Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2022, 9(5):30-38

Research Article ISSN: 2394 - 658X

Modelling Slope Stability of Slurry Dams using Cone Penetration Method

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ABSTRACT

Most mines that extract precious minerals like gold and diamonds usually process the ore on site to recover the minerals. The tailings from the processing plants have to be contained in tailings or slurry dams in a safe and an environmentally friendly manner. Tatama Mine, a hypothetical mine, has been mining and processing ore to recover a precious mineral over five decades and dumping the slurry from its processing plant initially into one slurry dam and later in a second slurry dam. This research involved slope stability analysis of Tatama Mine's secondslurry dam. Finite Element (FE) strength reduction technique was used and the findings were compared with the results from three Limit Equilibrium (LE) analysis techniques, namely Bishop Simplified, Spencer's and Morgenstern-Price methods. FE analysis was executed using RS2 2019 while the LE analysis was done using Slide 2018. Cone Penetration Testing with pore pressure measurements (CPTu) was usedto properly define the slurry embankment materialsto assess the stability of the slurry dam. The results show that the LE and FE factors of safety (FoS) were in agreement with an average difference of ±5.28%. The overall probability of failure of the slurry dam was zero and overall reliability was satisfactory with factors of safety for all slurry dam walls averaging at 1.65. The key governing parameter was the friction angle of the materials that make up the dam walls.

Key words: Cone Penetration Testing, Slurry, Slope, Dam, Stability, Slide, RS2, Factor of Safety

INTRODUCTION

Tatama Mine (TM) is a hypothetical large scale open pit mine. The mine's concession covers an area of 118 km^2 and has been ranked as one of the world's largest open pit mine by area. The Tatama deposit comprises a cluster of ore bodies referred to as the Tatamaore cluster. Production at TM commenced in the early seventies. The mine has an average stripping ratio of 2.2:1 and mines about 20 million tonnes of ore per year. The mine life is expected to be up to 2033. The mine's production has been increasing over the years and doubled after 30 years of production. Doubling the production meant an increase in the quantity of slurry produced requiring extra disposal facilities. The second slurry dam is the oldest dam in the expansion project of TM. It is positioned to the south of the older slurry dam, within the constraints of the main access road on the northern side with the mining concession boundary on the south and a built-up area on the west. As per the mine design report the slurry dam under investigation is about 1.30 km (north-south) by 2.04 km (east-west), giving a total area of about 265 ha [1]. The slurry dam is currently at an elevation of 1,000 m above mean sea level. Due to the poor deposition practices in its history, it has been undergoing instability problems caused by a high rate of rise, see page and erosion. A dam breach analysis byan engineering and environmental firm [2] showed that the Tatama area is dipping in a north-easterly direction. Therefore, in the event of failure of the slurry dam walls the slurry would flow in the same direction. This north-easterly dipping topography caused segregation of tailings towards the north-eastern corner which could potentially cause instability on the east and north dam walls [2].

Slurry dam stability is a major challenge in geotechnical engineering. According to Lyu [3] keeping a slurry dam safe and stable is the most challenging task in the entire mining process. By their nature, slurry dams are normally very stratified and layered with very thin fine-grained beds trapped between thick beds of medium grained beds. Cone Penetration Testing with pore pressure measurements (CPTu) has been used extensively by researchers in delineating the nature and sequence of subsurface strata [4]. It has been relied upon as a powerful, quick and cost-effective in-situ technique [5]. According to Lunne [4] CPTu has exceptional logging capabilities in delineating complex stratigraphy of Tailings Storage Facilities (TSFs). Its usefulness in slope stability is mainly to enable the construction of geometric sections of slopes for analysis.

MATERIALS AND METHODS

In this study, while the mine is said to be a hypothetical mine, actual data and tests conducted on an operating site have been used. CPTu was used as part of a large geotechnical site investigation programme for a proper definition of the geotechnical properties of the materials in the slurry storage facility. Fifteen tests were carried out around the perimeter of the slurry dam. The geographic locations of the CPTu test points around the slurry dam are shown in Fig. 1. Dissipation tests were conducted at the required depths to attain equilibrium pore pressure and the results were used in estimating the phreatic surface depth.

