Embankment Failures – Local Experiences

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ABSTRACT

There have been six embankment dam failures, 40 notices issued for non-compliance with the Building Act (2004), and five abatement notices issued under the Resource Management Act (1991) in respect to small irrigation dams in Otago since 2011. Investigations into three failures in Otago, and one access embankment on the West Coast, are used to illustrate common mechanisms of failure and how these could have been mitigated by good engineering practice. Each case study is summarised, a probable failure mechanism postulated, and remedial measures to avoid recurrence identified. These case studies present common examples from the spectrum of failures associated with these structures, including: foundation/fill contact piping, spillway failure, piping of the conduit, and overtopping. Common design elements to prevent, minimise the likelihood of, or safeguard against failure are introduced, and the challenges of implementing these post-failure emphasized. Because failures tend to develop very rapidly, the importance of getting the right level of design input and QA with any potentially hazardous water retaining structure, irrespective of the size of the structure, is emphasized.

Keywords: embankment dam failure, earth dams, small dams dam failure, dam failure statistics

1 INTRODUCTION

Agricultural intensification and over-allocated water resources have resulted in increased demand for decentralised irrigation water storage across Otago. Earthfill dams are a popular choice because they have comparably low operating costs, can supplement water rights by harvesting catchment runoff, and can be built at relatively low cost from on-site materials. They are, however, potentially hazardous structures should their contents be released in the event of a failure, and thus require sound engineering knowledge and construction experience to minimise the risk to downstream receptors.

This paper discusses recorded small dam failure experiences in Otago since 2011, focusing primarily on the technical aspects such as mechanisms of failure, remedial options, and consequences.

2 IRRIGATION DAMS IN OTAGO AND NON-COMPLIANCE ENFORCEMENT

Otago is the second biggest irrigated region in New Zealand, contributing 15% (c.86,000ha) of the overall irrigated land (Heiler, 2014). Farms are often remote, have intermittent or unreliable water supply, and lie within ephemeral catchments. These factors make them good candidates for a dam.

In the author's experience, a typical farm dam would be ~2-4m high, have batter slopes of 3:1 (H:V), a 3m crest width, include a low-level pipe conduit, be constructed of homogeneous alluvial/aeolian/lacustrine silt and have the potential to store <50,000m^3. In fact, many are intentionally built below the 'large dam' threshold (being dam height ≥4m high <u>and</u> potential to store ≥20,000m^3 of water or other fluid, (Building Act, 2015)) to avoid the requirements for a building consent and for a code compliance certificate (CCC). Many are constructed without specific engineering design, construction supervision, or compaction verification.

Irrespective of the location, size, purpose, or need for a consent, dam construction is building work and must comply with the Building Act (2004) and relevant provisions of the Resource Management Act (RMA) (1991) and Regional Plan: Water (ORC, 2015). The New Zealand Dam Safety Guidelines (NZSOLD, 2015) are the most common means of demonstrating compliance with the building code.

The Otago Regional Council (ORC) is responsible for issuing building consents for large dams and compliance matters for all dams in Otago. Since 2011, the ORC has documented six dam failures, issued 40 notices to fix for non-compliance with the building code, and five abatement notices for dams in breach of the RMA (refer Figure 1). These equate to approximately one incident per month. The most precarious dams in the database are summarised in Table 1.

In some cases, the dam was in the process of failure at the time of inspection. In others, the dam failed a short time after the notice to fix was issued. Some owners were issued with multiple notices to fix for the same non-compliance before the dam was removed or certified. One owner was prosecuted for repeated non-compliance.

