Modified Centreline Construction of Tailings Embankments

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Abstract: A new approach to compacted fill embankments for tailings storage facilities has been developed which is seismically stable and minimizes the fill requirements, and hence costs, for embankment construction. Modified centreline construction is similar to conventional centreline construction but with the contact between the compacted fill and the tailings sloping slightly upstream. It is, however, different from upstream construction as the stability of the embankment relies on the relatively wide thickness of compacted fill at any elevation, is independent of the tailings strength and is inherently stable even with complete liquefaction of the tailings mass. The design approach significantly reduces the quantity of fill required for on-going raises compared to conventional centreline and downstream construction as on-going construction on the downstream face is not required. This also allows for reclamation of the downstream embankment face during operations. It has been successfully implemented at the Montana Tunnels Mine in Montana, where a final embankment height of over 100 metres is planned, and forms the basis for the tailings embankment design for new projects in Alaska and British Columbia, Canada. This paper describes the principal features of this construction technique, analytical procedures and case histories.

Key Words: mine tailings storage, embankment construction, waste reclamation, seismic stability

1. Introduction

The design of tailings facility embankments in seismically active areas, or for fine-grained, low strength tailings, has historically utilized conventional earth or rockfill embankments constructed as a full embankment section similar to a water retaining dam. No reliance is placed on the strength of the tailings and the embankment section is stable under all conditions of static and seismic loading. In some instances centreline construction using either the coarse fraction of the tailings or compacted fill is used to achieve the same design objectives.

Both of these approaches require a relatively large volume of fill material for the embankment section. With staged construction the volume of fill required for each incremental raise of the embankment crest gets larger as the height of the embankment increases, and requires construction on the downstream face of the embankment over the full height. This has the added disadvantage of not allowing reclamation of the downstream face to be carried out during mining operations. Staged construction of downstream and centreline embankments is shown schematically in Figure 1.

In most instances where these embankment cross-sections are required, upstream construction on the tailings mass itself would not be an appropriate alternative, either because of poor consolidation and/or drainage conditions within the tailings, potential liquefaction and low strength of the tailings. Upstream tailings embankments can only be constructed with fine grained tailings and in seismically active areas if proper measures are taken to ensure full consolidation and drainage of the tailings [1].

The modified centreline embankment, however, offers a cost effective alternative to downstream or centreline construction in areas of high seismic risk and for tailings with little or no strength. This paper describes the principal features of this construction technique, along with analytical procedures and case histories.

3rd International Conference on Environmental Issues and Waste Management in Energy and Mineral Production, August, 1994. Perth, Australia

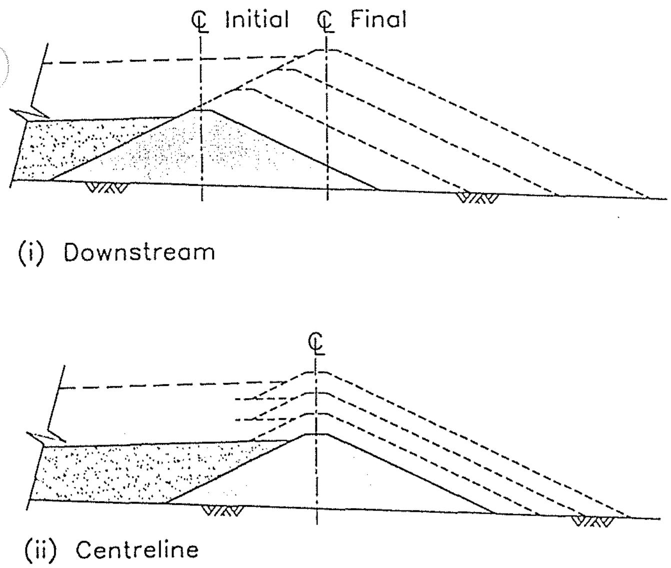


Figure 1 Downstream and centreline embankments

2. Design Concept

The modified centreline cross-section is similar to a centreline cross-section but with the contact between the embankment fill and the tailings sloping slightly upstream. It results in the minimum volume of embankment fill for an embankment that is stable under all conditions of static and seismic loading. Furthermore, on-going construction on the downstream face is not required and reclamation can be carried out during operations. A schematic cross-section through a modified centreline embankment is shown on Figure 2.