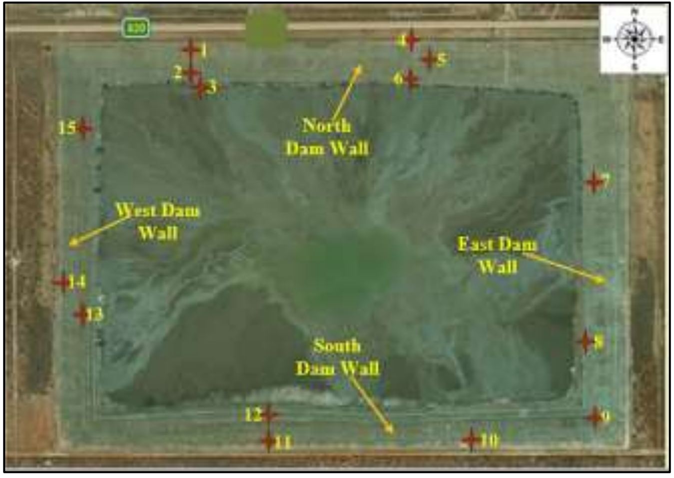

Fig. 1 CPTu Geographic Locations onTatama Mine Slurry Dam

The CPTu testing involved penetration into the ground a series of one-meter steel rods with 60º steel cones at the end. Continuous measurement and recording of resistance to penetration of the cone tip and surface sleeve including changes in pore pressure were made. The raw data was recorded with respect to depth and interpreted using CpeT-IT3.0 software which is used to interpret the raw CPTu data in terms of geotechnical parameters such as Soil Behaviour type (SBT). It uses current published correlations based on reviews [4, 5]. CpeT-IT 3.0 software uses the common CPTu Soil Behaviour Type (SBT) charts that have been developed [6]. It has a proven track record of being easy to use and also for providing detailed CPTu data interpretation tools for geotechnical engineers [6]. It has been widely used in engineering for site characterisation, soil classification and stability analysis.

The CPTu data was in the form of geotechnical profiles that showed the types of soils intersected during probing in terms of SBT. The data was also presented in the form of SBT charts, pore pressure, sleeve friction and tip resistance profiles, and tables containing the derived geotechnical parameters. Together with the topographic data, the CPTu data was used in constructing slope geometries for slope stability analysis. The geotechnical parameters derived were used in Slide 2018 and RS2 2019 to define and classify the material properties. Topographic data was obtained from Tatama Light Detection and Ranging (TLIDAR) survey data of 2018 and interpreted using CIVIL 3D 2019 software to obtain the geometric boundary coordinates. Figs. 2 to 5 show the slope geometries that were constructed using Slide 2018. The SBT layers were grouped into overflow, underflow, starter wall and foundation materials as shown in Figs. 2 to 5.

