Nigerian Journal of Technology (NIJOTECH)
Vol. 42, No. 1, March, 2023, pp.83 - 91
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
https://doi.org/10.4314/njt.v42i1.10

SLOPE STABILITY ASSESSMENT OF SOME WASTE ROCK DUMPS AT A TYPICAL GOLD MINE IN GHANA

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Article history: Received 10 May, 2022. Revised 14 March, 2023. Accepted 18 March, 2023

Abstract

Mining results in both economic and uneconomic materials being generated. The uneconomic materials (wastes) are stacked in a convenient place for further use or stored permanently as a slope or embankment. In Ghana, a typical gold mine set up dumping sites to accommodate the waste generated from its operations. Samples were collected from three waste dumps and tested in the laboratory, and the parameters obtained were used as input for 2D model development. The Factor of Safety (FS) of the three waste dumps were determined using the Janbu Generalised slope stability analysis method. Path and slope surface (circular and non-circular) search methods were used for the three cases. The FS for the waste dumps were determined and ranged from 1.61-2.74, 1.49-2.50 and 1.32-2.10 under dry, static and pseudo-static loading conditions, respectively. These values exceed the minimum requirements of 1.1-1.5 for stability conditions. The geometry of the waste dumps, Suraw Waste Dump (SWD), is within the standard and hence, does not require reshaping, while the slope angles for the remaining waste dumps, Tano Waste Dump (TWD) and Akoti Waste Dump (AWD) need to be reshaped to achieve the proposed slope angle of 3H:1V (18.40 degrees) as stipulated in the mine's Environmental Impact Statement (EIS).

Keywords: Factor of Safety, Janbu Generalised Method, Waste Rock Dumps, Slope Stability, Pseudo-Static.

1.0 INTRODUCTION

Mining is an essential act for the production of economic minerals. However, a vast amount of waste is generated in the production process. Waste dump stability is of high importance to every mine to ensure a smooth transition at the end of mine life (mine closure) to reclamation. The waste materials are stacked conveniently for further use or stored permanently in the form of a slope or embankment. However, it has become a more scientific approach to waste rock dump management and audit of these man-made structures in recent years. Designs of waste dumps should include a detailed stability assessment for each stage of development, considering the variations in rock quality and the rate of dumping [1]. At the same time, the possible modes of failure should be rigorously evaluated to mitigate slope instability [2].

Slope stability investigation in mines is critical to the profitability of the mines in relation to slope failures [3]. Stability evaluations are regularly conducted in order to measure the safe and efficient design of man-made slopes (e.g. open pit mining, waste rock dump, road cuts, embankments, excavations, and landfills) and the stability conditions of a natural slope, which has been an issue of concern to numerous previous investigators [4].

According to Cruikshank and Johnson [2], three general types of parameters are well known to determine the stability or instability of waste dump slopes. These parameters are the strength of the waste rock (including cohesion and angle of internal friction), geometry (including the shape of the ground surface, shape of possible slide surface, the pattern of layering within the waste dump and forms of significant discontinuities-joints or shear zones) and pore pressure (including pore-water pressure and seepage forces).

Soil and rock slopes generally fail along with existing geological defects. Therefore, most slope problems require consideration of the geometrical relationships between discontinuity planes, the slope and the force vectors involved. In weathered or highly jointed rock masses, the failure plane may be less controlled by single throughgoing discontinuities [5]. The analytical procedures for such slopes tend to be similar to those for soils. The most critical requirement for rock slopes is determining the correct failure mechanism. This will generally demand a specific site investigation to evaluate the geology of the slope, the properties of the rocks, the characteristics of the discontinuities and the groundwater condition.

Furthermore, slope failure occurs when the downward movements of material due to gravity and shear stresses exceed the shear strength. Therefore, factors that tend to increase the shear stresses or decrease the shear strength increase the chances of failure of a slope. Different processes lead to a reduction in the shear strengths of the rock mass. That is, increased pore pressure, cracking, swelling, decomposition of clayey rock fills, creep under sustained loads, leaching, strain softening, weathering, and cyclic loading are common factors that decrease the shear strength of rock mass. In addition, a factor contributing to the failure of the slope are properties of rock mass, slope geometry, state of stress, temperature and erosion. The factors affecting slope failure, according to Brahimaj and Dambov [6], are geological discontinuities (fault, joint, bedding plane); water (groundwater, drainage pattern, rainfall, aquifer); strength (shear strength, compressive strength, tensile strength); geotechnical parameters (moisture content, particle size distribution, density, permeability, plasticity and angle of repose); method of construction (shovel, dumper, BWE or combination); dynamic forces (blasting seismic activity) and geometry of slope (height and angle of slope, bench height and angle).

