Interpretation of Internal Erosion Susceptibility in a New Zealand Canal Embankment

Crawford-Flett[1], K.A., Eldridge[2], J.J., Bowman[3], E.T., Gordon, C[4]

[1]*University of Canterbury Quake Centre*

[2]*Resource Development Consultants Limited (RDCL)*

[3]*University of Sheffield*

[4]*Genesis Energy*

This paper provides an interpretation of factors governing the manifestation of internal erosion in a New Zealand canal that was constructed during the 1970s. Liner and subgrade soils were sampled during de-watering of Tekapo Canal in 2013, following the surveillance of erosion events over the preceding decades. This paper focuses on the interpretation of erosion susceptibility of liner and subgrade soil gradations sampled at four locations. Of the four locations, Sites 2, 3, and 4 were associated with internal erosion defects. A single location (Site 1) was selected to provide benchmark "intact" (un-eroded) samples.

Interpretation of susceptibility of the widely-graded soils to internal erosion mechanisms was achieved through the application of established empirical techniques for internal stability, filter compatibility, and segregation. Analysis of gradations, which are believed representative of some – but likely not all - canal soils, showed that Sites associated with erosion defects had liner-subgrade interfaces that permitted "some erosion" (NE < D_{15F} < EE), while the Site showing no sign of erosion possessed an interface that met modern filter retention criteria for No Erosion. Based on gradation analysis, internal instability is considered a possibility for subgrade materials in particular. It is possible that subgrade materials that fail No Erosion criteria for liner retention may not represent as-built material and may instead have lost finer fractions in situ due to seepage-induced instability, leaving a coarser-than-placed and filter-incompatible subgrade.

This case study demonstrates the use of gradation-based empirical methods as initial screening tools to assess the susceptibility of soils to internal instability, filter compatibility, and segregation. The relationship between the internal stability of a filter and the filter's particle retention performance (compatibility) is emphasised. As well as gradation susceptibility, the assessment of other factors such as segregation and hydraulic loads must be considered in order to better-understand susceptibility to erosion mechanisms.

Introduction

New Zealand has over 3,000 earth embankment dams and canals, many of which were constructed prior to the evolution of modern granular filter criteria for dam design in the mid-1980s. Tekapo Canal is one such structure, constructed from 1971 to 1977 as a 26 km long conveyance canal, linking two hydropower stations in the inland Canterbury region. Tekapo canal is constructed of widely-graded soils of glacial origin. Challenges with material compaction and constructability were reported during construction.

Since commissioning in 1977, monitoring and surveillance processes have identified seeps, sinkholes, and voids at various locations along the canal. An extensive repair programme, involving the installation of a geomembrane liner, was carried out in 2012-2014 in order to address ongoing liner erosion incidents along two canal reaches (Campbell et al. 2014).

Objectives

With the benefit of gradation data obtained during repair processes in 2013, this paper further develops findings presented by Benson (2011) regarding material susceptibility to internal instability and filter incompatibility. The present analysis focuses on: (1) insights gained from gradation data obtained from liner and subgrade soils sampled from four locations during repair works during 2013, and (2) factors other than gradation susceptibility that may have contributed to the manifestation of internal erosion at Tekapo Canal.

Canal embankment description

The Tekapo Canal embankment cross-section is governed along its length by natural topography and includes reaches in cut, fill, cut & fill, and sidling fill. The embankment is zoned, with a low-permeability till soil liner compacted cross the invert and interior canal slopes (Figure 1). Interior and exterior canal slopes along the study length are 2H:1V. The invert width is typically 11 m in width, with crest widths between 6 and 9 m. Water depth to invert at normal operating level is approximately 5.5 m, with 1.5 m freeboard.

Soil liner design remained generally consistent along the length of the canal, however, depending on cross-section type, underlying material comprises either embankment fill or natural ground (glacial outwash or till). Further details of design, construction, and performance history along the canal length are presented by Walker et al. (2008), Amos et al. (2010), and Benson (2011). The classification of subgrade (foundation or fill) is not reported for the 2013 samples due to uncertainty regarding material origin, particularly in sections of the canal formed in combined cut-fill. Therefore, for the purposes of this paper, the term ‘subgrade’ is used to describe the sampled material immediately underlying (interfacing) with the canal liner material, whether that be embankment fill or underlying foundation material.

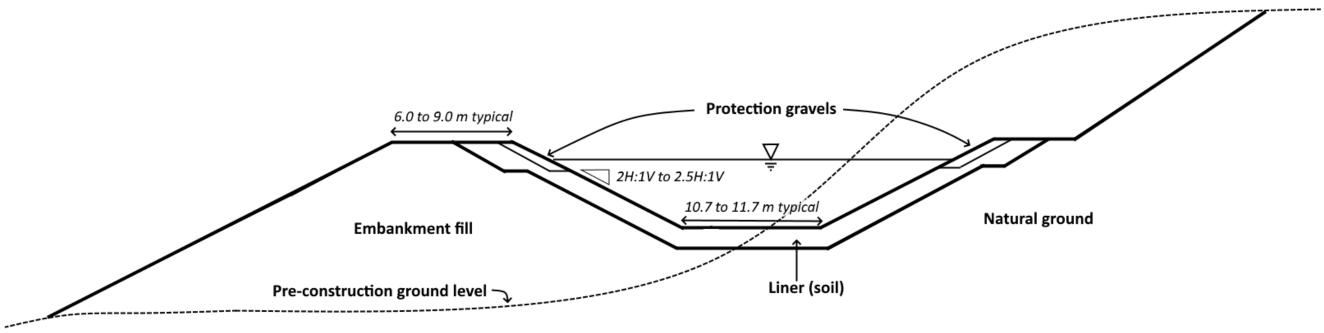

Figure 1: Cross section schematic: Tekapo Canal (Not to Scale)
Liner subgrade along the canal comprises either: (1) embankment fill (illustrated left) or (2) natural ground (illustrated right), depending on natural topography.

