Investigation and Assessment of the Whakamarino Earth Dam

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Summary The 10m high Whakamarino earth dam was completed in 1943 and forms part of Genesis Power's Waikaremoana Power Scheme on New Zealand's east coast. The dam is located on the margin of one of the world's largest intact landslide dams, the Waikaremoana Barrier. The barrier has a volume of approximately 2.2 km^3 and was emplaced about 2,200 years ago. Whakamarino dam has been investigated following evidence of downstream shoulder deformation. Foundation conditions were found to include a significant deposit of permeable boulder alluvium that has been derived from downcutting through the barrier debris. Indications of minor internal erosion in the homogeneous earth embankment were discovered, as was leakage past the upstream section of a culvert penetrating the dam. An assessment of the dam has resulted in preliminary recommendations for the installation of a vertical sand filter through the embankment.

INTRODUCTION

The Whakamarino earth dam is part of the 128 MW Waikaremoana Power Scheme on the east coast of New Zealand's North Island. The scheme consists of three power stations (Kaitawa, Tuai, Piripaua) operating in cascade from the primary storage facility of Lake Waikaremoana. Lake Whakamarino, with a volume of approximately 0.8Mm^3 forms a regulating storage facility for the lower power station, Piripaua, and the tailwater for the middle power station, Tuai.

The homogeneous earthfill Whakamarino dam ranges in height to approximately 10m and was constructed between 1929 and 1943. The dam incorporates a tip gate spillway on the left abutment and a box culvert low level dewatering sluice in the centre of the dam. The dam is classified as having a low potential impact category under the NZSOLD Dam Safety Guidelines (NZSOLD, 2000).

During 2002, dam surveillance officers reported an apparent increase in deformation of the dam downstream shoulder. Investigation and assessment of the dam to determine the cause of the deformation was recommended. Aspects of the investigations are the subject of this paper.

DAM HISTORY

Construction of the dam commenced circa 1929 near the southern margin of an area of flat swampy ground known as the Whakamarino Flat in the Kahutangaroa Steam valley (Figures 1 and 2). Initially the sluice culvert and a small diversion dam only were built, with a purpose of providing control for the Tuai power station tailwater (the lower power station, Piripaua, was not built at this time). Figure 1 shows an overview of the Flat, with the sluice culvert in operation circa 1930. The extent of the final dam is overlain on the photograph. Grouting of the dam foundation followed in 1940, with placement of the main embankment shortly thereafter. The dam was commissioned in 1942.