The limit and finite equilibrium methods are two basic types of slope stability analysis. The limit equilibrium method of slices is based purely on the principles of statics: the summation of moments, vertical forces, and horizontal forces [6–8]. The method does not consider stress, strain and displacements and, as a result, does not satisfy displacement compatibility. It investigates the equilibrium of a soil mass tending to slide down under the influence of gravity [10]. The most basic purpose of slope stability analysis is to determine a factor of safety against a potential failure or landslide. If this factor of safety is determined to be large enough, the slope is judged to be stable (safe) [11]. In order to compare the stability of slope under a condition other than those of limiting equilibrium, some form of index is required. The factor of Safety (FS) is the most commonly used index, which is the ratio of the shear strength to the shear stress required for equilibrium. This is the ratio of the total force available to resist sliding to the total force to induce sliding, as shown in Equation (1).

$$FS = \frac{Resisting\ Force}{Driving\ Force} = \frac{cA + \sum N\ tan\emptyset}{\sum S} \qquad (1)$$

where c is the cohesion, A is the area of the sliding plane, and ϕ is the angle of internal friction. At limiting equilibrium, FS = 1, FS > 1 (stable) and FS < 1 (unstable).

Avci [12] also established the relationship between the angle of slope and factor of safety (FS) by a correlation chart under different cohesion of rock materials. The application of the finite element method (FEM) in geotechnical analysis has become increasingly common to model slopes with a degree of very high realism (complex geometry, sequences of loading, presence of material for reinforcement, action of water, laws for complex soil behaviour) and visualise the deformations of soils in place [13]. Rabie [14] did a study in which he compared the Janbu Generalised Method and other traditional methods to the FEM; the results indicated that the traditional methods were more conservative with the FS values, whereas the FEM produced greater values. This research prefers to use conservative values for the FS because the waste rock is not in-situ and is thus more prone to failure. A conservative conclusion would therefore influence a thorough design of the dump.

The strength of rock mass is a very significant factor that affects the stability of slopes. It is a function of strain rate, drainage condition during shear, effective stresses acting on the soil prior to shear, the stress history of the soil, stress path, and any changes in water content and density that may occur over time [6]. It consists of the cohesion and friction angle of the material, which depends on factors, including material properties, magnitude and direction of the applied force and the rate of application, drainage conditions in the mass, and the magnitude of the confining pressure. The Mohr-Coulomb equation can denote the relationship between the peak shear strength, τ and the normal stress, σ, (Equation (2)).

$$\tau = c + \sigma tan\emptyset \qquad (2)$$

where c is the cohesive strength, and ϕ is the angle of friction.

The waste dump stability is essential during and after reclamation for every mine. The goal of waste rock dumps is to remain stable under both long-term (static) and pseudo-static loading conditions. Hence, there is a need to perform stability analysis to evaluate the general stability of waste rock dumps. Therefore, this study seeks to evaluate the overall stability of the existing as-built waste dumps of a typical gold mine for the reclamation and mine closure. The objectives are to assess the as-built geometries of the existing waste dumps, material properties and hydrogeological conditions; determine the shear strength properties (cohesion and angle of internal friction) and engineering properties of the waste dumps; determine the factor of safety (FS) of the slope based on the geotechnical data obtained using Limit Equilibrium slope stability analysis, and evaluate the stability factors for appropriate waste dumps geometries.

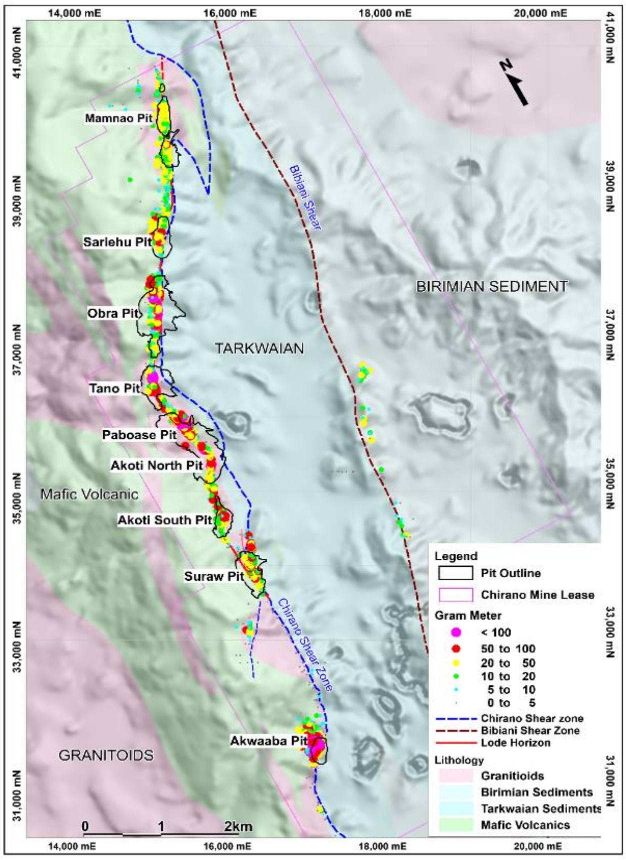

Figure 1: Geological Map of the Area Showing Locations of the Gold Deposits

The study area is located within the gold belt of southwestern Ghana, as shown in Figure 1. The area is dominated by steep terrain and dense vegetation interspersed with small agricultural plots. Three deposits from the gold mine with a total daily ore production and waste generation of 10,000 and 13,000 tonnes, respectively, from the mines' operations. The mine set up dumping sites to accommodate the waste generated from its operations. The waste rock dumps are grouped into three locations: Tano Waste Dump (TWD), Akoti Waste Dump (AWD), and Suraw Waste Dump (SWD). The surface areas of the waste dumps are 519,609 m^2, 641,361 m^2 and 255,584 m^2 for TWD, AWD and SWD, respectively. Their geometric parameters are detailed in Section 3. The waste dumps are situated in relatively close proximity to the various pits and are about 820 m distant apart. During the construction of the waste dumps, lifts of 10 m in height were placed at the angle of repose with a bench width of 10 m with a maximum height of 55 m.

