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CONSULTING

Memorandum

Date:	25 November 25, 2005	Our Ref:	VA101-1/10-A.01
To:	Les Galbraith	Cont.#:	V5-1185
From:	Mark Locke		
Re:	Mt Polley Mine – Review of Tailings Dam Filter Performance		

INTRODUCTION

The core (Zone S) and filter (Zone F) material for the Mt Polley Mine Tailings Dam are broadly graded, cohesionless materials. Recent research has shown that these type of materials sometimes behave differently than well graded materials during filtration. Because of this concern, a review of the filter performance has been carried out.

The review initially considers the conformance of the filter grading to filter design criteria developed for conventional, water retaining dams. The Mt Polley Tailings Dam retains coarse tailings adjacent to the embankment and has drainage provisions installed upstream of the dam core to drain these tailings. The effect of these differences from a water retaining dam is discussed at the end of the review.

The core grading limits are shown on Figure 1, which also shows a range of gradings of the 17 samples of core material (Zone S). Figure 2 shows the filter grading limits and 26 samples of filter (Zone F) material taken during Stage 3C construction. Based on statistical analysis of the Stage 3C samples, the 90% finest core grading and 90% coarsest filter grading are plotted on Figures 1 and 2 respectively. These gradings are considered in the following analysis.

CONFORMANCE TO FILTER DESIGN CRITERIA

Review of the filter design criteria has been carried out based on the guidelines provided by the US Department of Agriculture (1994). These guidelines are based on the recommendations of Sherard and Dunnigan (1985) which are currently adopted internationally as suitable criteria. The design criteria include filtering criteria, and requirements to prevent gap graded filters and segregation. The criteria refer to the filter grading limits.

FILTERING CRITERIA

The filter grading limits should be based on the finest allowable core material grading after re-grading to remove material coarser than 4.75mm. The fine filter limit has approximately 60% of particles finer than the no. 200 sieve (0.075mm), which places it into soil category 2. The recommended filter for this category has D_{15}=0.7mm. The Mt Polley coarse filter limit meets this requirement.

PREVENT GAP-GRADED FILTERS CRITERIA

1) The width of the filter band should be such that the ratio of the maximum diameter to the minimum diameter, at any given percentage passing value less than or equal to 60 percent, is less than or equal to 5. Based on the filter grading limits shown in Figure 1, the width of the filter band varies between 4.4 and 4.7 which is acceptable.

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2) Both sides of the design filter band should have a coefficient of uniformity ($C_u = D_{60}/D_{10}$) less than or equal to 6. The coarse filter limit has C_u=30 and the fine filter limit has C_u=28. The filter design clearly does not meet this requirement and there is a risk of having gap graded or internally unstable filters.

A discussion of potential internal stability and the effects of the very broad grading is provided later.

PERMEABILITY CRITERIA

The D_{15} size of the filter should be greater than 4 times the d_{15B} size of the base soil but not less than 0.1mm. The ratio D_{15}/d_{15B} is in excess of 100. The fine limit of the filter has D_{15}=0.15mm so this requirement is clearly met.

MAXIMUM AND MINIMUM PARTICLE SIZE CRITERIA

The maximum D_{100} size of the filter should be 75mm, the coarse limit is 50mm so this requirement is met.

The minimum D_5 size should be 0.075mm. The fine filter limit does not show a D_5 size (it shows D_{15}>0.15mm). Most of the filter samples tested during construction have between 5% and 11% of particles finer than 0.075mm, these filters do not meet the minimum particle size requirement.

The minimum particle size criteria is provided to ensure that the filter will not be cohesive and it will collapse in the event of a crack or void forming rather than staying open. It is likely that the manufactured filter material will be sufficiently non-cohesive to function correctly despite the high fines content. This can be confirmed by laboratory testing such as the 'sand castle' slump test described by ICOLD (1994). In this test a cylinder of compacted filter material is placed in a tub which is then filled with water. If the sample slumps to its natural angle of repose while the water level rises then it is considered non-cohesive.

SEGREGATION CRITERIA

If D_{10} of the filter is < 0.5mm (coarse filter limit has D_{15}=0.7 so assume the filter is in this category), the maximum D_{90} size should be 20mm. The filter coarse limit has D_{90}=35mm so segregation is a risk. This can be managed by careful construction practices.

SUMMARY OF CONFORMANCE TO FILTER DESIGN CRITERIA

The filter grading limits do not meet the design criteria adopted for the review for the following reasons:

- The coefficient of uniformity of the filter grading limits is too high which may lead to gap-graded or internally unstable filters
- The fines fraction is too high which may hinder the crack filling property of the filter.
- The filter limits are broadly graded (ratio of D_{90}/D_{10} is too high) which may result in segregation during placement.

On this basis, it is considered necessary to examine the filter performance using the results of new research for filter behaviour. It should be noted that the conventional filter design criteria are based on water retaining dams and there are additional features at the Mt Polley Tailings Dam, which allow some flexibility in the filter design.

INTERNAL STABILITY OF CORE MATERIAL

The core material is a very broadly graded glacial till, recent research has shown that these materials can be susceptible to internal instability, where the fines of the material can be washed out of the soil skeleton formed by the coarser particles.

