Possible indicators of internal erosion prone dams comprising broadly graded materials

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SYNOPSIS. Embankment dams comprising broadly graded materials of glacial origin in the impervious core (base soil) and protective filter have in the past been identified as being prone to develop sinkholes more frequent than dams composed of materials of other origin. Sinkholes on the crest of a dam are many times an indicator of internal erosion. An internal erosion process can initiate and continue to develop for many reasons, but mainly due to root causes coming from core/filter properties and interaction, possibly affected by the dam design and/or construction related reasons. More than 70 existing embankment dams are reviewed in this paper, predominately Swedish glacial moraine core dams, with objective to see if there are indicators in dams with performance history of internal erosion. The investigation shows that a coarsely graded filter, grading instability of the core and filter, and high susceptibility for filter segregation makes an over-represented combination for dams with performance history of internal erosion. Internal erosion of dams is an important concern from a dam safety and dam engineering perspective.

INTRODUCTION

It was early on recognized that dams constructed from broadly graded filling materials of glacial origin, exhibited signs of internal erosion such as sinkholes to a larger extent than dams comprising other types of materials. Numerous internal erosion incidents in the 1960s and 1970s with piping occurred in dams surprisingly similar in design (Sherard (1979), Vestad (1976), Lafleur *et al.* (1989) and Ripley (1986)); i.e. thin core rockfill dams with core materials of broadly graded materials (often glacial) and widely graded filters. This is confirmed in Foster *et al.* (2000) by statistical analysis that the great majority of cases of piping accidents to central core earth and rockfill dams involves dams with broadly graded core materials of glacial origin with piping into coarse segregated filters.

In a survey carried out on Swedish moraine (till) core dams by Nilsson *et al.* (1999) a total of 84 rock- and earthfill embankment, with objective to

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investigate the ageing and deterioration processes, showed that a considerable amount of the dams (20 %) reported to have experienced some kind of internal erosion either in the dam's body or its foundation. This is also discussed in Norstedt & Nilsson (1997).

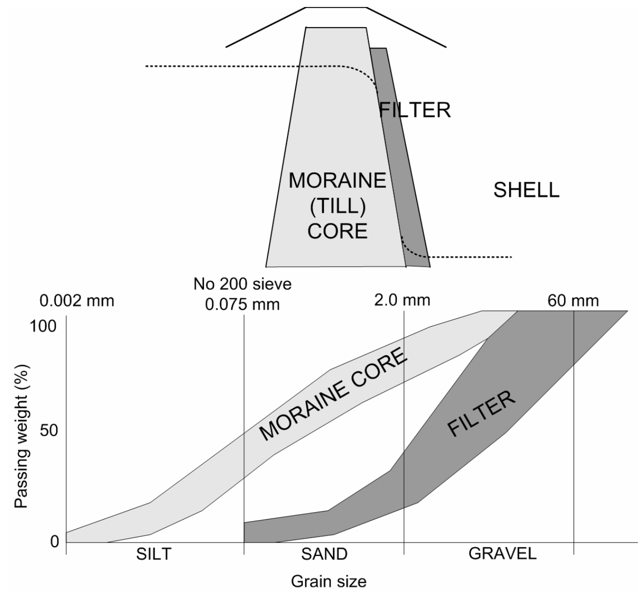

Figure 1. Typical cross-section of moraine core dams and typical sieve curves of widely graded material of glacial origin.

Sinkholes can often be attributed to internal erosion in the dam body or its foundation and can serve as a late indicator of internal erosion if occurring on the dam crest or the upstream face. Other signs may be dirty water (turbidity) and unexpected increases in seepage downstream. 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 creating an unfiltered interface to the core the filter is intended to protect, 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).

Existing moraine (till) core dams are reviewed in this paper, predominately Swedish moraine core dams, with objective to statistically investigate whether embankment dams that have a performance history of internal erosion have features/properties that are over-represented, properties such as coarsely graded filters for instance. Such common denominators can be used as indicators and provide an idea of which dams that are prone to develop internal erosion. A dam with only one potential indicator may not necessarily affect the potential for internal erosion, but several combined will probably influence a dam's susceptibility for internal erosion and thus give a heads-up during dam safety assessments.