2.0 MATERIALS AND METHODS

2.1 Materials

Samples were randomly selected from the waste rock dumps: TWD, AWD and SWD (See Figure 1). The samples were sent to Council for Scientific and Industrial Research Kumasi, Ghana (Building and Road Research Institute) to determine the uniaxial compressive strength (UCS) and abrasiveness. The Point Load Strength Index (PLI) was also performed in the University of Mines and Technology geotechnical laboratory.

2.2 Methods

Three waste dump sites, TWD, AWD, and SWD, in the study location, were studied in conducting this research. The resulting geometries were evaluated using Janbu's Generalised Method of slope stability analysis because it considers both interslice forces, assumes a line of thrust for interslice forces, satisfies both force and moment equilibriums, handles complex geometry and failure surfaces, an advanced method among Limit Equilibrium Methods and the method can be used for both total and effective stress analyses [14, 15]. According to the authors, the FS for cohesive and frictional soil/waste rock can be computed using Equations (3-5).

$$FS = Ncf + \frac{c}{pd} \tag{3}$$

$$\Upsilon c\emptyset = \frac{pe}{c} tan\emptyset \tag{4}$$

$$pe = (1 - ru) \tag{5}$$

where Ncf is the stability number, which depends on a dimensionless factor (Υcφ), and $ru = u/yz$ is the pore pressure ratio. pd is the total stress, and pe is the effective stress. Figure 2 depicts slope geometry illustrating Janbu's Direct Method.

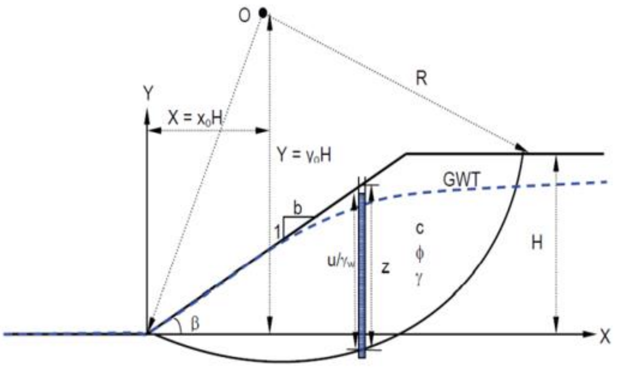

Figure 2: Slope Geometry Illustrating Janbu's Direct Method [16]

Ten samples were randomly selected from each of the waste rock dumps. Laboratory analysis was carried out on them at the Council for Scientific and Industrial Research Kumasi, Ghana, to determine the uniaxial compressive strength (UCS) and abrasiveness. The PLI was also determined. The tests were performed in accordance with the American Society for Testing and Material, ASTM D2938 [17]. Triaxial compressive strength tests were also performed on selected samples following the International Society of Rock Mechanics (ISRM) [18]. The test provides data for determining the major and minor principal stresses. RocLab Version 1, a software program for determining rock mass strength parameters based on the generalised Hoek-Brown failure criterion [19], was used. This provides a simple and intuitive implementation of the Hoek-Brown failure criterion, allowing users to easily obtain reliable estimates of rock mass properties and visualise the effects of changing rock mass parameters on the failure envelopes. These parameters determined from the rock mass properties were used as input values for numerical analysis, which require material properties to perform limit equilibrium slope stability analysis of the waste dumps.

The slope stability analysis of the waste dumps was conducted using Rocscience Slide software, a commercial program that performs two-dimensional limit equilibrium analysis [20]. The Rocscience Slide software is a geotechnical software that analyses slope stability using the limit equilibrium method. Its mode of operation involves defining slope geometry, material properties, and boundary conditions. The software then divides the slope into slices, calculates forces, and checks the factor of safety. Rocscience Slide provides various output options, including a factor of safety, critical failure surface location, and stability charts. Required inputs include slope geometry, material properties, and boundary conditions, while output options include a factor of safety, critical failure surface location, and stability charts. All three waste dumps were analysed for both circular and non-circular surfaces using the Janbu corrected method, and the Path and slope surface search methods were used for all cases while considering the following stability conditions: (i) waste dump is dry; (ii) piezometric surface is present between natural and dump material; and (iii) seismic loading. The design criteria are based on the recommended "Case A" FS according to [21], as shown in (Table 1). The recommended FS given in "Case A" is higher than "Case B". The design criteria of "Case A" were chosen over "Case B" because of uncertainties in the input parameters and assumed conditions. The elevated phreatic surface in the waste rock dump was not considered owing to the coarseness of the material and the infiltration capacity of the surface. The runoff water surface was considered at the natural ground and waste rock interface. B-bar was considered for NWD due to low permeability as the excess pore water within the clay cannot readily dissipate.

