Applying available internal erosion criteria to dams with cores of glacial till - a reassessment of a 1980s sinkhole

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SYNOPSIS Most available criteria for assessing susceptibility to internal erosion and internal instability are laboratory or empirically based on narrowly graded materials. Glacial till, which is a typical material used for impervious cores in Swedish dams as well as in dams in Canada and other areas once glaciated, is generally broadly graded, a characteristic that primarily stems from its glacial origin and mode of formation. Assessing internal erosion in glacial till core dams may be difficult, and their track record shows a greater susceptibility to internal erosion and sinkhole development than that of other types of dams. This paper will, on the one hand, discuss ways of assessing dams composed of glacial till, and on the other hand it will cover the reassessment of a 1980s sinkhole incident in a Swedish dam, where a sinkhole was believed, at the time, to be caused by internal erosion. A step-by-step assessment is conducted by applying current available and suitable methods to help determine whether the incident was internal erosion dependent.

INTRODUCTION

Sherard (1979) was perhaps the first to recognise that dams with cores of broadly graded glacial soils tend to develop sinkholes from internal erosion more frequently than dams with other types of fillings. Such dam types, i.e., central core dams with base (core) material of glacial till (often referred to as moraine) and widely graded filters, are common in Scandinavia and North America, where land areas were once glaciated. For erosion control in dams the filter to the core is the most important zone. To avoid erosion of a glacial till core, Sherard and Dunnigan (1989) reported that a filter with a D_{15} less than 0.7mm is required. This is currently the accepted filter criterion when designing new filters and assessing existing filters for no-erosion. Assessing the susceptibility to internal erosion in glacial till core dams may be difficult. While the incidence of sinkholes is not directly proportional to the no-erosion boundary, a filter coarser than the design requirement in an existing glacial till core dam does not necessarily mean that the dam is highly susceptible to internal erosion (Rönnqvist, 2010). Up to a point, filter coarseness alone is not a clear-cut predictor of internal

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erosion propensity. Filter coarseness should be combined with the filter and core's internal stability and the filter's susceptibility to segregate, as well as considering any other design features that unintentionally promote internal erosion. This paper will discuss the available internal erosion criteria for glacial till core dams and the relative success of the criteria using a data-set of dams from Rönnqvist (2010) which comprises dams with and without a history of internal erosion. The paper will also conduct a reassessment using these criteria on a Swedish dam that experienced a sinkhole-incident in the 1980s.

INTERNAL EROSION CRITERIA AND RELATIVE SUCCESS ON DAMS OF BROADLY GRADED GLACIAL MATERIALS

There are numerous available criteria to assess internal erosion susceptibility and internal stability, but few were developed to assess these characteristics on broadly graded soils, making the applicability of the criteria less clear. In Rönnqvist (2010) dam data with respect to filter material, core material and dam design were inventoried, exclusively for those dams of broadly graded glacial soils and cores that classify according to grouping of Sherard and Dunnigan (1989) as soil group 2 base soils (40% to 85% finer than No. 200 (0.075mm) sieve, the amount determined by regrading the base soil on the 4.75mm sieve). The data set consists of 91 glacial till core dams, of which 21 are afflicted by confirmed internal erosion with reported sinkholes or other internal-erosion-related signs. The inventoried dams were grouped as follows:

- Category 1-dams – dams with a probable occurrence of internal erosion (the dam has had documented internal erosion).
- Category 2-dams – dams where observations may indicate signs of internal erosion (presence of internal erosion is not clear, until proven otherwise, signs are considered unrelated to internal erosion).
- Category 3-dams – dams with no observations to indicate internal erosion (fully functional dams with no sinkholes or settlements and no leakage with eroded material).

Foster and Fell method to assess filter performance in existing dams

Foster and Fell (2001) investigated the factors that influence whether the base will erode into its protective filter. They proposed a method to assess the likely filter performance in existing dams during a concentrated leak through the core that incorporates filter boundaries for no erosion, excessive erosion and continuing erosion. Three categories for filter performance were proposed based on the filter boundaries, including the filter seals with "no erosion"; seals with "some erosion"; and partial or no seal with "large erosion". Foster and Fell (2001) found that relative to "soil group 2A" (as denoted by Foster and Fell, 2001), the group to which cores of glacial till normally belong, the more gap-graded the base (over the fine-medium sand fraction 0.075mm to 1.18mm), the finer the necessary D_{15} filter must be for excessive erosion to occur. With respect to no-erosion, Foster and Fell (2001) adopted the Sherard and Dunnigan (1989) filter design limit D_{15} = 0.7mm. The continuing erosion boundary was found to be equal to the filter's opening size (0.11 D_{15}), i.e., filter $D_{15} > 9d_{95}$.