DATA SET OF EXISTING DAMS IN THE STUDY

To date there are 72 glacial moraine core embankment dams comprised in this study (53 % earthfill dams). In the data set of 72 dams there are 13 dams with confirmed internal erosion (whereof rockfill dams are somewhat over-represented with 62 %). 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 are cohesionless with generally low to nil clay content and classifies as Sherard & Dunnigan (1989) soil group 2 base soils (40-85 % finer than No. 200 sieve (0.075 mm) determined from base soils re-graded on the 4.75 mm sieve).

The dam data in this study has been collected by the author, as part of an ongoing review of Swedish moraine core dams, which was started in Rönnqvist (2006) and further developed in Rönnqvist (2007). Data from previous inventories of Swedish dams by Nilsson (1995) and Nilsson *et al.* (1999) has also been used where applicable. The data set is predominately comprised of Swedish dams, except for two dams; a Norwegian glacial moraine core dam with rockfill shoulders that experienced internal erosion (dam data from Vestad (1976)) and a Pennsylvanian dam (US) with materials of glacial origin that suffered extensive sinkhole development at first filling of the reservoir (dam data from Talbot (1991)).

The typical Swedish embankment dam is a central and vertically placed core composed of a broadly graded glacial moraine (till), protected by filters of sand and gravel (in many cases also widely graded) and shell material comprising rockfill or earthfill, see examples of gradation curves in Fig. 1. The glacial moraine (till) in Sweden, and northern Scandinavia, was formed sub-glacially under conditions of hard crystalline bedrock giving it negligible clay content and up to around 40 % fines content (<0.075 mm). Glacial soils depend to an extent of the mother-rock from which it is formed, e.g. British tills with relatively high clay content (up to 25 %) and also Canadian tills in the Western Prairie provinces with high plasticity fines (Milligan (2003), this due to the formation in softer sedimentary bedrock conditions. Tills in eastern Canada are formed in conditions of igneous and metamorphic bedrock giving the till fines with non-plastic characteristics

(Milligan (2003)), which are conditions resembling to that of Scandinavian moraines (tills).

The dams have been categorized in regards of occurrence of internal erosion, in three proposed categories; namely 1-dams, 2-dams and 3-dams, with qualitative 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.

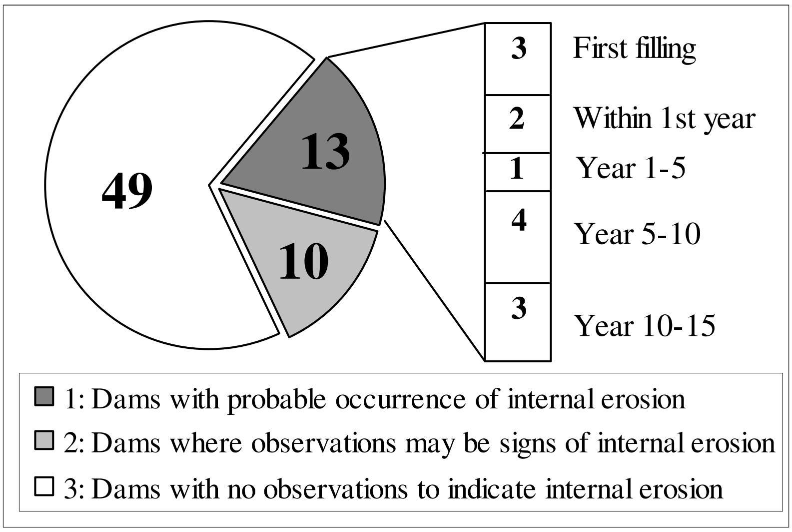

Figure 2. Number of dams and elapsed time until first internal erosion sign.

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.

There are 13 dams that qualify as "1-dams" (with probable occurrence of internal erosion), see Fig. 2, out of these there are 3 embankment dams where the internal erosion (in the shape of sinkholes and turbidity) surfaced almost immediately after the first raising of the reservoir. But as can be interpreted from Fig. 2 the majority of the "1-dams" experienced signs of internal erosion as long as 5-15 years after the dam's commissioning. Similar findings in Norway where internal erosion have surfaced not only during initial filling of the reservoir, but also first several years after (Höeg (2001)). This is somewhat contrary to the findings of Sherard (1979) that noted that sinkholes in dams with broadly graded materials usually appears in connection to the first filling of the reservoir.

