THE INTERNATIONAL JOURNAL ON HYDROPOWER & DAMS

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Volume Twenty Five, Issue 4, 2018

HYDRO AND DAMS IN NORTH AMERICA ~ CYBER SECURITY
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The performance of embankment dams with filters coarser than 'no-erosion' design criteria

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This paper summarizes case histories of 28 embankment dams which have experienced internal erosion and piping incidents. All the dams have filters or transition zones downstream of the core which were coarser than required by modern no-erosion design criteria, but the filters appear to have eventually sealed (arrested erosion) despite experiencing significant leakage flows. The performance of the dams is shown to relate to whether the filter or transition zone falls into the 'some erosion', 'excessive erosion' or 'continuing erosion' category. This includes leakage rates. These results can be used to assess existing dams which have filters or transitions which are coarser than no-erosion filters, and to assess the probability of the dam being able to experience the likely leakage without failing by slope instability or unravelling of the downstream slope, before the filter starts to seal.

Modern embankment dam filters are designed to control internal erosion in the dam and the foundation. The filters are designed to be no-erosion filters, sealing with no or very minor erosion. Many design methods have been based on the method developed by Sherard and Dunnigan [1989[1]] using extensive laboratory testing reported in Sherard *et al* [1984[2,3]]. Foster and Fell [2001[4]] used the original test data reported in these papers and additional laboratory tests to confirm the Sherard and Dunnigan [1989[1]] no-erosion design criteria, and suggest slightly modified criteria for dispersive soils. They also proposed criteria for what they defined as excessive and continuing erosion filters. Filters falling between 'no-erosion' and 'excessive erosion' criteria experience 'some erosion', and will seal with the potential for some damage and a minor to moderate increase in leakage before the filter seals. Those falling between 'excessive erosion' and 'continuing erosion' criteria experience 'excessive erosion' and seal with the potential for large erosion losses in the dam core, and a major increase in seepage before the filter seals. Filters coarser than continuing erosion will not seal.

Filter sealing in the context of this paper refers to the process of the eroded core particles being caught by a downstream filter zone, leading to the progressive formation of an accumulation of eroded particles (filter seal) at the core-filter interface [Sherard and Dunnigan, 1989[1]]. This paper summarizes case histories and relates their performance to whether the filter or transition zone falls into the some erosion, excessive erosion or continuing erosion category. This includes leakage rates. These results can be used to assess existing dams which have filters or transitions which are coarser than no-erosion filters, and to assess the probability of the dam experiencing the likely leakage without failing by slope instability or unravelling of the downstream slope before the filter seals.

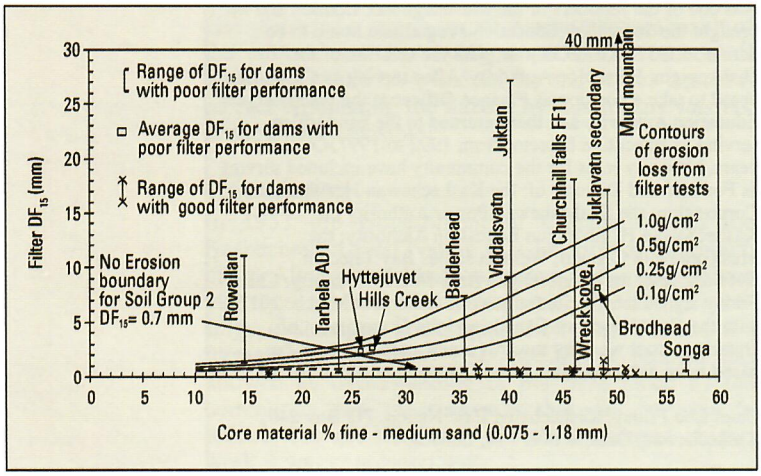


Fig. 1. Comparison of erosion losses measured in filter tests to dams with poor and good filter performance [Foster, 1999[14]; Foster and Fell, 1999[15], 2001[4]].

Method

The data have been gathered from published papers supplemented for some dams in Sweden, with project-specific information provided to the second author by dam owners. Some of that information is detailed in Rönnqvist [2015[5]]. Table 1 lists the dams, and the references used are available at:

www.RQV.se/FosterRqvFell2018/

All the dams have experienced internal erosion and piping incidents, so the capability of the filters has been tested.

Typically, these dams have central cores, and rockfill or gravel shell zones with a single-stage filter or transition zone between the core zone and outer shells. The gradation of the filter materials for these dams tends to be more widely graded than recommended by current design practices.

Table 2 summarizes the characteristics of the embankment core and the filter or transition downstream of the core. The gradations of these materials have been analysed to give no-erosion, excessive erosion, and continuing erosion filter sizes, using the Foster and Fell [2001[4]] criteria which are shown in Table 3 and Fig. 1. For the core, the gradings are re-graded on the 4.75 mm sieve, as the Foster and Fell [2001[4]] and Sherard and Dunnigan [1989[1]] methods require. For many of the soils, the range of core gradings after re-grading is not great, so this has not been considered. For others the range is shown.

The DF_{15} sizes of the filter materials, as obtained directly from published data, are shown in Column 6.