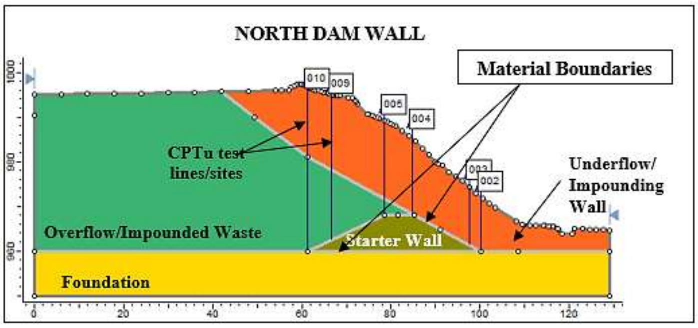

Fig. 2 North Dam Wall Geometry obtained from Stability Analysis using Slide 2018

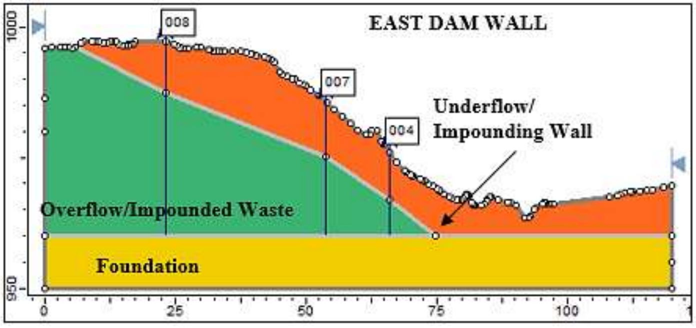

Fig. 3 East Dam Wall Geometry obtained from Stability Analysis using Slide 2018

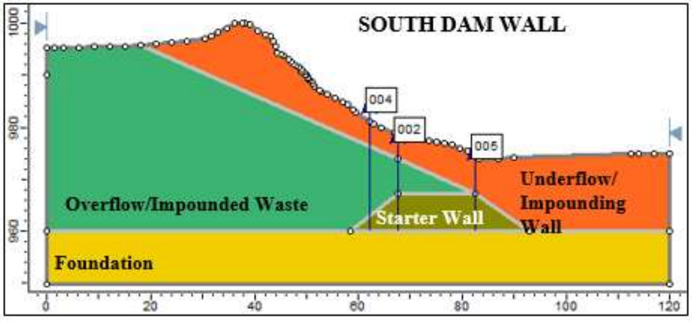

Fig. 4 South Dam Wall Geometry obtained from Stability Analysis using Slide 2018

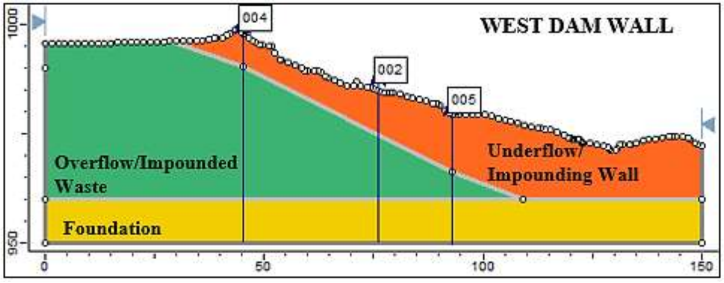

Fig. 5 West Dam Wall Geometry obtained from Stability Analysis using Slide **2018**

A Robertson SBT chart which is a plot of cone tip resistance against friction ratio was used in classifying the slurry embankment materials. The Robertson SBT chart only predicts the Soil Behaviour Type (SBT) which means that it classifies the soils according to their mechanical behaviour. Generally, sleeve friction and cone tip resistance increase with depth as a result of an increase in overburden stress. Therefore, it is necessary to normalise or correct the CPTu data for overburden stress in very shallow and/or very deep soundings [7, 8]. The results of normalised charts are more reliable than the non-normalised ones. Fig. 6 shows the soil types at Tatama Slurry Dam using the normalised Soil Behaviour Type (SBT) data.

The input parameters used in both the Limit Equilibrium (LE) and Finite Element **(**FE) slope stability analyses were obtained from the CPTu data. These were in the form of mechanical properties of four different material layers which constitute each slurry dam wall. These are summarised in Table 1.

A finite element groundwater seepage analysis was carried out on each slurry dam wall using both Slide 2018 and RS2 2019 software. The analysis was done to determine and compute the pore pressures in the slope stability problems. Two sets of hydraulic parameters were used to estimate the location of the phreatic surface. These were dam material permeability and the depth of the pore pressure transition point when the pore pressure is equal to zero (i.e. when P = 0). The average depth of the pore pressure transition points encountered at all CPTu test points was about 978 m above mean sea level (±5 m). A distribution of pore pressures throughout each dam wall was computed and the boundary conditions used in the computations were also used in the slope stability analysis.

