Design optimisation of Jwaneng mine cut 9 waste dumps

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Abstract
This study includes a detailed review of the Jwaneng Diamond Mine waste dumps using a recent comprehensive rock waste, stockpiles and tailings stability assessment method called Waste Dump Stability Rating and Hazard Classification System (WSRHC), a finite element method-based program called RS2 and a limit equilibrium program called SLIDE both from Rocscience Inc. They prove to be more hazardous as the dumps are growing in size and are getting affected by major mine developments like Cut 9 pushback which is advancing to the place where most of the old waste dumps are located. The stability status of these Jwaneng Diamond Mine waste dumps has not been studied at large convincingly. As with the open pit, monitoring of the current waste dumps should be an integral part of Jwaneng mine operations. Visual inspections are recommended to be done around the dumps and on-top to check for failed material and newly formed tension cracks. Intense tracking/monitoring of displacements/failures within the dumps, is a must practice specially a day after significant blasting in the Cut 9 walls and about 3 days after heavy rainfalls of the magnitude like the one of Cyclone Dineo.

For such visual inspection, several recommendations are proposed. These are installation of different Radar systems such as Time Domain Reflectometers (TDR) and inclinometers, to detect movements of deep-seated slip surfaces, installation of Piezometers to monitor water table levels and seasonal ground moisture variations, installation of interferometric Synthetic Aperture Radars and comparison of weekly Digital Terrain Models (DTM), installation of Frequent field tests to obtain bearing capacities of the foundation material in the Jwaneng mine dumps, monitoring of saturated unit weights for the individual rock units (and sand), designing a systematic drainage or relief plan and construction of complete hydrogeological model considering regional water flow patterns of the study area.

Keywords: Jwaneng, mine, Hazardous waste, WSRHC, TDR, RS2, SLIDE.

Introduction

This study focuses on the review of the Jwaneng Diamond Mine waste dumps. Cut 9 pushbacks is estimated to produce 1 billion tons of waste rock from implementation by 2036.With waste from earlier cuts, they form an approximated total of 1.7 billion tonnes which need to be dumped safely and at controlled costs. The dumps become more hazardous as they grow in size. Slope instability is further aggravated major mine development activities.The current work has been carried out using a recent comprehensive rock waste, stockpiles and tailings stability assessment method called Waste Dump Stability Rating and Hazard Classification system (WSRHC), a finite element method-based program called RS2 and a limit equilibrium program called SLIDE both from Rocscience Inc.

As with the open pit, monitoring of the current waste dumps should be an integral part of Jwaneng mine operations. Visual inspections are recommended to be done around the dumps and on-top to check for failed material and newly formed tension cracks. Intense tracking/monitoring of displacements/failures within the dumps is a must practice.

Location: Jwaneng mine is in the Southern District of Botswana at about 120 km due west of the capital city Gaborone. Fig. 1 shows the location of Jwaneng mine and Debswana Diamond Company's other mine site locations[2].

Geology: The Jwaneng Mine stratigraphy comprises of Paleoproterozoic aged sedimentary rocks of the Pretoria Group within the Transvaal Super group. Table 1 shows the general stratigraphy of the Jwaneng mine.

Background of Jwaneng mine waste dumps: Cut 9 pushbacks is estimated to produce 1 billion tons of waste rock from implementation by 2036. With waste from earlier cuts, they form an approximated total of 1.7 billion tonnes which need to be dumped safely and at controlled costs. An extensive and comprehensive review of existing dumps in terms of their safety and hazard standings quantitatively by latest and improved systems is required for their optimized extensions and stability monitoring. As per the long-term planning section of the Jwaneng Diamond Mine, the mine's rock waste dumps have been divided into seven subsections; dumps 1 - 7. Dumps 1, 2, 5 and 6 are active dumps while dumps 3, 4 and 7 are closed/inactive. Top soil/sand has its separate dump just next to the waste rock dumps. Fig. 3 is showing locations of all the waste dumps studied in this study.

This present study for the Jwaneng mine dumps designs provides valuable addition to the current understanding of the stability status of the dumps in the phase of Cut 9 expansion and future extensions. Cut 9 pushback is anticipated to produce about a billion tonnes of waste rock from its implementation to around year 2036. Combined with waste from earlier cuts, they form an approximate total of 1.7 billion tonnes worth of waste dump. This alarming figure necessitates very safe dumping safely and at controlled costs.

Stability performance: Based on failure history of the existing waste dumps, dumps 1,2,6 and 7 had a stable performancewith minor tension cracks. Dump 7 experienced a circular failure during *Cyclone Dineo* in 2018 caused by the heavy rains, but the impact was negligible on operations shown in fig. 4.

