Piping Failure of the Poihipi Reservoir

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KEYWORDS; piping failure, active fault, volcanic terrain

ABSTRACT

The Poihipi Reservoir formed a water storage for fire fighting purposes at the Poihipi Geothermal Scheme located near Taupo. Soon after initial filling of the HDPE lined reservoir, the reservoir breached by a piping mechanism. The nature of the failure was remarkable in several respects. The outflow from the breach occurred at two separate locations, located 500m and 300m respectively from the reservoir in opposite directions. The failure seepage path followed a linear active fault which was present beneath the footprint of the reservoir.

This paper describes the mechanism of the piping process, the investigations which were carried out for an alternative reservoir site and the design solutions adopted. A discussion of recent research by Australian researchers on piping failures in the context of this failure is also presented. This event highlighted many risk factors associated with seepage from water retaining structures in general, and specific risks associated with water retaining structures in volcanic terrain.

INTRODUCTION

The original reservoir was located on the top of a hill about 300m west of the power station. It was constructed from local pumiceous gravel, sand and silts. The majority of the reservoir was constructed in natural material with fill used to increase the height of the embankment to the required level on the south side. The reservoir was about 6m deep and was lined with HDPE to prevent water leakage. All seams were site welded. Three pipes penetrated the liner for inlets and outlets (Figure 1).

DESCRIPTION OF RESERVOIR FAILURE

The reservoir began filling in early March 1996. It was noted by site staff that the reservoir was losing a significant amount of water prior to the collapse, particularly in the week prior to the failure. The breach was first noticed at midday on 11 April. Failure is believed to have occurred during the preceding night. Moisture was also noted at the face of the embankment about three weeks prior to the collapse.

The visual evidence of the failure was remarkable. At the reservoir site, a very deep trench occurred diagonally through the centre of the reservoir, and the HDPE liner had been torn completely along the line of the trench (Figure 2). The trench was estimated to be at least 10m deep and up to a few metres in width.

Extensive linear ground cracking, subsidence and heave extended some 500m to the southwest and 270m northeast of the reservoir. The eastern corner of the reservoir wall had collapsed over a width between 4 and 10m, where the service pipes were located. Beyond this point the line of cracking and subsidence veered away from the service pipe trench.

The reservoir water discharged at two main “break-out” locations well away from the reservoir. Beyond the eastern corner a long line of slumping and cracking was visible on the ground surface extending to drill pad 64. This pad was a large flat area created by cut and fill. A series of “erosion pipes” were observed in excavations clearly showing the erosion path (Figures 3, 4).

Figure 1. Original Reservoir during Construction.

Figure 2. View along Failed Reservoir from Eastern Corner.

Figure 3. Breakout Point on Drill Pad 64.

Figure 4. Erosion Tunnel at Drill Pad 64. The Tunnel was Encountered on the Reservoir Side of the Break Out Point.

The reservoir water also discharged to the west of the reservoir. A line of slumping was visible down to the base of a ridge about 250m away. No cracking or slumping was visible until the breakout point at the base of a valley about 500m from and 55m below the reservoir (Figures 5, 6).

Figure 5. Subsidence Extending Southwest from the Western Corner of the Reservoir. The Gully in which the Water Exited (Figure 6) is Beyond the Far Ridge with Trees.

A line of ground cracking was also observable running roughly at right angles to the southeast of the two features described above. The cracking could be followed to the base of a small hill about 50m from the reservoir. Ground cracking was also observed on the opposite side of the hill but there was no indication of a breakout from the reservoir in the area of these cracks.

Figure 6. View Towards South Showing the Main Southern Water Outlet Area and the Flow Path Across the Valley Floor Marked by Sediment.

Figure 7 shows the location of the breakout zones and prominent ground cracking relative to the reservoir. A cross-section is shown on Figure 8.

GEOLOGICAL CONDITIONS

General

The geological conditions at the Poihipi site are typical for the area, where the soils are predominantly tephra erupted from the Taupo Volcanic Centre. At the reservoir site there is a sequence of silts, sands to highly permeable pumice gravels. The site is also transected by a series of relatively closely spaced faults, many of them active. Investigations carried out at the powerhouse and subsequent to the reservoir failure confirms this.

Subsoils at Reservoir Site

Photographs taken during construction show a complex distribution of materials in the excavation. The materials exposed in the reservoir walls comprised young surficial tephras (layers of loosely packed pumice gravel and sand alternating with silty sand layers), loess and, at lower levels, Oruanui Ignimbrite. The ignimbrite forms the engineering basement of the area. This material was typically a tightly packed gravely sand.

The floor of the reservoir was partly on the surficial tephras and partly on loess and/or Oruanui Ignimbrite. The contact was interpreted to be a fault coinciding with the position of the service pipes and the chasm produced by the failure.

