REPORT

Tonkin+Taylor

Dannevirke Water Supply Reservoir

Preliminary dam safety advice on abnormal seepage

Prepared for
Tararua District Council
Prepared by
Tonkin & Taylor Ltd
Date
September 2022
Job Number
1020688 v2

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Document control

Title: Dannevirke Water Supply Reservoir					
Date	**Version**	**Description**	**Prepared by:**	**Reviewed by:**	**Authorised by:**
19/7/2022	1	First issue	D Knappstein & T Hoang	D Knappstein	H Cherrill
16/9/2022	2	Removal of draft status following TDC comment	D Knappstein	T Hoang & H Cherrill	H Cherrill

Distribution:

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Abbreviations

ARI	Average Recurrence Interval – The average time between events (i.e. earthquakes or floods) of a certain size. For example, a 100-year ARI flow will occur on average once every 100 years.
CDSR	Comprehensive Dam Safety Review – An engineering review of a dam's condition and performance at a Comprehensive level of detail.
DEM	Digital Elevation Model – A digital representation of elevation data to represent terrain.
DSAP	Dam Safety Assurance Programme - A structured framework of plans and procedures for safe operation and management of a dam in the form set out in the Building (Dam Safety) Regulations 2022.
DSMS	Dam Safety Management System - A structured framework of plans and procedures for safe operation and management of a dam through its entire life cycle in accordance with recommended industry practice. The scope of a DSMS usually includes and expands on the elements of a DSAP.
FMEA	Failure Modes and Effects Analysis - An inductive method of analysis where particular faults or initiating conditions are postulated and the analysis reveals the full range of effects of the fault or the initiating condition on the system.
HDPE	High-density polyethylene – A thermoplastic polymer produced from the monomer ethylene. In the context of this report, HDPE is the material comprising the reservoir liner.
IDSR	Intermediate Dam Safety Review - An engineering review of a dam's condition and performance at an Intermediate level of detail.
JSA	Job Safety Analysis - A procedure which helps integrate accepted safety and health principles and practices into a particular task or job operation.
LiDAR	Light Detection and Ranging - A method for determining ranges (variable distance) by targeting an object or a surface with a laser and measuring the time for the reflected light to return to the receiver. The data can be used to build a DEM.
mRL	metres Reduced Level – A representation of elevation, defined as the vertical distance between a point and adopted datum plane.
NZSOLD	New Zealand Society on Large Dams - https://nzsold.org.nz/
PIC	Potential Impact Classification – A system for classifying dams according to the incremental consequences of a hypothetical dam failure so that appropriate dam safety criteria can be applied. The PIC is based solely on consequences, independent of probability i.e., a higher PIC does not mean that a failure is at all likely to occur.

ROV	Remotely Operated Vehicle – A tethered underwater mobile device or robot.
RPP	Reinforced polypropylene – A thermoplastic polymer produced from the monomer propylene. In the context of this report, RPP is the material comprising the floating reservoir cover.
T+T	Tonkin & Taylor Ltd - https://www.tonkintaylor.co.nz/
TDC	Tararua District Council - https://www.tararuadc.govt.nz/
WRC	Waikato Regional Council – https://www.waikatoregion.govt.nz/

Glossary

Appurtenant structure	Defined in the Building Act 20004 as a structure that is integral to the safe functioning of the dam as a structure for retaining water or other fluid. Examples include spillways, intakes, outlets, together with their associated gates / valves and control equipment.
Classifiable dam	Defined in the Building (Dam Safety) Regulations 2022 as a dam that— a Has a height of 4 m or more and stores a volume of water or other fluid of 20,000 m^3 or more; or b Has a height of 1 m or more and stores a volume of water or other fluid of 40,000 m^3 or more.
Dam failure	An uncontrolled release of reservoir contents through failure of a dam or an appurtenant structure.
Dam safety	Safety from a "dam failure", as defined above.
Failure mode	A failure mode comprises a combination and sequence of condition(s), event(s), and mechanism(s) that could theoretically result in a "dam failure" as defined above. At a general level, potential dam failure modes include overtopping, erosion, contaminated seepage, instability, and structural failure.
Freeboard	The vertical distance between the still water surface elevation in the reservoir and the lowest elevation of the top of the dam.
Internal erosion	A mechanism where soil particles within an embankment dam or its foundation are carried downstream by seepage flow. There are four main types of internal erosion: concentrated leak, backward erosion, suffusion, and contact erosion.
Large dam	Defined in the Building Act 2004 as a dam that has a height of 4 m or more and holds a volume of water or other fluid of 20 000 m^3 or more.
Piezometer	A device used to measure liquid pressure in a system by measuring the height to which a column of the liquid rises against gravity, or a device which measures the pressure (more precisely, the piezometric head) of groundwater at a specific point.
Subsoil	The layer of soil under the topsoil on the surface of the ground.
Transducer	A device that converts energy from one form to another. Usually a transducer converts a signal in one form of energy to a signal in another.
Turbidity	The measure of relative clarity of a liquid.

Executive summary

Introduction

Following a leak from the Dannevirke Water Supply Reservoir in 2021, Tararua District Council (TDC) has been closely monitoring seepage from the reservoir. TDC's monitoring indicates that the rate of seepage continues to be abnormally fast. There is also a "wet patch" on the downstream face of the eastern fill embankment where vegetation indicates long-term saturated conditions. Tonkin & Taylor Ltd (T+T) has been engaged as external experts in water retaining structures to support TDC staff with further investigation.

The "main dam safety issue" referred to in this report relates to the ongoing abnormal seepage observations i.e., the fast rate of seepage, and the presence of the wet patch. The purpose of this report is to present T+T's preliminary dam safety advice on this issue. The assessment and recommendations are limited to what is reasonably foreseeable based on a site inspection on 10 June 2022 and review of available information. New investigations, design, and detailed analysis have not yet been completed, and where required, will be separate undertakings.

The report focusses on dam safety, which in the dam engineering industry refers specifically to safety from a dam failure, which is defined as an uncontrolled release of reservoir contents. The dam safety focus considers the "worst that could happen" in a hypothetical situation for the purposes of being suitably cautious; the focus on dam failure does not mean that a failure is at all likely to occur.

The reservoir

Dannevirke Water Supply Reservoir is owned and operated by TDC. The purpose of the reservoir is community water supply, and is particularly critical when direct supply from the Tāmaki River is limited due to naturally low or turbid stream flows.

Dams in New Zealand are categorised as Low, Medium, or High Potential Impact Classification (PIC) based on the consequences of failure. During the original design, consenting, and construction, the Dannevirke Water Supply Reservoir was identified as Low PIC, i.e., in the category of dams with the least severe consequences of failure.

The reservoir is located on a natural terrace, comprising up to 5 m of silty clay (loess), overlying gravelly clay, in turn overlying "papa" type clay. The reservoir is mostly formed by excavation into these natural materials, with the excavation just intersecting the top of the "papa" close to reservoir floor level. Sections of the reservoir rim are formed by earthfill bunds, the largest of which is the eastern fill embankment.

The reservoir has negligible local catchment and is filled by raw water piped from the Tāmaki River. The full supply depth is approximately 12 m. There is approximately 1.2 to 1.4 m freeboard from the spillway level to the dam crest. The full supply volume is approximately 120,000 m^3 and the volume at dam crest level[1] is approximately 160,000 m^3. The reservoir is topped by a floating geomembrane cover. The inside faces and floor of the reservoir are lined with HDPE, in turn overlying 300 mm of compacted clay. Below this, a network of subsoil drains was installed to prevent uplift pressures on the liner from natural groundwater seepage. The outlet pipe from the subsoil drainage network penetrates the eastern fill embankment.

The "abnormal rate of seepage" related to the main dam safety issue, comprises discharge from this outlet pipe. The discharge is faster than accounted for by normal (minor) rates of liner leakage, and

[1] The volume at dam crest level is relevant for definitions and requirements under the Building Act 2004.

likely natural groundwater seepage. As such, the seepage is expected to be originating from reservoir water leaking through significant tears / damage of the liner system.

Investigation and assessment of the main dam safety issue

In the dam engineering industry, dam safety issues are considered in a framework based on "failure modes". A failure mode comprises a combination and sequence of condition(s), event(s), and mechanism(s) that could theoretically result in an uncontrolled release of reservoir contents.

The investigation and assessment of the main dam safety issue has identified a potential failure mode that could plausibly explain the abnormal seepage observations. The steps in this failure mode are listed below from upstream to downstream (see also Figure 0.1 for locations):

1 A major leak through tear(s) in the HDPE liner, most likely near the inlet structure.
2 Scour of the clay liner from the leaked water flowing under the HDPE liner and down the 1V:3H slope of the reservoir.
3 Internal erosion[2] of the clay liner, and / or natural "papa" into and through the 40 mm round stone used in the subsoil drains.
4 Internal erosion through the embankment fill alongside / bypassing 10 m long sections of concrete backfill / encasement around the subsoil outlet pipes.
5 Internal erosion along the non-perforated section of subsoil outlet pipe or through the adjacent embankment fill where the pipe penetrates the eastern fill embankment (between the 10 m sections of concrete and a 2050 mm diameter manhole).
6 Internal erosion through the foundation materials (natural gravelly clay), deviating from the subsoil outlet pipeline at the 2050 mm diameter manhole and daylighting at the "wet patch" on the downstream face of the eastern fill embankment.
7 Progression of the steps above (most plausibly by gross enlargement of the internal erosion "pipes" in steps 5 and 6 or by development of sinkholes connecting into these internal erosion "pipes") to the extent needed to drop the crest below reservoir level and thus release water through a "breached" section of the embankment.

Although some steps in the failure mode sequence have already occurred (steps 1 to 3 are considered almost certain / very likely), other steps in the sequence above would also need to occur before resulting in a failure. These other steps, particularly steps 4, 6 and 7, are considered relatively unlikely but cannot be ruled out based on currently available information. Several of the recommendations following aim to resolve these areas of uncertainty.

It is not conclusively known that failure will progress as described above. Nevertheless, a precautionary approach is strongly recommended based on what has been found thus far.

Recommendations for the main dam safety issue

Table 0.1 summarises the recommendations for the main dam safety issue, which have been developed based on the investigation and assessment described above. In terms of urgency, we advise attending to these recommendations immediately.

[2] "Internal erosion" is a mechanism where soil particles within an embankment dam or its foundation are carried downstream by seepage flow.

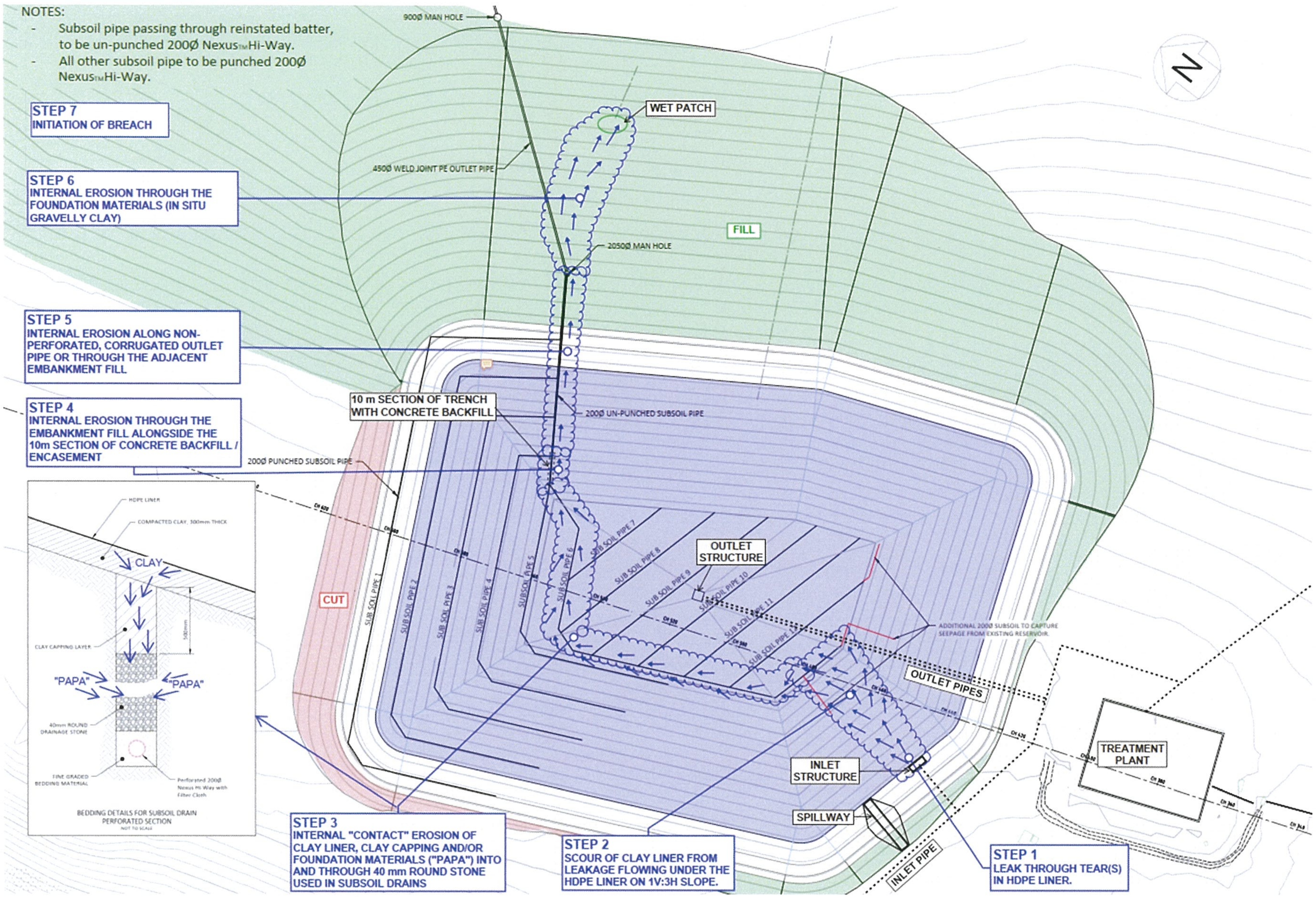

Figure 0.1: Steps in postulated failure mode for subject dam safety issue

Table 0.1: Recommendations for the main dam safety issue (abnormal seepage)