Also shown as bracketed values are the maximum DF_{15} sizes for those filter materials that are susceptible to suffusion [Kenney and Lau 1985[6] and 1986[7]; Douglas *et al*, 2017[8]]. Suffusion could render the filter somewhat coarser, and could increase the likelihood of the filter falling into the next class; for example, from 'some' to 'excessive' erosion. The likely maximum DF_{15} after suffusion was estimated by the authors, assuming the finer unstable fraction had been washed out of the filter materials. The authors made a judgement of what proportion of the finer fraction is susceptible to being washed out based on the test data in Douglas *et al* [2017[8]].

The published data includes cases where segregation was reported to have affected the published filter gradations, and hence no adjustments were made to the data for possible segregation effects.

In column 7 of Table 2 the 'Erosion class' is determined by comparing the filter size required for no erosion (NE), excessive erosion (EE), and continuing erosion (CE) to the actual filter gradings. The bracketed values are for the adjusted filter gradations allowing for suffusion.

Table 4 summarizes the observed leakage rates and the dams' potential self-healing characteristics. If readers would like to obtain further information on the observed evidence of internal erosion and the resulting damage to the core, the authors suggest consulting www.RQV.se/FosterRqvFell2018/ where the background to the compilation of case studies is available. Also shown at this link are the authors' interpretation of the likely internal erosion mechanism initiating erosion, which takes account of the opinions expressed in the technical papers from which the data is taken but in the context of more recent research as summarized in ICOLD [2017[9]] and Fell *et al* [2015[10]].

Discussion of the case history information

The following are some observations from the data:

- All the case histories experienced internal erosion incidents and piping, and had filters coarser than no-erosion filters, but the filters acted to arrest erosion.
- Some incidents occur on first filling, but many occur years into service. A number of dams have had multiple sinkholes/incidents.
- Many of the case histories showed evidence of self-healing behaviour (that is, leakage flows decreasing despite constant reservoir level), but returned to a metastable condition where further episodes of increased leakage re-occurred. It is not clear if this behaviour is associated with progressive filtering action, crack filling from upstream zones and/or collapse of erosion tunnels in the core. Possibly it is a combination of one, some or all of these actions. There is evidence for all these mechanisms occurring in the incidents.
- The ability to self-heal was for both non-plastic and plastic core materials. This is consistent with what is seen in laboratory tests.
- Even dams with filters just coarser than no-erosion have experienced internal erosion/incidents. Segregation may be a factor and not seen properly in the filter gradings.
- The mechanisms of initiation of internal erosion within the core include concentrated leak erosion, suffusion and global backward erosion. In the case histories, concentrated leak erosion often seems to be related to collapse settlement of core material compacted in thick layers forming a pathway through the core or facilitating low stresses and hydraulic fracture. In some cases this is related to arching of the core onto the filters which are stiffer than the core. Global backward erosion and suffusion are also more likely to occur in poorly compacted soil, because the void space will be larger, making it easier for the finer fraction to move within the soil. It is noted that the cores in the Juklavatn, Juktan, Porjus, and Viddalsvatn dams were compacted in 700 to 800 mm-thick layers, and the Hällby and Songa dams in 500 mm layers, which may mean the lower parts of each layer were not well compacted. Grundsjön dam core was initially placed in 400 mm lifts and compacted by six passes using 9.0 t rollers, but later increased to 750 mm and eight passes. Similarly, for Hällby dam, where a 300 mm initial lift was allowed to increase to 500 mm and using relatively light equipment of 3.5 t rollers. Bullileo dam was compacted to average 88 per cent standard maximum dry density (SMDD) with 20 per cent of tests achieving 80 per cent SMDD or lower. Mud Mountain dam was also reported to be not well compacted, particularly in the upper part of the dam. Other dams had well compacted core material so while poor compaction is a factor it is not a pre-requisite to initiation of internal erosion.
- For those dams where leakage rates were measured, these can be related to whether the filter or transition downstream of the core has some erosion or excessive erosion filters as the coarsest filter. This is discussed in the next section.

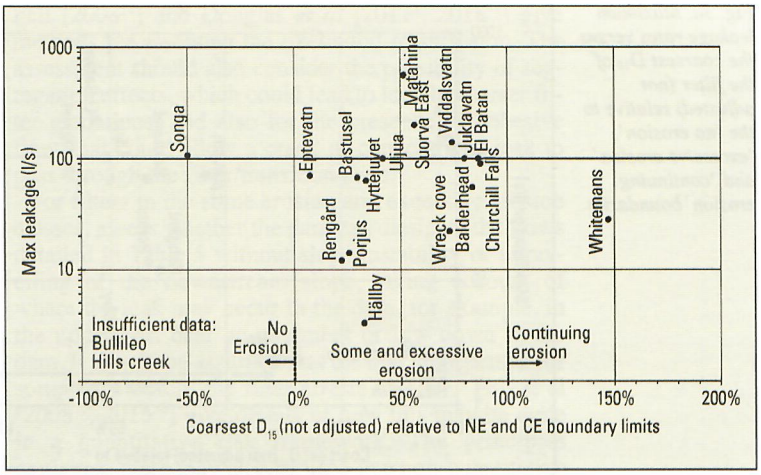


Fig. 2a. Maximum leakage rates versus the coarsest D_{15} of the filter relative to the 'no erosion', and 'continuing erosion' boundaries.