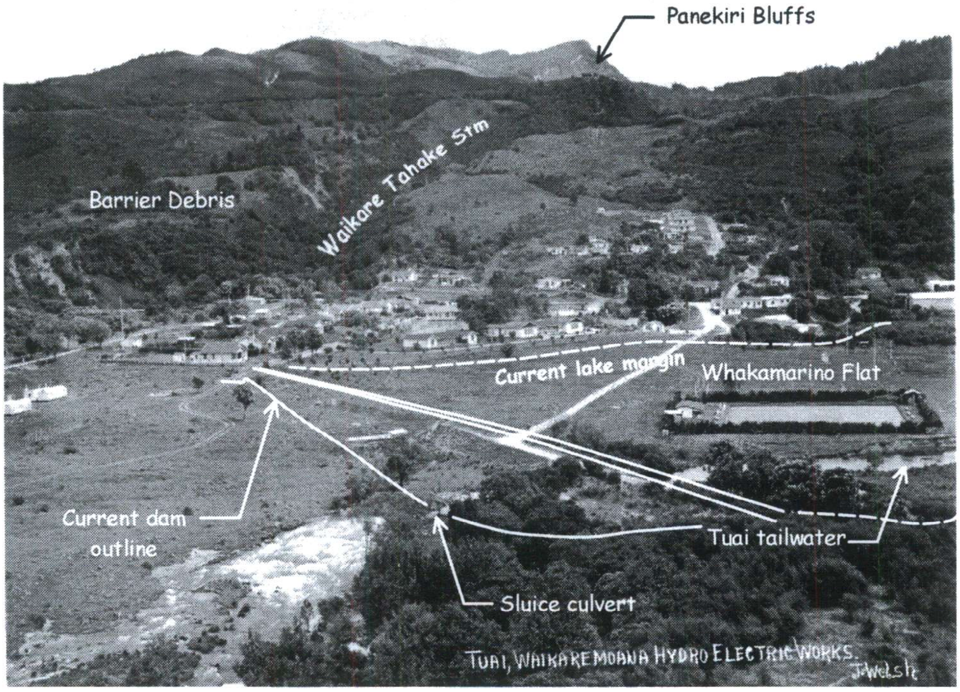

Figure 1. Whakamarino Flat Circa 1930.

Shortly following initial filling, leakage from the lake occurred via a feature in the lakebed near the right abutment. Further foundation grouting in that area, and installation of a clay blanket, was successful in stemming the leakage. Seepage from uplift relief wells in the newly constructed sluice outfall stilling basin, and further downstream in the bed of the now dry Kahutangaroa Stream, was also noted around the time of initial filling.

Movement of the sluice culvert, noted as early as 1943, is mostly defined by displacement at construction joints. Seepage from culvert joints located below the dam crest also occurred from that time, although seepage does not appear to have progressed to open joints in the culvert further downstream. The sluice has not been operated since the dam was commissioned, and the inlet is now buried by up to 4m of silt.

Lakebed leakage near the right abutment again occurred on at least one occasion during the mid 1960's, with two holes described as taking flow of about 70 l/min. The leakage appears to have been identified only as a result of low lake levels and may have been in existence for some time. The outlet for the leaks was unable to be conclusively traced. It appears that remedial work involved construction of a further clay blanket in association with localised grouting.

Deformation of the downstream dam shoulder in the vicinity of the sluice has been in evidence since the mid 1960's. Two transverse shallow depressions approximately aligned with the sluice walls, and a general appearance of shallow creep has gradually become more prominent over the years.

The dam has not experienced a significant seismic event to date, with the well-known Napier (1931) and Wairoa (1932) earthquakes both occurring prior to construction of the main embankment. The sluice and diversion dam would have experienced these seismic events however.

ENGINEERING GEOLOGY

Geological Setting

The geology of the area comprises Upper Miocene (mid-Tertiary) sedimentary rocks (papa), which form prominent northeast/southwest oriented strike ridges with southeast-facing dip slopes. The dip slopes typically range up to 20° with some locally steeper sections. The rock mass is indistinctly bedded and poorly jointed and comprises weak siltstone and mudstone and weak to moderately strong fine sandstone. The stronger sandstone lithologies are calcareous and commonly form the more prominent strike ridges.

The Waikaremoana landslide, an event that blocked the original Waikare Taheke River and impounded Lake Waikaremoana, substantially modified this Tertiary terrain. The Waikaremoana Power Scheme takes advantage of the large head created by the landslide and Whakamarino Dam is founded on sediments deposited as a result of the slide.

The Waikaremoana slide is considered to have occurred in two distinct phases, probably separated by only a short period of time. The initial phase was collapse of the high, steep slopes of the gorge formed by Waikare Taheke River down-cutting normally across the Panekiri/Ngamoko ranges. The initial $10^9 m^3$ of failed materials are dominated by calcareous sandstone and siltstone and these spread about 7km downstream, choking the Waikare Taheke valley and blocking the outlets to the Mangaone (right bank) and Kahutangaroa (left bank) tributary valleys (Figure 2).

The second phase of landsliding involved translation of a large ($1.2x10^9 m^3$) essentially intact block of calcareous sandstone and siltstone from the Ngamoko Range into the head of the slide, deforming and raising the landslide mass resulting from the initial failure. It is probable that the block was released by the removal of toe support as a result of the initial failure (Read, 1989), combined with elevated porewater pressure along the failure surface (Riley & Read, 1989). Lake Waikaremoana was impounded behind the landslide barrier and has survived principally because of the erosion resistance of the massive intact block.