Table 1
The Stratigraphic Column of Jwaneng Pit

STRATIGRAPHIC NAME	ROCK TYPES	THICKNESS (M)	AGE
Kalahari Sequence	Sand & Calcrete	55-60	2.6 million to 11,700 years ago
Timeball Hill Formation	Laminated Shale	Residual	2,320 to 2,250 million years
Lower Timeball Hill Formation	Carbonaceous Shale	30	2.5 billion to 1.6 billion years ago
Rooighoogte Formation	Quartzitic Shale	135	Approximately 2.4 to 2.3 billion years ago,
Chert Pebble Conglomerate	Bevets	0-4	
Rooighhoogte Formation	Quartzitic Shale	375	
Lower Rooighoogte Formation	Carbonaceous Shale	10	
Malmani Subgroup	Dolomite	Residual	Approximately 2.5 billion years ago

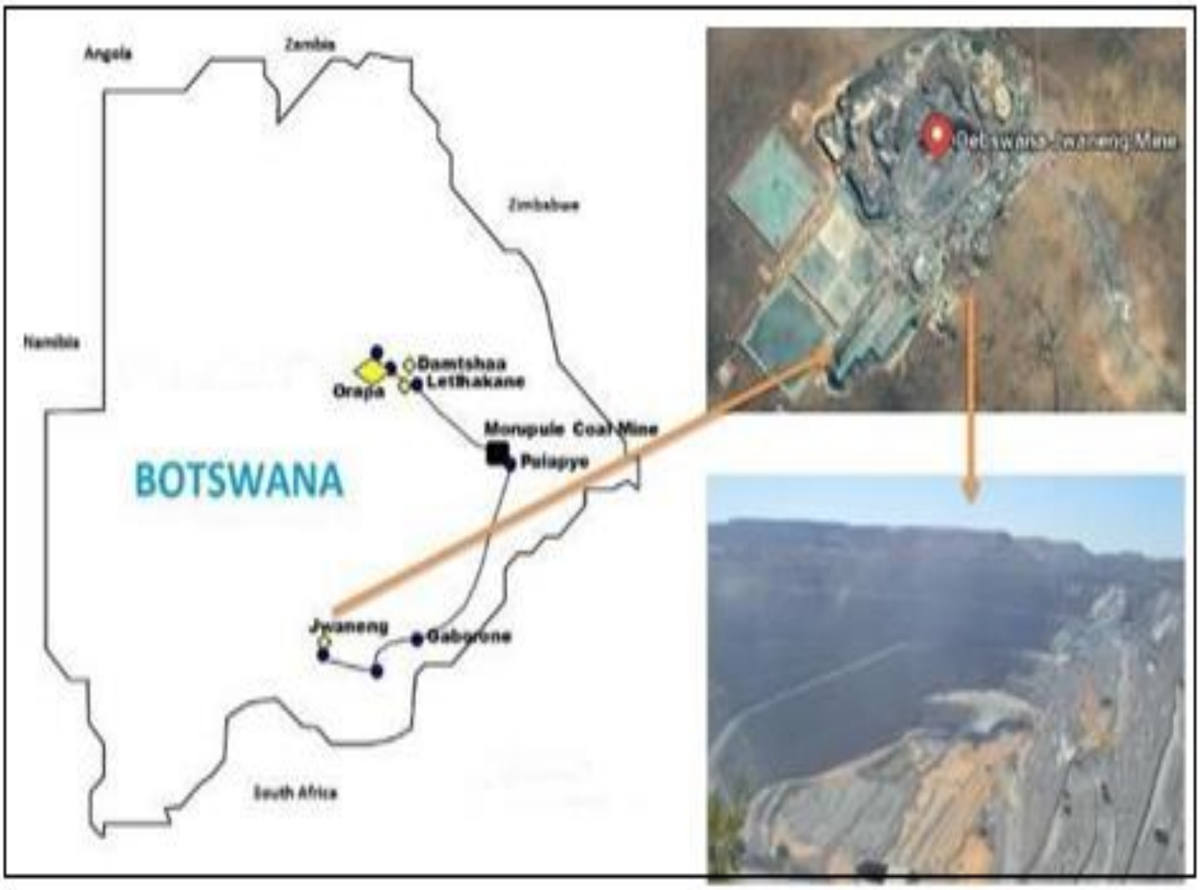

Fig. 1: Location of Jwaneng Mine from the map of Botswana and satellite image

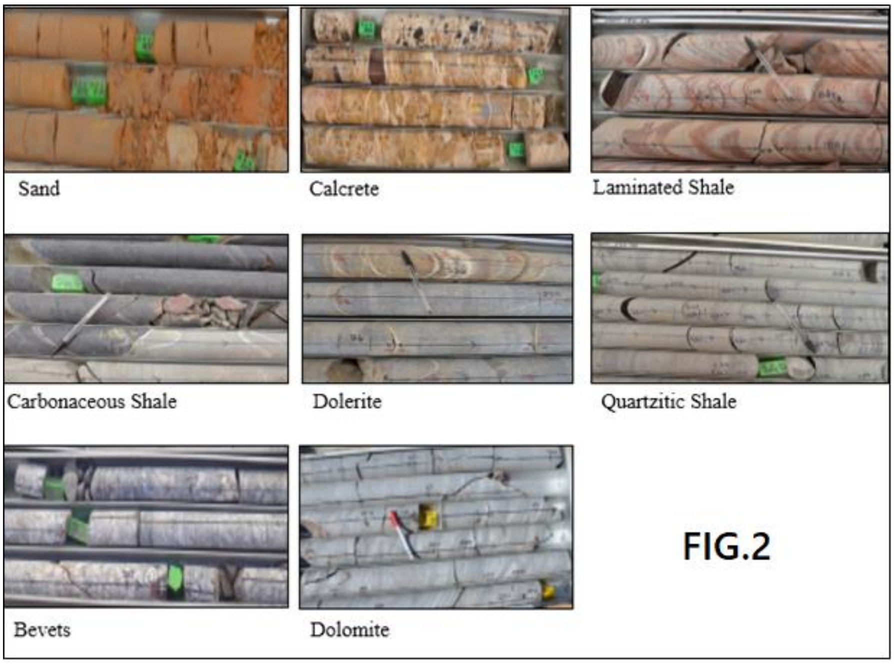

Fig. 2: Cores of the representative rocks encountered

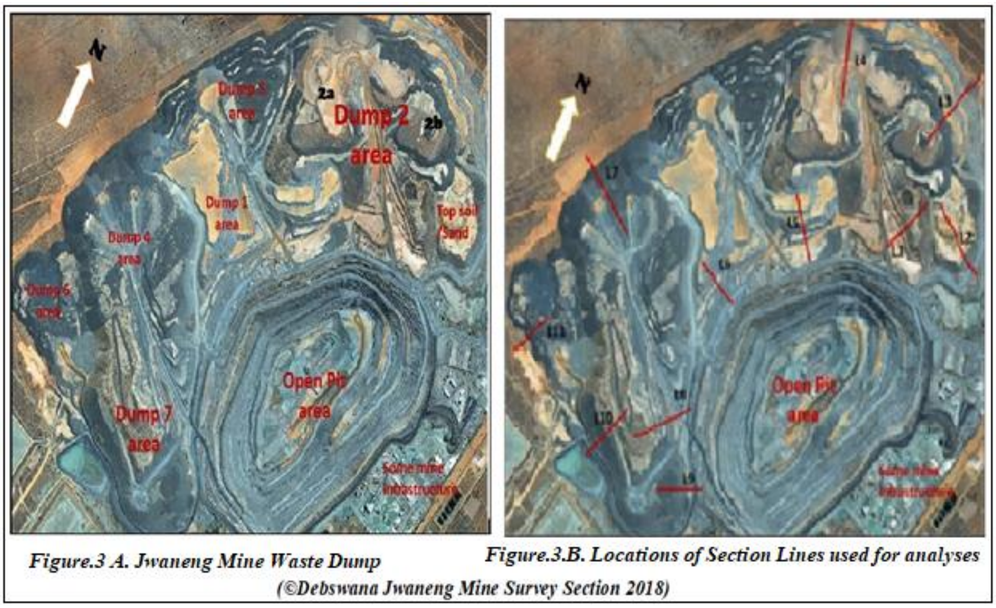

Figure.3 A. Jwaneng Mine Waste Dump *Figure.3.B. Locations of Section Lines used for analyses*
(©Debswana Jwaneng Mine Survey Section 2018)

Fig. 3: Location and section lines of Jwaneng Waste Dump

Review of Literature

Slope stability in the surface and underground mines has always been a big challenge. McQuillan et al[11] advocated the necessity of 3D analysis for open-pit rock slope stability studies. The mine waste can be reused and recycled in mining in a cost-effective manner through offsetting raw material requirements and can result in decreasing the volumes of waste[1]. There had been advocates for Automation and AI Technology in the surface mining[9]. The location for dumping the waste from the open pit mine has significant weight for the establishment of the waste treatment costs. By using the constructive parameters of the waste dump and the terrain's characteristics, the volume of the affected area can be determined in relation to the waste volume generated from the exploitation of a mineral deposit[8].

The significance of hybrid model for optimization of waste dump design and site selection in open pit mining has been studied[4]. The model is based on different mathematical methods (Monte Carlo simulation, genetic algorithm, analytic hierarchy process and heuristic methods) adapted to different aspects of the problem. Probabilistic Stability Analysis for Pit Slope Optimisation was carried out at Jwaneng Diamond Mine, Botswana using the "Response-Surface" methodology, considering the rock parameters UCS and GSI as uncertain variables for the probabilistic calculation[3].

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The low likelihood of overall failures and low potential of economic impact from these events was confirmed. Also South African mining has many positive aspects and good future[6]. A structural data bias assessment at Jwaneng mine was conducted too[5]. Bias assessment undertaken from the data covered a review of existing drillhole core orientations and mapped discontinuity orientations. Stereonet plots and 3D plotting of the drillholes, together with discontinuity from geophysical televiewer logs were used for the bias assessment. Evident from the assessment is bias that results from unfavorable drillhole orientation with respect to certain geological structures. The methodology provided a means of proactively realizing the gaps and adequately addressing them. Guidelines on how to design an optimal survey slope monitoring system were provided[10]. The survey monitoring system yielded desirable results.

