TULLAROOP DAM: EMBANKMENT CRACKING AND RISK BASED ASSESSMENT OF REMEDIAL WORKS

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\textbf{ABSTRACT}

The main embankment at Tullaroop Reservoir is a 42m high zoned earth and rockfill dam that was constructed in the late 1950s. The constructed embankment has a very broad, well compacted clay earthfill zone with dumped rockfill on the mid to lower upstream and downstream shoulders.

Over a two week period in April 2004 a diagonal crack of 60mm width and greater than 2m depth developed on the downstream shoulder of the main embankment. The crack was located on the left abutment and extended from the crest to the toe of the embankment. The diagonal crack terminated at the downstream edge of the crest. A continuous longitudinal crack extended along the downstream edge of the crest from the diagonal crack almost to the left abutment. Since April 2004 no further widening of the diagonal crack has been observed.

This paper presents the findings of a series of site investigations and analysis to understand the mechanism for formation of the diagonal crack, and the risk assessment process that culminated in the eventual construction of a full height filter buttress on the left abutment of the main embankment. Factors that influenced the cracking included the change in slope in the foundation profile, the temporary diversion channel on the left abutment, residual stresses in the dam abutment due to differential settlement during construction, a complex foundation geology and presence of shear surfaces in a Tertiary alluvial sequence that formed due to valley formation, an historic dry period and a prolonged period of drawdown. The presence of the crack and its assessed mechanism of formation presented a dam safety risk of piping through the embankment. The risk evaluation process was worked through with URS, Goulburn-Murray Water (G-MW), and G-MW’s expert panel, and eventuated in construction of the localised filter buttress in February – March 2006 to address the dam safety deficiency.

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1 INTRODUCTION

Tullaroop Reservoir is a 74,500 ML storage located on Tullaroop Creek in central Victoria. It supplies town water to Maryborough and irrigation water to the local district. The dam and appurtenant works were constructed in the late 1950s. The main embankment is a zoned earth and rockfill embankment of 42m maximum height and 427m length (Figures 1 and 2).

Over a two week period in April 2004 a diagonal crack of 60mm width and greater than 2m depth developed on the downstream shoulder of the main embankment over the left abutment. The crack extended from the crest to the toe, terminating at the downstream edge of the crest, but did not extend across the crest. A continuous longitudinal crack extended along the downstream edge of the crest from the diagonal crack almost to the left abutment. Since April 2004 no further widening of the diagonal crack has been observed.

The diagonal crack formation is unusual for this type of broad earthfill embankment. In particular, the diagonal nature of the crack itself, its time of observation after construction (some 55 years), its formation over a period of several weeks in April 2004 without further movement thereafter. The authors are not aware of a reported similar cracking observation in a similar type embankment.

A series of investigations and analysis were undertaken to understand the mechanism for crack formation. The findings were used in a risk assessment of piping failure modes initiated by the presence of the crack. The risk profile for Tullaroop Reservoir plotted above the ANCOLD (2003) Limit of Tolerability for existing dams with the risk of piping along the crack contributing significantly to the risk profile.

The first stage of risk reduction (undertaken immediately following the risk workshop) was to further update the Dam Safety Emergency Plan and increase the surveillance levels at the main embankment. The purpose of these measures was to provide as early detection as possible of seepage through the embankment, stockpile materials in preparation for a dam safety incident, thereby reducing the risk profile as low as practicable in the very short term.

The second stage of risk reduction was the construction of a filter buttress on the left abutment of the main embankment. The works were started in February 2006 and practically completed by March.

The paper presents details of the cracking observations, key findings of the investigations and analysis, and the two postulated mechanisms for the cracking leading up to the workshop. Additional observations during the construction period are also presented, which indicate the presence of a pre-existing shear plane in the foundation contributing to the failure mechanism (Crack Mechanism 2). The risk profile before and after the filter buttress construction is presented and the upgrade works summarised.

2 GEOLOGY AND EMBANKMENT HISTORY

Regional Geology

Ordovician age sediments underlie the region including the Tullaroop Reservoir. This is a deep marine deposit comprising interbedded sandstone and siltstone with minor shale and chert. Cycles of erosion and deposition including glaciation occurred until the Tertiary age when alluvial deposits of clays, sands and gravels infilled valleys. These deposits were subsequently eroded, however some deposits remain either as isolated outcrops or as “deep lead” deposits buried by Early Quaternary aged sheet and valley infill flows of olivine basalt from multiple eruption points distributed around the region.

Within the Tullaroop creek valley, Late Quaternary aged flood plain deposits of gravel, sand, silt and clay overlie the Ordovician bedrock.

Geology on the Left Abutment of the Main Embankment

The geological sequence on the left abutment of the main embankment (Figure 3) consists of a basalt cap overlying Tertiary alluvials in turn
overlying Ordovician sediments. The Ordovician bedrock is dominantly siltstone with interbedded sandstone units. It is steeply dipping and tightly jointed, and on the left abutment is extremely to highly weathered to 15 to 20m depth.

