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Effect of Tailings Liquefaction on Upstream Construction (Case Study)

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Summary The prevention of acid drainage from mine tailings storages is a major consideration for mining operations on the west coast of Tasmania. Current best practice is for "sub-aqueous" storage in conventional dams. Increasing the capacity of these dams by "downstream construction" can be extremely costly and have a significant effect on mine viability. The method of "upstream construction," where the dam crest is raised by constructing over the tailings, can result in significant cost savings. However the risk of seismic induced liquefaction of the tailings must be considered in planning for this method of construction, particularly when the risk of liquefaction is increased by maintaining a high phreatic surface within the dam to keep tailings saturated. This paper presents the results of an investigation into the effect of tailings liquefaction on the stability of the C Dam tailings dam at the Renison Tin Mine. It is planned to raise the crest of C Dam by a total of 12.0 metres in a series of 2 metre lifts using upstream construction for the remainder of mine life but it is critical to maintain a pond over the tailings to prevent oxidation. Tasmania is not normally regarded as a high earthquake risk area but analysis showed that significant accelerations are possible and significant design changes were found necessary to allow upstream construction to proceed at this project.

1. INTRODUCTION

This paper presents the results of an investigation into the effect of tailings liquefaction on the stability of C Dam, a tailings dam at the Renison Mine on the west coast of Tasmania.

Tailings from the Renison Mine operations have been stored in a series of three dams known as A, B and C Dam as shown on Figure 1. C Dam is the current active dam with A and B dams at design capacity. Due to the sulphide content of the

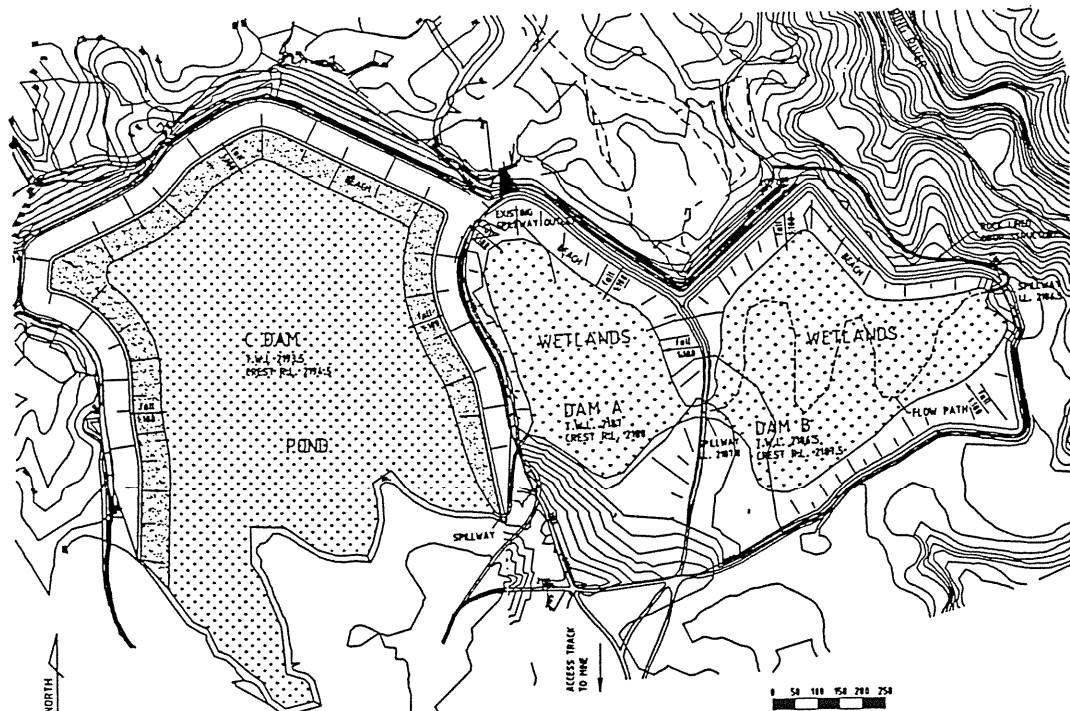


Figure 1. Site plan.

tailings it is necessary to maintain water cover over the tailings surface to prevent oxidation and generation of acid drainage. The planning for closure of the dam system allows for a pond over C-Dam spilling water into wetlands established over A and B Dams.

