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Assessing the Potential for Internal Erosion in Glacial Moraine Core Embankment Dams

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ABSTRACT

Internal erosion, the process of wash-out of fine-grained material by seepage flow from an embankment dam filling material, can pose a major threat to dam safety. Many embankment dams in Sweden, having the typical composition with an impervious core of widely-graded glacial moraine (till) and protective filter of glaciofluvial sand and gravel, have experienced internal erosion that surfaced in the shape of sinkholes, turbidity and sudden increased leakage. The general consensus, as far as internal erosion is concerned, is that the downstream filter to the core is the most important protection against internal erosion. This paper is based on a study comprising 45 existing Swedish embankment dams and the results reveals that: on one hand a majority of the dams have filters that do not satisfy current filter requirements, and on the other hand only a few of these dams have developed internal erosion that surfaced in the shape of sinkholes or other related signs. This indicates that the current filter criteria is somewhat limited from an analysis point of view, preferably intended for design use with built-in factors of safety. A more discriminatory predictor appears to be needed if embankment dams with widely graded glacial cores with high potential for surfacing internal erosion are to be analytically distinguished from dams with low potential, apparently internal erosion free. This paper will show that not only filter coarseness needs to be addressed when analyzing potential for internal erosion in embankment dams with glacial moraine cores, but also the internal stability of the core and filter.

1 INTRODUCTION

The majority of Swedish embankment dams are comprised of broadly graded glacial moraines (tills) in the core, protected by filters of sand and gravel, in many cases widely graded, see examples of gradation curves in Fig. 1. It was early on recognized by Sherard [1979] that dams of this type, with filling materials of broadly graded glacial origin, exhibited signs of internal erosion such as sinkholes to a larger extent than dams comprising other types of materials. To this comes the complexity that broadly graded core materials bring on the design of protective filters (Sherard&Dunnigan [1989], Lafleur et al. [1989]). The typical Swedish embankment dam is a zoned embankment with a vertical, and centrally placed moraine core, filters of sand and gravel, in most cases of glaciofluvial origin, and shoulders (support fills) of earthfill or rockfill, see Fig. 2. There have been several incidents with reported sinkholes in Swedish embankment dams. Sinkholes can often be attributed to internal erosion in the dam body or its foundation and can serve as an indicator of internal erosion if occurring on the dam crest or the upstream face, simultaneously with dirty water (turbidity) and unexpected increases in seepage downstream. A survey carried out by Nilsson et al [1999] of 84 rock- and earthfill embankment dams in Sweden, with objective to investigate the ageing and deterioration processes, revealed that a considerable number of the dams (27 dams) had been reported to have developed sinkholes on the crest. 20 % were estimated to have experienced some kind of internal erosion either in the dam's body or its foundation (Norstedt&Nilsson [1997]). To date, there have been no dam failures due to internal erosion of large hydropower embankment dams in Sweden, but in an international perspective ICOLD [1995] statistics show that internal erosion in the dam body or its foundation poses a major reason for dam failures.

The process of internal erosion is usually described by the initiation, continuation and progression phases (Foster&Fell [2001]). Initiated internal erosion, resulting in the loss of impervious core function, can in many cases be traced back to a “root cause” for internal erosion, and the subsequent continuation of the internal erosion is mainly dependent on the protective filter function (Nilsson&Rönnqvist [2004]), root causes being e.g. internal instability of the core, coarsely graded filters unable to protect the core, or different structural or construction related reasons (e.g. arching effects, low effective stresses or unintentional seepage paths created due to ways of construction or design).

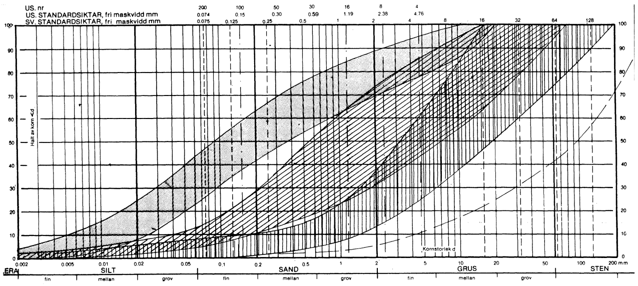

Fig. 1: Examples of gradation curves of a widely graded moraine core (left) and filters of sand/gravel (right) used in Swedish dams.

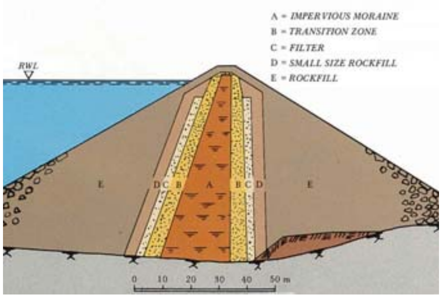

Fig. 2: Outline of typical Swedish embankment dam.