Fill and foundation soils

Soil gradation data

Benson (2011) summarises known construction-era gradation information regarding canal liner and embankment materials. Most historic gradations are reported in terms of four sizes: maximum particle size D_{100} (D_{max}), and mass percent passing 76 mm, 4.76 mm, and 0.075 mm. These gradations lack sufficient resolution for reliable geometric analysis using state-of-practice techniques, particularly in the sand sizes. For this reason, this paper focuses on the analysis of higher-resolution gradation data obtained in 2013.

In 2013, liner and subgrade soils were sampled during de-watering of Tekapo Canal for remediation works, following the surveillance of erosion events over the preceding decades. This paper focuses on eight large bulk samples taken from four select locations, comprising one sample of liner and one sample of subgrade at each of the four locations. Of the four locations, Sites 2, 3, and 4 were associated with internal erosion defects. A single location (Site 1) was selected to provide benchmark “intact” (un-eroded) samples. The eight liner and subgrade samples from Sites 1 to 4 were tested for particle size and hydrometer analysis in accordance with NZS4402:1986 (Test 2.8.1 and 2.8.4). The liner samples from Sites 1 to 4 were also tested for plasticity indices in accordance with NZS4402:1986 (Test 2.2, 2.3, and 2.4).

The eight large bulk samples (liner and subgrade from Sites 1 to 4) are shown in Figure 2

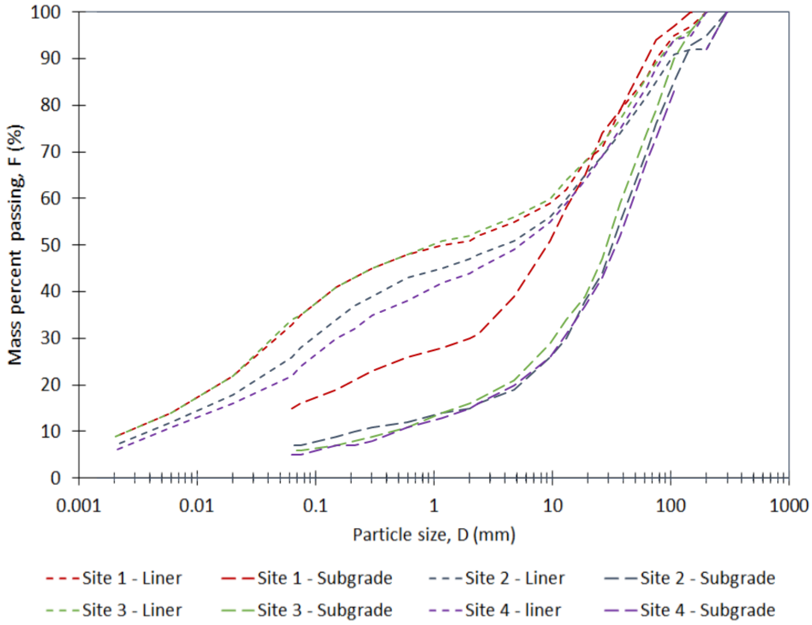

Figure 2: Tekapo Canal, gradation data: 2013 samples

Liner samples are silty or sandy gravel with minor fractions of cobbles and clay. All four 2013 liner samples demonstrate a similar gradation shape, with a slight flattening of the grading curve slope in the sand and fine-gravel fraction. No plasticity or dispersivity tests are reported in available construction-era documentation. However, fines fractions of the liner materials sampled in 2013 are of low plasticity, with plasticity indices PI = 7 (Sites 2, 3, 4) to 9 (Site 1).

All four subgrade materials comprise a major gravel fraction and demonstrate a concave-upward gradation shape. The Site 1 subgrade gradation (GRAVEL with some sand, some silt / clay and minor cobbles) is notably finer than subgrade samples taken at Sites 2, 3, and 4 (cobbly GRAVELS, with minor fractions of silt/clay, sand and boulders). The fines content of the Site 1 sample (15% <0.075 mm) is more than double that of Samples 2, 3 and 4 (5 to 7% <0.075 mm). Two possibilities exist for the presence of coarser subgrade soils at Sites 2, 3, and 4:

1. The subgrade material was coarser in its as-placed condition, and/or
2. Finer fractions were lost from the as-placed subgrade material as a result of internal instability mechanisms over the 35 year service life of the canal prior to sampling (1977-2013).

Considering the past performance of the canal and as-sampled state of 2013 materials, the possibility of internal instability is considered for the eight liner and subgrade samples below. The filter compatibility of subgrade materials when acting as a filter to liner materials is then considered for Sites 1-4 in following sections.

Soil susceptibility to internal instability

Internal instability describes the inability of a soil to prevent the loss of its own small particles in the presence of seepage forces. Internal instability is typically of most concern in granular materials, particularly gap-graded and widely-graded soils with low fines contents. Both liner and subgrade materials at the four Tekapo Canal sample sites comprise widely-graded silt-sand-gravel soils of glacial origin. The subgrade materials contain less than 15% fines (<0.075mm), while the liner material contain between 22 and 34% fines and 6 to 9% clay-sized particles (Table 1, Figure 2).

Early geometric screening methods (e.g. Kezdi 1979, and Kenney and Lau, 1985, 1986) use the shape of the gradation curve to empirically estimate whether finer particles can fit through the void spaces formed by larger particles in the gradation. These methods were developed strictly for cohesionless sand and gravel mixtures. Since the 2000s and acknowledging the well-documented occurrence of sinkhole and erosion phenomena in widely-graded till cores (e.g. Sherard 1979), a significant body of experimental and analytical research has addressed the applicability of geometric screening techniques to widely-graded tills (e.g. Wan, 2006; Moffat, 2005; Li 2008; Ronnqvist et al. 2014; Ronnqvist and Viklander 2014a,b; Crawford-Flett, 2014; Crawford-Flett and Haskell, 2016). The authors' experience with testing of New Zealand and Canadian till materials concurs with the findings of Ronnqvist et al. (2014), suggesting that – of common empirical screening methods – the method of Kenney and Lau (1985, 1986) (denoted 'K&L' herein) with the Li and Fannin (2008) ('L&F') adaptation proves most applicable to widely-graded silt-sand-gravel mixtures with fines of no to low plasticity. For this reason, this paper focuses on geometric analysis using K&L and L&F criteria using logarithmic-linear interpolation of particle size data.