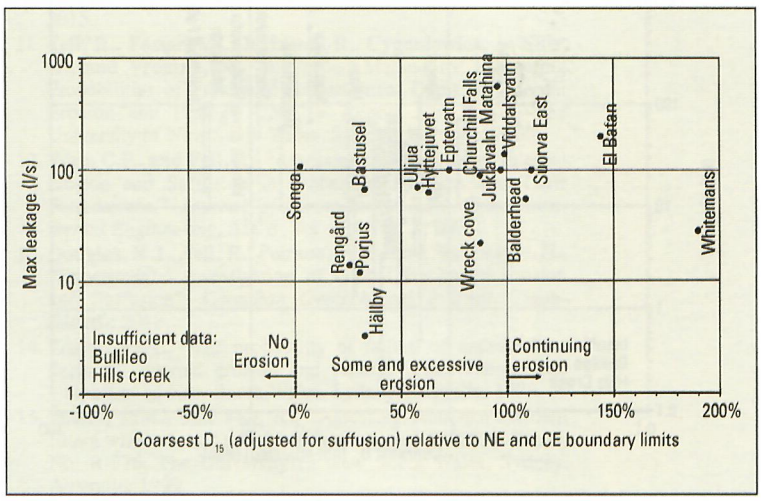


Fig. 2b. Maximum leakage rates versus the coarsest D_{15} of the filter relative to the 'no-erosion', and 'continuing erosion' boundaries with filter gradations allowing for suffusion.

Fig. 3a. Maximum leakage rates versus the coarsest D_{15} of the filter (not adjusted) relative to the 'no erosion', 'excessive erosion' and 'continuing erosion' boundaries.

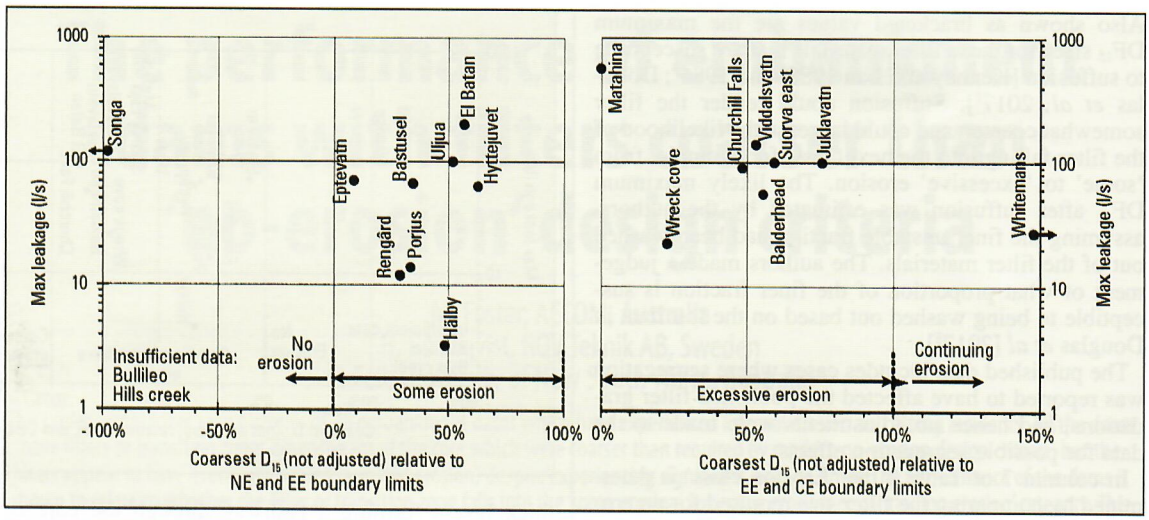


Fig. 3b. Maximum leakage rates versus the coarsest D_{15} of the filter (adjusted for suffusion) relative to the 'no-erosion, 'excessive erosion' and 'continuing erosion' boundaries.