C Dam has been raised in several stages since 1978 using downstream construction to a height of approximately 30m. In 1986 the cost to raise the dam crest by a further 2m using the conventional method of downstream construction was estimated at \$1.2M. A new dam site was also investigated and costs for construction were estimated at \$2.4M. Due to the economic environment that existed at the time the cost of either of the two proposals would have had a significant effect on the viability of the mine.

In 1991 the possibility of upstream construction was reviewed. This form of construction was noted to provide significant cost savings over conventional downstream construction but has been associated with dam failures as a result of seismic induced liquefaction of the tailings.

The tailings gradings lie in the range known to be prone to liquefaction as shown on Figure 2. However, at the time of initial assessment, the tailings were thought to be relatively dense and earthquake accelerations in Tasmania believed to be only modest.

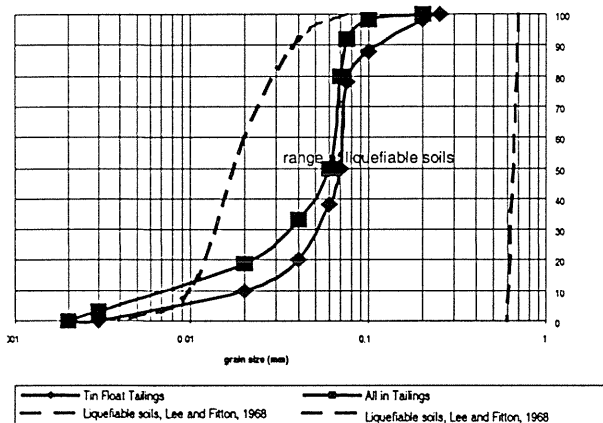


Figure 2. Tailings grading.

Preliminary laboratory testing of the Renison tailings was undertaken to determine gradings and densities. Laboratory simulation of sub-aerial tailings deposition was conducted to establish typical in-situ density. The preliminary results indicated that tailings deposited under sub-aerial conditions would be relative dense. Consolidated Undrained Trial Tests were also conducted to establish shear strength parameters. Results are shown in Table 1.

Table 1. Results of simulated tailings discharge.

Wet Density	2000 kg/m ³
Dry Density	1655 kg/m ³
Maximum Dry Density	1840 kg/m ³
Minimum Dry Density	1300 kg/m ³
Relative Density	73%
Shear Strength Parameters	
Cohesion	0 kPa
Friction Angle	36 degrees

Preliminary investigations of seismic activity at the Renison site (Baynes, 1991) used Probabilistic earthquake risk maps to establish the Operating Basis Earthquake (OBE) and a Deterministic/Probabilistic approach to determine the Maximum Design Earthquake (MDE). Return periods were set at 1:500 for the OBE and 1:10,000 for the MDE to take account of the significant economic and environmental costs which would result in the event of a failure. It was concluded that the Renison site was only a low to moderate risk area. However, it was recognised that further work should be carried out if the indicated ground accelerations of 0.05g OBE and 0.15 to 0.25g MDE were likely to cause instability.

Following the favourable results of the preliminary investigations, the water level within C Dam was maintained at a minimum to allow exposed beaches to develop to form a stable foundation for upstream construction.

A trial embankment was constructed in January 1994 over a section of the exposed tailings beach to ensure that construction was practical, prior to a large scale commitment to upstream construction. Construction of the trial embankment was successful and since 1994 the crest of C Dam has been raised a total of 4m by upstream construction in two 2m stages. Each stage lift has cost less than \$0.3M.