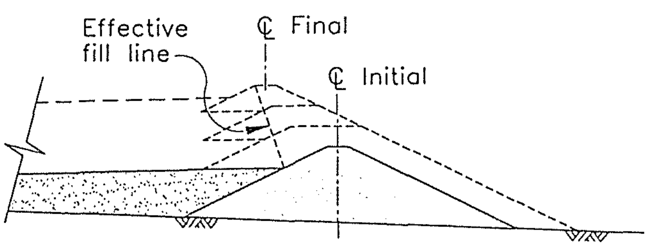


Figure 2 Modified centreline embankment

The modified centreline embankment achieves its stability from the relatively wide thickness of compacted fill at any elevation, and is independent of the strength of the tailings. The embankment is designed to be stable even if the tailings are fully liquefied and imposing both full fluid pressure and hydrodynamic loading on the upstream contact. The upstream contact remains stable even if the tailings are fully liquefied, when they would act as a dense fluid. The analogy is that of a slurry wall, where a dense fluid such as bentonite mud can be used to support very deep excavations.

The construction technique does require some placing of fill on the tailings beach, and hence deposition of at least a portion of the tailings stream from the embankment face is required. Ideally, the beach should be at least strong enough to support the first lift of fill. This can be achieved on very soft tailings with the assistance of a geotextile separation layer. If the beach cannot support the first lift, then the tailings can be displaced using dumped rockfill.

Modified centreline tailings embankments can be designed as either water retaining structures or fully drained embankments. When designed to be water retaining, which is obviously a more severe loading condition than if fully drained, the water retaining zone, or core, should be located as far upstream as possible, in order to provide the necessary width of drained granular material downstream of the core for stability.

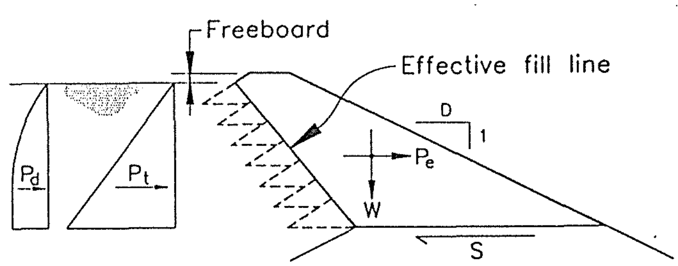
3. Stability and Deformation Analyses

Stability analyses of a modified centreline embankment can be considered under three separate headings:

(i) Downstream stability,
(ii) Upstream stability,
(iii) Deformation Analyses.

Downstream Stability

Downstream stability can be analyzed initially as pseudo-static loading on the modified centreline portion of embankment only, i.e. that portion of the embankment above the full section. The forces acting on this section of the embankment are shown schematically on Figure 3.



SUMMARY OF LOADING CONDITIONS	
SYMBOL	DESCRIPTION
P_t	LIQUEFIED TAILINGS
P_d	HYDRODYNAMIC THRUST
P_e	EARTHQUAKE LOADING ON EMBANKMENT
W	WEIGHT OF EMBANKMENT
S	SHEAR RESISTANCE

Figure 3 Downstream pseudo-static loading for stability analyses

In designing a modified centreline embankment the main variables to be considered in the geometry of the section are the height of the modified centreline portion, the downstream slope and the upstream contact slope between the fill and tailings.

The downstream slope will generally be dictated by the construction materials available, but the height of the modified centreline portion and the upstream contact slope will be a function of the seismicity of the site. The height of the modified centreline portion can be considered in terms of Critical Height (H_c), which is defined as that height at which the pseudo-static factor of safety is equal to 1.0 under a given acceleration. The relationships between H_c, acceleration and the upstream contact slope are shown on Figure 4, for a given set of assumptions and the loading conditions shown on Figure 3.

