The long-term performance of seepage improvement works at New Zealand dams and canals

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Abstract. Failure modes of seepage and internal erosion have been identified as one of the key issues for the ongoing safety of dams and canals in New Zealand. Accordingly, many dams and canals have had improvement works carried out to mitigate this issue. This paper examines the long-term performance of these measures including three case studies. It is concluded that the performance of these measures has been variable, but ongoing monitoring and periodic review has identified deterioration in performance. There are a number of technical areas where uncertainties on long-term performance may still remain, such as geotextiles in important filter functions and waterstops of various types.

Introduction

Historically, issues associated with seepage and internal erosion have been common in embankment dams of all types throughout New Zealand (Crawford-Flett & Haskell 2016) and (Tate & Matuschka 2011). No complete failures of larger dams have occurred causing loss of life although there have been many incidents requiring emergency actions and subsequent repairs. The purpose of this paper is to discuss the long-term performance of seepage improvement works that have been carried out to address these issues and highlight some matters of interest for the continued safe operation of these dams. Provided these works continue to be monitored, and their performance periodically reviewed, the dam assets should continue to have resilience against further problems.

Some general observations are made on the performance of seepage improvement works that have been undertaken, and several case studies are discussed in more detail.

Background of issues encountered with New Zealand dams

It has been identified that the failure mode of seepage and associated internal erosion is one of the most significant issues associated with New Zealand embankment dams and canals, and probably the most important. In the author's experience, failure mode workshops, which have become increasingly common in New Zealand practice (particularly since the New Zealand Dam Safety Guidelines (New Zealand Society on Large Dams (NZSOLD) 2015) specifically recommended they be carried out for medium and high PIC dams), inevitably identify internal erosion as a key failure mode.

At past NZSOLD seminars, individual papers have been presented on incidents and subsequent remedial works, for example, the internal erosion incidents at Matahina dam in 1967 and 1987, the remedial works at Tekapo canal, and the upgrade of Cosseys dam. A workshop on internal erosion was also organised by NZSOLD in 2011, highlighting the continuing importance of the topic to the dam industry. Since the Canterbury earthquakes seismic resilience of New Zealand dams has come under the spotlight, and the Quake Centre at Canterbury University has implemented a programme of research. The commissioning of a large-scale laboratory permeameter, which will allow research into the seepage performance of New Zealand soils, is presently underway.

The geological environment in New Zealand poses challenges such as dispersivity, erodibility, and internal instability, and the behaviour in these terms of certain types of soils is not completely understood. Also, the relatively high seismic risk throughout most of the country places additional demands on seepage performance of dams although, to date, few dams have been subject to high seismic forces. There are some interesting case histories related to the seismic performance of dams: Matahina dam after the 1987 Edgecumbe earthquake (internal erosion at the left abutment initiated by transverse cracking and concentrated leakage (Gillon 2007)), and the performance of some dams after the severe Seddon and Kaikoura earthquakes. Despite very high seismic loading in the Seddon and Kaikoura earthquakes, none of the dams affected appear to have suffered significant internal erosion; although one dam was damaged, internal erosion does not appear to be the reported cause.

Properties of New Zealand soils that present challenges include dispersivity, erodibility, and internal instability. For example, volcanic soils, particularly of pumice origin such as in the central North Island are very light and susceptible to seepage problems. Glacial soils in the South Island are commonly widely graded, of nil to low plasticity, and often exhibit internal instability.

Modern design practices can mitigate these geotechnical uncertainties and challenges by a range of measures including installing filters to control seepage and internal erosion; however, many older dams do not have filters or drains that conform to modern standards and criteria, and some smaller dams may not have any filters at all i.e. homogeneous dams.

Reasons for a requirement to undertake remedial works

As a result of the above issues there is often concern regarding the performance of a dam with respect to seepage and internal erosion. Typical reasons for works to be undertaken or considered for a dam or canal include:

- Uncontrolled seepage is observed at or near the toe of the dam or abutments; this could be a new wet area or historically wet such as reeds growing. Sometimes seepages may be associated with initiation of internal erosion although this is not common. Clearly, initiation of internal erosion or evidence of muddy seepage water is of significant concern.
- Monitoring instruments such as piezometers or flow monitoring points detect an adverse change in seepage conditions. This could be either a flow increase or flow decrease. There may be visual evidence of a change in conditions as well as a trend in instrument readings although this is not always the case.
- A safety review may highlight issues such as uncertainties in filter performance, or risks of internal erosion may be considered higher than tolerable for the potential impact classification of the dam.
- There may be a lack of appropriate filter protection or drainage as many dams do not have continuous filter protection, such as chimney drains or foundation blanket drains.
- There may also be concerns on overall slope stability or seismic resistance that relate to high piezometric levels.

Typical remedial works undertaken

A range of measures have been adopted to mitigate concerns on seepage and internal erosion.

It is noted that extensive literature is available on worldwide experience with seepage improvement measures. The measures are in two main categories: seepage reduction and drains/filters. Some typical examples include:

- Cut off within the dam or abutment (e.g. steel sheetpiles, bentonite slurry).
- Grouting.
- Low permeability liners (e.g. clay or HDPE).
- Additional drains and/or filters.
- Toe or trench drains, blanket drains, bored drains, wells are variants (sometimes using geotextiles).
- Buttressing earthfill or rockfill usually in association with additional filters/drains.

Associated with the above physical works it is common to adopt enhanced monitoring e.g. additional piezometers, flow monitoring points, and visual inspection.