Regarding the data set in Rönnqvist (2010), the Foster and Fell (2001) method correlates well with dams that have an internal erosion history (category 1 dams) because erosion is possible (some or large) in the event of a concentrated leak and because none of the category 1 dams are highly likely to seal with no erosion. There may be a conservative side to the method when applying it to till core dams because one out of three dams with no internal erosion (category 3 dams) are placed in the "large erosion" group (see Figure 1) as well, and because the proportion of dams with internal erosion (category 1 dams) versus dams without internal erosion (category 3 dams) in this group is almost equal (i.e., 46% versus 43%).

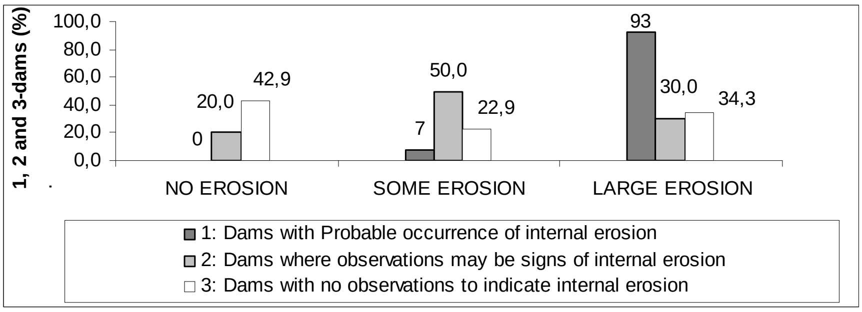

Figure 1. Likely filter performance using the Foster and Fell method (Rönnqvist, 2010).

<u>Kenney and Lau criterion and extensions by others</u>

Kenney and Lau criterion

Kenney and Lau (1985) understood the importance of the "primary fabric of particles" that takes up load and transfer stress in a material. Within the pores of these interlocked particles, there may exist unfixed particles that potentially may move through constrictions of the fixed particles. A criterion to assess internal stability was proposed by Kenny and Lau (1985) in which the ratio of the mass fraction of particle sizes between d and 4d (denoted by H) and the passing weight at particle size d (i.e., F), i.e. the "H:F shape curve" must be established. A deficiency in the number of particles of a certain fraction between d and 4d, will potentially allow for the erosion of particles more fine-grained than d. The boundary between stable and unstable was initially H=1.3F (Kenney and Lau, 1985) but this was later adjusted to that of a Fuller curve with H=1.0F (Kenney and Lau, 1986) based on the advice of Ripley (1986) and Milligan (1986). For widely-graded materials the evaluation range is between passing weight 0% to 20%, which, according to Kenney and Lau (1985), is the maximum range for loose particles.

When applied to the data set in Rönnqvist (2010), the Kenney and Lau criterion provides a potential indicator of dams with internal erosion. The majority of category 1 dams were assessed as having internal instability of both the core and filter, for which the proportion is 75% for category 1-dams and 25% for categories 2 and 3 dams. Furthermore, a simultaneous internally stable core and filter provides a strict boundary to dams without internal erosion (category 3 dams).

Wan and Fell approach (Kenney and Lau combined with Burenkova)

In Wan and Fell (2004), the factors that affect the internal stability of widely graded soils were investigated using seepage tests and validated with currently available methods. Wan and Fell (2004) concluded that combining the criteria of Burenkova (1993) and Kenney and Lau (1985, 1986) (Table 1) provides a reliable estimation of the internal stability of silt, sand and gravel mixtures. In Burenkova (1993), the suffusiveness of a soil can be predicted considering grain sizes D90, D60 and D15, from which the ratios $h' = d_{90}/d_{60}$ and $h'' = d_{90}/d_{15}$ can be determined. According to Burenkova (1993) a soil is internally stable if $0.76\log(h'')+1 < h' < 1.86\log(h'')+1$. Only the lower bound of the Burenkova criterion is included in Wan and Fell (2004) as one of the predictors of internal instability (Table 1).