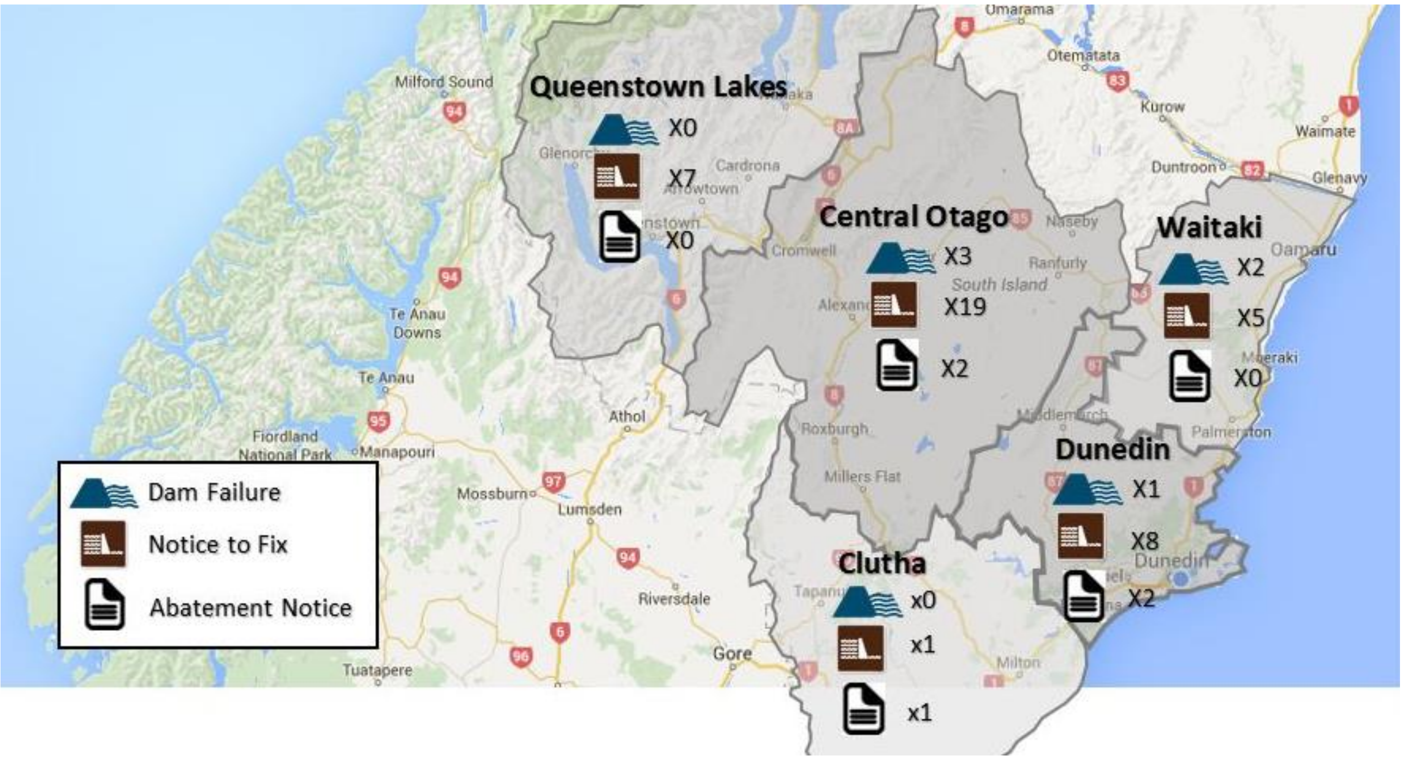

Figure 1. Failure rates and dam enforcement for dams in Otago since 2011.