Observations on performance of remedial works

Overall there is some variability in the long-term performance of remedial works undertaken. Whilst the majority of works have been completely successful, with no adverse trends or concerns on performance, some issues have become apparent. In some cases, remedial works have been in place for a considerable time e.g. from the 1970s or 1980s, or even earlier. There are some examples in New Zealand where a dam has a long history of seepage problems and issues, and attempted remedies have met with varying degrees of success. Some key observations are:

- Visual observation often pick up a deterioration in performance.
- There may be a slow adverse trend in piezometric levels and drainflows, or sometimes a change may be dramatic over a short time period.
- Where improvement works have incorporated modern design practices, performance has been satisfactory (e.g. filters meet no erosion criteria, adequate drain capacity, and construction has followed the design).
- There are examples of technical issues such as geotextiles partially clogging with time and deterioration of various types of waterstops.

Comprehensive safety reviews should evaluate the design and performance of the improvement works. Some concepts that have been used in the past, such as the use of geotextiles for filter protection in the late 1970s and 1980s in critical locations do not meet current practice. It should not be assumed that long-term adequate performance is necessarily assured.

Case studies

The following case studies demonstrate various types and combinations of improvement works. The author has been involved with each of these projects.

Ratapiko dam

Ratapiko dam is a 12m high earthfill dam located in rural Taranaki, the dam forms part of the headworks of the Motukawa hydro scheme owned by Trustpower. The dam was commissioned in 1927 and the original construction applied the puddle clay core technique. The dam has a long history of performance issues and remediation works. A chronology of events is as follows:

Date	Issue/event	Action/Detail*
1927 to 1930s	Leakage through dam/abutments	Core replaced, issue not resolved, steel sheet pile on right abutment in sand layer
1960s	Leakage continuing, toe of dam showing signs of instability	Excavation and re-compaction of material
1988 to 1992	Severe toe slumping	1992 buttress fill at toe
1994	Extensive investigations/remediation works	Various additional drainage works at dam toe and left abutment in sand layer, extensive monitoring network
2000 to 2015	Slowly increasing trend in piezometric levels	2015 report addressed these issues
2018	Additional investigations and assessments of seepage issues	2018 reports on further remediation options

*(Riley Consultants Ltd 2018)

Seepage issues observed at this dam are principally related to permeable sand layers at the abutments, which have saturated the toe of the dam (Refer Figure 1 and Figure 2). The original steel sheet pile wall on the right abutment appears to have performed well over a long period and a significant head loss is recorded in piezometric levels either side of the wall and with no uncontrolled seepages. The 1994 works showed satisfactory performance for a time i.e. reduction in piezometric levels and control of seepage in the critical toe area of the dam. However, there were concerns of a slow deterioration in performance over a period from 2000 to 2015. The key observations were that total drainflows decreased from an average of 174 litres per minute in the three years after 1994 to an average of 50 litres per minute by 2015 (Refer Figure 3). There were also corresponding increases in piezometric levels although individual trends were complex. The most marked increases were at or near the dam toe where increases of 0.8m to 1.5m were recorded. This was about 500mm below ground level (Refer Figure 4).

