THE PERFORMANCE OF EMBANKMENT DAMS WITH FILTERS COARSER THAN NO-EROSION DESIGN CRITERIA

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Table 1. Dam details and references for data.

DAM DETAILS				REFERENCES FOR DATA
Dam Name (Country)	Height (m)	Year Comp-leted	Zoning Type	
Åsele (a) (Sweden)	20	1981	Central core earth and rockfill	Nilsson et al (1999), Rönnqvist (2015)
Bastusel (a) (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. (a) (Sweden)	15	1977	Central core earth and rockfill	Kjellberg et al (1985), Nilsson et at (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 (a) (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 (a) (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 Aux. Dam 1. And Main Dam (Pakistan)	105 150	1974	Zoned earthfill	Lowe III (1982), Aslam Bhatti (1994), Khan and Javaid (1997),
Uljua (a) (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 (1997).
Wreck Cove D11-2 (Canada)	14	1978	Central core earth and rockfill	Kenney et al (1980), Ripley (1988), SNC 1978).

Note. (a) Additional project specific information provided to the second author by dam owners.

Table 4 Internal erosion incident details.

DAM NAME	OBSERVATIONS, DAMAGE AND LIKELY INITIATION MECHANISM	OBSERVED LEAKAGE	LEAKAGE SELF-HEALING?
Åsele (1981)	Muddy discharge and sinkholes 1988, 1992 Not known	Not known	Yes
Bastusel (1972)	Muddy seepage. Sinkholes in 1972, 1973, 1988 and 1993. Cavities, wet seams in core and possible piping tunnels. Not known	Range 18 L/s to 67 L/s. See Note (1),	Yes
Balderhead (1964)	Reservoir filled in 1966. Increased leakage on first fill, Sinkhole on crest 3 m dia. by 2.5 m deep in 1967. Softened and water washed zones in core. Hydraulic fracture related to arching of narrow core onto filters.	Increases from 10 L/s to 25L/s on first filling, remained steady for 6 months, then increased erratically to 45L/s and then to a maximum of 55L/s over 4 months.	Partial
Brodhead (1975)	Large cavities, vertical holes up to 2.5 m dia. and 8.5 m deep. Tunnel 1.2-1.8 m dia. Estimated 190 m^3 material lost. All on first filling. Contact erosion into coarse blanket drain and / or concentrated leak erosion resulting from differential settlements over abutment.	Incident not observed. Investigations showed flow into the blanket drain was from open joints in foundation	Unknown
Bullileo (1945)	In 1982, muddy leakage of some hundreds of L/s at contact of embankment and right abutment. Sinkhole 6m diameter, 2m deep in upper right abutment. Concentrated leak erosion in crack formed by differential settlement over slope change in valley profile.	Seepage measured prior to incident ranged from zero to 1,000 L/s varying with reservoir level. Attributed to leakage through foundation. Maximum leakage during incident 8,000 L/s.	Self limiting but not self healing?
Churchill Falls FF-11 (1972)	Total six muddy leaks and 11 sinkholes. Estimated 37 cubic metres erosion occurred. Global backward erosion / suffusion? Cutoff foundation was slush grouted so not contact erosion.	Muddy leak in 1972, flow increasing from 15L/s 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)	During first reservoir filling in 1991, muddy flow started at toe near outlet pipe and increased over several days. Two sinkholes appeared at the crest. Concentrated leak erosion associated with changes in slope above the original diversion channel.	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)	A sinkhole in the upper part of the upstream was discovered two months after leak occurred. The postulated cause is piping due to segregated filter. Global backward erosion / suffusion?	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
Grundsjö -dammen (1972)	Sinkhole 0.5m dia. and 1.6m deep formed in 1990. Investigations showed small cavities, loose zones and layers	No details available	Yes

	with finer fraction washed out. Hydraulic fracture possibly exacerbated by collapse settlement, and concentrated leak erosion; or global backward erosion / suffusion		
Hällby (1970)	Sinkhole 0.7m deep, 7 cubic metres formed upstream of crest adjacent spillway wall in 1985. Collapse settlement resulting in concentrated leak.	Leakage rose to 3.3 L/s, previously 0.3 L/s	Yes
Hills Creek (1961)	Increased leakage in 1967. Zones of openwork gravel in core	Gradually increased to 11L/s	No
Hyttejuvet (1965)	Muddy leakage on first filling and in 1970. Sinkhole in 1972 on crest 3 m x 5 m by 2 m deep. Soft zones in the core up to 4 m below the sinkhole. Hydraulic fracture resulting from arching onto filters. Also cross valley differential settlement resulting in cracking and concentrated leak erosion.	First filling increase from 1-2L/s to max. 63L/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)	Three piping tunnels through the core near foundation, 300-500 mm wide. Concentrated leak in cracking / hydraulic fracture resulting from collapse settlement of poorly compacted core, and differential settlement over irregularities in foundation profile.	Initially 12-15L/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. See Figure 2.	Yes
Juktan Dams 1 and 3 (1977)	Two pipes in Dam 1, and 5 in Dam 3. All near foundation. Collapse settlement in poorly compacted core leading to concentrated leak; or global backward erosion / suffusion.	Leakage in 1979, 1980. Dam No. 3 had leakages in 1979, 1980, 1981, and 1982. Leakage rates not known.	Unknown
Lövön (1973)	Sinkholes in 1983, 6-8 m^3 and in 1986. Investigations showed layers of core with finer fraction washed out. Hydraulic fracture resulting from collapse settlement, and or global backward erosion / suffusion.	No details available.	Unknown
Matahina (1967)	Muddy leakage on first filling. *Right abutment* cavity 3m wide, 6m long in downstream inner transition. Volume 40 m^3. Concentrated leak erosion in crack formed over step in foundation formed by concrete during construction. Erosion was arrested by crack filling from the upstream transition.	On first filling leakage increased rapidly from 70 L/s to 560 L/s, then decreased to 250 L/s within 24 hours.	Yes
Mud Mountain (1953)	Zones of loose areas, voids, clean gravelly material and water loss in the core. Hydraulic fracture due to arching in narrow valley lower part of dam, and	Gradually increasing and erratic pore pressures No leakage rates available.	Unknown