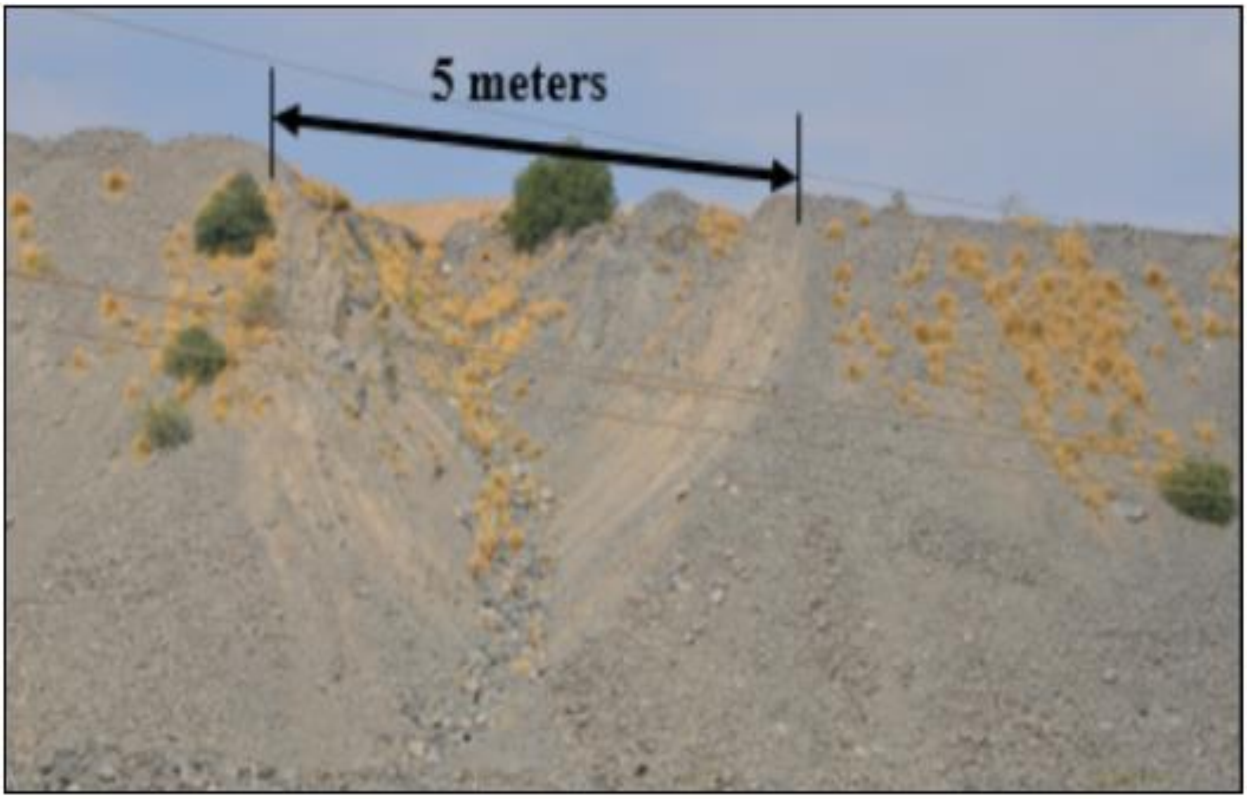

Fig. 4: Circular Failure on Dump 7 due to Cyclone Dineo and heavy downpours in 2018