The Tertiary alluvium is a heavily over-consolidated dominantly sandy and silty clay of medium plasticity (but variable) of hard strength consistency and fissured. Deposits of clayey to gravelly sand and gravelly clay are much less frequent. On the left abutment, the Tertiary alluvium reflects deposition within a minor tributary to a larger north flowing river. The embankment is positioned over this broad minor tributary and therefore a relatively thick deposit of Tertiary alluvium is present in the foundation on the left abutment.

There is evidence of pre dam landslide activity on the left abutment of the main embankment and is consistent with the geomorphologic evolution of the valley. This was likely formed by undercutting from the Tullaroop creek removing the relatively softer Ordovician and Tertiary alluvium, resulting in over-steepening and landsliding. A large and old landslide feature extending back into the basalt capping is likely present upstream of the embankment, but was assessed as not likely to extend beneath the embankment.

Site investigations intersected and original drawings showed up to several metres of colluvium on the left abutment at the embankment location. This colluvium would likely be formed by landslide activity and would therefore suggest a series of shallow landslides within the Tertiary alluvium in the region now occupied by the embankment.

**Main Embankment**

The main embankment is a zoned earth and rockfill embankment of 42m maximum height (Figures 1 and 2, Plates 1 and 2). It has a very broad central earthfill zone with rockfill zones at the outer upstream and downstream toe regions. Transition zones of rounded quartz gravel separate the earthfill and rockfill zones.

The earthfill consists of sandy clay and clay of low to medium plasticity. It was borrowed locally from colluvial soils and residual soils derived from the Ordovician sedimentary formation. It was placed on the dry side of optimum and compacted using sheepfoot rollers to produce a well compacted earthfill.

Basalt for the rockfill zones was sourced from the spillway excavation and a nearby quarry area. The basalt was dumped in layers, spread and trafficked by dozers and haul trucks. Investigations encountered a dirty rockfill in a loose condition comprising basalt boulders within a clayey gravel matrix.
Foundation Preparation

The alluvium from the valley floor was removed (by dragline) to expose the underlying weathered Ordovician bedrock. Stripping by scraper was undertaken on the hill slopes. Stripping over the Tertiary alluvium was typically in the order of 2 to 3m according to the as constructed drawings.

It was not clear from the historical records if the colluvium overlying the Tertiary alluvium was removed during stripping. Investigations (URS 2005a) confirmed the presence of several metres of colluvium below the embankment on the left abutment region. In addition, during the construction works in 2006, several slickensided slide planes were encountered within the Tertiary alluvial foundation. These were assessed as remnant from shallow landslide features that were not removed during stripping. Further details are given in Section 7.

3 HISTORY OF CRACKING AND CRACK OBSERVATION

The history of cracking and defect observations was sourced through Goulburn-Murray Water (G-MW) records, mainly visual inspection reports, dating back to 1987. Cracking on the main embankment has been reported back to as early as 1988, but probably pre-dates this.

Diagonal Crack on Left Abutment

The surveillance records indicate that diagonal cracking was first observed on the downstream shoulder of the embankment in March 2001. The cracking may have progressed in March 2002, but is not clear from the records. In April 2004, a 50 to 60mm wide diagonal crack (Plate 3) formed over a period of two weeks from 14th to 27th April. No further progression or widening of the diagonal crack has been observed since 27th April 2004.

Figure 4 shows the main crack locations including the estimated location of the diagonal crack in March 2001, the surveyed location of the cracking in April 2004 (diagonal and longitudinal cracks), and the region of concentrated longitudinal cracking in the crest. The surveyed diagonal crack location in February 2006 (surveyed following stripping of the embankment face) virtually overlay the April 2004 crack location.

In March 2001 a diagonal crack was observed on the downstream shoulder toward the left abutment and a sink hole on the upper berm (refer Figure 4). The diagonal crack is within 10m of the 2004 crack and was 4m in length, 5 to 25mm in width and was probed up to 0.5 to 1.0m depth. The crack and sinkhole were repaired.

Between 6th and 27th April 2004 G-MW reported cracking on the main embankment. It comprised the diagonal crack on the downstream shoulder toward the left abutment and the longitudinal crack on the downstream edge of the crest, and continued longitudinal cracking in the roadway on the crest. First observation of the diagonal crack was on the 14th April, with the crack continuing to open in the following two week period (to 27th April).