FILTER GRADATION RELATED INDICATORS

The fundamentals of protective filter design is to design the filter's grain size curve so that the filter void openings are small enough to prevent and limit erosion from the base the filter is protecting. The generally accepted filter criteria nowadays in regards to filters for broadly graded base soils are based on the testing in the 1980s by the Soil Conservation Service (SCS) that amounted to the guidelines proposed in Sherard & Dunnigan (1989). A filter designed accordingly is usually expected to be "self-filtering", meaning that some base erosion needs to take place at the filter interface in order for gradually finer particles to be prevented from eroding into the filter. Prior to the SCS investigations the filter requirements were generally less strict and filter design criteria for broadly graded core materials were at the time of the bulk of hydropower dam build-out that occurred in the 1960s and 1970s (at least the Swedish peak construction period) somewhat uncertain. This resulted in many embankment dams constructed from broadly graded materials having filters too coarse to satisfy today's filter requirements.

Filter D15-distribution

The void opening size in filter is dependent on the filter's finer graded particles, and for design purposes the D15 (particle's size at 15 % passing weight) is usually used to describe this void size. Sherard *et al.* (1984a) showed that for granular soils the opening size is given by D15/9, confirmed in Foster (2001) by testing. The filter D15-distribution of in total 72 existing embankment dams is given in fig. 3. Filter D15 is plotted in relation to performance history of internal erosion (categories 1 to 3 where 1-dams being dams with probable occurrence of internal erosion). The "CE-boundary" in fig. 3 is the Foster & Fell (2001) continuing erosion boundary, i.e. DF15>9DB95, that when exceeded a filter is too coarse to allow the eroded core particles to seal the filter.

Dams with confirmed internal erosion (1-dams) generally have coarse filters, since more than 90 % of the 1-dams have filters with D15 coarser or equal to 1.4 mm. The filter D15 coarser or equal to 1.4 mm is one filter characteristic suggested in Rönnqvist (2007) for analysis of potential for internal erosion in moraine core dams. Almost 20 % of the dams apparently without internal erosion (3-dams) also have filter D15 coarser than 1.4 mm. Foster & Fell (2001) found that dams with poor filter performance generally have filters with an average D15 coarser than 1.0 mm as one of general characteristics of dams with poor filter performance. Filter coarseness by itself is not a clear-cut indicator of the potential for internal erosion but provides a pointer. None of the dams with internal erosion (in the data set) satisfy current filter criteria in relation to broadly graded base soils; Sherard & Dunnigan (1989) criterion filter D15 smaller or equal to 0.7 mm).

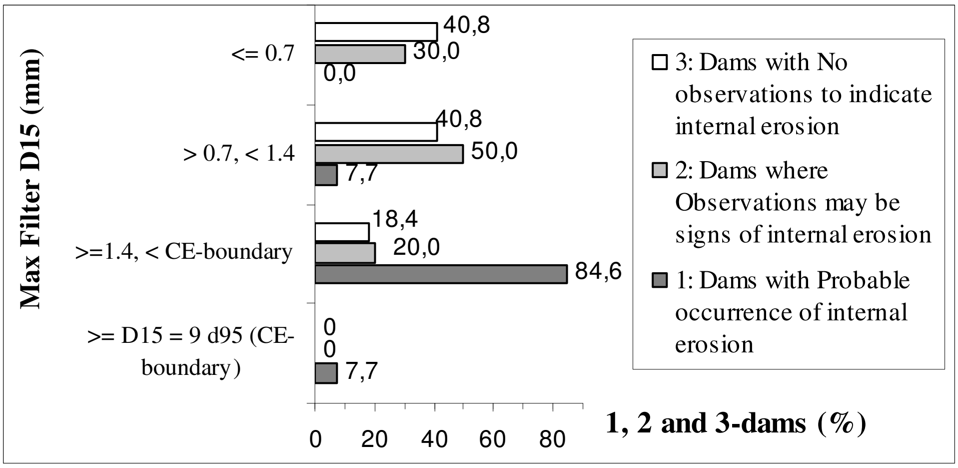

Figure 3. Filter D15-distribution in relation to performance history of internal erosion (dam categories 1-3).