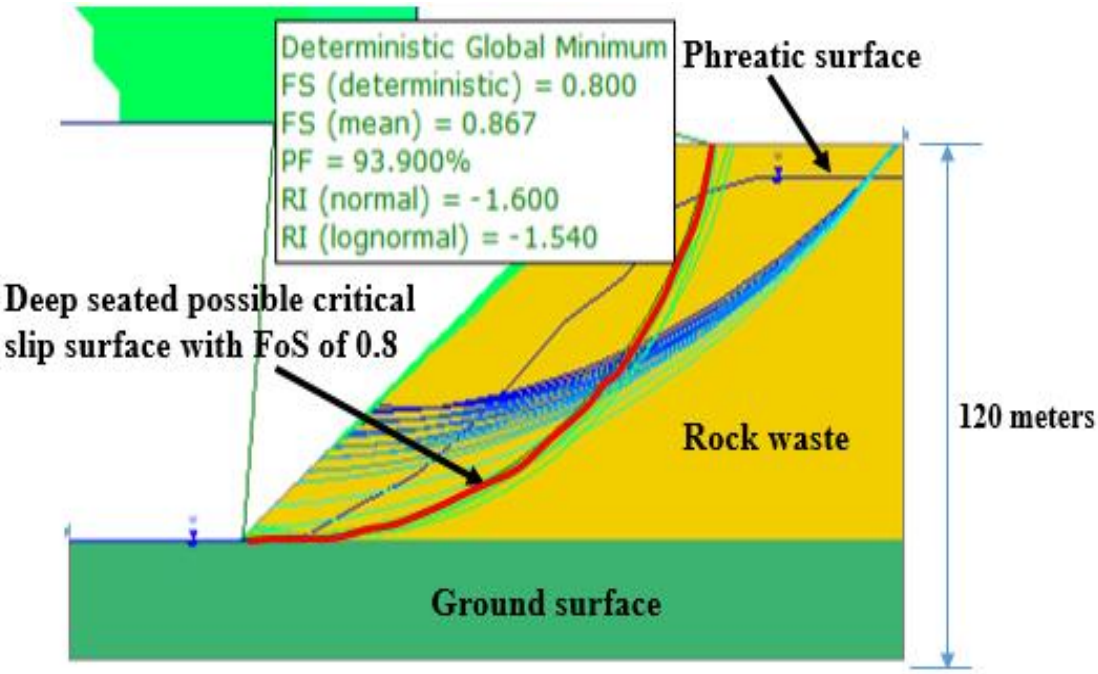

Fig. 5: Critical slip surface on L4 huge lift which has no benches (using Janbu).

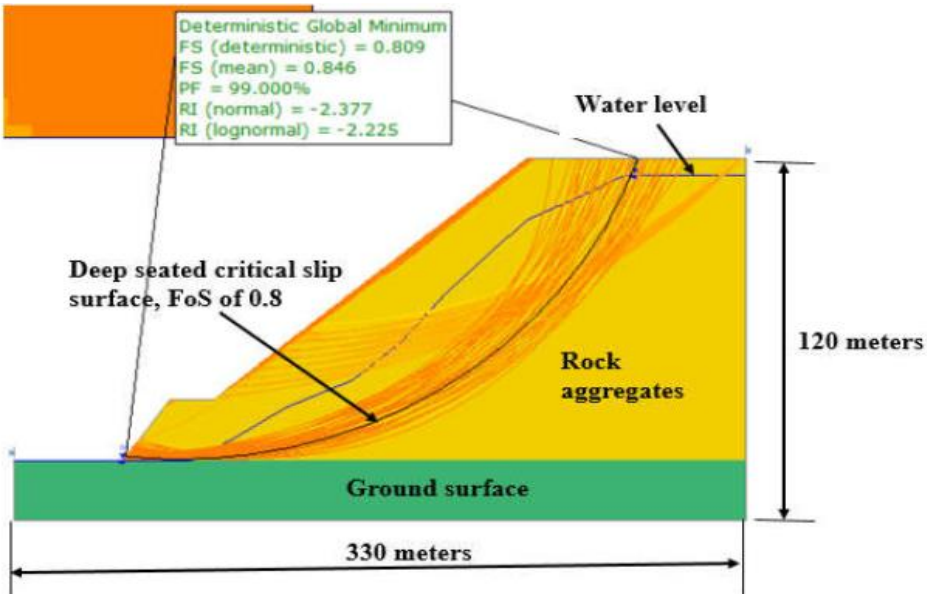

Fig. 6: Possible deep-seated critical slip surface under wet conditions with FoS under 1 (using Janbu).