A program of Standard Penetration Tests (SPT) was conducted on the in-situ tailings following the completion of the first staged lift to confirm laboratory test results. The SPT results indicated higher densities in the tailings deposited sub-aerially compared to those deposited sub-aqueously. However, the results also indicated generally lower Relative Density than had been indicated by laboratory simulation. This prompted further investigations to be undertaken to determine the characteristics of the deposited tailings and to assess the effects of seismic induced liquefaction on the overall stability of the upstream dam wall of C Dam.

2. SEISMIC INDUCED LIQUEFACTION

It is well documented that cyclic loading from seismic events can produce densification of granular soils by particle rearrangement due to the back and forth straining. If the soil subjected to cyclic loading is saturated and not allowed to drain, the tendency to decrease volume is counteracted by an increase in pore pressure and decrease in effective stress and strength. Under continuing cyclic loading pore pressures can build up to a point where they equal the total stress. At this point the effective stress equals zero and a condition of "liquefaction" occurs. The number of cycles to reach the zero effective stress condition depends on the Relative Density of the granular material and the magnitude of the cyclic stress. For any given magnitude of Cyclic stress the number of cycles required to induce liquefaction increases with increases in Relative Density. Under seismic activity the number of cycles of loading is dependent on the magnitude of the earthquake. Generally it can be assumed that earthquakes of Magnitude 5.0 or less will not normally induce liquefaction in tailings due to the short duration of cyclic loading.

3. FURTHER INVESTIGATIONS

In order to better quantify the risk of tailings liquefaction at the Renison mine site investigations were undertaken to:

- Review the initial earthquake parameters
- Investigate the in-situ density of the stored tailings using Electric Cone Penetration Test equipment (CPT)
- Determine the potential extent of liquefaction
- Analyse the post liquefaction behaviour of the upstream construction to determine the potential extent of tailings release in any failure.

4. SEISMICITY ASSESSMENT

A detailed analysis of potential earthquake parameters for the Renison site (Seismology Research Centre, 1996) used data collected by the University of Tasmania and attenuation functions derived for similar sites. The relationship between Peak Ground Acceleration and Annual Exceedence Probability (AEP) for the site is shown in Figure 3.

The Operating Basis Earthquake (OBE) proposed by the SRC had a Modified Mercalli Intensity of 5.6 and the Maximum Design Earthquake (MDE) an intensity of 7.6. These are quite high by Australian standards. Earthquakes with magnitude greater than 5.0 are of sufficient duration to induce liquefaction depending on field densities.

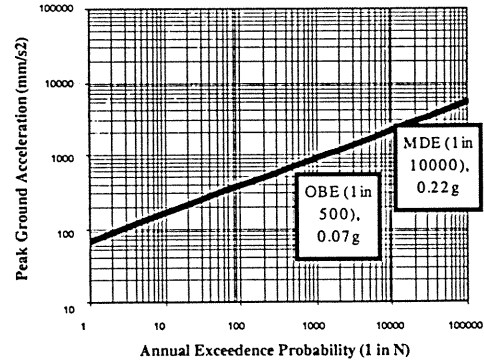


Figure 3. Peak ground acceleration.

5. FIELD DENSITY TESTING

Static Penetration Tests (SPT) undertaken in the tailings beneath the first upstream dam lift indicated Relative Densities of between 10% and 40%, considerably lower than the Relative Density of 73% estimated from laboratory testing. Typical SPT values ranged from 5 to 10 in the top 4m of tailings to 0 to 9, with an average of 3, for tailings below 4m. A distinct layering was noted from the data with very soft bands being sandwiched between somewhat stiffer bands at roughly metre intervals. This layering appeared to correspond with levels at which tailings had been discharged either sub-aerially (higher density) or sub-aqueously (lower density).

Due to the significant differences in the Relative Density of tailings obtained from laboratory and Static Penetration Tests, additional in-situ testing using an Electric Cone Penetrometer (CPT) was undertaken in the summer of 1995 to validate the field tests results. CPT results indicated relative densities of between 10% and 40%, which correlated well with those obtained by Static Penetration Testing.