Table 1: Dam Enforcements in Otago since 2011 (case studies 12 to 14 included in Section 3)

Ref.	Date NTF issued	Location	Stage			Non-compliance					
			Imminent risk	Incipient	Failure	Compaction	Fill Materials	Pipe conduit	Erosion Protection	Spillway	Seepage
1	Mar 2011	Dunedin		X						X	
2	Mar 2011	Waitaki			X				X		
3	Mar 2011	Waitaki			X		X		X		
4	Apr 2011	Queenstown Lakes	X							X	
5	May 2012	Queenstown Lakes	X							X	
6	May 2012	Waitaki	X			X	X		X		X
7	Aug 2013	Dunedin	X				X			X	
8	Aug 2013	Dunedin	X		X				X	X	
9	Dec 2013	Central Otago							X	X	
10	Mar 2014	Queenstown Lakes		X		X	X		X		
11	Apr 2014	Central Otago	X			X	X			X	
12	Oct 2014	Central Otago			X	X	X				
13	Feb 2015	Central Otago			X	X	X	X	X		X
14	Oct 2015	Central Otago			X			X			
15	Mar 2016	Dunedin	X			X	X	X	X	X	X
16	Mar 2016	Clutha District	X			X	X		X	X	
Total			8	2	6	7	9	3	9	9	2

The case study database indicates:

- Non-compliant dams are a widespread issue across Otago rather than isolated to one location;
- Improper fill materials, poorly designed or inadequate erosion protection, and inadequate spillway provisions are the most common non-compliant features of these dams;
- The majority of non-compliant dams were deficient for more than one reason; and
- Intervention by ORC may very well have prevented or reduced further damage.

3 CASE STUDIES

The following case studies illustrate the four of the most common mechanisms of failure from the Otago record: foundation piping, spillway erosion, piping along the conduit, and overtopping. These are consistent with international experiences of embankment dam failures (Table 8.1. Fell et al. 2015).

Each dam/embankment discussed is classified as small and low potential impact (PIC). Three of the four had no specific engineering design, construction supervision, or compaction verification. Failures were initiated rapidly, occurring under normal operating or flood conditions, often shortly after construction upon first filling. All have since been remediated with no signs of ongoing distress reported.

Discussions with contracting staff and owners, combined with information sourced from post-failure inspection of the dam and surrounding environment, were used to postulate probable failure mechanisms. Remedial measures to avoid future such failures are then identified with concluding remarks summarising the key lessons learnt.

Figures 2 to 5.Clockwise from left:
Figure 2 Case Study A – Foundation piping failure at downstream dam toe immediately post failure;
Figure 3 Case Study B – Erosion of spillway throat and deposited sediment down plain post failure;
Figure 4 Case Study C – Piping failure around conduit viewed from the downstream toe during failure;
Figure 5 Case Study D – Crest overtopping during flood.

3.1 Case Study A: Foundation Piping - DS0172 (Figure 2, top left)

This dam was constructed to provide short-term irrigation storage while a larger dam was constructed downstream. Compaction was stated in 300mm lifts using scrapers and a smooth drum roller.

Dam type: Homogeneous earthfill of non-plastic silty gravel/gravelly silt materials
Maximum dam height: 3.95m **Storage potential:** ~30,000m^3
Upstream batter slope: 3:1 (H:V) **Downstream batter slope:** 2.5:1 (H:V) **Crest width:** 3m
Geological setting: shallow alluvial and lacustrine sediments overlying sedimentary rock (mudstone)

Failure mechanism: Seepage at the foundation contact leading to headward void migration and subsequent piping failure soon after first-filling. This is one of the most common form of distress on initial filling of a reservoir.

Principal contributors to the failure include:

- Planar compaction surfaces with rare clumps of turf that would tend to facilitate piping
- Permeable gravel lenses providing an environment that readily transmits high pore water pressures at the foundation interface
- Sinkholes observed in the reservoir floor suggesting permeable gravel lenses do not meet filter compatibility with overlying silt

Downstream consequences: Erosion of pasture; scour of an unsealed public road; damage to a buried power cable; floodwaters approached within 5-10m of an occupied dwelling; discharge of sediment into receiving waterways.

Remediation: Undertake engineering inspection of the stripped foundation, investigate the persistence of permeable strata at/near foundation level, reduce compaction thickness, utilize a sheepsfoot roller. A new keyway and additional shoulder material was formed on the upstream dam slope.