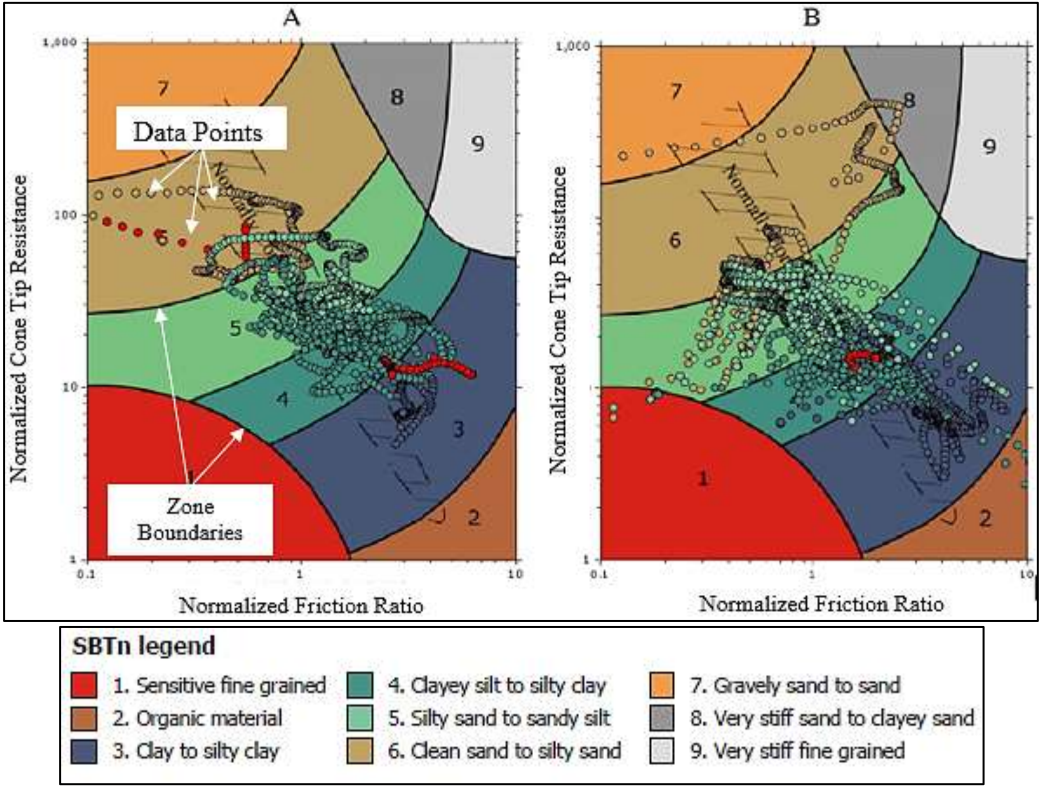

Fig. 6 Overall Normalised SBT Charts Representative of Slurry Dam Materials

Table -1 Input Parameters from CPTu, used for Modelling Slurry Embankments

Property	Foundation	Overflow	Underflow	Starter Wall
Colour	Yellow	Green	Orange	Military Green
Strength Type	Mohr-Coulomb			
Unit Weight (kN/m^3)	19.5	16.0	20.4	19.5
Cohesion (kPa)	0.0	5.0	1.0	0.0
Friction Angle (deg)	37.0	23.0	30.0	37.0
Poisson's Ratio	0.4	0.4	0.4	0.4
Elastic Modulus (MPa)	50.0	38.2	39.4	49.5
SBT Material Type	Organic Soil	Clay and Silty Clay	Sand, Silty Sand and Sandy Silt	Sand and Silty Sand

Deterministic, probabilistic and sensitivity analyses were carried out on the results obtained in this study. A circular failure analysis was done using three Slide circular slip search methods (i.e. Grid, Slope and Auto-refine searches). The simplified Bishop, Spencer and Morgenstern-Price limit equilibrium methods were used to calculate the factor of safety to determine the overall safety of the slopes of the dams. According to Herza [9], a back-calculation of the FoS of existing dams was carried out in the United States during the 20th century to determine the minimum acceptable FoS. A factor of safety of 1.5 was found to provide enough stability and flexibility and is generally considered acceptable by most geotechnical engineers. The recommended minimum FoS for embankment dams was also discussed and stated by the Australian National Committee on Large Dams (ANCOLD) [10]. The recommended minimum FoS for failures towards the downstream slope of a dam under steady-state seepage conditions was stated as 1.5. Therefore, a minimum design FoS of 1.5 was considered to be reliable for use in this study. This is to take into account uncertainties associated with the many factors influencing slope stability (e.g. material type, slope angle and height). A deterministic finite element analysis was carried out using RS2 2019 after the importation of slope geometries and definition of groundwater seepage analysis boundary conditions from Slide 2018. The results from both LE and FE methods were compared and conclusions were drawn from the differences between the factors of safety and the geotechnical performance of the slurry dam.

DISCUSSION OF RESULTS

In-depth stability analyses were carried out on the Tatama Slurry Dam using limit equilibrium methods namely deterministic, probabilistic and sensitivity analyses. Deterministic finite element analyses were also carried out and the results were compared with those from the limit equilibrium computations. The findings from the various analyses are discussed in the following sections.

Limit Equilibrium Deterministic Analysis

A search for circular slip surfaces in Slide 2018 was carried out using three methods (Slope search, Auto Refine search and Grid search). Figs. 7 to 10 show the results from the Bishop Simplified deterministic slope stability analysis from the three slip search methods (from left to right: Slope search → Auto Refine search → Grid search). From the figures, the failure slip arc (shown in Fig. 7) which points towards the FoS is the critical slip circle located during a grid search. This arc represents the path of a circular failure surface with the lowest FoS [11]. In general, the locations of the slip circles and factors of safety obtained from all three slip circle search methods are very similar. Also, the Auto Refine search method is known to have the capability of locating critical slip circles with the lowest factors of safety [11]. This was observed from the FoS values obtained along the north and west dam walls. It was also noticed that the differences between the factors of safety obtained from the Auto Refine search method and those from Grid and Slope search method were very small (i.e. ≤ 0.03). The differences were considered insignificant and show that the paths of the slip circles and factors of safety obtained were accurate and reliable.