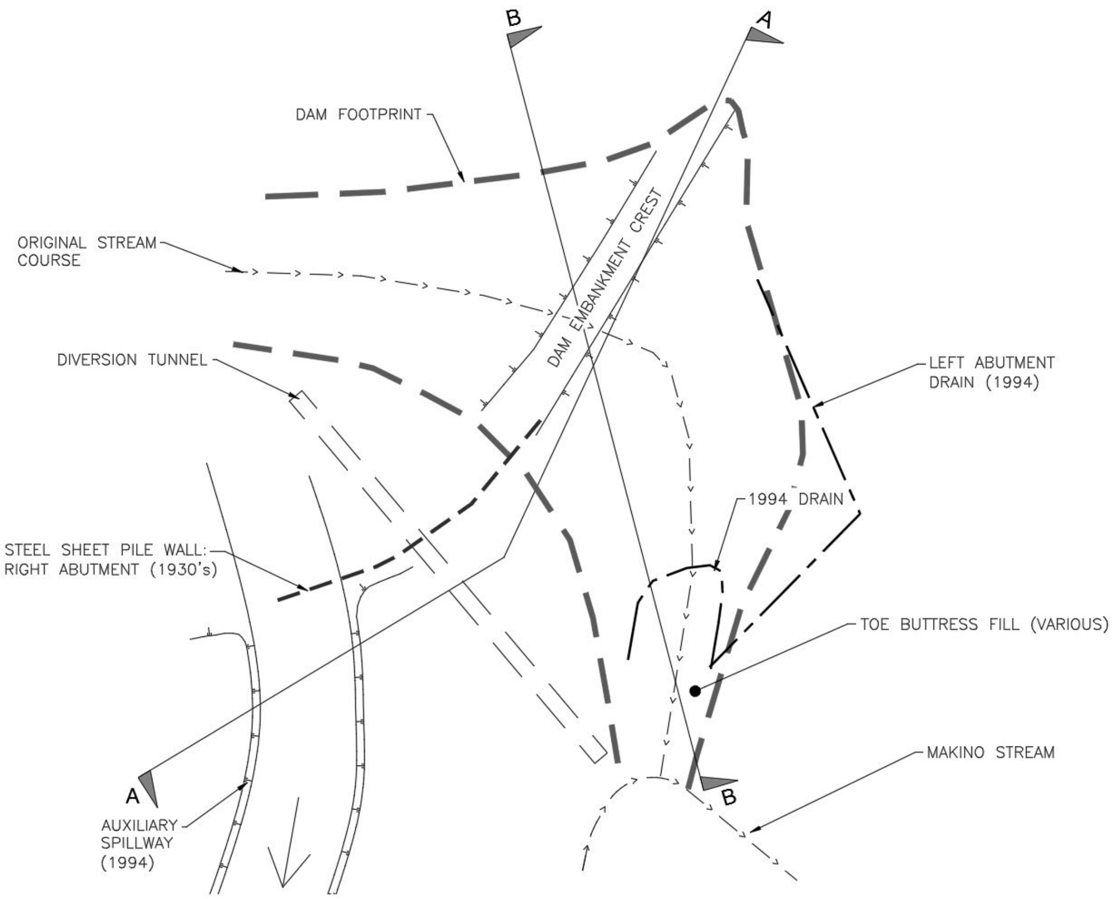

Figure 1: Ratapiko dam plan

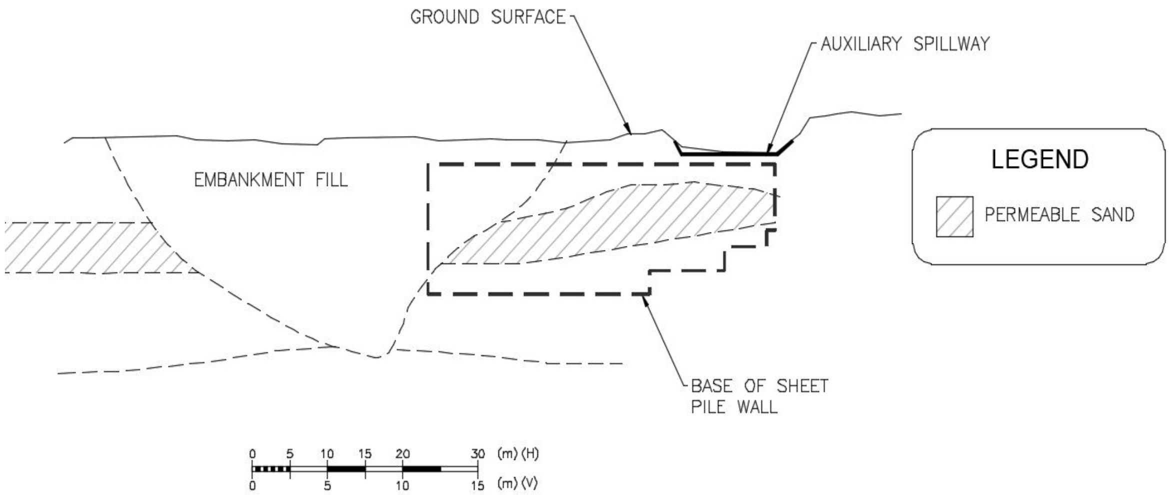

Figure 2: Ratapiko dam elevation cross section A

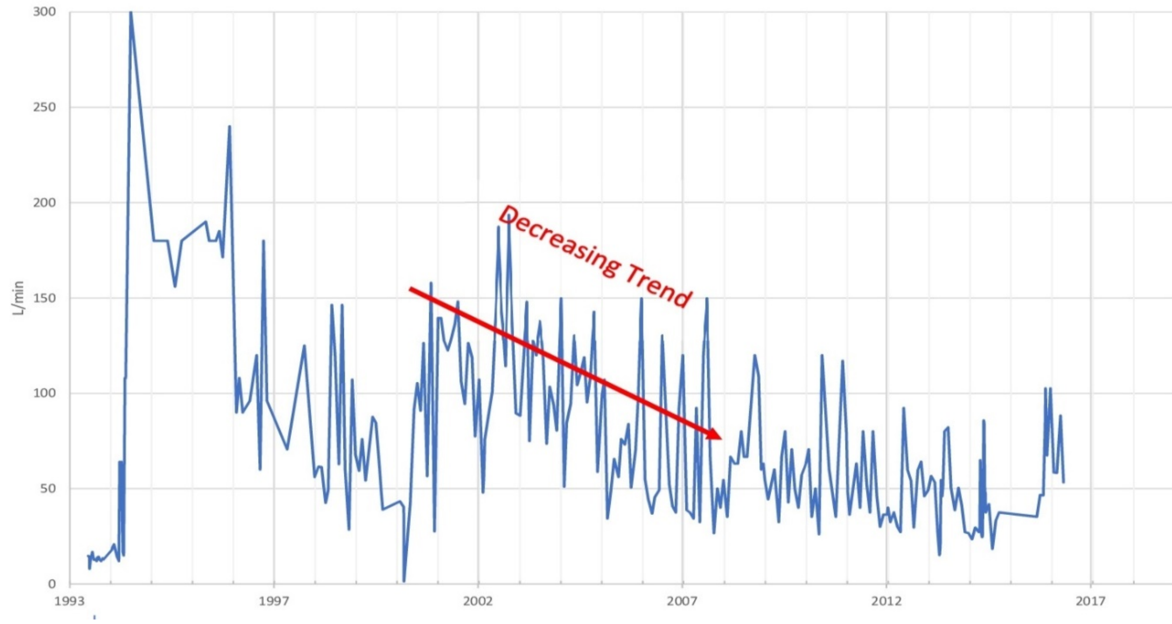

Figure 3: Ratapiko dam measured drain flows after 1994 works (largest outlet flow)