GHD (2004) investigated the cracking and reported the following additional findings:
1) On the downstream shoulder the crack was up to 50mm to 60mm wide at the surface and was probed to 1.8m depth at several locations.
2) In test pits excavated over the crack, it was observed that the crack width had reduced to 1 to 2mm below 1.3m where exposed.
3) No shearing type movement was observed either vertically or laterally along the crack. The crack was effectively a tension type feature.
4) The direction of movement of the diagonal crack on the upper berm was at 40 degrees to the dam axis (refer Figure 4). This direction is close to perpendicular to the alignment of the crack.
5) The crack is rough and irregular.
6) At the junction of the diagonal crack and downstream edge of the crest the crack was observed to 0.6m depth then continued as a 30mm wide softened zone to 1.5m depth.

Other Notable Cracking Observations

Apart from the diagonal crack observations described above, the most notable cracking has been longitudinal cracks on the crest and downstream shoulder of the embankment.

Longitudinal cracking in the crest roadway have been observed since at least the 1980s. Whilst cracking is present along the length of the crest, it is concentrated on the left abutment (refer Figure 4). Since the installation of temporary survey targets in 2004, lateral spreading of the crest is notable in this area of concentrated longitudinal cracking.

GHD (2004) excavated a test pit in the embankment crest over a longitudinal crack and reported that the crack extended to depths in excess of 1.5 to 2m (crack widths of 1 to 2mm persisted to the 2m depth of the excavation); sand wash into the crack and bitumen runs from sealing was evident; the crack was slightly inclined off vertical to upstream; its surface varied from smooth and planar to irregular; and no signs of shearing along the crack were observed.

The longitudinal cracking on the downstream shoulder has been observed along the embankment. The cracking typically follows significant periods of low rainfall, generally over summer to autumn, with crack observations typically in the period from March to June. These cracks usually close up following rainfall.

Minor tranverse cracks are also present in the embankment crest. These cracks are typically less than 1mm wide and of limited depth (0.3 to 0.6m) as reported by GHD (2004).

4 PROPERTIES OF EARTHFILL

The very broad earthfill zone consists of sandy clay and clay of low to medium plasticity and of very stiff to hard strength consistency. Particle size distributions show the fines content (minus 75 micron) ranges from 40 to 94% and clay fractions (minus 2 micron) from 7 to 56%. Shrink swell indices range from 0.9 to 2.1% and linear shrinkage from 3 to 12.5%, indicating the earthfill is typically of low reactivity, but does contain some moderately reactive clays.

Hole erosion tests indicate the rate of the erosion is Moderately Slow according to the UNSW Classification System (Fell et. al, 2004). Pin hole and Emerson class tests indicate the earthfill is non dispersive in reservoir water, but slightly dispersive in distilled water.

The moisture content profile of the earthfill in the downstream shoulder (from 2004 investigation results) shows substantial drying in the upper 1.5 to 2m. The moisture content in this region is well dry of the average moisture content at placement and Standard Optimum moisture content reflecting the dry, hard and desiccated condition of the earthfill in this region.

Under the sealed crest of the embankment the extent of drying is not as extensive, although moisture contents in the upper 2m are 2 to 4% below the average moisture content at placement. This variation in moisture content between the crest and downstream shoulder is due to the pavement capping the crest.

On the upstream face, the earthfill below the upstream rockfill surfacing was in a moist to very moist and firm to stiff condition. This region was significantly wetter than that
encountered elsewhere in the embankment. No diagonal or transverse cracks were observed in the excavated upstream face on the left abutment (Excavation 1, Figure 1).

5 DAM SURVEILLANCE

Reservoir Operation

Figure 5 presents the reservoir operation for Tullaroop from first filling through to March 2005. Also shown is the annual rainfall. The reservoir is subjected to an annual cycle of drawdown and re-filling, with drawdown during the summer to winter period and re-filling during the winter to spring period. Up until 1997 the reservoir was generally operated above RL 214m AHD and subject to an annual drawdown up to 7 to 9 metres.

Since 1997 the reservoir has been at a sustained drawn down level, generally operated below RL 215m AHD. The minimum reservoir level of RL 208.61m AHD was reached in June 2004. This period corresponds with the sustained drought period in Victoria (6 of 8 years from 1997 to 2004 of below average rainfall) and to the driest period in recorded history in the Maryborough area (126 years of records).

Piezometers

A total of 35 piezometers have been installed in the main embankment at Tullaroop. All were virtually dry prior to first filling. On establishing equilibrium conditions after first filling, the piezometers show a gradual reduction in piezometric level across the broad earthfill zone. A number of piezometers at the higher elevations, particularly those in the downstream shoulder, are dry.

The piezometers respond to fluctuations in reservoir level. Those piezometers in the upstream shoulder have the shortest lag and the higher amplitude of response to change. Under the downstream shoulder the piezometers show a general long-term trend and do not appear to respond to short term fluctuations.

From pre 1997 to 2005, the reduction in piezometric level in the central to downstream section of the earthfill has been small at less than approximately 10 to 20 kPa. The standpipe piezometers installed in the left abutment in November 2004 have been dry since installation.

