INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 8th Australia New Zealand Conference on Geomechanics and was edited by Nihal Vitharana and Randal Colman. The conference was held in Hobart, Tasmania, Australia, 15 - 17 February 1999.

Stability of a Mine Tailings Impoundment Structure after Decommissioning

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Summary The Tailings Dam wall at Kidston Gold Mines is constructed of fresh waste rock and compacted oxide waste rock, with internal drains constructed of river sand protected by a geotextile and a wrap of fresh waste rock. The waste rock materials have been characterised, and various scalped samples subjected to direct shear strength testing to assess their short and long term strength parameters. It was found that the strength of the erodable oxide waste rock is characterised by a cohesion and a friction angle, the cohesion increasing and the friction angle decreasing with decreasing maximum particle size. The fresh waste rock is durable and its strength is characterised by a friction angle only, with a value of at least 45°. The impounded tailings were investigated by cone penetration testing, and the phreatic line within the tailings adjacent to the wall has been monitored since June 1997. Deposition within the Tailings Dam ceased in late August 1997. Based on the measured strength parameters and the recorded location of the phreatic line, it was found that the Kidston Tailings Dam has more than adequate long term geotechnical stability, even under earthquake loading.

1. INTRODUCTION

The overburden at Kidston comprises coarse grained wastes in the form of oxide waste rock and fresh waste rock up to boulder size (typically up to 1 m in size, depending on the blasting pattern used). Both the oxide waste rock and the fresh waste rock have a natural moisture content of about 3%. The oxide waste rock is initially relatively free-draining, but is prone to weathering on exposure. The fresh waste rock is durable and free-draining.

The Kidston Tailings Dam has been constructed in up to five lifts to a maximum elevation of RL 557.6 m, with a localised maximum height of almost 40 m. Typically, the eastern section of the Tailings Dam wall is about 23.5 m high, and the western section is about 12.6 m high. Fresh waste rock was used to construct the early lifts of the Tailings Dam wall, and compacted oxide waste rock was used for the later lifts. The internal blanket and chimney drains were constructed using river sand protected by a geotextile and a wrap of fresh waste rock. The final Tailings Dam wall is about 5 km long and encircles about 70% of the perimeter of the 310 ha tailings storage.

Investigation of the stability of the Tailings Dam has included laboratory testing of the construction materials used, cone penetration testing of the impounded tailings adjacent to the wall, monitoring of the phreatic line within the tailings since June 1997, and stability calculations using both the circular slip program XSLOPE and the wedge program GWEDGEM, with and without earthquake loading.

2. CONSTRUCTION MATERIALS

2.1 Oxide Waste Rock

Compacted oxide waste rock was taken to represent the bulk of the material used to construct the Tailings Dam wall, excluding the internal drains and their fresh waste rock wrap.

2.1.1 Particle Size Distribution

The approximate particle size distribution of the whole oxide waste rock is shown on Figure 1. Also shown on Figure 1 are the particle size distributions of the material scalped (by removing oversize material) to pass 9.5 mm, 4.75 mm, 2.36 mm, and 1.18 mm. The maximum particle size limit of 9.5 mm was governed by the 100 mm size of the direct shear box used for strength testing. Testing of the different samples allowed evaluation of scale effects and particle breakdown due to weathering over time.

Table 1. Results of Standard compaction testing of scalped oxide waste rock.

SCALPED SAMPLE	MDD (t/m^3)	95% of MDD (t/m^3)	OMC (%)
- 9.50 mm	2.028	1.927	10.5
- 4.75 mm	1.994	1.894	11.5
- 2.36 mm	1.956	1.858	10.0
- 1.18 mm	1.915	1.819	13.0

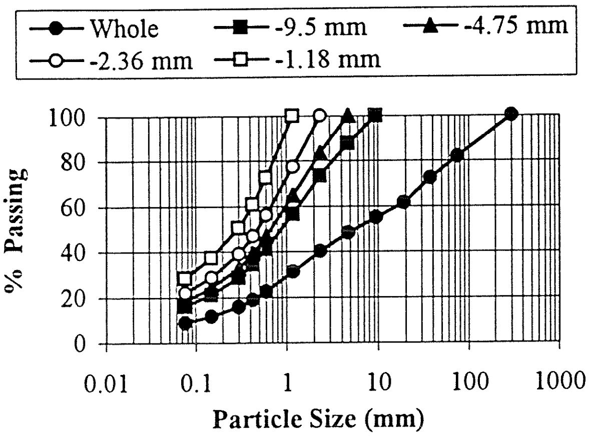

Figure 1. Particle size distributions of whole and scalped oxide waste rock.

