

MEMORANDUM



Golder Associates Ltd.

#500 - 4260 Still Creek Drive
Burnaby, B.C., Canada V5C 6C6

Telephone: 604-296-4200
Fax Access: 604-298-5253

TO: John Brodie, P. Eng.
Technical Manager
Faro Mine Closure Planning Office

DATE: September 8, 2006

FROM: Mike Jefferies, John Cunning

JOB NO: 06-1413-068

EMAIL: mjefferies@golder.com; jcunning@golder.com

RE: **SEISMIC STABILITY OF TAILINGS COVERS –Anvil Range Mining Complex (FARO MINE), YUKON**

INTRODUCTION

In 2003, Golder Associates Ltd. (Golder) was retained to evaluate the tailings stability as part of the Faro Mine Closure planning. Our findings were reported in “Rose Creek Tailings Impoundment Site Characterization and Seismic Stability Assessment Report ARMC, Yukon” dated June 30, 2004. The evaluation of tailings stability involved in-situ testing using CPT methods, laboratory testing of samples of the tailings, and engineering analyses of the data. A key conclusion of the work as presented in Section 9.1 of this report stated “This adopted approach predicts widespread liquefaction of the tailings slimes, and with a high potential for subsequent flow-slides under the MCE.”

Subsequent to the issuing of our report, and as part of the ongoing studies related to the mine closure planning, the Tailings Cover Working Group has considered the report’s findings and requested further comments regarding the potential for large displacements of the tailings under seismic loading. In particular, since all soils have some residual strength post-liquefaction, the Working Group’s view is that displacements might be expected to be limited to a few meters provided that the below-water part of the tailings upstream of the Intermediate Dam was infilled as part of the remediation strategy.

Since working on the ARMC tailings impoundment, we have cooperated with UBC to address an aspect of the data evaluation used and which led to a paper presently in-press with the Canadian Geotechnical Journal (Ref. 1, copy attached). We have reviewed our assessment of the CPT data in light of this research, and further in the light of a new text on liquefaction (Ref. 2). This Memorandum provides the requested clarifications to our 2004 Report using the new information.



The scope of this current work was presented in our Proposal letter P62-1398 to Mr. Brodie on August 21, 2006 and subsequent authorization to proceed with the work was given in a letter from Deloitte & Touche dated 10 August 2006.

TAILINGS POND SLOPES AND REQUIRED STRENGTH

It is understood that the Working Group regard 1% as the characteristic surface slope of the impoundment where cover stability is a concern. In our report we were more concerned with the potential for larger scale movements to inundate the Intermediate

Dam and calculated a basin-wide slope of 0.8 degree (1.4%). Since local cover stability is the concern, about 1 degree is not unreasonable as characteristic of the above water part of the impoundment.

As an approximation, such flat slopes can be treated as sliding with a shear zone or sliding surface parallel to the ground surface (an approach used in many published back-analyses of liquefaction slides). For a slope of angle θ to the horizontal the required post-liquefaction strength s_r to prevent large scale sliding is:

$$s_r = \gamma_t z \cos \theta \sin \theta \quad [1]$$

where z is the depth to the sliding plane and γ_t is the bulk unit weight. Because soil behaviour depends on its initial effective stress, and because the depth to potential sliding planes is uncertain, it is usual to normalize [1] by the initial effective stress. For groundwater table at surface (a somewhat conservative assumption for most of the ARMC impoundment) the initial effective stress is approximated as:

$$\sigma'_{v0} = \gamma' z \quad [2]$$

Equations [1] and [2] are combined to remove z giving:

$$\frac{s_r}{\sigma'_{v0}} = \frac{\gamma_t}{\gamma'} \cos \theta \sin \theta \quad [3]$$

Equation [3] is also standard in back analysis of liquefaction slides in which the sliding mass has an essentially flat shape (as it must in a large flowslide at flat slopes).

Using an average saturated bulk unit weight of $\gamma_t = 22 \text{ kN/m}^3$ (loose tailings with high specific gravity) the required post-liquefaction strength ratio for avoidance of large scale movement of a 1 degree slope is:

$$\frac{s_r}{\sigma'_{v0}} > 0.032 \quad [4]$$

The determination of available post liquefaction strength is now discussed.

DETERMINATION OF AVAILABLE POST-LIQUEFACTION STRENGTH

Because undisturbed samples of material like the ARMC tailings are essentially impossible to obtain (without resorting to expensive ground freezing techniques), estimating the available post-liquefaction strength largely depends on penetration tests. There are three methods for determining post-liquefaction undrained strength from penetration tests:

1. A correlation between the strength s_r , estimated from back-analysis of case histories and correlated to penetration resistance (usually the SPT).
2. A correlation between the strength ratio s_r / σ'_{v0} estimated from back-analysis of case histories and correlated to penetration resistance (either CPT or SPT).
3. A theoretically-based relationship between strength ratio s_r / σ'_{v0} and the state parameter ψ .