Embarkment Deformation Behaviour

In general, the post construction deformation behaviour of the crest and downstream shoulder of the main embankment are consistent with the general trends for similar type embankments. The trend of the settlement and displacement show a gradually decreasing rate of settlement and downstream displacement with time (time on normal scale). Long-term settlement rates range from 0.23 to 0.53% for the crest points and downstream shoulder, and are within the expected range. Since the mid 1990s, lateral displacements have virtually stopped; in fact several points show a small and gradual displacement to upstream (total displacement to upstream of less than 5 to 10mm).
The two internal settlement gauges also show a trend consistent with similar type embankments and “normal” type deformation behaviour. Figure 6 is from the settlement gauge at the maximum section and shows a total settlement of approximately 200mm since end of construction. Close to 60% of this occurred during first filling in 1959/60 and 90% by 1981. During the prolonged drought period (from 1997), total settlements were less than 5mm.

6 FACTORS INFLUENCING CRACK FORMATION

A number of possible contributing factors were evaluated as part of the assessment of mechanics of crack formation, and these are discussed in the following sub-sections.

**Embankment Deformation Under Sustained Drawdown**

The surface deformation and internal settlement profiles (Figure 6) show only small deformations during the sustained period of drawdown from 1997. It was assessed therefore, that embankment deformation under sustained drawdown had a negligible contribution to the formation of the diagonal crack.

However, a possible contributing factor could be localised higher deformation in the area of the diversion channel on the left abutment attributed to a lesser quality of earthfill placement in the restricted working area and the short time for placement. The nearest settlement point (located on the dam side of the diversion channel) recorded no significantly greater deformation.

**Shrink and Swelling of Earthfill**

There are a number of factors that point toward shrinkage and swelling of the earthfill as having some influence on the diagonal crack observation. These include the low to moderate reactivity of the earthfill, the substantial drying in the upper 1.5 to 2m depth of the downstream shoulder, the reduction in crack width below about 1.3m, and opening and closing of cracks depending on climatic conditions.

The seasonal deformation behaviour of the temporary survey points on the left abutment (from April 2004 to late 2005) shows a cyclical pattern of deformation. Deformation in seasonally drier periods is into the plane of the downstream face (settlement and upstream displacement) and out of the plane of the downstream face in seasonally wetter periods (upward and downstream displacement). This cyclical response to climatic conditions is assessed as reflecting seasonal shrinkage and swelling of the earthfill.

The observation of the reduction in crack width below the upper zone of significant drying was assessed as confirmation that shrinkage and swelling of the earthfill was a factor in the crack formation. Also, the reduced drying below the crest and moist condition below the upstream shoulder could partly be the reason why the crack had not progressed across the crest. However, on its own shrink-swell does not fully explain the observed cracking (i.e. why a diagonal crack on the left abutment as observed).

During the construction works in 2006 when the outer face of the embankment was exposed and further excavation along the crack was performed, it was evident that the crack width persisted to greater depth than initially thought. This is discussed further in Section 7.

**Landslide on the Left Abutment**

The formation of landslides in the left abutment prior to dam construction is consistent with the geomorphologic evolution of the valley and there is evidence of pre dam landslide activity on the left abutment as discussed in Section 2. However, it was assessed that deep seated mass instability of the left abutment was not likely to be a contributing factor to the crack mechanism.

It was assessed as possible that pre-existing slide planes from shallow landslips in the Tertiary alluvium or weathered Ordovician units could be present below the embankment. The shallow stripping in this area may not have removed these potential shear surfaces thereby leaving a potential plane of weakness within the Tertiary alluvium at close to the
embankment interface above the steepened cut section of the former diversion channel.

This mechanism was considered as a contributing factor in the mechanics of the crack formation and included in the risk assessment.

During the construction works several pre-existing shear surfaces were observed within the Tertiary alluvium on the left abutment (Section 7). These observations provide strong evidence that the presence of pre-existing shear surfaces in the foundation are a significant contributing factor in explaining the crack mechanism.

**Change in Foundation Slope on the Left Abutment**

Excavation for the temporary diversion culvert resulted in a steep step in the foundation profile from upstream to downstream across the embankment. As shown in Figure 3, the diagonal crack is located above this change in slope.

Numerical modeling was undertaken to evaluate the potential for development of tensile stresses within the earthfill during construction due to the change in slope on the left abutment. A 2-dimensional model of the embankment construction (in long section) was undertaken using the computer program DIANA (modeling by NSW Department of Commerce). Embankment construction was modeled in 10 stages and the staging of works around the temporary diversion channel.

The modeling showed that a zone of reduced minor principal stress over the change in abutment slope. In some cases a small tensile stress was observed on the crest of the constructed layer. The zone of reduced compressive stress to low tensile stress from the numerical analysis is shown on Figure 3.