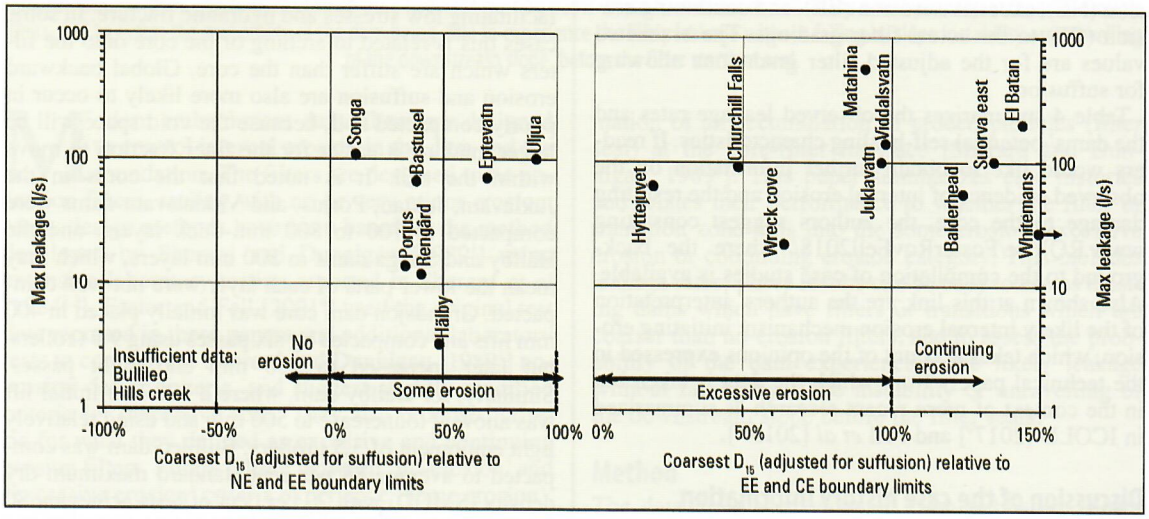
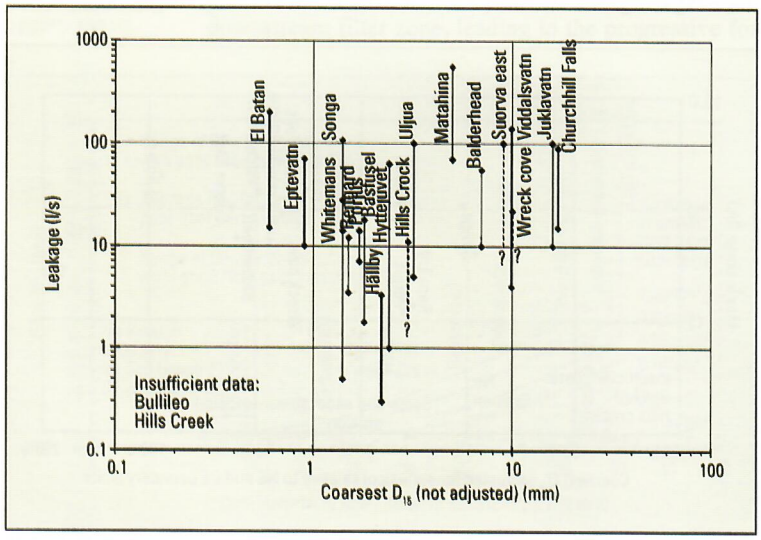


Fig. 4. Maximum and minimum lakage rates versus filter maximum D_{15} size.



• Songa dam apparently had no-erosion filters, but experienced leakage of up to 107 l/s indicating there must have been defects in the filters (such as resulting from segregation).

• Bullileo dam, which was probably in the continuing erosion range, experienced leakage of 8000 l/s. In this case, the transition zone contained cohesive fines (clayey gravel) and as such the concentrated leak probably passed through the transition zone and exited directly into the downstream rockfill zone. It survived this leakage without failure because of the high discharge capacity of the coarse downstream rockfill zone.

• Many dams (for example, Juklavatn Secondary, Viddalsvatn, Hyttejuvet, Suorva East and Balderhead, see Table 4) exhibited typical self-healing behaviour as the rapid rise in leakage flows subsequently returned to either normal seepage flows or to values much smaller than the peak flows as the filters started to seal. The reduction in flows were in some cases accompanied by the formation of one or more sinkholes, which suggests that self-filtering occurs by core erosion clogging, or collapse, and/or washing in of upstream filter.

Leakage rates experienced by the dams prior to the filters sealing

The maximum leakage for the some erosion cases ranged from 3 l/s to 70 l/s with three in the range 3 to 12 l/s and the other three 63 to 70 l/s. Excessive erosion maximum leakage ranged from 22 l/s to 560 l/s with six in the range 22 to 100 l/s and the other one 560 l/s.

Fig. 4 shows the range of observed leakage rates versus the filter maximum D_{15} size. There is a general trend to larger leakage with increasing D_{15}.

Figs. 2a and 3a show the maximum leakage rate observed compared with the gradation of the coarsest

filter related to the no-erosion, excessive erosion and continuing erosion size. For this the assessment is made without allowance for potential suffusion of the filter. This shows the general trend of larger leakage rates for filters which are coarsest in relation to the no-erosion filter criteria, with the largest leakage for filters close to the continuing erosion size for unadjusted gradings.

Figs. 2b and 3b shows the maximum leakage rate observed compared with the gradation of the coarsest filter related to the no-erosion, excessive erosion and continuing erosion size. For this, the assessment is made with allowance for potential suffusion of the filter.

When the filter gradings are adjusted for potential suffusion, the coarsest filter gradations for the Balderhead, Suorva East, El Baton and Whiteman's dams fall into the continuing erosion category, when in fact the filters did seal. This could be because only some of the filter gradations were in the continuing erosion category, and these controlled the erosion process, or because the hydraulic load was insufficient in driving the process to continuation. This could also be because of the washing-in of coarser particles from the upstream zones to aid in sealing the downstream filter. Washing-in of materials into the core defects was commonly evident in the case histories by the appearance of sinkholes above the upstream zones.