On the basis of 45 existing Swedish embankment dams, with moraine cores and filters of sand and gravel, this paper will show that the majority (approximately 70 %) do not satisfy current filter criteria, but this amount does not stand in relation to the number of dams that actually have developed confirmed internal erosion (approximately 20 %). This indicates that current filter criteria are intended for design use with built-in factors of safety, and because of that being too conservative and somewhat limited from an analysis point of view. This paper investigates if a more discriminatory tool can be derived for assessing potential for surfacing internal erosion in embankment dams with widely graded glacial cores. *Surfacing* internal erosion (Rönnqvist [2006]) refers to the point when the process has exceeded the initiation phase, and passed into the continuation and progression phase of internal erosion and manifested itself in a sinkhole.

Questions can be raised whether it is possible to analytically distinguish glacial moraine core embankment dams with high potential for surfacing internal erosion from dams with low potential, apparently internal erosion free. Introduced in Rönnqvist [2006] and further developed in Rönnqvist [2007], an evaluation is carried out on inventoried dam records of core and filter gradation curves, mainly from the time of construction, but also in some cases on soil samples from test pits or drill cores made in the dams years after construction.

The notation and terminology used in this paper is described as follows: D15 = particle size for which 15 % by weight is finer, DF15 = particle size in filter for which 15 % by weight is finer, DB95 = particle size in core base soil for which 95 % by weight is finer.

2 PROPOSED DAM CATEGORIES WITH RESPECT TO INTERNAL EROSION

The embankment dams incorporated in this paper are part of an ongoing inventory of Swedish embankment dams. To date there are 45 dams comprised in this study and out of these are 10 confirmed cases of glacial moraine core embankment dams with internal erosion. The distribution of the dams is shown in Fig. 3. The composition and structure of the dams in the study varies slightly, but common features are the core of glacial moraine and a sand-gravel filter of some sort (see examples of gradation curves in Fig. 1). All of the dam’s impervious moraine cores classifies as Sherard&Dunnigan [1989] soil group 2 base soils (40-85 % finer than No. 200 (0.075 mm) sieve determined from base soils re-graded on the 4.75 mm sieve). In this study it has been necessary to categorize the dams regarding its occurrence of internal erosion, and this has been done in three proposed categories; namely 1, 2 and 3, with definition as described below.

“1-dams” Embankment dams with *Probable occurrence of internal erosion* – The dam has had incidents with visible sinkholes and settlements on the surface of the dam and leakage with dirty waters (eroded material in suspension) or other observed signs of internal erosion. The presence of internal erosion is documented (e.g. by test pits or drill cores).

“2-dams” Embankment dams where *Observations may be signs of internal erosion* – Sinkholes and settlements have occurred on the dam, but no leakage with eroded material has been noted.

“3-dams” Embankment dams with *No observations to indicate internal erosion* – No sinkholes or settlements have occurred on the dam and no leakage with eroded material has been sighted.

Category “1-dams” has experienced typical signs of deterioration related to internal erosion and the prerequisite on category “1-dams” is a “confirmed and documented” occurrence of *surfaced* internal erosion in the dam in question. Category “2-dams” are “borderline cases” that have exhibit signs that can be related to internal erosion but it is not clear-cut, and until further notice the signs of the dam in question is considered not internal erosion related. Category “3-dams” have exhibited no signs of internal erosion, and are regarded as fully functional embankment dams.

Placing existing dams into categories of internal erosion is delicate because in most cases the process of internal erosion is concealed and often with a very slow progression. There are 10 dams that qualify as “1-dams” (with probable occurrence of internal erosion), see Fig. 3, out of these there are 2 embankment dams where the internal erosion (in the shape of sinkholes and turbidity) surfaced almost immediately after the first raising of the reservoir (Nilsson et al [1999]). But as can be interpreted from Fig. 3 the majority of the “1-dams” experienced signs of internal erosion as long as 5-15 years after the dam’s commissioning.

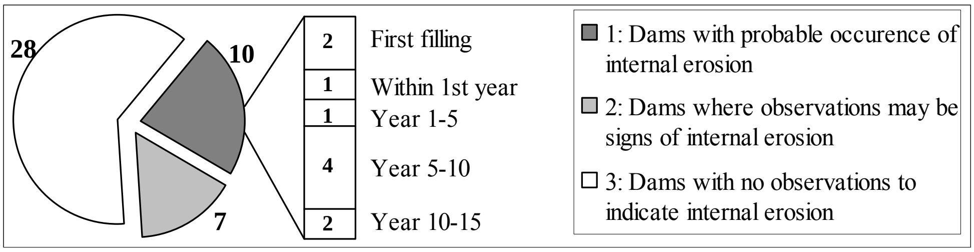

Fig. 3: Number of dams in categories 1 to 3 and elapsed time until first internal erosion sign.