Lessons learnt: Foundations preparation should include: 1) removal of all organic/soft materials, 2) scarification, and 3) moisture conditioning, and use of a sheepsfoot or padfoot roller to ensure a good bond between the embankment fill and foundation materials. A rigorous ground investigation should identify the potential for high-permeability conduits near the foundation, and a sufficiently deep cut-off included in the design as appropriate. Construction plant should be suitable for the soil type and fit for purpose.

3.2 Case Study B: Spillway Failure – DS0173A (Figure 3, top right)

This dam was constructed progressively over three years using predominantly site-won loess soils. Water enters the upper dam via. a 32ha upstream catchment and from neighbouring irrigation races.

Dam type: Twin homogeneous earthfill ring dams of non-plastic silt (loess), connected in series
Maximum dam height: ~3m **Storage potential:** ~20-30,000m^3
Upstream batter slope: 3-4:1 (H:V) **Downstream batter slope:** 3-4:1 (H:V) **Crest width:** 3m
Geological setting: alluvial and lacustrine sediments overlying sedimentary and volcanic rock

Failure mechanism: Erosion of the spillway lining and part of the embankment during sustained rainfall of moderate intensity (20-30mm of rain over 24hrs).

Principal contributors to the failure include:

- Incompatible liner materials, being coarse graded riprap overlying erosive/dispersive silt
- Coarse riprap tending to induce turbulence causing entrainment of finer soils
- Hydraulically steep spillway (embankment slope ~15-20°)
- Flows of damaging magnitude entering the reservoir from an external source, possibly from sidling runoff beyond the natural catchment conveyed into the reservoir via a water race

Downstream consequences: Erosion of pastures; discharge of sediment into multiple receiving waterways.

Remediation: A new spillway with riprap liner and geotextile underlay was formed into natural soil.

Lessons learnt: Spillways are high energy environments where scour is often exacerbated by steep hydraulic gradients and liner roughness. Riprap is a suitable means of erosion protection, but should include appropriate bedding or geotextile at the embankment interface. Wherever possible, spillways should be formed away from the dam into competent erosion-resistant material. Inflow design floods, on which spillway capacity is designed, should be based on hydrological study which includes all contributions.

3.3 Case Study C: Piping of the Conduit - DS0176 (Figure 4, bottom right)

This dam had typical geometry, fill compaction, and wave protection. Two concrete seepage collars (~1.2m cube) were installed around the low-level pipe conduit, presumably as a defence against piping.

Dam type: Homogeneous earthfill dam constructed of non-plastic clayey silt with minor gravel
Maximum dam height: 3.95m **Storage potential:** ~45,000m^3
Upstream batter slope: 3:1 (H:V) **Downstream batter slope:** 3:1 (H:V) **Crest width:** 3.5m
Geological setting: shallow lacustrine and alluvial sediments over sedimentary and metamorphic rock

Failure mechanism: Piping of soils along the outside of the conduit caused by tractive hydraulic forces from the reservoir leading to erosion of the downstream toe and subsequent headward breach migration, i.e. FEMA's Failure Mode 3 (Federal Emergency Management Agency FEMA, 2005). Failure occurred shortly after first filling.

Principal contributors to the failure include:

- Lack of provisions for the safe passage of seepage along the pipe without entraining fines
- Accounts from the contractor are of the inlet screen displacing laterally under high wind causing uplift, permitting water ingress along the conduit
- Trenching method and inability of compaction plant to suitably compact fill around the conduit
- Fill around the pipe being potentially dispersive and/or erosive
- Silty gravel layers near the foundation toe

Downstream consequences: Erosion of pasture; flooding of multiple public roads and closure of the state highway; floodwaters approached residential dwellings and a disused hotel.

Remediation: The pipe was re-laid with the inlet screen secured. A filter diaphragm and filter drain was installed for the downstream pipe section. New clayey silt was imported and compacted around the pipe by a small mechanical tamper.