The authors postulate that the filtering action that occurs at the core-filter interface limits the flow that passes through the damaged core zone. The flow is limited by the lower permeability of the skin of eroded particles from the core that forms at the filter face. This is a similar action to that reported by Sherard and Dunnigan [1989[1]] and observed by the authors in laboratory filter tests. The resulting increase in water pressure at the downstream end of the concentrated leak reduces the hydraulic gradient along the flow path, such that erosion reduces or ceases. However, in the case of dams with filters coarser than no-erosion filters, the filtering action often leads to a meta-stable condition or partial seal such that erosion can re-occur as new pathways break out into the adjoining 'unsealed' portions of the core-filter interface.

From this information it is concluded that dams with filters in the some erosion and excessive erosion classes will seal, but will experience leaks before the filters arrest the internal erosion. The likely maximum leakage rates are as shown in Table 5. These are as was recommended in Fell *et al* [2008[11]] except the flow for excessive erosion is increased from 600 l/s to 1000 l/s to give some margin over the recorded leakages. It should be noted that as is evident from Figs. 2 and 3 these are the likely maximum values and smaller leaks may be more likely.

Application of this information

The authors believe that the evidence from the case histories consistently shows that filters in the some and excessive erosion range will seal and that the leakage flows before sealing occurs are limited, and in many dams can be accommodated without the dam breaching.

Therefore, for existing dams with filters or transitions downstream of the core, it is recommended that the filters be assessed to determine if they fall into the no-erosion, some erosion, excessive erosion or continuing erosion range using the Foster and Fell [2001[4]] method. This assessment should allow for potential suffusion of the filter resulting in it being coarser as detailed in Fell *et al* [2015[10]; 2008[11]] and ICOLD [2017[9]]. Wan and Fell [2008[12]] and Douglas *et al* [2017[8], 2018[13]] give methods for assessing the likelihood of suffusion. The assessment should also consider the possibility of segregation effects, which could lead to locally coarser filter gradations, and also for the presence of cohesive fines that could allow a crack or concentrated leak to pass through the filter/transition zone.

For filters in the some erosion and excessive erosion classes, assess whether the dam can dissipate the flows detailed in Table 5 without slope instability or unravelling of the downstream slope, taking account of where the leak may occur in the dam, for example, in the upper part near an abutment or low down in the dam. It should be assumed that the leak may persist for some days before the filter arrests erosion. Fell et al [2008[11], 2015[10]] give details of how this may be done in a quantitative risk framework. The principles explained there may also be used in a non-quantitative risk approach to dam safety management. ◊

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Dam details				References
Dam (Country)	Height (m)	Year completed	Zoning type	Full reference list at: www.RQV.se/FosterRqvFell2018
Åsele* (Sweden)	20	1981	Central core earth and rockfill	[Nilsson *et al.*, 1999; Rönnqvist, 2015]
Bastusel* (Sweden)	40	1972	Central core earth and rockfill	[Nilsson *et al.*, 1999; Rönnqvist, 2015]
Balderhead (UK)	48	1965	Central core earth and rockfill	[Vaughan *et al.*, 1970; Sherard, 1973; Vaughan and Soares, 1982]
Brodhead (USA)	27	1975	Homogeneous earthfill with blanket drain	[Talbot and Ralston, 1985; Talbot, 1991]
Bullileo (Chile)	70	1945	Zoned earth and rockfill	[Castro and Garces, 1985]
Churchill Falls FF-11 (Canada)	21	1972	Central core earth and rockfill	[Chadwick, 1979; Seemel and Colwell, 1976]
El Batan (Mexico)	45	1990	Central core earth and rockfill	[Flores-Berrones *et al.*, 2011]
Eptevatn (Norway)	30	1971	Central core earth and rockfill	[Ødemark and Nilsen, 2015]
Grundsjödammen (Sweden)	43	1972	Central core earth and rockfill	[Bartsch, 1995; Nilsson *et al*, 1999; Rönnqvist et al., 2015]
Hällby (Sweden)	25	1970	Central core earth and rockfill	[Bronner *et al.*, 1988; Rönnqvist, 2012]
Hills Creek (USA)	103	1961	Zoned earthfill	[Jenkins and Banksfier, 1972; Sherard, 1979]
Hyttejuvet (Norway)	93	1965	Central core earth and rockfill	[Kjaernsli and Torblaa, 1968; Wood *et al.*, 1976; Sherard, 1973]
Juklavatn Secondary (Norway)	22	1974	Central core earth and rockfill	[NGI, 1984; Hoff and Nilssen, 1985; Johansen and Eikevik, 1997]
Juktan Dams 1 and 3* (Sweden)	15	1977	Central core earth and rockfill	[Kjellberg *et al.*, 1985; Nilsson *et al.*, 1999; Rönnqvist, 2015]
Lövön (Sweden)	15	1973	Central core earth and rockfill	[Nilsson *et al.*, 1999; Ericsson and Jender, 1998]
Matahina (NZ)	86	1967	Central core earth and rockfill	[Gillon and Newton, 1991; Sherard, 1973; Gillon, 2007]
Mud Mountain (USA)	128	1953	Central core earth and rockfill	[Graybeal, 1988; Graybeal and Levallois, 1991; Eckerlin, 1992; 1993]
Näs* (Sweden)	18	1978	Central core earth and rockfill	[Nilsson *et al.*, 1999; Rönnqvist, 2015]
Porjus (Sweden)	22	1975	Central core earth and rockfill	[Johansson *et al.*, 1996; Nilsson *et al.*, 1999; Bartsch *et al.*, 2006; Bartsch, 2007]
Rengård (Sweden)	20	1970	Central core earth and rockfill	[Nilsson *et al.*, 1999; Rick and Wahlqvist, 2010]
Rowallan (Australia)	43	1967	Central core earth and rockfill	[Mitchell and Fitzpatrick, 1979; Hunter *et al.*, 2012; Hunter *et al.*, 2017; Hunter *et al.*, 2018]
Songa (Norway)	42	1962	Central core earth and rockfill	[Torblaa and Rikartsen, 1997]
Suorva East* (Sweden)	50	1972	Central core earth and rockfill	[Norstedt and Nilsson, 1997; Bronner *et al.*, 1988; Bartsch *et al.*, 2006; Nilsson, 2007; Rönnqvist, 2015]
Tarbela auxiliary dam 1 and main dam (Pakistan)	105 and 150	1974	Zoned earthfill	[Lowe III, 1982; Aslam Bhatti, 1994; Khan and Javaid, 1997]
Uljua* (Finland)	13	1970	Central core earth and rockfill	[Loukola and Slunga, 1982; Rathmayer and Pöllä, 1998; Rönnqvist, 2015]
Viddalsvatn (Norway)	80	1971	Central core earth and rockfill	[Vestad, 1976; Kjaernsli *et al.*, 1992]
Whiteman's (Canada)	24	1951	Zoned earthfill	[Courage et al., 199]
Wreck Cove D11-2 (Canada)	14	1978	Central core earth and rockfill	[Kenney *et al.*, 1980; Ripley, 1988; SNC, 1978]
*Additional project specific information provided to the second author by dam owners.				