Method (1), while commonly used, is incorrect and has no predictive power (Ref. 2). Using method (1) for the ARMC tailings will simply mislead. Method (2) is a correlation for materials unlike the ARMC tailings, and its applicability for the ARMC tailings are uncertain. The figure below, copied from Ref. 2, illustrated how well the theoretical relationship (“locus of localization during undrained shear in NorSand”) of Method (3) matches the back-analysis of various case histories. Figure 6.11 of our report presented this information but without the case histories being identified. Although these back-analyses have substantial uncertainties (shown by error bars), overall the theoretical relationship is a good match to experience. And, being theoretically based, there is substantial confidence in extrapolation to different soils. We adopted Method (3) for application to ARMC, and allowed for the effect of actual soil properties.

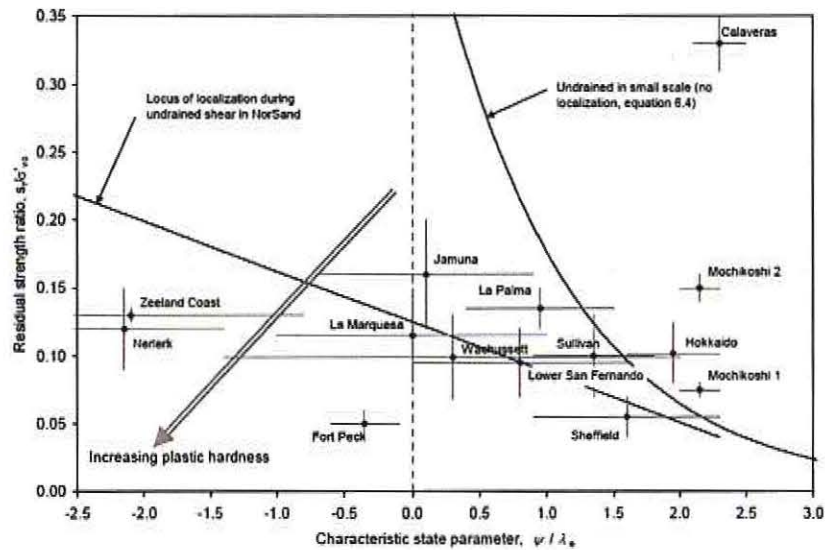


Figure 6.43 Relationship between initial *in situ* state parameter and mobilized steady state strength from case history data. Bars show uncertainty in the strengths and uncertainty in characteristic state

AVAILABLE UNDRAINED STRENGTHS

Appendix V of our report presented all the CPT data from the Rose Creek impoundment processed into profiles of s_r / σ'_{v0} with depth (amongst other plots). We noted in the text of the report that strengths of $s_r / \sigma'_{v0} < 0.01$ were commonly found, and it is this data that lead to our conclusion that widespread large-scale movements appeared likely following a large earthquake.

Figure 5.18 of our report showed the fraction of each CPT sounding that was identified as substantially contractive behaviour. To provide more detail on the potential for large movements, the fraction of each CPT sounding for which the estimated post-liquefaction strength is less than the ratio $s_r / \sigma'_{v0} = 0.032$ needed for stability is tabulated on the next page. Although, not all soundings are weak some 21 of the 33 sounding do have insufficient post-liquefaction strengths over part of their profiles. Neglecting the soundings with only a small fraction of weak layers, comparing these too-low strengths with location of the respective CPT within the impoundment indicates the following conclusions:

- A 200 m wide zone upstream and about parallel to the crest of the Secondary Dam is vulnerable to large displacements. Broadly this centers on SCPT03-21 and CPT03-19, with extension northwards out to CPT03-22 and tapering in the east to a narrow zone adjacent to the dam at CPT03-14.

- About half of the impoundment between the Intermediate and Secondary Dams is vulnerable to large displacements, based on clearly inadequate strengths in immediately upstream of the pond in SCPT03-32 and CPT03-33 and recognizing that the underwater slope is steeper than that of the tailings surface. This vulnerable area forms a zone about 600 – 700 m wide upstream and parallel to the crest of the Intermediate Dam.

It is also noteworthy that not only are post-liquefaction strengths in part of the impoundment less than required for post-earthquake stability but some of these strengths are exceedingly low. This is unsurprising as in some CPT soundings complete static liquefaction was measured around the CPT transducer (indicated by $B_q \leq 1.0$) during the sounding itself, for example SCPT 03-21. Some of the CPT's in the Rose Creek impoundment are the weakest seen in two-decades of CPT soundings by Golder.