Recommendation	Purpose
1 Operate the reservoir at the minimum level acceptable for water supply.	• Mitigate dam safety risk while the dam safety issue is being resolved.
2 Undertake enhanced dam safety surveillance / monitoring: – Undertake visual inspections, including the dam crest and slopes, the "wet patch", clarity / cloudiness of subsoil flows, and the ground around the stream outlet. – Maintain areas that are visually inspected as short grass. – Assess whether the floating reservoir cover can be removed permanently to enable routine visual inspection of the HDPE liner (at least above reservoir level). – Continue hydrometric monitoring of reservoir water level, rainfall, inflows, and outflows, including subsoil seepage. – Confirm the accuracy of measured reservoir water levels is satisfactory, noting that a transducer was recently installed to address concerns about the accuracy of these readings. – Improve subsoil seepage monitoring by redirecting ponded rainwater from the reservoir cover, monitoring the portion of subsoil seepage that is pumped back to the reservoir, and verifying that only one monitoring point is needed. – Undertake turbidity monitoring of the subsoil seepage. – Undertake pore water pressure monitoring within the eastern fill embankment. – Improve systems for storing surveillance data, including standardised formatting, clear labelling, and checking. – Seek specialist advice urgently if there are unusual or adverse observations or readings (as listed in Table 3.3). – Review the data once the recommendations above have been implemented and a representative period of data has been collected. This should include setting specific alert and alarm levels.	• Detect onsite changes that may indicate deterioration of the situation requiring more urgent action, which may include emergency response. • Provide information on the dam safety issue to improve understanding of risk and urgency, and to inform effective design of remedial works.
3 Develop a contingency plan in case the situation deteriorates. The plan should define the situations and conditions under which to activate the plan, identify responsibilities and actions to mitigate risk if the situation worsens, and include contact details. Arrange for communication systems, equipment and plant to be ready to implement the plan.	• Mitigate dam safety risk while the dam safety issue is being resolved.
4 Prepare for repairs: – Undertake work to remove operational constraints to enable dewatering for investigation and remedial works. – Review PIC based on latest industry practice, upcoming legislative changes, and criticality for water supply (the latter may depend on the outcome from the previous bullet point). – Geotechnical investigation and detailed design of remedial works. – Resource consent for remedial works. – Building consent for remedial works. – Contractor selection and engagement.	• Progress towards resolving the dam safety issue.
5 Update Health and Safety systems for risks related to the dam safety issue: – Update risk registers, Safe Work Method Statements, JSAs, etc. – Provide information, training, instruction and / or supervision for employees, contractors, and visitors to site. – Update workplace emergency plans.	• Mitigate health and safety risks while the dam safety issue is being resolved.
6 Undertake a reservoir water balance to identify unexpected losses that may correlate to leakage.	• Provide information on the dam safety issue to improve understanding of risk and urgency, and to inform effective design of remedial works.
7 Locate HDPE liner damage above reservoir level, especially near the inlet structure where liner damage occurred in the 2021 incident.	
8 Inspection below reservoir level by remotely operated vehicle (ROV) and leakage tracing	
9 Geotechnical investigation and piezometer installation, including: – Two drillholes in the downstream shoulder of the eastern fill embankment. – Installation of multi-level piezometers in the drillholes to monitor pore water pressures. – Sampling and laboratory testing.	• Enable monitoring of pore water pressures for recommendation 2 above. • Provide information on the dam safety issue to improve understanding of risk and urgency, and to inform effective design of remedial works.

Other dam safety recommendations

The report also presents three extra dam safety recommendations that were identified incidentally in the course of investigating the main dam safety issue:

i Check that TDC has legal power to maintain the safety of the downstream shoulder of the eastern fill embankment, which is on privately owned property. This may comprise agreements to enable access for dam safety activities (surveillance, monitoring, and maintenance) and to limit activities that could compromise dam safety, i.e., excluding cattle and other large stock that can damage the embankment. Investigation and remedial works for the main dam safety issue are also expected to require access to the downstream shoulder.

ii Check that unfinished tasks from the original building consent process have concluded, including documentation and approval of as-built arrangements, construction of the overland flow path from the spillway and provision of documents to Waikato Regional Council (Building Consent Authority for Large dams).

iii Undertake a Comprehensive Dam Safety Review (CDSR), which will provide a holistic stocktake of the site-specific dam safety issues based on the confirmed PIC, latest industry practice, and upcoming legislative changes. If the PIC is revised from Low to Medium or High, the recommendations from the CDSR are likely to be more extensive and may drive a programme of future work that could include investigations, updated analyses, increased performance standards and work to comply with those standards, updated dam safety management systems, and installation of dam safety surveillance instrumentation.

1 Introduction

1.1 Scope

The scope of T+T's work and this report has been in accordance with a Letter of Engagement (T+T 7 June 2022, ref. 1020688.000).

The assessment and recommendations are limited to what is reasonably foreseeable based on a review of the information listed in Appendix A. This information includes an initial site inspection on 10 June 2022, brief screening of the full list of documents (reports, photos, emails, spreadsheets), and more detailed consideration of selected documents that appeared most relevant during the screening.

1.2 Dam safety

This report focusses on dam safety, which in the dam engineering industry refers specifically to safety from a dam failure. The New Zealand Dam Safety Guidelines (NZSOLD 2015) defines a "dam failure", in terms of structural integrity, as the uncontrolled release of reservoir contents through failure of the dam or an appurtenant structure[3]. The dam safety focus considers the "worst that could happen" in a hypothetical situation for the purposes of being suitably cautious; the focus on dam failure does not mean that a failure is at all likely to occur.

Both the *consequences* of failure and *probability* of failure must be taken into account in combination to develop a realistic view of *risk* of failure. A key principle of dam engineering is that the control measures[4] applied that influence the *probability* of dam failure should be proportionate to the *consequences* of failure to appropriately manage the level of *risk* (i.e., net result of probability and consequences combined).

Dams in New Zealand are categorised as Low, Medium, or High Potential Impact Classification (PIC) based on the consequences of failure. Those dams that are High PIC, i.e., having the most severe consequences of failure, also have the most stringent standards, such as being designed for a 10,000 year ARI[5] flood as a minimum. As already noted, during the original design, consenting, and construction, the Dannevirke Water Supply Reservoir was identified as Low PIC, i.e., in the category of dams with the least severe consequences of failure.

1.3 Structure of report

The sections of this report cover the following:

- Section 2 provides background information, such as the reservoir location, geological setting, reservoir arrangement, dam size, and legislative requirements.
- Section 3 describes the investigation and assessment of the main dam safety issue, and the resulting recommendations.
- Section 4 provides three extra dam safety recommendations that were noted while investigating the main dam safety issue above. While not strictly within the scope of T+T's engagement, these recommendations are included in case they are helpful for TDC's forward planning.

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[3] The Building Act 2004 defines an appurtenant structure as "a structure that is integral to the safe functioning of the dam as a structure for retaining water or other fluid".
[4] I.e., design / performance standards for the dam, expertise of people involved, frequency and scope of ongoing monitoring, level of emergency preparedness etc.
[5] ARI = Average Recurrence Interval.

2 About the reservoir

2.1 Operation

Dannevirke Water Supply Reservoir is owned and operated by TDC. Raw water is abstracted from the Tāmaki River and piped to fill the reservoir, where the water is temporarily stored, before being treated at the plant at the southern end of the reservoir, and then distributed to the community. The storage provides continuity of supply when direct supply from the Tāmaki River is limited due to naturally low or turbid stream flows.

2.2 Location and geological setting

The reservoir is located on a 25 m high natural terrace on the north-eastern side of Laws Road, Dannevirke, approximately 3.3 km north-west of the town centre.

The "in situ" or natural materials that form the terrace are summarised in Table 2.1, inferred from the information sources listed in Appendix A.

Table 2.1: In situ materials at reservoir site

Location	Description[6]
Top layer of terrace. Up to 5 m thick.	Firm to stiff, silty clay. Likely a loess deposit.
Middle layer. Exposed in the sides of the reservoir below the top layer. Also exposed in the eastern part of the reservoir floor.	Dense, gravelly clay. Occurring in horizontal layers of variable clay content. Gravel clasts likely derived from weathered greywacke rock. Some clasts are rounded, indicative of an alluvial deposit.
Bottom layer. Exposed in the western part of the reservoir floor, then appears to dip down below floor level towards the east.	"Papa" type clay.

[6] There is inconsistency in how in situ materials are described between the different sources of information in Appendix A. Where material characteristics are critical, we recommend confirming characteristics based on current logging practices, supported by field and laboratory testing.

2.3 Reservoir arrangement and dam size

The reservoir and dam layout is shown in Figure 2.1 and key characteristics are summarised in Table 2.2

The floor of the reservoir, the northern edge of the reservoir, and part of the western edge of the reservoir is excavated into the natural terrace described in Section 2.2. The rest of the reservoir rim (eastern edge, southern edge, and rest of the western edge) is formed by earthfill bunds that rise slightly above the terrace surface. These earthfill bunds are generally low in height, except along the eastern side where the maximum fill height occurs.

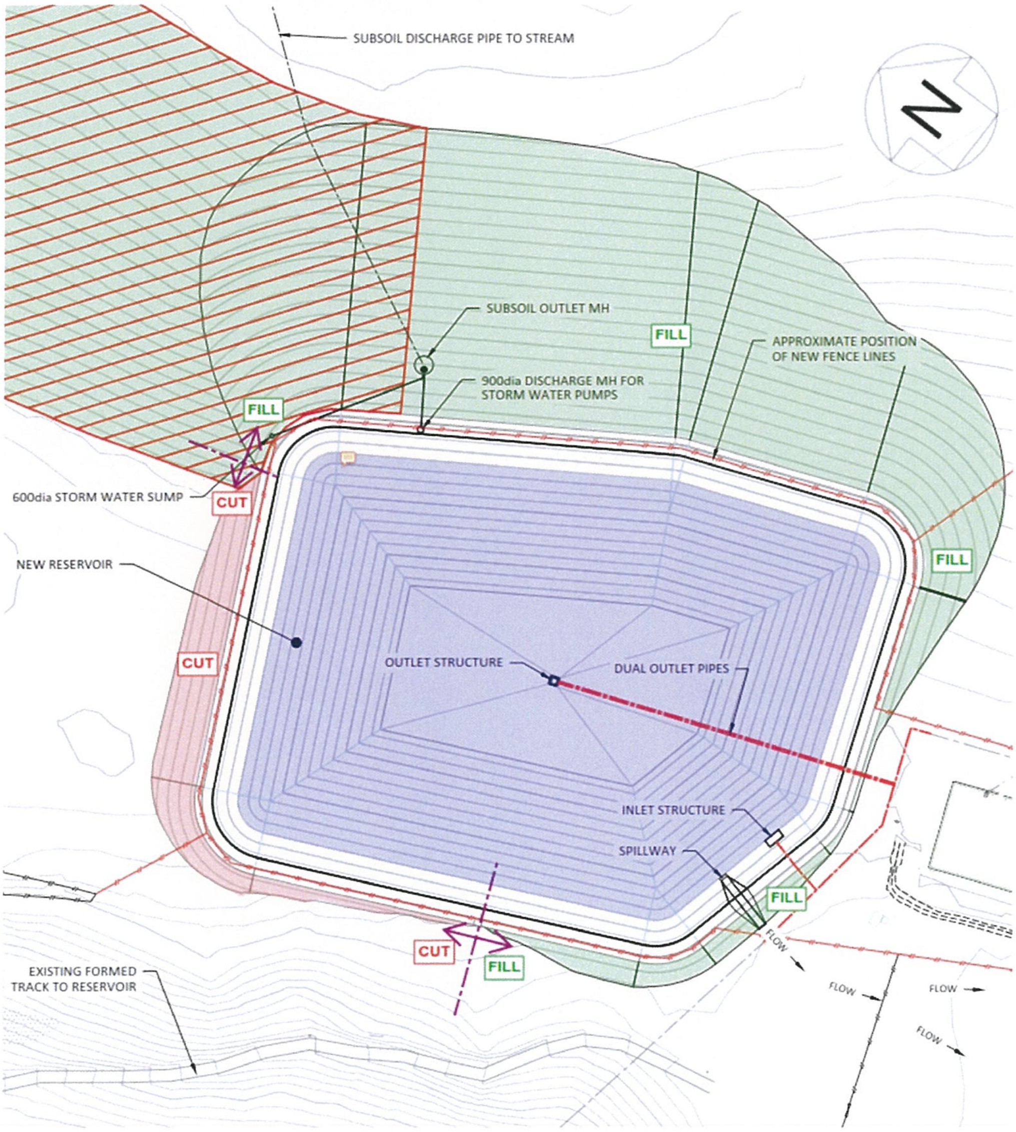


Figure 2.1: Reservoir and dam arrangement

Based on the as-built drawings, the dam is approximately 20.7 m high on the eastern side (measured from the crest to downstream toe as per the Building Act 2004 definition). The height of 20.7 m is misleading since the dam embankment fill is constructed over a natural slope on the eastern side of the terrace. The downstream toe of the dam embankment fill extends down the slope onto a second lower terrace. The internal base of the pond is excavated into natural ground and is positioned approximately 14 m below the dam crest. The maximum vertical thickness of fill on the natural slope is approximately 8 m.

The full supply depth is approximately 12 m and approximately 1.2 to 1.4 m freeboard is provided above spillway sill level to dam crest level. The internal slopes of the reservoir are 1V:3H and external slopes of the fill embankments are 1V:4H. A reinforced polypropylene (RPP) geomembrane cover floats on top of the reservoir water surface. The inside faces and floor of the reservoir are lined with an HDPE geomembrane, in turn overlying 300 mm of compacted clay. A network of subsoil drains is located under the liner system as shown in Figure 2.2. The original design intent of the subsoil drains was to prevent uplift pressures on the liner from natural groundwater seepage.

The reservoir stores approximately 160,000 m^3 at dam crest level. An approximate storage-elevation curve has been derived based on the contours in the as-built drawings, as presented in Figure 2.3.