3 CORE/FILTER INTERNAL STABILITY AND FILTER GEOMETRY – RESULTS AND EVALUATION

As mentioned previously out of the 45 dams in the study, 10 are documented cases of dams with internal erosion that have exhibit signs like sinkholes at the crest and dirty water downstream, i.e. the dams referred to as category 1-dams. In Rönnqvist [2006], a selection of methods (i.e. Kenney&Lau [1985, 1986], Sherard&Dunnigan [1989], USACE [1953] and Burenkova [1993]) derived by others, in the field of internal stability and internal erosion assessment, were applied to the inventoried gradation curves of the core and the protective filter of the embankment dams. It revealed that attempting to single out the dams with internal erosion (the 1-dams) from dams without were more or less unsuccessful using the selected methods by others mentioned above.

But as can be interpreted from Fig. 4, the Kenney&Lau [1985, 1986] method, which is a method for assessing internal stability in materials, prove to be comparably more accurate than the other methods tested. 80 % of the “1-dams” (dams with probable occurrence of internal erosion) are tested having an unstable core and unstable filter. The extremes of the categories, i.e. 1 and 3-dams, are effectively separated as only approximately 12 % of the 3-dams have an unstable core and filter.

Generally due to less strict requirements at the time of construction, and uncertainties in the guidelines (the build-out of embankment dams in Sweden peaked in the 1970:s), the majority of Swedish dams have protective filters too coarse to meet today’s standards. For instance out of the 45 randomly picked dams in this study approximately 70 % have filters with D15 coarser than today’s guideline of 0.7 mm (filter criteria according to Sherard&Dunnigan [1989], soil group 2 base soil). In another inventory made on Swedish embankment dams (Norstedt&Nilsson [1997]), comprising of 44 existing Swedish embankment dams, the share amounts to more than 64 %. The number of dams that actually developed internal erosion (confirmed cases) is not in relation to the amount not meeting today's filter requirements. This is probably due to that current filter criteria are design-oriented with built in factors of safety, and thereby less effective from analysis standpoint. Hence, no clear pattern can be seen in this case as to a dam is prone to develop surfacing internal erosion or not, solely from the basis of current filter criteria.

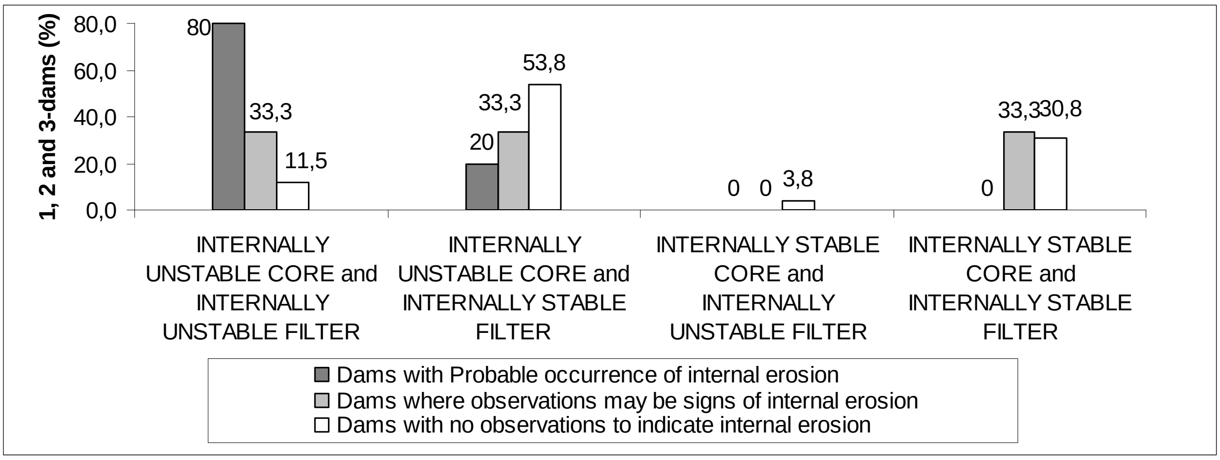

Fig. 4: Internal stability distribution of dams in categories 1-3
applying Kenney&Lau (1985, 1986).