Table 2: Characteristics of the dam core and filter/transition materials

Dam name	Core characteristics				Filter/transition characteristics				
	Finer than 75μm minus 4.75mm (%)	Finer than 4.75 mm (%)	Classification, Plasticity index (%)	Geological origin	DF_{15} (mm)	NE/EE/CE (mm) Erosion class	Finer than 4.75 mm (%)	Max. size (mm)	Geological origin
Åsele	22-54	90?	Gravel-sand-silt mixtures SM ML	Glacial moraine	0.15-0.9(a)	0.7/8/18 No, Some	65-94	>16	Glaciofluvial or fluvial
Bastusel	23-58	n/a	Gravel-sand-silt mixtures GM, SM-ML	Glacial moraine	0.3-1.8(a)	0.7/11/17 No, Some	43-92	>16	Glaciofluvial or fluvial
Balderhead	33-66 (40-70)	83-94	Gravelly sandy clay, CH PI 18	Glacial, boulder, clay	0.4-7 (avg. 1.2)	0.7/4/11 No, Some, Excessive	8-62	70	Crushed limestone
Brodhead	30 (40)	75	Silty gravelly sandy SM	Glacial moraine	6.5-8.2	0.7/7.5/2.7 Some, Excessive	5	38	Natural gravel?
Bulileo	22-54	n/a	Clayey gravel, GC-CL PI 10-17	Glacial moraine	Random fill, as for core, higher percentage of gravel, downstream rockfill became the filtering material			200	Glacial moraine
Churchill Falls FF-11	6-35 (14-41)	43-86	Silty gravelly sand SM	Glacial moraine	0.3-17	0.7/11/27 Some, Excessive	0-60	75	Crushed & screened sand gravel
El Batan	92 (92)	100	Clay CH LL 100-130 % PI 70-105	Residual basalt	0.6	0.2/1.4/1.4	50	38	Sand-gravel
Eptevatn	33-66 (40-70)	75	Gravel-sand-silt mixtures	Glacial moraine	0.3-0.9	0.7/12/21 No, Some	32-84	250	Natural sand gravel
Grundsjö-dammen	30 (40)	75	Gravel-sand-silt mixtures GM	Glacial moraine	0.4-3.5	0.7/4.5/25	19-73	>60	Glaciofluvial or fluvial
Hällby	16-48	70-93	Gravelly, silty sand SM	Glacial till	0.15-2.2	0.7/7.5/23 No, Some	27-86	>64	Glaciofluvial or fluvial
Hills Creek	20 (51)	19-39	Silt sandy gravel, GM	Alluvial	Avg. 2-3	0.7/?/? Some	19-39	>75	Alluvial and quarried rock
Hyttejuvet	35 (60)	58	Gravelly clayey sand, SC PI 6	Glacial moraine	0.3-2.4	0.7/5/27 No, Some	22	250	Natural sand gravel
Juklavatn Secondary	15-24 (24-39)	44-68	Silty sandy gravel, GM	Glacial moraine	0.3-16	2/3.2/27 Some, Excessive	8-34	160	Natural sand gravel
Juktan 1 and 3	12-17 (29-34)	42-50	Silty sandy gravel, GM	Glacial moraine	0.2-30	0.7/10/27 No, Some, Excessive, Continuing	0-64	>200	Tunnel spoil
Lövön	10-41	70-93	Gravelly silty sand, SM	Glacial moraine	0.25-3.5	0.7/9.5/22 No, Some	18-54	>100	Glaciofluvial or fluvial
Matahina	23-79 (44-80)	52-98	Gravelly clay, GC	Weathered sandstone	0.15-5	0.7/5-9/32 Some, Excessive	12-45	>200	Ripped ignimbrite
Mud Mountain	7-27 (22-28)	32-96	Silty gravelly sand, SM	Glacial till and natural sand, gravel	9-42	2.3/3.6/22 Excessive, Continuing	0-9	100	Crushed rock
Näs	28-45	63-84	Gravel-sand-silt mixtures GM, SM-ML	Glacial moraine	0.5-1.2	0.7/9/18 No, Some	74-94	>60	Glaciofluvial
Porjus	25-50	85-95	Gravelly silty sand, SM-ML	Glacial moraine	0.1-1.7	0.7/10/22 Some	55-99	300	Glaciofluvial or fluvial
Rengard	30-50	85-96	Silty gravelly sand, SM-ML	Glacial moraine	0.5-1.5	0.7/9.5/22 No, Some	28-45	200	Glaciofluvial or wave-washed alluvial
Rowallan	73-80 (80-81)	90-100	Sandy clay, CH (contact clay)	Residual clay (basaltic)	1.2-11	0.7/1/6.3 Excessive, Continuing	5-47	300	Fluvio-glacial
Songa	14-22 (23-31)	62-72	Silty gravelly sand GM, SM	Glacial moraine	0.3-1.4	3.6/6/28 No	30-45	300	Alluvial sand gravel
Suorva East	18-52 (34-54)	52-95	Gravel-sand-silt mixtures, GM, SM-ML	Glacial moraine	0.1-9	0.7/5/13.5 No, Some, Excessive	n/a	200	Glaciofluvial or fluvial
Tarbela aux. dam 1 and main dam	28-43 (60-69)	51-62	Silty sandy gravel, GM	Alluvial (blended)	Aux. 0.3-7 Main 0.5-15; 20-25 seg'd	0.7/2/36 Aux. Main: No, Some, Excessive Main Seg.: Excessive	15-50	>250	Alluvial?
Uljua	31-42	n/a	Gravel-sand-silt mixtures GM, SM-ML	Glacial moraine	0.1-3.2	0.7/13/27 No, Some	n/a	60	n/a
Viddalsvatn	19-27 (30-38)	62-71	Silty gravelly sand, SM-GM	Glacial moraine	0.6-9.9	0.7/3.5/25 No, Some, Excessive	13-32	250	Screened tunnel spoil
Whiteman's	82-95 (87-95)	94-100	Gravelly sandy clay, CL PI 6	Glacial till	0.035-1.4	0.1/0.2/0.6 Excessive, Continuing	28-57	50	Talus
Wreck Cove D11-2	9-32 (24-46)	51-72	Silty sandy gravel, GM-SM	Glacial till	0.5-10	0.7/7.5/27 No, Some, Excessive	12-44	100	Natural gravel, crushed rock