The results of the modeling show that the change in slope of the left abutment does reduce the minor principal stress within the earthfill as construction proceeds. However, the stresses are generally still compressive. The small to negligible formation of tensile stress above the change in slope was possibly due to the relatively low height of the steep section of slope. The results indicate that a tensile crack is unlikely to have formed during embankment construction.

Post construction deformation across the change in slope was estimated to be in the range 75 to 95mm from the internal settlement gauge records (note, the gauges are located at the maximum section and on the right abutment). Most of this differential settlement would have occurred in the period of first filling.

Although not modelled numerically, the post construction differential settlement is likely to further reduce the compressive stress over the change in slope, and possibly result in the formation of tensile stress in the outer slope of the embankment. Longitudinal strains on the embankment crest would be expected to be tensile in the zone directly over and upslope of the change in slope and compressive below the change in slope, much the same as was modelled during construction.

Another factor to consider in the potential for tensile stress formation is the properties of the earthfill itself. The low to medium plasticity earthfill was placed on the dry side of optimum and would potentially be relatively brittle.

In summary, the numerical modelling showed the formation of a zone of reduced minor principal stress over the change in abutment slope, and minor tensile stress formation. Post construction deformations are likely to have further reduced the stresses in this area. It is postulated that these stress conditions have been effectively “locked in” since construction and the period of significant post construction settlement.

**Foundation Compressibility**

Compressibility of the foundation was ruled out as a possible contributing factor given the heavily over-consolidated nature of the Tertiary alluvium.


7 OBSERVATIONS DURING CONSTRUCTION WORKS IN 2006

Crack Mapping

After stripping the downstream face of the embankment, the diagonal crack on the embankment was mapped and surveyed. Figure 7 shows the surveyed crack location. The separation between the mapped crack on the upper and mid slopes of the shoulder is because this is the location of one of the test pits. The lower termination position of the crack is because filter had been placed to this elevation.

Plate 4 shows the crack on the mid slope (above the embankment toe) at an estimated depth of 2 to 2.5m below the original embankment surface. At this depth the crack was continuous and its width measured at 5 to 10mm.

Plates 5 and 6 show the diagonal crack on upper slope. Towards the crest of the embankment the crack was discontinuous (Plate 5) and the angle of the crack to the dam axis decreased as the crest is approached. As shown, the surface of the crack was irregular and rough. No evidence of shear movement was observed.

Plate 5. Crack in upper slope within 5m of the crest

Plate 6. Crack in upper slope (mid to lower section)

Along the downstream edge of the crest the excavation was 1.5m deep, and at this depth there was no trace of the longitudinal crack as mapped on the surface (refer Figure 3).
Sections of the diagonal crack on this upper slope were then excavated locally to approximately 1m depth to further assess the extent of cracking with depth and to remove longitudinal cracking from around the main crack. The crack was clearly visible in the base of the excavated section on the upper slope (approximately 1.5m below the original embankment surface). At these depths the crack was measured at 10-15mm width, occasionally up to 40mm. The crack was probed with a 12mm reinforcement rod to depths from 0.3m (near crest) up to 1.5m depth (lower end of the crack in Plate 6).

These findings indicate that the crack is persistent at depth. Crack widths of 5 to 15mm persist to depths of 2.5 to 3.0m below the original embankment surface. At these depths, the crack is open below the region of drying. Previously it was thought that the crack narrowed to less than 1 to 2mm below the upper zone of drying. Therefore, the significance of shrinkage and swelling of the earthfill is not as great as previously evaluated.

**Slip Surfaces in Tertiary Alluvium**

Part of the upgrade works involved a 2 to 2.5m deep excavation along the downstream toe of the embankment on the left abutment. Two slide planes (Slide Plane 1 and Slide Plane 2) were observed in the Tertiary alluvium within this excavation. Test pitting was undertaken along the upstream toe of the embankment on the left abutment. A slide plane (Slide Plane 3) was observed within this excavation and was at similar elevation to Slide Plane 1. The location, orientation and measured dip of these surfaces is shown in Figure 7. Figure 8 presents a section showing the location of Slide Plane 1 and 3.

All three slide planes were oriented near normally to the natural slope, the slide surface dipped into the slope at a low angle (0 to 6 degrees) and the plane of movement (evident from slickensides and striations) was out of the slope.

Slide Plane 1 (Plate 7 and 8) was observed in the Tertiary alluvium at the contact between a layer of light grey high plasticity clay and the lower zone white friable sandy clays. It was continuous across the excavation and exposed in the side of the excavation (Plate 8), the surface was polished and slickensided, there was no evidence of self healing as the surface was readily separated by hand along the slip plane. The surface was slightly undulating normal to the direction of movement.

Slide Plane 3 (Plate 9) had similar attributes to Slide Plane 1. Slide Plane 2 was less developed than either 1 or 3.