The internal stability of the 90% finest core grading and the fine filter grading limit has been examined using the Reduced PSD Method described by Locke and Indraratna (2002). The results are shown in Figure 3. The fine filter grading limit is relatively well graded and a material with this grading would be internally unstable. However, most samples of the core material are significantly more broadly graded.

The 90% finest core grading has some sand and gravel sized particles, which are unable to retain the finer fraction, however the particles finer than 0.75mm are predicted to be internally stable. A successful filter must be able to retain the stable fraction of this soil (ie. The fraction finer than 0.75mm). The design criteria recommended by Locke and Indraratna (2002) for a glacial till core is:

$$D_{15F} / d_{85\,Reduced} \leq 4$$

where $d_{85Reduced}$ is the d_{85} size measured from the Reduced PSD shown in Figure 3, in this case 0.185mm. Hence a suitable filter would have $D_{15F} \leq 0.74$mm.

PERFORMANCE OF BROADLY GRADED FILTER

Similar to the broadly graded core material, it is possible that the fine fraction of the broadly graded filter is not internally stable and can wash out through the coarse particles. This loss of fines could affect the filter performance. The potential for wash out of fines has been examined with an analytical model of time-dependent filter behaviour, described by Locke et al. (2001). The 90% coarsest filter grading was modelled. The model has considered a case where a flow rate of $3x10^{-9}$ m^3/s, which is the maximum flow rate predicted by seepage analysis with no upstream toe drain, occurs through the filter interface. This model case considered only the filter and not the core material.

The model results are summarised in Figure 4. The filter material initially contains a long tail of fine material. However, the particles finer than about 0.75mm cannot be retained by the coarse fraction and are unstable. As water passes through the material, these fines are washed out and the overall filter grading becomes coarser. After about 2 months of water flow the filter stabilises, however at this point the D_{15} size has increased from 0.58mm to 1.8mm. Hence the filtration requirement $D_{15}<0.7$mm (or 0.74mm required by the Reduced PSD Method) is not met.

Foster and Fell (1999) carried out statistical analysis of filter tests to consider the effect of a filter which is coarser than the no-erosion boundary on which the abovementioned design criteria are set. They observed three categories of filter behaviour:

1) No erosion – the filter seals with practially no erosion of the core
2) Some erosion – the filter seals after 'some' erosion of the core
3) Continuing erosion – the filter is too coarse to allow the eroded core material to seal the filter, allow unrestricted erosion of the core.

Their analysis suggests that the filter size at the continuing erosion boundary has D_{15} about 2.5 times the no-erosion boundary. Based on the Reduced PSD Method, the continuing erosion boundary filter D_{15CE} can be estimated from:

$$D_{15CE} / d_{85\,Reduced} \leq 10$$

Based on the values obtained above, the ratio is

$$D_{15CE} \Big/ d_{85\,\mathrm{Reduced}} = \frac{1.8}{0.185} = 9.7$$

The filter is marginally finer than the continuing erosion boundary and the most likely behaviour is that significant erosion will occur before the filter finally seals.

PREDICTED PERFORMANCE OF FILTER TO RETAIN THE CORE MATERIAL

The analytical model developed by Locke et al. (2001) has been run to predict the performance of the core material adjacent to the filter (based on the 90% limit gradings shown in Figures 1 and 2). Seepage analysis described in the Design Report (Knight Piesold 2005) shows predicted seepage for the case of the tailings embankment with and without an upstream toe drain. The model was run under the highest hydraulic gradient conditions predicted by seepage analysis for the no upstream toe drain case.

Figure 5 shows the predicted loss of mass from the core material and change in flow rate through the system with time. At about 180 hrs (7.5 days) the rate of mass loss starts to accelerate which is typical of a filter which is not able to retain the core material. At the same time the flow rate starts to increase, which is a sign that fines are being washed out of the system and increasing the permeability of the soils, allowing more flow.

After about 300 hours (12.5 days) the base material has lost about 1.6g/cm^2 of material, this corresponds with an increase in porosity of the base soil of about 50% which is a significant loss of material. For comparison, researchers in laboratory tests have suggested that a failed core – filter combination has a mass loss of greater than 1.0 g/cm^2.

At this time (300 hours) the erosion rate and flow rate both decrease significantly. This is because many of the fines from the core have become clogged at the filter interface and formed a very low permeability zone, a process known as blinding. After about 600 hours (25 days) a sufficient number of the clogged particles have migrated into the filter and the permeability and erosion rate begin increasing again.

At about 1100 hours (45 days) erosion ceases and the flow rate stabilises. The prediction of the model is that a stable filter interface will eventually be established but the amount of core material eroded before this occurs is very high.

Figure 6 shows the changes in the particle size gradings of the core and filter during the establishment of a stable filter interface. As can be seen, the core material becomes significantly coarser as particles finer than about 0.2mm wash out and some particles in the 0.2mm to 1mm range wash into the filter and are captured. The filter material looses all particles finer than 0.2mm and at the same time captures the coarser core particles, resulting in the particle size gradings shown in Figure 6. The general trend shown in Figure 6 is a significant loss of fines in the base soil and the capture of sand size particles within the filter, this is typical of a partially successful filter.