Relationship to Faulting

Previous studies for the site specifically addressed geological and seismic hazards. These studies identified possible faults on various orientations in the vicinity of the reservoir. Sections of the ground cracking/slumping coincide with previously identified faults, but none coincided precisely with the failure over its entire length. Figure 7 shows the proximity of the ground features to previously identified or suspected faults.

The faults on the site typically contain a persistent shear plane a few millimetres wide on the up thrown side and a network of discontinuous secondary shear planes on the downthrown side.

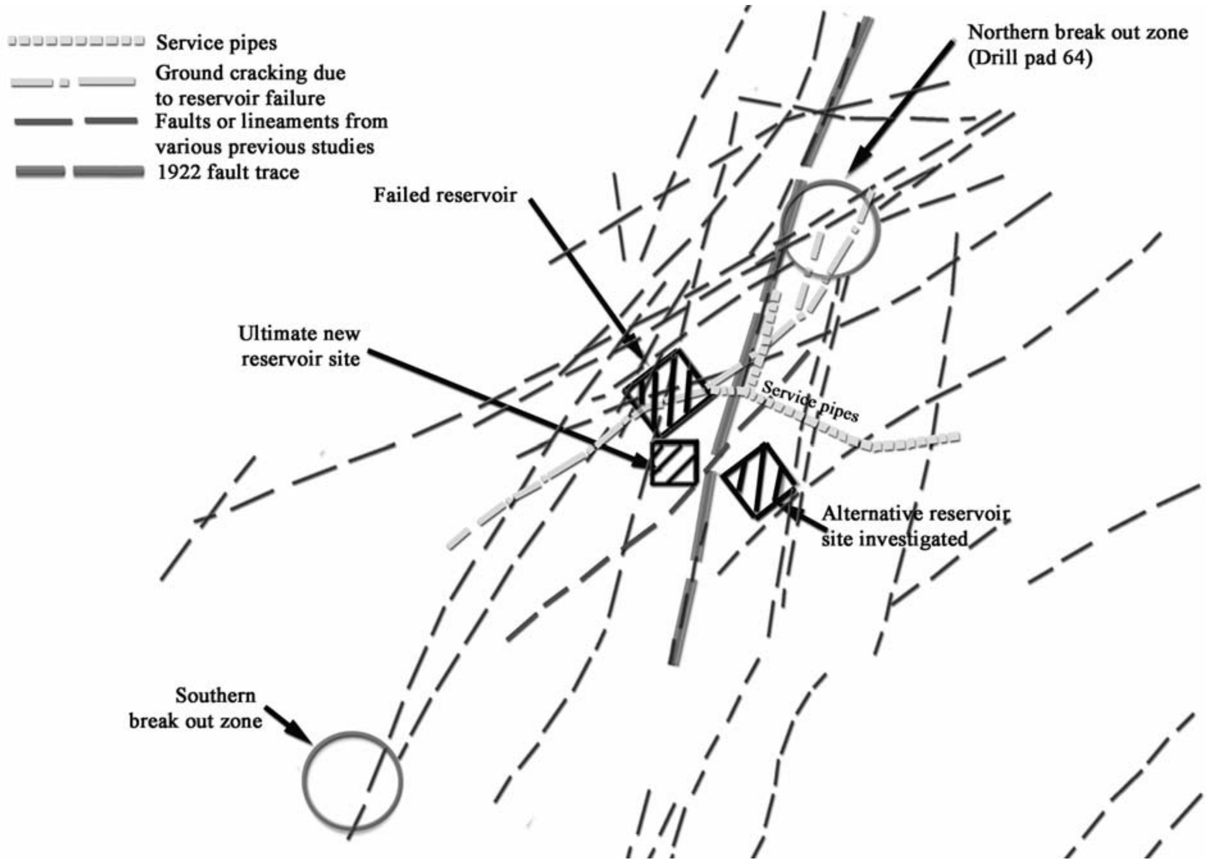

Figure 7. Previously Indicated Faults and Lineaments

REASONS FOR FAILURE

Postulated Mechanism of Failure

The fundamental cause of the reservoir failure was an uncontrolled concentrated leak from the reservoir, which led to internal erosion between a "breakout" point or points and the reservoir. The internal erosion occurred along the weakest line of resistance. The narrow linear nature of the erosion paths over extremely long distances indicate the erosion occurred along faults. The most likely sequence of events leading to the failure is summarised below:

- An initial leak occurred through the liner, most probably in the area where the pipes penetrated the liner.
- Seepage occurred at depth, along paths of low resistance provided by the fault. High pressures occurred because of the confined nature of the seepage path along a thin zone, and the rapid fall in ground contour away from the reservoir.
- Parallel cracking occurred on the ground surface coincident with the leakage paths. This cracking occurred by hydraulic fracturing, which is a phenomenon whereby water pressure exceeds the horizontal stress in the ground and cracks enlarge and propagate to the ground surface. Faults and the junction of the access trench (for the pipes) with natural ground are points of low horizontal stress. The tendency for cracking at the ground surface decreased as the overburden stress increased ie when the seepage path went beneath a hill
- The seepage water broke out at the ground surface when the overburden stress decreased ie at the toe of the slope at the drill pad and/or the valley base. The heaved ground is evidence of high water pressure at depth.
- Internal erosion occurred backwards from the "breakout" point(s) forming a "pipe", progressively back to the reservoir.