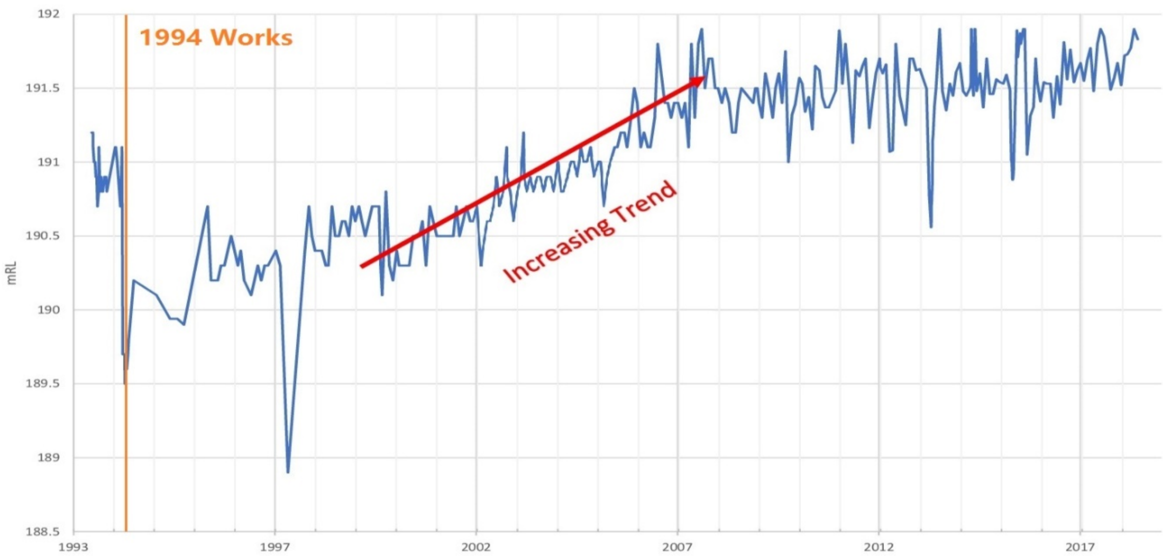

Figure 4: Piezometric level (near dam toe) before and after 1994 works

Investigations in 2018 highlighted the following key points:

- The left abutment drain in the sand layer has a high capacity, well in excess of the recorded flows, and largely meets no erosion criteria with respect to the permeable sand (Refer Figure 5).

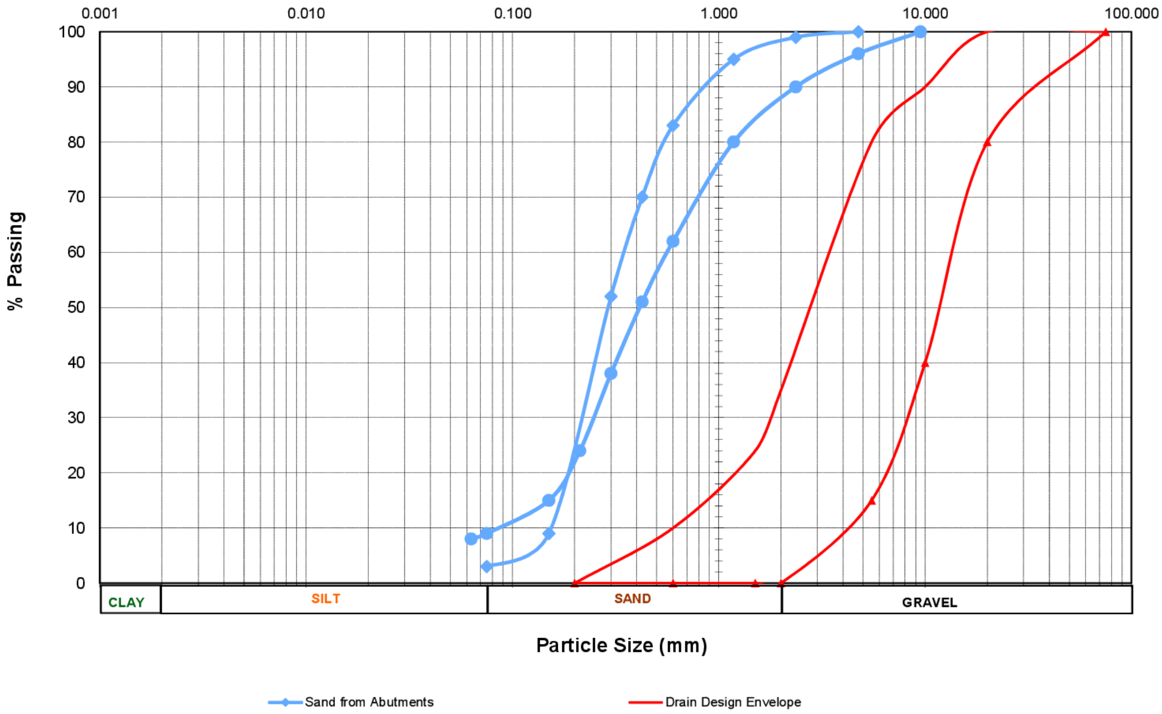

Figure 5: Grading curves of in-situ sand and drainage material

- The deterioration in drain performance, as evidenced by increasing piezometric levels and decreasing drain flows, is largely related to the low capacity of the trench drain at the dam toe, although the drain meets the no erosion filter criteria. It is also postulated that some clogging of the drainage system may have contributed to the deterioration. Investigations showed that either side of the drain. there was a similar piezometric level whereas some head loss would be expected (Refer Figure 6). If the drain was fully effective, seepage flows would flow into the near-vertical trench drain and reduce the piezometric level on the downstream side of the drain.
- The sand materials are susceptible to liquefaction, which has serious implications for dam stability by several mechanisms.