Table 2.2: Reservoir and dam characteristics

Parameter	Value / description	Source
Name	Dannevirke Water Supply Reservoir	
Date of construction	March 2011 to June 2013	Construction Completion Report (TDC June 2013).
Location	Laws Road, Dannevirke, 3.3 km north-west of the town centre	
Purpose	Water supply to Dannevirke	
Designer, construction monitoring, owner, and operator	TDC	
PIC	Currently Low PIC, but review of the PIC is recommended as discussed in Section 2.4	Building consent application.
Dam type	Predominantly an excavated pond, with earthfill embankments along parts of the reservoir rim	
Crest level	101.32 mRL	As-built drawings.
Full supply level	99.32 mRL (as designed, note spillway crest was constructed above this level)	
Reservoir floor level	87.27 mRL	
Freeboard above spillway crest	1.2 to 1.4 m approximately	Estimated from TDC 2022 survey.
Full supply depth	12.05 m	
Storage volume at full supply level	120,000 m^3	Estimated from contours in as-built drawings.
Storage volume at dam crest (per Building Act 2004 definition)	160,000 m^3	
Dam height (dam crest to dam toe, per Building Act 2004 definition)	20.7 m	
Crest width	3 m	As-built drawings.

Parameter	Value / description	Source
Crest length	550 m	As-built drawings (scaled).
Internal slopes	1V:3H	As-built drawings.
External slopes	1V:4H	
Leakage control	1.5 mm thick HDPE liner overlying 300mm thick clay liner, in turn overlying a network of subsoil drains	As-built drawings. Quality Control & Assurance Report (Viking July 2013).
Reservoir cover	1.14 mm thick RPP floating cover	
Spillway	2 m wide concrete-lined open channel spillway with spillway crest / sill level at approximately 99.92 to 100.12 mRL. Note this level is based on 2022 survey and differs from as-built drawings. A gate prevents wind getting under the reservoir cover.	As-built drawings, except for spillway sill level, which is based on TDC 2022 survey.
Operational inlet	A 300 mm diameter inlet pipe supplies raw water from the Tāmaki River to a 5 m by 2.5 m concrete box structure (with internal baffle) at the southern end of the reservoir. Inflows to the reservoir are released from the inlet box structure, entering the reservoir between the HDPE liner and floating reservoir cover, controlled by a 4.45 m wide weir with sill at 99.32 mRL.	
Operational outlet	A 2.7 m square concrete box structure is recessed centrally into the reservoir floor. Twin 300 mm diameter outlet pipes take water from the outlet box structure, up the southern internal slope of the reservoir (in trenches just below the HDPE and clay liner) before connecting to the water supply pipe network beyond the reservoir.	

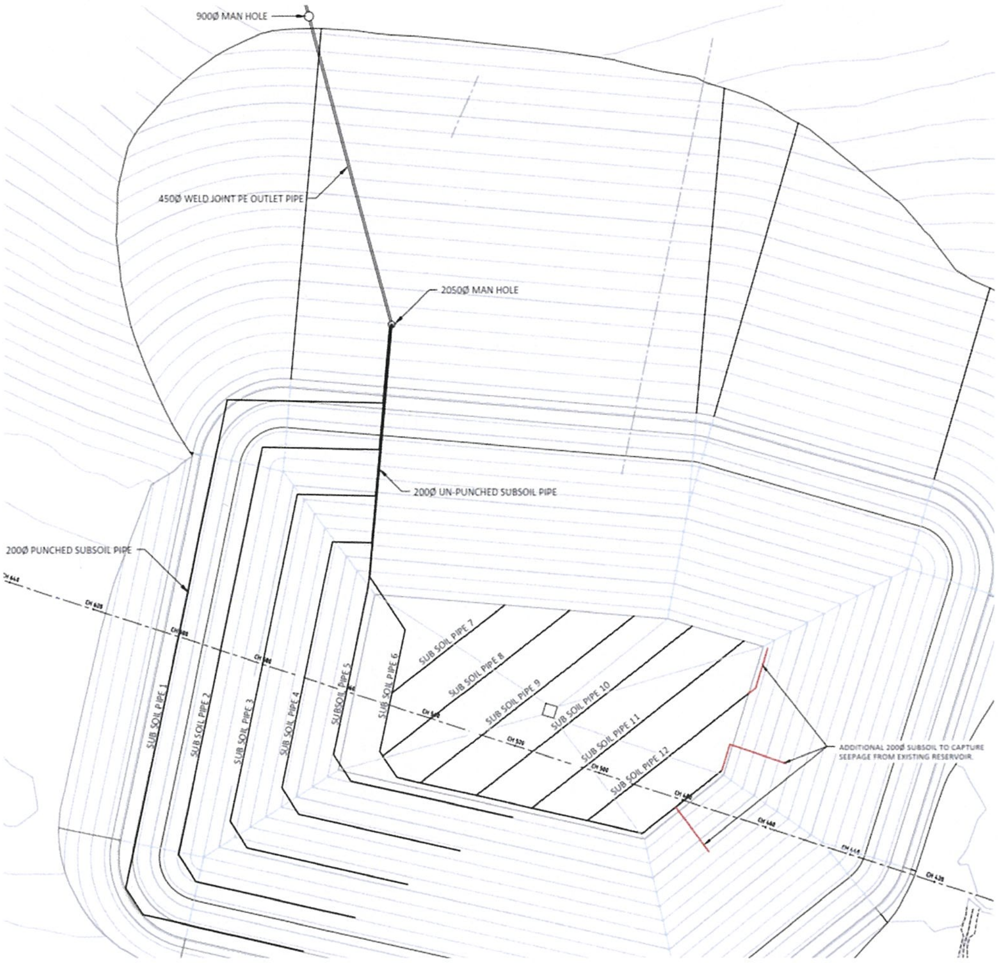


Figure 2.2: Subsoil drainage network underlying HDPE and clay liner

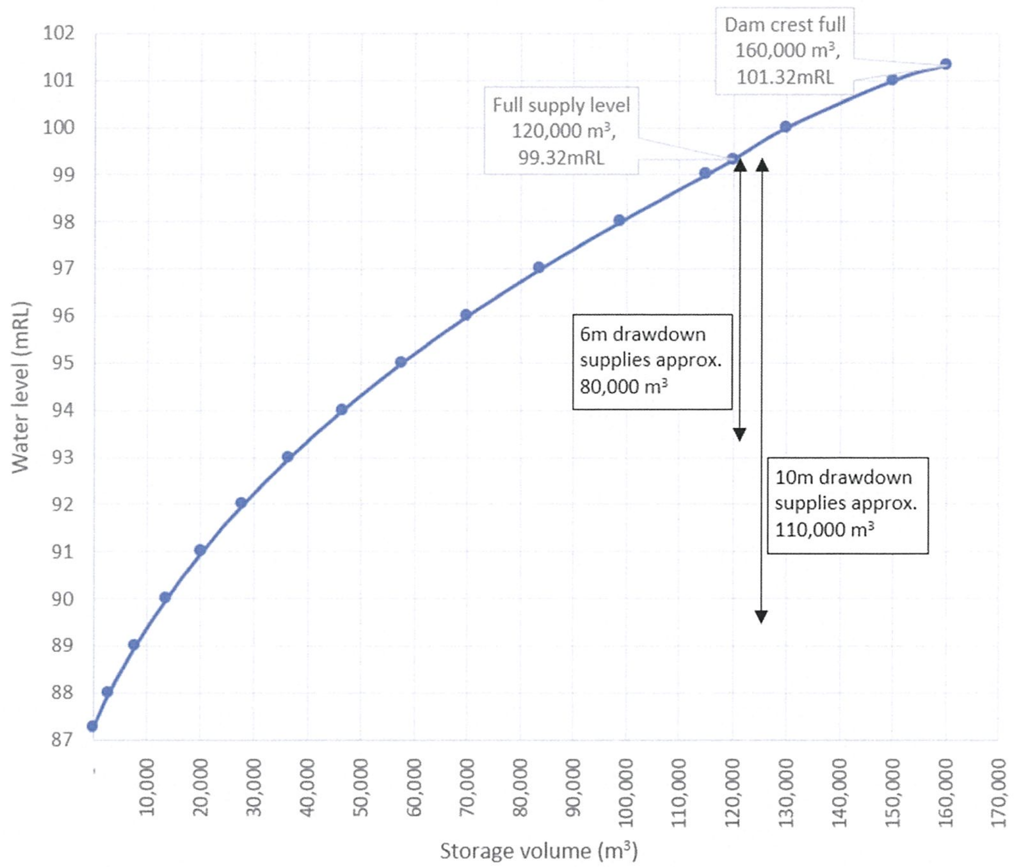


Figure 2.3: Storage-elevation curve based on Drawing Sheet No 10 (as-built version 13 June 2013)

2.4 Legislative requirements

Based on the height and storage volume, the Dannevirke Water Supply Reservoir dam is defined as "Large" under the Building Act 2004 and "Classifiable" under the Building (Dam Safety) Regulations 2022.

As a "Large" dam, building consent is required for construction and modification of the dam and appurtenant structures. The requirements for building consent as a Large dam are already in force under the Building Act 2004. Building consent is likely to be required if remedial or upgrade works are undertaken.

As a "Classifiable" dam, ongoing dam safety management will be required in the future under the Building (Dam Safety) Regulations 2022, which are scheduled to come into force from May 2024. The ongoing dam safety management requirements are expected to include the following:

i Confirm the dam is covered by the 2022 regulations i.e., comprises a "Classifiable" dam.

ii Assess the consequences of the Classifiable dam failing through a PIC assessment.

iii For Medium and High PIC Classifiable dams, develop and implement a Dam Safety Assurance Programme (DSAP), which includes:

- Dam and reservoir operation and maintenance procedures.

  - Surveillance procedures.
  - Inspection, maintenance and testing procedures for appurtenant structures and gate and valve systems with dam safety functions.
  - Intermediate dam safety reviews (IDSRs).
  - Comprehensive dam safety reviews (CDSRs).
  - Emergency planning and response.
  - Dam safety issue management.

iv Have the PIC, DSAP, and annual compliance certificates audited and certified by a Recognised Engineer, then submitted to regional authorities.

v Review the PIC and DSAP at specified intervals.

Some requirements in the 2022 regulations do not apply to Low PIC dams such as the Dannevirke Water Supply Reservoir. However, we recommend that the PIC is reviewed and confirmed based on the latest advances in industry practice, upcoming legislative changes, changes in the dambreak area downstream of the dam, and changes to how the dam is operated. A review of the PIC could lead to the PIC changing. For example, a Medium PIC could apply if the following conditions are met:

- If water supply to the community cannot reasonably be provided by alternative means such that the reservoir is defined as "critical or major infrastructure" under the 2022 regulations.
- If it is likely to take 3 months or more but less than 1 year to restore normal operation following a dam failure.

Other legislation that is relevant to dams includes:

- Civil law
- Resource Management Act 1991
- Building Act 2004
- Civil Defence Emergency Management Act 2002
- Healthy and Safety at Work Act 2015
- Hazardous Substances and New Organisms Act 1996
- Local Government Act 2002

If a dam failure occurs, liability and penalties may be possible under existing legislation, specifically Civil law and the Resource Management Act 1991. Refer to Module 1 of the New Zealand Dam Safety Guidelines[7] (NZSOLD 2015) for further detail on legislation.

[7] NZSOLD 2015 is free to download: https://nzsold.org.nz/dam-safety-guidelines-2015/. Some parts of Module 1 refer to out-of-date legislation (Health and Safety in Employment Act 1992, Building (Dam Safety) Regulations 2008) and are being updated.

3 Investigation, assessment, and recommendations for main dam safety issue (abnormal seepage)

3.1 Introduction

This section addresses the main dam safety issue that T+T has been engaged to consider, which relates to ongoing abnormal seepage observations by TDC. These observations include the unusually fast rate of discharge from the subsoil drainage network and a "wet patch" on the downslope face of the eastern fill embankment.

This particular dam safety issue has been given priority due to a leakage incident in 2021 as described in Section 3.2.4.4 and ongoing adverse observations. An exhaustive investigation to identify all dam safety issues from first principles has not been undertaken and is anticipated as part of the Comprehensive Dam Safety Review recommended in Section 4 (refer NC2022-02 in Table 4.1). The dam safety issue relating to abnormal seepage has been brought forward as more urgent because adverse performance, inconsistent with design intents, has already been observed.

The subsections cover the following:

- Section 3.2 "Investigation" covers collation and filtering of relevant information.
- Section 3.3 "Assessment" covers assessment of the relevant information to identify dam safety implications.
- Section 3.4 "Recommendations" presents recommendations for immediate and longer term actions to manage the dam safety issue.

3.2 Investigation

3.2.1 Introduction

Our investigation into the main dam safety issue (abnormal seepage) has been based on review of the following:

- A site inspection, as described in Section 3.2.2.
- TDC's surveillance / monitoring data, as described in Section 3.2.3.
- Existing documents, including reports, drawings, photos, emails, spreadsheets, survey etc, as listed in Appendix A.

Relevant vulnerabilities and adverse observations were identified from these information sources and are summarised in Section 3.2.4.

3.2.2 Site inspection

The site inspection was undertaken on 10 June 2022 by Tung Hoang (T+T), Dewi Knappstein (T+T), Derek Wood (TDC), and Tom Dodd (TDC). The weather during the inspection was very windy with intermittent rain.

The following areas were inspected:

- Dam crest at the southern end of the reservoir, near the water treatment plant.
- Dam crest of the eastern fill embankment.
- A 900 mm diameter manhole at the north-eastern toe of the eastern fill embankment.
- The subsoil drain outlet to the stream located 170 m to the north-east of the reservoir.
- The downstream face of the eastern fill embankment, including the "wet patch".

- The spillway at the south-western end of the reservoir.
- The cut face on the upslope side of the access track, which is excavated into the sloping western face of the natural terrace on which the reservoir is situated.

The following key observations were made during the site inspection:

- The downstream face of the eastern fill embankment was uneven and wet underfoot in many places and at all levels. The wet soil conditions have persisted for enough time for reeds to grow across the full downstream face, also at all levels.
- The "wet patch" identified by TDC prior to the site inspection is located partway down the downstream slope of the eastern fill embankment towards the north-eastern corner of the reservoir. The location is 20 to 30 m south of the subsoil discharge line, between a 2050 mm diameter manhole and 900 mm diameter manhole (see Figure 2.2 for the location). The elevation of the "wet patch" is close to the elevation of the reservoir floor, which is 6.6 m vertically above the toe of the 20.7 m high downstream face. The "wet patch" appears slightly depressed / sunken, and vegetation differs from the rest of the slope. No water was visibly emerging from the ground at the time of the site inspection.
- A less pronounced but similar "wet patch" was observed further south at a similar elevation.
- Water was observed ponding on the dam crest of the eastern fill embankment and in the field on the lower terrace below the embankment toe. TDC advised that the ponding on the field had been present for a few weeks prior to the site inspection.
- Subsoil seepage flows at the outlet to the stream appeared clear with no visible cloudiness. The rate of subsoil seepage was abnormally fast for a dam of this size; greater than typical allowances for liner seepage, and expected natural groundwater seepage.
- The upstream (internal) faces of the reservoir were under the floating reservoir cover so were not able to be directly inspected. The cover was visibly "rippling" below the inlet structure where water is released into the reservoir between the cover and liner. Generally (not specifically at the inlet structure), the cover is wrinkled and buckled in places. There is evidence of abrasion damage near the dam crest, which TDC advised is likely caused by the westerly wind pushing the cover over to rub against the anchor fixings on the dam crest.