The large mass of landslide debris has a characteristic hummocky topography (Figure 2) with pressure ridges, graben structures, internal drainage features (ponds and lakes) and chaotic sandstone blocks at the surface. The morphology of the debris has been little modified in the 2,200 years since failure, other than Waikare Taheke River incising into the mass, in places by up to 30m.

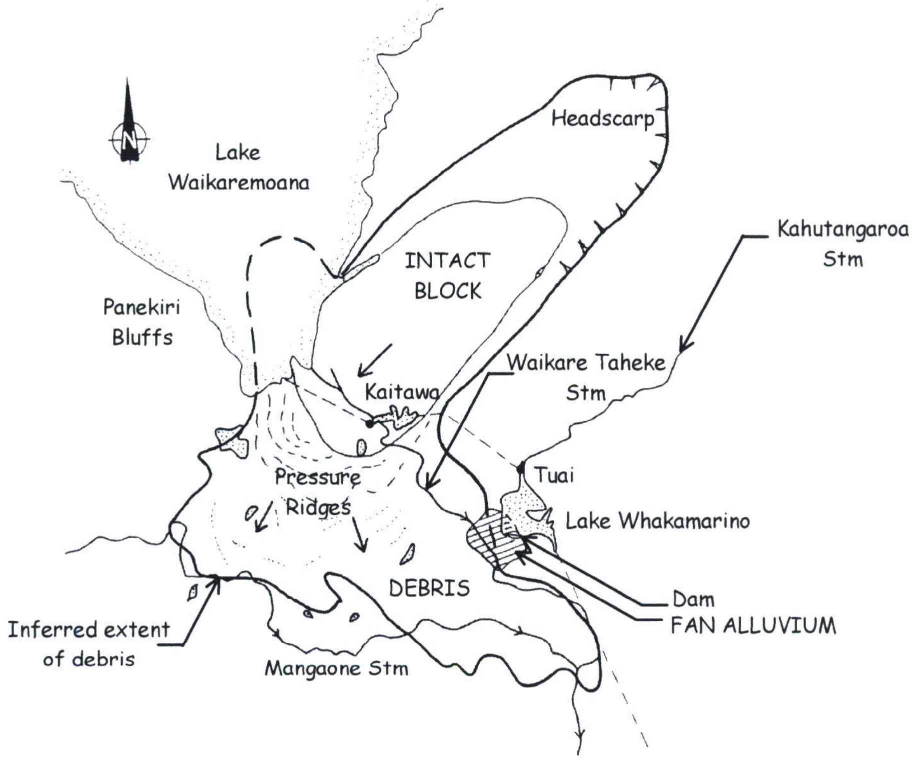

Figure 2. The Waikaremoana Barrier and Extent of Debris

Kahutangaroa Valley

Kahutangaroa Stream is a left bank tributary of Waikare Taheke River (Figure 2). The debris from the initial phase of the Waikaremoana slide blocked the mouth of the Kahutangaroa Stream valley, forming a small lake. The lake filled with sediment creating a swampy flat. Prior to construction of the Whakamarino sluice and low diversion embankment in the late 1920's, the Kahutangaroa Stream meandered across the flat, becoming incised only near its confluence with the rapidly incising Waikare Taheke River (Figure 1).

The depositional environment of the different materials in the area is complex. Investigation drilling by percussion rig in 1938 and later for the grouting programme during construction, encountered coarse, variable materials (sand and gravel) to about 30 feet (10m) overlying sandy clay with pumiceous and swampy zones to about 130 feet (40m), overlying 'grey, hard papa'. The drilling for the present study indicates that the coarse material comprises weak to moderately strong sandstone gravel, cobbles and boulders (angular and sub-rounded) in a highly variable matrix of silt and clay with some organic matter.

Read (1989) considers that the clay materials below 10m are lake sediments deposited when Kahutangaroa Stream was blocked by the landslide debris, while the overlying coarse material is alluvium deposited later by Waikare Taheke River spilling into Kahutangaroa valley. The source of the alluvium is uncertain but is likely to be landslide materials eroded and reworked by Waikare Taheke River during the period of major incision upstream (Figure 1 & 2).