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Plate 7. Slide Plane 1

Plate 8. Slide Plane 1

Plate 9. Slide Plane 3
Inclinometer INC01 was installed in the crest of the embankment (refer Figure 7 for its location). Continuous tube sampling was successfully undertaken across the elevation interval of Slide Plane 1 and 3; however, no sign of a shear surface was observed in the extruded samples.

### 8 MECHANICS OF CRACK FORMATION

Following the investigations and prior to the risk workshop, two potential mechanisms were postulated for the development of the observed diagonal crack. Subsequent to the findings during the construction works, Crack Mechanism 2 is now considered the most likely mechanism.

**Crack Mechanism 1**

Crack Mechanism 1 is a combination of the tensile stress formation due to the change in slope and shrink-swell. The events resulting in the formation of the diagonal crack were postulated as follows (Figure 9):

1. Formation of a “locked in” zone of reduced compressive stress within the earthfill and tensile stress formation in the outer slope of the earthfill across the change in slope. These stress conditions resulted from differential settlement across the change in slope during and post construction and were present well before the observation of the cracking in April 2004;
2. The prolonged dry period since 1997 has resulted in the observed drying of the earthfill in the downstream shoulder to 1.5 to 2m depth (this is potentially the driest the earthfill has been to these depths in its history). This drying has resulted in shrinkage of the earthfill.
3. The combination of the tensile stress and shrinkage of the earthfill has resulted in the formation and location of the diagonal crack now present on the downstream face of the embankment.

Extension of the crack into the crest and upstream shoulder was not observed because the earthfill in the upper 1.5 to 2m in these areas is at a much higher moisture content than in the downstream shoulder. The tensile stresses are present in these areas, but a crack is not visible due to the higher moisture content and possibly plastic type deformation of the earthfill.

The strong evidence for the influence of shrink-swell behaviour was the correlation between moisture content of the earthfill and crack width.

What does not fit well with Crack Mechanism 1 is the direction of movement across the crack. It is inclined to the dam axis at approximately 40 degrees. For this mechanism the movement would be expected to occur parallel with the dam axis.

**Crack Mechanism 2**

Crack Mechanism 2 is similar to Crack Mechanism 1, with the major difference being that a basal plane of sliding is present within the foundation that has had a significant influence of the crack formation.

Crack Mechanism 2 (Figure 10) involves movement along this postulated basal slide plane within the foundation. The trigger to the movement would be the sustained period of drawdown and resulting change in stress conditions acting on and within the embankment, and the effects of shrinkage of the earthfill from the sustained drought period (to explain the crack width reduction).

The evidence pointing toward this mechanism and the influence of internal stress changes resulting from the sustained drawdown is the direction of movement across the crack, the diagonal angle of the crack and the observation of cracking post the sustained period of drawdown. Why the crack does not extend across the embankment crest is not known, although at the risk workshop it was considered that the longitudinal crack on the downstream edge of the crest could form the extension to the backscarp.

Evidence that does not fit well with Crack Mechanism 2 is that the reservoir has previously been drawdown to levels below the basal plane of movement (i.e. below about EL 212m AHD) and no evidence of movement has previously been observed.
Additional Comments on Crack Mechanism

In postulating the mechanism/s for cracking the known factors potentially influencing the formation of the crack as described in Section 6 were taken into consideration. There are likely to be other factors that are not known or are known and cannot be quantified that may influence the mechanism for cracking. Amongst other factors, this included the properties of the earthfill placed within the temporary diversion channel. It is not known if the clays in this confined zone were placed to the same standards as for the bulk of the earthfill.

Although desirable, it was not necessary to fully understand the crack mechanism for the risk workshop as weightings could be given to the postulated crack mechanisms. However, it was important that the factors affecting the crack mechanism were understood and the crack properties (its thickness and depth) approximated for evaluation of the risk of piping.

Implications of the Observed Slide Planes

Pre-existing slide planes were observed within the Tertiary alluvium on the left abutment. It is unlikely that these slide planes would have been fully removed as part of the original dam construction stripping works, and are therefore present within the Tertiary alluvium below the embankment.

Figure 8 shows the transposed location of the Slide Planes 1 and 3 onto the cross section through the embankment centreline on the left abutment. Also shown is the crack location and the zone of tensile stress / low compressive stress determined from numerical modeling.

The characteristics of Slide Planes 1 and 3 are very similar (elevation, dip and strike, direction of movement, located within light grey high plasticity clay, presence of clay seam on slip plane) and would suggest the presence of a continuous slide plane below the embankment on the left abutment. However, the slide plane was not observed within the “undisturbed” tube samples recovered from the borehole drilled for Inclinometer INC01. It is possible therefore that the slide plane may not be continuous across the embankment.

In terms of the crack mechanism, the presence of the slide planes supports Crack Mechanism 2. As shown in Figure 8, it is likely that the slide plane within the Tertiary alluvium forms a basal plane of sliding above the steepened cut section of the temporary diversion channel. The observed diagonal crack is likely to be a backscarp to a slip surface involving the downstream shoulder of the embankment.

