Assessing the risks associated with internal erosion phenomena in aging embankment dams: a New Zealand perspective

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ABSTRACT: Earth embankment dams form a vital part of New Zealand's hydropower, agricultural, and water supply infrastructure. The challenges faced in the management of aging embankment dams are compounded by factors specific to New Zealand, including large variability in soil types and the highly tectonic environment in which the dams are located. Internal erosion, triggered by both seismic and non-seismic events, is considered one of the primary risks to New Zealand embankment dams. Spurred by the recent Canterbury Earthquake Sequence, hydropower asset owners in New Zealand have expressed a need for improved guidance for the evaluation of embankments (1) following significant earthquake ground motions, and (2) from a whole-life perspective. This study considers the applicability of existing empirical methods to assess the potential for internal erosion in the New Zealand context. Two distinct mechanisms of internal erosion are considered: (1) internal instability, and (2) filter incompatibility. Four existing empirical geometric methods were used to assess the potential for internal instability in 19 widely-graded New Zealand soils. One existing method was found to be mathematically ineffectual with respect to the widely-graded soils considered in this study and all methods lack reliable verification using volcanic soils. Existing screening methods suggest that a number of glacial, alluvial, and volcanic materials used in construction of New Zealand's large earth dams may be susceptible to some degree of internal instability phenomena, irrespective of seismic hazard. Secondly, a case-study concerning a common type of widely-graded base-filter soil interface demonstrates ambiguous analysis results arising from overlap in No Erosion and Excessive Erosion thresholds. Uncertainties in interpretation could be resolved by the future development of statistical guidelines for filter assessment. With regard to both internal instability and filter incompatibility mechanisms, the applicability of existing empirical analysis techniques to New Zealand soils appears limited due to a lack verification for the diverse geological range of fill soils encountered. In addition, existing stability thresholds have not been verified for long-term or seismic loading conditions inherent in the New Zealand context. This study highlights significant shortcomings in the applicability of existing screening methods used to assess the potential for internal erosion in New Zealand soils.

1 INTRODUCTION

1.1 *Dam Assets in New Zealand*

New Zealand (NZ) has a large number of earth embankment dams, many of which were constructed from 1920 to 1980 to enable hydroelectric power generation and provide reliable water storage. Given the nation's heavy reliance on irrigation for agriculture (4% of GDP, SNZ 2013), and considering that hydropower accounts for approximately 55% of total electricity generation in New Zealand, dams form a vital part of New Zealand infrastructure.

A National Dam Inventory (NDI), recently compiled by the authors, includes over 1000 structures over three metres in height. Inventory analysis shows (Figures 1 and 2):

- Earth or rockfill structures account for over 75% of dams over 5m in height (not including earth dams categorized as 'unknown')
- 64% of High Potential Impact Classification (PIC) dams are earth structures and, of these, approximately 60% were constructed prior to 1960.

Information compiled within the NDI demonstrates

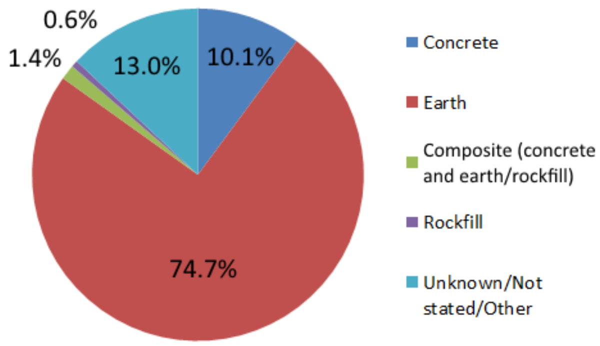

Figure 1: New Zealand Dam Inventory: dams over 5m in height, by type (621 dams)

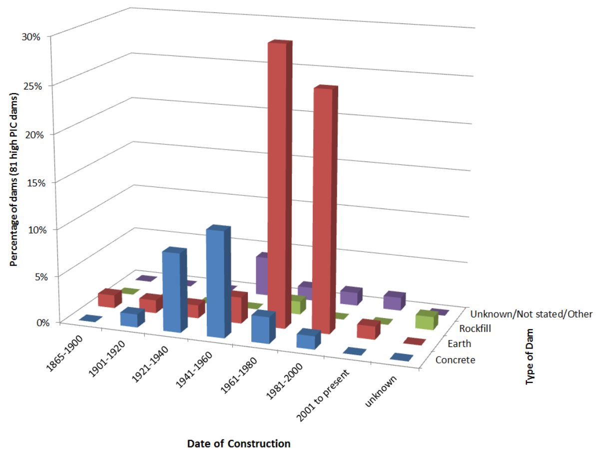

Figure 2: New Zealand Dam Inventory: High PIC dams by type and year of construction (81 High PIC dams)

that the majority of large High PIC dams serving NZ's hydropower, water supply, and agricultural sectors are earth dams, the majority of which were constructed from 1940 to 1980. Aging earth dams therefore play a vital role in New Zealand's economy and their ongoing reliability is of significant economic and societal importance.