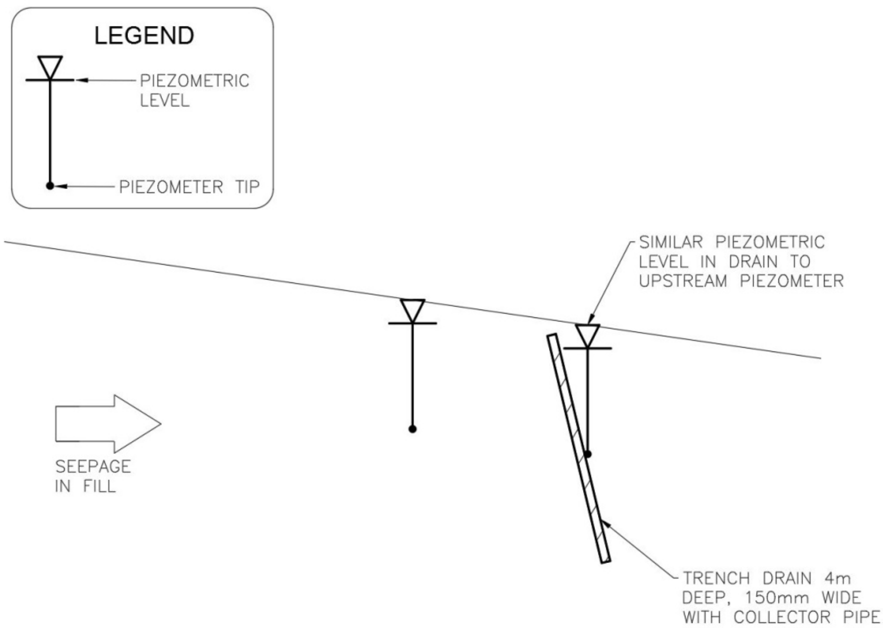

Figure 6: Piezometric levels and 1994 trench drain

The 2018 reports recommended further remediation involving a fully intercepting filter to the dam crest and associated buttressing and higher capacity drainage in the dam toe area. At this stage, preliminary design concepts have been developed. The proposed filter layer is placed over the full extent of the downstream face and extends up to the dam crest. At lower levels a three-layer drain increases flow capacity where piezometric levels are highest and is covered by the fill buttress (Refer Figure 7).

Overall, the seepage issues at this dam have been challenging to overcome, even in more recent remediation works. The advantages of ongoing monitoring of performance detecting deterioration is highlighted along with ongoing intermediate and five-yearly comprehensive safety reviews reinforcing these concerns.

Wheao and Flaxy forebay structures, canals at Wheao hydro scheme

In 1982 the Rangitaiki canal breached at or near the penstock intake structure at the Wheao hydro scheme. The scheme is located in extensive pine forest in a remote area to the north-east of Lake Taupo in the central North Island. The key water retaining structures on the Wheao scheme include two canals (Rangitaiki canal and Flaxy canal) and a number of small concrete and earth dams. The failure highlighted seepage risks associated with the volcanic terrain of the central volcanic region of the North Island. The various water retaining structures at the scheme were reviewed in detail, and a significant number of improvements made. The forebay at the Rangitaiki canal was moved upstream to a more favourable position, and an extensive concrete lining installed to reduce seepage with a continuous drainage layer installed beneath. Defects in the ignimbrite rock were treated extensively; the lack of such treatment in the original design was one of the key factors in the 1982 failure. The forebay area at the Flaxy canal was improved in a similar manner even though no problems had been experienced in the commissioning process. An extensive monitoring system was installed that included piezometers, and measurement of drain flows. The concrete lining to minimise leakage was only utilised in the most vulnerable part of the canal system at each forebay and a short distance upstream. In the remainder of the canal system the original brown ash lining remained as the low permeability barrier.

The repaired areas operated without incident for about 25 years. After this time, however, both forebay areas suffered deterioration as evidenced by increased leakages that were detected by the monitoring system (Refer Figure 8). The following describes the repairs at the Flaxy forebay. Dewatering and shutdown of the canal was required to allow further repairs to be made in 2009, as shown in Illustration 1. The joints between concrete sections had deteriorated and allowed increased amounts of water through. There was no indication of any threat of an uncontrolled failure as the drain systems controlled the increased leakage, and there was no visual evidence of water breaking out in an uncontrolled manner, i.e. downslope of the forebay area as had occurred in the 1982 failure.

Illustration 1: Dewatered forebay area in 2009

The Flaxy forebay remedial works was a particularly challenging design as the new concrete lining had to be attached to an existing concrete intake structure with vertical walls (Refer Figure 9). The detail used was a stainless-steel strap bolted to the existing and new concrete, which was the primary waterstop. The new concrete slab was locally thickened and attached to the existing wall with dowel bars. A gap (20mm) was designed between existing and new concrete with sealants within the gap. This was regarded as a secondary waterstop and would rely on adhesion to maintain a seal. When the canal was dewatered and inspections were carried out in 2009 it was clear that this sealing detail was ineffective. It was replaced by a proprietary product that could accommodate movement. The work involved replacement of the damaged sealant with a new sealant product and an exterior waterstop to replace the stainless-steel strap. The exterior waterstop comprised a Hypalon sheet embedded in an adhesive that was fitted to the concrete (Refer Figure 10). The work was undertaken by specialist contractors with continuous supervision by an experienced engineer. In the 10 years since the repairs were made, the performance has been satisfactory, and leakage has been reduced to background levels. The lessons learned here are that the designed remedial drainage system and monitoring had quickly picked up a deteriorating situation, and the conservative design had ensured no risk of an uncontrolled release of water. A lack of appropriate monitoring in the original design had been highlighted in the reports on the 1982 failure. In the original failure there was no formal monitoring regime, and it was postulated that there would have been observable signs of distress, such as uncontrolled seepages that would have been a precursor to the failure. In the remediation works for the scheme after the failure, monitoring of performance was an integral part of the dam safety management system that proved effective in practice.

