ICOLD EUROPEAN CLUB

Working Group on Internal Erosion in Embankment Dams

PROGRESS REPORT

Co-ordinator: J. Fry (France)

2004

NOTICE - DISCLAIMER:

Internal erosion in European embankment dams

J. A. Charles
Chairman, European Working Group on internal erosion in embankment dams
Building Research Establishment, Garston, Watford, United Kingdom

ABSTRACT: The safety of an ageing population of embankment dams is a cause for concern in many European countries. A European Working Group on Internal Erosion in Embankment Dams was formed in 1993 and has examined the hazard posed by internal erosion to existing dams. From a study of case histories, the features in an embankment dam that are critical in rendering it vulnerable to internal erosion have been identified. The significance of the risk of failure and the warning signs that might be expected prior to failure have also been assessed.

1 INTRODUCTION

The long-term performance and safety of an ageing population of embankment dams is a cause for concern in many European countries. Many of the dams were not built to modern standards and there is likely to be deterioration with time. Most European countries with sizeable populations of embankment dams have experienced cases of internal erosion and this hazard is of crucial significance in assessing long-term safety. The national experience of serious incidents will, to some extent, reflect the number of embankment dams in the country and the age of these dams. The type of incidents and their seriousness will also depend on the regional geology and the prevalent type of embankment dam construction. Modern practice, incorporating specially designed filters, should greatly reduce vulnerability to internal erosion.

A European Working Group on Internal Erosion in Embankment Dams was formed in 1993. The Working Group currently has representatives from Austria, Bulgaria, Finland, France, Germany, Italy, Norway, Romania, Spain, Sweden, Switzerland and the United Kingdom. A progress report was presented at the Barcelona symposium (Charles, 1998). The activities of the Working Group have been confined to a study of the hazard posed by internal erosion to existing dams. Filter design for new dams has not been studied because the extensive research that has been carried out on this subject has been comprehensively reviewed in ICOLD Bulletin 95.

Internal erosion involves the removal of solid material, usually in suspension, from within an embankment or its foundation by the flow of water. The various mechanisms of internal erosion may be associated with construction defects and weaknesses or with the deformations and stress conditions within the embankment. Internal erosion may cause increased leakage and some form of surface settlement, possibly in the form of a sinkhole.

A helpful distinction can be made between localised and mass internal erosion. The former may be related to some local defect or may be associated with piping or hydraulic fracture. The term 'piping' is usually applied to a process that starts at the exit point of seepage and in which a continuous passage or pipe is developed in the soil by backward erosion. Where a central clay core is supported by stiffer granular shoulders and internal stress transfer is caused by differential settlement, cracks formed in the clay core may be associated with hydraulic fracture by the reservoir water pressure. Flow along preferential paths also may result from the inherent heterogeneity of the core fill. In a cohesive soil which is capable of sustaining an open crack, concentrated leaks may occur with erosion of soil particles along the walls of the cracks.

In contrast to these localised forms of erosion, the type of mass erosion known as 'suffosion' can occur by seepage flow in soils which are internally unstable.

Soils inadequately compacted at low moisture contents may be susceptible to collapse compression on saturation. Layers of better compacted material may arch over the collapsing soil resulting in the formation of loose, credible, wet seams.

Certain clay soils disperse or deflocculate in the presence of relatively pure water and are therefore highly susceptible to internal erosion. The tendency for dispersive erosion depends on the mineralogy and chemistry of the clay, and dissolved salts in the pore water and the eroding water (ICOLD, 1990).

Internal erosion is often associated with the presence of structures such as outlet conduits and culverts which pass through an embankment. The contact between the embankment fill and the structure can be a potential zone of weakness as the fill may have been inadequately compacted making suffosion and piping more probable. Leakage into a culvert may cause internal erosion and, where an unprotected outlet pipe has been placed in the embankment fill, any leakage from the pipe may result in severe erosion of the embankment fill.