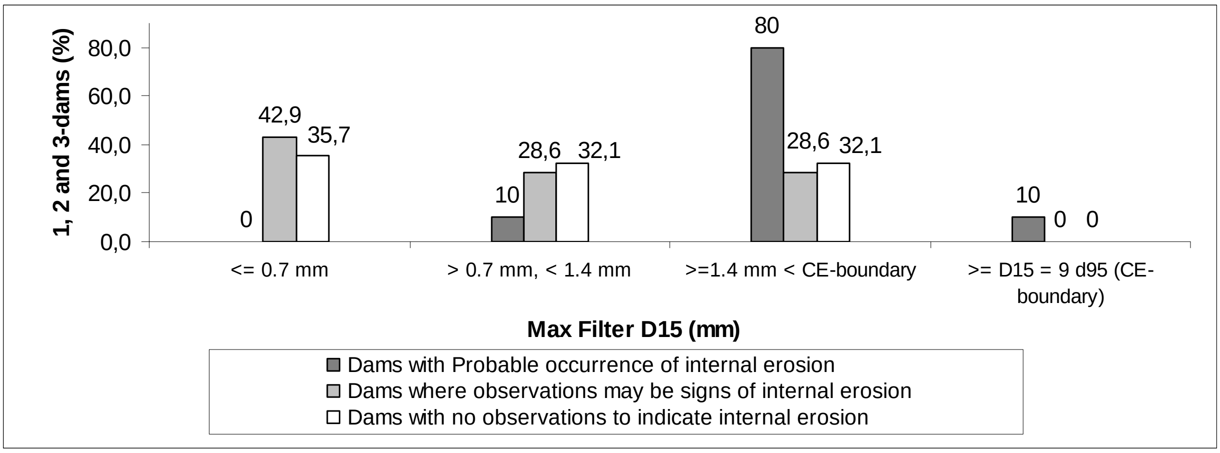

Fig. 5: Max filter D15 distribution of dams in categories 1-3.

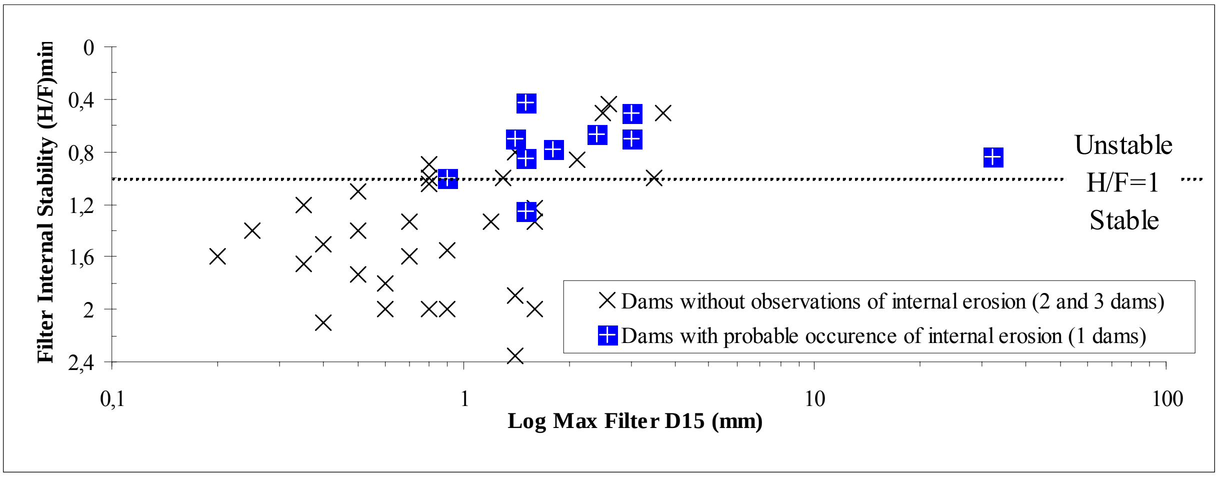

Fig. 6: Max filter D15 and filter internal stability distribution of dams in categories 1-3.

As seen in Fig. 5 if the distribution of the max filter D15 is plotted in terms of categories 1 to 3-dams (definition described above), it indicates that a more discriminating filter boundary can be suggested for analysis purposes, namely D15 ≥ 1.4 mm. This limit is adjusted in regards to dams in the study, and provides a more discernible boundary between 1 and 3-dams compared to current filter criteria; since 80 % of the 1-dams (probable occurrence of internal erosion) have a filter D15 coarser or equal to 1.4 mm, as oppose to about 30 % of the dams without internal erosion (3-dams). The CE-boundary in Fig. 5, i.e. D15 = 9xd95, is the Continuing Erosion boundary from Foster&Fell [2001].

Combining filter internal stability (according to the method by Kenney&Lau [1985, 1986]) with filter D15 a distribution comes up as plotted in Fig. 6. When the filter internal stability is plotted against the filter coarseness (here in the shape of max D15) a possible correlation appears, that indicates that the coarser D15 of the filter, the more likely the filter is unstable. Furthermore, from Fig. 6, it appears that as the filter is getting increasingly coarser and passing the boundary into internal instability, the more likely the dam is a 1-dam (i.e. dam with probable occurrence of internal erosion). This indicates that terms like internal instability and filter coarseness can be combined in order to efficiently make it possible to identify 1-dams from 3-dams.

4 FILTER PERFORMANCE – RESULTS AND EVALUATION

The Foster&Fell [2001] filter testing method for existing dams makes it possible to assess the filter performance of existing embankment dams with regards to the no, excessive and continuing erosion boundaries in case of a concentrated leak. Foster&Fell [2001] introduced a link between the filter D15 and the percentage of fine-medium sand in the core material to define the large erosion boundary, suggesting that for "Group 2A base soils"; the lower the degree of fine-medium sand in the core and the higher filter D15, the more likely with large erosion. Three categories for filter performance in existing dams are suggested in Foster&Fell [2001]; namely seal with No erosion, seal with Some erosion and partial or no seal with Large erosion.