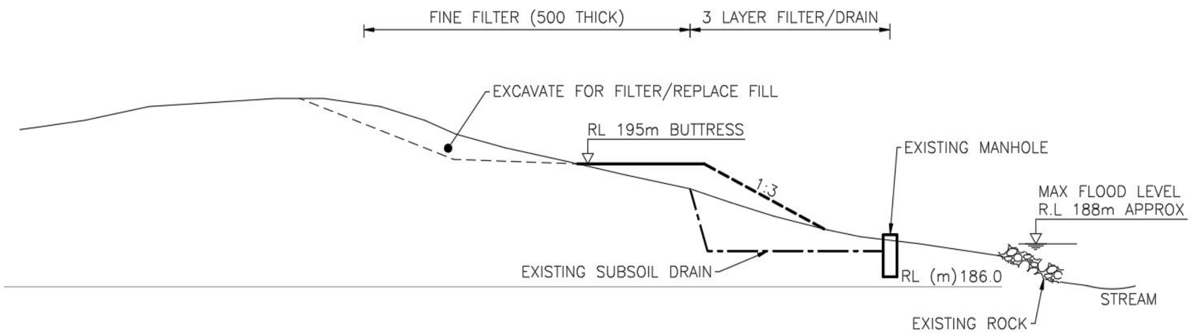

Figure 7: Ratapiko dam cross section B

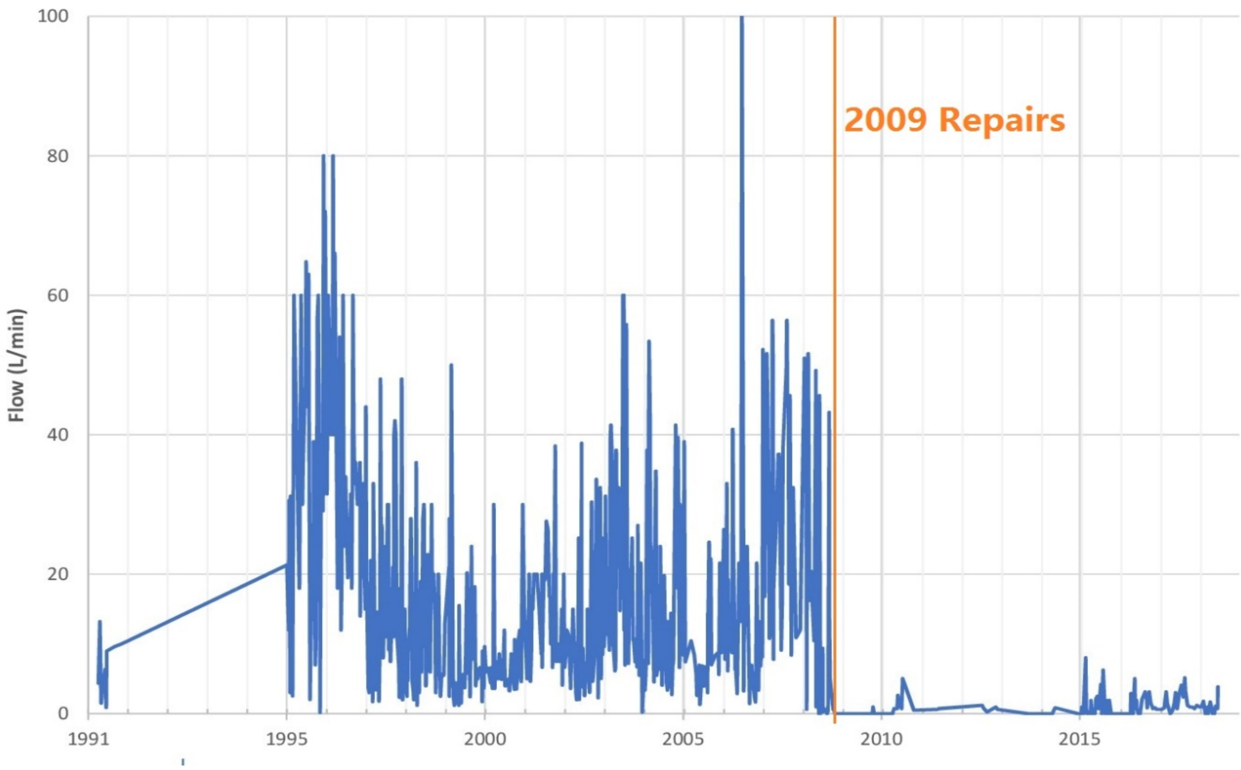

Figure 8: Flaxy forebay measured drain flows

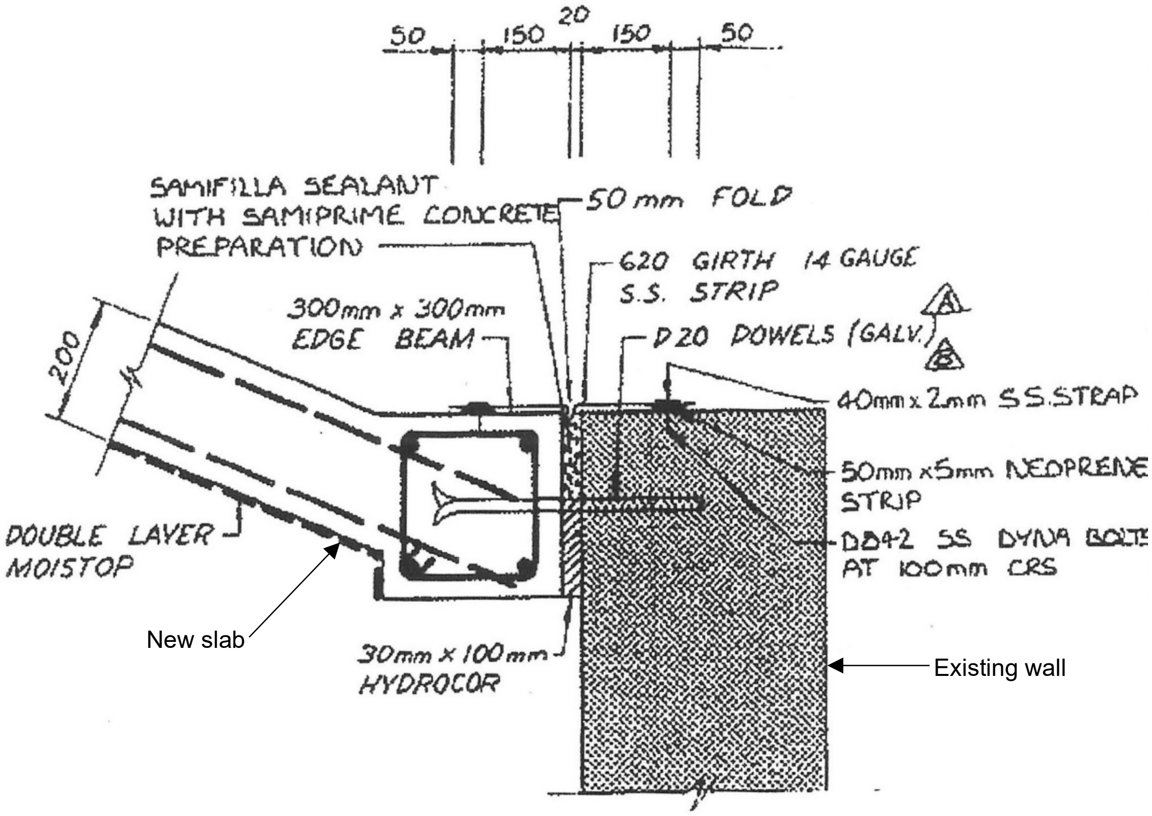

Figure 9: Flaxy forebay sealing detail – 1983

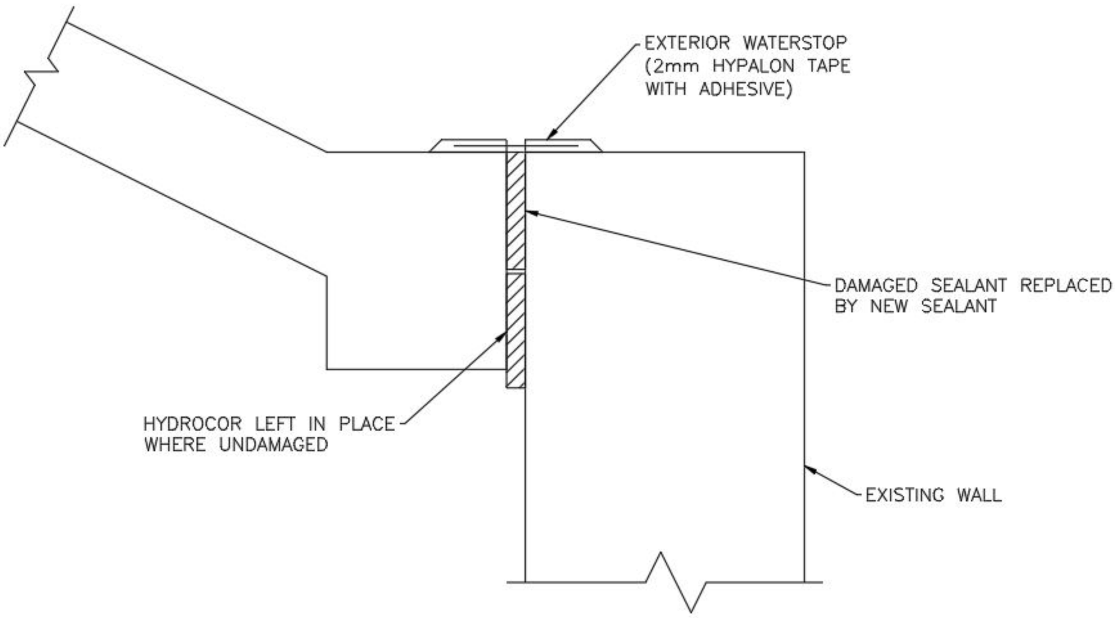

Figure 10: Flaxy forebay replacement detail – 2009

Buttressing of an earth dam (Dam A)

Dam A was designed and constructed in the mid-1960s with a height of about 15m. It was essentially of homogeneous construction with borrow materials described as gravelly silts. The dam abutments comprise weathered volcanic rock, whilst the central section is founded on deep alluvial deposits. Seepage problems, as evidenced by wet areas on the downstream face, were identified soon after lake filling and subsequent reports identified the following contributing factors:

- Poorly supervised construction.
- Inadequate compaction of fill material.
- Progressive deterioration of the borrow source with lower proportions of fine-grained materials.
- Highly jointed rock in the left abutment with some open joints leading to high permeability.