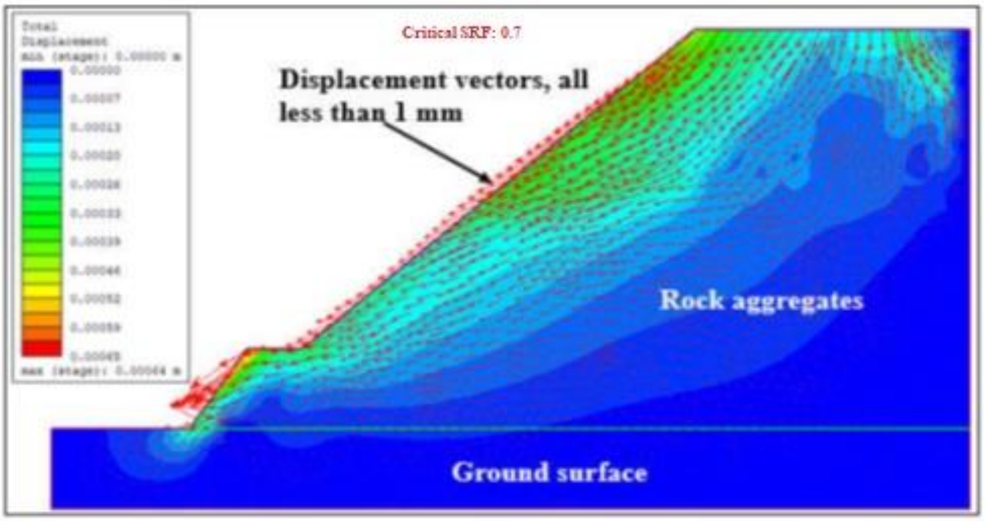

Fig.7: Minor displacements under dry conditions, all under 1mm

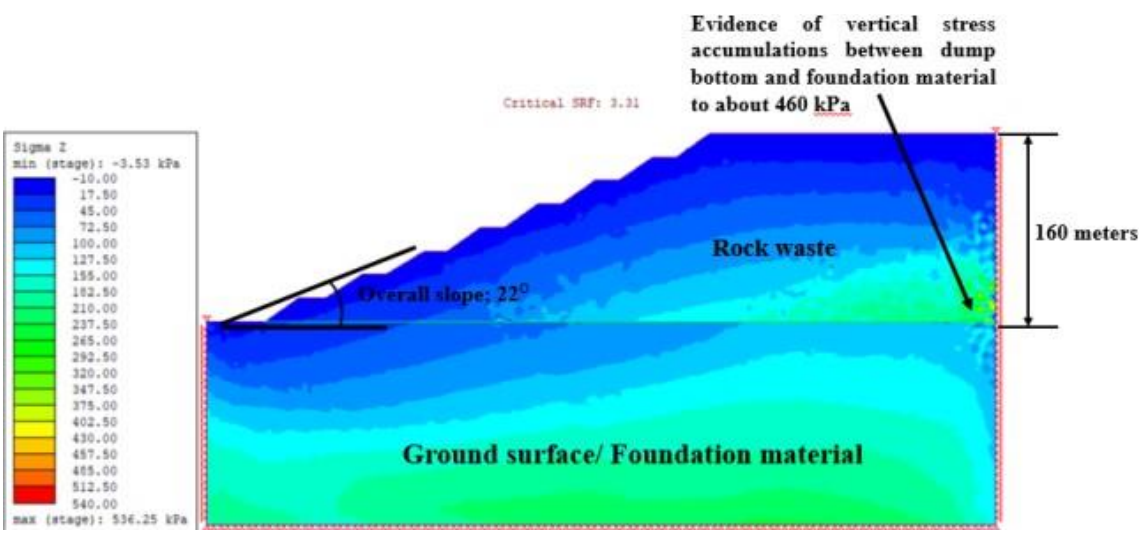

Fig. 8: Vertical stress distribution in a dump of 20 by 20m lifts (using Spencer).

Material and Methods

The methodology consists of two parts, the first being the "Waste dump Stability Rating and Hazard Classification System (WSRHC)" and the second one is the "*Dump Stability Analysis Using Software"*.

Waste dumps analysis using WSRHC system: The Waste Dump and Stockpile Stability Rating and Hazard Classification (WSRHC) system is a comprehensive framework developed to assess the stability and hazard potential of mine waste dumps and stockpiles. The WSRHC system is designed to assist engineers and geotechnical professionals in making informed decisions regarding the design, operation and monitoring of waste dumps.

The Waste Dump Stability Rating and Hazard Classification system (WSRHC) has been used for analyses[7]. It requires evaluation of 22 key factors considered to affect waste dumps and stockpiles stability. Weightings in the system total to 100%. The considered factors/parameters include: Seismicity, Precipitation, Foundation slope, Foundation shape, Overburden thickness, Undrained Failure Potential, Foundation Liquefaction Potential, Bedrock, Groundwater, Intact Strength and Durability, Material liquefaction potential, Chemical stability, Height, Slope Angle, Volume and Mass, Static stability, Dynamic stability, Construction method, Loading rate and Stability performance. Calculated values are shown in table 2. It is important to note that the dumps, length and width parameters are rough estimations based on the dump's longest and shortest extent, since none of the dumps have a perfect regular shape.

Dump stability analysis using software: A finite element-based program RS2 and a limit equilibrium-based program SLIDE were used for this part. From conducting stability analysis along chosen sections on the current waste dumps using the programs, factor of safety, probability of failure, strength reduction factor values and stress-strain distributions were obtained for the individual dump areas. The Jwaneng Mine dumps majorly contain loose/non-coherent mixed rock fragments of various sizes which tend to behave like soil under stress/strain, so the prominent mode of failure likely to occur is circular failure, which became the sole focus of this study. Most engineering input parameters adopted here are from existing literature on Jwaneng Mine location's geology and performed tests contained in both external and internal sources. Table 3 records the parameters to be used for computer-based stability analysis as well as for the WSRHC.

Fig. 3 B highlights the approximate locations of section lines adopted in constructing computer models for the different sections of the dumps. Representative models are made roughly from these points for stability analysis in RS2 and SLIDE to obtain Factor of Safety, Probability of Failures, Shear stress Distribution patterns and Progressive failure within the existing dump materials. The sections lines' locations were chosen considering factors like, how steep the side slope of a dump looks, how is the position and configuration of the dump towards the pit or important infrastructure (e.g. dams) and points showing obvious non-conformance to the 2014 Jwaneng Mine dumps extension/ construction plan. Table 4 presents De Beers GoC Acceptance Criteria for Rock Waste dumps.

Table 2
Calculated values of the volume and mass for the Jwaneng Mine waste dumps, to be used in the WSRHC.