Table 1: Mined Rock and Overburden Pile Minimum Factor of Safety Guidelines [21]

Stability Condition	Suggested Minimum Design Values for FS	
Stability of Dump Surface	**Case A**	**Case B**
Short-term (during construction)	1.00	1.00
Long-term (reclamation - abandonment)	1.20	1.10
Overall Stability (Deep Seated Stability)		
Short-term (Static)	1.30 - 1.50	1.10-1.30
Long-term (Static)	1.50	1.30
Pseudo-static (earthquake)	1.10 - 1.30	1.00

3.0 RESULTS AND DISCUSSIONS

Uniaxial Compressive Strength (UCS) test results are presented in Table 2, while Table 3 depicts the selected samples' triaxial compressive strength test results.

Table 2: Results of Uniaxial Compressive Strength Test

Sample ID	Length (mm)	Mass (kg)	Load (kN)	UCS (MPa)
1	50 x 50	0.5325	300.10	120.04
2	50 x 50	0.5710	262.21	104.88
3	50 x 50	0.5660	311.00	124.4
4	50 x 50	0.5800	294.11	117.64
5	50 x 50	0.5485	216.00	86.40
6	50 x 50	0.5610	220.16	88.06
7	50 x 50	0.5690	189.89	75.96
8	50 x 50	0.5575	200.67	80.27
9	50 x 50	0.5550	236.78	94.71

Table 3: Results of Triaxial Compressive Strength Test

Sample ID	Lithology	Diametre (D)	Height (H)	Ratio (H/D)	Mass	Density	Confining Pressure δ3	Failure Load (P)	Strength (TCS) δ1
		mm	mm		g	g/cm³	MPa	kN	MPa
PB0039	Dolerite/ quartz	50.69	1030	2	570.80	2.75	20.00	300.90	149.10
PB0030	Dolerite	50.52	105.20	2.10	586.20	2.78	40.00	753.20	375.70
PB0024	Dolerite	50.49	105.10	2.10	600.80	2.86	10.00	392.10	195.90
PB0034	Dolerite	50.19	106.00	2.10	581.90	2.77	20.00	308.10	155.70
PB0035	Dolerite	50.23	104.70	2.10	571.70	2.76	40.00	635.90	320.90
PB0036	Dolerite	50.63	104.30	2.10	582.10	2.77	10.00	251.90	125.10
PB0037	Dolerite	50.66	105.10	2.10	598.50	2.83	20.00	312.70	155.10
PB0032	Brecciated quartz	50.38	104.70	2.10	576.50	2.76	10.00	988.60	495.90
PB0026	Quartz Dolerite	50.52	104.60	2.10	604.10	2.88	20.00	1179.50	588.40
PB0033	Quartz Dolerite	50.56	105.60	2.10	600.50	2.83	40.00	794.90	395.90
PB0020	Sheared Tonalite	50.66	106.10	2.10	572.20	2.68	10.00	829.20	411.40
PB0022	Tonalite	50.58	103.90	2.10	571.20	2.74	20.00	1172.70	583.70
PB0041	Tonalite	50.32	103.60	2.10	568.90	2.76	40.00	1278.50	642.90
PB0031	Tonalite/ quartz dolerite	50.17	104.30	2.10	561.20	2.72	10.00	766.00	387.50
PB0028	Tonalite/ quartz dolerite	50.59	105.10	2.10	565.40	2.68	20.00	1477.70	735.10
PB0040	Brecciated tonalite	50.50	106.20	2.10	597.40	2.81	40.00	992.90	495.70

The values of UCS of the three waste dumps range from 75.96 MPa to 120.04 MPa, which can be classified as very high strength according to ISRM, which indicates the competency of the rocks in the waste dumps. The results of the triaxial compression show that the major principal stresses average 323.16 MPa, 394.52 MPa and 446.22 MPa, corresponding to average minor principal stresses of 10 MPa, 20 MPa and 40 MPa, respectively. This test provides data for determining cohesion (c) and angle of internal friction (ϕ) of the rock, which are two internal mechanisms by which rock resists shear stress.

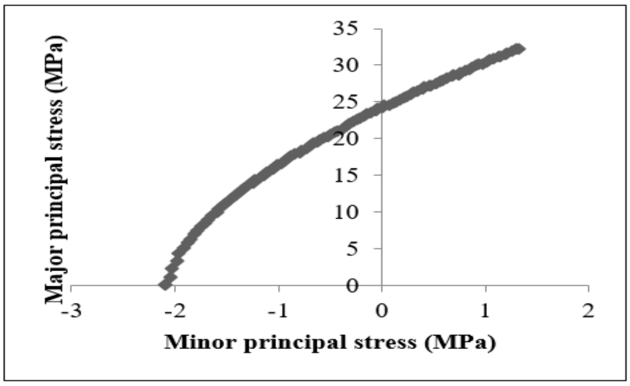

Figure 3: Variation of Major and Minor Principal Stresses within the Footwall

Graphs of major and minor principal stresses and normal and shear stresses were plotted (Figures 3 and 4) using RocLab Version 1 to determine the rock mass strength based on the generalised Hoek-Brown failure criterion. Figures 3 and 4 exhibit linear relationships and show typical results of increasing confining stress on the strength of the sample, which indicates that the effect of the confining stress is vital in the application of forces in rock. Tables 4 and 5 show the waste rock's Hoek–Brown Criterion parameters [19] and material properties.