Out of the 72 dams in the data set, 70 are Swedish embankment dams and approximately 68 % of these (regardless history of internal erosion) have filters that do not satisfy current filter criteria. But coarsely graded filters are not unique for Swedish dams, the situation is similar in Norway for instance; Höeg (2001) indicate that out of 122 Norwegian large rockfill dams with broadly graded moraine cores only few, if any, would satisfy today's strict filter criteria.

Filter grading instability

Grading stability can be assessed using the method by Kenney & Lau (1985, 1986). A soil having a smaller volume of fines in relation to volume of voids between coarser load-bearing particles can be suffusive/internally unstable, i.e. finer particles risk passing through the openings between the coarser particles by seepage flow. The boundary between internally stable and unstable material (Kenney & Lau (1985, 1986) shape curve ratio H/F = 1) is determined by the passing weight between particle size D and 4D. The interval of x4 being the size of the predominant constriction in a void network of a filter which is approximately equal to ¼ the size of the small particle making up the filter (Kenney *et al.* (1985)). A material is considered internally unstable if the Kenney & Lau (1985, 1986) H/F ratio is smaller than 1, meaning that the soil assessed as unstable has a grain size curve with inclination flatter than that of the "Fuller curve" (i.e. gradation curve for optimum density).

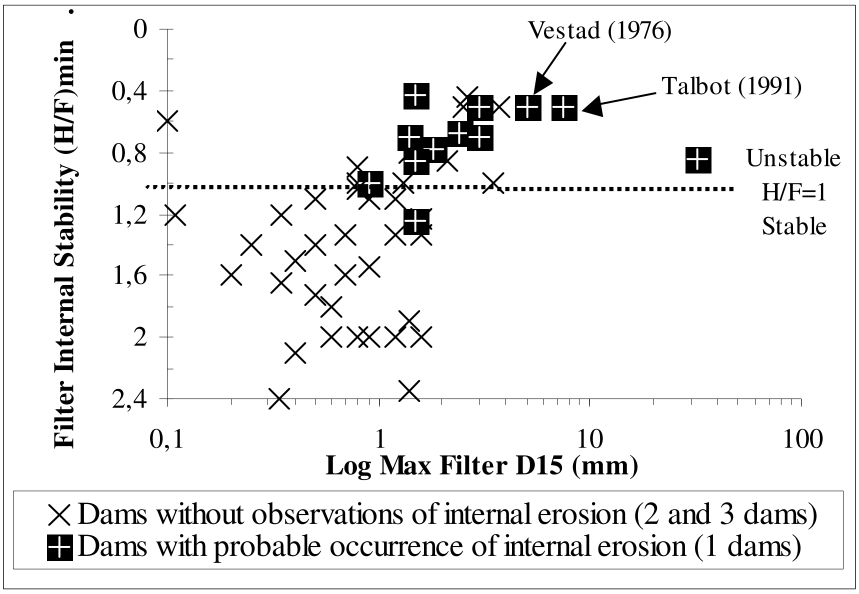

Figure 4. Filter D15 put against filter internal stability in relation to performance history of internal erosion (dam categories 1-3).

By cross-referencing filter instability (assessed according to the method by Kenney & Lau (1985, 1986)) and maximum filter D15 a plot as seen in fig. 4 is achieved. Internal stability against filter coarseness indicates that the coarser D15 of the filter, the more likely the filter is unstable. Furthermore, from Fig. 4, it appears that as the filter is getting 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). The data set in fig. 4 consist of 53 dams (the rest of the dams in fig. 2, 19 dams, have incomplete records). 90 % of dams with internal erosion (1-dams) have an internally unstable filter; 30 % of the dams without internal erosion (2 and 3-dams). The (H/F)min in fig. 4 is the minimum value of the ratio along the sieve curve within the Kenney & Lau (1985) evaluation range of 0-20 % passing weight (applies to widely graded material). In Kenney *et al.* (1985) it is furthermore suggested that for larger values of the coefficient of uniformity (Cu = d60/d10) of the filter the loss of base is increased. It is explained by saying the wider the gradation of the filter, the larger are the pores, and the larger is the amount of base that penetrates the filter before equilibrium.