When testing the Wan and Fell (2004) on the data set in Rönnqvist (2010), the approach did not provide a distinction between dams with internal erosion and dams without (Figure 2). Most filter material is assessed as internally stable with no correlation with the dams' history of internal erosion. Therefore, the Wan and Fell approach may be less suitable for glacial till core dams and widely graded filters, and also because although the Kenney and Lau criterion indicates internal instability (H/F<1), the Burenkova criterion, if the soil is assessed as a Burenkova non-suffusive (i.e., having $h' = d_{90}/d_{60} > 0.76\log(h'')+1$), overrides Kenney and Lau and deems the filter internally stable. Another explanation may be that the Wan and Fell (2004) approach excludes the upper bound of Burenkova (i.e., that $h' = d_{90}/d_{60} < 1,86\log(h'')+1$) which basically means that there is no upper limit regarding how widely graded the material can be on its coarse part. By not taking into account the upper bound of Burenkova it promotes the widest possible grading on the top part of the sieve curve (i.e., d_{90}/d_{60}), while at the same time the narrowest possible grading over the middle part (i.e., d_{60} and d_{15}). By so doing, the highest possible ratio of d_{90}/d_{60} compared to d_{90}/d_{15} is obtained, leading to a condition where internal instability is unlikely (Table 1). The aim of the Burenkova criterion is to obtain not necessarily a narrow grading, but rather a grading as uniform as possible which requires satisfying both the lower and the upper bounds.

Table 1. Assessing the likelihood for internal instability of silt, sand and gravel mixtures (Wan and Fell, 2004).

Likelihood of Internal Instability		Kenney & Lau (1985, 1986) method		
		$H < F$	$F \leq H < 1.3F$	$H \geq 1.3F$
Burenkova (1993) method	$h' \leq 0.76\log(h'') + 1$	Likely - Very likely	Neutral - Likely	Very unlikely
	$h' > 0.76\log(h'') + 1$	Unlikely	Very unlikely - Unlikely	Very unlikely

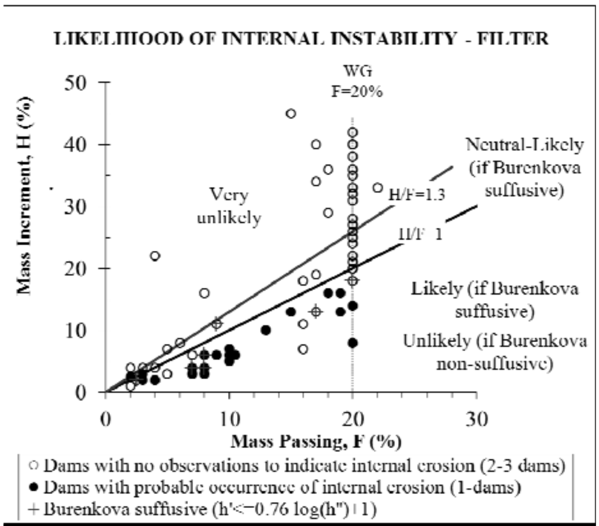

Figure 2. Illustration of the Wan and Fell approach to evaluate likelihood of internal instability.

Li and Fannin approach (Kenney and Lau combined with Kezdi)

Primarily based on the research of Li (2008) on widely graded soils, Li and Fannin (2008) proposed to extend the Kenney and Lau (1985, 1986) criterion to include Kezdi (1979). As both criteria examine the slope of the grading curve, Li and Fannin (2008) showed that it may be useful to combine aspects of the two empirical methods to improve the assessment of internal stability and make it less conservative. Li and Fannin (2008) recommended applying the Kenny and Lau criterion up to a passing weight of 15% and then transitioning to the Kezdi criterion beyond that. When testing the Li and Fannin (2008) approach to the data set in Rönnqvist (2010), it indeed reduced the degree of conservatism (Figure 3) and improved the accuracy in pinpointing dams with internal erosion (category 1 dams) when evaluating widely graded base materials (tills). Dams without internal erosion (category 2 and 3 dams) that were previously assessed as internally unstable were now excluded. In terms of evaluating sand-gravel filters using the Li and Fannin approach, any improvement from implementing the Kenney and Lau criterion is less clear (Figure 4). The figures show the minimum H:F established within the envelope of the material and indicate that if the fine limit or coarse limit is assessed as unstable, the material is assumed to be unstable.