Testing was also undertaken on B Dam, to determine if there was any increase in density due to consolidation. The results indicated that there had been no substantial increase in Relative Density with time or depth over the period since filling (approximately 10 years).

6. ASSESSMENT OF LIQUEFACTION POTENTIAL

There are various methods available to assess the potential for liquefaction using data collected from Static Penetration and Cone Penetration tests and seismic evaluation. An evaluation was undertaken during late 1996 using the following three empirical methods.

The first method, developed by Seed, (Schwertmann, 1988) is a semi-empirical method and relates:

- maximum acceleration induced by an earthquake
- the SPT “N” value (corrected for the SPT Hammer energy and for overburden pressure)
- earthquake magnitude (M) and
- fines content of the soil (% passing 75µm).

The method is based on recorded cases of liquefaction during earthquakes in USA, Japan and China. Analysis using this method showed there would be substantial liquefaction of tailings under an earthquake magnitude between the OBE and the MDE.

A second method, developed by Robertson, (Schwertmann, 1988) uses a modified cone bearing obtained from Cone Penetration Testing and relates it directly to lower bound values of the cyclic stress ratio. Analysis using this method also showed there would be substantial liquefaction of tailings under an earthquake magnitude between the OBE and the MDE. Using this method, the required value of cone bearing at corresponding depths to resist liquefaction by earthquake-induced acceleration of 0.15g was plotted on the CPT data as shown on Figure 4. Tailings with cone bearing pressures to the left of the line drawn are predicted to liquefy and to the right of the line would not. It should be noted that a minimum Cyclic Stress Ratio of 0.1 has been adopted.

A third method for identifying liquefiable soils, proposed by Douglas, (Schwertmann, 1988) uses a classification chart developed for sand and silts and recordings of cone bearing and friction ratio (cone bearing/sleeve friction) from Cone Penetration Testing. Charting of the CPT data showed that the tailings were generally susceptible to liquefaction.

7. POST LIQUEFACTION BEHAVIOUR OF UPSTREAM CONSTRUCTION

Once analysis had determined that the Renison tailings were at risk of liquefaction, it was necessary to reassess the post liquefaction stability of the upstream construction. This needed to consider the potential extent of liquefaction, the post liquefaction strength and the extent of deformation and potential tailings release if liquefaction was to occur. Deformation of the upstream construction at current crest level and at close out following liquefaction was assessed using the computer program FLAC (Khalili, 1997). FLAC is a general purpose explicit finite difference code, capable of simulating structures built of soil, rock or any other material that may undergo elastic or plastic deformations. The material properties adopted for the analysis are shown in Table 2. The static strength properties of the embankment materials were derived from laboratory testing previously undertaken. The static strength properties for the tailings were derived from

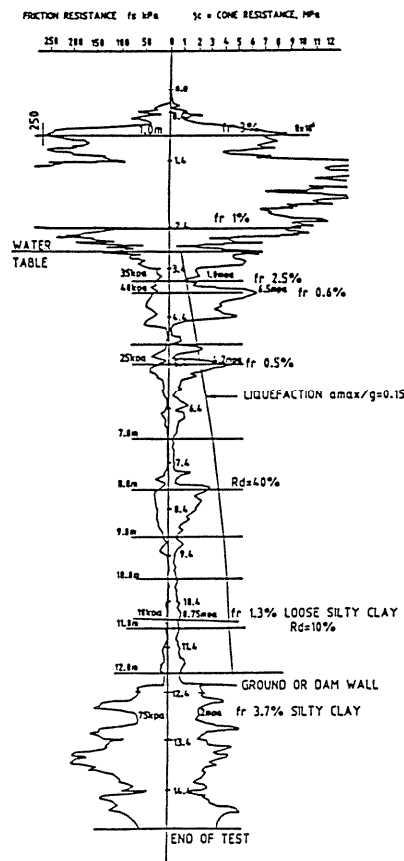


Figure 4. Typical CPT plot v's liquefaction potential.

the SPT data and established empirical relationships. The post liquefaction residual strength parameters were derived from SPT data and the relationship proposed by Stark and Mesri (1992):

$$\frac{S_{ur}}{\sigma'_{vo}} = 0.0055(N_1)_{60-cs}$$

in which

- S_{ur} = Residual undrained strength
- σ'_{vo} = Effective overburden pressure
- $(N_1)_{60-cs}$ = SPT “N” value, corrected for σ'_{vo} , input energy and fines content.