The alluvium constructed a broad fan represented by the gently sloping surfaces on which Tuai village and the sportsfield below Whakamarino dam are located. Continued downcutting by Waikare Taheke River eventually removed the supply of sediment to the fan. Given the short period since the landslide occurred (2,200 years), the rate of fan sedimentation has been rapid, depositing 40m thickness of materials at the dam site. The wide range of particle sizes and angularity of coarse clasts reflects the high rates of deposition and very short transport paths for the alluvium. The fan alluvium dammed Kahutangaroa Stream, creating a further shallow pond over the Whakamarino flat, in which was deposited a layer of fine sediment.

Investigations

Investigations of the dam comprised a review of published data, examination of aerial photography dating back to 1945 and two phases of physical investigation. The investigations included rotary drilling from the dam crest through the dam into the foundation, handauger drilling through the downstream shoulder, and installation of standpipe piezometers. The handauger drilling proved particularly useful in identifying seepages through the embankment, which could be easily identified and measured without the complications of fluids introduced by rotary drilling.

Dam Foundations

The dam is located mainly on the alluvial fan materials at the southern margin of Whakamarino flat. The left abutment is a narrow spur of silty fine sandstone overlain by a veneer of stiff silty clay forming a terrace in this area. The terrace material may be derived from weathered Tertiary rock or colluvium (slope debris), but its local origin is unclear.

From the left abutment, the level of the sandstone deepens westward under the dam (figure 3). The sandstone, which is weak and relatively massive, appears to be about 8m below the dam crest near the sluice and 40m near the western end. The western (right) abutment is formed by the surface of the gently sloping alluvial fan. The spillway is excavated through the left abutment sandstone spur.

It appears that the sluice structure is founded in a cutting of sandstone and / or terrace materials at the end of the left abutment spur. The level of sandstone dips steeply westward, and probably north and south, off the end of the spur. The sluice outlet apron is apparently founded on fan alluvium and fill placed as a result of scour that had occurred in this area before the structure was built.

The fan alluvium encountered in drillholes is predominantly sub-rounded to angular clasts of weak to moderately strong sandstone, ranging to 600mm diameter, in a variable matrix of sandy silt, silty clay and silty sand. Beds of fine silty sand and gravely silt and clay were also encountered. The boulder material is confirmed by the recent drilling to be highly permeable. These materials were grouted as part of foundation pre-treatment prior to construction of the embankment.

The lake sediment underlying the fan alluvium is described on power station records as 'clayey sand', 'muddy clay', 'swamp' and 'pumice' and strength as 'soft' and 'firm.

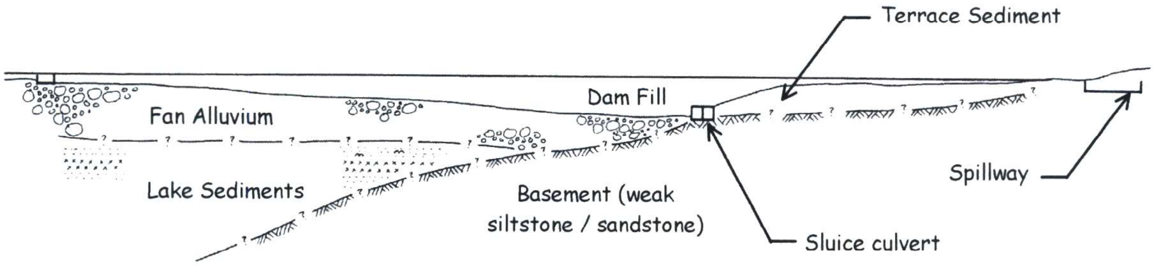

Figure 3. Geological Long Section Through the Dam Foundation (viewed from downstream)

Dam Embankment Materials

The Whakamarino dam is a homogeneous earthfill embankment constructed in two phases. A small diversion embankment was constructed in 1929, together with the sluice structure, followed by the main phase of embankment construction in the early 1940's.

Construction records describe the embankment fill material as 'local clay overburden and papa' from nearby borrows, compacted with tandem sheepsfoot rollers at controlled water contents (Alecock, 1944). Compacted layers were reported to have been lightly scarified prior to placing subsequent layers.