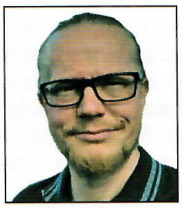
Table 3: Criteria for the excessive and continuing erosion boundaries [Foster, 1999[14]; Foster and Fell, 1999[15]; 2001]		
Base soil	Proposed criteria for excessive erosion boundary	Proposed criteria for continuing erosion boundary
Soils with $D_{95}B < 0.3$ mm	$D_{15}F > 9\ D_{95}B$	
Soils with $0.3 < D_{95}B < 2$ mm	$D_{15}F > 9\ D_{90}B$	For all soils: $D_{15}F > 9D_{95}B$
Soils with $D_{95}B > 2$ mm and fines content >35 %	Average $D_{15}F > D_{15}F$ which gives an erosion loss of 0.25 g/cm² in the CEF test (0.25 g/cm² contour line in Fig. 1) or Coarse limit $D_{15}F > D_{15}F$ which gives an erosion loss of 1.0 g/cm² in the CEF test (1.0 g/cm² contour line in Fig. 1)	
Soils with $D_{95}B > 2$ mm and fines content <15 %	$D_{15}F > 9\ D_{85}B$	
Soils with $D_{95}B > 2$ mm and fines content 15–35 %	$D_{15}F > 2.5\ D_{15}F$ design, where $D_{15}F$ design is given by: $D_{15}F$ design = (35-pp% 0.075 mm)$(4D_{85}B–0.7)/ 20 + 0.7$	
Note: Criteria are directly applicable to soils with DB95 up to 4.75 mm. For soils with coarser particles determine DB_{85} and DB_{95} using grading curves adjusted to give a maximum size of 4.75 mm		

