

Re-Design of Mine Tailings Storage Facility for Adamus Resources Limited*

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Abstract

The suitability of a centerline or upstream design as a sustainable option for construction of future raises for the existing Life of Mine (LoM) downstream Tailings Storage Facility (TSF) at Adamus Resources Limited (ARL) was investigated using Slope/W in GeoStudio Software. Review of technical information, evaluation of the performance of the existing Stage 6 dam, and geotechnical investigations of available construction materials were undertaken in this research. Insights were gained about the TSF's life cycle and current bearing capacity for intended future raises. Viable geotechnical parameters were established to define construction material specifications as well as input data for modelling the new designs. The British Standards Institute (BSI) standards were adopted for all the material testing protocols carried out at the Council for Scientific and Industrial Research-Building and Road Research Institute (CSIR-BRRRI) laboratory in Kumasi. The scope of modelling covered the original downstream as well as the centerline and upstream options. The geometric design and stability analysis focused only on the southern and northern embankments of the TSF. The modelling outputs yielded reliable Stability Factors of Safety (FoS) for all designs investigated, above the regulatory criteria. Subsequently, a semi-quantitative multi-criteria evaluation was used to select the preferred option between the centreline and upstream alternatives. The results showed that technically, economically and by regulatory compliance, the centreline design is a better alternative and therefore recommended for adoption by ARL.

Keywords: Tailings Storage Facility, Geotechnical Parameters, Stability Analysis, Modelling, Multi-Criteria

1 Introduction

1.1 The Company

Adamus Resources Limited (ARL) operates an open pit gold mine which is owned 90% by BCM International (Ghana) Limited and 10% by the Ghanaian Government. ARL is located approximately 70 km from the port city of Takoradi in south-west Ghana. ARL treats mined ore with a 2.0 Mt/yr. CIL process plant that produces tailings materials for storage within an 18 Mt capacity LoM Class "C" TSF (Johnson, *et al.*, 2013).

1.2 Challenge, Strategy and Compliance

ARL is currently constrained by cash flow challenges due to impacts from reducing gold price and inflationary trends in cost of major mining inputs. The implications for sustainable tailings management is dire especially when the annual raises of the TSF have hitherto been accomplished at progressively high development cost coupled with significant adverse environmental effects and liabilities. These prohibitive economic and environmental risks therefore becomes a matter of an urgent concern. ARL thus needed to investigate the merits of a centreline or upstream raise method for adoption in order to sustainably contain the anticipated volume of process waste production beyond the Stage 6 TSF development. The re-design

option should provide significant savings in construction costs, maintain adequate structural FoS and help to reduce the burden of environmental impacts among other factors.

The existing TSF was re-categorised to Hazard Class "C" in line with provisions of Regulation 263 of the current Minerals and Mining (Health, Safety and Technical) Regulations 2012, LI 2182. Thus subject to the approval of the Chief Inspector of Mines, the LI considers the possibility of a centerline or upstream raise re-design as modification to the existing downstream design at a minimum Factor of Safety (FoS) of 1.5 as specified in Regulation 264 (b) and (k). ARL's LoM TSF is strictly regulated and periodically monitored by government agencies according to stipulations in the LI and Environmental Protection Agency's specific Environmental Permit conditions and guidelines.

1.3 The LoM TSF

1.3.1 Features of the Current TSF

The zoned embankments of the dam were built from Stage 1 between adjoining hills to the northwest and southeast in order to define the containment for storage of tailings (Fig. 1). At Stage 6, the facility was about 80% full at a general elevation of 1044.5 mRL and had a total dam perimeter of about 4.2 km. The assessed structural FoS had consistently been

maintained above the minimum 1.5 as per the LI 2182. The various Stage 6 embankments include:

- (i) South (Main) Embankment;
- (ii) South Low Embankment;
- (iii) The Eastern Embankment;
- (iv) The North Embankment;
- (v) The Northwest Embankment;
- (vi) The West Embankment; and
- (vii) Dividing Embankment.

The current conditions of the main North and South Embankments are presented in Table 1.