2 CASE HISTORIES

A study of internal erosion incidents at European dams has been undertaken by the Working Group. A selected group of 47 case histories has been summarised in Appendix 1 and has been cross-referenced to an extensive bibliography which forms Appendix 3. Examples have been included from most European countries where there is a substantial population of embankment dams.

Internal erosion incidents involving sink holes and turbid leakage have been relatively common in Scandinavian dams with moraine cores, but very rarely do they appear to have caused failure. There has been a high incidence of sinkholes and concentrated leakage at Swedish dams (Bartsch, 1995). Internal erosion usually appears to be self-healing in these moraine soils, but some very serious events have occurred. A number of small dams have breached in Sweden due to internal erosion, but no large Swedish dam has failed.

The United Kingdom has a much larger population of embankment dams than other European countries. There are numerous examples of internal erosion at these dams, many of which were built to a traditional design using a central puddle clay core, but there have been very few instances of failure.

Although there has been no failure of a major dam in France since 1970, there have been 70 internal erosion incidents (Comité Français des Grands Barrages, 1997). Ten serious incidents occurred at small dams, including three that breached the embankment.

There are not many published cases of internal erosion at German dams. However, there have been major failures of canal embankments.

Concrete dams generally predominate in southern Europe and, consequently, there are fewer cases of internal erosion. Nevertheless, there are a number of interesting cases of internal erosion in embankment dams in Spain.

In Romania many hydro-power plants have reservoirs formed by embankments up to 30 m high and 2 km to 3 km in length with a thin upstream concrete facing. Problems are occurring due to deterioration of the bituminous sealing in the joints between concrete slabs and leakages have increased (Hulea, 1997).

3 ANALYSIS OF CASE HISTORIES

An analysis of the case histories has been carried out to identify critical factors associated with internal erosion. In order to assist in this analysis, each dam listed in Appendix 1 has been given a classification under four headings:

(A) severity of problem or incident
(B) cause of problem or incident
(C) symptoms of problem or incident
(D) remedial works.

The classifications for each of the above headings are defined in Appendix 2.

(A) *Severity of problem or incident* There are fourteen case histories of dams where the severity of the problem or incident has been classified as either *A1*(failure) or *A2a* (serious incident involving emergency action or drawdown where, without emergency action, a breach was likely). In eight of these cases the problem occurred during, or immediately following first filling of the reservoir. Such incidents during the early life of the dam are of considerable significance for new dams, but, from the aspect of long-term safety, the other six dams are of greater relevance. These six dams are now considered. References for each of the dams are listed in Appendix 1.

Peruca. At 10.48 on 28 January 1993 explosions were activated by military action at five locations in the inspection gallery of the 63 m high Peruca rock fill dam in Croatia. The dam, which has a narrow central clay core, suffered major damage and 3000 people in the most endangered area close to the dam were evacuated. The reservoir level had been lowered 5 m below the maximum water level prior to the explosions and was lowered at a rate of 0.9 m per day subsequent to the attack. Nevertheless, between 30 January and 5 February the leakage rate increased from 400 Vs to 570 Vs. Subsequently the flow rate decreased. It was calculated that 1500 m^3 of clay was eroded out of the dam by this leakage.

Saint Aignan. The 8 m high, homogeneous earth fill embankment dam failed catastrophically almost 20 years after construction. The embankment was constructed of variable fills and had no internal drainage. **It** was believed that suffosion had eventually turned into piping. No alarm was given prior to failure, but the downstream slope had shown signs of saturation. Failure was attributed to variable permeability in the fill inducing high seepage rates, the lack of an internal drain, and the absence of monitoring and maintenance.

Sapins. In 1988, ten years after first filling, flows of water and a shallow slip occurred in the lower part of the downstream slope of the 16 m high, homogeneous sand fill embankment. The situation rapidly worsened, and the reservoir was emptied. The homogeneous embankment was composed of a sand fill with a chimney drain which stopped 2 m below the top water level. The problem was attributed to suffosion within the embankment.