By applying the Foster&Fell [2001] method on the 45 existing Swedish glacial moraine core embankment dams comprising the study and comparing the result to the dams "history of internal erosion" the following distribution comes up, see Fig. 7. Dams with probable occurrence of internal erosion (1-dams) are dams where the Foster&Fell [2001] method says erosion is possible (some or large) under a concentrated leak. Furthermore, none of the dams with probable occurrence of internal erosion (1-dams) is highly likely to seal with no erosion in case of a leak, which corresponds well to the dams in the study. 90 % of the dams with probable occurrence of internal erosion (1-dams) are assessed as being likely to highly likely with large erosion in case of a leak, which relates quite well with the operative history of internal erosion, see Fig. 7.

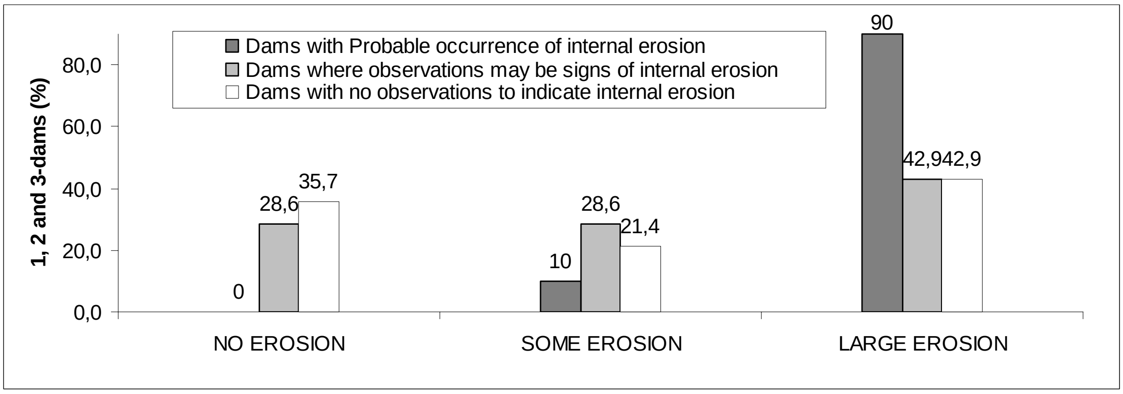

Fig. 7: Likely filter performance using the Foster&Fell [2001] method.

On the other hand over 40 % of the dams with no observations of internal erosion (3-dams) are placed in the "Large erosion" category also, which can suggest that the method is on the conservative side. Only about 1 dam out of 4 with no observations of internal erosion (3-dams) falls under the "no erosion" boundary, which suggests that there could be an over-prediction of likelihood for internal erosion. As with the other methods by others applied on the dams in this study (Kenney&Lau [1985, 1986], Sherard&Dunnigan [1989], USACE [1953] and Burenkova [1993], in detail described in Rönnqvist [2006]), the method by Foster&Fell [2001] by itself is also unable to clearly distinguish between dams with internal erosion (1-dams) from dams without (2 and 3-dams).

Combining the method by Foster&Fell [2001] with Kenney&Lau [1985, 1986], similar to what was done in Fig. 6, a distribution according to Table 1 comes up, which results in an improved distinguishing between 1 and 3-dams. For instance: 80 % of the dams with probable occurrence of internal erosion (1-dams) have unstable cores and unstable filters and are likely with large erosion in case of a concentrated leak, only 11 % of the dams no observations to indicate internal erosion (3-dams) acquire the same results. The “high, neutral and low potential” mentioned in Table 1 refers to Fig. 8 and Fig. 9 and related discussions.

Table 1. Distribution of dams with internal erosion (1-dams) and dams without internal erosion (2 and 3-dams) when combining Kenney&Lau [1985, 1986] and Foster&Fell [2001].

	Kenney & Lau [1985, 86]		Foster & Fell [2001]
Unstable core Unstable filter	Unstable core+Stable filter or Stable core+Unstable filter	Stable core Stable filter	
HIGH 80 % 1	10 % 1	0 % 1	SOME/LARGE EROSION Equally likely
POTENT 16,7 % 2	33 % 2	0 % 2	
IAL 11 % 3	19 % 3	11 % 3	
-	10 % 1	0 % 1	NO/SOME EROSION Equally likely
	NEUTRAL 0 % 2	16,7 % 2	
	11 % 3	11 % 3	
-	0 % 1	LOW 0 % 1	NO EROSION Highly likely
	17 % 2	POTEN 16,7 % 2	
	26 % 3	TIAL 11 % 3	

5 PROPOSED METHOD FOR ASSESSING POTENTIAL FOR INTERNAL EROSION IN MORAINE CORE DAMS

By putting the filter internal stability (in the shape of the H/Fmin from Kenney&Lau [1985, 1986]) against the filter coarseness (log of max filter D15) a spread of dams is obtained, see Fig. 8. The filters at the interface to a core assessed as unstable are indicated on the plot in Fig. 8 with a circle. The boundaries proposed in the methods by others are also plotted; such as the boundary between internally stable and unstable material (Kenney&Lau [1985, 1986] shape curve ratio H/F = 1) and the Sherard&Dunnigan [1989] filter criteria and later on adopted no erosion boundary in Foster&Fell [2001] D15 ≤ 0.7 mm (soil group 2 base soils, 40-85 % finer than No. 200 0.075 mm). Furthermore the proposed filter boundary, adapted from the dams in this study, of D15 = 1.4 mm is also included.