Table 1 Current Beach Conditions of Main North and South Embankments (June 2018)

No	Embankments	Length (m)	Beach Dist. (m)	Piezometer Level (m RL)
1	North Embankment	600	>150	1027
2	North West Embankment	225	>150	1027
3	South Embankment	270	<200	1031
4	South Low Embankments	225	<200	1031

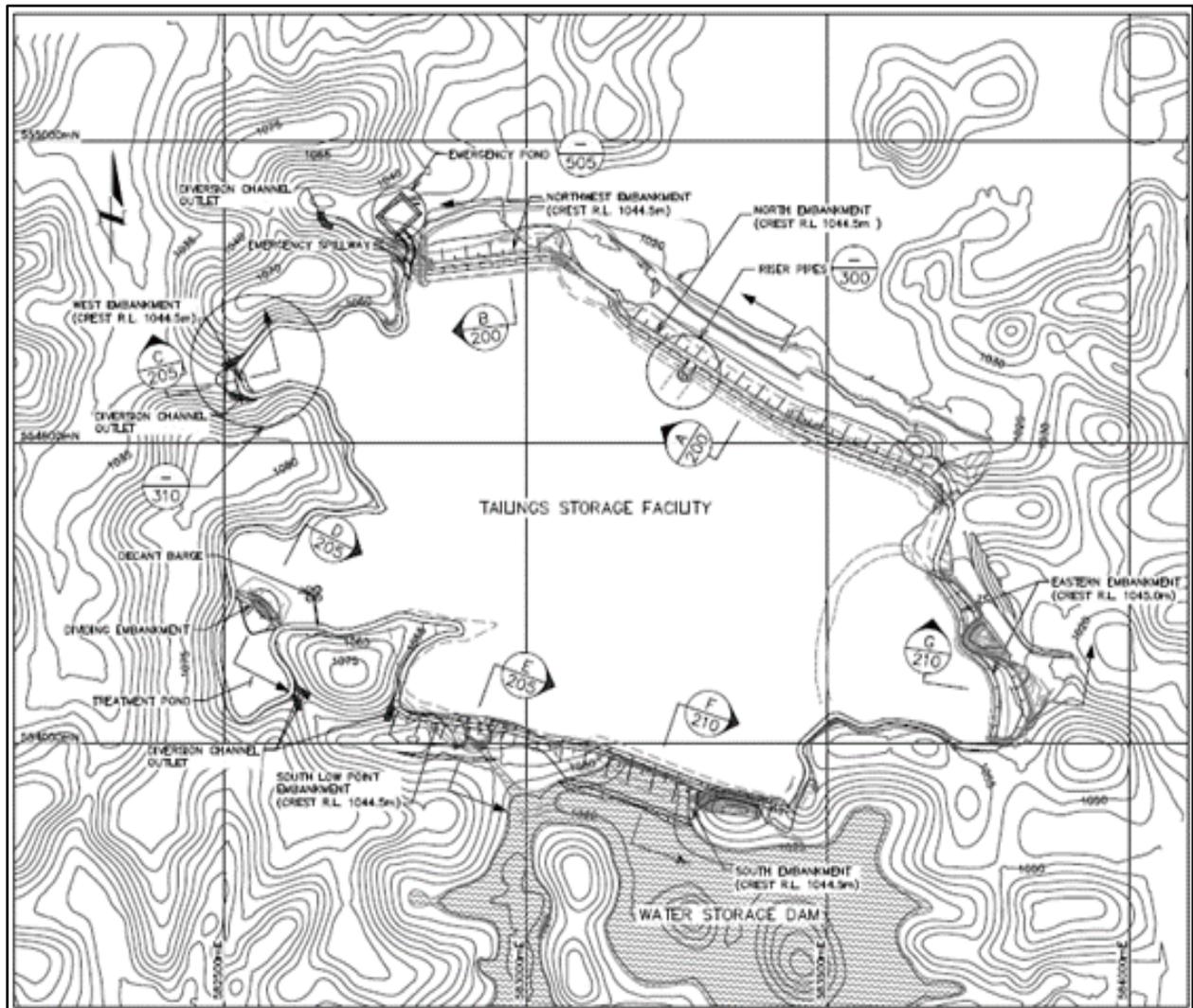


Fig. 1 Configuration of the Stage 6 TSF (Source: Knight Piésold, 2016)

1.3.2 Operation of the TSF

Tailings are transported via 300 mm HDPE pipelines for sub aerial deposition around the beaches using combination of spigots and hydro cyclones at offtake points.