DUMP	AVERAGE LENGTH (m)	AVERAGE WIDTH (m)	AVERAGE HEIGHT (m)	VOLUME (m3)	UNIT WEIGHT (kN/m3)	MASS (Kg)
Topsoil	286	189	20	1 077 547	17	1 869 214
D1	343	229	130	10 187 732	19	19 751 725
D2A	457	343	200	31 346 936	19	60 774 672
D2B	457	240	95	10 422 860	19	20 207 586
D4	371	257	150	14 326 555	19	27 775 974
D5	274	217	80	4 764 743	19	9 237 767
D6	314	143	60	2 693 877	19	5 222 823
D7	686	217	123	18 363 590	18	33 729 043

Table 3
Input parameters adopted for computer-based stability analysis

MATERIAL	DENSITY (KN/m^3)	COHESION (kPa)	FRICTION ANGLE (º)
Waste rock	19	0	35
Sand/topsoil	17	10	35

Table 4
De Beers GoC Acceptance Criteria for Rock Waste dumps

LOAD ON OVERALL SLOPE	FACTOR OF SAFETY (FoS)
Dynamic Loading	1.05
Static Load	1.3

Table 5
Input Parameters adopted for Computer-based Stability Analysis

MATERIAL	DENSITY (KN/m^3)	COHESION (kPa)	FRICTION ANGLE (º)
Waste rock	19	0	35
Sand/topsoil	17	10	35

Table 6
List of Slicing Method and Equilibrium Analyses

SLICE METHOD	FORCE EQUILIBRIUM		MOMENT EQUILIBRIUM
	1st DIRECTION	2nd DIRECTION	
Bishop's simplified	Yes	No	Yes
Janbu's simplified	Yes	Yes	No
Spencer	Yes	Yes	Yes
Ordinary Fellenius	Yes	No	Yes

Table 7
WSRHC Ratings on the existing waste dumps in Jwaneng Mine.

PARAMETER RATINGS								
	DUMP 1	DUMP 2A	DUMP 2B	DUMP 7	DUMP 4	DUMP 5	DUMP 6	TOPSOIL/ SAND
WSR (Stability rating)	48.5	47.5	46.5	54.5	57.5	58.5	49.5	46.0
WHC (Hazard classification)	III (Moderate)	III (Moderate)	III (Moderate)	III (Moderate)	III (Moderate)	III (Moderate)	III (Moderate)	III (Moderate)

Table 8
FoS, PoF of Critical Slip Surfaces and SRF on assigned section Lines on the dumps.

Section Line	Related Dump	Factor of Probabaility of Failure		Safety Failure (%)		Stress reduction Factor
		Janbu	*Spencer*	*Janbu*	*Spencer*	
L1	Dump 2b	0.05	0.23	100.00	100.00	Didn't converge
L2	Topsoil	2.38	2.46	0.00	0.00	2.53
L3	Dump 2b	0.26	0.37	100.00	100.00	0.33
L4	Dump 2a	0.80	0.80	98.29	98.29	0.81
L5	Dump 2a	0.13	0.24	100.00	100.00	0.12
L6	Dump 1	0.10	0.41	100.00	64.42	0.25
L7	Dump 4	0.49	0.49	84.62	83.33	0.70
L8	Dump 7	0.15	0.25	75.00	46.34	0.21
L9	Dump 7	0.18	0.24	33.33	100.00	0.39
L10	Dump 7	0.41	0.41	90.00	80.00	0.58
L11	Dump 6	1.00	1.00	18.18	18.18	1.07

Table 9
FoS and PoF under wet conditions

DUMP	TOPSOIL	DUMP 1	DUMP 2A	DUMP 2B	DUMP 4	DUMP 6	DUMP 7
FoS	1.80	0.30	0.90	0.38	0.84	1.00	0.41
PoF (%)	0.00	65.00	52.10	79.56	22.22	41.67	66.36

Table 10
Recommended optimal dump extension geometries

TERRACE WIDTH (m)	LIFT HEIGHT (m)	BENCH ANGLES (°)	MAXIMUM HEIGHT (m)	OVERALL SLOPE (°)
15-20	10-20	35-40	160	20-35

The dumps studied majorly contain rock aggregates, hence the prominent mode of failure likely to occur is circular failure, so it is the only one which will be considered in stability analysis for this study. Most engineering input parameters are adopted from existing literature on Jwaneng Mine location's geology and performed tests contained in both external and internal sources.

Analysis using computer programs: For the purposes of this project, Slide and RS2 were used. Slide is a 2D slope stability analysis program to obtain FoS and PoF. It analyzes stability of estimated slip surfaces using vertical slice or non-vertical slice limit equilibrium methods like Spencer, Janbu. RS2 is a 2D finite element program for SRF. The Strength Reduction Factor (SRF) is a critical concept in the analysis of slope stability, particularly when using numerical methods like the Shear Strength Reduction (SSR) technique. It carries out finite element slope stability analysis using the shear strength reduction method.