As can be interpreted from the plot; most dams without internal erosion (2 and 3-dams) have an internally stable filter and a filter D15 finer than 1.4 mm. Their counterpart; dams with internal erosion (1-dams) generally have an unstable filter and a filter D15 coarser or equal to 1.4 mm. The core is unstable in most cases, but most distinct in the case of dams with internal erosion (1-dams). From this it is reasonable to suggest that the potential for surfacing internal erosion is High for dams with a filter and core placing in the shaded area in the lower right corner (where the filter is coarser or equal to 1.4 mm and the filter and core are assessed as unstable) or at the far right where the filter’s D15 exceeds the CE-boundary, D15>9xd95 (Foster&Fell [2001]), as indicated in Fig. 8. Furthermore it is reasonable to suggest that the potential is Low for dams in the upper left corner box in Fig. 8 (where the filter is finer grained than the “no erosion boundary” of 0.7 mm and the filters and cores are evaluated as being internally stable).

This suggests that *surfacing* internal erosion (i.e. internal erosion process in the continuing phase) when it comes to embankment dams composed of moraine cores, is dependent not only on filter coarseness at this stage, but also on internal stability in the core and filter. This is relevant for dams with filters with “somewhat” too coarse filters. However, it has been recognized that at some “tipping point” of the filter coarseness High potential for surfacing internal erosion must be reached regardless the internal stability. Logically, at some "critical coarseness" of the filter, a sufficiently coarse filter would, independently of the internal stability, or instability, of the core or the filter, wash out the core enough to create sinkholes.

In Foster&Fell [1999, 2001] a "continuing erosion" boundary is suggested, i.e. DF15>9DB95, when exceeded a filter is too coarse to allow the eroded core particles to seal the filter. Foster&Fell [2001] confirmed that the filter D15 size is an appropriate indicator for the opening size of a filter (based on D15/9 as first concluded by Sherard et al. [1984a]). In regards to the dams in this study that would result in a CE-boundary varying approximately between 6<DF15<30 mm depending on the dam. The majority of dams in the study, at least according to the gradation curves from the dam records, do not reach the CE-boundary; the maximum filter D15 for most of the dams in the study vary around 1.0-1.5 mm with only a few dams peaking at 3.5-3.7mm (Rönnqvist [2006]).