Average annual production from 2016 to 2018 was about 1.60 Mt and average monthly tailings deposited during the first half of 2018 was about 0.20 Mt. Typical beach distances currently averaged 150 m at the main northern and southern embankments and the operational freeboard measured above 1.7 m.

The supernatant pond location was maintained centrally as per design at elevation of 1041 mRL. A barge-mounted decant system returns about 75% of supernatant water directly to the plant and 25% diverted to a water treatment plant for treatment and storage in the Water Storage Dam (WSD) targeting As. WSD compliant water may be discharged as effluent water into the environment in accordance with EPA's specific guidelines.

1.4 Research Objectives

This paper sought to study the structural and environmental performance of the existing dam, anticipated tonnage of LoM tailings production and geotechnical properties of available construction materials. It also sought to model alternative designs to raise the dam, conduct stability analysis and determine the most feasible raise option.

1.5 Design Objectives and Concepts

The re-design assumes most of the basic objectives and philosophies of the existing TSF design for permanent storage of tailings, pollution prevention, resource use efficiency, regulatory compliance and industry best practice (Anon., 2015). The concept specifically focused on the geometric designs and stability analysis which basically underpin the facility's risk profile. Evaluations were based only on the main north and south embankments. The re-design involves raising the entire dam embankments by a 5.5 m height to the permitted elevation 1050 mRL maintaining existing downstream slope angles, crest widths and grade, and safety berms. The re-design should provide significantly reduced land take beyond the downstream toes, quantity of fill materials as well as the period of construction. However, it is expected that some loss of deposition volume will occur due to step-in of sections of the new embankment unto the tailings beaches.

2 Resources and Methods Used

2.1 Resources

Resources used in the research work included primary and secondary data collected from ARL site, internet materials from various research sites, Slope/W in GeoStudio Application Software and financial assistance from ARL. The primary data included field and laboratory geotechnical tests whereas the secondary data comprised published and unpublished company reports, updates and memoranda. Internet materials included publications, journals, technical reports and others regarding mine TSFs development, operations and maintenance, associated risks and their sustainable management.

2.2 Methods Used

The methods used involved review of relevant technical literature, assessment of the performance of the existing Stage 6 TSF, modelling designs and stability using Slope/W in GeoStudio software and suitability analysis of alternative options using a multi-criteria ranking approach. Modelling of geometric designs and stability analysis, including multi-criteria suitability evaluations were used to determine the best design option for adoption by ARL.

2.2.1 Theory and Model

The stability of earthen structures is a key issue in any new geotechnical project design in view of potential safety and economic risks posed to society and businesses in the event of facility's accidental collapse (Anon, 2012 and Lu and Lai, 2011). Therefore, the geometric designs and stability of the alternative raise options proposed for ARL's consideration were modelled to ascertain the safety and economic implications for overall sustainable tailings management.

The general limit equilibrium theory approach was used for this scale of project design analysis based mainly on its rigour and popularity in industry (Anon., 2012). The concept of numerically dividing or discretising a potential sliding mass into slices over a circular slip surface for iterative evaluation of a minimum Factor of Safety (FoS) forms the basis of the Morgenstern-Price (M-P) General Limit Equilibrium (GLE) method for stability analysis. The GLE analysis is based on equations of statics to determine a common FoS from two non-linear FoS equations which take into account a range of interslice shear and normal force conditions. One equation gives the FoS with respect to moment equilibrium, the other equation gives the FoS with respect to horizontal force equilibrium. The analysis

seeks to meet two basic conditions, namely to find the forces acting on each slice in order to keep it in equilibrium as well as to attain single common FoS for each slice (Anon., 2012).

2.2.2 Material Testing

Soil fabric and mineralogical composition determine the response of clays to events occurring during construction and operation of engineered works; and in engineering applications, properties of earth materials such as clays are obtained from rapid and comparatively cheaper field and laboratory tests (Mielenz and King, 1952).

Field and laboratory tests, (1) and (8) respectively, were carried out on borrow fill and tailings samples at the CSRI-BRRI Geotechnical Laboratory in Kumasi based on the British Standards Institute (BSI) standards (Anon., 2000). Specifically, the shear strength, consolidation strength, compaction, hydraulic conductivity, gradation and plasticity were ascertained. Results of field and laboratory tests were compared with mine established data as well as industry standards.