In fig. 5 the filter Cu of the dams (set of 53 dams, the rest in fig. 2, 19 dams, have incomplete records) is put against the filter's D15 and no clear pattern can be seen regarding dams with internal erosion (1-dams). From fig. 5 it is clear that the majority of the filters are widely graded, with Cu generally exceeding 5-10.

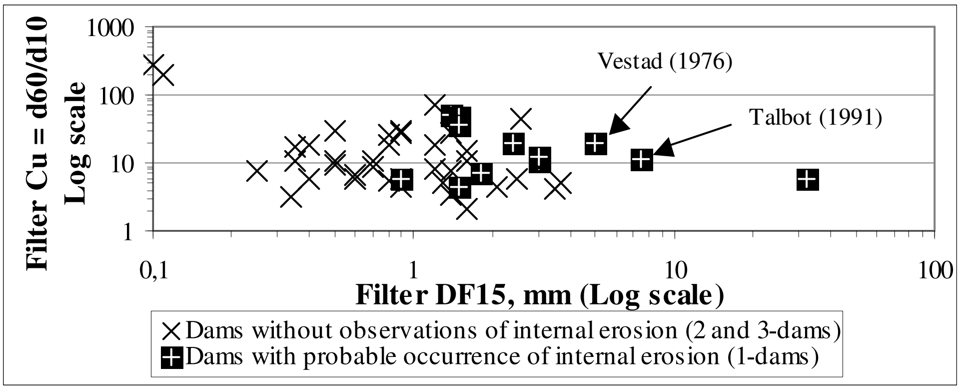

Figure 5. Filter D15 put against coefficient of uniformity (Cu) of the filter in relation to performance history of internal erosion (dam categories 1-3).

FILTER SEGREGATION RELATED INDICATORS

The significance of segregation in filters, especially concerning coarsely and widely graded filters, in relation to internal erosion is strongly emphasised in many references; e.g. Ripley (1986) and Sherard (1979). As pointed out by Milligan (2003) some segregation will probably occur when practicably placing most broadly graded materials, so in the processing, handling, placing, spreading or compaction of widely graded materials there is evidently a risk for segregation, and thus forming streaks or pockets of gravel-sized particles at the core/filter connection. The insufficient finer grained material in the voids can create grounds for an unfiltered interface to the impervious core. Noticeable filter (and core) segregation was observed while reconstructing the Swedish Juktan dam (Kjellberg *et al* (1985)), and also at the filterface of the Swedish Lövön dam (Ericsson&Jender (1998)).

In Ripley (1986), Sherard *et al.* (1984b) and Foster & Fell (2001) there is guidance on how to minimize the susceptibility for segregation in the practical handling of widely graded filter materials. These guidelines are plotted in fig. 6, i.e. Ripley (1986) suggested to limit the maximum particle size in the filter to 20 mm and at least 60 % finer than 4.75 mm in the filter, and Sherard *et al.* (1984b) suggested that the filter should be no coarser than 50 mm and at least 40 % finer than 4.75 mm. Foster & Fell (2001) found based on their research that if maximum particle size in filters are coarser than 75 mm it increases the likelihood for segregation. In fig. 6 the amount coarser than 4.75 mm in the filter is plotted against the filter's maximum particle (max. particle sieved to be correct).