1.2 *Historic performance incidents*

Since 2010, significant engineering resources have been mobilised within NZ as a result of the Canterbury Earthquake Sequence (CES). While no large earth dams appear to have been significantly directly impacted by the CES to date, the wider engineering impacts on infrastructure arising from the CES have highlighted the need for improved engineering guidance for dam owners.

Historically, a number of NZ embankment dams have experienced dam safety incidents as a result of seismic and non-seismic loads. Statistics indicate that internal erosion accounts for approximately half of embankment dam failures internationally (Foster et al. 2000). In the NZ context, previous studies by Riley (1997) and Tate & Matuschka (2011) suggest:

- Internal erosion accounts for the majority of dam safety incidents in New Zealand.
- Around 60% of serious incidents in New Zealand have occurred in volcanic fill or foundation soils.

Although no fatal or major-damage failures have occurred in NZ to date, the initiation of internal erosion at Matahina Dam following the 6.5M_w Edgecumbe earthquake in 1987 is an example of a major dam incident that would likely have led to complete failure without appropriate intervention. Published case-studies on failures and serious incidents in smaller embankments include Ruahihi Canal (Hatrick 1982), Wheao Canal (Jones 1983), Poihipi Reservoir (Tate & Matuschka 2011), and Tekapo Canal (Benson 2011); all of which are attributed to erosion of fill soils.

Based on the performance history of NZ dams, internal erosion is considered the primary embankment safety issue in New Zealand for the management of both new and existing structures. This paper considers the applicability of existing empirical methods to assess the potential for internal erosion in the New Zealand context.

2 GEOTECHNICAL PROPERTIES OF NEW ZEALAND EMBANKMENT DAMS

2.1 *Characteristics of fill soils*

New Zealand is located at the boundary of the Pacific and Indo-Australian tectonic plates. Active geological and geomorphological processes have resulted in wide variability in rock and soil properties across the country. The range of soils available for engineering fill can vary significantly based on locality and commonly include challenging materials such as widely-graded alluvium or glacial tills, volcanically-derived soils, soft alluvial deposits, and/or loess.

Given the wide range of formative geological processes, soils used in the construction of NZ dams possess a wide range of geotechnical characteristics, including large variations in particle size distribution, plasticity, dispersivitiy, sensitivity, durability, and stress-strain response. Accordingly, the geotechnical design and geometry of New Zealand embankments varies greatly: successful geotechnical solutions must be determined based on site location and local geology.

2.2 *Main challenges in the geotechnical assessment of embankment dams*

Like many large dams internationally, the majority of NZ earth dams were constructed prior to the development of 'modern' filter and internal instability criteria in the late 1980's (Figure 1). Accordingly, there exists global concern that earth dams may possess design deficiencies attributed to the state-of-practice at the time of design.

The management of aging embankment dams in NZ is compounded by large variability in soil types and the highly tectonic environment in which the dams are located. In the context of the performance history of NZ dams (Section 1.1), internal erosion processes are considered one of the primary risks to NZ embankment dams. This paper focuses on the susceptibility of NZ soils to two specific modes of internal erosion: (1) internal instability, and (2) filter incompatibility.

3 ASSESSING THE POTENTIAL FOR INTERNAL INSTABILITY

Internal instability describes the migration of finer soil particles within or out of a body of soil. Widely-graded soils are at particular risk to internal instability given the presence of finer particles - commonly silts or sands - within a matrix of coarser gravels.

Internal instability is governed by material, stress, and hydraulic factors (Garner & Fannin 2010). Material properties control susceptibility to internal instability and, in a susceptible material, will influence the seepage conditions required to trigger instability. Unlike stress and hydraulic factors, which can be difficult to quantify in a three-dimensional structure (due to spatial and temporal, micro- and macro- scale variations), material susceptibility can be assessed for specific soils using particle size information.

Various geometric (particle-size) methods have been proposed to assess material susceptibility to internal instability, four of which are described briefly below. While not a definitive predictor of internal instability, these empirical screening tools were developed from laboratory tests for particle migration.

The Kenney & Lau (1985)(1986) method (**Method 1**) was derived from laboratory tests on clean sands and gravels. The method considers the slope of the lower grading curve using a 'mass increment to represent the percent of the total soil mass falling within a given range of particle sizes. Considering a conventional grading curve, with particle size (D, mm) on the x-axis and mass passing (F, %) on the y-axis, the mass increment (H) is defined as the mass within the range D to $4D$. Kenney & Lau (1986) consider that soils with $\frac{H}{F} < 1$ are potentially unstable. For widely-graded soils, Kenney & Lau (1985) consider the finest 20% of the soil to be potentially mobile. While microstructural analysis suggests that the finest 25% to 30% of some soils could be susceptible to particle migration (Crawford-Flett 2014), the 20% cut-off is adopted in this analysis for ease of comparison.