2.1.2 Standard Compaction Testing

The scalped samples were subjected to Standard compaction testing to determine their maximum dry density (MDD) and optimum moisture content (OMC). The results of the compaction testing are summarised in Table 1, which shows that the MDD decreases with decreasing maximum particle size. The OMC shows no marked trend with maximum particle size, and a nominal average OMC of 11.0% may be adopted for all samples. The values of 95% of MDD also given in Table 1 represent the specified level of compaction to be achieved in the construction of the Tailings Dam wall. Direct shear specimens were prepared to these initial dry densities.

The laboratory Standard compaction of the oxide waste rock carried out at Kidston yielded an minimum MDD of 2.0 t/m^3, at an average OMC of 8.5%. This testing was carried out on the whole oxide waste rock with only those particles which would not fit into the compaction mould removed. The relative coarseness of these samples explains their slightly higher MDD and lower OMC relative to the values obtained for the scalped oxide waste rock samples. However, the laboratory and on-site values are similar.

2.1.3 Direct Shear Strength Testing

Direct shear strength testing is appropriate for the determination of strength parameters for application in slope stability calculations, since the material tested is forced to shear along a pre-determined plane.

Direct shear strength testing was carried out in a 100 mm shear box on the four scalped samples. Specimens were compacted at a nominal average OMC of 11.0% to a density of 95% of the relevant MDD, reflecting the expected state of compaction of the material in the Tailings Dam wall. Testing was carried out on separate specimens under nominal normal stresses of 50 kPa, 100 kPa, 200 kPa, and 400 kPa, at a shearing rate of 0.25 mm/min. Nominal normal stresses of 10 kPa and 25 kPa were also applied to specimens passing 9.5 mm to assess the shape of the strength envelope at low stresses. Separate specimens were used in preference to multi-stage testing since multi-stage testing was found to have a negative impact on the strength obtained in subsequent stages. This was attributed to particle breakdown. Shearing was continued in each test to a maximum of about 10 mm (10% strain).

The results of the direct shear testing are summarised in Table 2. Straight line strength envelopes were found to fit the data very well. The tabulated cohesion and friction angle values (Table 2) show that as the maximum particle size of the oxide waste rock is reduced, the cohesion tends to increase and the friction angle tends to decrease. Hence the limitation on the maximum particle size of the fresh oxide waste rock which could be tested will have the effect of increasing the resulting cohesion and reducing the resulting friction angle. At an applied normal stress of 100 kPa, which is typical of that felt within the body of the Tailings Dam wall, the overall shear strength of the different scalped samples of oxide waste rock is approximately constant at about 128 kPa. The breakdown of the oxide waste rock on weathering over time would therefore not be expected to significantly effect the overall shear strength of the material.

2.2 Fresh Waste Rock

The fresh waste rock was taken to represent the material used to construct the internal blanket and chimney drains of the Tailings Dam wall.

Table 2. Results of strength testing of oxide waste rock.

SCALPED SAMPLE	INITIAL MOISTURE CONTENT (%)	INITIAL DRY DENSITY (t/m^3)	COHESION (kPa)	FRICTION ANGLE (degrees)
- 9.50 mm	11.0	1.927	38.0	42.3
- 4.75 mm	11.0	1.894	46.0	38.6
- 2.36 mm	11.0	1.858	58.5	33.9
- 1.18 mm	11.0	1.819	55.8	35.7

2.2.1 Particle Size Distribution

The particle size distribution of the whole fresh waste rock was determined by combining coarse sieving at the mine with laboratory sieving of the -40 mm fraction, resulting in the estimated curve shown on Figure 2. Also shown on Figure 2 are the particle size distributions of the material scalped to pass 9.5 mm and 1.18 mm, and of the material in the size range from 1.18 to 9.5 mm.