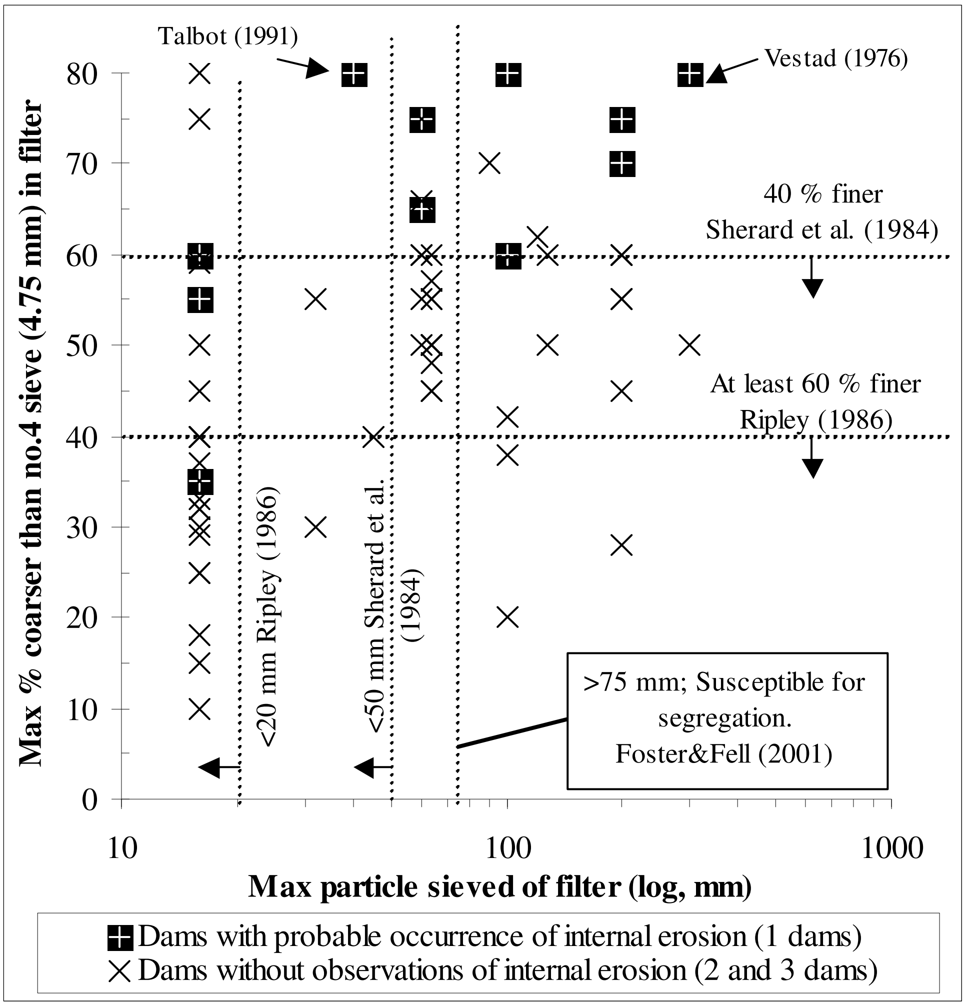

Figure 6. Percentage coarser than no. 4 sieve in filter put against maximum particle sieved in filter in relation to performance history of internal erosion.

There are 72 dams in the set. When using data sets from Nilsson (1995) and Nilsson *et al.* (1999) no complete grain size curves were available, only specific grain sizes (e.g. filter D15, filter D50 and maximum sieved particle). In these cases some degree of judgment were necessary in determining amount coarser than 4.75 mm. It is also important to point out that in the dam safety guidelines at the time of the hydropower build-out in Sweden (peaked in the 1960s and 1970s) no instructions were given regarding maximum particle size in filters nor obligation to document amount of material coarser than maximum sieved. That is why many dams in fig. 6 appears to have maximum particle size of not more than 16-20 mm, which is up to today's standard, but probably the maximum particle size is coarser than that and these values are therefore less reliable.

As can be seen in fig. 6 most filters in the dams are widely graded, having low amount of sand fraction and a large maximum particle size and these properties together increases the likelihood that the filter segregated during placing. Furthermore dams with internal erosion (1-dams) are over-represented in the upper right corner of the plot, where the filter's maximum particle is coarse (exceeding 100 mm) and the amount coarser than 4.75 mm is high (i.e. the sand fraction is lower than 40 % in the filter), which agrees with the research of Foster & Fell (2001) on characteristics of dams with poor filter performance.