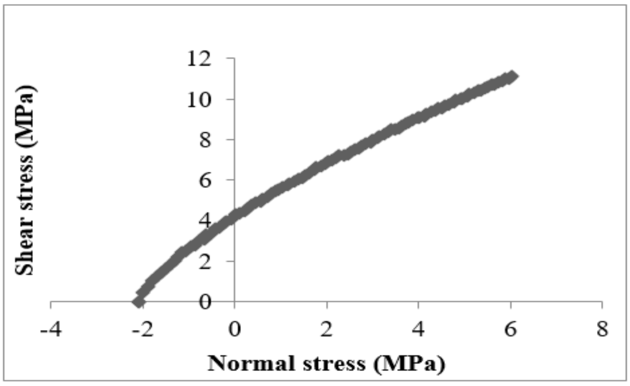

Figure 4: Variation of Normal and Shear Stresses within the Footwall

Table 4: Rock Mass and Hoek–Brown Parameters within the Waste Rock

PARAMETER					
Rock Mass (MPa)		Hoek-Brown		Mohr-Coulomb	
		Constants	Value	Constants	Value
Tensile strength	-2.093	mb	0.967	Cohesion	4.064MPa
Uniaxial compressive strength	24.176	s	0.0067	Friction Angle	51.65
Global strength	42.487	a	0.504		
Deformation modulus	4899.37				

Table 5: Material Properties

Material	Unit Weight (kN/m^3)	Cohesion (MPa)	Friction Angle (°)	Stiffness E' (MPa)
Clay silt	20	10	30	-
Foundation (Clayey silt)	18	10	28	25

The survey pick-ups of the as-built waste dumps were used for the slope stability analysis, with sections prepared from the most critical areas considering slope heights and angles, as shown in Table 6. It can be observed that the waste dump TWD has the highest slope height and angle of inclination with a minimum FS of 1.61, while the waste dump SWD has the lowest value with a minimum FS of 1.32 (Table 7). This implies that the stability of the waste dump is influenced by the slope height and slope angle [3].

Table 6: Waste Dump Geometry

Name	TWD	AWD	SWD
Vertical Height (m)	55.4	35	27.3
Slope angle (°)	23	27	18

Table 7: Summary of Model Results

Circular Surface and Slope Search				
Stability Condition	**Target FS**	**TWD**	**AWD**	**SWD**
Dry Condition	-	1.83	1.63	2.74
Long-term (Static)	1.5	1.75	1.53	2.50
Pseudo-static (earthquake)	1.1-1.3	1.50	1.35	2.10

Figures 4 to 19 depict the modelling of the various waste rock dumps using Rocscience Slide software [20], while Figures 20, 21 and 22 show the geometry of the waste rock dumps. All site waste rock dumps were analysed for circular and non-circular surfaces using the Path and slope surface search methods, while Hoek-Brown and Mohr-Coulomb constitutive models were used for the simulation. From Figures 17, 18 and 19, the geometry of SWD is within the Environmental Impact Statement requirement, and it does not require reshaping, while the slope angles of the remaining waste dumps (TWD and AWD) need to be reshaped to achieve the proposed minimum standard.

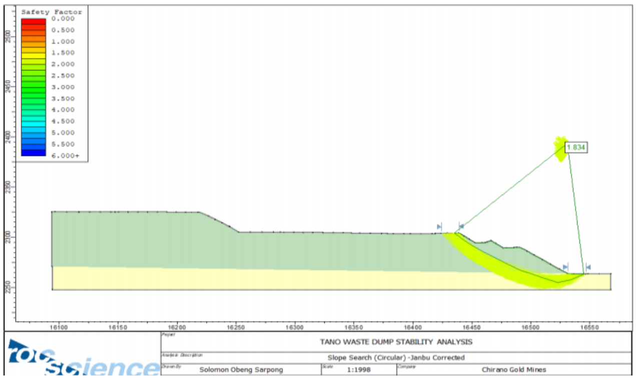

Figure 5: Normal Operating for TWD, Circular Slope Search

A summary of the slope stability results of the waste rock dumps is presented in Tables 7 and 8. The FS for the waste dumps ranged from 1.61-2.74, 1.49-2.50 and 1.32-2.10 under dry, static and pseudo-static loading conditions, respectively. These values are above the minimum required standard of 1.1-1.5 for stability conditions. It can therefore be established that the FS for TWD, AWD and SWD waste dumps are above the minimum FS requirement under dry, static and pseudo-static loading conditions. Also, the geometry of waste dump SWD is within the standard, and it does not require reshaping, while the slope angles of waste dump TWD and AWD fall below standard and therefore need to be reshaped to conform with the minimum standard.