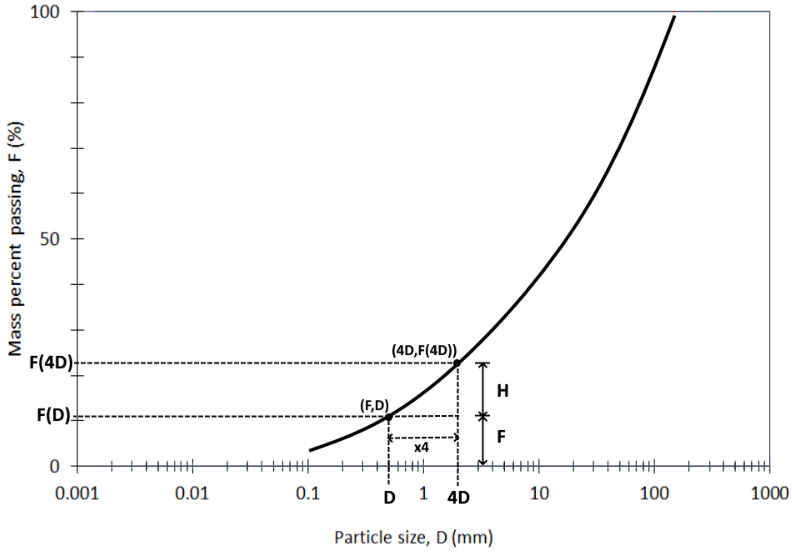

Figure 3: Method of describing gradation shape, after Kenney and Lau (1985)

The K&L and L&F methods are empirical gradation-shape methods, derived from laboratory seepage test results. The methods delineate 'stable' and 'potentially unstable' soils based on the shape of the particle size distribution curve in the finest 20% or 30% of the gradation curve (for widely graded and narrowly graded soils, respectively). For any point on a gradation curve in (D,F) (D = Particle size; F = mass % passing) space, a ratio of mass increment, H, to mass percent passing, F, is obtained. As illustrated in Figure 3, mass increment, H, is the percentage of mass between particle size, D, and four times the particle size (4D):

$$H = F(4D) - F(D)$$

Based on a geometric assessment of tested soils, the minimum value of H/F indicates the most susceptible region of the gradation curve to internal instability. The gradation is determined to be susceptible to internal instability if: $H/F_{min} \leq 1.0$ (Figure 4).

Li and Fannin (2008) found the secant slope limit of Kenney and Lau (1986) to best predict stability in the mass fraction range $0\% \leq F \leq 15\%$, while the gradation slope limit of Kezdi (1979) (H=15) proved most accurate in the range $15\% \leq F \leq 30\%$. The resulting L&F two-part geometric threshold for internal instability (Figure 4) is described as:

$$\boldsymbol{H} = \begin{cases} \boldsymbol{F}\ if\ 0 \leq F \leq 15\% \\ \mathbf{15}\ \ if\ F \geq 15\% \end{cases}$$

Subgrade materials

The validity of K&L and L&F methods to soils with <15% non-plastic fines has been reasonably established in studies of widely-graded tills (Ronnqvist et al. 2014, Ronnqvist and Viklander, 2014a), suggesting that Tekapo subgrade samples can be assessed by the K&L and L&F methods with some degree of confidence.

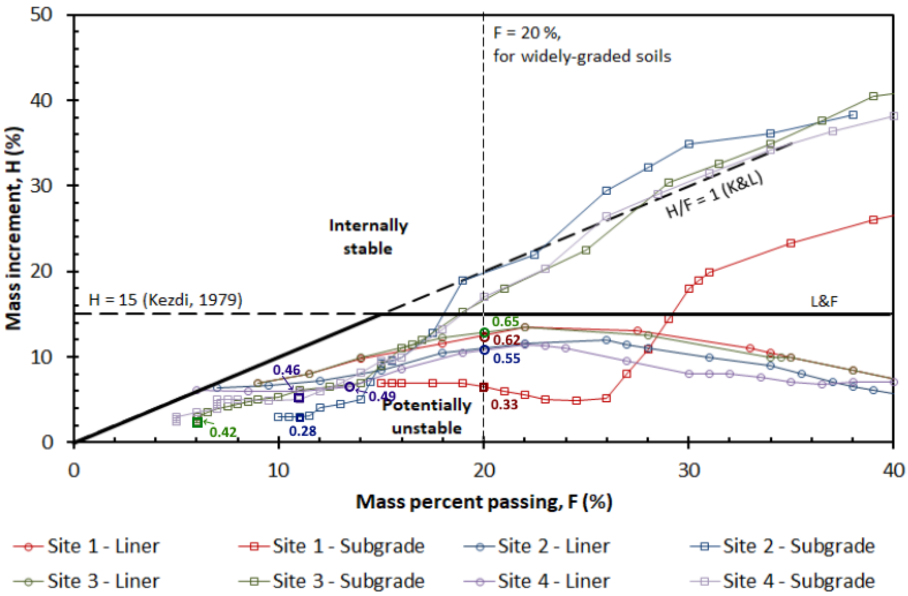

Figure 4: Assessment of internal instability susceptibility by K&L (Kenney and Lau, 1985,1986) and L&F (Li and Fannin,2008) methods

Figure 4 shows that all subgrade materials are assessed as being potentially susceptible to internal instability. The subgrade samples possess $H/F_{(min)}$ values in the range 0.28 to 0.46, well below the proposed stability threshold of H/F = 1. The corresponding point of greatest geometric susceptibility in subgrade gradations corresponds to fine sand sizes ($H/F_{(min)}$ at particle sizes D = 0.18, 0.42, 0.63 and 0.60 mm for Sites 1, 2, 3 and 4, respectively, Table 1). Fine sands are considered most geometrically and hydrodynamically susceptible to transportation within granular void networks due to low particle mass, and lack of significant contact-level (electro-chemical) binding effects characteristic of fine silts and clays (Sherard 1979, Perzlmaier, 2007). Using the K&L and L&F methods, the intact Site 1 subgrade material is found to be as similarly geometrically susceptible as subgrade samples at defect locations (Sites 2-4).