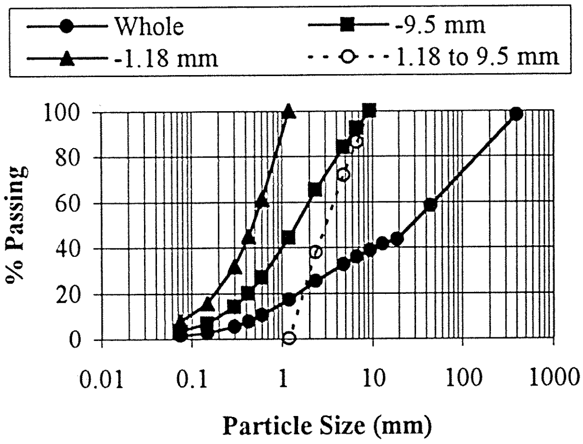

Figure 2. Particle size distributions of whole and scalped fresh waste rock.

The fresh waste rock is durable, and is not expected to undergo significant breakdown except in the very long term. The Tailings Dam drains are therefore expected to remain free-draining.

2.2.2 Direct Shear Strength Testing

Direct shear strength testing was carried out in a 100 mm shear box on the two scalped samples. The tests on the -1.18 mm sample were carried out to enable some assessment of scale effects to be made. A test was also carried out on a sample of fresh waste rock in the size range from 1.18 to 9.5 mm, to assess the effects of fines. Specimens were prepared loose (initial dry density of about 1.64 t/m^3), and at natural moisture content (about 3%) or saturated. Multi-stage testing was carried out under nominal normal stresses of 25 kPa, 50 kPa, 100 kPa, 200 kPa, and 400 kPa, at a shearing rate of 0.25 mm/min. Multi-stage testing was adopted since the fresh waste rock is durable, showing negligible breakdown on direct shear testing. Shearing was continued during each stage to a maximum shear displacement of about 2.5 mm (2.5% strain).

The results of the direct shear testing are summarised in Table 3. Straight line strength envelopes passing through the origin (zero cohesion) were found to fit the data very well. The tabulated friction angle values (Table 2) show that scale and high applied normal stresses have significant effects on the friction angle of fresh waste rock. Saturation has some effect on the friction angle, but eliminating the -1.18 mm fraction has little effect. The limitation on the maximum particle size of the fresh waste rock which could be tested would have the effect of reducing the friction angle. Based on the data in Table 3, the whole fresh waste rock is expected to have a minimum friction angle of 45°. The shear strength mobilised within the fresh waste rock wrapping the base blanket drain generally exceeds 200 kPa.

3. FIELD TESTING AND MONITORING

Cone penetration testing of the impounded tailings and the installation of standpipe piezometers within the tailings at Kidston were carried out by Douglas

Table 3. Results of strength testing of fresh waste rock.

SCALPED SAMPLE	MOISTURE CONTENT	FRICTION ANGLE (degrees)
- 9.50 mm	Natural moisture content	48.4
- 1.18 mm		39.8
1.18 to 9.5 mm		48.4
-9.5 mm	Saturated	45.4

Partners Pty Ltd using a truck-mounted rig, under the supervision of Associate Professor David Williams and Kidston personnel, in June 1997.

3.1 Cone Penetration Testing of Tailings

Piezocone testing was carried out at a typical (high) eastern section of the dam, at a typical (low) western section of the Tailings Dam wall, and towards the shallow, southern end of the impounded tailings (Figure 3). At the time of testing, the edge of the ponded water was located about 300 m and 380 m away from the dam crests at the eastern and western sections, respectively.