Selected photos from the inspection are provided in Appendix B.

3.2.3 Surveillance / monitoring data

3.2.3.1 Introduction

Following the 2021 leakage incident, TDC increased monitoring of reservoir water levels, inflows and outflows, including subsoil seepage. The following data were provided[8] for comment as part of the current investigation:

a Reservoir water levels, inflows, outflows from the water treatment plant between 13 February 2022 and 9 June 2022.

b Subsoil seepage flows between 1 November 2021 and 30 May 2022.

c Two LiDAR point clouds, captured on 10 November 2021 and 2 June 2022 respectively.

TDC's monitoring programme represents "enhanced surveillance" in response to the 2021 leakage incident and ongoing abnormal seepage readings, rather than "routine surveillance" for normal operating conditions for a Low PIC dam. The monitoring programme continues to be adjusted as more information is collected and the understanding of the dam safety issue develops.

[8] Email from M Clifford to T Hoang on 20 June 2022 at 3:39pm.

We have reviewed the data and make several recommendations to improve the monitoring programme. Until additional data is collected over a representative time period with the recommendations in effect, our review and interpretation of implications for dam safety is unavoidably limited. However, our comments based on the monitoring data currently available are provided in Sections 3.2.3.2 to 3.2.3.5.

3.2.3.2 Reservoir water levels, inflows, and outflows from the water treatment plant between 13 February 2022 and 9 June 2022

This section presents our comments based on preliminary consideration of the available information on reservoir water levels, inflows, and outflows.

The reservoir levels over the period:

- Have varied between a minimum of 4.9 m on 31 March 2022 and maximum of 14.2 m on 16 May 2022.
- Step up sharply from 9.0 m on 26 May 2022 to 10.2 m on 27 May 2022.
- Step down sharply from 11.4 m on 6 June 2022 to 8.1 m on 7 June 2022.
- Vary more gradually for the rest of the period.
- Have been provided in terms of SCADA output and are missing a vertical datum reference.

TDC advise that the relative changes / trends in reservoir water levels are accurate but that the absolute values of the water levels may not be accurate. TDC installed a transducer on the reservoir floor at the start of June 2022 to improve the accuracy of absolute values.

3.2.3.3 Subsoil seepage flows between 1 November 2021 and 30 May 2022

Based on preliminary consideration of the available information on subsoil seepage flows, we note the following:

- The measured flows over the period mostly vary between 2 L/s and 22 L/s, excluding short-duration spikes.
- The measured flows step up and down abruptly between flow bands. Individual flow bands have a typical peak to peak amplitude of 2 to 5 L/s. The abrupt steps up and down between bands can be by as much as 15 L/s.
- Within individual flow bands, there appears to be a positive correlation between increasing subsoil flows and increasing reservoir levels, and vice versa. This correlation is disrupted if analysing the full data set i.e., including data across multiple flow bands with step changes between the bands.
- The measured flows (summarised above) are potentially misleading if used to understand discharge from the subsoil drainage network under the HDPE and clay liner system. Further explanation is provided below.
- The monitoring point for the measured flows is at the downstream end of the subsoil drainage pipeline at the outlet to the stream. A weir has been installed inside the 900 mm diameter manhole located on the subsoil drainage pipeline (refer Figure 2.2 for location), upstream of the monitoring point.
- At times, the measured flows are *increased* by rainwater that ponds on the floating reservoir cover that is directed into the 900 mm diameter manhole (downstream of the weir since considered contaminated). At other times, the measured flows are *decreased* by pumping a portion of the subsoil seepage discharge back up to the reservoir from the 900 mm diameter manhole (from upstream of the weir).

- This arrangement of diverting ponding rainwater into the subsoil drainage pipeline and pumping some subsoil seepage back to the reservoir (both occurring upstream of the monitoring point) means that both the minimum and maximum measured flows (2 L/s and 22 L/s respectively) may be beyond actual minimum and maximum values for discharge from the subsoil drainage network. The arrangement also likely accounts for the abrupt steps between flow bands in the measured flows.
- Despite the above, the rate of subsoil seepage discharge is still considered to be abnormally fast and should continue to be investigated as a dam safety issue. Although the diverted ponding rainwater will increase measured flows beyond true subsoil seepage at times, the measured flows are relatively fast (greater than 15 L/s) for more of the period than the diversion is likely to be operating.

We recommend improving how discharge from the subsoil drainage network is monitored as follows:

- Rainwater that ponds on the reservoir cover should be kept separate from subsoil seepage flows upstream of where subsoil seepage flows are monitored.
- The portion of subsoil seepage flow that is pumped back into the reservoir should be monitored in the same manner (i.e., frequency and accuracy) as subsoil discharge at the stream outlet. Both the subsoil seepage pumped back and discharged at the stream should be recorded separately, and *also* summed to track total subsoil seepage. Furthermore, measurement of the subsoil seepage pumped back is an input for analysing the reservoir water balance (inflows, outflows, storage), which is valuable to identify leakage.
- Five separate discharge points at different elevations in the 2050 mm diameter manhole (refer Figure 2.2 for location) provide opportunity to monitor flows from different parts of the subsoil drainage network independently. This information could be used to identify the location and spatial extent of liner damage and leakage. TDC believe that seepage is emerging solely from the lowest discharge point, which we recommend verifying across the range of relevant conditions. If seepage is emerging from more than one discharge point in the 2050 mm diameter manhole, these flows should be monitored individually.

We also recommend daily visual surveillance of the "wet patch" on the downstream face of the eastern fill embankment. This should involve:

- Marking out the extent of the "wet patch".
- Taking a photo at the same location each day.
- Inspecting the ground for visible emerging flow and recording the observation.

3.2.3.4 Information systems for monitoring data (reservoir levels, inflows, outflows, subsoil seepage, visual observations)

We recommend that a standardised format is developed and used consistently for recording and storing all monitoring data. Those recording the data should be trained to use the standardised format as intended. Data entry should be checked. Readings that appear anomalous upon entry should be verified, including extra field readings where needed for verification.

The standardised monitoring file / database should clearly label each and every element:

- Raw data should be labelled with a sufficiently detailed description so that there can be no misunderstanding regarding what the data represents physically, who collected the data, when and how the data was collected. Units, coordinate systems, and vertical datums should be noted wherever relevant.
- Incorrect or suspect data should be labelled as such.

- Where manipulation, analysis, and interpretation of data is included, the purpose, methodology, person responsible, and level of confidence / checking should be noted.

Once a representative period of monitoring data has been collected, the data should be provided to a dam safety specialist to advise appropriate alert and alarm trigger levels.

3.2.3.5 Two LiDAR point clouds, captured on 10 November 2021 and 2 June 2022 respectively

We generated a digital elevation model (DEM) for each dataset. The 2021 DEM was then subtracted from the 2022 DEM to identify the vertical differences between the two datasets. The resulting difference plot is included in Appendix D for the record.

The pattern of vertical differences between the two datasets appears to be an artifact of the LiDAR process and accuracy. There were no significant findings from the analysis for the specific dam safety issue under investigation.

3.2.4 Identified vulnerabilities and adverse observations

3.2.4.1 Introduction

Based on information from the site inspection, surveillance / monitoring data, and available documentation (as listed in Appendix A), we have identified relevant vulnerabilities and key adverse observations, which are summarised in Sections 3.2.4.2 and 3.2.4.3 respectively.

The identified vulnerabilities and adverse observations have then been taken forward as an input into the assessment of the subject dam safety issue in Section 3.3.

3.2.4.2 Vulnerabilities

The vulnerabilities that have been identified comprise the following:

a The eastern fill embankment was likely to have been "'melded' in with the original slope by cutting small benches in the slope as the fill rises"[9]. Benching in foundations can (depending on the geometry of the benches) sometimes lead to cracking of the embankment fill due to differential settlement, which increases vulnerability to "concentrated leak" type internal erosion[10].

b As-built drawing sheet 11 indicates that the clay liner is in direct contact with "40 mm round drainage stone" used to backfill the subsoil drainage trenches. The clay liner is unlikely to be filter compatible with the drainage stone, which means that the clay liner could be eroded and washed into and through the drainage stone via "contact" type internal erosion.

c The Construction Completion Report notes that some of the subsoil drainage trenches were excavated into "papa" on the western side of the reservoir floor. Similar to the clay liner, the "papa" is unlikely to be filter compatible with the 40 mm round drainage stone and could similarly be vulnerable to "contact" type internal erosion into and though the drainage stone.

d The backfill detail for the non-perforated Nexus outlet pipes from the subsoil drainage network shown on as-built drawing sheet 11 creates a vulnerability to "concentrated leak" type internal erosion along the pipe. Firstly, it is difficult to effectively compact the clay backfill:

  – Into the corrugations of the outer wall of the pipe, especially without damaging the pipe.

---

[9] Letter L Wesley to B King dated 24 March 2011.

[10] "Internal erosion" is a mechanism where soil particles within an embankment dam or its foundation are carried downstream by seepage flow. The mechanism has been responsible for a substantial percentage of historical dam failures. There are four main types of internal erosion: concentrated leak, backward erosion, suffusion, and contact erosion.

- Under the haunches of the circular pipe.

The vulnerability / risk is mitigated to some degree by a 10 m long section of each subsoil trench line that has been backfilled with concrete rather than clay or drainage stone.

e The reservoir has been excavated into natural terrace materials that could potentially be vulnerable to internal erosion. In particular:

- The upper layer (up to 5 m thick) is expected to comprise a loess deposit, which can frequently be a dispersive material that is more vulnerable to internal erosion.
- The grading / particle size distribution of the middle layer of gravelly clay is uncertain and could potentially be internally unstable and vulnerable to "suffusion" type internal erosion.

f At the time of the 2021 leakage incident, substantial damage was observed and was only able to be partially repaired. The unrepaired damage represents an ongoing vulnerability, which the current enhanced monitoring programme and investigations are intended to mitigate and eventually resolve. Refer to Section 3.2.4.4 for further information on the 2021 incident.

g Deep trenches with battered side slopes were excavated through natural ground below the eastern fill embankment in two locations during construction (see also Figure 3.1):

- Near the north-eastern corner of the reservoir for installation of the subsoil outlet pipe, likely close to reservoir floor level.
- Near the south-eastern corner of the reservoir for construction plant access, elevation uncertain.

These deeper excavations represent locations where the dam embankment fill is locally higher and the contact with underlying, natural ground is locally lower. If the dam embankment fill is higher permeability than the natural ground, seepage could potentially track along the contact. The localised "valley" shape formed by the trenches could potentially represent a preferred seepage path, and an area that could be more vulnerable to internal erosion. The locally higher fill embankments can also generate larger hypothetical dambreak flows than lower fill embankments (all other factors being equal).

Figure 3.1: Deep trenches cut through eastern fill embankment during construction (photo dated 23 August 2012, taken from Google Earth, overlaid on as-built drawing sheet 2)

3.2.4.3 Adverse observations

The following adverse observations have been identified:

a Prior to construction of the Dannevirke Water Supply Reservoir, a smaller reservoir (now decommissioned) was present to the south of the current location. The Construction Completion Report describes a substantial leak from the previous reservoir during construction of the current reservoir. Water leaked from the original reservoir, seeped through the natural ground, and emerged from the southern excavated batter slope of the current reservoir. Extra subsoil drains were installed where seepage was more obvious as shown as red lines on as-built drawing sheet 10. The extra subsoil drains only partially stopped the seepage inflows until the existing reservoir was dewatered. The leak demonstrated that the in situ terrace materials are capable of transmitting substantial flows. It is possible (dependent on the characteristics of the in situ terrace materials) that the leak could have created a preferential (higher permeability) seepage path.

b Inspection of the reservoir floor using an ROV[11] following the 2021 leakage incident, identified two depressions under the liner along the western side of the reservoir floor as shown in Figure 3.2 and Figure 3.3. These depressions appear close to the main trunk line of the reservoir floor subsoil drainage network (subsoil pipe 6), which the Construction Completion Report indicates is trenched into "papa".

c The different vegetation at the "wet patch", already described in Section 3.2.2, indicates long-term saturated conditions. The long-term saturation at the "wet patch" could indicate a preferential seepage path created by internal erosion. However, this is only one possible mechanism. There could alternatively be preferential seepage through a naturally higher permeability horizon in the foundation that is stable i.e., not subject to ongoing deterioration and increases in permeability due to internal erosion. Another possibility is that the seepage could comprise rainwater that has infiltrated the embankment fill and is directed back to the surface by the contact with lower permeability foundation materials or lower permeability horizons perched within the fill.

d As already described in Sections 3.2.2 and 3.2.3, the rate of subsoil seepage discharge is considered abnormally fast for a dam of this size, typical allowances for liner seepage[12], and expected natural groundwater seepage[13]. Moreover, based on the drain capacity[14] and assumption that most of the subsoil seepage is conveyed solely via the lowest subsoil drain, it is possible that this subsoil drain is slightly pressurised, which further increases the risk of internal erosion.