The magnitudes of potential movements were not calculated in for our report. As indicated above, we used an infinite slope stability analysis and which give a stable/unstable result. As the slope will not stop moving until the shear stress in the slope is less than the post-liquefaction strength, and the available post-liquefaction strengths in many of the weak layers is less than a third of the present shear stress, substantial flattening of the impoundment is indicated – likely accompanied by the development of back scarps where the weak soils abut stronger. We cannot concur with the Tailings Working Group's view that such movements will likely be less than 2 m based on presently available information.

Table A1: Estimated Vulnerability to Large-Displacement Slides

CPT	Fraction of CPT profile indicating post-liquefaction strength less than needed for stability ($s_r / \sigma'_{v0} = 0.32$)	Comment
CPT03-01	≈ 13%	Most profile $s_r / \sigma'_{v0} \approx 0.05$
CPT03-02	≈ 3%	Only very thin layers
CPT03-03	≈ 7%	Three layers of very low strength
CPT03-04	None	
SCPT03-05	None	
CPT03-06	None	
CPT03-07	≈ 1%	Three very thin layers
CPT03-08	None	
CPT03-09	≈ 1%	One layer at 3m depth
CPT03-10	≈ 3%	Mainly in a 1m thick base layer

CPT	Fraction of CPT profile indicating post-liquefaction strength less than needed for stability ($s_r / \sigma'_{v0} = 0.32$)	Comment
CPT03-11B	None	
CPT03-12B	≈ 4%	An exceedingly weak base layer
CPT03-13	≈ 3%	Three layers of very low strength
CPT03-14	≈ 25%	Most profile $s_r / \sigma'_{v0} \approx 0.02$
CPT03-15	≈ 24%	Two very weak layers
CPT03-16	≈ 11%	Basal 3m has $s_r / \sigma'_{v0} < 0.03$
SCPT03-17	≈ 14%	Two very weak layers
CPT03-18	≈ 6%	Three weak layers, one at base
CPT03-19	≈ 43%	Pervasively $s_r / \sigma'_{v0} < 0.01$
CPT03-20X	None	
SCPT03-21	≈ 30%	Pervasively $s_r / \sigma'_{v0} < 0.02$
CPT03-22	≈ 13%	Many layers $s_r / \sigma'_{v0} < 0.03$
CPT03-23	None	
CPT03-24	≈ 12%	Many layers $s_r / \sigma'_{v0} < 0.03$
SCPT03-25	≈ 1%	Marginally weak layer at base
CPT03-26	None	
CPT03-27	≈ 1%	One exceedingly weak thin layer
CPT03-28	None	
CPT03-29	None	
CPT03-30	None	
CPT03-31	None	
SCPT03-32	≈ 15%	Pervasively $s_r / \sigma'_{v0} < 0.03$
CPT03-33	≈ 27%	Pervasively $s_r / \sigma'_{v0} < 0.03$

It may be possible to refine the estimate of tailings movement in a post-earthquake situation. A first step would be to assume that too-weak tailings flowed to a level surface and that the tailings with adequate post-liquefaction strength did not move. Our report recommended that a bathymetric survey of the pond be undertaken and we can estimate a likely tailings movement using this scenario once that information is available.

Moving to more sophisticated estimates of potential displacements, our evaluation effectively assumed all weak layers form a continuous mass. Some researchers have stochastic models which could represent the actual the distribution and scale of these weak layers and including factors such as the high compressibility of the tailings. While we judge it unlikely that a stochastic model would change our judgment that movements likely exceed 2m in the too-weak tailings, if very large costs depend on understanding

tailings behaviour at this level then we suggest that Dr. Shuttle at UBC be contacted. A PhD candidate has modified FLAC under Dr. Shuttle's direction for just this type of situation, and this modified version of FLAC might be used to obtain further insight on the ARMC tailings impoundment.