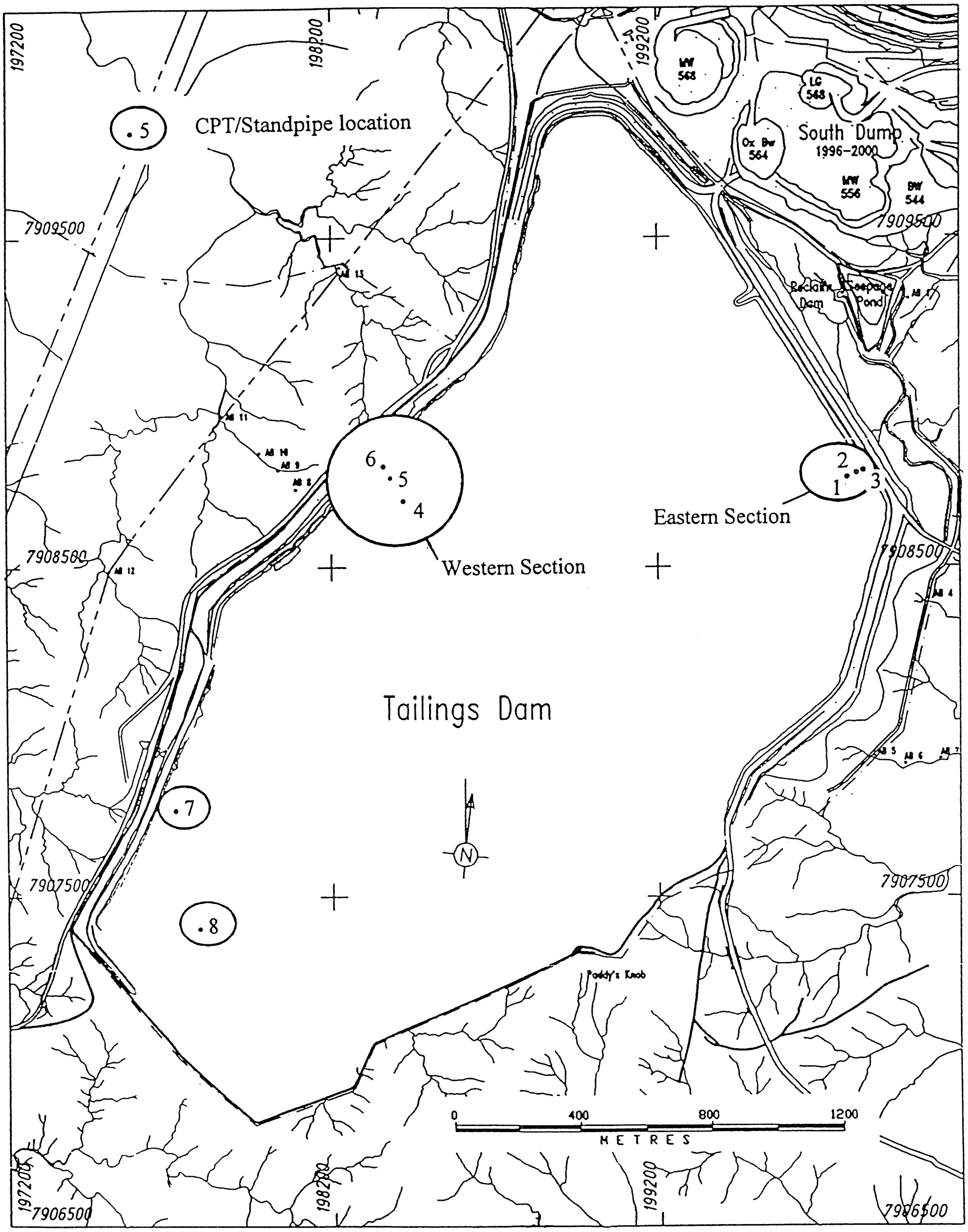

Figure 3. Locations of cone penetration testing, standpipes, and sections.

Table 4. Water levels within tailings impoundment.

WATER RL (m)	POND	SP1	SP2	SP4	SP5	SP6	SP7	SP8
HIGHEST	554.33	544.09	541.01	551.81	551.43	550.76	554.63	552.21
LOWEST	553.42	543.20	540.08	550.20	547.78	547.12	551.12	548.78

The results of the piezocone testing indicated "residual" water perched above slimes layers within the impounded tailings, with the "permanent" water table located several metres lower.

3.2 Monitoring of Phreatic Line

Standpipe piezometers were installed at seven locations (1, 2, 4, 5, 6, 7, and 8; see Figure 3). Standpipes 1 and 2 are located at the eastern section of the Tailings Dam wall, and Standpipes 4, 5, and 6 are located at the western section of the Tailings Dam wall. The highest and lowest ponded water levels measured from June 1997 to March 1998, and the highest and lowest water level readings made in the standpipes over the same period are summarised in Table 4.