Sorpe. The 69 m high embankment was damaged during air raids on the nights of 16/17 May 1943 and 15 October 1944. On the latter occasion craters 12 m deep and 25 m to 30 m in diameter were produced. A breach was avoided largely because the reservoir level had been lowered by 6 m prior to the air raid. The central concrete core wall of the earth and rock fill embankment was severely damaged and subsequently the dam suffered serious leakage problems with remedial works undertaken in the 1950s.

Uljua. On 29 May 1990, twenty years after construction, a major incident occurred in which a sinkhole appeared in the upstream slope near the crest. The upstream slope dropped 3 m over a length of 7 m and the rate of leakage increased to 100 Vs. Rapid remedial measures saved the dam from total collapse. An erosion channel 1 m in diameter across the dam core was found during the repair works.

Warmwithens. During remedial works between 1964 and 1966, a 1.5 m diameter tunnel, formed in concrete segments, was driven through the 10 m high embankment to contain new outlet pipes. On 24 November 1970 the dam failed and it is thought that internal erosion took place along the line of the tunnel. The breach, 20 m wide at crest level, extended down to the tunnel, which was washed out, large sections of the concrete segments being deposited downstream.

At Peruca, Sorpe and Warmwithens internal erosion followed external actions which may be regarded as unusual. At both Peruca and Sorpe, the lowering of the reservoir water level before the military action took place was a critical factor in avoiding breaching of the dams. The other three cases. Saint Agnan, Sapins and Uljua, demonstrate that the long-term safety of embankment dams is ultimately contingent on adequate maintenance and surveillance, together with preparedness for emergency lowering of the reservoir.

(B) *Cause of problem or incident*

Although internal erosion problems are not restricted to one particular type of fill or form of dam construction, the type of problem experienced by the various dams is related to the type of embankment construction. Of the fourteen dams classified in the *A1* and *A2a* severity categories, four are homogeneous earth fill embankments, five have upstream membranes, four have internal earth fill cores and one has a central concrete core wall.

In five cases, erosion at the contact between the embankment and a structure or pipe passing through the embankment (57) was a major factor in the incident. This type of interface within an embankment clearly represents a significant potential hazard. It is noteworthy that, following incidents at two dams, Italian regulations prohibited this type of construction (Dolcetta, 1997).

In three cases, the failure of the upstream membrane *(B4)* was critical. The hydraulic gradient across such a membrane is very high and flows can be very great at a localised defect.

(C) *Symptoms of problem or incident*

Of the total 47 case histories, internal erosion manifested itself in the form of a sinkhole (*C1*) in 20 of the dams. In one case, a vortex *(C8)* was observed in the reservoir.

In the majority of the 47 case histories, seepage and leakage gave some indication of a problem. This could be in the form of excessive or increasing flows (*C2*), turbid flows (*C3*), wet areas on the downstream slope *{C4)* or leakage into or around a culvert (*C5*).

(D) *Remedial works*

In about half the 47 case histories, grouting *(D2*) formed a major part of the remedial works. In ten cases diaphragm walls (*D1*) were installed. In about one third of the cases, remedial works included earthmoving operations in the form of slope flattening, berm construction and reconstruction of the embankment.

4 CONCLUSIONS

The work of the group has addressed three basic questions:

Is there a significant risk that an old embankment dam, with a long record of apparently satisfactory *behaviour, could fail suddenly and catastrophically due to internal erosion?*

In many European countries there are a significant number of embankment dams which could pose a threat to public safety and their long-term satisfactory performance is of considerable importance. Internal erosion is likely to be the major hazard for many of these old dams. While internal erosion problems often occur during first filling of the reservoir, there are many cases where the phenomenon does not manifest itself until a much later stage. A lack of problems during the early life of a dam, therefore, does not guarantee continuing satisfactory performance.