2.2.3 TSF Performance

Extensive monitoring and periodic surveillance of all aspects of the dam operation is undertaken by ARL and appointed second and third party geotechnical consultants in fulfilment of operational and regulatory objectives. TSF monitoring data and third party audit reports from 2017 to date indicate that the facility's performance, in terms of structural integrity, environmental safety and social cohesion has been consistent with operational requirements and regulatory conditions.

3 Results and Discussion

3.1 Field Results

The outcome of the twenty Dynamic Cone Penetration (DCP) tests performed at sections of the Stage 6 embankment crest and tailings beaches to determine the strength of foundation for the ensuing Stage 7 raise showed that strength parameters increase with depth yielding estimated minimum strengths of 12 kPa at 3 m depth and 60 kPa at 1 m depth respectively for beach and crest foundations. Experience from similar engineering evaluations for completely upstream facility raise constructions at a neighboring site in the Western Region indicate that the estimated bearing capacity values are conservative for similar beach distances and embankment raise heights. Allowable Bearing Capacity (kPa) plots in Figs. 2, 3 and 4 show variation of bearing capacity at depths for beach embankments.

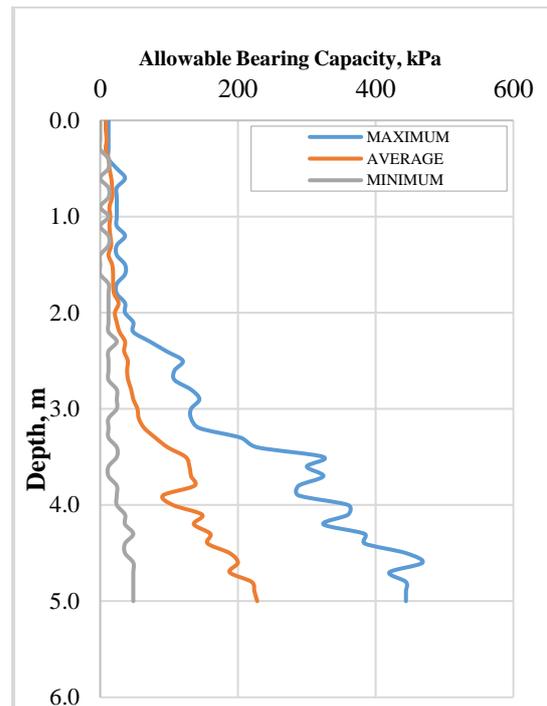


Fig. 2 Allowable Bearing Capacity (kPa) for South Embankment Beaches

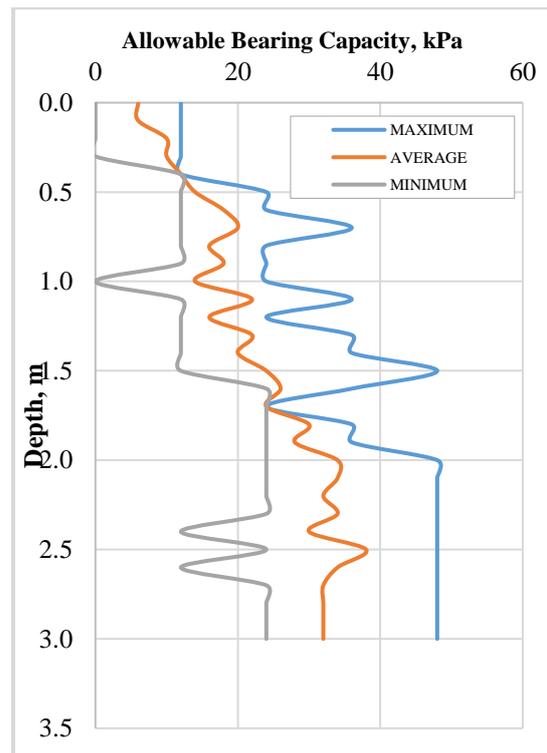


Fig. 3 Allowable Bearing Capacity (kPa) for North Embankment Beaches

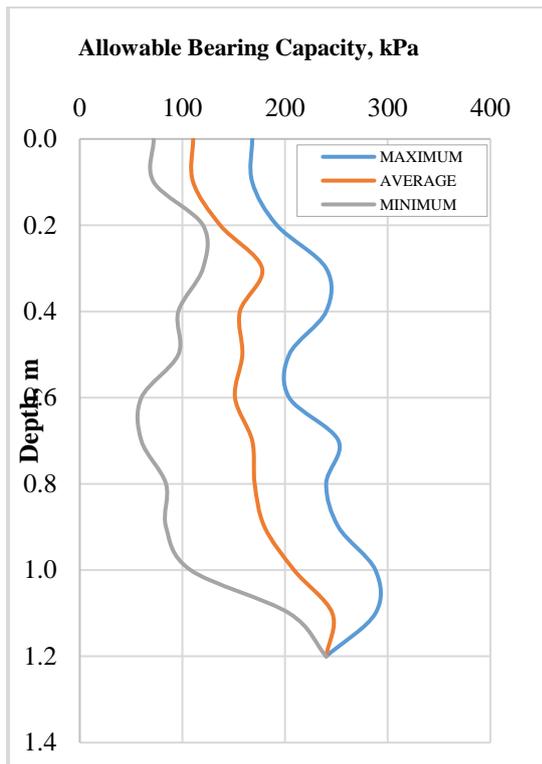


Fig. 4 Average Bearing Capacity (kPa) for Embankments

3.2 Laboratory Results

Samples of borrow and tailings materials were tested at the CSIR-BRRI geotechnical laboratory in Kumasi using the BSI standards and procedures. Tests performed included the Shear Box, Compaction, Consolidation, Atterbergs, Permeability, Particle Size Distribution, Moisture Content, and Specific Gravity. Summaries of the laboratory results which were meant for construction control and as input for the modelling respectively have been provided in Tables 2 and 3.

Table 2 Summary of Laboratory Test Results (Construction Specification)

No	Parameters	Zone A	Zone C	Tailings
1	Permeability, k , (1×10^{-08} m/s)	6.8	9.1	4.2
2	MDD (Mg/m^3)	1.5	1.7	-
3	OMC	26%	15%	-
4	NMC	27%	20%	-
5	Void Ratio	0.65	0.55	0.78
6	Compression Index	0.18	0.18	0.12
7	Bearing Capacity (kPa) at TSF	60	60	12