Based on laboratory testing of widely-graded soils and geometric examination of the Kenney & Lau (1986) and Kézdi (1979) techniques, Li & Fannin (2008) proposed a refinement to the Kenney & Lau (1986) method (**Method 2**). Li & Fannin (2008) specify the Kenney & Lau (1986) stability threshold of $H = F$ for $F < 15\%$, and the $H = 15\%$ threshold for $F > 15\%$ (after Kézdi 1979). This, in effect, lowers the Kenney & Lau (1986) criteria for the region 15% to 20% mass passing in widely-graded soils.

The Burenkova (1993) and Wan & Fell (2008) methods consider ratios of characteristic particle sizes

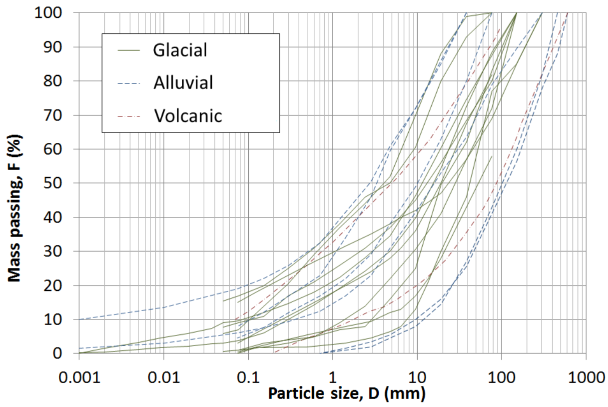

Figure 3: Particle size distributions of widely-graded silt-sand-gravel soils, from five New Zealand dams

from the upper and lower portions of the gradation curve to assess susceptibility. The Burenkova (1993) method (**Method 3**) resulted from laboratory tests on silt-sand-gravel soils characterised by $C_u = \frac{D_{60}}{D_{10}} < 200$, $< 10\%$ fines, and $D_{100} < 100$ mm.

Following probabilistic consideration of the Burenkova (1993) method using additional laboratory data, Wan & Fell (2008) proposed an alternative assessment method (**Method 4**) to assess material susceptibility to internal instability. The empirical database of Wan & Fell (2008) explicitly considered widely-graded soils containing silt and clay-sized fraction (5 to 40% fines) with D_{100} of approximately 100 mm.

The present study considers the applicability of the four aforementioned screening methods to 19 widely-graded soils from existing dams within New Zealand. The gradations shown in Figure 3 were obtained from construction records for five zoned embankments: three constructed of glacial tills, one of alluvial soils, and one of volcanically-derived soils. The gradations represent core, shoulder, or transition materials, with no more than two gradations from any zone within a single embankment. All soils contain less than 20% non-plastic fines.

Dam performance data corresponding to the locations of the Figure 3 gradations has not been made available and this study does not intend to correlate screening results with field performance. Rather, this section considers the applicability of existing screening methods to New Zealand soils.

3.1 *Assessment of NZ soils by existing techniques*

3.1.1 *Methods 1 and 2: Kenney & Lau (1985)(1986) and Li & Fannin (2008)*

The Kenney & Lau (1986) and Li & Fannin (2008) stability thresholds are shown in Figure 4, along with results from screening of NZ soils (Figure 3). Both methods were applied to the finer portion ($F \leq 20\%$) of all 19 NZ soils. Stability indices for the most critical point on the gradation curve ($[\frac{H}{F}]_{min}$) are presented (Figure 4). Results are summarised in Table 1 and discussed in the following paragraphs.

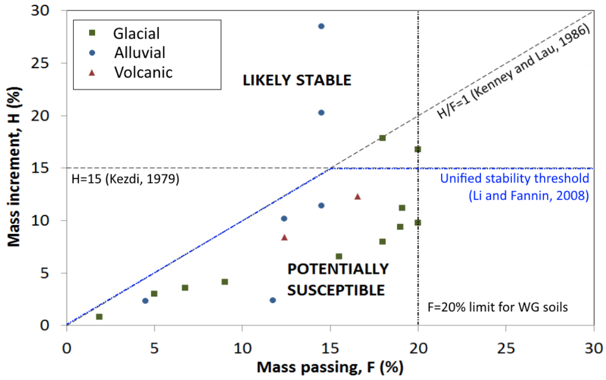

Figure 4: Internal instability screening results by Kenney & Lau (1985) and Li & Fannin (2008) methods

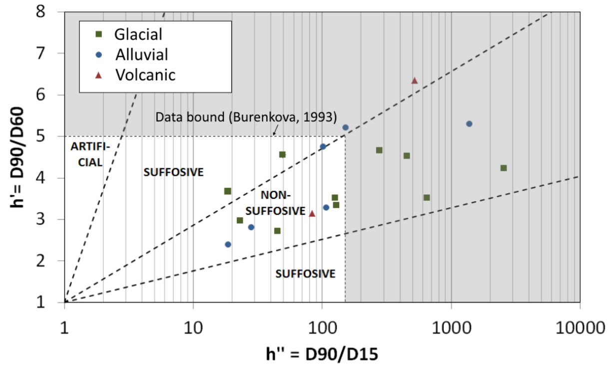

Figure 5: Internal instability screening results by the method of Burenkova (1993)