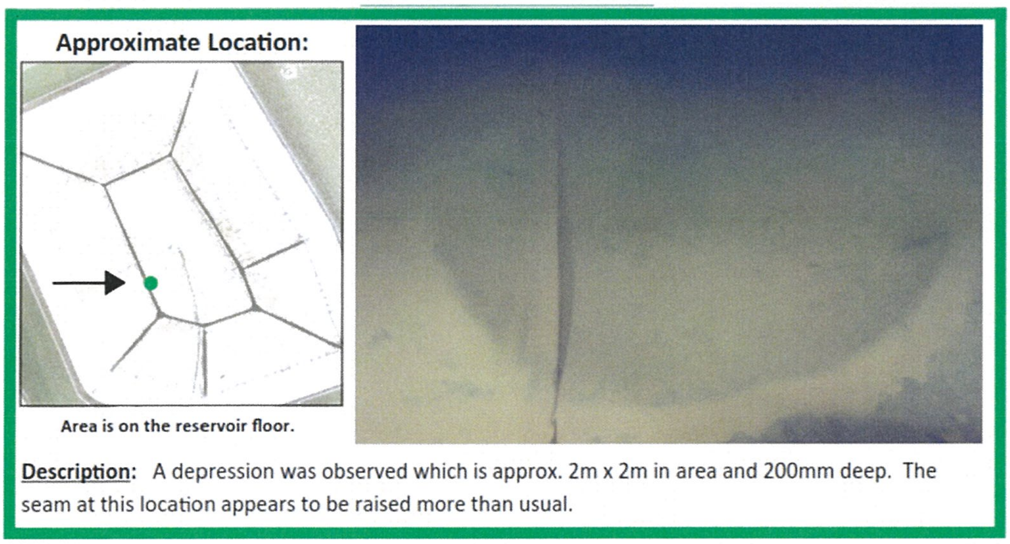
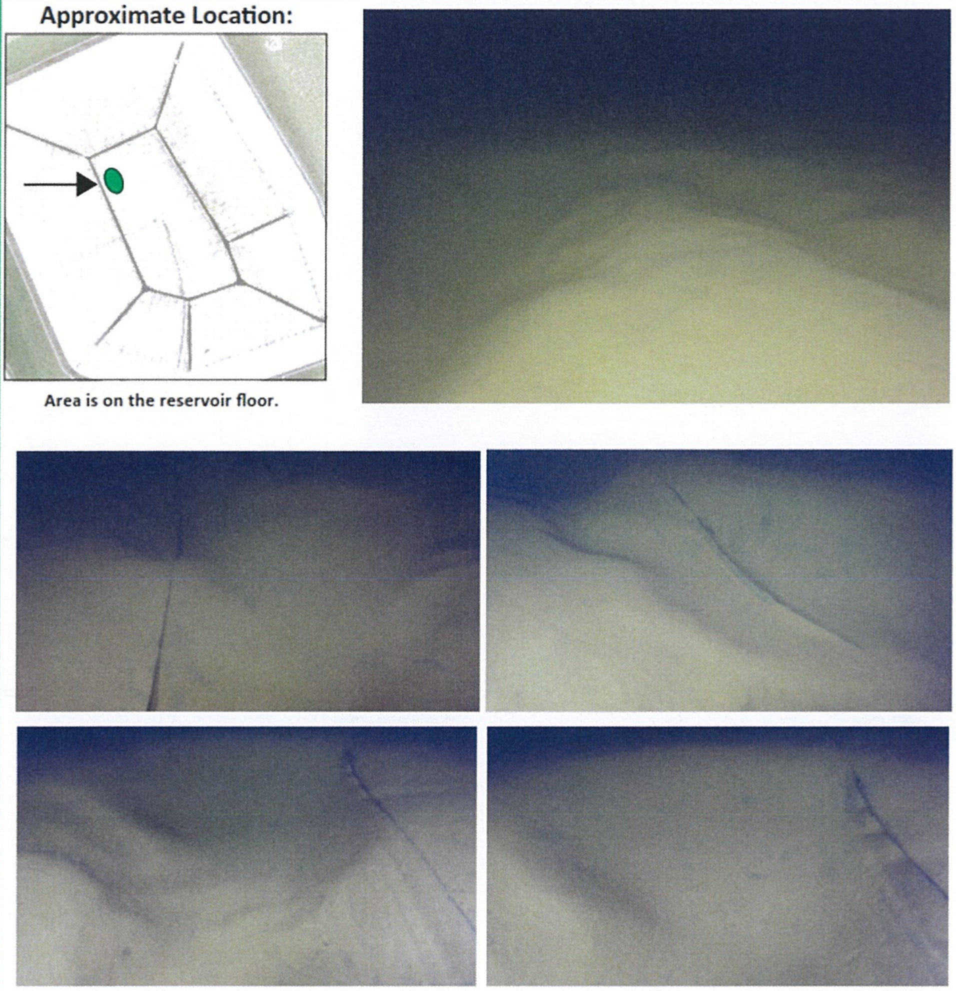


Figure 3.2: Depression (approx. 2 m by 2 m by 200 mm) under liner on western side of reservoir floor (image and description extracted from Bayview Dynamics NZ Report dated 24 August 2021)

[11] "Laws Rd Reservoir In Water Survey" Bay Dynamics New Zealand 24 August 2021.
[12] Viking Containment (HDPE liner supplier) advised an allowance of 30 m^3/day or 0.35 L/s for this reservoir based on normal rates of liner leakage. This advice was provided in an email from M Gilray to J Webster dated 10 February 2012, which in turn was attached to a letter from TDC to Waikato Regional Council dated 15 February 2012.
[13] The Construction Completion Report includes several observations that indicate the natural groundwater seepage during construction was much less than the current rate of subsoil seepage.
[14] A letter from TDC to T+T dated 2 February 2011 notes that the supplier advised a capacity of 9 Ls for each 200 mm diameter pipe at a 0.2% grade.



Description: Large area of multiple depressions and sediment build up. Seam is exposed at multiple locations in this area. Approximately 10mx10m coverage, multiple depths down to estimated 300mm deep, and build up of heights above the normal ground levels.

Figure 3.3: Depression (approx. 10 m by 10 m by 300 mm) under liner at north-western end of reservoir floor (image and description extracted from Bayview Dynamics NZ Report dated 24 August 2021)

3.2.4.4 Previous leakage incident in July 2021 to September 2021

This section summarises information that has been collated on the 2021 leakage incident.

The following points were advised verbally by TDC during the site visit:

a Once the floating RPP reservoir cover was removed after detecting the leak, the HDPE liner was found to be "shredded" near the top of the slope but intact elsewhere.

b The HDPE liner felt unsupported underfoot, indicating loss of material from the compacted clay liner below the HDPE liner, all the way down the slope. The HDPE liner was also observed to be "rippling", indicating flow under the HDPE, at the toe of the slope below the inlet structure.

c Viking Containment New Zealand, the HDPE liner supplier and installer, completed a temporary repair but could not undertake a full repair without dewatering the reservoir.

d During the leakage incident, TDC estimated that the reservoir fell by approximately 130 mm/day, then eventually stabilised a few metres above the reservoir floor. TDC has cautioned that systems for monitoring and measuring flows and reservoir levels were limited at the time of the incident.

e The subsoil seepage flows were estimated to be consistently a few litres per second (not measured directly) prior to the July 2021 leakage incident but increased to approximately 15 to 22 L/s following the incident[15]. TDC advise that the subsoil seepage flows following the incident are consistently clear and emerge from the lowest subsoil drain only.

TDC provided the photo in Figure 3.4 and notes below by email following the site visit:

> *"Lime was used to fill some of the trench damage.*
>
> *I believe the lime was only compacted by foot.*
>
> *Repairs further down the dam wall did not all have lime fill put into them.*
>
> *The liner further down still had areas totally unsupported by lime. When able to access you can bounce over the trenches and feel stones through the liner and cover.*
>
> *The original trench damage was up to 600mm deep and often had stones in the bottom of the trench.*
>
> *These stones often resulted in large circular depressions with the stone in the centre at the bottom.*
>
> *At one stage we isolated the impound. Nothing in and nothing out. Average daily loss then was around 130mm.*
>
> *26 April 2021, with the impound at 8089mm, we had trouble with pump cavitation.*
>
> *23 September 2021, with impound @ 2451mm and nothing in or out, the impound stabilised at this level."*
>
> Email C Brown to D Wood 13 June 2022

[15] TDC started monitoring the subsoil seepage flows following the 2021 leakage incident. However, there is some uncertainty regarding measured flows, and Section 3.2.3.3 provides recommendations to improve the accuracy.

Figure 3.4: Damage below liner near top of slope during 2021 leakage incident

ROV inspection of the reservoir floor was undertaken following detection of the leak. Relevant findings from the ROV inspections include the following:

a As already noted in Section 3.2.4.3, an ROV inspection (24 August 2021) identified two depressed areas (10 m x 10 m, and 2 m x 2 m) below the HDPE liner along the western side of the reservoir floor in line with subsoil line 6, which comprises a primary trunk line for the subsoil drainage network.

b ROV inspections (24 August 2021 and 2 September 2021) showed rippling movement of the HDPE liner, indicating air / water flow below the liner. The area of rippling extended 10 m to either side of the inlet structure and at least 2 m below the 5.8 m water level on 2 September 2021 inspection. The rippling increased in intensity when filling the reservoir and also did not stop entirely when valves controlling filling were closed. An email from the ROV survey company (M Mooney to C Chapman 3 September 2021) indicated that the ground in this area felt depressed while walking on the cover.

3.3 Assessment

3.3.1 Introduction

This section presents our assessment of the main dam safety issue (abnormal seepage). The subsections cover the following:

- Section 3.3.2 introduces the concept of potential failure modes, which is the framework within which the dam safety issue is assessed.
- Section 3.3.3 describes the sequence of steps comprising a failure mode that could plausibly explain the dam safety issue, based on the available information, vulnerabilities and relevant adverse observations identified in the preceding Section 3.2.
- Section 3.3.4 categorises the dam safety issue in accordance with industry definitions.

3.3.2 Potential failure modes

As already noted, a failure mode comprises a combination and sequence of condition(s), event(s), and mechanism(s) that could theoretically result in a dam failure, meaning an uncontrolled release of reservoir contents. An understanding of the most credible failure modes is used to focus all elements of dam safety management on the most significant vulnerabilities of the dam.

For the purposes of the current assessment, an understanding of failure modes is important for the following:

- Understanding the significance and urgency of the dam safety issue under discussion.
- Providing a more specific and granular context that enables development of more effective risk mitigation measures.

NZSOLD 2015 recommends that potential failure modes for Medium and High PIC dams are identified via a Failure Modes and Effects Analysis (FMEA). An FMEA typically involves:

- A dam-specific review of available information.
- A facilitated workshop attended by representatives of parties with relevant knowledge of the dam i.e., owner, technical advisors, specialists, designers, contractors, and surveillance staff.
- Identification of all credible potential failure modes.
- Assessment of the likelihood of development of those identified modes.
- Identification of key performance indicators and surveillance and emergency preparedness requirements for the higher risk potential failure modes.
- Formal reporting.

An FMEA does not appear to have been completed for the Dannevirke Water Supply Reservoir, which is not unusual for a Low PIC dam. In the absence of a formal FMEA, typical potential failure modes for earthfill embankment dams are summarised in Table 3.1 for the purposes of the current investigation.

Table 3.1: Typical potential failure modes for embankment dams (from NZSOLD 2015)

Potential Failure Mode	Common Causes
Overtopping	Insufficient freeboard to accommodate storms and flood events
Internal erosion of embankment materials	Presence of defect or crack, cohesionless core material or core material with a Plasticity Index less than 7, dispersive soils, lack of adequate filter protection
Suffusion of embankment materials	Cohesionless core material or core material with a Plasticity Index less than 7, gap graded embankment materials
Internal erosion of embankment materials into foundation materials	Open joints at interfaces, lack of adequate filter protection, lack of or inappropriate foundation treatment
Internal erosion of foundation materials	Foundation material has a Plasticity Index less than 7, dispersive foundation materials, lack of or inappropriate foundation treatment
Instability of downstream shoulder	Weak foundation, weak shallow seam in foundation, poor conditioning and compaction, lack of effective drainage and saturation of downstream shoulder, insufficient shear strength, strong earthquake shaking
Instability of upstream shoulder	Weak foundation, poor conditioning and compaction, rapid drawdown of reservoir, insufficient shear strength, strong earthquake shaking
Loss of freeboard, overtopping and subsequent erosion	Insufficient freeboard to accommodate foundation and embankment settlement, settlement following seismic loading, liquefaction of embankment and/or foundation materials, seiches generated by earthquakes, uplift of the reservoir due to fault displacement, reservoir landslides
Erosion along embankment/structure interfaces	Inappropriate design details, lack of filter and drainage protection, poor compaction adjacent to structure

3.3.3 Postulated failure mode for main dam safety issue (abnormal seepage)

This section hypothesises a potential failure mode that could plausibly explain the abnormally fast rate of seepage and "wet patch" based on the information currently available. An exhaustive, detailed review of all dam safety issues and potential failure modes from first principles has not been completed.

Table 3.2 below and Figure 0.1 in the Executive Summary set out the sequence of steps envisaged for the hypothesised failure mode. These steps represent dam-specific variations of the general failure modes described in Table 3.1. Other information that is provided in Table 3.2 includes:

- Commentary on timeframes for progression of the steps in the failure mode sequence, which is relevant to priorities and urgency for management of the dam safety issue.
- Recommendations to address areas of uncertainty for specific steps in the sequence, which are also taken forward into the overall recommendations in Section 3.4.
- Onsite indicators of progression of the various steps, which should be monitored to detect if the situation is deteriorating and more urgent action is needed.

Although some steps in the failure mode sequence have already occurred, additional (much less probable) steps would also need to occur before the dam safety issue could progress to a failure. There is unavoidable uncertainty relating to the likelihood of progression and timing for some steps, and as noted above, we have made recommendations to resolve the uncertainty. New information from implementing these recommendations could identify that certain steps are less likely to progress than currently assumed, and in turn, this may reduce the urgency of the overall dam safety issue. Nevertheless, in the interim, we recommend a precautionary approach where there is uncertainty given the potential consequences of a dam failure.