The analysis described above is based on the 90% coarsest filter and 90% finest core material. This is a conservative assumption that is commonly adopted in filter design. By demonstrating the behaviour of these gradings of the core and filter, it is reasonably certain that all of the filter will perform similarly or better.

It is important to note that for this predicted erosion of the core and filter material to occur, seepage flow and a hydraulic gradient are necessary. If the hydraulic gradient is low, then the wash-out of fines from the filter cannot occur and no erosion of the core will occur. The analysis above was based on the assumption that the upstream toe drain is not present or not functional.

The tailings dam design has a carefully designed upstream toe drain which is expected to lower the phreatic surface in the tailings such that there is almost zero hydraulic pressure on the dam core. If this upstream drain is operational, then no seepage can occur across the core, and the filter becomes a secondary safety measure. The design of such non-critical filters is not required to adhere to strict filter design criteria. However, the long-term effectiveness of the upstream drain must be considered for the post-closure case.

CRACK FILLING POTENTIAL OF TAILINGS SAND

Upstream of the dam core (Zone S) is a zone of cycloned tailings sand. If a crack or void were to form through the dam core, it is possible that this material could wash through the crack and assist by sealing against the filter and filling the crack. There are two conditions required for this to be effective: the upstream sand must be non-cohesive so that it will be mobilised by seepage; and it should be coarse enough that it can be retained by the filter.

Samples of the cycloned sand tested during an earlier embankment raising in 1999 had approximately 25-30% fines (passing 0.075mm). The fines are expected to be silt particles with little or no plasticity. Despite the high fines content, the cycloned sand should be sufficiently non-cohesive that it could wash into the crack or void.

The cycloned sand has d_{85} between 0.25mm to 0.3mm. Based on the filter design criteria adopted earlier (US Dept. of Agriculture 1994), the necessary filter would have $D_{15} \leq 0.85$mm. The analysis shown above suggests that the filter could become coarser than this as the filter fines are washed out.

The actual crack-filling potential of sands placed upstream of dam cores has been debated in many publications. It is generally agreed that this is a secondary line of defence and should not be relied upon for safety of the dam. The presence of the tailings sand does provide some additional safety to the embankment, but it is not possible to quantify this benefit.

CONCLUSIONS

The core and filter materials of the Mt Polley Tailings Dam were assessed against current filter design criteria and new analytical models of filter performance to examine the potential for erosion of the glacial till core (Zone S).

The Zone F filter grading limits do not meet current filter design criteria because they are too broadly graded and allow too high a percentage of fines.

While the filter material meets the filtering requirement of $D_{15} < 0.7$mm, it has been shown that the broad grading of the filter samples means that some filter fines may wash out with seepage and the D_{15} size is predicted to increase to about 1.8mm.

Model predictions and published laboratory observations suggest that as the fines wash out of the filter and it becomes coarser, it will only be partially effective in retaining the core material. A stable filter interface is expected to eventually develop, but a considerable amount of core material can erode before this occurs. This core erosion could result in regions of high porosity or localised voids within the core material.

It is important to note that the design criteria and analytical models were developed for water retaining dams and assume that high seepage forces exist between the core and filter. The Mt Polley tailings dam is different to these structures because of the presence of tailings upstream of the core. The fine grained tailings reduce potential seepage and may flow into any cracks or voids in the core and reduce seepage. The embankment design also provides an upstream toe drain which will reduce seepage flows to negligible amounts and make the filter a secondary defence measure which may not require such stringent design criteria.

Some laboratory testing could be carried out on the core and filter materials to gain a better understanding of their performance, this may improve confidence in the Zone F filter. This testing should include:

- Direct testing of the core and filter material in a filtration test such as the No-Erosion filter test.
- 'Sand Castle' slump testing as described in ICOLD (1994) to confirm the filter is non-cohesive.

This review is not intended to condemn the existing dam structure and remedial action is not immediately required. It is noted that there are a large number of dams throughout the world that have filters that do not meet current design criteria or have no filters at all.

The review has shown that in the event of high hydraulic gradients occurring across the boundary between the clay core and filter, there is potential that erosion could occur, but this is unlikely to lead to failure of the structure due to the various secondary safety measures. The future design and construction of embankment raising and TSF closure should consider the potential for core erosion and provide mitigating measures, some features which could be provided are:

- maintaining low phreatic levels across the dam with the provision of an upstream toe drain which will remain functional after closure of the embankment. Design of this should ensure that the drain is sufficiently robust and has sufficient redundancy within the drainage system to remain operational in the post-closure case.
- Modifying the filter zone gradation in future dam raising stages in areas where significant hydraulic gradients may occur.
- Monitoring of phreatic levels within the embankment to ensure the hydraulic gradients remain low.
- Other design measures to ensure the hydraulic gradients remain low.

REFERENCES

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Enclosures:
V5-1185-Figures.xls (6 pages - Figure 1 to Figure 6)