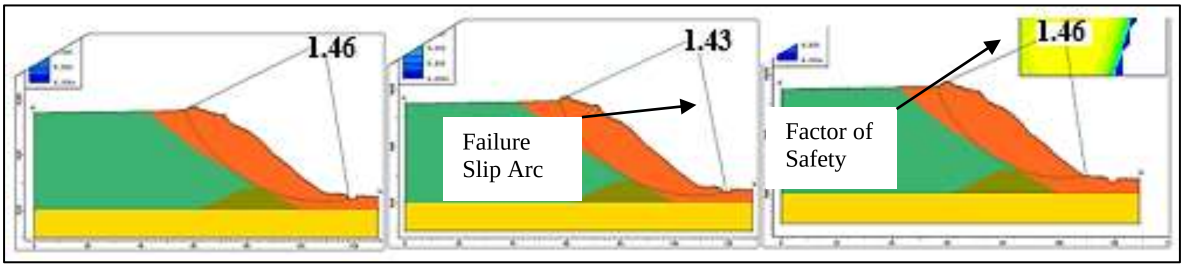

Fig. 7 Results of Bishop Simplified Deterministic Analysis Slip Search along North Dam Wall

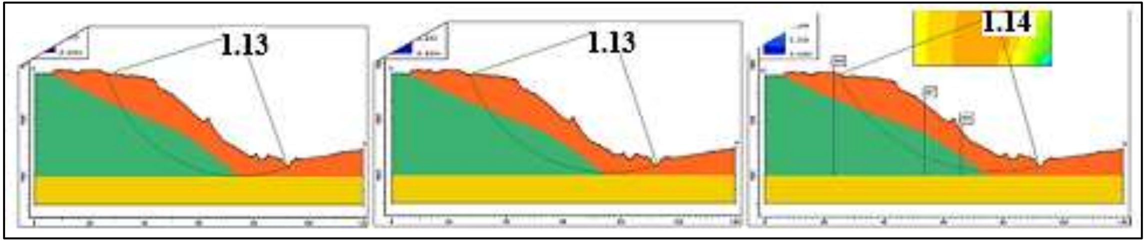

Fig. 8 Results of Bishop Simplified Deterministic Analysis Slip Search along East Dam Wall

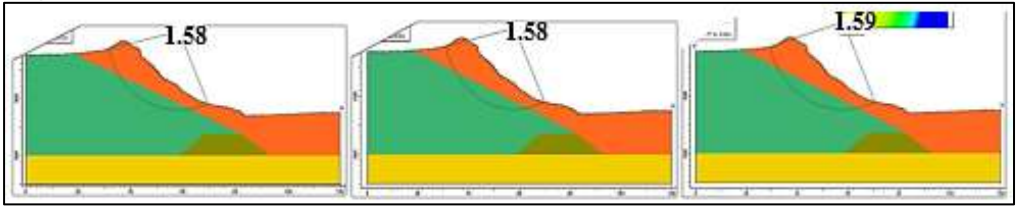

Fig. 9 Results of Bishop Simplified Deterministic Analysis Slip Search along South Dam Wall

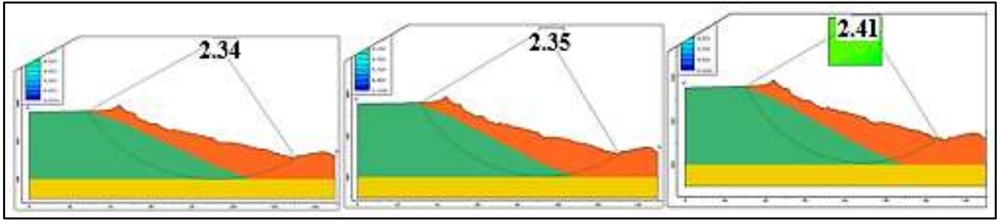

Fig. 10 Results of Bishop Simplified Deterministic Analysis Slip Search along West Dam Wall

Fig. 11 shows the factors of safety obtained from the three LE methods that were conducted along each dam wall. It shows that there is close agreement between the three Slide 2018 slip search methods and the three LE methods. It further confirms that the methods are reliable for use in rating the stability of the dam walls.