Table 3 Summary of Laboratory Results (Parameters for Stability Analysis)

No	Parameter	Zone A	Zone C	Tailings	Foundation
1	Unit weight, γ , (kN/m^3)	15	17	15	18*
2	Cohesion, c' , (kPa)	44	64	12.6	5*
3	Friction Angle, ϕ	39°	25°	39°	27°*

Established mine data (*)

3.3 Re-Design Options

Slope/W in GeoStudio Software was used to generate the geometric designs and stability analysis of the current downstream method if maintained, as well as the centreline and upstream alternatives for examination as discussed in the following subsections.

3.3.1 The Downstream Option

The current raise approach if maintained for the Stage 7 development will involve using the downstream method to install a 5.5 m raise from elevation 1044.5 mRL to the permitted 1050 mRL. The existing slopes of upstream and downstream faces of the identified embankments will be maintained at 1:2 (V: H) vs. 1:2 (V: H) and 1:2 (V:H) vs. 1:2.75 (V:H) respectively for the northern and southern walls. Fig. 5 shows a Schematic Section of the Regular Downstream Raise at Stage 7.

3.3.2 The Upstream Option

The first alternative design considered the upstream method of construction which involves the installation of a 5.5 m lift from elevation 1044.5 mRL to the permitted 1050 mRL mostly sitting upon the tailings beach. The geometry of the modified upstream design shows an extended 16 m crest with an upstream face at 1:1.125 (V: H) slope that extends about 22 m on to the tailings beach as a foundation. The downstream toe of the raise entirely covers the Stage 6 crest tying in to maintain the same slope at the rear side without further land take at the natural ground. Fig. 6 shows a Schematic Section of the Modified Upstream Raise at Stage 7.

3.3.3 The Centreline Option

The second alternative design considered is the centreline method of construction which is basically a compromise design of the downstream and upstream methods. Again, it involves the installation

of a 5.5 m lift from elevation 1044.5 mRL to the regulated 1050 mRL above the Stage 6 raise with a section of the upstream toe sitting upon the tailings beach as platform. Fig. 7 shows a Schematic Section of the Centreline Raise at Stage 7. The geometry shows regular 10 m crest with an upstream face at

1:1.25 (V: H) slope that extends about 6 m on to the tailings beach. The downstream arm of the raise will be placed entirely over the Stage 6 face to maintain the same slope at the rear side with a reduced expanse of land take at the natural ground level compared to the downstream method.