CONSTRUCTION AND DESIGN RELATED INDICATORS

Guidelines and trends

Both Ripley (1986) and Foster *et al.* (2005) speaks of the increase in embankment dam undertakings in the 1960s and 1970s, and how this coincided with a period of less stringent construction requirements. During this period it appears that when it comes to dams with cores of broadly graded materials there was an over-reliance in the capacities of the glacial moraine (till) core as being self-filtering in itself, which resulted in the use of wide single filters (of wide gradation) instead of multiple filters and filter/transition components. This agrees with the review made on Swedish dams in Nilsson *et al.* (1999) where it was found that dams constructed around the 1970s were appears to be equipped with coarser graded filters than previously, presumably due to design factors with relaxed filter requirements and poor construction practices at the time.

Table 1. Number of rockfill dams with and without filter-transition component in relation to performance history of internal erosion.

With transition layer(s)	Without transition layer	
17 dams	9 dams	Without internal erosion (2 and 3-dams)
1 dam	7 dams	With internal erosion (1-dams)
18 dams	16 dams	

Filter-transition component

Filter-transition components, between the core's protective filter and the shell material, are generally necessary if filter and drainage functions are to be upheld between a moraine (till) core and the support fill, especially if the shell consists of rockfill. Based on the data set of 72 dams in this study, 34 are rockfill dams. 56 % (18 dams) of these rockfill dams are equipped with one or more transition layer(s) between the filter and the rockfill shell as shown table 1. Only 1 of 8 dams of the rockfill dams with internal erosion (1-dams) is equipped with transition layers, and conversely 44 % (or seven dams of 16) of the dams without transition layers are dams with internal erosion (1-dams), see table 1.

CONCLUSIONS

With objective to investigate possible indicators of internal erosion prone embankment dams of broadly graded soils a review is made in this paper comprising existing embankment dams constructed from broadly graded moraine (till) cores and generally widely graded filters. By back-analyzing performance history of internal erosion and comparing with sets of dams internal erosion free it is possible to suggest some common features of dams that experienced internal erosion (that surfaced in shape of sinkholes or other clear signs). The internal erosion prone dams can in this study statistically be traced back to the use of filters of coarse and unstable gradings with high susceptibility for filter segregation and in the case of rockfill dams there is usually a devoid of filter-transition components. Statistically, based on the data set of dam records of 72 dams in this study, the following core/filter properties have been shown to be over-represented among reviewed dams with a performance history of internal erosion:

- Coarsely graded filter (generally with max. D15 coarser or equal to 1.4 mm).
- Grading instability of the filter.
- Grading instability of the core (base) soil (Rönnqvist (2007)).
- High susceptibility for filter segregation.
- No filter-transition component (applies to rockfill dams).

These properties, when combined, can serve as indicators and give an idea of dams with potential for internal erosion. One factor by itself may not necessarily influence the potential for internal erosion, but an unfavorable combination of the above core/filter properties appears to increase the potential for internal erosion in embankment dams of broadly graded soils. Nevertheless it is important to point out that there can still be dams having the above-mentioned factors that operate without problems connected to internal erosion.

Best practice for protective filters for broadly graded moraine (till) core dams would be to provide the dam with:

- A uniformly graded sand-filter satisfying current filter criteria (e.g. Sherard & Dunnigan (1989) filter D15 finer or equal to 0.7 mm).

- A filter with internally stable grading. (Internal stability assessed by using the Kenney & Lau (1985, 1986) method).
- A filter with low to nil susceptibility to segregate. The guidelines for this are less clear, although Ripley (1986) suggested an upper limit of particle size of 18 mm and high amount of sand fraction (at least 60% finer than 4.75 mm).
- A cohesionless filter unable to sustain a crack. Although Ripley (1986) suggested a clean sand filter with preferably 0 % passing the no. 100 sieve (0.150 mm), but max. 2 % minus the no. 200 sieve (0.075 mm), the Vaughan & Soares (1982) "bucket test" can also be used to detect cohesion in filters.
- Sufficient filter-transition components to the shell material that the current filter criteria require.
- A filter that will not degrade or change in gradation with time (Fell *et al.* (2005)).

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