Liner materials

The sampled till liner materials contain 24-35% fines. The fines fractions include 6-9% clay-sized particles and are of low plasticity with plasticity index PI = 7 (Sites 2, 3, 4) to 9 (Site 1). ICOLD (2017) excludes the possibility of internal instability if the soil has PI ≥ 7, or if a broadly graded non-plastic soils contains a finer fraction greater than 40% of the total mass of the soil, hence the liner materials lie (just) within the bounds in which internal instability is considered a possibility. Using the K&L and L&F methods, liner materials from the four Sites sampled in 2013 demonstrate $H/F_{(min)}$ values in the range 0.49 to 0.65 (<1), indicating potential susceptibility to internal instability.

In addition, Douglas et al. (2016, 2019) report three permeameter tests for internal instability undertaken on replicated Site 4 liner material. The performance of the replicated Site 4 liner material was found to vary as a result of base (exit) mesh opening size, with performance varying from 'locally internally unstable but self-filtering' (no external particle loss outside of the specimen) for meshes bases of 2.36 mm and 4.75 mm, to 'suffusive' (external particle loss, specimen 'eroded throughout') with a base mesh size of 9.5 mm[1]. These targeted tests provide some confidence in the recommendations of Ronnqvist and Viklander (2014a): that despite a significant fines fraction and some plasticity, liner material may experience internal instability when subjected adverse hydraulic conditions (particularly if a poor interface exists at the flow exit

[1] Note that the three base mesh sizes (2.36 mm, 4.75 mm, and 9.5 mm) are reported to correspond to filter Equivalent Opening Sizes (EOS) less than, equal to, and exceeding, the Continuing Erosion (CE) criterion for the liner, respectively.

boundary). In addition, laboratory tests verify the geometric susceptibility of the Site 4 Liner gradation to internal instability, as assessed by K&L and L&F methods.

Interpretation of internal instability potential

Comparison to field performance database

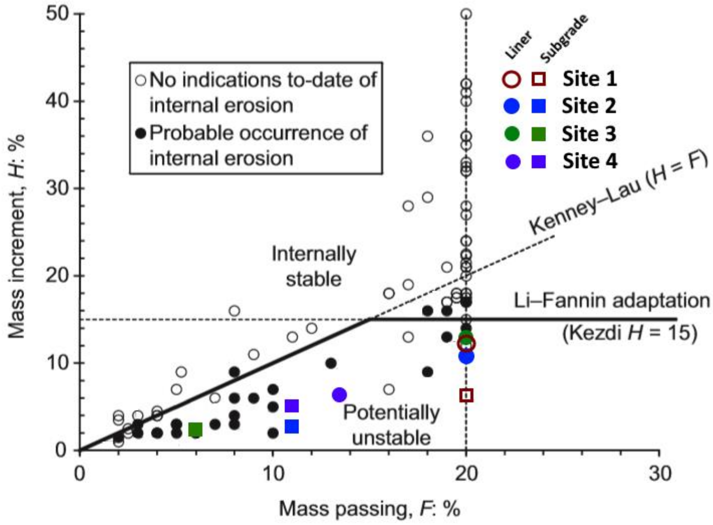

Figure 5: Internal stability indices for field case histories of dams with widely-graded fills (after Ronnqvist et al, 2014)

Figure 5 (after Ronnqvist et al 2014) shows field performance data for dams with widely-graded filters and cores in terms of $H/F_{(min)}$. The stability indices for the eight Tekapo gradations are additionally plotted to overlie this data. The subgrade ('filter') materials for Sites 2, 3, and 4 (defect sites) all lie in the potentially unstable domain, with all reported dams immediately adjacent having experienced "probable occurrence(s) of internal erosion". The remaining Tekapo gradations plot in the potentially unstable domain adjacent to dams with "probable occurrence(s) of internal erosion", but with fewer adjacent datapoints and/or with next-closest data corresponding dams that have demonstrated "no indications to-date of internal erosion".

Synthesis

From geometric analysis and comparison against a field performance database, we note the following:

- All subgrade samples (intact and defect locations) are considered similarly susceptible to internal instability in terms of geometric H/F stability indices. The Site 1 (presumed "intact") subgrade is a significantly finer material than the subgrade samples obtained from defect locations (Sites 2, 3, and 4). This leaves open the hypothesis that subgrade samples obtained from defect locations could represent degraded materials. That is, it is possible that subgrade soils in the vicinity of defects were similar to Site 1 when placed, but subsequently experienced internal instability over the service life of the canal and lost a proportion of finer material from the soil matrix.
- $H/F_{(min)}$ indices for liner gradations ($H/F_{(min)}$ = 0.49 to 0.65) are higher than those obtained for subgrade materials ($H/F_{(min)}$ = 0.28 to 0.46), suggesting that the subgrade gradations should be more geometrically susceptible to internal instability than liner gradations. The presence of some plasticity in the fines fraction of the liner materials additionally would likely inhibit instability, resulting in a less adverse susceptibility than that assessed by gradation alone.
- Laboratory tests undertaken by Douglas et al. (2019) show that internal instability in the Site 4 liner material is possible; however, the relative degree of instability is categorised as minor.
- Given the findings above, subgrade soils are considered more susceptible to internal instability than liner soils.

Susceptibility to filter (interface) incompatibility

While internal stability describes the ability of a soil unit to retain its own finer particles, filter compatibility describes the ability for an underlying soil unit to prevent the transportation of particles from upstream soil units. For Tekapo Canal, filter compatibility between the liner and subgrade soils is a key consideration.