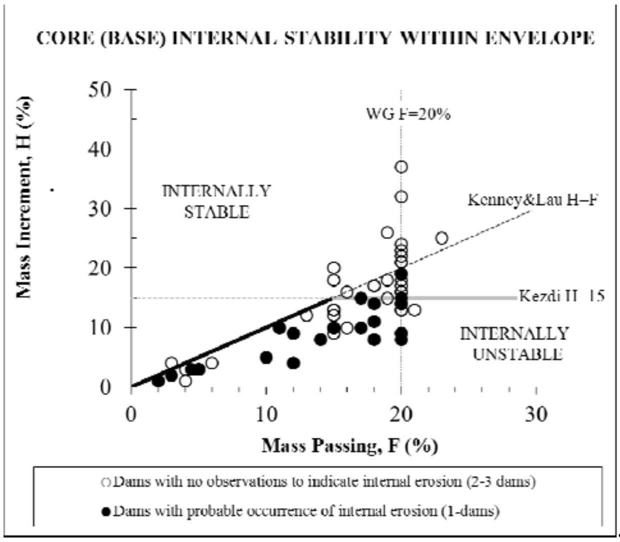

Figure 3. The results of the Li and Fannin approach when tested on core materials of existing dams with and without internal erosion.

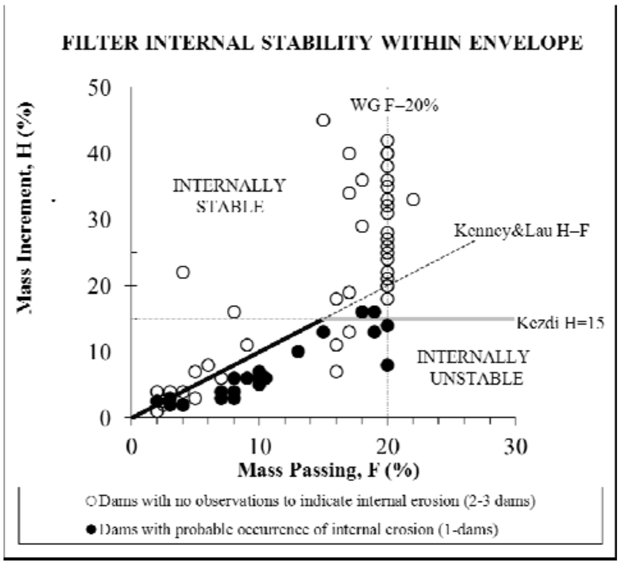

Figure 4. The results of the Li and Fannin approach when tested on filter materials of existing dams with and without internal erosion.

Rönnqvist approach (Kenney and Lau combined with filter D15 and indicators)

In the investigation of possible predictors of internal erosion prone glacial till core dams, Rönnqvist (2010) found the following unfavourable coinciding properties for till core dams with a history of internal erosion:

i) coarsely graded filter (generally with a maximum $D_{15} \geq 1.4$mm); ii) grading instability of the filter material; iii) grading instability of the core (base) soil; and iv) high susceptibility to filter segregation (low on sand and large particle sizes). A method to assess the potential for surfacing internal erosion (i.e., erosion in the excessive or continuation phase) is proposed (Table 2), and qualitative terms are set from low to high, depending on the degree of predictors that are fulfilled. According to Rönnqvist (2010), based on more than 90 existing glacial till core dams, for dams assessed as low potential the proportion of dams with internal erosion (category 1-dams) is nil, while 10% at neutral, 20% at increased potential and at high potential the category 1 dams account for more than 80%.

Table 2. Potential for surfacing internal erosion in glacial till core embankment dams (Rönnqvist, 2010).

	Kenney and Lau [(1)] (1985, 1986)		
Max Filter D_{15} (mm)	Unstable core Unstable filter	Unstable core + Stable filter or Stable core + Unstable filter	Stable core Stable filter
≥ 1.4 [(2)]	HIGH [(2)]	INCREASED	NEUTRAL
< 1.4 > 0.7	INCREASED	NEUTRAL	REDUCED
≤ 0.7 [(3)]	NEUTRAL	REDUCED	LOW

otes: [1] Internally unstable if (H/F)min < 1, internally stable if (H/F)min ≥ 1.
[2] Always a high potential if DF15 > 9 DB95 regardless of the internal stability. Foster and Fell (2001) continuing erosion boundary. Re-grade core soil on the 4.75 mm sieve.
[3] Sherard and Dunnigan (1989) no erosion boundary (soil group 2 base soils).