The concepts presented in Figure 4 can be used for an initial determination of H_c. However, it is important to realize that this critical height is not a limiting height and only defines the height at which the critical acceleration for the embankment section k_c, is equal to the design acceleration for the site, a_{max}. Higher embankments, with a value of k_c less than a_{max}, can be safely designed but will be subject to some deformation during the earthquake shaking.

The modified centreline embankment must also incorporate suitable provisions for seepage control and for piping prevention. Since the embankment fill extends slightly over more compressible tailings materials, consolidation settlement may result in cracking of the embankment core zone. Therefore, the embankment design must incorporate suitable filter criteria and drainage provisions. In general, the tailings mass forms an ideal crack stopping filter medium so that piping failure is not a major consideration. Embankment stability can also be enhanced by incorporating drainage features such as chimney drains to reduce pore pressures within the structural zone of the embankment.

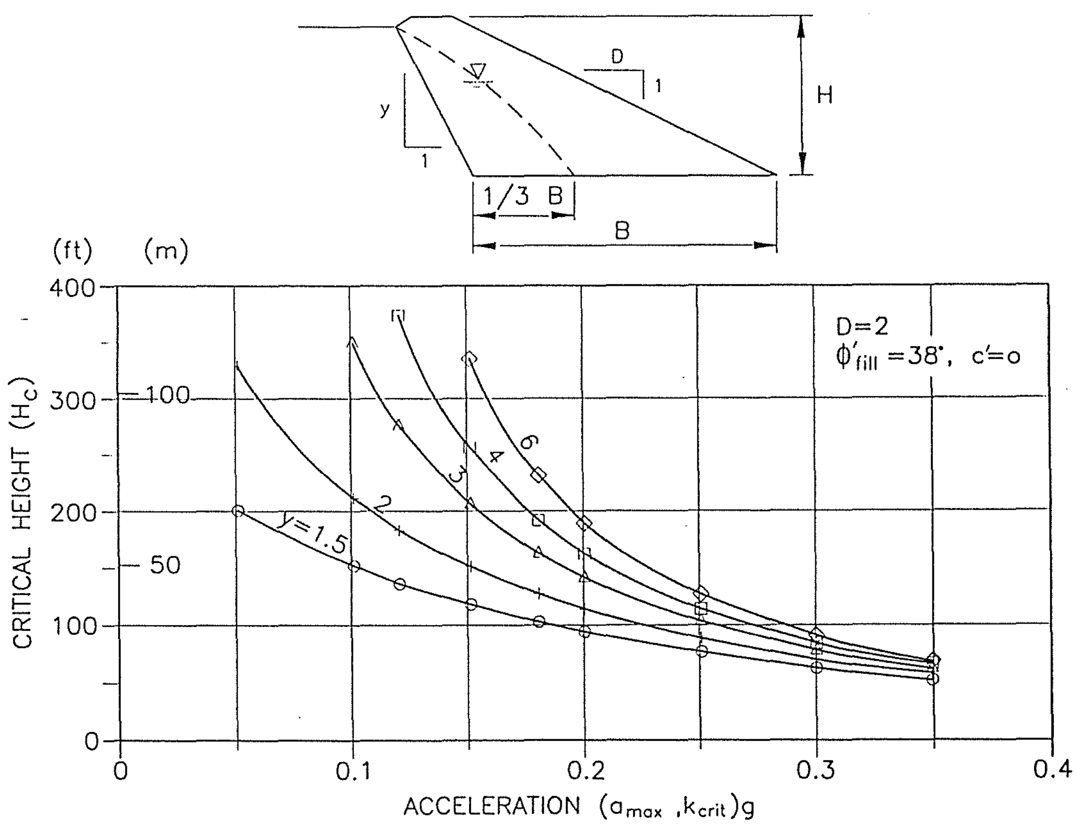
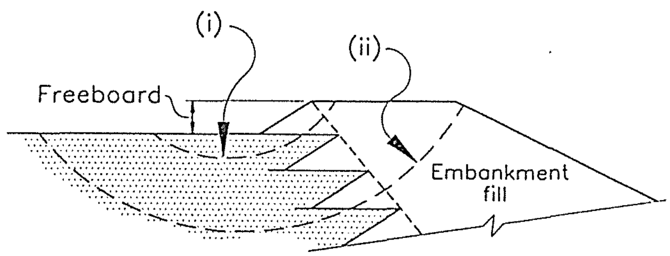