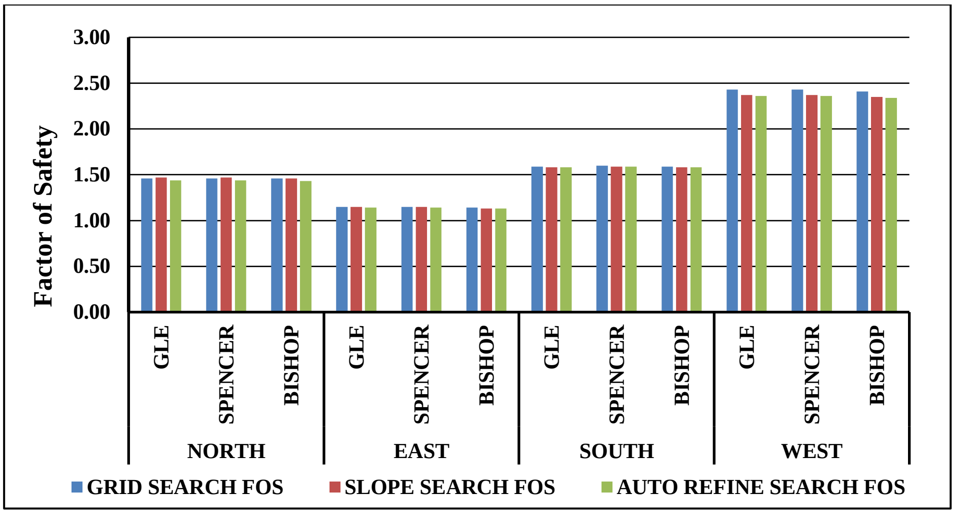

Fig. 11 Graph of Safety Factor from Deterministic Analysis

It is significant to note that the safety factors obtained along the north and east dam walls were less than 1.5 while those along the south and west dam walls were greater than 1.5 (see Fig. 11). However, it was also observed that the factors of safety along the south dam wall were marginal and therefore could not be rated as satisfactory as any slight increment in additional load would render the FoS less than 1.5. The low factors of safety may be attributed to reasons ranging from geometry to the geotechnical parameters used in the analysis.

Even though the FoS is not entirely reliable and has little meaning in terms of slope stability, it is useful when assessing the safety margin of a slope and in finding out whether there is a need to perform further analyses for more informed assessments. The results of the deterministic analysis of the LE conducted on the Tatama Mine Slurry Dam show that appropriate measures should be taken to improve the strength/stability of north and east dam walls and further assessments done to identify the possible causes of the low factors of safety along those walls.

Probabilistic Analysis of Limit Equilibrium

A probabilistic analysis was carried out in which random variables were chosen for the cohesion, friction angle and unit weight for all the material types. These were defined using a uniform probability density function which simulates random variations between two values (minimum and maximum values) where all values in the range are equally probable.

A deterministic FoS is one that is computed for the global minimum slip surface (i.e. a slip surface with the minimum FoS) in a non-probabilistic slope stability analysis. This FoS is usually computed with the mean values of input parameters.

Table 2 summarises the calculated results from the probabilistic analysis of LE on the Tatama Slurry Dam. The results show that deterministic factors of safety are not always equal to the probabilistic factors of safety. In all the four cases, the probabilistic factors of safety are either equal to or greater than the deterministic factors of safety. This is because a deterministic analysis searches for a slip surface with the lowest FoS while the probabilistic analysis searches for a slip surface with the highest probability of failure (a slip surface that is most likely to fail).

Table -2 Results of Probabilistic Analysis of Limit Equilibrium

Dam Wall	Overall Slope			Critical Probabilistic Surface			Critical Deterministic Surface		
	FS	PF	RI	FS	PF	RI	FS	PF	RI
North Dam Wall	1.4	0	5.1	1.5	0	3.8	1.5	0	5.0
South Dam Wall	1.6	0	6.9	1.7	0	6.5	1.6	0	6.8
West Dam Wall	2.4	0	8.6	2.6	0	8.2	2.4	0	8.5
East Dam Wall	1.2	0	2.8	1.2	0	2.8	1.2	0	2.9

In general, the probability of failure (PF) was zero as none of the samples analysed had a FoS less than 1. The reliability index (RI) measures the overall slope stability after a probability of failure analysis. It indicates the number of standard deviations separating the mean safety factor from the critical FoSof 1. To ensure minimal assurance of a safe slope design, a reliability index of 3 is usually recommended [11]. In this study, all the RI values were greater than 3 except for the east dam wall. This implies the south, north and west dam walls are satisfactory in terms of safety but measures are required to stabilise the east dam wall to improve its level of safety.