EXAMPLE OF APPLICATION OF CRITERIA

The Hällby dam, located in Sweden and put into service in 1970, consists of a left embankment dam, a left connecting concrete monolith, the concrete dam (spillway section and power station intake), a right connecting concrete monolith, and a right embankment dam. The embankment dams are approximately 30m high at the highest section and have a centrally located core, surrounding transitions and shoulders of rockfill (Figure 5). The core material consists of glacial till (with fines content, material < 0.075mm, on the order of 30% to 50% regraded on the 4.75mm sieve) and critical filters of sand and gravel (denoted as “support fill” in the records). The base soil was initially compacted in 300mm lift but was later increased to 500mm because satisfactory compaction was obtained even at this lift height. Eight passes by 3.5T rollers were generally completed for compaction, but at those sections that were more difficult to compact, lighter equipment was used. Different compaction procedures were implemented. On the one hand dry compaction at optimum water content (± 2%) and on the other hand wet compaction at water content at the material’s yield point. It is not clear however where these different procedures were used, but it is known that dry compaction with light equipment (vibratory plates and rammers) was carried out where the embankment connects to the concrete dam.

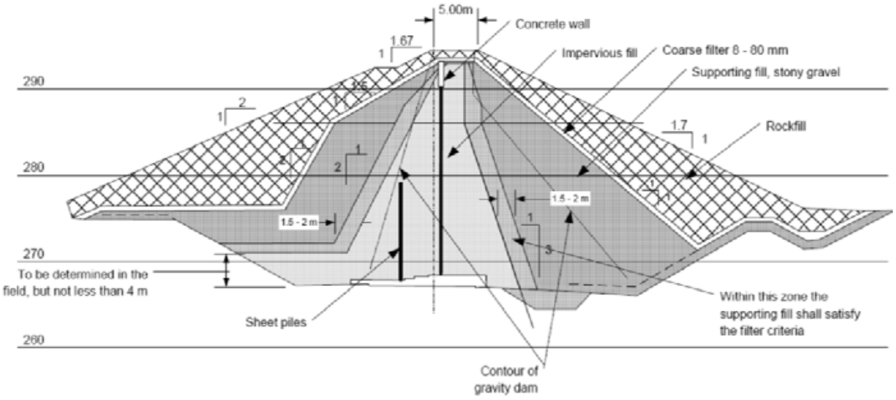

Figure 5. Cross-section of embankment dam at the connection to the concrete dam (courtesy of EON).

The concrete dam is, in its entirety, founded on granite rock, including the embankment dams where these abut the concrete dam. However, towards the shores, the foundation gradually becomes morainic deposits. Because the bedrock was found to be of poor quality, multiple rows of grouting were performed (deep grouting, double rows of surface grouting and contact grouting at the surface). It is not clear, however, if the bedrock to the embankment dams was sealed in the same way as the concrete dam, though this appears to be the case based on construction photos (Status Assessment, 2011). Both the left and right embankment dams connect vertically to the concrete dam with two sheet pile walls extending centrally into the dam core. The sheet piles were cast into the concrete slab at the foundation and to the pillars of the concrete dam. While the upstream sheet pile is lower, the downstream extends up to the retention level, and at the top part, it is lengthened into a concrete wing. The wing goes out from the vertical pillar and creates an upward slope. For the core to fit alongside the sheet pile and concrete wing, the core is at this part very narrow and locally lowered a few metres below the retention level (Status Assessment, 2011), thus transferring over a short distance the impermeable duty of the core to the concrete wing at the abutment.

The 1985 sinkhole incident and remedial measures

In September 1985 damage to the roadway was discovered where the left embankment dam abuts the concrete structure; the asphalt had cracked and a depression had formed along the crack. The depression, assumed to be a sinkhole that extended to the upstream side of the crest, was located between the two sheet piles, and it was approximately 0.7m in depth and $7m^3$ in size. At this time, seepage of approximately 200 l/min was measured with a bucket and stop watch at the regular measuring point. The water was clear and free from discoloration. Earlier seepage measurements had not been conducted routinely, and prior to the incident, it had been four months since the last reading. Previous measurements averaged 20 l/min.