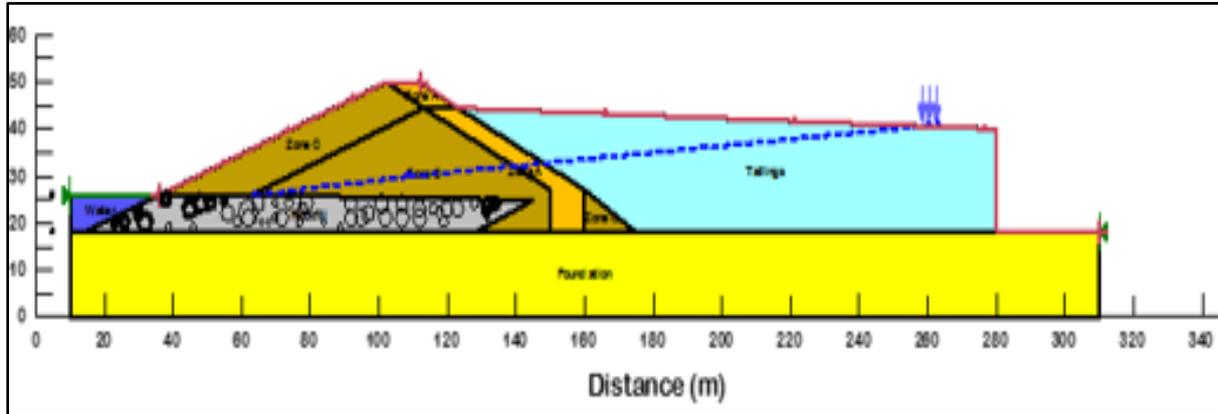


Fig. 5 Schematic Section of the Regular Downstream Raise at Stage 7 Raise

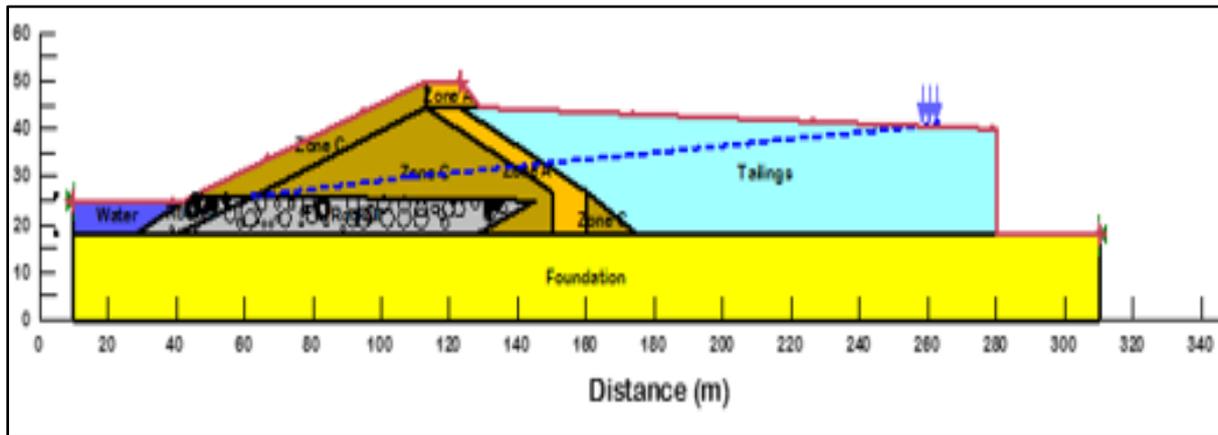


Fig. 6 Schematic of a Modified Upstream Raise at Stage 7 Raise

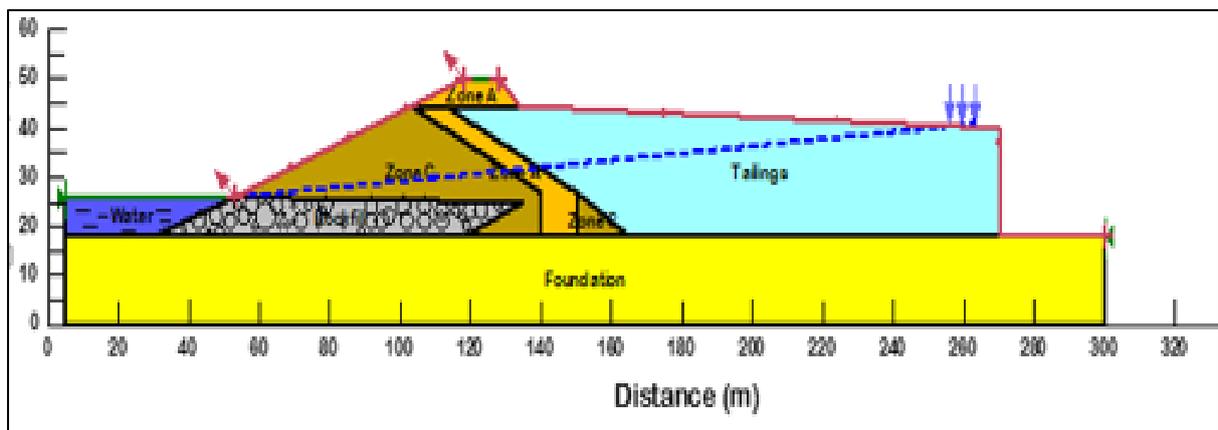


Fig. 7 Schematic of the Proposed Centreline Raise at Stage 7 Raise

A Summary of Key Model Outcomes gleaned from the modelling of the three designs have been presented in Table 4

Table 4 Summary of Key Model Outcomes

Raise Aspects	Down-stream	Centre-line	Up stream
Materials Quantity (Mm ³)	1.0	0.58	0.16
Comparative Cost (%)	100	58%	16%
Land take (m/ha)	25 / 35	11 / 14	Nil
Beach Encroachment (m)	Nil	6	22
Capacity at Stage 7 (Mt)	2.62	2.58	2.39
Material Use Efficiency (t/m ³)	2.62	4.5	15
Ultimate LoM Elevation (mRL)	1051.49	1051.59	1052.32

Modelled outputs showing upstream and downstream analysis' critical slip surface locations and FoS for the centreline design (South Embankment) are presented for review. Fig. 8 shows a Model of Slip Surface locations and FoS for the centreline option.

3.4 Stability Analysis

A Summary of Stability Analysis for the current downstream and alternative centerline and upstream raise approaches have been presented in Table 5 for the identified southern and northern embankments.

Table 5 Summary of Stability Analysis Results

STABILITY FACTORS OF SAFETY (STATIC ANALYSIS)					
No.	Raise Methods	North Embankments Analysis		South Embankments Analysis	
		D/S	U/S	D/S	U/S
1	Downstream Raise	1.7	3.8	2.8	3.2
2	Centreline Raise	1.7	3.3	2.2	3.2
3	Upstream Raise	1.6	3.3	2.5	2.8

The analysis was based on the assumption that the Stage 6 capacity was filled up and the Stage 7 raise construction was just completed and available for operations. Upstream and downstream analysis of the critical slip surfaces for the three methods revealed that upstream analysis yielded sufficiently high FoS values (minimum 2.8) for all walls whereas the downstream analysis yielded FoS values ranging from 2.8 to a minimum of 1.6. These values are consistent with the minimum FoS value of 1.5 required under Regulation 264 (b) and (k) of LI 2182. The upstream FoS values for the northern embankments were higher than those of the southern embankments whilst the downstream values were lower than the latter respectively. The recent use of cycloning at the northern beaches and the rockfill zone within the southern walls may possibly explain the observed patterns in FoS data.