All 11 glacial soils plot within the potentially unstable domain by Method 1 (Kenney & Lau 1986), with $[\frac{H}{F}]_{min}$ values ranging from 0.42 to 0.99. Nine of 11 gradations possess $[\frac{H}{F}]_{min} < 0.60$. Four of six alluvial gradations are judged potentially unstable by the method of Kenney & Lau (1986), with $[\frac{H}{F}]_{min}$ as low as 0.20. Two gradings possess $[\frac{H}{F}]_{min} > 1$ (1.56 and 1.97) and are therefore assessed as stable. Both volcanic soils are assessed a potentially unstable, with $[\frac{H}{F}]_{min}$ values of 0.68 and 0.74.

Method 2 considers the modified Li & Fannin (2008) threshold, which differs from that of Kenney & Lau (1986) in the range $15 < F \leq 20\%$. As evidenced in Figure 4, results for volcanic and alluvial soils remain unchanged. Two glacial soils judged potentially unstable by the Kenney & Lau (1986) method are assessed as likely stable by Li & Fannin (2008). The assessment of the nine remaining glacial soils remains unchanged (potentially susceptible).

Five of the 19 NZ soils lack particle size data for silt and clay-sized fractions ($D < 0.05$ mm or $D < 0.075$ mm) given that the respective test methods for particle size distribution did not include hydrometer analysis. Accordingly, the susceptibility of the lower portion of the gradation cannot be geometrically assessed by Kenney & Lau (1986) or Li & Fannin (2008) methods (assuming, as discussed below, that the methods remain valid for soils with minor non-plastic fines content). The inscrutable regions include $F < 10\%$ for two soils (one volcanic, one alluvial), $F < 15\%$ for one glacial soil, and $F < 6\%$ for an additional two glacial soils. Due to the lack of fine particle size information, it is possible that the most susceptible fraction of these soils has not be identified by Kenney & Lau (1986) or Li & Fannin (2008) methods.

3.1.2 *Methods 3 and 4: Burenkova (1993) and Wan & Fell (2008)*

Eighteen of 19 NZ gradations (Figure 3) possess sufficient D_{90} and D_{60} particle size information for assessment using Methods 3 and 4.

The empirical database of Burenkova (1993) is bounded by $\frac{D_{90}}{D_{15}} \leq 150$ and $\frac{D_{90}}{D_{60}} \leq 5$ (Figure 5) due to the particle-size characteristics of the soils used to development the method. Eleven of the 18 analysed NZ gradations plot within the bounds of the Method 3 (Burenkova 1993) empirical dataset. Of the six glacial till soils plotting within empirical bounds, four are deemed 'non-suffosive' (stable) and two 'suffosive' (unstable). Of the four alluvial soils within the empirical domain, three plot within the 'non-suffosive' region and one plots, marginally, in the suffosive region. One volcanic soil plots within the 'non-suffosive' empirical domain (Table 2).

The remaining seven NZ soils plot outside of the empirical bounds defined by Burenkova (1993) (Figure 5). Assuming the stability thresholds can be extrapolated, five of these seven NZ soils (four glacial, one alluvial) would be deemed 'non-suffosive' and two NZ soils would be deemed 'suffosive'.

Method 4 (Wan & Fell 2008) uses D_{90}, D_{60}, D_{20}, and D_5 particle sizes to assess stability. Seven NZ soils (Figure 3) lack characterisation of the D_5 particle size and therefore are not able to be plotted on the y-axis of Figure 6. Of the 11 NZ soils for which D_{90}, D_{60}, D_{20}, and D_5 particle sizes are defined, all plot in the 'stable' zone on account of individual soils' $\frac{D_{90}}{D_{60}}$ ratios: specifically, $\frac{30}{log\frac{D_{90}}{D_{60}}} < 80$ for all 11 soils.

Figure 6 presents values of $\frac{30}{log\frac{D_{90}}{D_{60}}}$, and relative x-axis plotting position, for the seven soils where D_{90} and D_{60} particle sizes are defined in the absence of D_5. By inspection, these seven soils will locate within the stable zone of the Wan & Fell (2008) plot, irrespective of D_{20} and D_5 characteristics, based on $\frac{D_{90}}{D_{60}}$ ratio alone.