Table 3.2: Steps in postulated failure mode for subject dam safety issue

Step	Likelihood and supporting observations	Timeframes[16]	Onsite indicators to monitor	Recommendations
1 **Major leak through damage / tear(s) in the HDPE liner** *(Location: near inlet structure)*	Very likely – • Major leakage through a tear near the inlet structure occurred previously in the 2021 leakage incident. The liner was patched at the time. • Subsoil flows are larger than accounted for by the size of dam, expected groundwater seepage, and normal (minor) rates of liner leakage, indicating that reservoir water is highly likely to be entering the subsoil drainage network. • While the presence of a major leak through a tear is "very likely", the cause of the tear is less certain. The tear may have been caused by dynamic effects where inlet flows enter the reservoir based on observations of "rippling" of the floating cover (seen during site inspection) and HDPE liner (seen during ROV inspections). Alternatively, the tear could have been caused by stresses on the HDPE liner induced by undermining of the supporting clay liner via internal erosion into the subsoil drainage stone (and possibly also into the foundation materials) under normal rates of groundwater seepage and minor liner leakage prior to a tear developing. A report[17] by Viking Containment Ltd identifies further potential mechanisms for a tear through the liner. • Alternatively, the major leak through the liner could be located at the two depressions described under Step 3 below rather than near the inlet structure. Long-term stresses on the liner caused by the weight of water above the depressions could plausibly cause a brittle failure. If there is a liner leak at these depressions, a failure mode could progress without Steps 1 and 2 being necessary, though Steps 4 to 6 would still need to occur before a failure could eventuate and are considered less probable.	**Likely to have already occurred** based on the magnitude of subsoil flows.	• Subsoil flows larger than expected for groundwater seepage and normal (minor) rates of liner leakage. • Increased seepage at the "wet patch". • Drop in reservoir level disproportionate to expected outflows. • Whirlpool in reservoir.	• Improve surveillance / monitoring as per recommendations in Section 3.2.3. • Undertake a reservoir water balance to estimate the rate of leakage. • Locate HDPE liner damage. A staged approach could be taken, starting first with what can be inspected above current reservoir level especially near the inlet structure where liner damage occurred in the 2021 incident. Further stages could involve underwater inspection by ROV or direct inspection following dewatering.
2 **Scour of clay liner from water flowing under the HDPE liner and down the 1V:3H slope of the reservoir** *(Location: reservoir slope below the inlet structure)*	Almost certain – • Scour under the HDPE liner occurred previously in the July-September 2021 leakage incident, and was only partially repaired at the time. • Clay-sized material is likely to erode with water flow down a 1V:3H slope.	**Already occurred** and only partially repaired.	• Gradual trends or sudden changes (increases / decreases) in subsoil flows. • Increased turbidity of subsoil flows. • Increased seepage at "wet patch". • HDPE liner unsupported under foot. • Depressions under the HDPE liner or "rippling" of the HDPE observed by visual or ROV inspection.	• Improve surveillance / monitoring as per recommendations in Section 3.2.3. • Undertake turbidity monitoring of subsoil flows. • ROV inspection (or direct inspection following dewatering) to identify the location and extent of depressions and "rippling" of the HDPE liner.
3 **Internal "contact" erosion of the clay liner, clay capping, and / or foundation materials ("papa") into and through the 40 mm round stone used in the subsoil drains** *(Location: reservoir floor, following sub soil pipe 6)*	Very likely – • Two depressions (10m x 10m, and 2m x 2m) below the HDPE liner were observed during an ROV inspection during the 2021 leakage incident, and have not been repaired. • The particle size distributions of the clay and "papa" are likely to be incompatible with the subsoil drainage stone. The as-built drawings indicate there is no protective filter cloth or granular filter present.	Contact erosion typically occurs over a period of >12 hours to weeks depending on soil properties. However, the erosion has **already progressed significantly** based on the observed depressions.	• As per Step 2 above, but observations of unsupported HDPE, depressions, and "rippling" would be in the vicinity of subsoil drains on the reservoir floor.	• As per Step 2. • In addition, obtain samples of clay liner, "papa", and drainage stone. Undertake laboratory testing on the samples, which will vary depending on the material, but may include particle size distribution, relative density, plasticity index, plasticity of fines, pinhole dispersion, permeability, and strength tests.

[16] Typical timeframes for development of internal erosion are taken from Section 20 of "Geotechnical engineering of dams, 2nd Edition" Fell et al 2014.
[17] "Review of the Failure of the HDPE Membrane Liner beneath the Inlet Structure" Viking Containment Ltd dated 3 August 2022 [note the report relates to the 2021 incident and repair despite the more recent report date]

Step	Likelihood and supporting observations	Timeframes[16]	Onsite indicators to monitor	Recommendations
4 **Internal erosion through the embankment fill** *(Location: alongside the 10 m section of concrete backfill / encasement around the subsoil outlet pipe)*	Unlikely, but cannot be ruled out based on current information – • There is insufficient information on material characteristics to assess the vulnerability of the embankment fill to internal erosion (suffusion, backward erosion, and concentrated leak erosion).	There is a **wide range of possible timeframes** for initiation of internal erosion from <3 hours to years. Internal erosion can progress in steps if the roof of the first "pipes" collapse, and then new pipes need to reform. Typical timeframes for specific types of internal erosion comprise: • Suffusion: >12 hours to months, or even years, depending on material. • Backward erosion: can progress slowly at first, then rapidly once it reaches a critical point i.e., >12 hours to days. • Concentrated leak: <3 hours to days.	• As per Step 2 above, but observations of unsupported HDPE, depressions, and "rippling" would be in the vicinity of the 10 m sections of concrete backfill / encasement near the north-eastern corner of the reservoir.	• As per Step 2. • In addition, obtain samples of the eastern embankment fill and undertake laboratory testing for a similar suite of possible tests as described for Step 3.
5 **Internal erosion along the subsoil outlet pipe or through the adjacent embankment fill** *(Location: between the 10 m section of trench with concrete backfill and 2050 mm diameter manhole)*	Moderately likely – • The clay backfill around the non-perforated section of pipe was likely to have been difficult to compact into the corrugations and under the haunches of the pipe, creating an increased vulnerability to "concentrated leak" internal erosion alongside the pipe. • "Contact" type internal erosion of the clay backfill around the outlet pipe into the surrounding gravelly clay foundation materials cannot be ruled out based on current information on materials. • There is also insufficient information on material characteristics to assess the likelihood of internal erosion within the embankment fill alongside the pipe (suffusion, backward erosion, and concentrated leak erosion).	• As per Step 4 above.	• As per Step 2 above, but observations of unsupported HDPE and depressions would be in the vicinity of the subsoil outlet pipe between the 10 m sections of trench with concrete backfill and the 2050 mm diameter manhole. • Settlement, deformation, cracking, and sinkholes in the dam crest and slopes above the subsoil pipe.	• As per Steps 3 and 4 above. This should include visual inspection of the dam crest and slopes.
6 **Internal erosion through the foundation materials (in situ gravelly clay)** *(Location: between the 2050 mm diameter manhole and "wet patch")*	Unlikely, but cannot be ruled out based on current information – • The "wet patch" on the downstream shoulder of the eastern embankment indicates long-term dampness at this location. This could indicate progression of internal erosion but alternatively could relate to mechanisms of lesser concern for dam safety, such as seepage through a permeable but stable horizon in the foundation or infiltrated rainwater emerging at the contact with in situ ground. At the time of the site inspection there was ponding but no significant flow visibly emerging from the dam face. • Based on the as-built drawings and photos from construction, the internal erosion would primarily need to occur through the in situ gravelly clay foundation materials to emerge at the elevation of the "wet patch", though some internal erosion through embankment fill could also be involved. There is insufficient information on material characteristics of both the gravelly clay foundation materials and embankment fill materials to assess vulnerability to internal erosion (suffusion, backward erosion, and concentrated leak erosion). • We have assumed the mostly likely pathway for the failure mode is between the 2050 mm diameter manhole and the "wet patch". Alternatively, the failure mode could progress alongside the 450 mm diameter weld jointed PE pipe and the stream outlet. There is insufficient information on the bedding of the 450 mm diameter pipe to rule out this alternative pathway. However, the pathway between the 2050 mm diameter manhole and the "wet patch" is considered more likely due to the shorter seepage path and observed "wet patch".	• As per Step 4 above.	• Increased seepage, muddy seepage, and sand boils at the "wet patch" or other parts of the downstream fill slope. • Settlement, deformation, cracking, and sinkholes in the downstream fill slope between the 2050 mm diameter manhole and the "wet patch". • Changes in pore water pressures within the eastern fill embankment. • Fell et al 2014 indicates that backward erosion is readily detected in most cases where the exit point is at the surface. Suffusion and concentrated leak erosion may not be detected in many cases.	• Improve surveillance / monitoring as per recommendations in Section 3.2.3. This should include visual inspection and monitoring of the dam crest, slopes, "wet patch", and area around the subsoil outlet to the stream. • In addition, obtain samples of the in situ gravelly clay and undertake laboratory testing for a similar suite of possible tests as described for Step 3. • Install multi-level piezometers in the downstream shoulder of the dam fill to monitor pore water pressures. The piezometers could be installed at the same time as drilling boreholes to obtain samples of fill, in situ gravelly clay, and "papa" for laboratory testing. The boreholes should also aim to identify the contact with the top of the "papa" and check for "softening" at the contact, which may comprise a plane of weakness for global stability. • Use dye tracers to identify where leakage from HDPE tears is emerging i.e., at the subsoil outlet and / or "wet patch". Specialised sensitive equipment is likely to be needed to detect very low concentrations of dye at the "wet patch".

Step	Likelihood and supporting observations	Timeframes[16]	Onsite indicators to monitor	Recommendations
7 **Initiation of breach, i.e., an uncontrolled release of the reservoir water through a section of the embankment in which the crest has dropped to below the reservoir level[18]** *(Location: between the 10 m section of trench with concrete backfill and "wet patch", especially portion below dam crest)*	Unlikely, but cannot be ruled out based on current information – • Four mechanisms have been considered as summarised below. Mechanisms 1 and 2 are considered more likely than mechanisms 3 and 4. Mechanism 1 is judged higher risk due to faster rates of progression and more difficult detection. • **Mechanism 1: "Gross enlargement"** of an internal erosion "pipe" in the embankment / foundation followed by settlement or collapse of the embankment into the pipe resulting in the crest dropping to below reservoir level and being overtopped. There is insufficient information on the gravelly clay foundation and embankment fill to assess if these materials have enough plasticity and fines to "hold a roof" for the necessary time to develop a pipe large enough to cause the crest to settle more than the freeboard. • **Mechanism 2: "Sinkhole progression"** i.e., development of a sinkhole connecting into a pipe in the embankment / foundation, resulting in settlement and overtopping of the crest. Similar to the preceding mechanism, there is insufficient information on the foundation and fill to assess if these materials can sustain a pipe for the necessary time to develop a sinkhole large enough to compromise the freeboard. • **Mechanism 3: "Unravelling"** or sloughing of the downstream face of the embankment. Unravelling involves the progressive removal of individual silt, sand and gravel particles by seepage flows emerging at the downstream face. For this to progress to a dam failure, the unravelling has to continue until it has eroded back to the dam crest and allowed the reservoir to overtop the embankment. This mechanism is considered very unlikely due to the long seepage path and relatively flat batter slope. • **Mechanism 4: "Slope instability"** of the downstream shoulder of the embankment and / or foundation, resulting in settlement and overtopping of the crest. Due to the relatively flat slope and ample freeboard, multiple adverse factors would be required in combination to result in a breach, such as substantially elevated pore water pressures in the downstream shoulder due to internal erosion, a large earthquake, and an unfavourably located plane of weakness (say a softened surface on the lower permeability "papa" beneath the gravelly clay). The combined probability of these adverse factors occurring together is considered very low i.e., very unlikely.	Typical timeframes for these mechanisms to develop are: • Mechanism 1 "gross enlargement": <3 hours to days. • Mechanism 2 "sinkhole progression", mechanism 3 "unravelling", and mechanism 4*** "slope instability": days to months, and even years. ***For mechanism 4, the unfavourable pore water pressures could build up over days to months, and then an earthquake trigger more sudden collapse.	• As per Steps 5 and 6 above. • Fell et al 2014 indicates that mechanisms 2, 3 and 4 are readily detected in most cases but mechanism 1 "gross enlargement" may be more difficult to detect in some cases.	• As per recommendations for other steps above.

[18] This follows the definition of "breach" in Section 8.11.1 Fell et al 2014, which states "Loss of the reservoir water through a pipe which does not collapse to breach the crest is not regarded as a breach in the dam since the rate of release of the water will be limited by the size of the pipe". It may be possible that 100% of the reservoir water is lost through an internal erosion "pipe" or sinkhole before the crest breaches, which would be a significantly adverse event even without a breach.

3.3.4 Categorisation of dam safety issue

The New Zealand Dam Safety Guidelines (NZSOLD 2015) defines categories of dam safety issues:

i **Physical infrastructure issues**, where equipment, access, instrumentation, communications or maintenance is insufficient to verify satisfactory dam performance.

ii **Dam safety deficiencies**, where a fundamental flaw (design, construction or previously unrecognised condition) or vulnerability exists that may develop, under certain circumstances or loading conditions, into an identifiable and credible potential failure mode. There are two sub-categories:

- **Potential dam safety deficiencies**, where particular performance requirements may not be met i.e., unknowns exist and further investigation and / or assessment is required.
- **Confirmed dam safety deficiencies**, where adverse performance has already been observed, or will definitely come to pass under realistically expected loading conditions.

iii **Non-conformances**, where dam safety management system processes and procedures have not been followed, or established dam safety practices have not been implemented.

The subject dam safety issue is considered a "confirmed dam safety deficiency" on the basis that adverse performance has already been observed, specifically:

- In the 2021 incident, significant leakage was observed through a damaged section of the HDPE liner near the inlet structure.
- Undermining of the supporting clay layer under the HDPE liner was also observed in the 2021 incident. The undermining was not fully repaired (backfilled in accessible locations only).
- Subsequent to the 2021 incident, the rate of discharge from the subsoil drainage network continues to be abnormally fast and beyond the original design intent of the subsoil drainage network, which was to prevent uplift of the liner under expected (minor) groundwater flows.

3.4 Recommendations

Table 3.3 presents our recommendations for the subject dam safety issue.

The priority rankings for recommendations comprise:

- P = Priority. Should be attended to immediately.
- N = Needed. Needs to be done as soon as practicable.
- D = Desirable. Should be attended to within a year.

All the recommendations in Table 3.3 relate to a Confirmed Dam Safety Deficiency and are ranked "P".

Following the initial site inspection and prior to this report, T+T provided preliminary recommendations that TDC has already started implementing. These previous recommendations are reiterated for completeness within Table 3.3 as recommendations CDSD2022-01 to CDSD2022-04.