Filter compatibility requirements were still evolving at the time of construction of the Tekapo Canal in the 1970s. Design practices were not equivalent to current state-of-practice filter design criteria, e.g. NRCS (1994); FEMA (2011); Fell et al. (2014). While soil retention concepts were likely understood in a pragmatic sense by site engineers, a compatibility specification - consistent with rudimentary 1970s state-of-practice - was first documented part-way through the Tekapo Canal earthworks sequence. Given that the 2013 soil samples were taken from canal locations built in the early stages of the construction programme, it is assumed that the liner-subgrade interfaces considered in this paper were not subject to a particle retention specification. The compatibility of the liner-subgrade interfaces at the four 2013 Tekapo sample Sites are therefore assessed using criteria for filters that do not meet modern design criteria, as proposed by Foster and Fell (2001) and advocated by ICOLD (2017).

Assessment of subgrade materials as filters

Filter retention thresholds were calculated for liner samples at each of the four Tekapo Sites. Filter retention thresholds (D_{15F}) were calculated for No Erosion (NE), Excessive Erosion (EE), and Continuing Erosion (CE) conditions (Table 1). The relation of the D_{15F} of the subgrade material to the NE, EE, and CE thresholds gives an indication of expected interface performance. For example, if the subgrade D_{15F} is finer than the NE threshold, No Erosion is expected. At all four sites, liner soils would require a D_{15F} of 0.7 mm for NE. The only Site with a subgrade D_{15F} that meets this is Site 1 (D_{15F} = 0.063 mm), where no defect was observed. The remaining three sites have subgrade D_{15} sizes that exceed the No Erosion threshold, but are finer than the Excessive Erosion limit. The subgrade soils at Sites 2, 3, and 4 (D_{15F} = 2.0 mm, 1.7 mm and 2.0 mm, respectively) are therefore considered to permit "some" erosion of liner materials into, and through, the underlying subgrade. This assessment is considered congruent with defect observations at Sites 2, 3, and 4.

Table 1: Soil properties, internal stability and filter compatibility indices.

		Internal instability screening (after Li and Fannin, 2008)					Subgrade (filter) compatibility screening (after Foster and Fell, 2001, and Ronnqvist et. al (2015)						
		<0.075 mm (%)	H/F (min)	@F (%)	@D (mm)	Range (H/F<1)	D_{15F} (mm)	NE (mm)	EE (mm)	CE (mm)	D_{15F}/NE	D_{15F}/EE	D_{15F}/CE
Site 1	Liner	33	0.62	20	0.02	<20	-	0.7	2	22.5	0.09	0.032	0.0028
	Subgrade	15	0.33	20	0.18	<18	0.063	-	-	-			
Site 2	Liner	34	0.55	20	0.035	<20	-	0.7	3.2	23.6	2.86	0.63	0.085
	Subgrade	7	0.28	11.5	0.42	<20	2	-	-	-			
Site 3	Liner	26	0.65	20	0.02	<20	-	0.7	2.4	22.3	2.43	0.71	0.076
	Subgrade	6	0.42	6	0.63	<19	1.7	-	-	-			
Site 4	Liner	22	0.49	13.5	0.01	<20	-	0.7	4	27.9	2.86	0.5	0.072
	Subgrade	5	0.46	11	0.6	<19	2	-	-	-			

Unified assessment of filter performance

As discussed in the previous section, the loss of finer particles from a soil unit due to internal instability will result in a coarser gradation. This possibility could result in worsening filter retention performance. Acknowledging this, Ronnqvist et al (2014) developed a 'unified' empirical approach to assessing filter performance of widely-graded soils using field observations of dam performance. This addresses both: (1) instability potential of a filter in terms of $H/F_{(min)}$ stability index, and (2) capacity for soil retention of the specific core or liner (D_{15F} retention thresholds, as calculated based on Foster and Fell, 2001).

The unified assessment of filter compatibility performance at Sites 1, 2, 3, and 4 is presented in Figure 6 below, in terms of both NE and EE criteria for liner retention. The Tekapo sites associated with defects (Sites 2, 3, and 4) all plot in the vicinity of dams that have experienced probable occurrences of internal erosion, in terms of both instability potential and filter compatibility properties. This reiterates a correlation between the attributes of a filter gradation and field observations of internal erosion defects. Site 1 plots in a sparsely-population region of the instability-compatibility domain, with few comparable case studies of field performance. Considering instability potential (y-axis) and filter compatibility (x-axis) separately:

- Site 1 may possess a margin of safety in terms of filter retention performance: none of the reported dams with similarly fine D_{15max}/D_{15NE} or D_{15max}/D_{15NE} ratios show signs of internal erosion (left domain of plot, Figure 6a and 6b). However,
- All dams with $H/F_{(min)}$ equivalent to, or less than, Site 1 have demonstrated probable occurrences of internal erosion.

It may be hypothesised that unless the Site 1 subgrade undergoes significant internal instability (resulting in a change in plotting position to the right and potentially upward), the filter retention performance at this interface will remain satisfactory.