3.2 *Applicability of existing assessment methods to widely-graded NZ soils*

3.2.1 *Prior development and verification of methods*

The methods of Kenney & Lau (1985) and Li & Fannin (2008) have been studied in depth by numerous researchers in the past decade (Li et al. 2009, Rönnqvist 2010, Crawford-Flett 2014, Rönnqvist 2015, among others). These studies have verified both methods using soils more widely-graded than those originally tested by Kenney & Lau (1985) in the labora-

Table 1: Susceptibility of widely-graded NZ soils to internal instability: Kenney & Lau (1985) and Li & Fannin (2008) methods

		Kenney & Lau (1985)		Li & Fannin (2008)	
Soil type	# of analysed gradations	Potentially unstable	Likely stable	Potentially susceptible	Likely stable
Glacial	11[1]	11	0	9	2
Alluvial	6[2]	4	2	4	2
Volcanic	2[3]	2	0	2	0

[1] One of which lacks data for $F < 15\%$, and an additional two of which lack data for $F < 6\%$
[2] One of which lacks data for $F < 10\%$
[3] One of which lacks data for $F < 10\%$

Table 2: Susceptibility of widely-graded NZ soils to internal instability: Burenkova (1993) method

		Within published limits		Assessed by extrapolation	
Soil type	# of analysed gradations	'Suffosive'	'Non-suffosive'	'Suffosive'	'Non-suffosive'
Glacial	10[1]	2	4	0	4
Alluvial	6	1 (marginal)	3	1	1
Volcanic	2	0	1	1	0

[1] One gradation lacks data for $F > 58\%$ and is therefore not analysed using Methods 3 (Burenkova 1993) or 4 (Wan & Fell 2008)

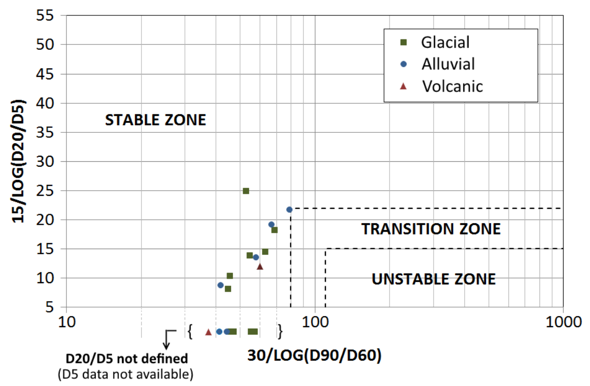

Figure 6: Internal instability screening results by the method of Wan & Fell (2008)

tory. Specifically, verification studies suggest that the methods may prove applicable: (1) to very widely-graded soils such as glacial tills, (2) to soils with a minor fraction of non-plastic silt, and (3) in the prediction of in-situ material performance (Rönnqvist 2010). The Li & Fannin (2008) method has been shown by Rönnqvist (2010) to reduce conservatism of the Kenney & Lau (1986) threshold. Accordingly, the Kenney & Lau (1985) and Li & Fannin (2008) methods are likely to be reasonably applicable and reliable in screening for internal instability potential in the 19 widely-graded NZ soils considered in this study.

Despite being derived from testing on silt-sand-gravel mixtures, the method of Burenkova (1993) has been shown by Wan & Fell (2008), Rönnqvist (2010), and Crawford-Flett (2014) (among others) to be less reliable in predicting internal instability in some widely-graded soils. In addition, many NZ soils plot outside the bounds of the initial study, with some $\frac{D_{90}}{D_{15}}$ ratios proving more than an order of magnitude greater than those cited in the initial study. Accordingly, some soils can be assessed relative to extrapolated thresholds of Burenkova (1993) only, with no support for the validity of the extrapolation.

3.2.2 *Specific remarks regarding widely-graded soils*

Given the widely-graded coarser fraction of the 19 NZ soils in this study, it does not appear possible for these soils to plot in the 'transition' or 'unstable' domains defined in the method of Wan & Fell (2008). Rather, we observe that the $\frac{D_{90}}{D_{60}}$ ratio controls the assessment outcome for some very widely-graded soils. By inspection of Figure 6, a stable domain can be defined as follows:

$$\frac{30}{log\frac{D_{90}}{D_{60}}} < 80 \tag{1}$$

Specifically, any soil will be assessed as stable for the condition:

$$\frac{D_{90}}{D_{60}} > 2.37 \tag{2}$$

Thus, any soil with a $\frac{D_{90}}{D_{60}}$ ratio greater than 2.37 will plot within the stable region of the Wan & Fell (2008) plot, regardless of the quantity, type, and/or distribution of finer particles. In other words, the method will judge very widely-graded soils as 'stable' on sole account of D_{90} and D_{60} sizes, irrespective of the size or distribution of potentially mobile particles below $F = 60\%$. Given that internal instability describes the movement of finer particles through the coarser soil matrix, and the fact that the methodology proves independent of finer particle properties, the Wan & Fell (2008) method appears ineffectual in assessing many widely-graded soils common in New Zealand. It is worth nothing that a similar database of 16 Swedish till cores (Rönnqvist & Viklander 2015) plot exclusively in the 'stable' domain, and that this plotting position results from the satisfaction of equations [1] and [2], above. This suggests that the concerns regarding method applicability are not exclusive to NZ soils.