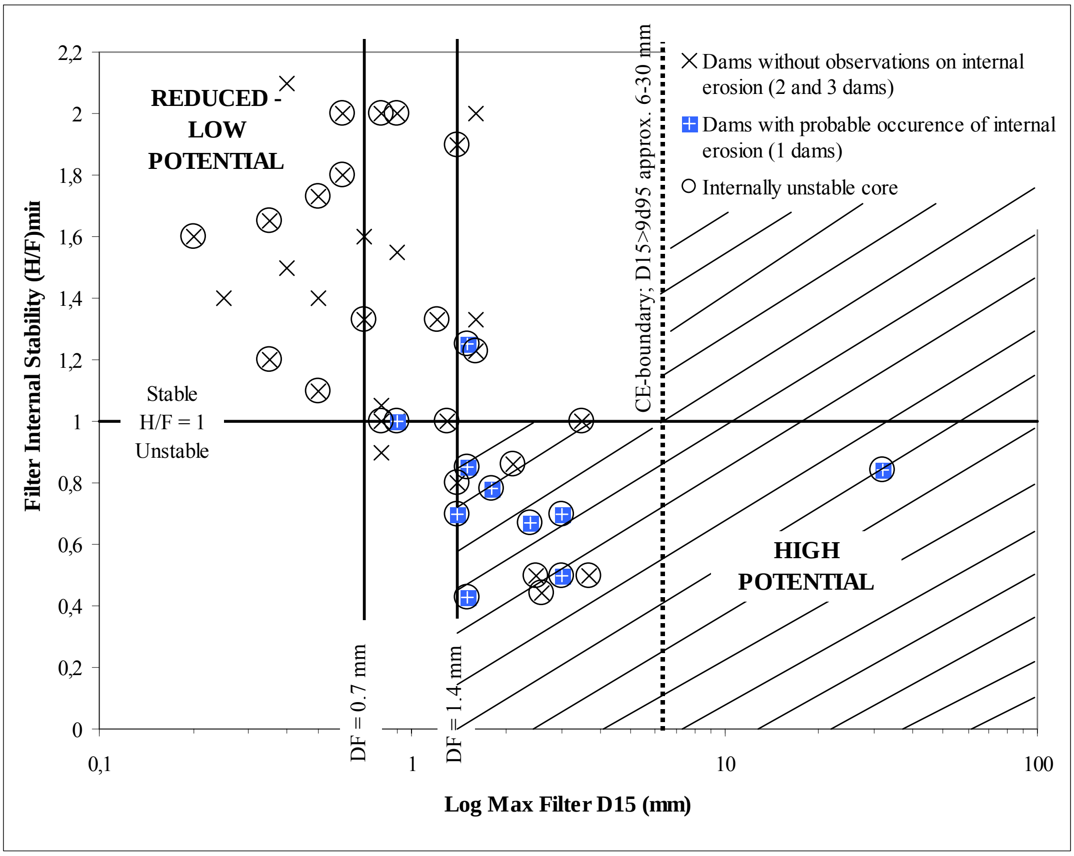

Fig. 8: Filter internal stability plotted against maximum filter D15 (log).

Clearly one dam, in the group of dams incorporated in the study, deviates quite significantly. This is a glacial moraine core embankment dam having a filter of tunnel spoil with D15 of 32 mm. At this particular dam leakage with dirty water occurred almost immediately after first filling (compare with Fig. 3) and subsequent investigations revealed that it had been due to internal erosion of the core. The dam's filter exceeds the Foster&Fell [1999, 2001] CE-boundary and seeing the immediate progress of internal erosion occurring in the dam it confirms the relevancy of the CE-boundary. So in order to present an upper boundary up to which the core and filter internal stability is still relevant, and a lower boundary beyond which only the filter coarseness is governing (regardless if the filter and core are stable or not), the Foster&Fell [2001] CE-boundary should be regarded.

The study shows that in order to be able to differentiate between dams with internal erosion (1-dams) and dams without (2 and 3-dams) it is necessary to include the properties of both the filter as well as the core into the assessment, assuming that the internal erosion process initiates from basically suffusion (internal instability) and backward erosion. In regards to the conceptual event tree in Fig. 9 three basic questions needs to be raised while assessing potential for surfacing internal erosion:

1. is the core internally stable or are there loose fines in the core that can migrate?
2. is the filter fine-grained enough to stop migration of the core fines at the interface?
3. is the filter internally unstable permitting fine particles in the filter to move in case the seepage velocity is sufficiently high?

Seeing that it is not uncommon with a considerable "fine tail" even in the *filters* of some Swedish embankment dams (some of the dams in the study has fines content (material finer than 0.075 mm) in the filter up to 20-30 % (Rönnqvist [2006])) it is plausible to suggest that the filter itself can experience internal erosion, taken that the seepage velocity is high enough. Foster&Fell [2001] indicate that particle sizes up to fine sand fraction (<0.2 mm) can be readily transported in concentrated leaks, and if the concentrated leak increases in size particles up to about 5 mm would also be transported. So with this in mind, assuming that the seepage velocity increases due to internal erosion (causing a property change in the core) the filter's internal stability can come into play. The third question can therefore be raised regarding "continuation" (see Fig. 9).