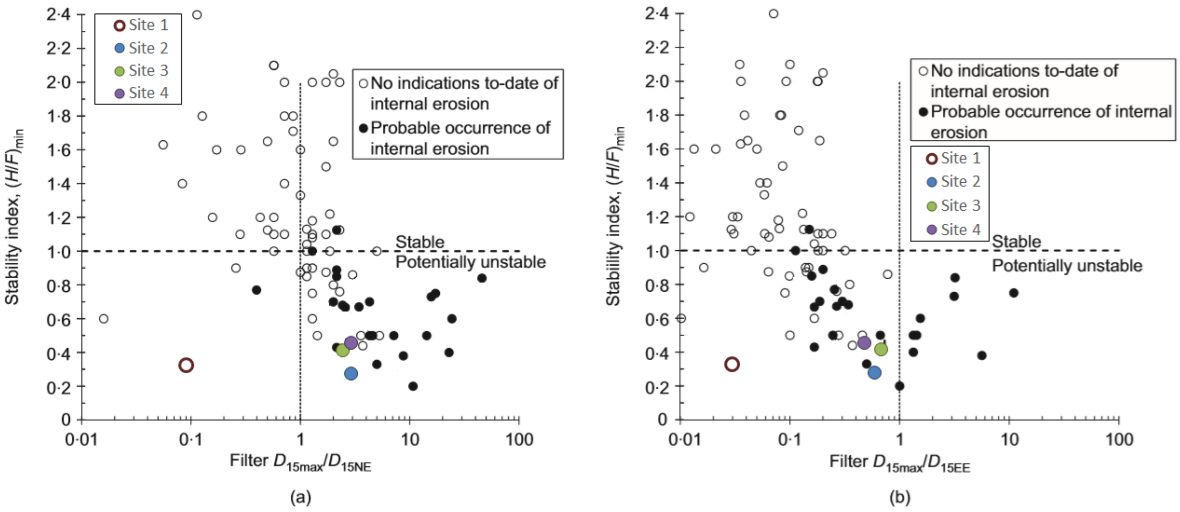

Figure 6: Unified assessment of filter performance, after Ronnqvist et al. (2014)

In summary, assessment of filter compatibility at four Tekapo Canal sites suggests that defect locations are associated with filters that do not meet modern design criteria for No Erosion, and instead possess NE < D15,F < EE. In contrast, the intact Site 1 location demonstrates an adequate D15F size for liner retention (D15,F < NE). Considering H/F(min) and D15F filter indices, sites associated with defects at Tekapo Canal plot in the vicinity of dams that have experienced probable occurrences of internal erosion reported by Ronnqvist et al (2014). The unified plot appears to serve as a useful screening tool to assess the performance of widely-graded glacial soil interfaces.

Screening results in context: additional factors influencing the likelihood of erosion manifestation

Assessment outcomes vs.in situ material susceptibility

Assessed soil gradations

One of the greatest limitations in applying generalised screening methods in the assessment of internal erosion susceptibility is the inherent variability in soil properties that exist in a large earth embankment and its foundations. The natural variability of in situ glacial deposits warrants additional consideration where these deposits function as a foundation for the canal. In the application of screening methods to the eight gradations sourced during de-watering in 2013, we assume they are “representative” of soils at the four sites. In reality, all soils will vary in their in situ properties and it is unlikely that single gradation analysis can reliably capture the performance of a large-scale embankment. Ideally, a large dataset of high-resolution gradations would permit statistical assessment of stability and retention properties in a spatial sense along the canal to provide an indication of best and worst case scenarios for fill and foundation performance.

Influence of placement method on segregation and gradation susceptibility

Internal erosion is a spatial and temporal process, oft described as a ‘weak link’ phenomenon; that is, initiating at a location of adverse material properties and/or hydraulic and/or stress conditions. Segregation processes could result in a “weak link” of soil properties within the structure that may not be adequately captured in the analysis of individual soil gradations. Widely-graded soils are particularly prone to segregation and most modern earthworks design criteria contain clauses regarding gradation limits to limit this.

The eight gradations from four sites at Tekapo were assessed using three methods to determine segregation potential (Table 2). NRCS (1994) guidelines are intended as design criteria and could be considered ‘ideal’ (conservative) criteria that should limit significant segregation. Sutherland and Grabinsky (2003) and Asmaei et al. (2018), both specifically consider the segregation potential of real granular earth dam fills.

None of the eight Tekapo gradations meet NRCS (1994) design criteria to prevent segregation in filters (Table 2). All liner gradations are assessed as having “weak” segregation potential by the method of Sutherland and Grabinsky (2003), while subgrade segregation potential ranges from “intermediate” (Site 1) to “strong” (Sites 2, 3 and 4). Asmaei et al. (2018) focused on segregation due to tipping and may not consider additional effects of spreading. Regardless, all Tekapo sample gradations were considered to have “strong” to “very strong” segregation potential (“more likely” to “much more likely” to segregate) (Figure 7, Table 2).

Overall, gradation susceptibility to segregation is likely to be a concern for Tekapo materials, based on three criteria intended for application in earth dam applications.

Table 2: Gradation susceptibility to segregation, by three criteria

		Site 1		Site 2		Site 3		Site 4	
	Criterion	**Liner**	**Subgrade**	**Liner**	**Subgrade**	**Liner**	**Subgrade**	**Liner**	**Subgrade**
NRCS (1994)	1. D_{100}<75 mm	×	×	×	×	×	×	×	×
	2. Cu<=6	×	×	×	×	×	×	×	×
	3. Gradation band $D_{i,max}/D_{i,min}$<=5 for i <= 60%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	4. Max $D_{90} = f(D_{10})$	×	×	×	×	×	×	×	×
Sutherland & Grabinsky (2003)[2]	(i) S_m<0: strong segregation potential, possibly leading to seepage problems (ii) S_m >0.25: weak segregation potential (iii) 0<S_m<0.25: intermediate segregation potential	0.54 Weak	0.20 Inter-mediate	0.49 Weak	-3.2 Strong	0.55 Weak	-2.2 Strong	0.48 Weak	-3.2 Strong
Asmaei et al. (2018)	Refer Figure 7	Strong/ More likely	Strong/ More likely	Strong/ More likely	Very strong/ Much more likely	Strong/ More likely	Very strong/ Much more likely	Strong/ More likely	Very strong/ Much more likely