Table 3.3: Recommendations for the dam safety issue related to abnormal seepage (large subsoil flows and "wet patch")

ID	Recommendation	Timeframe	Purpose
CDSD2022-01	**Operate the reservoir at the minimum level acceptable for water supply** The *lower* the reservoir level: • The *lower* the risk of a dam failure in terms of both[19] likelihood and consequences. • The *greater* the risk of interruption in water supply to the community and associated health risks. We understand that TDC is reviewing historical levels to identify an optimal operating level to balance these risks.	Immediate, and continuing until dam safety issue is resolved.	• Mitigate dam safety risk while the dam safety issue is being resolved.
CDSD2022-02	**Undertake enhanced dam safety surveillance / monitoring** *Surveillance monitoring should include:* 1 Visual inspection – a dam-specific visual inspection checklist should be developed but in the interim, an example checklist from the New Zealand Dam Safety Guidelines can be found in Appendix C. Over and above the areas for inspection in the example checklist, the visual inspection should include: – Checking the dam crest and slopes (particularly along the failure mode pathway in Figure 0.1 in the Executive Summary) for settlement, deformation, cracking and sinkholes. – Monitoring the "wet patch" on the downstream face of the north-eastern dam embankment, which should include: o Marking out the extent of seepage with pegs or similar. o Taking a photo at the same location each day. o Inspecting the ground for visible emerging flow and recording the observation. – Visually checking subsoil seepage flows for "cloudiness" and sediment. – Checking for seepage and tomos emerging from the ground in the vicinity of the subsoil outlet pipe and the stream outlet. Vegetation in the areas for visual inspection should be maintained as short grass to enable effective inspection. Consideration should be given to whether the floating RPP reservoir cover is required or could be removed. For dam safety purposes, it is preferable for the cover to be removed permanently to enable visual inspection of the HDPE liner (at least above reservoir water level) to detect damage and undermining / depressions as early as possible. There may be other reasons the reservoir cover cannot be removed permanently, such as for water quality or UV protection of the HDPE liner. 2 Hydrometric monitoring of reservoir water level, rainfall, inflows, and outflows including subsoil seepage – TDC recently installed a new transducer because of concerns about the accuracy of measured reservoir water levels. We recommend verifying that the accuracy concern has been resolved. We also recommend the following changes to subsoil seepage monitoring: – Rainwater that ponds on the reservoir cover should be kept separate from subsoil seepage upstream of the subsoil monitoring point. – The portion of subsoil seepage that is pumped back into the reservoir should be monitored at the same frequency and accuracy as subsoil discharge at the stream outlet. Both the subsoil seepage pumped back and discharged at the stream should be recorded separately, and also summed to track total subsoil seepage. – There are five discharge points at different elevations in the 2050 mm diameter manhole for subsoil drains from different parts of the reservoir. It should be verified that flows are emerging solely from the lowest discharge point across the range of relevant conditions. If there is flow from more than one discharge point, the flows should be monitored individually. 3 Turbidity monitoring of the subsoil seepage - this could involve installation of a sensor, taking readings with a meter, or sending samples for laboratory testing. We expect this will be a decision for TDC based on costs and benefits, supported by advice from a dam safety specialist. 4 Pore water pressure monitoring within the eastern fill embankment - this will require installation of piezometers as per recommendation CDSD2022-09. *Frequency* The visual inspection should be recorded daily as a minimum. Hydrometric, turbidity and pore water pressure monitoring should be recorded as continuously as readily practicable, but daily as a minimum for hydrometric and pore water pressure monitoring, and weekly as a minimum for turbidity monitoring. The frequency of readings should be reviewed by a dam safety specialist following the first two weeks of surveillance. *Data management* A standardised format (i.e., a spreadsheet or database) should be developed and used consistently for recording and storing all visual observations and monitoring data. Those recording the data should be trained to use the standardised format as intended. Data entry should be checked. Readings that appear anomalous upon entry should be verified, and extra field readings taken if needed for verification. Each and every element in the standardised format should be labelled clearly, including: • What the data represents physically on site. • Who, when, what and how the data was collected.	Immediate. Plus ongoing adjustment to the monitoring programme as the situation develops.	• Detect onsite changes that may indicate deterioration of the situation requiring more urgent action, which may include emergency response. • Provide information on the dam safety issue to improve understanding of risk and urgency, and to inform effective design of remedial works.

[19] When the reservoir level is lower, a dam failure is less *likely* because the hydraulic loads and seepage gradient through the dam are reduced. The *consequences* of a dam failure are also reduced since the potential dambreak flood is smaller when the reservoir level is lower.

ID	Recommendation	Timeframe	Purpose
	• Tagging the data as incorrect or suspicious where relevant. • Identifying if the data is raw or has been manipulated. • Where manipulation, analysis, and interpretation of data is included in the spreadsheet / database, the purpose, methodology, person responsible, and level of confidence / checking should be noted. *Escalation* Advice from a dam safety specialist should be sought urgently if there are unusual or adverse observations or readings, such as the following (listed in order of increasing concern and urgency for dam safety): • A gradual upwards trend in subsoil seepage. • A sudden increase or decrease in subsoil seepage. • Increased turbidity of subsoil seepage. • Visually cloudy / discoloured subsoil seepage. • A change in the extent and condition of the "wet patch". • A gradual upwards trend in pore water pressures within the dam fill embankment. • A sudden increase or decrease in pore water pressures within the dam fill embankment. • Visible seepage emerging, increased seepage, muddy seepage, and sandboils at the "wet patch" or other parts of the dam slopes. • Any signs of instability, settlement, deformation, cracking, and sinkholes in the dam crest and dam slopes, particularly (but not exclusively) along the postulated failure mode pathway in Figure 0.1 in the Executive Summary. • A drop in reservoir level disproportionate to expected outflows. • A whirlpool in the reservoir. The triggers above are qualitative and general. Specific alert and alarm levels should be specified by a dam safety specialist once monitoring recommendations have been implemented and a representative period of data has been collected and reviewed. The situations above may require action, which in the worst case could involve emergency response. The appropriate action will depend on multiple factors, including which triggers have been occurred in combination, degree of triggering, locations in the dam, conditions on the day, and practical considerations. As such, we recommend that the response is adaptive and is formulated by TDC with technical support from a dam safety specialist.		
CDSD2022-03	**Develop a contingency plan in case the situation deteriorates** The contingency plan should: 1 Identify parties that may be affected by a dambreak flood and will require warning if the situation deteriorates. 2 Identify situations and conditions that would trigger an emergency response. 3 Develop a plan for emergency response covering roles and responsibilities, communications, preventative and emergency actions, health and safety, and evacuation (if relevant). 4 Identify how long it would take to dewater the reservoir. 5 Establish agreements for supply of earthmoving plant, operators, and materials for preventive and emergency actions. This may include emergency power supply, high-capacity pumps, filter cloth, sand, gravel, rock armour, and sandbags. 6 Establish agreements for technical dam safety advice for emergency response. 7 Prepare lists of contact details for emergency response, including affected downstream parties, suppliers, advisors, and emergency response partners (CDEM, Police etc).	Immediate	• Mitigate dam safety risk while the dam safety issue is being resolved.
CDSD2022-04	**Prepare for repairs** Repairs will be necessary for ongoing long-term operation of the reservoir. Alternatively, TDC could consider decommissioning the reservoir and pursuing alternative water supply options though this would still entail significant work, time, cost, and risk. Preparing for repairs is expected to involve: 1 Work to remove operational constraints to enable dewatering for investigation and remedial works. 2 Investigation into the dam safety issue to resolve areas of uncertainty. 3 Update PIC based on latest industry practice and upcoming legislative changes i.e., the Building (Dam Safety) Regulations 2022, which come into force in 2024. The PIC may depend on whether water supply to the community can reasonably be provided by an alternative means than from the reservoir, which may change depending on the work to remove operational constraints described above. 4 Geotechnical investigation and detailed design of remedial works. 5 Resource consent for remedial works. 6 Building consent for remedial works. 7 Contractor selection and engagement.	Immediate, and continuing until remedial works are underway.	• Progress towards resolving the dam safety issue.

ID	Recommendation	Timeframe	Purpose
CDSD2022-05	**Update Health and Safety systems for risks related to the dam safety issue** This may include: 1 Reviewing and updating risk management tools, such as risk registers, Safe Work Method Statements for working in the dambreak area, and JSAs for surveillance / monitoring and emergency response tasks. 2 Providing information, training, instruction or supervision for employees, contractors, and visitors to site. 3 Updating workplace emergency plans.	Immediate. Plus ongoing review as the situation develops.	• Mitigate health and safety risks while the dam safety issue is being resolved.
CDSD2022-06	**Undertake a reservoir water balance** Model the reservoir water balance based on records of inflows, outflows, and storage / reservoir water level to identify unexpected losses that may correlate to leakage.	Following implementation of CDSD2022-01 and collection of a representative period of data.	• Provide information on the dam safety issue to improve understanding of risk and urgency, and to inform effective design of remedial works.
CDSD2022-07	**Locate HDPE liner damage above reservoir level** The HDPE liner should be inspected to identify where damage, and thus leakage, is occurring. A staged approach could be taken, starting first with what can be inspected above current reservoir level especially near the inlet structure where liner damage occurred in the 2021 incident. Further stages could involve underwater inspection by ROV (refer also CDSD2022-08) or direct inspection following dewatering.	Immediate.	• Provide information on the dam safety issue to improve understanding of risk and urgency, and to inform effective design of remedial works.
CDSD2022-08	**ROV inspection and leakage tracing below reservoir level** The underwater inspection of the reservoir floor and sides should aim to: 1 Identify the location and extent of damage to the HDPE liner, including a description of any observed leakage. 2 Identify the location and extent of depressions / undermining of the supporting layer under the HDPE liner. 3 Identify locations where there is "rippling" of the HDPE, indicative of air or water flow under the HDPE liner. 4 Inject dye at leak locations and track where this emerges downstream of the dam i.e., at the subsoil outlet to the stream and / or "wet patch". Specialised sensitive equipment is likely to be needed to detect very low concentrations of dye at the "wet patch".	As soon as practicable.	• Provide information on the dam safety issue to improve understanding of risk and urgency, and to inform effective design of remedial works.
CDSD2022-09	**Geotechnical investigation and piezometer installation** This work would involve: 1 Approximately two drillholes in the downstream shoulder of the eastern fill embankment. 2 Accurate logs of the drillholes, which include: – The interface between dam embankment fill, in situ gravelly clay, and underlying in situ "papa", and changes in material characteristics within those units. – Evidence of softening or sliding on the contact with the top of the "papa", which may comprise a plane of weakness for global stability. 3 Installation of multi-level piezometers in the drillholes to monitor pore water pressures (refer also CDSD2022-01). 4 The location of the drillholes should be surveyed accurately. 5 Special methods will be needed for drilling and reinstatement to avoid damage to the dam embankment. 6 Samples of the embankment fill, in situ gravelly clay, and in situ "papa" should be taken from the drill holes for laboratory testing. Shovel samples of the clay liner should also be taken for laboratory testing. If there is opportunity, a shovel sample of the 40 mm round drainage stone should also be obtained from the subsoil drains though this is not expected to be practicable given the location of the drains. 7 Undertake laboratory testing on the samples, which will vary depending on the material, but may include testing of particle size distribution, relative density, plasticity index, plasticity of fines, pinhole dispersion, permeability, and strength.	As soon as practicable.	• Enable monitoring of pore water pressures in the dam embankment to detect changes that may indicate deterioration of the situation requiring more urgent action, which may include emergency response. • Provide information on the dam safety issue to improve understanding of risk and urgency, and to inform effective design of remedial works.

Note: All the recommendations in Table 5 relate to a Confirmed Dam Safety Deficiency and are ranked "P".

4 Other dam safety recommendations

Several other dam safety issues, not directly related to the main dam safety issue, were noted in the course of investigating the main dam safety issue. Although not strictly within the scope of the current exercise, recommendations to address these additional issues are presented in the table below in case these provide information that is helpful for TDC's forward planning.

Table 4.1: Miscellaneous extra dam safety recommendations

ID	Recommendation	Priority ranking***
Dam Safety Issue Category = Physical Infrastructure Issue (PII)		
PII2022-01	Check TDC has legal power to access and maintain the safety of the downstream shoulder of the eastern fill embankment. Current property information indicates that TDC only owns the crest of the dam and internal faces of the reservoir, while the external slopes of the dam are in private ownership[20]. During the site inspection, TDC advised that the private owner grazes stock on the downstream shoulder of the eastern fill embankment, which is not recommended practice for dams. This item has been given a priority ranking of "P" since access will likely be needed to enable investigation and remedial works for the subject dam safety issue relating to abnormal seepage.	**"P"**
Dam Safety Issue Category = Non-conformance (NC)		
NC2022-01	Check work has been completed and documentation provided to conclude the building consent process. At the time of the final inspection for code compliance on 14 June 2013, the overland flowpath from the spillway was not constructed. "Regulatory review of Code Compliance Certificate application BC123041 – Dannevirke water reservoir" (T+T 30 July 2013, ref 61572.001) suggested that the following documentation should be submitted by TDC to Waikato Regional Council: • Design calculations and drawings of the overland flowpath from the spillway • Photographic evidence that the overland flowpath from the spillway is constructed in accordance with the design • A construction review producer statement signed by Mr King In addition to the above, it appears that the spillway crest / sill was constructed higher than indicated in the as-built drawings. Photos from the final inspection for code compliance indicate that the spillway sill (and gate) were not yet constructed at the time of inspection. As-built drawings should be updated to reflect the final arrangement, and approval for an amendment / variation to the building consent should be sought.	**"N"**
NC2022-02	Engage an external specialist to undertake a Comprehensive Dam Safety Review (CDSR). The CDSR provides a holistic stocktake of the site-specific dam safety issues based on the latest industry practice and upcoming legislative changes. The CDSR should be undertaken following the PIC review recommended in CDSD2022-04 in Table 3.3. If the current Low PIC is revised to Medium or	"**N**" if Medium / High PIC. "**D**" if Low PIC.

[20] This seems to be at odds with Item (e) of Section 4.1 of "Building Consent No. 123041: Regulatory review of HDPE lined earth dam, Dannevirke" (T+T 22 February 2012, ref 61572 Rev A), which noted that the dam was expected to be constructed entirely on a land parcel (PT Lot 5 DP1159) that was being purchased by TDC.

ID	Recommendation	Priority ranking***
	High, the urgency and scope of the CDSR will both increase, including undertaking a Failure Modes and Effects Analysis (FMEA) as described in Section 3.3.2 at the outset of the CDSR.	

*** P = Priority. Should be attended to immediately.
N = Needed. Needs to be done as soon as practicable.
D = Desirable. Should be attended to within a year.

As already noted, a review of PIC was recommended in CDSD2022-04 of Table 3.3. See also Section 2.4 for related discussion.