RELIABILITY OF ASSESSMENT METHOD USED

A difficulty with all the methods for estimating post-liquefaction strength is that they are based on either drained penetration tests (the CPT-based methods) or involve speculative "corrections" for partly drained behaviour (the SPT methods for which the pore pressure during testing are not measured). As noted above, our assessment was based on a quasi-theoretical approach (Ref. 3) and which is often referred to as a "screening method". This method relates the soil's state parameter ψ to the measured CPT data (transformed into the dimensionless variables Q_p, B_q) through:

$$Q_p(1 - B_q) + 1 = \bar{k} \exp(-\bar{m} \psi) \quad [5]$$

where k, m are soil-specific coefficients. Although [5] was developed using trends observed in various case histories, it has been given a sound basis subsequent to our report. As noted earlier, Golder has been collaborating with the geotechnical group at UBC. One area of this collaboration has been just this issue of reliable determination of the *in-situ* state parameter in silt. Extensive numerical simulations, using a good soil model, resulted in the figure shown below (copied from Ref. 1.). The trend line through the numerical results is Equation [5], and it is readily apparent that it is a remarkably accurate relationship. Thus, although there was an element of engineering judgment in the assessment method adopted for our report, subsequent work has demonstrated that it is indeed a sound method.

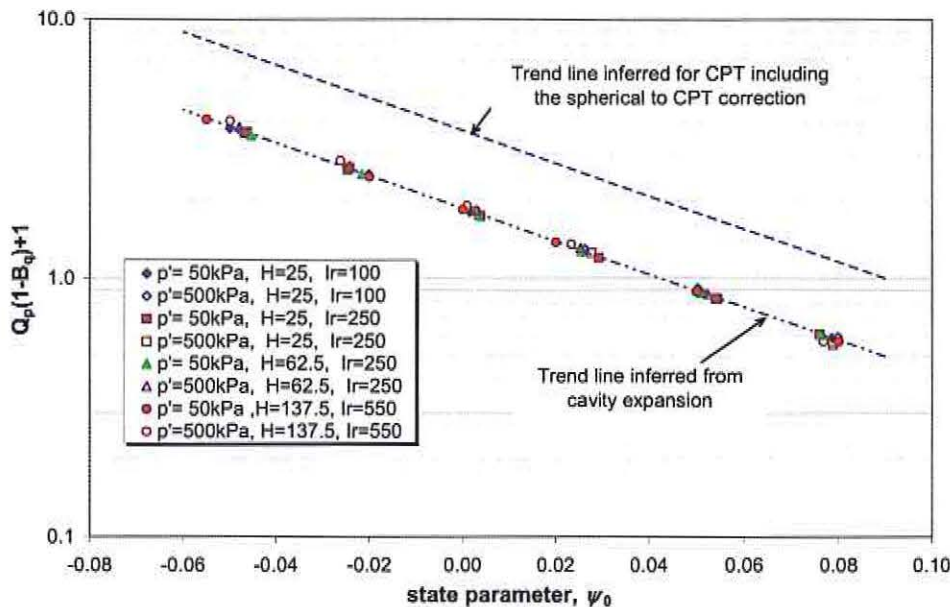


Figure 1: Normalized results of numerical simulations (all 36 simulation results plotted)

RELEVANCE OF SUBMITTED CASE HISTORY

The letter requesting the clarifications presented in this Memorandum also provided a copy of a tailings impoundment case history as background. However, this case history provided neither material properties nor CPT data from which its relevance to the ARMC tailings might be estimated.

CLOSURE

We trust that this memorandum clarifies the questions raised by the Tailings Working Group and how we developed the conclusions presented in our report. Not being party to the discussion of the Working Group, we are unclear quite how they developed the view that large scale movements were unlikely – some of the CPT's in the Rose Creek impoundment are as weak as we have ever seen.

As set out in the report and elaborated in this memorandum, the CPT data, when systematically evaluated allowing for the properties of the tailings, indicates about a quarter of the plan area of the impoundment has post-liquefaction strengths less than needed for stability at the present surface slopes. This area comprises about a 200 m wide zone upstream of the Secondary Dam and a zone about 600-700 m wide upstream of the Intermediate Dam. Our best estimate is that the final post-earthquake slopes in these zones might be about half the present slopes, with formation of back scarps at the junction between weak and strong areas.

Further work is possible to better refine the corresponding estimates of potential displacement in a post-earthquake movement of the very weak tailings, but such work depends on bathymetric data for the existing ponds and which we understand is not presently available.

MJ/JCC/kt

N:\Final\2006\1413\06-1413-068\TM-0908_06 Faro Mine-Seismic Stability of Tailings Covers-Anvil Range Mining Complex.doc

References

Ref. 1. Shuttle, D. & Cunning, J.; Liquefaction potential of silts from CPTu. *In Press*, Canadian Geotechnical Journal (preprint attached).

Ref. 2. Jefferies, M. & Been, K. (2006); Soil liquefaction – A critical state approach. Spon Press, ISBN: 0419161708.

Ref. 3. Plewes, H.D., Davies, M.P., and Jefferies, M.G. (1992); CPT based screening procedure for evaluating liquefaction susceptibility. Proc 45th Can Geot Conf, Toronto.