3.2.3 *Applicability and shortcomings of existing methods in the NZ context*

In terms of general applicability to the widely-graded soils considered in this study, the Kenney & Lau (1986) threshold and Li & Fannin (2008) refinement appear reasonably well-verified for the non-plastic widely-graded NZ glacial tills considered in this study. Given general similarities in grain shape, surface roughness, and parent rock, these verification findings may extend to alluvial gradations with similar particle-size distributions. Yet, while the glacial, alluvial, and volcanic soils considered in this study display similar particle-size distributions, the existing literature provides no systematic verification of the existing geometric methods to assess potential instability in volcanic soils.

3.3 *Interpretation of screening results*

The four empirical methods utilised in this study to assess the potential for internal instability do not yield consistent results (Section 3.1). This section considers the interpretation of screening results for the 19 widely-graded NZ soils considered in this chapter with reference to the reliability, verification, and suitability of the four methods used in analysis.

Despite lacking verification for volcanic soils, the methods of Kenney & Lau (1986) and Li & Fannin (2008) are well-verified for particle-size distributions similar to those considered in this study. Results indicate that 17 of 19 widely-graded NZ soils of volcanic, alluvial, and glacial origin may be susceptible to internal instability. Two alluvial gradations are assessed as internally stable.

The method of Burenkova (1993) assessed eight NZ gradations as internally stable and considered three to be internally unstable. However, the Burenkova (1993) method is considered to be less reliable given: (1) a reported lack of correlation to stability test results in some widely-graded soils, and (2) the plotting positions of many NZ soils lie beyond the bounds of the published method. This can be attributed to differing material properties; specifically, the NZ soils considered in this study are much more widely-graded than those used in the derivation of analysis methods.

The 'stable' assessment obtained for each of the 18 sufficiently-defined NZ soil gradations by the Wan & Fell (2008) method cannot be considered reliable, given that a 'stable' result is predetermined for any widely-graded soil with $\frac{D_{90}}{D_{60}} > 2.37$.

In summary, the majority of widely-graded NZ soils considered in this study appear susceptible to internal instability. The potentially unstable gradations include soils of glacial, alluvial, and volcanic origins. This interpretation is based on the assessment methods of Kenney & Lau (1986) and Li & Fannin (2008) which are considered most applicable to, and reliable for, the widely-graded soils considered in this study.

3.4 *Limitations in the current State-of-Practice*

The observed inconsistencies in results across existing empirical screening methods is perhaps unsurprising given the limited scope and nature of laboratory tests used to define the methods. Notwithstanding attempts to verify and refine existing empirical methods, most authors (e.g. Li & Fannin 2008, Wan & Fell 2008) recommend laboratory testing to assess the potential for particle migration in critical applications.

However, in the case of existing structures, laboratory testing may not be feasible for reasons including budgetary constraints, a lack of risk comprehension, restrictions on material sourcing, and/or lack of testing facilities. The availability of reliable screening methods for erosion susceptibility is therefore important in the management of existing dams and the prioritisation of deficiency investigation works.

In the New Zealand context, one of the main concerns in the management of existing embankment dams is the unknown impact of seismic ground motions on particle migration over the lifetime of a structure. Particle migration is a phenomenon that can initiate and progress within earth dams in a continuous or episodic fashion, over periods spanning decades (e.g. Garner & Fannin 2010 and Moffat et al. 2011). No existing empirical methods explicitly address the effects of seismic ground motions on the susceptibility of a soil to particle migration. Greater confidence in the use of empirical screening tools would be gained if proposed stability thresholds for internal instability could be verified under dynamic loading conditions.

A further 'knowledge gap' exists as a result of the geological and geomorphological diversity within New Zealand. Many international studies have focussed on the factors controlling internal instability in widely-graded glacial and alluvial materials (e.g. Skempton & Brogan 1994, Moffat et al. 2011, Rönnqvist 2010, among others); however, few studies have addressed the behaviour of volcanic soils which could prove more or less susceptible to internal instability due to varying particle shape, particle roughness, durability, or mineralogical properties.

While some existing screening methods for internal instability prove a useful 'first indicator' of material susceptibility, New Zealand dam owners require further verification of the methods for use in geologically diverse seismic environments.

4 ASSESSING THE POTENTIAL FOR FILTER INCOMPATIBILITY

Filter incompatibility concerns the transportation of soil particles at, and beyond, the interface between two soil zones. A filter (coarser soil zone) is termed incompatible when the inter-particle voids are large enough to allow continuing passage of finer particles from the base material (finer soil zone) through the filter.