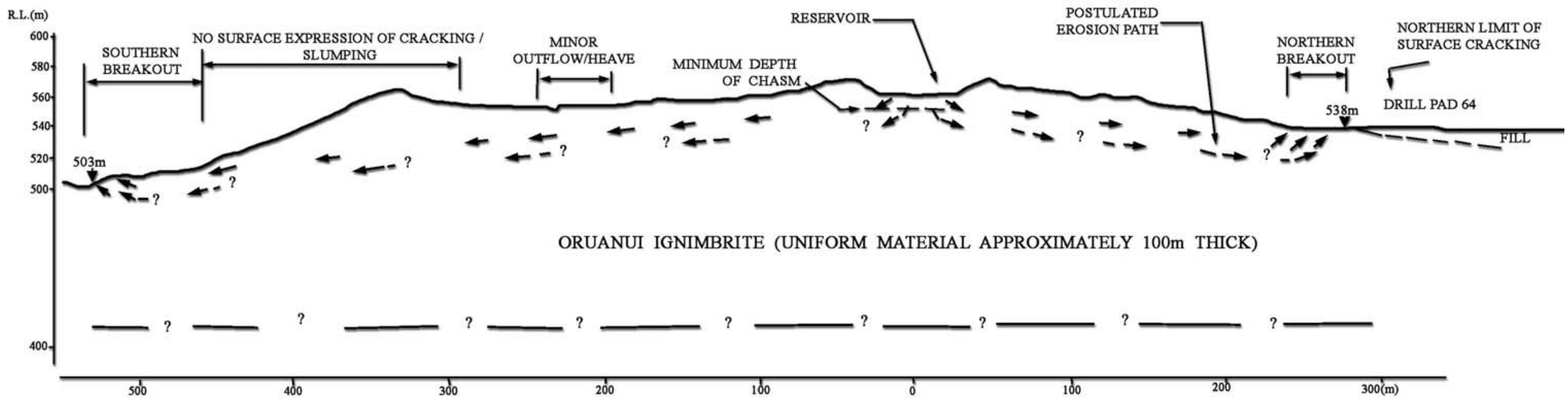

Figure 8. Cross Section along Failure Path

- When the erosion pipe reached the reservoir, material was lost directly beneath the HDPE liner, removing support.
- The liner tore where the support was lost. Leakage then increased rapidly. Multiple flow paths with subsequent erosion were created, leading to total draining of the reservoir.

Reasons for Initial Leak

The most likely point of the initial leak is around the inlet/outlet pipes. At this position several adverse conditions existed:

- The pipes penetrated the liner at several points. The pipes penetrated the liner at a low level, and thus the area around them was subject to maximum hydraulic loads of about 6m of water.
- The trenches carrying the pipes were potential areas of differential settlement, because of the likely difference in compressibility of the trench backfill and the surrounding ground. The differential settlement would put the liner under considerable tension.
- The pipe locations coincided with the fault zone and contact between surficial tephra and loess and the more compact Oruanui Ignimbrite which could also lead to differential settlement.

DISCUSSION ON RECENT RESEARCH ON PIPING FAILURES

International statistics on dam incidents indicate that 2% of embankment dams have historically experienced a piping incident. About 40% have occurred in the foundation and almost half are associated with conduits through the dam. About 64% of failures occur on first filling or in the first five years of operation. In New Zealand, a number of piping incidents and failures have occurred in volcanic materials and the hazards are well known. Statistics on dam incidents in New Zealand indicate that inadequate attention to drainage and presence of volcanic materials are the major causes. 57% of serious incidents occurred in volcanic materials, mostly within the Taupo Volcanic Zone (Riley, 1997). None of the incidents have been directly due to active faulting.

Recent research by Australian engineers has produced a framework to estimate risks of piping for both existing and new dams (Foster and Fell, 2000, Bell et al, 2001). The process of internal erosion and piping is broken up into four phases; initiation of erosion, continuation of erosion, progression to form a pipe, and formation of a breach. The influence of the various factors for the Poihipi Reservoir failure is shown in Table 1. Although the Poihipi Reservoir is only a very small dam (water depth 6m, height of fill embankment <5m), the concept is applicable.