	cross valley differential settlement in upper part		
Näs (1978)	Sinkhole on first filling and 1985, 1988, 1989, 1996 Not known	Not known	Yes
Porjus (1975)	Sinkholes on first filling in 1976, 1979; then in 1985 on upstream side of crest. In 1993 a sinkhole 4 m dia. by 3 m deep. Concentrated leak erosion resulting from collapse settlement of poorly compacted core, and global backward erosion / suffusion.	No data for 1976 and 1979. For 1985 max. 12 LL/s then reduced to 7 LL/s. In 1993 seepage increased from 7 LL/s to 14 L/s then reduced to 6 L/s. Core was grouted in 1993 showed cavities 10m to 15m below crest.	Yes
Rengård (1970)	Muddy discharge occasionally over time, sinkhole incidents in 1980 and 1993. Concentrated leak erosion resulting from hydraulic fracture.	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)	In 1968 a sinkhole formed on crest adjacent spillway wall 1.5 m dia. by 1.3 m deep. Concentrated leak erosion in gap formed by differential settlement of fill away from spillway wall. Erosion occurred in contact clay which was in direct contact with filter contrary to design.	Leakage not observed	Yes
Songa (1962)	Localized settlement of 0.5-1.0 m of upstream rockfill was associated with 1991 leakage. Investigations detected loose zones in the core and core deficient in fines low in the core. Hydraulic fracture possibly related to moderate compaction and irregular foundation profile. Global backward erosion / suffusion also possible.	"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 1.24L/s to 107 L/s then reduced to normal in 6.3 hours	Yes - self healing bursts of leakage
Suorva East (1972)	Muddy discharge in 1983 and a sinkhole on the crest. Global backward erosion, and possibly contact erosion into open joints in the foundation.	Max. 100 L/s reduced to 75 L/s prior to reservoir drawdown.	Yes
Tarbela Aux. Dam 1 and Main Dam (1974)	In 1977 a sinkhole on upstream slope of Auxiliary Dam. In 1984 a sinkhole 4.2m dia. by 1.5m deep appeared on the upstream slope of the Main Dam. Global backward erosion / suffusion in poorly compacted core around instrument risers.	No details	Yes
Uljua (1970)	Wet spots on first filling, Sinkhole in 1990. Concentrated leak resulting from frost action?	Normal seepage 5 l/min. After 20 years of operation, turbidity was observed. 2 weeks after first observation of turbidity, a sinkhole formed on the upstream face and the leakage increased to 100 L/s.	Unknown
Viddalsvatn (1971)	Muddy discharge first filling associated with large increase in leakage. Two sinkholes - 5 m x 5 m by 1 m deep on	Leakage increased suddenly from 4 L/s to 50 L/s on 11th October 1972 during first filling. Returned to previous rate	Yes

	upstream slope, and 2.5 m x 0.8 m by 1.8 m deep on crest in 1973. Soft zones in the core. Concentrated leak erosion in cracks or hydraulic fracture related to cross valley differential settlement and arching of core onto filters. Possibly related to poor compaction of core.	after 12 days. In mid-November leakage increased from 8 L/s 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 210L/s.	
Whiteman's	Cloudy leakage in 1994; In 1995 a sinkhole formed on crest, 2 m dia. by 1 m deep, soft wet zones and gravelly layers in the core. Concentrated leak erosion resulting from cross valley differential settlement	Max. 28 L/s up to 1995. No increase at time of sinkhole.	Unknown
Wreck Cove D11-2	Two sinkholes on crest related to leakage flows on first filling. During remedial works two 300 mm dia. tunnels through core were exposed near foundation level. Dam was re-built in 1978. In 1979 muddy leakage occurred and a one 3 m dia. by 0.6 m deep sinkhole formed on the downstream side of the crest. Suffusion or Global Backward Erosion related to segregation; or concentrated leak erosion related to marked change in foundation profile.	Leak at 14 L/s on first filling increasing to 22 L/s over three days.	Unknown

NOTES. (1).Gradual increase in seepage from 35 L/s to 67 L/s over the first 2 months after commissioning. Reduced to 17 L/s by lowering the reservoir 2 m. Two weeks later there was an increase in leakage again, sometimes cloudy, and the formation of a sinkhole at section 0/196. 1 m lowering of the reservoir, leakage reduced to 25 L/s. A new incident one year after commissioning, leakage increased from 18 to 43 L/s and a sinkhole 3 weeks later at section 0/168. Additional sinkholes the following year and a constant high leakage rate of 35-40 L/s.