Typical input data for FLAC showing the original proposed cross section at close out is shown as Figure 5.

Liquefaction only develops in saturated tailings so the location of the phreatic surface is critical to the analysis. The level of the phreatic surface is set by the level of surface water in the dam and ultimately determines the extent of tailings beaches exposed to the atmosphere. The FLAC analysis determined that with a low ponded water level within the dam the structure underwent minimal deformation with no

Table 2. Material properties used in FLAC analysis.

Zone	Modulus (MPa)	Poissons Ratio	Unit Weight (kN/m ³)	Cohesion (kPa)	Friction Angle (degrees)
Embankment					
Compacted Weathered Argillite	23	0.35	20	15	32
Compacted Gravelly Argillite	23	0.35	20	15	28
Weathered					
Filter					
Coarse "Floats"	18	0.3	20	0	35
Upstream Construction Bund					
Compacted Weathered Argillite	23	0.35	20	15	28
Tailings					
Upper 2.5m					
Static	15	0.35	15	0	30
Post liquefaction	15	0.49	15	0	6
Below 2.5m					
Static	10	0.35	14	0	23
Post liquefaction	10	0.49	14	0	4
Foundation	2000	0.2	21	1000	45

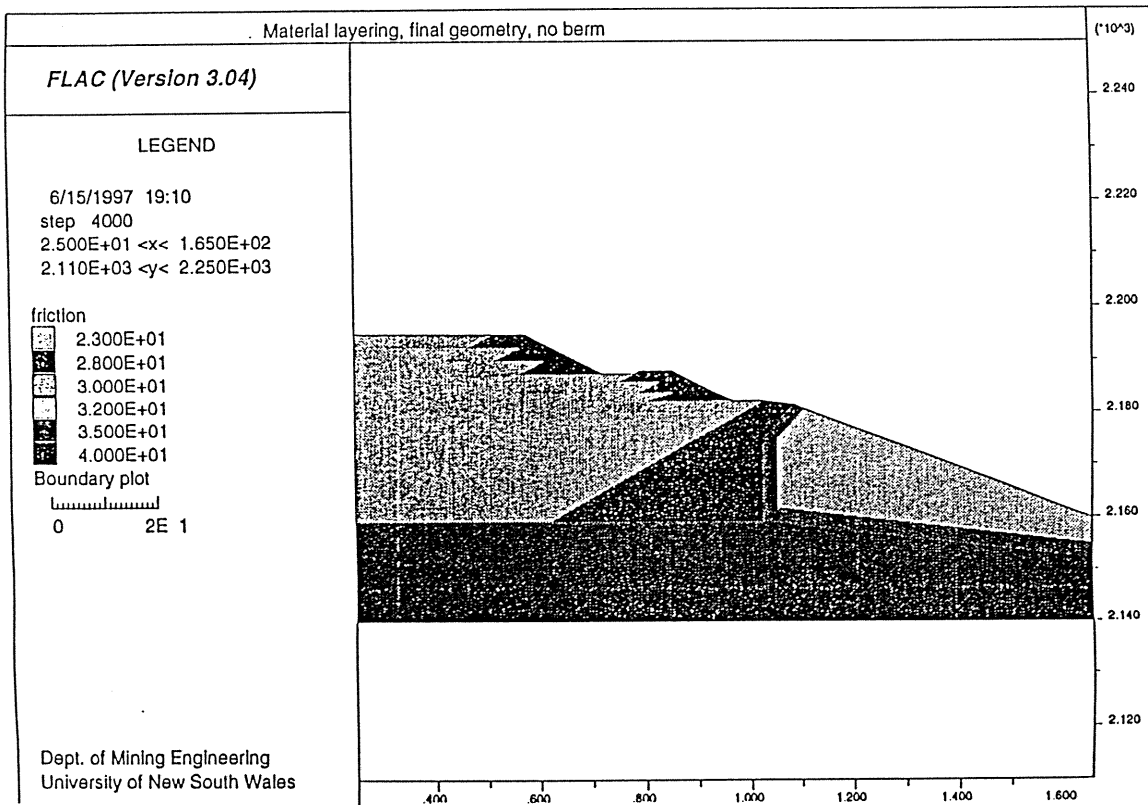


Figure 5. Typical cross section original design geometry.

release of tailings. However, with a high pond level the upstream construction underwent significant deformation, as shown in Figure 6, corresponding to bunds sinking into the tailings and resulted in a potential major release of tailings.

This outcome signified the need to maintain as low as possible water level in the dam to ensure the phreatic surface does not saturate tailings forming the foundation of the upstream construction. This needs to be balanced by the environmental

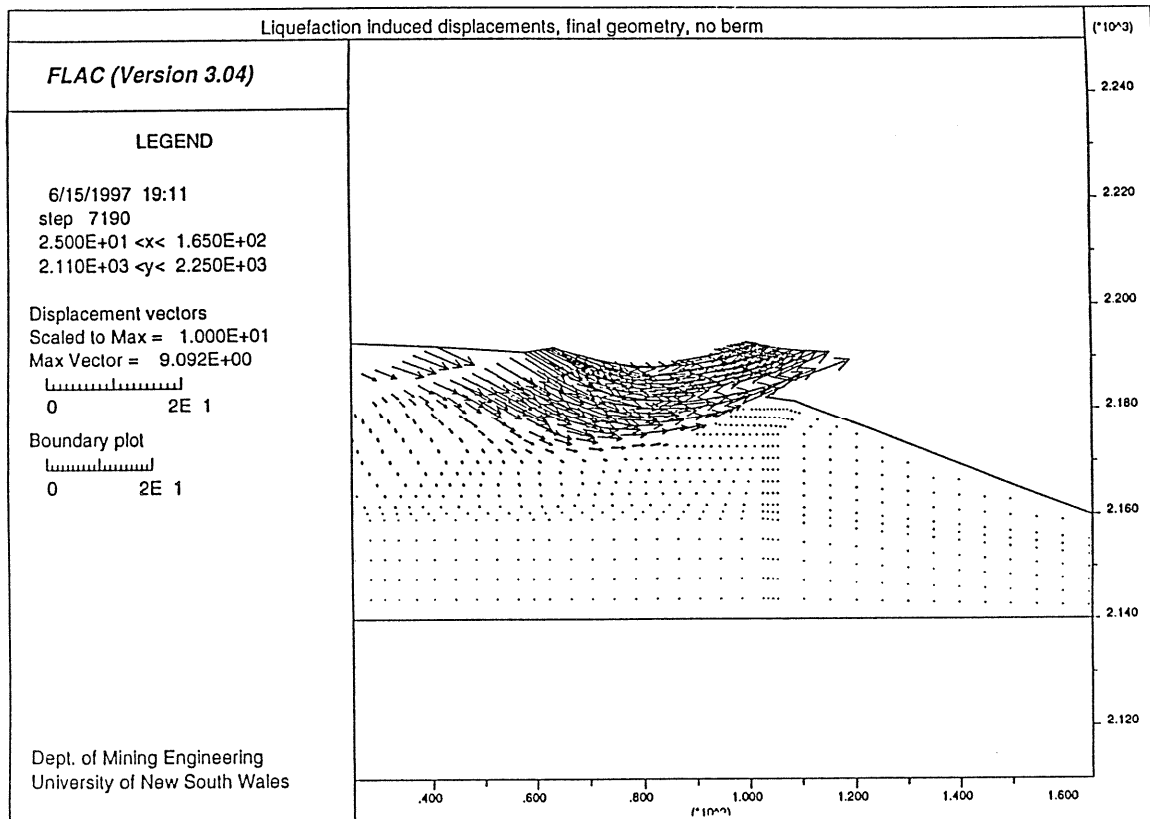


Figure 6. FLAC output for original geometry.

requirement to limit the width of beaches to prevent oxidation of the tailings.