The research and accepted practice indicates that many of the risk factors associated with the site geology and the design adopted were high. However there was a high likelihood of avoiding the breach if expert advice was sought given that seepage was observed and the reservoir was losing water. This reinforces the desirability of expert overview of the commissioning process; even for a reservoir such as this which appears quite innocuous.

There are some features of this failure which are unusual, even in a global context. The predominant unusual feature is that piping occurred along an active fault. A similar mechanism occurred at the Baldwin Hills Reservoir failure which occurred in California in 1963 with the loss of a number of lives (Sherard et al, 1974). Similar site conditions were apparent with cohesive soil overlying a more permeable horizon. This is a dangerous combination for a water retaining structure. The clay layers were sufficiently cohesive to allow very large erosion tunnels to form in the sand layers below. This mechanism was also very evident at the Poihipi site.

At Poihipi, the main influence of the fault is that it provided a low resistance seepage path, and promoted hydraulic fracturing or cracking. Hence minimal head loss due to seepage occurred and the hydraulic gradient associated with the failure is very low at about 0.1. It is thus apparent that hydraulic gradient alone is not a good indicator of the likelihood of a piping failure, especially in these highly erodible volcanic soils. This is also highlighted in Australian research where piping failures and accidents have occurred at gradients as low as 0.05.

Phase of Process	**Factors**	**Assessed Influence or Likelihood**	**Overall Probability**
Initiation of Erosion	Conduit penetrating liner with poor sealing detail	More likely	High
	Differential settlement of trench back fill, vertical sides	More likely	
	Hydraulic fracturing due to low stress zone in active fault	More likely	
	Continuous feature	More likely	
	Silty low permeability layers overlying high permeability layer	More likely	
	Factor of Safety low for blow-out (only in retrospect)	More likely	
Continuation of Erosion	No filter or drainage zones	More likely	High
Progression to Formation and Enlargement of Pipe	Silty materials support a roof of a pipe	More likely	High to Moderate
	Erodible fine sands	More likely	
	Dispersive soil	Unknown probably unlikely	
	Hydraulic Gradient low (less than 0.2)	Less likely	
	No restriction on flows by upstream zones	More likely	
Formation of Breach Mechanism	Small storage	Unlikely	High as occurred but less likely if monitoring procedures were adequate
	Intervention to prevent breach	In hindsight was possible	
		Overall Likelihood	High

Table 1. Influence of Factors on Piping Mechanism

NEW RESERVOIR

It was immediately apparent that the existing site was not suitable. Accordingly an alternative site was investigated on a hill some 100m south of the failed reservoir. A series of trenches were excavated. The main finding was that three closely spaced active faults were encountered. One of the faults, displace the Rotongaio Ash by a small amount; this ash is one of the deposits resulting from the most recent eruption in the Taupo area dated at 1850 years before present. There was evidence of as many as five movements in the past 10,000 years.

The intensity of faulting indicated that it was impractical to avoid the likely presence of active faults; given constraints on reservoir siting. The final site chosen is shown on the site plan, Figure 7.

The geotechnical design principles included the following:

- A continuous 1 metre thick zone of cohesionless filter material was placed as a drainage layer beneath the impermeable liner. This zone also acts as a "crack stopper" because it cannot sustain an open crack.
- The reservoir volume and depth was reduced, compatible with the project requirements.
- Comprehensive monitoring, particularly of first filling, was recommended.

The new reservoir has performed well with no unusual incidents recorded.

CONCLUSIONS

1. The piping failure of the reservoir occurred in volcanic materials in the foundations. A number of similar incidents and failures of water retaining structures have occurred in volcanic materials in New Zealand. Conservative filter and drainage zones for these materials are essential. This point is also emphasised in the New Zealand Society on Large Dams (NZSOLD) Dam Safety Guidelines 2000.
2. This failure associated with an active fault is very unusual. This feature allowed piping failure to occur at a very low hydraulic gradient of about 0.1. The remarkably long failure path lengths of 300m and 500m respectively in opposite directions, is a unique situation with a water retaining structure located at the top of a hill.
3. The following additional factors are highlighted for water retaining structures in volcanic terrain:
    - Cohesive or silty soils overlying permeable strata are a dangerous combination, as they can form a roof to a piping tunnel. Soils with fines content exceeding 15% in the overlying layer are a high risk.
    - Piping failure in these highly erodible volcanic soils can occur at very low hydraulic gradients.
    - The framework for assessing piping risk developed by Australian Researchers is useful for both existing and new water retaining structures. This method is recommended for dam practitioners.
    - Pipe penetrations and conduits penetrating embankments require very careful design.
    - Specialist geological advice should be sought if active faulting is suspected, as at this site they were often very subtle features and could be easily missed. In general, siting similar structures on an active fault should be avoided.

ACKNOWLEDGEMENTS

I acknowledge the permission of Contact Energy to publish this paper.

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