The embankment materials encountered in investigations are mainly firm to stiff yellowish brown clayey silt and silty clay with clasts of sandstone (crushable by hand). It is apparent that some sandy ash was incorporated as thin discreet layers in the fill. The water content of the fill in drillcore and augers ranges from moist to wet and free water is described at a number of levels in the fill. The free water is typically associated with coarser ash layers, or zones of more clastic fill (i.e. the fill has a slightly open, 'knobbly' appearance). Some of the clasts in these zones have a thin coating of clay, which probably represents fine material mobilised within the fill.

Groundwater and Piezometric Conditions

The phreatic surface in the embankment generally falls with increasing distance downstream as would be expected for a homogeneous earth dam. From observations of the downstream face, and inflows during drilling, it is apparent that minor seepage daylights above the toe in some areas via semi-continuous, more permeable subhorizontal layers. The sluice was constructed without waterstops at joints. Seepage along the sluice structure appears to be intercepted by open construction joints beneath the crest of the embankment. Downstream of the dam crest, open construction joints are generally dry.

Piezometric levels in the fan alluvium foundation (downstream of the grout curtain) vary from slightly above the interface between the embankment and foundation, to entirely within the foundation itself. It is apparent that the seepage barriers provided by lake siltation and the grout curtain, combined with the high permeability fan alluvium at the toe, currently provide control of groundwater pressure.

EMBANKMENT CONDITION ASSESSMENT

A condition assessment of the dam identified safety deficiencies, primarily in relation to the potential for piping. For example, although a cause for the downstream shoulder deformation in the vicinity of the sluice could not be conclusively established, it was suspected that it might be associated with the observed leakage into the sluice structure. This combined with evidence in drill core of clay mobilisation promoted a recommendation for a Failure Modes and Effects Analysis (FMEA)[1].

Failure Modes and Risks

An FMEA workshop was held to identify potential failure modes significant to safe operation of the Whakamarino Dam. The workshop also sought to provide a foundation for later risk assessment and monitoring work. Failure modes were considered under a variety of load conditions (static, seismic, hydraulic etc.) for the various dam elements. The failure mode considered to have the potential to lead to

[1] *The terminology used in this paper regarding dam safety and risk follows that published in the ANCOLD draft Guidelines on Risk Assessment (ANCOLD 2001).*

dam breach was piping, either through the embankment, from the embankment to the foundation, through the foundation, or associated with the sluice. The latter was identified as particularly important, especially under the seismic load condition.

Following the FMEA, the probability of dam failure by piping was assessed by two methods. An initial assessment utilised the University of New South Wales (UNSW) method (Foster, Fell, Spannagle, 2000). This was followed by assessment using an event tree based on UNICIV Report R-377 (Foster, Fell, 1999). The UNSW method estimates the relative likelihood of piping failure based on an analysis of historic failures and accidents in embankment dams. Weighting factors on elements such as dam type, core materials and dam age amongst others, are used to 'best fit' the dam under consideration with the methods statistics. The method provided useful preliminary information.

The event tree provided a more detailed examination of the factors contributing to the initiation, continuation and progression of piping, and the mechanisms associated with breach. The variety of case histories presented in the UNICIV report provided an invaluable reference point for further research on dams with similar characteristics to Whakamarino. Insufficient information was available to assign quantitative conditional probabilities to each of the events on the 'tree', and a qualitative result only was produced. This was however, useful in understanding the likelihood of piping failure leading to breach.

Following a dam break study, and in consultation with the dam owner, it was concluded that measures to reduce and / or control the risks of piping, particularly through the embankment in the vicinity of the sluice, were required.

RISK REDUCTION AND CONTROL MEASURES

A vertical sand filter through the downstream crest of the dam was proposed to reduce the risk of embankment piping (Figure 4). The filter completely surrounds the sluice culvert penetration to address what is considered the primary piping risk element. The filter also extends along the length of the embankment.