The initial remedial action was to draw down the reservoir to the minimum retaining level, but the mere 0.8m reduction in head did not yield any noticeable change in the 200 l/min seepage. An examination was conducted compassing test pits, thus exposing the core, where penetration tests were conducted to determine its condition. The investigation revealed that the core was loose at the crest, and damage to the bottom parts of the core was discovered between the sheet piles and at locations further up the core. The crest was backfilled and restored, and the reservoir level was increased to its maximum level. A grouting program commenced with cement-bentonite and silicate mixtures to repair and seal the bedrock, the core-foundation contact and the core soil in the vicinity of the sinkhole incident. As a result of these actions, seepage initially decreased from 200 l/min to 40 l/min, and during the next several years seepage decreased to a steady 10 l/min. From the records, it is possible to determine that the bedrock was basically impermeable and required only a small amount of grout, while the major take of grout was at the core-foundation contact (Status Assessment, 2011).

Applying the internal erosion criteria to the Hällby dam

The envelopes of the core and filter gradings are presented in Figure 6. The filter ("support fill" but with appropriate grading to satisfy current filter criteria to the core) comprised gravelly sand with D_{15} that varies from 0.3mm to 1.5mm and one outlier grading with 2.1mm, which, in view of the overall distribution of gradings is not assumed to be characteristic of the filter as a whole. The Foster and Fell (2001) D_{15} boundaries for no erosion (0.7mm), some erosion (0.7mm to 5.0mm), excessive erosion (> 5.0mm) and continuing erosion (> 23mm) are shown in Figure 6 (presented in accordance with application advice given in Foster, 2007). At the most, the filter satisfies the no-erosion limit of 0.7mm (Figure 6), which means that the filter is highly likely to seal a leak with no erosion, but the coarse portion of the filter exceeds the limit of some erosion, making it equally likely that it will seal with some erosion. A partial seal or no seal with large erosion as a consequence is unlikely because the filter falls below the excessive erosion boundary. Continuing erosion is highly unlikely as the filter is clearly far finer-grained than one which would allow unrestricted erosion (Figure 6).

Applying the Kenney and Lau (1985, 1986) criterion, as proposed by Li and Fannin (2008) by combining it with Kezdi (1979), the core soil is basically assessed as internally stable if an isolated curve is dismissed as uncharacteristic of the core as a whole (Figure 7). Similarly, the filter material is internally stable. For reference, the point values of (H/F)min (i.e., the minimum value of the Kenney and Lau stability index along the evaluated curve) of existing glacial till dams from Rönnqvist (2010) are shown.

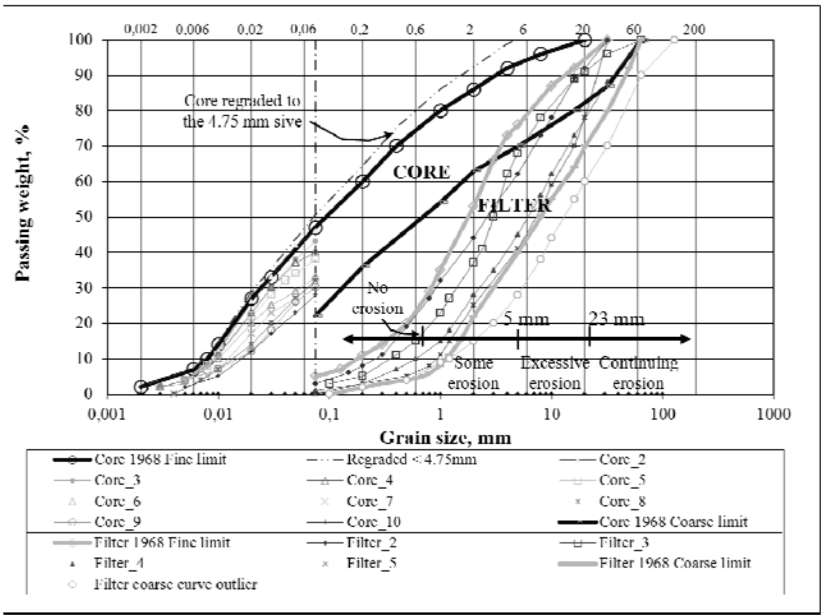

Figure 6. Core and filter gradings, and the evaluation of filter performance according to Foster and Fell (2001).