Table 4: Internal erosion incident details		
Dam name	Observed leakage*	Leakage self-healing?
Åsele (1981)	Not known.	Yes
Bastusel (1972)	Range 18 l/s to 67 l/s.	Yes
Balderhead (1964)	Increases from 10 to 25 l/s on first filling, remained steady for 6 months, then increased erratically to 45 l/s and then to a maximum of 55 l/s over 4 months.	Partial
Brodhead (1975)	Incident not observed. Investigations showed flow into the blanket drain was from open joints in foundation.	Unknown
Bullileo (1945)	Seepage measured prior to incident ranged from 0 to 1000 l/s varying with reservoir level. Attributed to leakage through foundation. Maximum leakage during incident 8000 l/s.	Self limiting but not self healing?
Churchill Falls FF-11 (1972)	Muddy leak in 1972, flow increasing from 15 to 60 l/s. In 1973 muddy leak up to 90 l/s. Muddy leakages 1977.	Yes, self healing with bursts of leakage
El Batan (1990)	Muddy leak increased gradually to 50 l/s. Leakage noticed to have increased to 200 l/s one morning. Flows decreased to 15 l/s after the appearance of the sinkholes.	Yes, self-healing
Eptevatn (1971)	Normal, steady-state until 2014, significant increase in leakage when 10-20 l/s rose suddenly to about 70 l/s, which within a day reduced to 20 l/s while lowering the reservoir by 6-7 m.	Yes
Grundsjödammen (1972)	No details available.	Yes
Hällby (1970)	Leakage rose to 3.3 l/s, previously 0.3 l/s.	Yes
Hills Creek (1961)	Gradually increased to 11 l/s.	No
Hyttejuvet (1965)	First filling increase from 1-2 l/s to max. 63 l/s then decreased to 45 l/s. Leakage reduced on grouting core. In 1970 leakage increased suddenly to 20 l/s.	Yes
Juklavatn Secondary (1974)	Initially 12-15 l/s, increase to 100 l/s in 1982; 50 l/s in 1983; 40 to 60 l/s from 1984 to 1992 when dam core was grouted. Then 10 to 13 l/s.	Yes
Juktan Dams 1 and 3 (1977)	Leakage in 1979, 1980. Dam 3 had leakages in 1979, 1980, 1981, and 1982. Leakage rates not known.	Unknown
Lövön (1973)	No details available.	Unknown
Matahina (1967)	On first filling leakage increased rapidly from 70 to 560 l/s, then decreased to 250 l/s within 24 hours.	Yes
Mud Mountain (1953)	Gradually increasing and erratic pore pressures. No leakage rates available.	Unknown
Nas (1978)	Not known.	Yes
Porjus (1975)	No data for 1976 and 1979. For 1985, max. 12 l/s then reduced to 7 l/s. In 1993 seepage increased from 7 to 14 l/s then reduced to 6 l/s. Core was grouted in 1993 showed cavities 10 to 15 m below crest.	Yes
Rengard (1970)	Prior to first sinkhole in 1980 12 l/s that decreased to 3.5 l/s in a month after the sinkhole.	Yes
Rowallan (1967)	Leakage not observed.	Yes

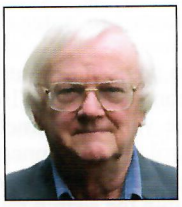
Table 4: Internal erosion incident details, cont'd		
Dam name	Observed leakage*	Leakage self-healing?
Songa (1962)	"Normal" leakage 1964 to 1991; right abutment 0.5-1 l/s; central 3-4 l/s; left abutment 0.7-1 l/s. Three leakage outbursts from 1976 to 1979. Another in 1991. No details on leak flows. In 1994 leakage increased from 1.24 to 107 l/s then reduced to normal in 6.3 hours.	Yes, self healing bursts of leakage
Suorva East (1972)	Max. 100 l/s reduced to 75 l/s prior to reservoir drawdown.	Yes
Tarbela aux. dam 1 and main dam (1974)	No details.	Yes
Uljua (1970)	Normal seepage 5 l/min. After 20 years of operation, turbidity was observed. Twp weeks after first observation of turbidity, a sinkhole formed on the upstream face and the leakage increased to 100 L/s.	Unknown
Viddalsvatn (1971)	Leakage increased suddenly from 4 to 50 l/s on 11 October 1972 during first filling. Returned to previous rate after 12 days. In mid-November leakage increased from 8 to 85 l/s within days; then decreased to 20 l/s. Bursts of leakage up 140 l/s followed. On second filling it reached 210 l/s.	Yes
Whiteman's	Max. 28 l/s up to 1995. No increase at time of sinkhole.	Unknown
Wreck Cove D11-2	Leak at 14 l/s on first filling increasing to 22 l/s over three days.	Unknown
*Further details on the background to the compilation of case studies are available at www.RQV.se/FosterRqvFell2018/).		

Table 5: Expected behaviour of filters related to the erosion class		
Erosion class	Likely behaviour	Increase in leakage flows from case histories
No erosion	Filter stops erosion with no or very little erosion of the material it is protecting.	Unlikely to be detectable
Some erosion	Filter initially allows erosion from the soil it is protecting, but it eventually seals up and stops erosion.	Up to 100 L/s
Excessive erosion	Filter allows erosion from the material it is protecting, but permits large increases in leakage flow, self-healing. Can form sinkholes on the crest and erosion tunnels through the core.	Up to 1000 L/s
Continuing erosion	Filter is too coarse to stop erosion and continuing erosion is permitted. Unlimited erosion and leakage flows are likely.	> 1000 L/s and increasing

M. Foster



H. Rönnqvist



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