Figure 4 Relationship between critical height and acceleration

Upstream Stability

Upstream stability needs to consider two critical loading conditions: short-term loading on the tailings beach during embankment crest raising; and post-seismic upstream stability when the tailings would have only post liquefaction residual strength. In the first case, the principal concern is safety, whereas for the second case the principal concern is for failures causing loss of freeboard. Both cases need to be analyzed to determine the maximum allowable freeboard, which can then be related to flood storage requirements (Figure 5). In both analyses the appropriate strength characteristics of the tailings need to be known, in addition to those of the embankment fill materials.



(i) Short term construction.
Tailings strength, $c_u/p' \simeq 0.2 - 0.3$

(ii) Post earthquake loss of freeboard.
Tailings residual strength, $c_u/p' \simeq 0.1 - 0.2$

Figure 5 Upstream stability loading cases to determine maximum freeboard

Deformation Analyses

Deformation analyses can be carried out using the simplified procedures of Newmark [2] and Makdisi and Seed[3]. The analyses compare the critical acceleration k_c, with the site design acceleration, a_{max}, and compute displacements using empirical relationships and case history data from conventional water retaining dams. Modification of the amplitude of the ground acceleration as it propagates up through the embankment can be determined using the SHAKE [4] program. Similarly, the value of k_c at any elevation in the embankment can be determined from standard stability analysis programs. In order to compensate for the geometry of the modified centreline embankment and uncertainties in the mode of deformation, the largest value of acceleration determined from SHAKE can be used together with the smallest value of k_c to compute potential deformations.

A pseudo-dynamic finite element displacement analysis has been developed by Byrne *et al* [5,6]. This analysis can be used to determine deformations under both upstream and downstream earthquake loading, and to define the location and magnitude of the largest deformations. In general it predicts deformations somewhat larger than those from the simplified Newmark analyses using the extreme values.

The stability analyses discussed above have only considered the more extreme loading conditions. In all embankment designs, all loading cases must be analyzed using relevant material parameters to ensure that acceptable factors of safety exist for each loading case.

4. Case Histories

Montana Tunnels Mine, Montana, USA.

The Montana Tunnels Mine is an open pit operation which involves processing gold, lead, zinc and silver ore at a rate of approximately 13,700 tonnes per day. The mine has been operating since 1987. Total mineable reserves from inception of mining have recently been expanded from 38 to 62 million tonnes.

The original tailings embankment was designed using a downstream method of construction for the annual staged expansions[7]. The compacted rockfill embankment layout was modified in 1990, when on-going expansions were constructed using the modified centreline method in order to minimize fill quantities and preserve a downstream process water pond[8]. The modified centreline section was changed again in 1993 to enable expansion of the tailings impoundment to provide storage for the increased ore reserves. The embankment is presently designed to reach a maximum ultimate height of 105 metres. A schematic cross-section through the embankment is shown on Figure 6.

The redesign of the modified centreline embankment in 1993 included an extensive site investigation program which incorporated drilling, sampling, standard penetration testing, seismic piezocone testwork and installation of vibrating wire piezometers. A line of wick drains was installed along the tailings beach to enhance drainage into the free-draining embankment. A second wick drain program[9] was also completed within the tailings impoundment to dissipate excess pore pressures, accelerate consolidation and enhance seismic stability.

