent and unreliable and contributes to the cause of the mine and tunnel collapse.
III. Rainfall and rising groundwater significantly reduce soil strength and triggering collapse in shaft and tunnels.
IV. Artisanal mining using shaft and tunneling techniques (Lotto) in thick alluvial tin deposit needs intensive support system to prevent collapse and/or navigate weak ground to enable recovery of the tin.

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