Static analysis of the upstream construction was then carried out at varying batter slopes using post liquefaction undrained shear strength parameters, to determine a stable configuration for the final dam crest level. The analysis showed that by constructing the upstream bund with an overall batter slope of 4

Horizontal to 1 Vertical the configuration remained stable under post liquefaction conditions. FLAC analysis confirmed that even given liquefaction developing for this case deformation was limited and no release of tailings would be expected.

A cross section of the resulting design is presented in Figure 7.

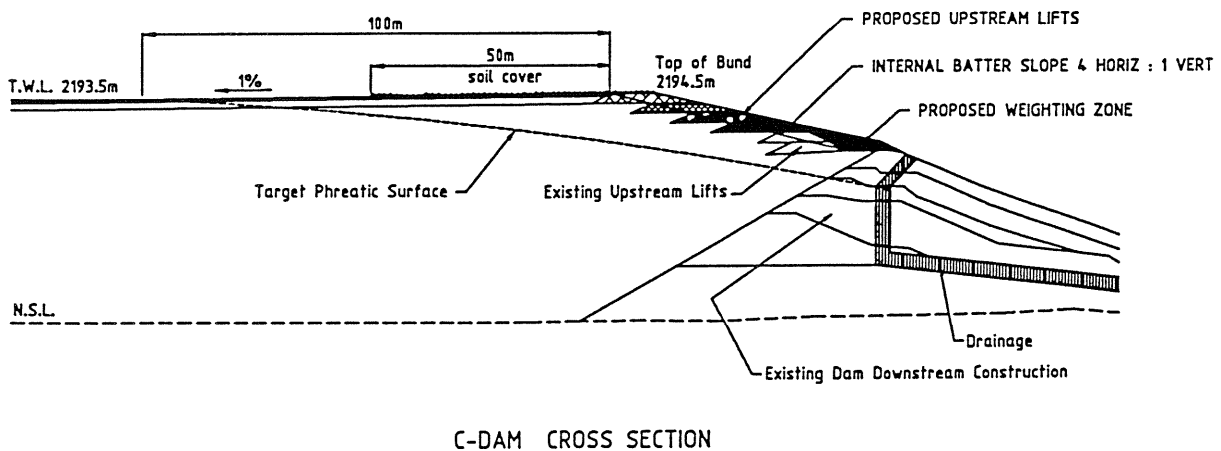


Figure 7. Typical final design cross section.

8. CONCLUSIONS

The following conclusions can be drawn from field data, assessment of the potential seismic risk and detailed analysis for the C Dam at Renison.

- The grading of the tailings lie within the boundaries of material susceptible to liquefaction
- The relative density of the tailings is low and does not increase with depth
- The highest relative densities are found within the top 2 to 3 metres of the tailings and appear to be as a result of recent sub-aerial deposition
- Field data is inconclusive with regard to cementation or chemical bonding of tailings with age
- Earthquakes of magnitude equal to or less than the 1 in 500 year return period (Operating Basis Earthquake) will not induce liquefaction
- Detailed analysis of Static Penetration Test and Cone Penetration Test data indicates that the tailings will liquefy under seismic loadings between the Operating Basis and Maximum Design Earthquake.
- Upstream construction with batter slopes of 4 horizontal to 1 vertical is stable under the Maximum Design Earthquake provided a 50 metre wide tailings beach is maintained at all times.

These conclusions show that it is possible to design tailings dams using upstream construction on the west coast of Tasmania. However, care in evaluation of liquefaction potential and detailed geometrical design is essential.

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