The stability assessment for the embankment included conventional limit equilibrium analyses for static, pseudo-static and post-earthquake conditions. Additional pseudo-dynamic finite element analyses, using the procedure described by Byrne *et al*[5], were also used to evaluate potential embankment deformations for a maximum credible earthquake with a peak horizontal ground acceleration of 0.22 g. The analysis includes both the inertia forces from the earthquake as well as the softening effect of the soil during cyclic loading. The fifth modified centreline embankment raise will be completed at the Montana Tunnels Mine during 1994, with annual expansions planned through 2001.

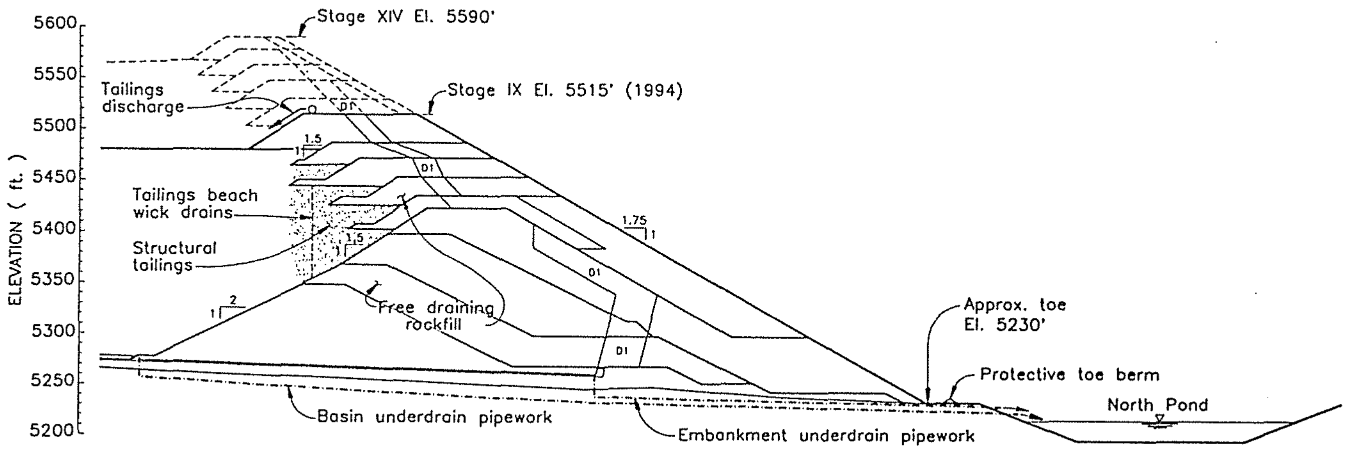


Figure 6 Typical section through Montana Tunnels embankment

Kensington Venture, Alaska, USA

The Kensington Project is a proposed underground gold mine located 40 miles north of Juneau, Alaska, on the east side of the Lynn Canal. The mine will require construction of a 89 metre high dam to contain the tailings from the mining operations. The dam is to be constructed in stages using compacted earthfill and rockfill and a modified centreline arrangement. The project is located in an area of high potential seismicity and earthquake-induced liquefaction of the tailings is possible. The stability of the top portion of the dam and the potential displacements resulting from earthquake loading are therefore of extreme importance. A cross-section through the proposed final embankment is shown on Figure 7.

Conventional limit equilibrium and Newmark analyses, including hydrodynamic loading from the liquefied tailings, indicate that the embankment is stable and deformations would be very small. Deformation analyses were also carried out using the pseudo-dynamic finite element procedure developed by Byrne *et al* [5]. The analysis allows both the inertia forces from the earthquake as well as the softening effect of the liquefied soil to be considered.

Peak horizontal ground accelerations ranging from 0.2 g to 0.6 g were considered with corresponding peak ground velocities of 0.2 and 0.6 metre/second. The predicted peak displacements of the crest of the dam are 0.48 metre horizontal and 0.09 metre vertical. The maximum movement of the dam predicted from the Newmark analysis using the same soil strengths was 0.14 metres.