Sensitivity Analysis of Limit Equilibrium

Sensitivity analysis was conducted with Slide 2018 using the same input variables that were used in the probabilistic analysis. The sensitivity of the safety factor to unit weight, cohesion, and friction angle was analysed for each layer of slurry dam walls. Table 3 summarises the results of the sensitivity analysis on the limit equilibrium. The results show that the most influential parameters were the underflow and overflow friction angles. It was only the west dam wall whose FoS was affected by overflow unit weight. Generally, the results of the sensitivity analysis show that friction angle has the greatest effect on changes in the FoS of the dam walls.

Table -3 Results of Sensitivity Analysis on Limit Equilibrium

Dam Wall	Parameter	Layer	Minimum Change (%)	Maximum Change (%)
North dam wall	Friction Angle	Underflow	10.3	10.3
	Friction Angle	Overflow	4.1	3.4
South dam wall	Friction Angle	Overflow	8.8	8.8
West dam wall	Friction Angle	Underflow	4.6	4.6
	Friction Angle	Overflow	8.7	10
	Unit Weight	Overflow	5.8	4.6
East dam wall	Friction Angle	Underflow	0.9	9.6
	Friction Angle	Overflow	4.6	18.4

In general, it was observed that the results of sensitivity analysis on LE are influenced more by the critical slip circle path. In most cases the dominant parameter was the friction angle of materials through which the failure surface passes. In some cases (e.g. on the west dam wall), where the slip circle was deep seated (located at high depths), the FoS was more sensitive to the unit weight of the material.

Deterministic Analysis using Finite Element Method

Finite Element (FE)strength reduction method was used in this work to compute the stresses along each dam wall and the corresponding Strength Reduction Factors (SRFs). The results are presented in Figs. 12 to 15 where the upper models are the FE models while the lower models are the LE models. The maximum shear strains are contoured in the FE models to signify areas susceptible to deformation as the maximum shear strain gives a good indication of where a slip will likely occur. The red contours signify maximum shear strain while the blue contours signify minimum shear strain. Also, in Figs. 12 to 15, green to yellow contours represent areas of maximum shear strain in the models. Fig. 12 shows a slip circle path which indicates that failure will occur along a weak boundary that exists between the north dam wall underflow and overflow. The LE slip circle path in Fig. 12 also sits on the underflow-overflow boundary which shows that failure will occur along that boundary. Figs. 13 to 15 show where the limit equilibrium critical slip circle paths are compared to the finite element slip circle paths. The results show that there is good correlation between the two methods in locating the paths of slip circles.

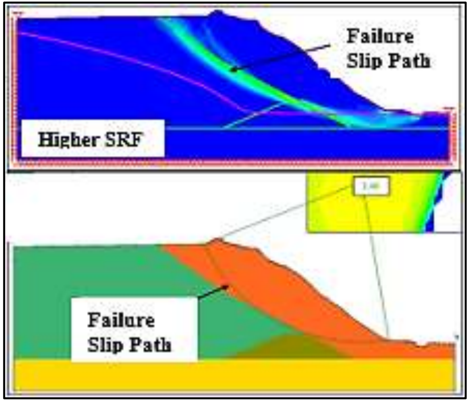

Fig. 12 North Dam Wall Maximum Shear Strain Contours (Upper)and LE Failure Slip Path (Bottom)

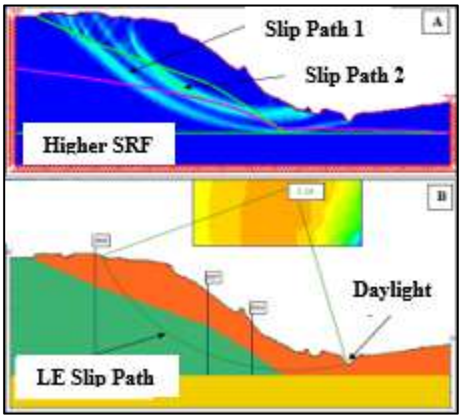

Fig. 13 (A) East Dam Wall Maximum Shear Strain Contours; (B) LE Failure Slip Path