4.1 *Filter compatibility criteria for design and assessment*

When correctly applied, modern filter design criteria (e.g. NRCS 1994, FEMA 2011, Fell et al. 2014) provide a sound basis for the safe design of soil interfaces in embankment dams. These criteria have developed over decades of practice and typically adopt an inherent degree of conservatism, in line with modern geotechnical practice. Many existing dams, however, were designed prior to the evolution of modern filter design criteria. Acknowledging the lack of guidance for the assessment of existing dams, Foster & Fell (2001) proposed filter performance thresholds based on a suite of laboratory seepage tests simulating a cracked base material in contact with a coarser filter. Specifically, No Erosion (NE), Excessive Erosion (EE), and Continuing Erosion (CE) boundaries were defined to assess the relative magnitude of filter incompatibility in existing dams. The NE, EE, and CE limits are determined by particle size and dispersivity characteristics of a given (retained) base material and expressed in terms of the filter D_{15}, i.e. the particle size assumed to control retention of base particles.

4.2 *Example analysis for a widely-graded base-filter interface*

This section presents an example of an base-filter interface within an existing dam designed around 70 years ago. The intent of this section is to illustrate, by means of this example, common challenges faced in the assessment of filters in existing dams that do not meet modern design criteria.

Figure 7 shows a filter envelope comprising seven unique soil gradations. Five of these gradations were obtained from recent site investigations, while two were obtained from construction records. For the purposes of visual clarity, the base soil envelope is not shown; however, the base soil envelope comprises over 20 widely-graded silt-sand-gravel gradations, all of which were obtained from construction records.

Filter retention thresholds for NE, EE, and CE conditions were calculated for all base soil gradations. The statistical distributions of filter D_{15} sizes for NE, EE, and CE conditions (per Foster & Fell 2001) are shown for the base soil gradation envelope in the context of the filter envelope. We observe the following (Figure 7):

- Based on the seven available filter gradings, the 'actual' filter D_{15} size may vary by more than an order of magnitude ($0.5 < D_{15} < 10$ mm).
- The range of calculated D_{15} sizes for NE and EE conditions each similarly vary by an approximate order of magnitude due to variation among base soil gradations.
- The filter envelope has a maximum D_{15} that is much smaller than the CE threshold for all base soil gradations, suggesting continuing erosion of the base soil may be unlikely.
- Considerable overlap is observed in the distribution of $D_{15,NE}$ and $D_{15,EE}$ sizes.
- The finest four filter gradations (at $F = 15\%$) fully satisfy the NE condition for all base gradations (the D_{15} sizes of the finest four filter gradations are finer than the NE thresholds for all base soil gradations).
- The coarsest three filter gradations (at $F = 15\%$) may permit No, some, or Excessive erosion, depending on the specific properties of the local base soil gradation.

Key challenges evidenced in this base-filter analysis example are as follows:

1. The assessment of base-filter interfaces in aging dams is rarely straightforward. Complexities arise from:
    - Design deficiencies attributed to the state of practice at the time of design: soil interfaces are unlikely to meet modern filter design criteria.
    - Poorly-defined gradation envelopes (limited gradation information restricts the ability to use statistical analysis methods).
    - Wide gradation envelopes: large variation in particle sizes at a given $F\%$ provide poor definition of 'characteristic' soil properties.
    - Overlapping NE and CE thresholds result due to a wide base gradation envelope.
2. In situ soil gradations may vary from construction records due to construction processes (segregation, poor blending of materials) or modification over the lifetime of the structure due to seepage-induced particle migration or seismic loading. With reference to Figure 7, it is possible that the coarser gradations of the widely-graded filter envelope were derived from finer filter materials by way of internal instability under ordinary service seepage conditions.
3. Modern filter design procedures typically determine filter retention criteria based on the finest base soil gradation. The analysis of an existing dam using the finest base soil gradation is likely to prove overly conservative, particularly where the base soil gradation envelope is wide and particle sizes within the envelope are normally distributed.

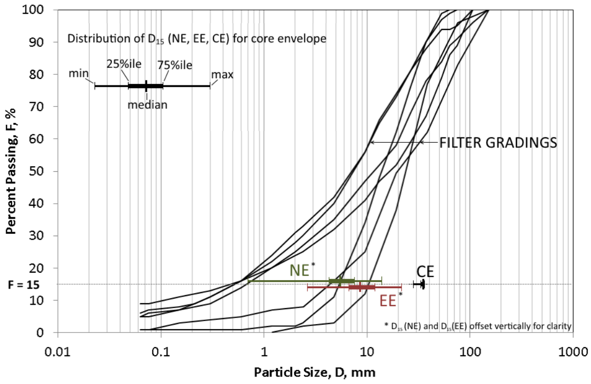

Figure 7: Example analysis of a widely-graded till base-filter interface, per Foster & Fell (2001)

4. For existing dams, gradation envelopes may span a wide range of particles sizes for any given F(%) or contain outlying gradation curves. A statistical or reliability approach to determining NE, EE, and CE thresholds, and assessing filter performance, may be warranted.

4.3 *Discussion of methods to assess filter performance*

While geometric analysis methods (Section 4.2) can serve as informative screening tools, the performance of a soil structure *as a system* cannot be definitively understood based on the analysis of a limited number of gradation curves such as those illustrated in Figure 7. Resulting performance criteria can be analysed by statistical means, but must inevitably be informed by empirical data and interpreted using engineering judgement.