The Kensington Venture is currently in the final stages of permitting.

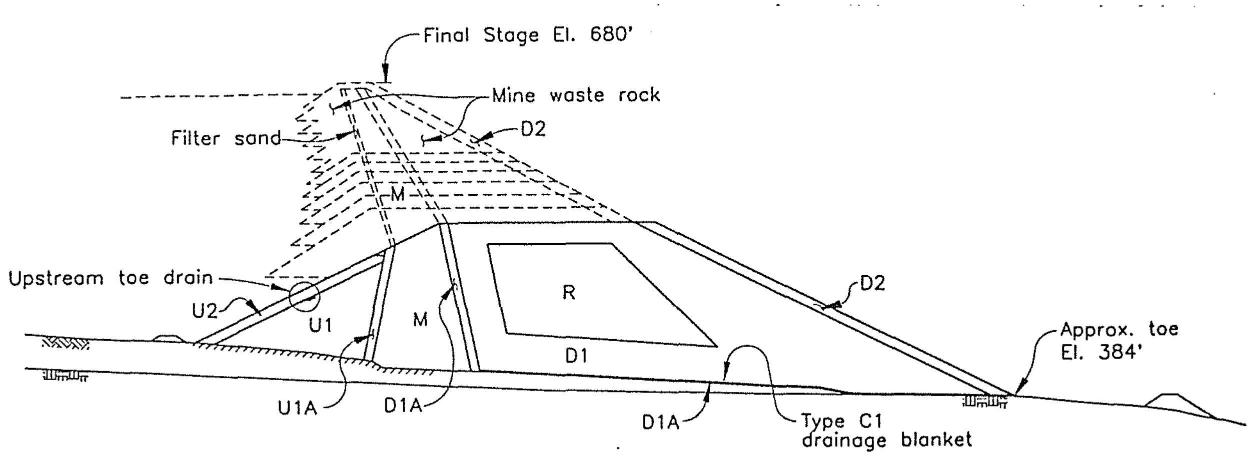


Figure 7 Typical section through Kensington embankment

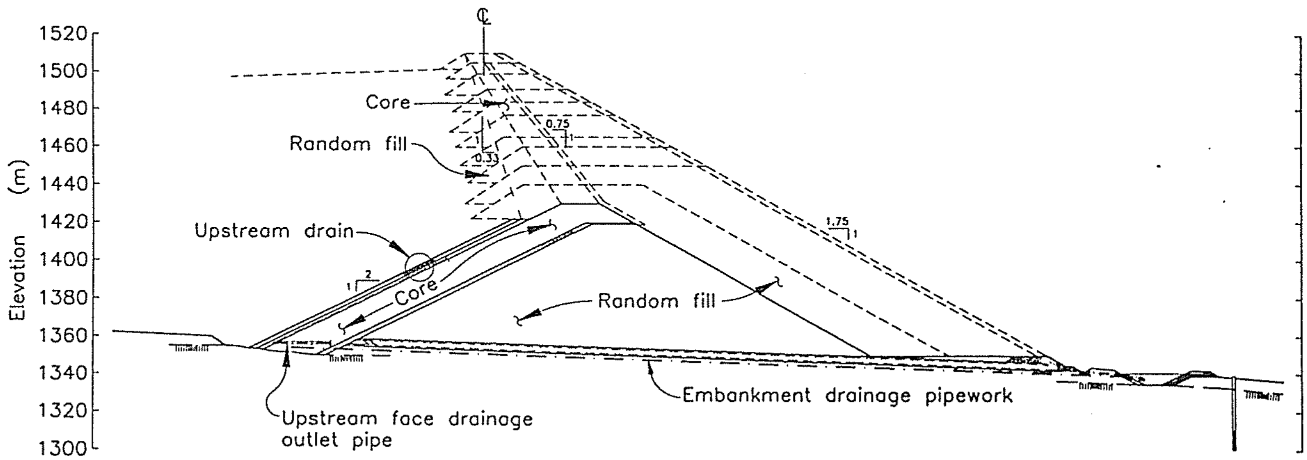


Figure 8 Typical section through Kemess South embankment

Kemess South Project, B.C., Canada

The Kemess South Project, situated in north central British Columbia, is presently in the final stages of permitting and is scheduled for development in 1995. A total reserve of 220 million tonnes of gold and copper ore will be processed at a rate of 40,000 tonnes per day. The project will include the staged construction of a compacted earthfill tailings embankment using the modified centreline technique to an ultimate height of 150 metres. A schematic embankment section is shown on Figure 8.

The project site is situated in an area of low seismicity and conventional pseudo-static limit equilibrium analyses indicate an adequate factor of safety against embankment deformation. The modified centreline embankment section was selected in order to minimize the quantity of fill required for staged expansions, and thus reduce on-going capital expenditures. Also, the downstream face of the embankment will be incrementally revegetated to minimize environmental impacts during operations and to reduce post-closure reclamation requirements.

5. Conclusions

The modified centreline embankment provides the least cost compacted fill embankment for tailings storage facilities in areas of high seismicity and for low strength tailings. These embankments are intrinsically stable under earthquake loading even with the tailings fully liquified. They can be constructed in stages using standard mining equipment and overburden materials from on-going mining operations. After the initial one or two stages no further construction is required on the downstream face, which allows for on-going reclamation during operations.