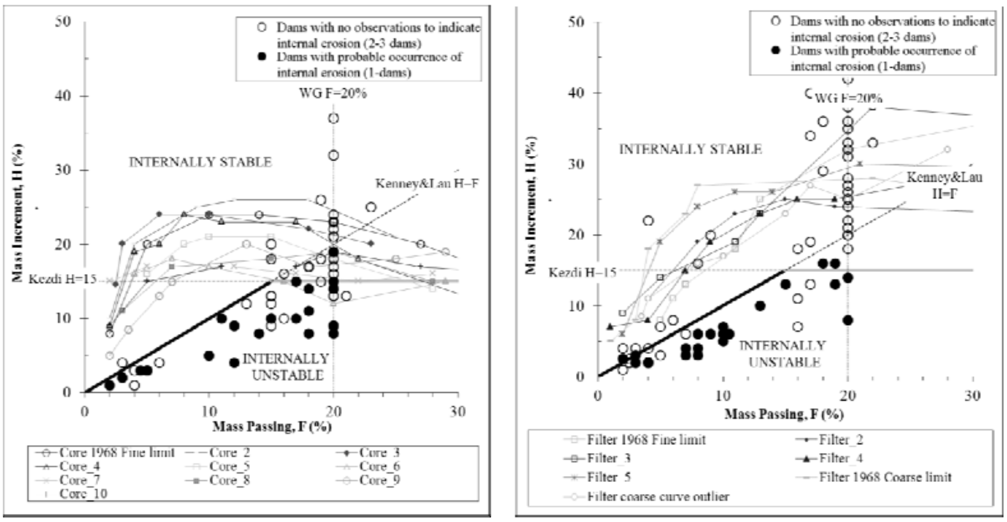

Figure 7. Evaluation of internal stability of the core material (left) and the filter material (right) using the Li and Fannin approach by combining the Kenney and Lau criterion with the Kezdi criterion.

Within the framework of a safety evaluation (Status Assessment, 2011), the Hällby dam was subject to an assessment of the potential for internal erosion using the method proposed by Rönnqvist (2010). In Figure 8, the distribution of point values of (H/F)min of all available gradings within the

Hällby dam's filter envelope is plotted against the corresponding D15 value (i.e., from the fine limit, with the intermediate curves, to the coarse limit).

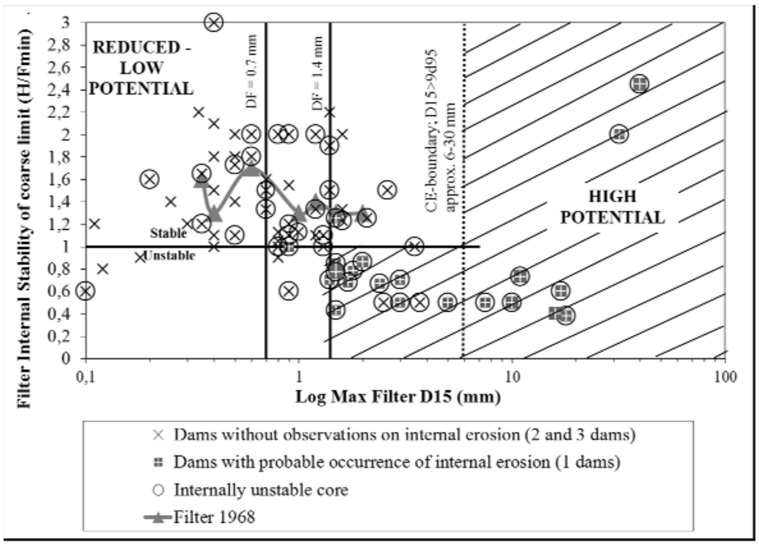

Figure 8. Filter internal stability (coarse limit) plotted against filter D15 (Rönnqvist, 2010).

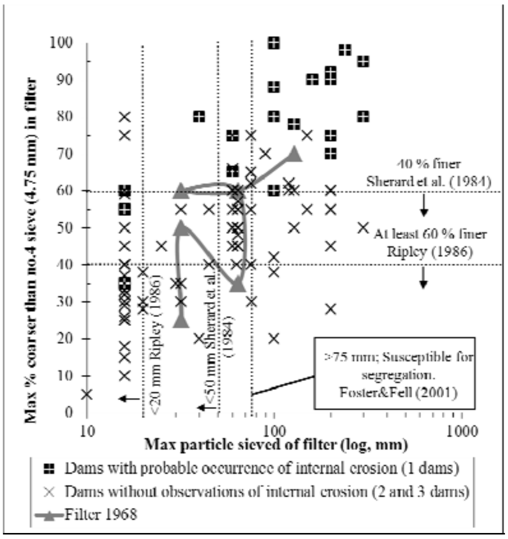

Figure 9. Gravel content plotted against maximum particle size in filter to assess susceptibility to segregation (Rönnqvist, 2010)