Like all experimental laboratory programs, the tests used to define NE, EE, and CE conditions (Foster & Fell 2001) are subject to limitations. Specifically, filter tests were undertaken using core material compacted with a simulated crack, under constant large hydraulic head (240-300 kPa), for a short duration (typically < 60 minutes). The long-term performance of the filter interface is not addressed, yet could be considered critical for interfaces within NE and EE limits where erosion 'self-heals' following some loss (and potential deformation) of the base soil. The self-healing of base material may result in lower material densities while low or fluctuating seepage flows may not encourage clogging and bridging of finer particles in the same manner as constant high head conditions. To this end, recent studies suggest that filter soils with a D_{15} size between NE and EE limits may perform poorly in service conditions (Rönnqvist 2015).

Additionally, the existing methodology for assessing filters that do not meet modern design criteria (Foster & Fell 2001) does not address the performance of internally unstable filter materials. This problem may be of particular relevance in the New Zealand context, given the potential susceptibility of widely-graded NZ soils to internal instability as illustrated in Section 3. Rönnqvist (2015) has recently proposed a 'unified' plot to assess field performance of internally unstable filter soils, which may warrant exploration in the New Zealand context.

4.4 *Findings and limitations in the current State-of-Practice*

In practice, the assessment of existing dams that do not meet modern design criteria is complex. Base and filter soils are not often well-characterised. In rare cases where complete construction records exist, it is possible that the materials in-situ following decades of service will vary from those tested at the time of construction. Additionally, wide variations in base and filter gradation envelopes can result in the overlap of NE, EE, and CE performance thresholds.

Ultimately, the performance of a large soil structure cannot be reliably understood based on the analysis of a limited number of gradation curves. Calculated filter performance thresholds can be analysed by statistical means, but reliable guidelines for statistical analysis of filter performance are yet to be developed. In the current State-of-Practice, the assessment of filter performance for existing dams is informed by a limited empirical dataset and must utilise a reasonable degree of engineering judgement.

Of specific concern in the New Zealand context is the impact of seismic loading on filter performance. Accordingly, the local verification of NE and EE thresholds for seismic loading conditions should be prioritised. Further research could address the performance of filter interfaces in volcanic soils, particularly finer (base soil) ash materials that may be prone to cracking. In summary, the filter analysis example presented in this section highlights the need for improved guidance with respect to:

1. The statistical application of filter assessment methods.

2. The applicability of NE, EE, and CE filter performance thresholds for filters subject to seismic ground motions.

3. The applicability of NE, EE, and CE filter performance threshold to geologically variable New Zealand soils.

5 SUMMARY REMARKS

Water-retaining dams form a vital part of New Zealand's hydropower, agricultural, and water supply infrastructure. The compilation of a National Dam inventory shows that earth or rockfill dams account for at least 75% of all dams in NZ and most of these embankment structures were designed at least 40 years ago. The challenges faced in the management of aging embankment dams are compounded by factors specific to NZ, including large variability in soil types and the highly tectonic environment in which the dams are located. Internal erosion, triggered by both seismic and non-seismic events, is considered one of the primary risks to NZ embankment dams.

Existing geometric methods were used to assess the susceptibility of NZ soils to two distinct mechanisms of internal erosion: (1) internal instability, and (2) filter incompatibility. Susceptibility to internal instability was assessed for 19 widely-graded NZ soils using four existing empirical analysis methods. One of the four methods was rendered mathematically unsuitable for application to the widely-graded soils considered in this study. Screening results from the two geometric methods considered most applicable to, and reliable for, the NZ soils considered in this study suggest that the majority of the subject soils may be geometrically susceptible to internal instability.

An assessment case-study concerning a NZ base-filter soil interface demonstrates a clear need for guidance in the assessment of existing dams that do not meet modern filter design criteria. Ambiguous analysis results arising from overlap in NE and EE thresholds could be resolved by the future development of statistical analysis guidelines.

With regard to both internal instability and filter incompatibility mechanisms, the applicability of existing empirical analysis techniques to NZ soils appears limited:

1. Stability thresholds lack verification for the diverse geological range of fill soils encountered in NZ.

2. Proposed stability thresholds have not been verified for long-term or seismic loading conditions.

Specifically, there is a nationwide need for guidance for the evaluation of earth dams, (1) following significant earthquake ground motions, and (2) from a whole-life perspective. This study demonstrates fundamental shortcomings in the application of existing screening methods used to assess the potential for internal erosion in NZ soils. The identified limitations are also likely to be relevant in other regions where widely-graded soils or seismic conditions are commonplace. In the NZ context, findings reinforce industry demand for local research-quality laboratory testing facilities that are able to accommodate widely-graded soils containing gravels, and possess capacity to investigate the effects of seismic loading conditions on particle migration.

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