Termination of the cracking at the downstream edge of the dam crest could be due to several reasons, including the lateral extent of the basal slide plane. This would assist in explaining the direction of movement across the crack, as it could be hinged somewhere about the dam centerline.

9 RISK WORKSHOP

Discussions during the risk workshop on the diagonal crack (on 9th September 2005) were unable to rule out the existence of either of the crack mechanisms. Hence it was agreed that the risk of failure associated with the cracking be evaluated for each of the mechanisms separately. Details of the workshop and outcomes are presented in URS (2005b).

Piping Implications due to Crack Presence

The presence of the diagonal crack on the left abutment has implications for internal erosion and piping through the embankment. The presence of the diagonal crack had a significant influence on the assessment of development of a concentrated leak through the earthfill and on initiation of erosion. The potential for continuation of erosion, progression and breach do not significantly change as a result of the presence of the crack.

It was assessed that Crack Mechanism 2 presented an increased risk of piping over Crack Mechanism 1 in the following main areas:

1) For Crack Mechanism 1, the crack depth, tensile zone and potential zone of hydraulic fracturing would be expected to be limited to
the upper, outer surface of the earthfill. For Crack Mechanism 2, the crack depth would extend to foundation level and it would be expected to be of similar width with depth. The probability of a concentrated leak was assessed as more likely for Crack Mechanism 2.

2) Due to the potential for a greater crack width for Crack Mechanism 2, the probability that erosion initiates was assessed as more likely for Crack Mechanism 2.

3) To detect and intervene, it was assessed as slightly more likely that piping failure could not be intervened for Crack Mechanism 2.

The potential for future opening and deepening of the crack was also considered. The internal settlement profiles have shown very little settlement in the last 8 years (less than 5 mm), indicating that it is unlikely there will be further differential settlement to increase the zone of tensile stress. Opposed to this are the effects of drying below the crest, creep and stress concentration from the existing diagonal crack on the downstream shoulder.

**Risk Profile**

Figure 1 shows the revised F-N curve for Tullaroop Dam for all failure modes as at September 2005.

The f, n pairs for the critical case of piping through the left abutment crack for both crack mechanisms is shown separately. These are shown separately to illustrate the relative difference in likelihood of the two mechanisms. The combined weighted case is based on a likelihood assessment of the crack mechanism at the workshop: 60% for Crack Mechanism 1 and 40% for Crack Mechanism 2.

The total F-N curve for Tullaroop Dam plots more than one order of magnitude above the Limit of Tolerability line, and hence did not satisfy ANCOLD Guidelines for societal risk. The estimated individual risk value for the person most at risk was $2.4 \times 10^{-4}$, and this also did not satisfy the ANCOLD criteria for individual risk.

The dominant failure modes were failure of the butterfly valve (works due to be undertaken in 2006) and piping through the main embankment involving the diagonal crack.

The main conclusions from the risk assessment were:

1) The risk of piping failure associated with the left abutment crack plots more than an order of magnitude above G-MW's First Interim Risk Target. The risk does not satisfy the ANCOLD societal risk criteria for existing dams.

2) The critical loading condition for this failure mode is refilling of the reservoir to Full Supply Level.

**Upgrade Options**

During and following the risk workshop, a number of options were developed to reduce the risks associated with piping through the main embankment. These included:

- **Option P1. Enhanced Monitoring and Surveillance (Revised DSEP).** This is a non-structural option that involved increasing the frequency of inspections during refilling of the reservoir and during flood surcharge conditions. It also involved stockpiling of filter materials on site and having ready access to equipment to construct a reverse filter should a seep be observed.

- **Option P2. Filter Buttress on Left Abutment.** Construction of a filter buttress locally over the area of cracking on the left abutment area.

- **Option P3. Filter Buttress on Upper Embankment.** Construction of a downstream filter buttress along the full length of the main embankment, including filter protection around the outlet culvert.

- **Option P4. Full Height Filter Buttress.** Construction of a downstream filter buttress over the upper and lower portions of the main embankment.

- **Option P5. Filter on main and Secondary Dams.** Option P4 plus construction of a full height filter buttress on the secondary embankments.

Figure 12 shows the revised F-N curve for Tullaroop Dam following the upgrade works. Shown is the upgrade of the butterfly valve, Option P1 and Option P2. Also shown is the current risk profile determined from the 2006 portfolio risk assessment (URS, 2006).
G-MW took the immediate step of implementing Option P1. Although the overall risk reduction shown in Figure 12 is small, the risk reduction for the piping failure mode was significant. This is because the risk profile for a loss of life of one is controlled by the butterfly valve failure mode.

G-MW also took the immediate action to undertake detailed design for Option P2 with a view to construction of the local filter buttress in early 2006. As shown in Figure 12, a significant reduction in risk was achieved by implementation of these actions.