Lessons learnt: Piped conduits through water retaining structures should be avoided wherever possible. If unavoidable, special design and construction attention should be applied. Compaction is difficult and often impaired around pipe haunches. Some degree of seepage is inevitable, hence a good design will include provision for both the mitigation and safe passage of seepage water. In this situation, international best practice has discontinued the use of concrete seepage collars in favour of filter diaphragms and filter drains (Damwatch, 2006).

3.4 Case Study D: Embankment Overtopping (Figure 5, bottom left)

An access embankment structure was constructed to support a piped aqueduct and permitted construction traffic to cross the confluence of two streams.

Dam type: Access embankment constructed of crushed sandstone with sandstone block slope facing
Maximum dam height: ~7m **Storage potential:** N/A
Upstream batter slope: 1:1 (H:V) **Downstream batter slope:** 1:1 (H:V) **Crest width:** 4m
Geological setting: The site lies within a steep incised gorge of sedimentary rock (sandstone)

Failure mechanism: A significant rain event overwhelmed three bypass culverts, causing water to build up behind the embankment resulting in subsequent crest overtopping and scour to the downstream slope.

Principal contributors to the failure include:

- Hydraulically steep slope batters (embankment slope ~45°)
- Insufficient pipe strength resulting in at least one bypass culvert being crushed under the embankment weight
- Debris from upstream clogging the bypass culverts
- Significant rainfall, probably in excess of the design event expected for this structure

Downstream consequences: Minor sedimentation of the waterway.

Remediation: The culverts were upgraded with stronger, larger pipes with debris screens. A new high-level spillway was provided at the true left abutment. Embankment slopes were eased.

Lessons learnt: While embankment batter slopes might be geotechnically stable, they are hydraulically steep causing high-velocity water flow and scour in the event of overtopping. Design of access embankments should include provision for culvert blockage or failure, and incorporate a debris screen and high-level spillway as a last defence against overtopping.

4 CONCLUSION / DISCUSSION

Every 1-2 months a dam in Otago is identified as potentially dangerous due to a known or suspected breach of the Building Act or the Resource Management Act (1991), sometimes a combination of both. ORC records indicate about one of these fails each year on average. None of the dams that failed had building consent, and no dam that obtained building consent and a code compliance certificate has failed.

The dam failure record in Otago reflects international embankment dam failure experiences. Failures are often an unfortunate combination of substandard design and poorly understood geological conditions that require close quality control procedures during construction, commissioning and operation. It is likely the aspects attributed to the failures would have been effectively addressed through the involvement of a dam professional either at the design, regulatory review, or construction phase. The absence of observable critical features once the dam is constructed, such as foundation condition and internal drainage provisions, along with the difficulty in applying corrective action following the onset of failure, easily justify the costs associated with seeking the correct level of professional input. Inevitably, many small dam owners may be unaware of the danger presented by their dam, and often omit seeking professional advice due to limited budgets or lack of perceived value.

The lessons learnt from four representative dam failures provide a concise summary of good small dam practice:

- A rigorous ground investigation is needed to identify any adverse conditions at the dam site
- Thorough foundation preparation is essential. This should include removal of all organic/soft materials and scarification to ensure a good bond between the embankment and foundation
- Construction plant should be suitable for the soil type and fit for purpose
- Dam building materials need to be carefully selected and compatible with surrounding soils
- Spillways should be formed away from the dam, preferably in competent erosion-resistant material, at shallow bed grade, and be sized to accommodate floods from external contributions in addition to the dam catchment
- Special design and construction attention is warranted for piped conduits. Compaction is often impaired around haunches leading to preferential seepage. Modern designs include provisions for the mitigation and safe passage of seepage water via filter diaphragms and drains

Consequences of failures are rarely contained within Owner’s property, and impact: pastures, infrastructure including roads and powerlines, dwellings and other buildings, and receiving waterways.

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