The highest measured ponded water level was obtained on 17 March 1998, following about 520 mm of summer rainfall (about 60% of the average annual rainfall) over the period from December 1997 to March 1998. There was some correlation between the measured ponded water and standpipe levels, suggesting that changes in standpipe levels lag changes in ponded water levels by about one month.

The measured phreatic line draws down rapidly towards the upstream toe (and base drain) of the Tailings Dam wall (see Figures 4 and 5 for the eastern and western sections, respectively). The hydraulic gradient towards the upstream toe of the Tailings Dam wall is about 0.5 and 0.3 at the eastern and (lower) western sections, respectively. The overall hydraulic gradients from the ponded water to the upstream toe of the Tailings Dam wall are about 0.067 and 0.015 at the eastern and western sections, respectively.

4. STABILITY ANALYSES

4.1 Typical Tailings Dam Sections

The oxide waste rock used to construct the upstream portion and later lifts of the Tailings Dam wall was conditioned to OMC ± 3%, where the OMC was 8.5%, and compacted to at least 95% of Standard MDD or 1.9 t/m^3 (a minimum wet unit weight of about 20.2 kN/m).

Typical sections of the Tailings Dam wall are the higher eastern section of the dam and the lower western section, shown on Figures 4 and 5, respectively. The eastern section is about 23.5 m high, with an upstream slope of 1.35H:1V (35.5°), a downstream slope of 1.40H:1V (36.5°), and a 6 m wide crest. The western section is about 12.6 m high, with upstream and downstream slopes of 1.35H:1V (35.5°), and a 7 m wide crest. The assumed free-board from the crest of the wall to the tailings surface is 1 m. Both sections have internal drains comprising blanket base drains and vertical chimney drains, as shown on the figures. The drains are represented by fresh waste rock, initially placed loose and at its natural moisture content, and the remainder of the sections is represented by compacted oxide waste rock.

1	Tailings
2, 4	Compacted oxide waste rock
3, 5	Fresh waste rock drain
6	Foundation

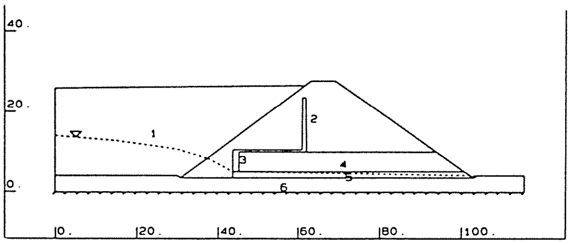

Figure 4. Typical geometry of eastern section of Tailings Dam wall.

1	Tailings
2	Compacted oxide waste rock
3	Fresh waste rock drain
4	Foundation

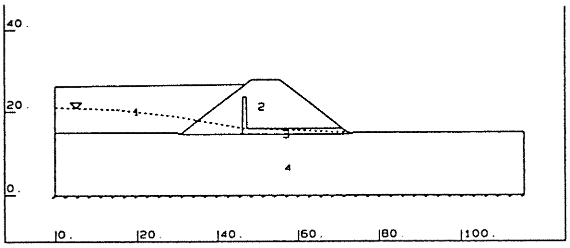

Figure 5. Typical geometry of western section of Tailings Dam wall.

4.2 Methods of Analysis

Two-dimensional stability analyses were carried out on the two typical Tailings Dam sections using the circular slip analysis program XSLOPE (Balaam, 1994), and the generalised wedge analysis program GWEDGEM (Donald and Zhao, 1995). Two-dimensional analysis is appropriate for the Tailings Dam given its large length compared with its height. XSLOPE incorporates the simplified Bishop method and an automatic search routine for the critical slip circle and minimum factor of safety.

GWEDGEM is a limit equilibrium-based Generalised WEDGE Method of stability analysis, in which both force and moment equilibrium are fully satisfied and the failure mechanism is kinematically admissible (that is, the sliding wedges may move without causing gaps or overlaps). Inclined internal interfaces are permissible. Various multi-variable, unconstrained search routines are available for selecting the most critical multi-linear failure mechanism. Although two to six wedges are usually sufficient, up to nine wedges may be specified, and this number of wedges has been adopted in the analyses.