The modified centreline design has been successfully implemented at the Montana Tunnels Mine in Montana, where a final embankment height of over 100 metres is planned. A detailed design has been developed for the Kensington Venture in Alaska and is in the final stages of the review process. Designs for new projects in B.C. and elsewhere in North America are currently at the development stage.

References

1. Haile, J.P. and Kerr, T.F., 1989. "Design and Operation of the Myra Falls Tailings Disposal Facility." Vancouver Geotechnical Society's 4th Annual Symposium on Geotechnical Aspects of Tailings Disposal and Acid Mine Drainage. May 26, 1989, Vancouver, B.C.

2. Newmark, N.M., 1965. "Effects of Earthquakes on Dams and Embankments." Geotechnique 15: 139-160.

3. Makdisi, F.I. and Seed, H.B., 1977. "A Simplified Procedure for Estimating Earthquake Induced Deformations in Dams and Embankments." Report No. UCB-EERC-77/19, College of Engineering, University of California, Berkeley.

4. Schnabel, P.B., Lysmer, J. and Seed, H.B., 1972. "SHAKE - A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites." Report No. EERC 72-12, University of California, Berkeley, California.

5. Byrne, P.M., Jitno, H, Haile, J, 1992. "A Procedure for Predicting the Seismic Response of Tailings Impoundments." First Canadian Symposium on Geotechnique and Natural Hazards. May 6-9, 1992, Vancouver, B.C.

6. Byrne, P.M, Jitno, H., Anderson, D.L, Haile, J., 1994. "A Procedure for Predicting Seismic Displacements of Earth Dams." Report No. XIII CSMFE, 1994, New Delhi, India/XIII CIMSTF, 1994, New Delhi.

7. Haile, J.P. and Brouwer, K.J., 1987. Design and Construction of the Montana Tunnels Tailings Disposal Facility: 89th Annual General Meeting of the Canadian Institute of Mining. May 3-7/87, Toronto, Ontario.

8. Brouwer, K.J., Weitz, T.J. and Haile, J.P., 1992. "Design and Operation of the Montana Tunnels Tailings Disposal Facility." Second International Conference on Environmental Issues & Management of Waste in Energy & Mineral Production. September 1 - 4, 1992, Calgary, Alberta.

9. Brouwer, K.J., Brown, B.S. and Stewart, D, 1994. "Tailings Consolidation Using Wick Drains." 3rd International Conference on Environmental Issues and Waste Management in Energy and Mineral Production, 1994. Perth, Australia.