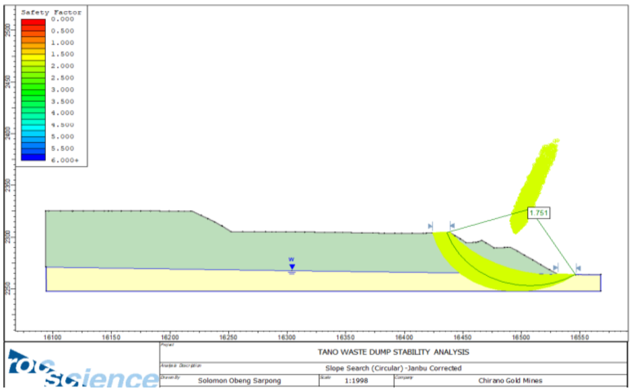

Figure 6: Operating with Piezometric Surface for TWD

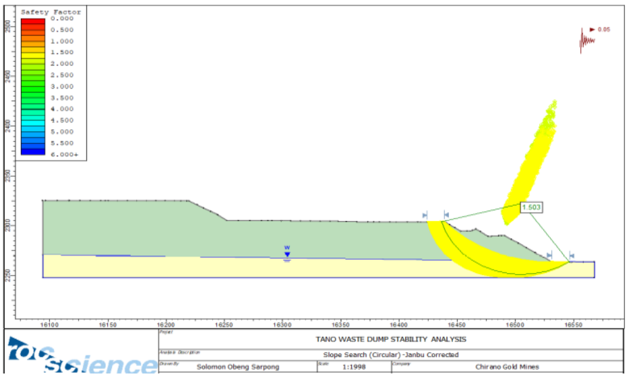

Figure 7: Operating with Piezometric Surface and Seismicity for TWD, Circular Surface

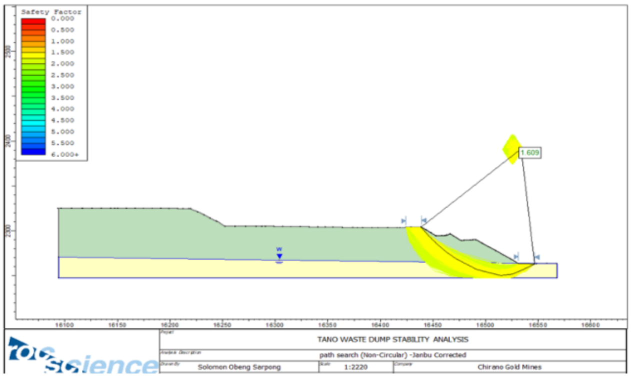

Figure 8: Normal Operating for TWD, Non-Circular Surface

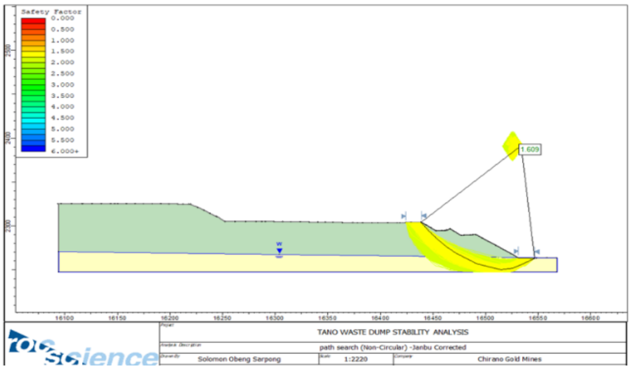

Figure 9: Operating with Piezometric Surface for TWD, Non-Circular Surface

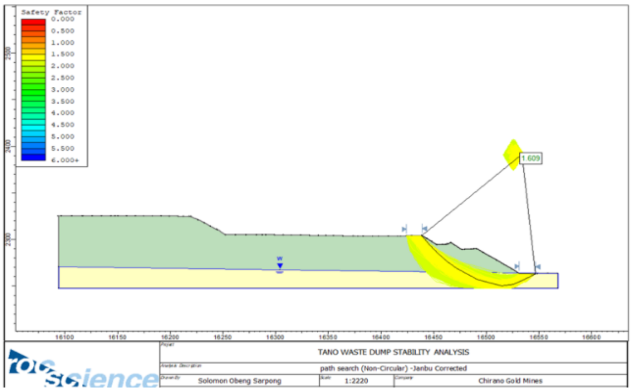

Figure 10: Operating with Piezometric Surface and Seismicity Loading for TWD, Non-Circular Surface