At the time of the September 2005 risk workshop, the risk profile for Tullaroop after Actions P1 and P2 and butterfly valve repair still plotted close to the ANCOLD limit of tolerability. The risk profile was reassessed as part of the 2006 portfolio risk assessment and as shown plotted slightly lower than that assessed at the 2005 workshop.

10 EMBANKMENT UPGRADE WORKS

The constructed filter buttress included a two stage filter (Zone 2A fine filter and Zone 2B coarse filter) and outer rockfill buttress zone (Zone 3). Each filter zone was 0.75m horizontal width giving a total combined filter width of 1.5m. Zone 3 was a minimum width of 3m at the crest.

The filter buttress covered the left abutment from 30m east of the diagonal crack, west to the dam crest (i.e. from RD 280m to 410m). The purpose of covering this area was to provide a filter over the area of the crack itself, over the extent of longitudinal cracking that is connected with the crack and the region of low compressive stress over the change in slope.

The initial design intent was to provide a sufficient filter and rockfill depth to resist water pressure from full supply level. After review by GMW it was decided to maximise the rock depth at the level of the upper berm by deepening the excavation by 1m at the level of the upper berm while maintaining the design rockfill level. This was for constructability of the solution, but also provided additional protection against piping for reservoir levels above full supply level.

Other features of this option included:
1) Excavation of the earthfill on the downstream shoulder to a vertical depth of 0.6m to remove the upper desiccated zone.
2) Additional local excavation around the diagonal crack and longitudinal crack on the downstream edge of the crest for assessment of the crack at depth and remove interconnection with longitudinal cracks on the downstream shoulder.
3) Excavation to a depth of 2m into the foundation at the toe of the embankment and blanketing for a horizontal width of up to 5m beyond the existing toe of the embankment.

11 CONCLUSIONS

Over a two week period in April 2004 a diagonal crack of 60mm width and greater than 2m depth developed on the downstream shoulder of the main embankment over the left abutment. The crack extended from the crest to the toe, terminating at the downstream edge of the crest, but did not extend across the crest.

The diagonal crack formation is unusual for this type of broad earthfill embankment. In particular, the diagonal nature of the crack itself, its time of observation after construction (some 55 years), its formation over a period of several weeks in April 2004 without further movement thereafter.

Investigation and analysis was undertaken to understand the mechanics of the crack formation. Significant factors contributing to the crack formation were the presence of pre-existing shear planes in the foundation not removed as part of the embankment construction, and the sharp change in foundation slope on the left abutment from excavation of the temporary diversion channel. The timing of the crack in 2004 was assessed as due to a combination of sustained drawdown and the extended drought period (resulting in drying profile in the downstream shoulder of the earthfill).

A risk assessment of piping failure modes was undertaken drawing on the findings of the study. The outcomes of the risk assessment
were that the presence of the diagonal crack dominated the piping failure modes and the risk profile plotted above the ANCOLD limit of tolerability for existing dams.

Based on the outcomes of the risk assessment, G-MW implemented two actions. The first action (implemented immediately) was to further enhance monitoring and surveillance frequency, and update the DSEP for a dam safety piping related emergency incident. This included stockpiling of filter materials and having contractors and plant on standby so that repair works could be undertaken as soon as seepage was detected.

The second action by G-MW was to initiate detailed design of a filter buttress on the left abutment with a view to construction in early 2006. These works were undertaken in February to March 2006.

Additional surveillance monitoring was installed to monitor embankment deformations, pore water pressures and seepage on the left abutment of the main embankment. The deformation monitoring included installation of two inclinometers and a series of surface survey targets on the embankment.

12 REFERENCES


Figure 1. Plan view of main embankment

Figure 2. Cross section of main embankment (RD. 200m, maximum section)

Figure 3. Long section of main embankment along dam axis
Figure 4. Crack locations on left abutment, main embankment

Figure 5. Reservoir operation and annual rainfall

Note: Average yearly rainfall from Maryborough station (126 years of records)
Figure 7. Site observations during construction works

Figure 8. Section of left abutment showing location of shear planes within foundation
Figure 9. Postulated Crack Mechanism 1

Figure 10. Postulated Crack Mechanism 2
Figure 11. Risk profile of Tullaroop Dam (September 2005)

Risks are unacceptable, except in exceptional circumstances

Risks are tolerable only if they satisfy the ALARP principle

Limit of tolerability for existing dams
Figure 12. Risk reduction for upgrade options (September 2005)

Risks are unacceptable, except in exceptional circumstances

Limit of tolerability for existing dams

Risks are tolerable only if they satisfy the ALARP principle

Legend:
- Original Assessment (2001)
- Revised Risk (Crack Workshop 2005)
- After Revised DSEP (Option P1)
- After Repair of BFV
- Option P2 - Filters left abutment
- 2006 Risk Assessment (80%)