For the purposes of analysis, the material parameters listed in Table 5 were adopted. The stability calculations are not very sensitive to the choice of wet unit weight, and a value of 20.4 kN/m^3 was adopted for both the compacted oxide and the fresh waste rock. The parameters adopted for the tailings and foundation are based on typical values for these materials. The stability calculations are insensitive to these parameters since the critical slip surface does not pass through either the tailings or the foundation.

The design earthquake loading applicable for the region in which Kidston Gold Mines are located is represented by a maximum horizontal ground acceleration a_{max} of 0.03g, where g is the gravitational acceleration (AS 1170.4 - 1993).

4.3 Results of Analyses

Minimum factors of safety for deep-seated instability were calculated using XSLOPE and GWEDGEM. The possibility of minor surficial ravelling of materials on the downstream slopes of the Tailings Dam wall was ignored.

4.3.1 Eastern Section of Tailings Dam Wall

The results obtained for the eastern section of the Tailings Dam wall using XSLOPE and GWEDGEM, with the highest phreatic line, are summarised in Table 6. The locations of the critical slip surfaces and the minimum factors of safety obtained are unaffected by the height of the phreatic line within the tailings.

4.3.2 Western Section of Tailings Dam Wall

The corresponding results obtained for the western section of the Tailings Dam wall using XSLOPE and GWEDGEM, with the highest phreatic line, are summarised in Table 7.

Table 5. Material parameters for stability analyses.

MATERIAL	COHESION (kPa)	FRICTION ANGLE (degrees)	WET UNIT WEIGHT (kN/m^3)
Tailings	30	0	16.0
Oxide waste rock:			
-9.50 mm	37.8	42.3	20.4
-4.75 mm	45.9	38.6	20.4
-2.36 mm	58.4	33.9	20.4
-1.18 mm	55.8	35.7	20.4
Fresh waste rock	0	45.0	20.4
Foundation	50.0	45.0	25.0

Table 6. Results of stability analyses of eastern section of Tailings Dam wall.

OXIDE WASTE ROCK	HORIZONTAL ACCELERATION (a/g)	MINIMUM FACTOR OF SAFETY	
		XSLOPE	GWEDGEM
-9.5 mm	0/0.03	2.15/2.03	2.21/2.09
-4.75 mm	0/0.03	2.10/1.99	2.18/2.07
-2.36 mm	0/0.03	2.07/1.96	2.18/2.07
-1.18 mm	0/0.03	2.11/2.00	2.21/2.10

Table 7. Results of stability analyses of western section of Tailings Dam wall.

OXIDE WASTE ROCK	HORIZONTAL ACCELERATION (a/g)	MINIMUM FACTOR OF SAFETY	
		XSLOPE	GWEDGEM
-9.5 mm	0/0.03	2.43/2.03	2.52/2.39
-4.75 mm	0/0.03	2.46/2.33	2.53/2.40
-2.36 mm	0/0.03	2.55/2.44	2.78/2.60
-1.18 mm	0/0.03	2.57/2.44	2.65/2.51

4.4 Adequacy of Stability

According to the then Queensland Department of Mines and Energy (1995), the minimum factor of safety conventionally specified to ensure adequate long-term stability for slopes is 1.5. The minimum factors of safety obtained using XSLOPE were consistently 3 to 5% lower than those obtained using GWEDGEM, but the similarity between the results obtained from the two methods confirm that both yield reliable results.

All minimum factors of safety calculated, both with and without earthquake loading, for the eastern and western sections of the Tailings Dam wall, exceed the required value of 1.5 by a substantial margin. This is attributed to the oxide waste rock having a near-constant overall shear strength irrespective of its topsize and % fines (passing 0.075 mm), and the fact that the internal drainage within the wall is very effective in maintaining a low phreatic line through the dam wall.

5. CONCLUSION

The well-drained Kidston Tailings Dam wall subjected to earthquake loading has a more than adequate geotechnical stability. The breakdown of the oxide waste rock within the wall due to weathering over time is not expected to significantly reduce the overall shear strength of the material. The fresh waste rock used to wrap the internal drains within the wall is not expected to undergo significant breakdown and is expected to remain free-draining, maintaining a low phreatic line. The Kidston Tailings Dam wall is therefore expected to remain geotechnically stable in the long-term.

6. ACKNOWLEDGEMENT

Kidston Gold Mines Limited are acknowledged for funding the research on which this paper is based and for allowing the publication of the results.

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