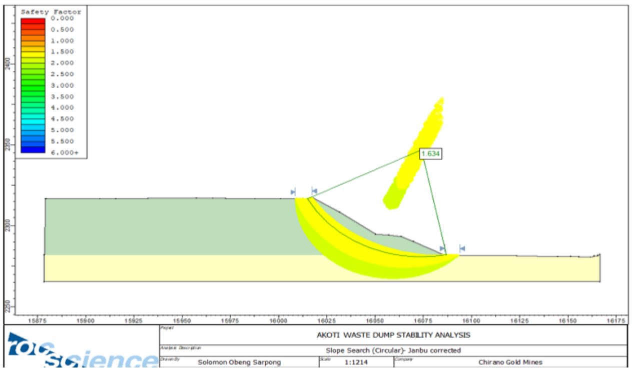

Figure 11: Normal Operating for AWD, Circular Surface

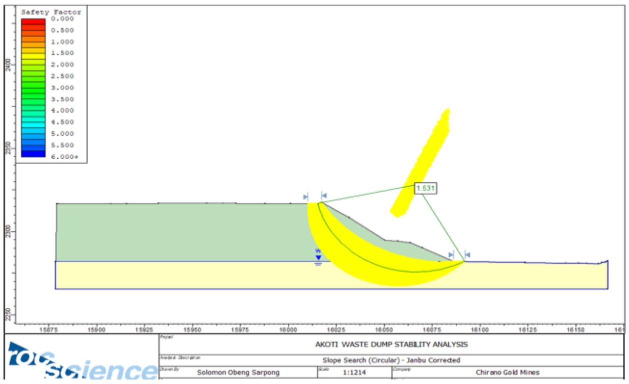

Figure 12: Operating with Piezometric for AWD, Circular Surface

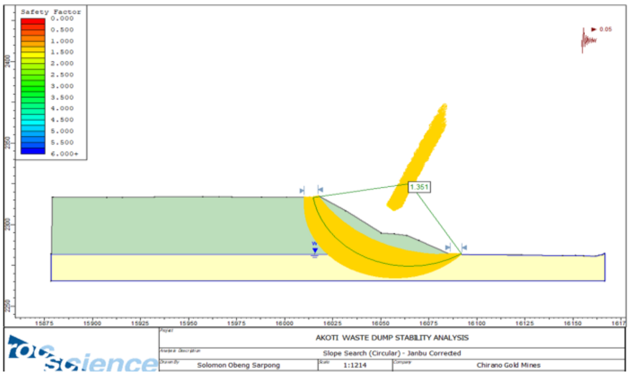

Figure 13: Operating with Piezometric Surface and Seismicity Loading for AWD, Circular Surface

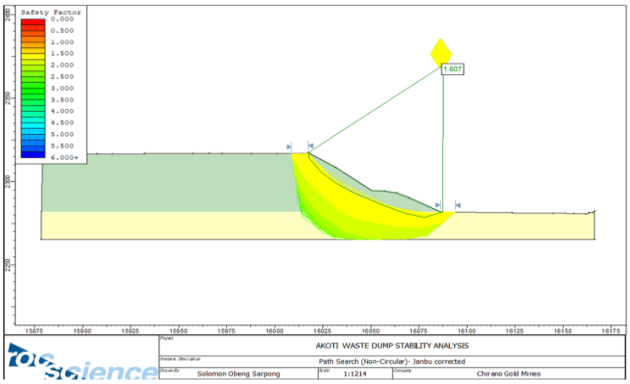

Figure 14: Normal Operating for AWD, Non-Circular Surface

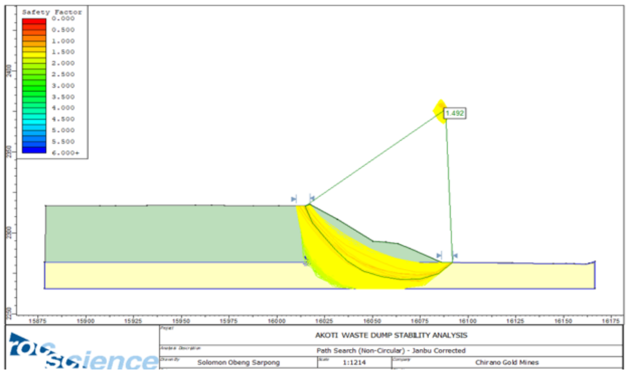

Figure 15: Operating with Piezometric Surface for AWD, Non-Circular Surface

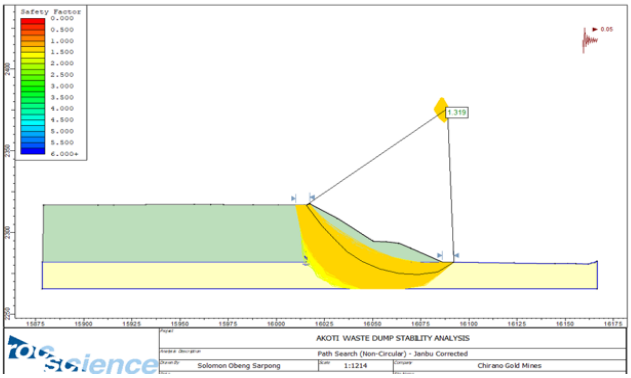

Figure 16: Operating with Piezometric Surface and Seismic Loading for AWD, Non-Circular Surface