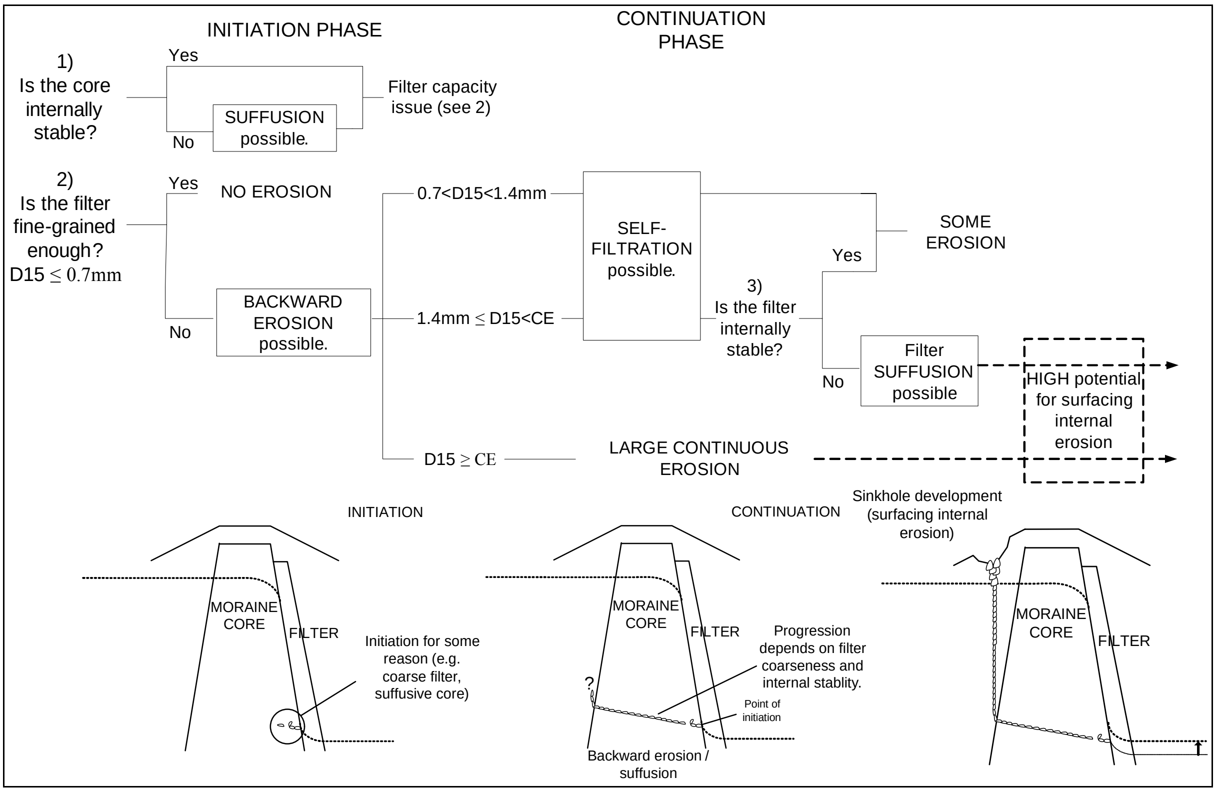

Fig. 9: Conceptual event tree showing suffusion and backward erosion processes leading up to High potential for surfacing internal erosion. Notation according to Foster&Fell [2001] "no, some and large erosion", and "initiation and continuation".

Based on the research results where methods by others are applied on existing dams with moraine cores, visualized in Fig. 8, a method is proposed in Table 2 in which internal erosion is approached from the core/filter interaction. The method addresses the potential for surfacing internal erosion in moraine core embankment dams with levels from High, Increased or Neutral if the filter D15 ≥ 1.4mm. High potential as indicated in Fig. 8 as the shaded area. With finer grained filter the potential ranges from Neutral, Reduced to Low. The potential for surfacing internal erosion is closer detailed depending on the internal stability of the core and filter. The basic internal erosion scenario, that can be suggested from the result of the assessment of the dams in this study, is schematically being outlined in the event tree in Fig. 9 which shows the possible chain of events leading up to "high potential for surfacing internal erosion" in glacial moraine core embankment dams.

The method (see Table 2) indicates that an unstable filter appears necessary for "High potential for surfacing internal erosion". The underlying logic to the relevancy of filter instability for potential for surfacing internal erosion, is that if the seepage velocity gets sufficiently high at the core/filter interface the filter, if unstable, starts losing fines progressively perhaps to the point that it is closing in on some “critical coarseness”, i.e. approaching the CE-boundary of Foster&Fell [1999, 2001]. This paper explains moreover how Foster&Fell [2001] filter performance with “no, some and large erosion” correlates to Kenney&Lau [1985, 1986] (see Table 1) and how this converts to the proposed method (when based on the 45 existing Swedish embankment dams with broadly graded glacial moraine cores). By taking the “no, some and large erosion” boundaries into account the suggested “potential for surfacing internal erosion” can be substantiated with the filter performance, see Fig. 9.

Table 2. Potential for surfacing internal erosion in glacial moraine core embankment dams. Proposed method that combines Kenney&Lau [1985, 1986], Sherard&Dunnigan [1989], Foster&Fell [1999, 2001] and filter D15.

	Kenney & Lau (1) [1985, 1986]		
Max Filter D15 (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

Notes:

[1] Internally unstable if (H/F)min<1, internally stable if (H/F)min≥1.

[2] Always High potential if DF15 > 9 DB95 regardless internal stability. Foster&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).

6 CONCLUSIONS

When dealing with surfacing internal erosion in moraine core embankment dams, not only the filter coarseness should be addressed, but also the internal stability of the filter and core material. Analyzing these properties combined, i.e. filter coarseness and core/filter stability, enhances the accuracy in finding dams prone to develop surfacing internal erosion; dams that previously were, from an internal erosion perspective, more or less analytically undetectable.

The overall objective of the proposed method in Table 2 is to offer means for assessing glacial moraine core embankment dams on their potential for developing surfacing internal erosion. Experience of Swedish dams shows that from a dam safety point of view there is often a need to improve the resistance in existing embankment dams against internal erosion (Nilsson&Rönnqvist [2004]), and the proposed method can provide a possible screening tool that can assist in tracing dams especially prone to develop internal erosion. A screening tool can prove especially useful when prioritizing among dams is necessary for remedial efforts. The method in Table 2 is still a work in progress, but is when final intended for analysis purposes and provides only a qualitative indication on the potential for sinkhole development. It is necessary to point out that when it comes to the design of protective filters to moraine cores this paper does not recommend to relax from the generally accepted design criteria (such as in Sherard&Dunnigan [1989]), but quite the opposite to promote these in order to get reliable filters that operates effectively in the event of an initiated internal erosion process.

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