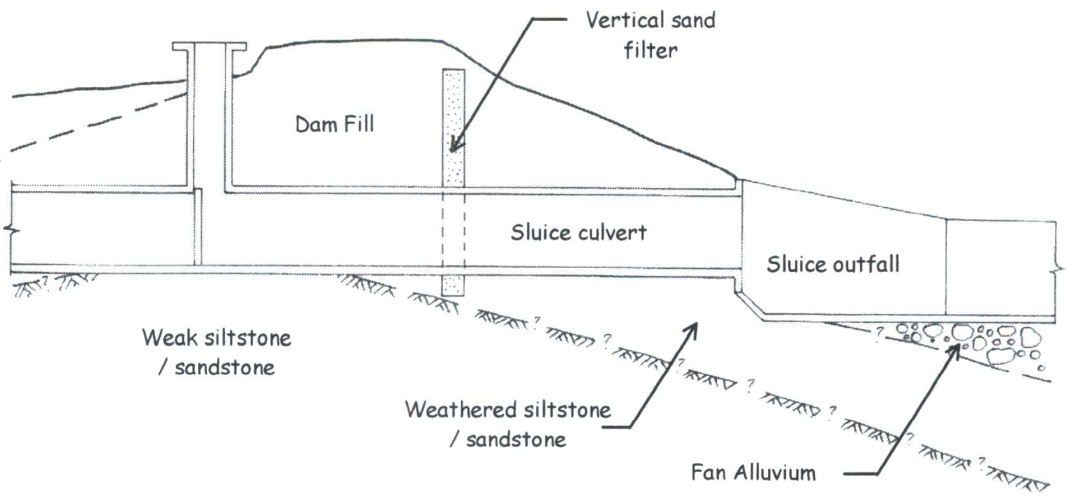

Figure 4. Proposed Vertical Sand Filter

The proposed construction method is to excavate a trench in sections of limited length, working from a benched dam crest. Lake Whakamarino will be drawn down to minimum operating level during the process, exposing a wide siltation beach upstream of the dam. Trial excavations and backup measures in the event that the open cut method proves unsuccessful, will be established prior to construction.

The risk of dam breach associated with foundation piping was the subject of detailed consideration. The following factors mitigate the potential for foundation piping:

- Fine alluvial and pond sediments washed into the upper layers of, and blanketing, the fan alluvium provide a natural seepage barrier that to date has proven resistant to erosion over the majority of the lakebed. Where erosion of these materials into the fan alluvium has occurred, the events have been self-limiting. The events number less than five, most likely 2 or 3, in 61 years of service.

- The fan alluvium is a dense, coarse gravel / boulder deposit, with a dominant coarse fraction that is internally stable.

- The relatively low fines content in the fan alluvium provides a free draining material, capable of dissipating elevated piezometric conditions generated by concentrated leaks. The groundwater level at the dam toe is 1.5m below ground level, and outlet seepages occur greater than 50m (mostly greater than 130m) downstream, under low hydraulic gradients.

Following consideration of the above, it was concluded that although erosion of the materials overlying the fan alluvium may recur at some stage, it is unlikely that this will lead to rapid development (either by backward or concentrated leak internal erosion) of a breach mechanism. In recognition of this no physical work was recommended to reduce the risk of foundation piping, however the implementation of close foundation monitoring procedures, and measures to allow rapid drawdown of reservoir water, were instigated.

CONCLUSIONS

The Whakamarino earth dam was commissioned over 60 years ago, and was constructed on a highly permeable, variable foundation, conditions that today would almost certainly cause some difficulty in achieving an economic solution. Since commissioning, the dam has experienced a number of apparently self-limiting piping incidents: through the foundation via the lakebed at the right abutment, and past the upstream part of the sluice culvert penetration. Despite this the dam has continued to provide 'satisfactory' performance, with the only sign of ongoing deterioration being possible ground deformation associated with the sluice piping. This is however qualified by the fact that the dam has not experienced a significant seismic event.

An investigation and careful assessment of the dam has resulted in the recommendation to reduce the risk of piping failure with the construction of a vertical sand filter. The assessment process was greatly aided by the relatively recent (post 1999) publications on piping failure probabilities from the University of New South Wales, and comprehensive publications on dam risk assessment.

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