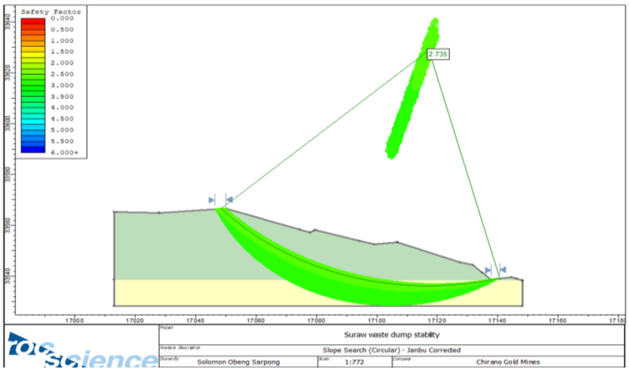

Figure 17: Normal Operating for SWD, Circular Surface

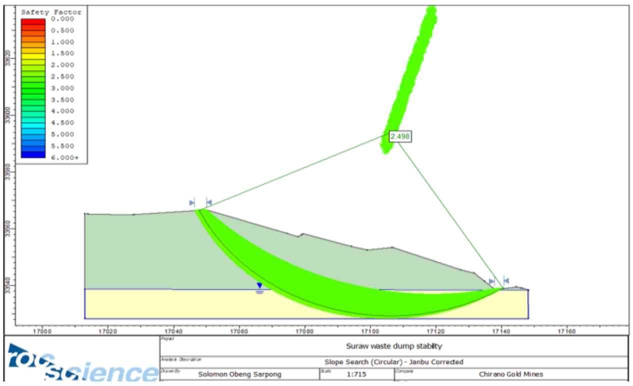

Figure 18: Operating with Piezometric Surface for SWD, Circular Surface

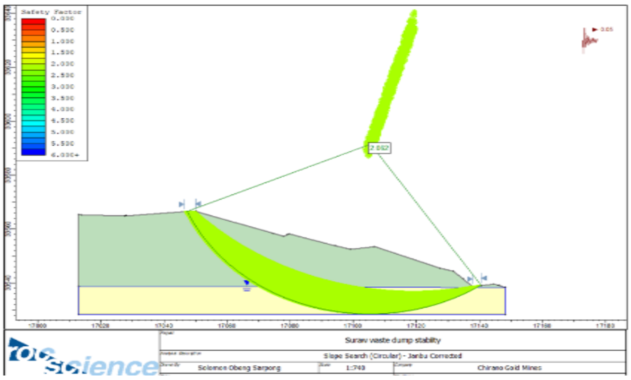

Figure 19: Operating with Piezometric Surface and Seismic Loading for SWD, Circular Surface

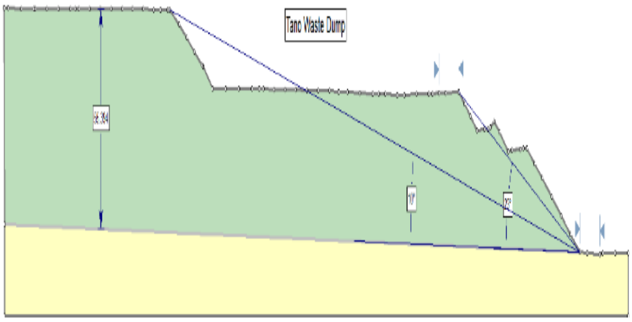

Figure 20: Geometry of TWD

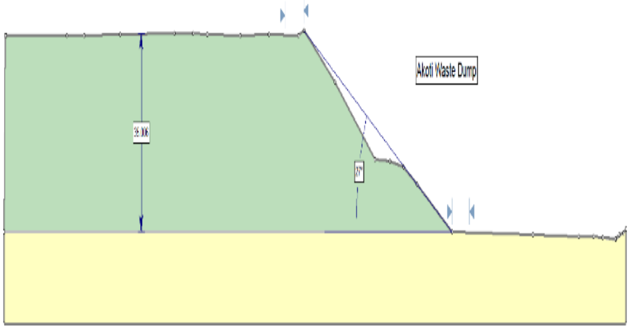

Figure 21: Geometry of AWD

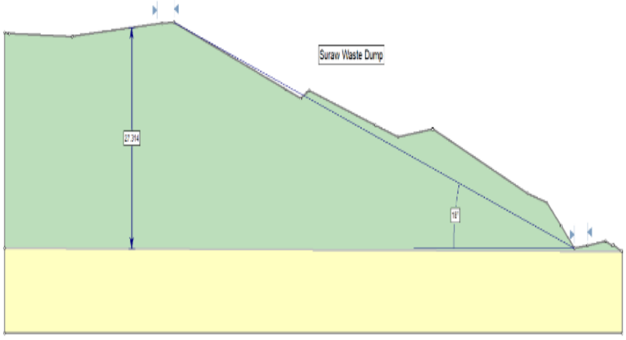

Figure 22: Geometry of SWD

Table 8: Summary of Model Results

Non-Circular Surface and Path Search				
Stability Condition	**Target FS**	**TWD**	**AWD**	**SWD**
Dry Condition	-	1.83	1.61	2.61
Long-term (Static)	1.5	1.61	1.49	2.38
Pseudo-static (earthquake)	1.1-1.3	1.40	1.32	1.98

4.0 CONCLUSION

This research was carried out to evaluate the overall stability of the existing as-built waste dumps of a typical gold mine for the reclamation and mine closure. Three different waste dumps were assessed, and their material properties, hydrogeological conditions; shear strength properties (cohesion and angle of internal friction), engineering properties; factor of safety (FS) of the slope based on the geotechnical data were determined using the Janbu Generalised Method of slope stability analysis which is an extension of the conventional Limit Equilibrium technique. Their stability factors for appropriate waste dumps geometries were also evaluated. The FS for the three waste dumps were determined and ranged from 1.61-2.74, 1.49-2.50 and 1.32-2.10 under dry, static and pseudo-static loading conditions, respectively. These values are above the EIS minimum standard of 1.1-1.5 for stability conditions. The geometry of one of the waste dumps (SWD) is within the standard, and it does not require reshaping, while the slope angles of the remaining waste dumps (TWD and AWD) need to be reshaped to achieve the proposed EIS slope angle of 3H:1V (18.4 degrees).

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