If the current Low PIC is revised to Medium or High PIC, the CDSR proposed in NC2022-02 in Table 4.1 is likely to make more extensive recommendations than if the dam remains Low PIC. As such, if the dam changes to Medium or High PIC, TDC should plan for an increased programme of work, which would likely include:

- Information and analysis available from the original investigation, design, and construction of the dam may be inadequate for a Medium or High PIC dam, which may result in the CDSR recommending forensic investigations and updated analyses. It is noted that some of the additional investigations and analyses would likely be undertaken in the course of resolving the current dam safety issue related to abnormal seepage.
- Performance standards, such as for static stability, earthquakes, and floods, are more onerous as the PIC increases. As such, assessing the dam against the performance standards for a Medium / High PIC dam for the updated analyses in the bullet point above, could result in identification of new dam safety deficiencies to resolve.
- Requirements for ongoing dam safety management are more onerous for a Medium or High PIC dam than for a Low PIC dam, which may result in the CDSR recommending a substantial update to the Dam Safety Management System (DSMS) for the dam. Implementation of the updated DSMS could include more onerous activities and systems for governance, training staff, operation, maintenance, surveillance, independent dam safety reviews, emergency preparedness, dam safety issue management, information management, and ongoing audits and reviews of the DSMS itself. New surveillance instrumentation, such as deformation markers, may need to be installed.
- The Building (Dam Safety) Regulations 2022, which come into force in 2024, include more requirements for Medium and High PIC dams than Low PIC dams, largely relating to Dam Safety Assurance Programmes (DSAPs). Further information is included in Section 2.4. Implementing the updated DSMS described in the bullet point above would also largely cover off the extra-over DSAP-related requirements in the 2022 regulations.

5 Applicability

This report has been prepared for the exclusive use of our client Tararua District Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Tonkin & Taylor Ltd

Environmental and Engineering Consultants

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Appendix A Available information

The information that has been considered for the purposes of this report is listed below.

a Visual observations and discussion with TDC at the site inspection described in Section 3.2.2.

b Documents provided by TDC to T+T on 1 June 2022:
- As built drawings titled "Asset Plans - Dannevirke Water Impounded Reservoir - As Built CAD Drawings - 04 July 2013"
- ROV Inspection & Leak Detection – Dannevirke Raw Water Reservoir inspection report by Detection Services dated May 2022
- Laws Road Water Reservoir Thermal Aerial Inspection by Aerial InfraRed also dated May 2022

c LiDAR and surveillance data provided by TDC to T+T on 20 June 2022:
- Two sets of LiDAR point clouds, flown on the following dates:
  - 10 November 2021
  - 2 June 2022
- Surveillance data comprising:
  - Reservoir water levels, inflows, outflows from the water treatment plant between 13 February 2022 and 9 June 2022
  - Subsoil seepage flows between 1 November 2021 and 30 May 2022

d Documents provided by TDC to Waikato Regional Council (WRC), and in turn to T+T as WRC's compliance reviewer for Building Consent No. 123041 (T+T Ref 61572)[21]:
- Building Consent "F2" Application Form
- Certificates of Title
- Horizons Regional Council Project Information Memorandum (PIM)
- TDC PIM
- TDC letter to Waikato Regional Council of 10 October 2011
- Auckland Uniservices Ltd. Letter to TDC of 5 November 2011
- Geotechnical report (Auckland Uniservices Ltd., 25 November 2011)
- Hydrologic and hydraulic calculations (Wai Waste Environmental Consultants Ltd letter to TDC of 12 December 2011 and revised 19 January 2012)
- TDC letter to Tonkin & Taylor Ltd. of 2 February 2012
- TDC letter to Tonkin & Taylor Ltd. and WRC of 15 February 2012
- Producer Statement – Design (PS1) signed by Blair King of TDC on 15 February 2012
- Construction Drawings, sheets 1 to 13c (Drawing list issued by TDC 14 February 2012)
- Construction specification (TNZ F/1:1997 with TDC amendments of 28 January 2012)
- Certificate of Acceptance "F8" Application Form
- TDC drawings showing Construction (Earthworks) to Date, Sheets 1 to 4, (Drawing list issued by TDC 14 February 2012)
- TDC drawings showing earthworks test locations to date, Sheet 1, (Drawing list issued by TDC 14 February 2012)
- TDC drawings showing Construction (Drainage Work) to Date, Sheet 1, (Drawing list issued by TDC 14 February 2012)

[21] TDC, WRC as the Building Consent Authority, and Horizons Regional Council as Regional Authority have provided permission to use these documents for the purposes of the current report.

- Producer Statement – Construction (Sixth Schedule of NZS 3910:2003) covering works completed to date signed by Stanton Hardgrave of Infracon Ltd on 30 January 2012
- Producer Statement – Construction Review (PS4) signed by R. B. Cannon of TDC Engineering Services
- Construction Completion Report by TDC dated 20 June 2013
- Quality control and assurance report by Viking Containment dated July 2013
- F6 Code Compliance Certificate signed by Blair King on 1 July 2013

e Documents provided by TDC to T+T on 5 September 2022:

- "Review of the Failure of the HDPE Membrane Liner beneath the Inlet Structure" Viking Containment Ltd dated 3 August 2022 [note relates to 2021 incident and repair]
- Geomembrane Test Results by TRI Australasia dated June to July 2022
- Ground Penetrating Radar Survey Report by Pathfinder Underground Utility Locators dated 11 December 2021

f Survey of spillway levels provided by TDC to T+T on 12 September 2022

The documents in the preceding list were briefly screened to identify those most likely to be relevant. This subset of more promising documents was then considered in further detail.

We have also requested the following information,:

a Scanned site diary pages for the period of leakage and investigation (received on 22 June 2022, yet to be reviewed)

b Photos and reports from temporary repair of the liner by Viking Containment (photos and notes received on 13 June 2022, as referred to in Section 3.2.4.4)

c Surveillance data, including comments on whether the data were or were not reliable, changes in operation such as installation of transducer at base of pond etc. (some already received and reviewed as noted above)

- Reservoir levels
- Offtake flows
- Subsoil seepage flows
- Portion of subsoil flows pumped back to reservoir

d Photos of the identified "wet patch" on as many dates as available (not yet received)

e All 3 drone surveys and reports including the first one that identified the slump in the north-western pond floor (not yet received)

f Previous chemical and/turbidity analysis and dates of samples of subsoil seepage

g All rounds of LiDAR (received on 20 June 2022 and reviewed as noted above).

Appendix B 10 June 2022 Inspection Photos

Figure A 1: Reservoir cover noting depression under the cover near the middle of the photo is the location of the inlet

Figure A 2: Downstream face of the eastern embankment - note "wet patch" in middle of photo

Figure A 3: Close up photo of the "wet patch"

Figure A 4: Downstream face of the eastern embankment – looking south

Figure A 5: Crest of the eastern embankment – looking south

Figure A 6: Water ponding on crest of the eastern embankment

Figure A 7: Seepage flow at subsoil drain outlet to stream

Figure A 8: Natural materials (silty gravel) exposed in cut alongside access track to reservoir

Appendix C Example Visual Inspection Checklist

Extracted from the New Zealand Dam Safety Guidelines (NZSOLD 2015).

reporting to the Owner on the safety of the dam and the need for specific responses or required actions.

4.2.5 Visual Inspections

Philosophy

Visual inspection by competent and trained personnel is the most effective means of dam surveillance. There is no substitute for the observations and preliminary judgements of individuals who:

- Are familiar with the dam's layout and features.
- Are familiar with the objectives of instrument monitoring and measurement, and instrument monitoring and measurement procedures.
- Are aware of the characteristic behaviour of the dam and installed instruments.
- Can detect, record and report any change in condition.
- Understand the dam's potential failure modes and vulnerabilities.
- Are able to recognise indicators of adverse dam performance and the initiation of potential failure modes.

Visual inspections should follow a repeatable checklist of items that is appropriate to the dam (and foundation) type, characteristic behaviour and potential failure modes. Inspection checklists should be developed in conjunction with a Technical Adviser. An example checklist for an embankment dam is provided in Figure 4.1. Note that this example is provided to illustrate the nature of the checklist, and as such, items E1 to E10 are not all inclusive. The checklist developed for each dam should be geared to the specific nature, features, characteristics, identified credible potential failure modes and performance history of the dam. An open ended question at the end of each section of the checklist should be included, such as, 'Are there any other conditions or observations of interest?'. It is very important that the checklist should not be so prescriptive that the inspector is not encouraged to look at other areas and features that may have a bearing on dam safety and this principle should be emphasised in the inspector's training.

Photographs of general and specific features, from repeatable locations provide an effective long term record of inspection observations. Video recording of features or unusual events can also be particularly valuable.

Figure 4.1: Example Routine Visual Inspection Checklist for an Embankment Dam

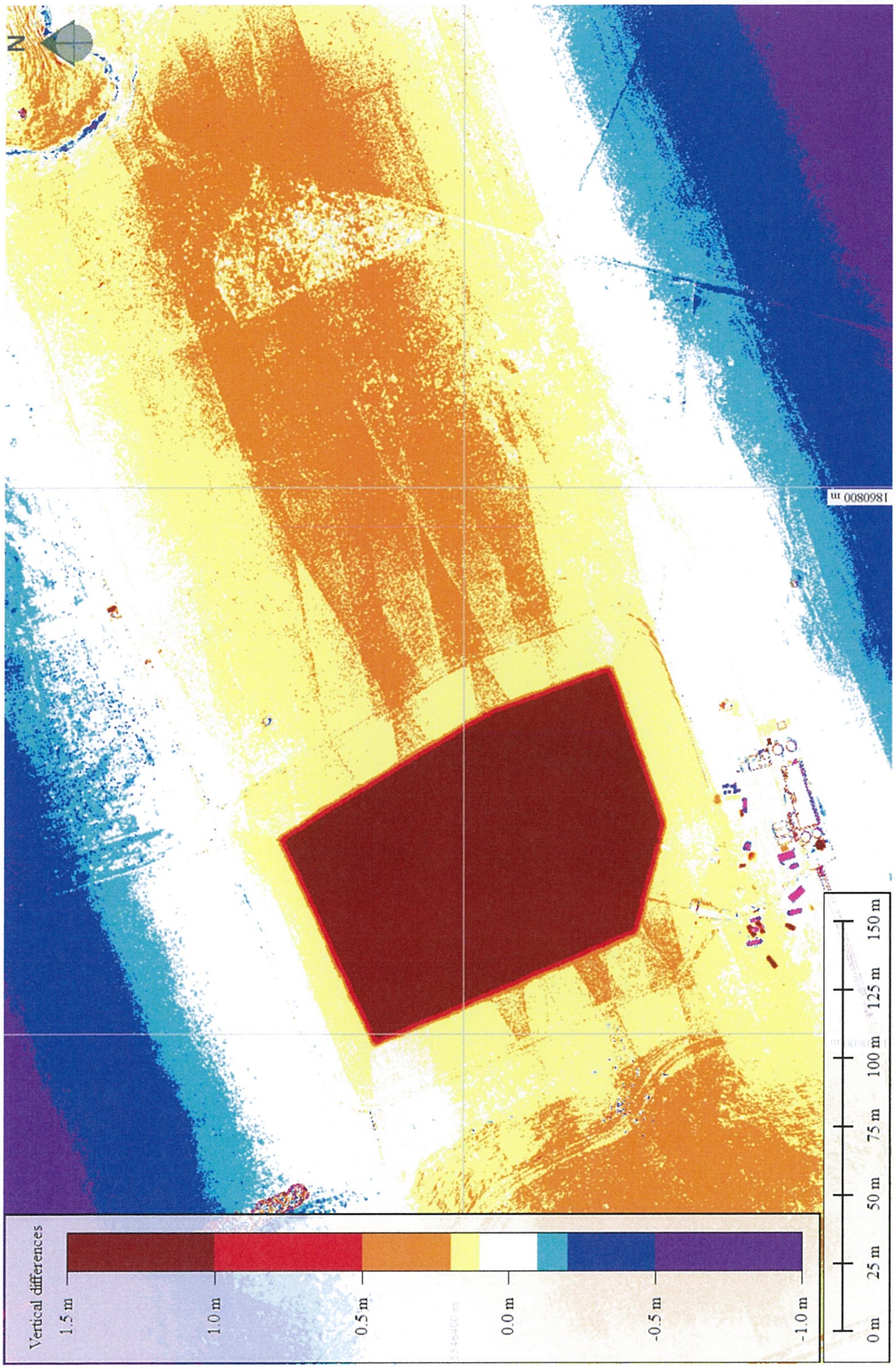
Routine Inspection List for Blue Dam
Inspected by:
Date and time:
Weather:
Potential Failure Modes:
PFM1: Embankment seepage and internal erosion leading to piping failure
PFM2: Foundation seepage and internal erosion leading to piping failure
PFM3: Flood-induced overtopping of embankment and erosion leading to failure
PFM4: Earthquake induced embankment cracking leading to seepage, internal erosion and piping failure
PFM5: Earthquake induced embankment deformation leading to loss of freeboard and overtopping failure
PFM6: Operational flow imbalance induced overtopping of embankment and erosion leading to failure

(cont'd next page)

Figure 4.1 (cont'd): Example Routine Visual Inspection Checklist for an Embankment Dam

Item No.	Description	Observation/Comment
E1	Record reservoir level (e.g. metres above mean sea level)	
E2	Is there reservoir shoreline instability or erosion?	
E3	Is the upstream face showing any erosion, instability, depression or cracking?	
E4	Is the dam crest showing any deformation, misalignment, depressions or cracking?	
E5	Is the left abutment showing any instability or seepage, including where the dam embankment contacts with the abutment?	
E6	Is the right abutment showing any instability or seepage, including where the dam embankment contacts with the abutment?	
E7	Is the downstream face showing any instability, deformation, depression, cracking or seepage?	
E8	Is the dam toe showing any erosion or seepage?	
E9	Measure the total dam seepage (e.g. time to fill 1 litre container, or mm head over a 90 degree v-notch weir)	
E10	Is the spillway entrance obstructed? Is the spillway chute or plunge pool damaged or eroded?	
Other Comments and Observations (e.g. unusual events since last inspection, vegetation issues, operating issues).		

Appendix D Differences between LiDAR data sets (June 2022 minus November 2021)


N
1860800 m
Vertical differences
1.5 m
1.0 m
0.5 m
0.0 m
-0.5 m
-1.0 m
0 m
25 m
50 m
75 m
100 m
125 m
150 m

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