Results and Discussion

The results are based on WSRHC ratings on the existing waste dumps in Jwaneng Mine as shown in table 7. Further, FoS, PoF of Critical Slip Surfaces and SRF are on assigned section Lines on the dumps. The values are calculated on the dry and wet basis. Table 8 presents the FoS, PoF of Critical Slip Surfaces and SRF on assigned section Lines on the dumps. Table 9 expresses the FoS and PoF under wet conditions. The Factor of Safety values along most of the analysis section lines prove that most of the slopes left after dump material relocation for Cut 9 preparations are not that safe. Care should be taken while working close to them. It is expected that the benches will keep chipping off until the material reaches angles that it can be stable at. Ramps and access roads passing next to the crumbling materials should be well maintained and cleaned.

It is important to notice that for some dumps, the wet FoS is slightly higher than the dry FoS. This might be because when a specific critical amount of water bridges the gaps between the dump particles/aggregates, some electrostatic attraction develops between the water and their surfaces which could improve the dumps' strength properties. Dumps with lifts of vertical heights of more than 20 m like dump 4 area along section line L7, are likely to form deep seated slip surfaces with low FoS which may lead to large scale circular failures in future possibly interrupting mine operations as shown in fig. 5. After the calculations of the Waste Stability Rating (WSR) the values were assigned Waste Dump Hazard Classification values (WHC). All existing waste dumps had moderate WSR values, with topsoil waste dump with the least value whilst dump 5 had the highest WSR value. Therefore, all the waste dumps had a moderate instability hazard shown in table 6 and table 7.

Another example is that of modelled deformation along L2 under extremely wet conditions, with maximum displacement close to 5m just under the force of gravity. Stability analysis results for critical slip surfaces gave FoS values approaching zero along section line L 4 as shown in fig. 5. During visual inspections as of October 2018, persistent/extensive tension cracks were observed on the crest of this dump 'stop lift which is a clear physical indicator that the slope along L1 is not currently safe and confirmed by the deterministic value of FoS (0.800) and Mean FoS (0.0867).

Case of Dump 4 is another example of low FoS. It mainly consists of compacted rock waste mixture and it is a closed dump. It has a spot height of about 120.0 meters. Dump 4 has a vastly large flat span/plan extending for about 260.0 meters, which could provide further room to extent it upwards with time but with proper stability analysis put in consideration. Stability analysis results along L7 gave FoS's of 0.5, PoF's above 80.0% and SRF of 0.7 as shown in fig. 6 and fig. 7. These low FoS values might be because its upper lift is significantly thick, about 90 meters, with no benches in between which proved to help many slopes to be stable in current practices around the world. The WSRHC gave it a stability rating of 57.5 and a hazard.

Extensions to the current waste dumps in terms of increasing their height is proposed as per the parameters in table 10, which were obtained as optimal by software analysis (SLIDE and RS2). The foundation material was set to be Kalahari sand with cohesion of 10 kPa, unit weight of

17kN/m3 and friction angle of 35º. Fig. 8 is a clear demonstration of vertical stress distribution in a dump of 20 by 20m lifts., with bench angles of 35 degrees and height of 160 m. The slope has FoS over 1.0.

Conclusion

As with the open pit, monitoring of the current waste dumps should be an integral part of Jwaneng mine operations. Visual inspections are recommended to be done around the dumps and on-top to check for failed material and newly formed tension cracks which could indicate the presence of deep-seated slip surfaces within the dump mass as seen in the stability analysis. To check for significant water ponding/accumulations which may indicate bad drainage/relief of the dump or may point out that there is excessive settlement/subsidence which may come as a result of creep deformation deep in the dump's foundation or within its mass due to high vertical stresses and excess pore pressures. A typical visual inspection plan could include doing the dumps inspection a day after significant blasting in the Cut 9 walls and about 3 days after heavy rainfalls of the magnitude like the one of Cyclone Dineo.

To track displacements/failures within the dumps, the following recommendations are proposed:

a) Time Domain Reflectometers (TDR) and inclinometers should be used to detect movements of deep-seated slip surfaces.
b) Different radar systems such as Interferometric Synthetic Aperture Radars and comparison of weekly Digital Terrain Models (DTM) obtained by surveying, should be practiced.
c) Piezometers could be installed to monitor water table levels and seasonal ground moisture variations beneath the dumps and on subsequent overlying lifts.
d) Field tests to obtain bearing capacities of the foundation material (Kalahari sands) around the Jwaneng mine dumps should be conducted before laying any dump on new ground in order to access the exact amount of waste material of specific unit weight and height.
e) Saturated unit weights be obtained for the individual rock units (and sand) for proper analysis of the dumps under saturated or wet conditions.
f) Designs for proposed new dumps should include detailed stability assessments for each stage of development, considering anticipated variations in the waste rock quality/properties and the rate of dumping.
g) The dumps drainage or relief plan should be designed separately incorporating both the surface water and seasonal variations of ground water leading to a construction of complete hydrogeological model considering regional water flow patterns of the Jwaneng area.

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