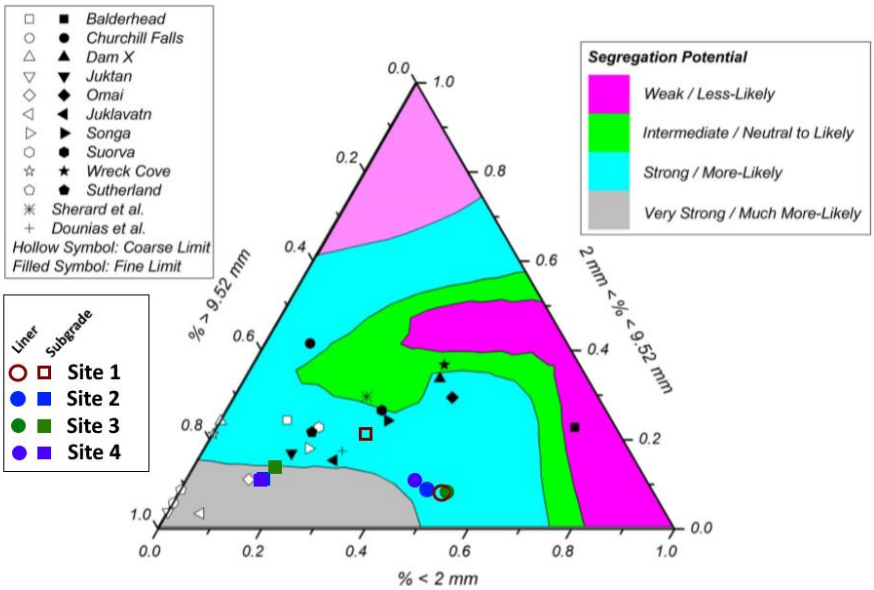

Figure 7: Susceptibility of dam fill gradations to segregation, after Asmaei et al. (2018)

Construction practices

Aside from gradation susceptibility, construction practices associated with placement and compaction of widely-graded fill material also introduce variability in soil properties and corresponding uncertainty in performance. Given large maximum particle sizes, stochastic variability, quantities of materials, the nature of lift placement and compaction, and seasonal variations in workability, local zones of segregation are thought to be almost inevitable and should be considered (Ripley 1986; Milligan, 1986; Sherard and Dunnigan, 1986).

Construction photos suggest that Tekapo Canal liner slopes were placed in near-horizontal lifts, with each lift sloped into the bank. This inward slope would encourage larger particles to roll toward the underlying embankment formation, potentially creating areas of coarser liner fill at the embankment-liner interface. The liner was formed and compacted on the near-horizontal within a working area that would, in places, have been for marginal for compaction plant. Poor compaction is a risk factor in internal erosion manifestation.

A revised earthworks specification introduced part-way through construction of Tekapo Canal contained additional clauses concerning cold weather construction and moisture control. Inadequate attention to these details could have resulted in local defects, horizontal seepage horizons due to frozen ground, or differential permeability or density conditions.

Liner thickness and resultant hydraulic loading

The actual manifestation of internal instability or filter incompatibility in a susceptible soil will be governed by in situ stress and hydraulic conditions. Material susceptibility alone is not enough to predict field manifestation.

[2] $S_m = \log(4.75/D_{30})/\log(D_{100}/D_{30})$ if D_{30} < 4.75mm, $S_m = \log(4.75/D_{30}) \times \log(D_{100}/D_{30})$ if D_{30} > 4.75mm

While the near-constant water depth in the canal introduces a limit to hydraulic head of approximately 6.0 m at the invert, the low-permeability liner material is relatively thin (1.2 m) in its design cross-section (Figure 1). The effective liner thickness could be less if segregation during tipping and spreading resulted in pockets of coarser material accumulating at the liner-subgrade interface. Assuming relatively free-draining subgrade soils in some locations, hydraulic gradients across the liner could be higher than six if zones of liner segregation or erosion have impacted the effective thickness of the liner.

Interpretation of erosion manifestation at Tekapo Canal

Considering gradation properties of soils that were sampled from four locations at Tekapo Canal during dewatering in 2013, we find that erosion defect locations are correlated to samples that do not meet modern filter design criteria for retention, and that internal instability of filter materials could exacerbate particle retention incompatibility. Site 1 showed no evidence of poor performance during the canal service life prior to sampling. The Site 1 liner material, while potentially susceptible to internal instability, is not considered highly susceptible in the presence of low hydraulic loads and an adequate filter interface with D_{15F} < NE. The most likely mode for erosion risk at Site 1 is degradation of the subgrade due to internal instability ($H/F_{(min)} = 0.33$), leading to a state of filter incompatibility and associated erosion. However, the manifestation of this mechanism would require sufficient hydraulic load to trigger instability in subgrade materials.

Sites 2, 3, and 4 were associated with erosion defects that had developed over the service life of the canal prior to sampling. As for Site 1, liner materials were assessed to be less susceptible to internal instability than subgrade materials. As well as being assessed as susceptible to internal instability, these subgrade materials also fail modern filter retention criteria and are instead categorised as 'some erosion' filters with respect to liner retention (NE < $D_{15,F}$ < EE). Given the unfavourable screening results for internal stability of subgrade materials at Sites 2, 3, and 4, ($H/F_{(min)} = 0.28 – 0.46$), it is possible that the degree of filter incompatibility at these sites could continue to worsen if internal instability further modified the subgrade gradations.

The presence of unfavourably coarse subgrade soils at Sites 2, 3, and 4 could be explained by either: (1) placement or presence of unsuitable gradations at the time of construction, or (2) the degradation of as-placed or in situ subgrade materials over the 35 year service life of the canal prior to sampling. Further work is required to examine these scenarios.

Finally, it is possible that localised areas of canal liner may be more susceptible to internal instability than reflected by geometric susceptibility screening. Specifically, Tekapo Canal materials possess high segregation potential and resultant field properties have the potential to decrease the effective liner thickness and cause an increase in hydraulic gradients experienced by liner materials. These additional material and hydraulic factors are not considered in empirical gradation screening methods applied above.