The plot is completed using a backdrop of dams with and without internal erosion from Rönnqvist (2010), and the Hällby dam's filter differs from dams with internal erosion. A slight adjustment has been made to the graph (Figure 8) compared to Rönnqvist (2010): the maximum D15 of the filter is put against the internal stability of the *coarse* limit, resulting in a less conservative assessment, than making it against the lowest stability index within the *whole envelope* (as originally done in Rönnqvist, 2010). In Figure 9, the gravel content and maximum particle size of the Hällby dam's fine limit, intermediate curves and the coarse limit of the filter are plotted to assess filter segregation susceptibility. The approach takes into account the guidance of Ripley (1986), Sherard *et al.* (1984) and Foster and Fell (2001), where Ripley (1986) and Sherard *et al.* (1984) recommend restrictions on the maximum particle size in the filter and gravel content (material coarser than 4.75mm). From this, it is reasonable to conclude that the filter has segregated at least the coarse limit because the maximum particle size is very large ($D_{max} \geq 100$mm) and the gravel content is high (>60% is coarser than 4.75mm). Given that the filter and core, as a whole, are assessed as internally stable (Figure 8) and that the filter has a D15 that varies from 0.3mm to 2.1mm if the outlier is taken into account (Figure 7, Figure 9), the potential for surfacing internal erosion (i.e., excessive and continuing erosion) varies from low to neutral (car. with Figure 5). Statistically, the proportion of dams with internal erosion in the neutral group is only 10% according to the results from over 90 existing glacial till core dams in Rönnqvist (2010).

<u>Discussion on the cause of the sinkhole in view of the internal erosion assessment</u>

At the time of the incident, many theories were put forward as to the cause of the sinkhole. One of the more dominant theories was internal erosion of the core into the foundation through bedrock cracks (Brunner *et al*., 1988). However, the grouting records from the remedial measures dismiss this possibility, as the bedrock took very little grout and was found to be virtually impermeable (Status Assessment, 2011). In the recent status assessment (2011) and the special review (2008), the later conducted by an international expert review board, the focus shifted from an internal erosion process to design conditions and the technical specifications of materials and procedures. The compaction of the core soil against the vertical connecting concrete structure, compaction between the sheet piles and up against the concrete wing with upward slope must have been difficult to achieve. Furthermore, dry compaction at or below optimum water content, which reportedly was done here, may have resulted in additional wetting settlements. The special review (2008) of Hällby dam noted also that it is likely that the compaction of the core was inadequate because of high lifts and light compaction equipment. These circumstances may have resulted in potential arching effects, the development of gaps and loose filling, all of which may have induced the initiation of internal erosion in the material itself or along the paths of concentrated leaks. Whether internal erosion progresses depend on the filter's ability to protect the core from eroding; an inadequate filter is unable to stop an initiated internal erosion process. The assessment of the Hällby dam's filter performance, internal stability and potential for internal erosion indicates that it is equally likely that the filter would seal a leak with no erosion as with some erosion (according to the method by Foster and Fell, 2001). Furthermore, the filter statistically differs from that of dams that typically develop internal erosion (Rönnqvist, 2010). Although it has characteristics making it susceptible to segregation, the risk is considerably reduced due to the thorough quality control that was in place (as seen in construction photos).

It is reasonable to suggest that the filter has been put to the test through concentrated leak erosion of the core against the filter face; some erosion may have been permitted at this stage, but any further progression was probably stopped. This may have caused the increase in seepage, although the sporadic nature of seepage measurements at the time makes it difficult to determine whether it was connected to the incident or induced by the particularly rainy autumn of 1985. In conclusion, the initiation of erosion may have had some part in the development of the sinkhole and the core's loose zones, but the redistribution of materials due to collapsing arching from bridging effects is likely the main cause (Status assessment, 2011).

CONCLUSIONS

Assessing the internal erosion susceptibility of dams with cores of glacial till may prove difficult, and the applicability of available criteria is less clear. This paper discusses the relative success of available criteria and finds that cross-referencing an assessment of filter performance, internal stability and typical indicators of dams that have developed internal erosion (based on historic performance data) may provide improved aid-to-judgment. In the case study of the Hällby dam, also described in this paper, this approach helped to determine that internal erosion of the core into the filter was not a significant contributing factor to the sinkhole incident, but primarily it was caused by construction- and design related factors.

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