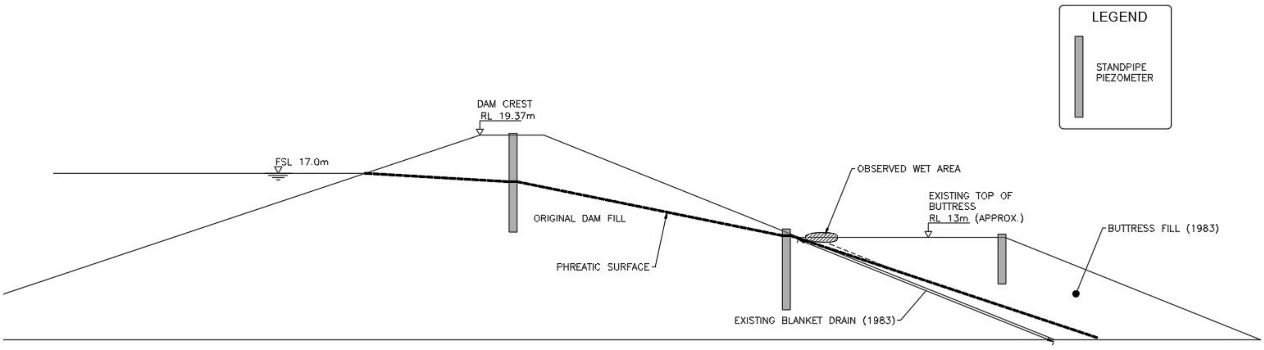

Figure 11: Dam A typical section

Increase in seepage in 1979 prompted investigations by a consultant. The outcome was the construction of a fill buttress to the downstream shoulder in 1983, incorporating a drainage blanket wrapped in geotextile (Refer Figure 11). The drainage blanket and buttress only extended to partway up the dam height, presumably to where seepage was observable on the dam face. The emergence of seepage at this location was related to the high horizontal permeability of the dam fill and likely some influence from seepage at the left abutment. Intermittent seepage monitoring continued up to 1995 when an inaugural dam safety evaluation was completed. At that time, a number of investigations comprising a series of deep machine boreholes, cone penetrometer tests, and installation of standpipe piezometers were undertaken as seepage was still apparent in some areas and there were still some uncertainties on seepage performance. In 1998 further works were undertaken: an array of horizontal bored drains into the base of the toe buttress and a trench drain adjacent to the left abutment where wet areas had persisted (Refer Figure 12). The bored drains were installed to draw down the phreatic surface at this location.

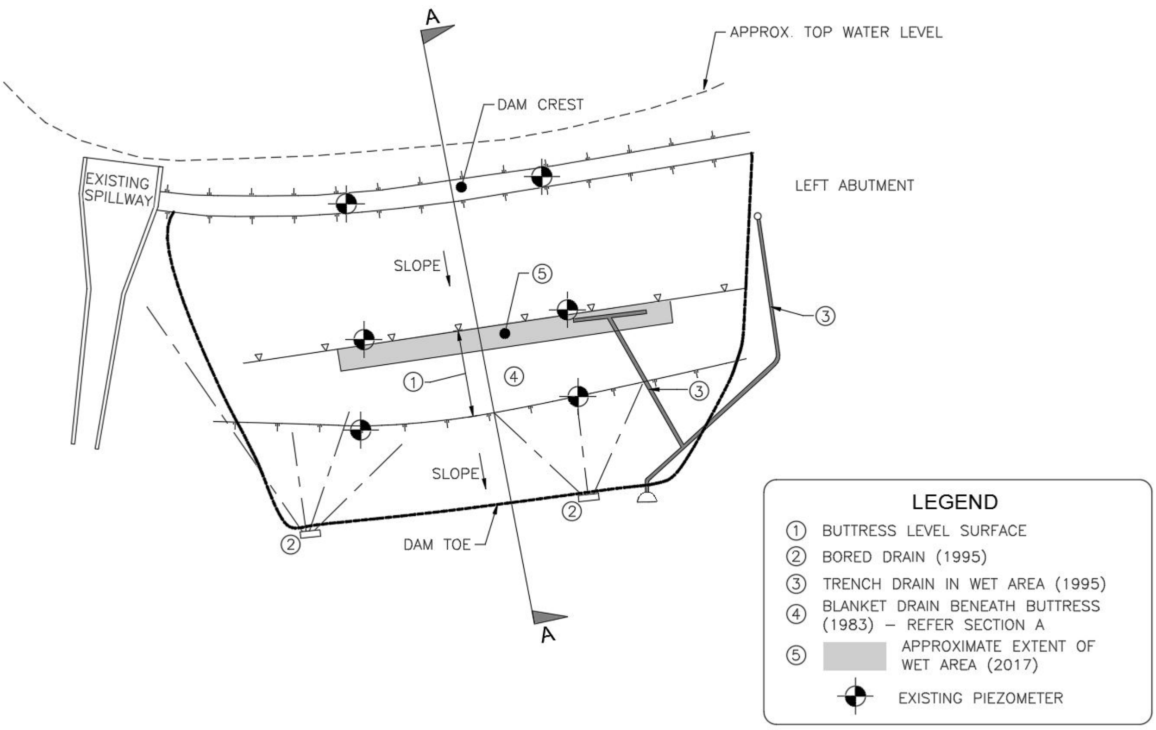

Figure 12: Dam A site plan

In 2017 an intermediate dam safety review identified that a new wet area was apparent on the buttress surface (Refer Figure 11), and further investigations were recommended on possible causes and remedial options. The author was involved in recent 2018/2019 investigations and implementation of additional shallow drainage trenches. Some surprises arose from this investigation; it appeared that the geotextile may not have extended as high as drawings indicated and the wet areas may be due to local filter incompatibility between the dam fill and the coarse drain material. Further down, the seepage appeared to be adequately controlled as the buttress was mainly dry, and 1983 photographs show the geotextile was present in the mid to lower sections of the buttress. The installation of further piezometers is pending as the seepage regime at present is not fully understood, although recent investigations have provided very useful information. The 1983 and 1998 remedial works have improved seepage control and overall stability but have not conclusively mitigated the seepage issues.

Again, the experiences at this dam have highlighted the importance of continued monitoring and intermediate safety reviews. The 1983 work was not well documented from the construction phase, for example, no completion report was available, and it appears the design was not followed correctly in some respects. The code of compliance regime implemented by regional councils in 2008 as part of the Building Act has improved transparency of required inspections and reporting by the designer during construction.

Conclusions

1. Many embankment dams and canals in New Zealand have had issues with seepage and internal erosion, that have required physical improvement or remedial works. It is considered that the performance of these works has been variable.
2. Ongoing monitoring and review of performance of these works has identified deterioration or uncertainty in performance over time in some cases.
3. It should not be assumed that long-term adequate performance is necessarily assured.
4. There are a number of technical areas where uncertainties on long-term performance may still remain e.g., geotextiles in important filter functions; filters coarser than modern no erosion criteria or drains with inadequate capacity; internal instability of widely graded gravels; and waterstops of various types.

Acknowledgements

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