Conclusions

Following the work of Benson (2011), Tekapo Canal liner soils and underlying subgrade soils were sampled at four locations during de-watering for repairs in 2013. Analysis of gradation data obtained from 2013 samples provides the following insights:

- All soils vary in composition. Samples can only provide a limited dataset that may not represent the possible variations of a placed, or in situ, soil.
- Empirical methods based on soil gradation can prove useful screening tools to assess for susceptibility to internal instability, filter compatibility, and segregation. However, material susceptibility is not sufficient to predict field manifestation of phenomena.
- Earthfill structures with thin soil liner systems require robust properties in terms of internal stability of the liner, internal stability of the subgrade, and the resultant interface compatibility between the two.
- Seepage through the liner has the potential to degrade an internally unstable subgrade material and thereby compromise the liner-subgrade interface compatibility. This could lead to erosion of the liner.
- Segregation of placed materials could result in more adverse performance than indicated by screening methods, in terms of the potential for: (1) adverse gradation properties, and (2) increased hydraulic gradients due to a reduction in effective liner thickness. Empirical methods presented by Sutherland and Grabinsky (2003) and Asmaei et al. (2018) appear to correlate well with the susceptibility for segregation.
- Our analysis of Tekapo Canal field performance affirms the findings of Ronnqvist et al.:
    - Field observations of internal erosion are often associated with potentially internally unstable filter materials for which D_{15} filter sizes are only somewhat coarser than the D_{15} for NE as specified by modern design practice (but not necessarily approaching or exceeding the EE threshold).
    - Observed field deficiencies that are attributed to internal erosion correlate to the attributes of corresponding filter gradations. The unified plot of Ronnqvist et al., (2014) appears to serve as a useful screening tool to initially assess the performance of widely-graded New Zealand glacial soil interfaces.

Acknowledgements

The authors gratefully acknowledge the support of Genesis Energy and the University of Canterbury Quake Centre industry partners.

References

Amos, P., Kilby, A., & Mills, T. (2010). Preventing failure of a large canal by using staunching to arrest leakage. In proceedings, Collaborative Management of Integrated Watersheds, 30th USSD Conference, California. April 2010.

Asmaei, S., Shourijeh, P. T., Binesh, S. M., & Ghaedsharafi, M. H. (2018). An experimental parametric study of segregation in cohesionless soils of embankment dams. Geotechnical Testing Journal, 41(3), 473–493.

Benson (2011). Internal Erosion Meta-stable Behaviour at Tekapo Canal. In proceedings, New Zealand Society on Large Dams, Short Course on Internal Erosion and Piping of Dams and their Foundations, Christchurch, September 2011.

Campbell, M., Eldridge, J.J., Cowland, J., Wilkes, J., Scuero, A., Vaschetti, G. (2014). Installation of a PVC geomembrane liner for the Tekapo canal remediation. Hydro Asia, Columbia March 2014.

Douglas, K., Fell, R., Peirson, B., & Studholme, H. (2016). Experimental investigation of global backward erosion and suffusion. University of New South Wales. Uniciv Report No. R-465.

Douglas, K. J., Fell, R., Peirson, W. L., & Studholme, H. (2019). Experimental investigation of global backward erosion and suffusion of soils in embankment dams. Canadian Geotechnical Journal, 56:789-807

Foster, M., Rönnqvist, H., & Fell, R. (2018). The performance of embankment dams with filters coarser than 'no-erosion' design criteria. Hydropower and Dams, 4:2018.

ICOLD. (2017). Bulletin 164 Internal erosion of existing dams, levees and dikes, and their foundations. International Commission on Large Dams. Paris, France.

Kenney, T C, & Lau, D. (1985). Internal stability of granular filters. Canadian Geotechnical Journal, 22, 215–225.

Kenney, T Cameron, & Lau, D. (1986). Internal stability of granular filters: Reply. Canadian Geotechnical Journal, 23(3), 420–423.

Milligan, V. (1986). Internal stability of granular filters: Discussion. Canadian Geotechnical Journal, 23(3), 414–418.

Moffat, R. (2005). Experiments on the internal stability of widelygraded cohesionless soils. Ph.D. Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, B.C.

Natural Resources Conservation Services. (1994). Gradation design of sand and gravel filters. National engineering handbook, Chap. 26, Part 633. USDA.

Perzlmaier, S., Muckenthaler, P., & Koelewijn, A. R. (2007). Hydraulic criteria for internal erosion in cohesionless soil. Assessment of Risk of Internal Erosion of Water Retaining Structures: Dams, Dykes and Levees. Intermediate Report of the European Working Group of ICOLD., 30–44. Technical University of Munich, Munich, Germany.

Ripley (1986). Internal stability of granular filters : Discussion. Canadian Geotechnical Journal, 23(3), 418–420.

Rönnqvist, H., Fannin, J., & Viklander, P. (2014). On the use of empirical methods for assessment of filters in embankment dams. Géotechnique Letters, 4(4), 272–282.

Rönnqvist, H. and Viklander, P. (2014a). Extending the Kenney–Lau method to dam core soils of glacial till. Geotechnical Research, 1(12), 73–87. https://doi.org/10.1680/gr.14.00007

Rönnqvist, Hans, & Viklander, P. (2014b). A unified-plot approach for the assessment of internal erosion in embankment dams. https://doi.org/10.1179/1939787915Y.0000000002

Sherard, J. L. (1979). Sinkholes in dams of coarse, broadly graded soils. Int Congr on Large Dams, 13th, Trans, October 29, 1979 - November 2, 1979, 2, 25–35.

Sherard, J. L., & Dunnigan, L. P. (1986). Internal stability of granular filters : Discussion. Canadian Geotechnical Journal, 23(3), 418–420.

Sutherland, K., & Grabinsky, M. (2003). Evaluating segregation in granular filters for earth dams. Canadian Geotechnical Conference, 144–150.

Walker, J., Vallesi, S., Amos, P., & Mills, T. (2008). Response and failure prevention , following the identification of a major lining defect in the Tekapo Canal. In Proceedings, Australian National Committee on Large Dams.

Wan, C. F., & Fell, R. (2004). Experimental investigation of internal instability of soils in embankment dams. University of New South Wales. Uniciv Report No. R- 429