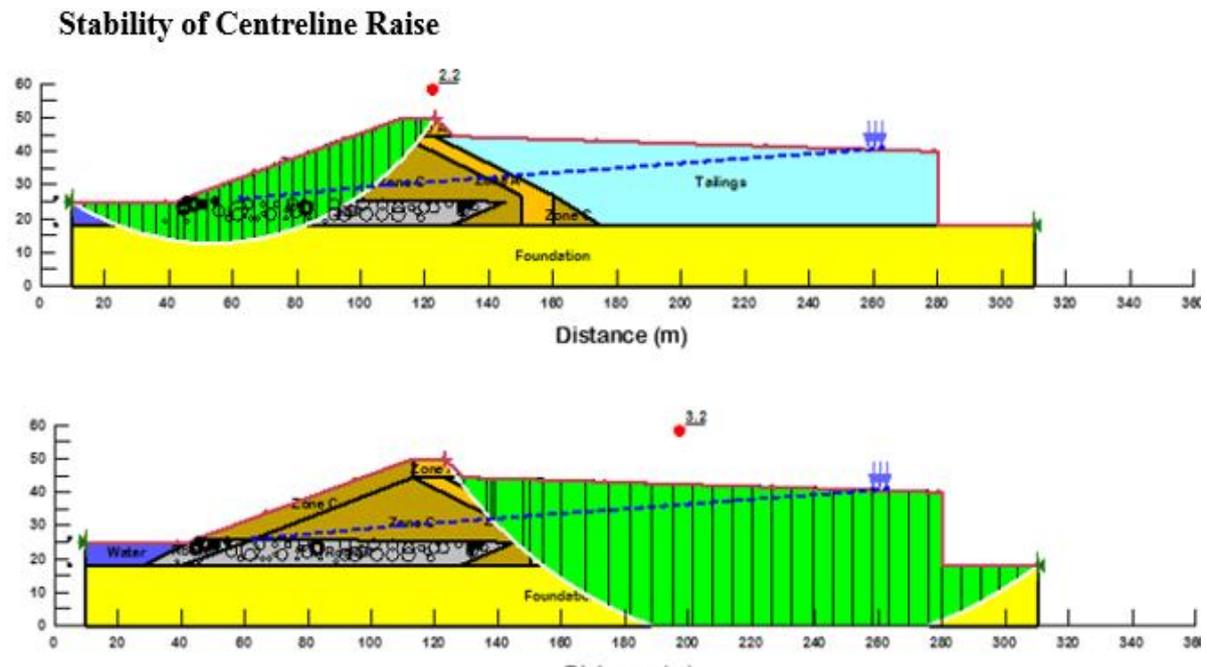


Fig. 8 Model of the Slip Surface Locations and FoS for the Centreline Option

3.5 Options Analysis

In view of the adequacy of FoS for both alternative options, a comparative multi-criteria suitability analysis was carried out for the upstream and centreline raise designs in order to discern the more feasible method for adoption. The analysis was based on geotechnical tests as well as technical, economic and compliance objectives of ARL. Table 6 depict summary of Suitability Analysis using factors such as dam capacity, stability FoS, construction material requirements, development cost and land encroachment among others. A semi-quantitative ranking system from 1 to 10 was used to evaluate technical, economic and regulatory factors. The magnitude 1 to 10 scale and combined value judgments in the ranking evaluation were based mainly on professional experience.

Table 6 Summary of Sustainability Analysis

Item	Sustainability Parameters	Upstream	Centreline
1	Technical	38	44
2	Economic	32	32
3	Regulatory/Compliance	21	29
4	Overall Feasibility	91	105

It is evident from Table 6 that the aggregate rankings for technical, economic and regulatory elements for upstream design was 91. However, the centreline option ranked 14 points higher at 105 and therefore considered a more suitable approach and thus recommended for adoption by ARL as short term strategy in developing future raises. Overall, the centreline method would present lower environmental and socio-economic risks to local area resources resulting from any accidental dam failure.

4 Conclusions and Recommendations

4.1 Conclusions

The study has assessed the feasibility of centreline and upstream options for the consideration of ARL. The under listed conclusions are drawn:

- (i) After the Stage 6 capacity, ARL requires about 3.4 Mt tailings deposition space to sustain the TSF operations;
- (ii) The current TSF performance show adequacy of stability, bearing capacity, operational controls and regulatory compliance necessary for future raises;

- (iii) The geotechnical parameters established for fill and foundation materials during the study are satisfactory for construction;
- (iv) FoS obtained for the centerline and upstream designs are above the minimum 1.5 stipulated in Regulation 264 (b) and (k) of LI 2182;
- (v) Based on the outcomes of the study, the centreline design is more feasible and recommended for adoption by ARL.

4.2 Recommendations

- (i) ARL can adopt the preferred centerline re-design beyond Stage 6 to sustain the LoM TSF operations;
- (ii) A more complete scope of modelling need to be carried out by ARL considering the remaining sections of built embankments and other design details critical for commercial certainty of the preferred option.

Acknowledgement

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- (iii) Management of Adamus Resources Limited (ARL), for permission to undertake the research work at the mine site and fully funding the cost of laboratory investigations; and
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