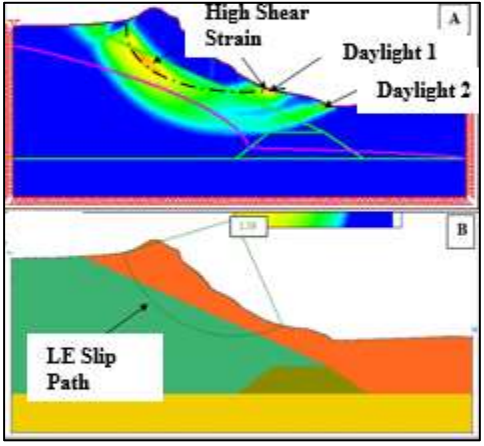

Fig. 14 (A) South Dam Wall Maximum Shear Strain Contours; (B) LE Failure Slip Path

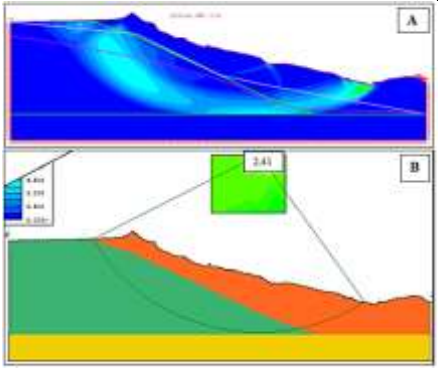

Fig. 15 (A) West Dam Wall Maximum Shear Strain Contours; (B) LE Failure Slip Path

Table 4 summarises the factors of safety using Limit LE methods and Strength Reduction Factors. The two slip circles in Fig. 13 terminate at the two depressions and terminate at the lowest depression in the LE model. This clearly indicates that the two depressions could negatively affect the stability of the slope.

Table -4 Limit Equilibrium Factors of Safety and Strength Reduction Factors

Dam Wall	SRF	Limit Equilibrium FoS from Grid Search	Differences	Percent Difference (%)
North	1.27	1.46	0.19	13.9
East	1.15	1.15	0	0
South	1.57	1.59	0.02	1.3
West	2.29	2.43	0.14	5.9

Fig. 14 shows that the critical slip circle path using FE method on the south dam wall has two downstream daylight positions (shown as Daylights 1 and 2). Two separate paths were located in the FE model in Fig. 14. However, the position of the high shear strain zone coincides with the LE slip circle path. A dotted arc that connects the two high shear zones is shown in Fig. 14A and this path coincides with the path in Fig. 14B.

There are several slip paths in Fig. 15. However, the general trends and locations were very similar. The LE slip path assumed a similar path between the two FE slip paths. The results in Table 4 show that the SRF and FoS of the east dam wall are both 1.15. This indicates that the two methods located the critical slip paths with a safety factor of

1.15 which were less than the recommended minimum value of 1.5. The dam wall was very steep and had two visible depressions at the toe. These two depressions could provide a path for seepage water to escape to the ground surface after leaving the dam, causing erosion at the toe of the slope and therefore destabilizing the slope.

When compared, the computed SRFs in Table 4 are generally lower than the factors of safety obtained from the deterministic LE methods. The FoS of LE is a force and/or moment equilibrium computation while the SRF is computed using a stress/strain analysis [12, 13]. Researchers such as Krahn [14] have stated that limit equilibrium analysis methods lack the fundamental physics of stress-strain relationships. Therefore, they are unable to compute realistic stress distributions. A finite element analysis requires no assumptions for the computation of SRF as it emerges naturally from the analysis without having to commit to any particular form of mechanism [12]. Therefore, the results obtained from the LE analysis in this study are more likely to give lower values of the FoS. Both the north and east dam walls have unsatisfactory SRFs (< 1.5) compared to the south and west dam walls. This may account for the stability problems being experienced at the north-eastern corner of the dam.

CONCLUSIONS

From the analysis in this study, it is concluded that the low factors of safety along the north and east dam walls may account for the stability problems being experienced at the north-eastern corner of the dam. The segregation that was observed along the north-eastern corner during site visits during this research is likely to be the cause of instability problems. The types of materials in the slurry dam walls have very low cohesion which means that the friction angle is the governing parameter of their stability. Even though the safety factors of the north and east dam walls are greater than 1, they are very close to failure and any added load may trigger instability mechanisms and sudden failure of the dam walls. To prevent unwanted events, it is recommended that the mine maintains a good drainage system to allow the dam to dry and consolidate quickly. Although a possible failure of this dam could be tragic, considering the fact that the average FoS of the Slurry Dam is around 1.65, it is reasonable to say that, in general, the dam has safe slopes.

Acknowledgements

We sincerely acknowledge the assistance of the management of Tatama Mine by granting access to the mine's slurry dams' data. We also thank the Geotechnical Consultants who carried out the cone penetration tests on the slurry dam at Tatama Mine during the data collection phase.

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