The case histories indicate that the risk of an old embankment dam, with a long record of apparently satisfactory behaviour, failing suddenly and catastrophically due to internal erosion is very small unless some unusual external circumstance arises. It would seem that the risk of internal erosion causing embankment breaching can be reduced to almost negligible proportions by appropriate maintenance, surveillance and, where necessary, remedial works, together with preparedness for emergency lowering of the reservoir. Smaller dams where surveillance may not be so effective may pose the greatest risk.

What features in an embankment dam are critical in rendering it vulnerable to such a development?

Internal erosion is not confined to a particular soil type, although the way the erosion develops will be strongly influenced by the nature of the soil. For example, the broadly graded moraines typically found in Scandinavia are prone to internal erosion but are usually self-healing. Internal erosion may be less likely in clay soils but, if it does occur, it may be more likely to lead to breaching of the dam. In almost half the cases where failure occurred (*A1*), or where failure almost certainly would have occurred very quickly if the reservoir had not been rapidly drawn down (*A2a*), the problem was associated with a structure passing through the embankment. The conditions at the interface of the soil and the structure are critical. In several cases the failure of an upstream membrane was a critical factor. There are very high hydraulic gradients and failure of the membrane can, in some circumstances, lead to rapid internal erosion of the fill.

What warning signs could be expected and how much warning would these give prior to failure?

Internal erosion is difficult to analyse and the continuing safety of embankment dams is dependent on an approach based on the observational method. However, internal erosion is a hidden phenomenon and until some feature such as a sinkhole appears at the surface of the soil, it is difficult to identify and investigate.

5 RECOMMENDATIONS FOR FURTHER WORK

Research on internal erosion is being undertaken in many countries around the world and the European Working Group fulfils a useful role in promoting European collaboration and bringing together dam engineers and research workers. It is recommended that it should continue its work.

The study of incidents has provided information on the types of dams affected and the speed with which internal erosion problems develop. This should assist in identifying analytical, laboratory and field studies which are needed to complement current national research programmes.

The identification and investigation of internal erosion is not easy as it can be very localised. Many different techniques have been used including electrical resistivity, ground-probing radar, self potential and temperature measurements. It is important to evaluate their effectiveness.

It is recommended that risk assessment methodology should be applied to the extensive information now contained in dam databases. This should assist in the identification of potentially hazardous conditions and, possibly, the quantification of the risk of internal erosion. There is a need to collaborate closely with the European Working Group on Risk Assessment. Detection and investigation are key issues and field investigation methods need to be critically assessed. Fundamental work in the laboratory to develop improved understanding of erosion mechanisms, particularly the erosion resistance of clays, would be valuable.

REFERENCES

Bartsch M (1995). Filtration processes and internal erosion in dams of broadly graded material. Technical Report, Royal Institute of Technology, Stockholm

Charles J A (1998). Internal erosion in European embankment dams - progress report of Working Group on internal erosion in embankment dams. *Dam safety* (ed L Berga) Proceedings of international symposium, Barcelona, vol 2 pp 1567-1576.

Comité Français des Grands Barrages (1997). Internal erosion typology, detection repair. *Barrages & Reservoirs,* no 6 May.126pp.

Dolcetta M (1997). Discussion on Q73, Transactions of 19th International Congress on Large Dams, Florence, vol 5, p. *339.*

Hulea D (1997). Private communication.

ICOLD (1990). Dispersive soils in embankment dams: review Bulletin 77. International Commission on Large Dams Paris.

ICOLD (1994). Embankment dams: granular filters and drain; Bulletin 95. International Commission on Large Dam; Paris.

APPENDIX 1
SUMMARY OF CASE HISTORIES

Dam	Refs	Country	Date built	Watertight element	Problem or incident			
					A	B	C	D
Arbon	50, 51	Spain	1967	Central gravel and silty sand core	2b	6	1, 3	1, 2
Balderhead	11, 55	United Kingdom	1965	Central rolled clay core	2b	6, 7	1, 2, 3	1, 2
Buget	12, 19	France	1980	Homogeneous clayey earth fill embankment	2a	2	2, 4	4
Caspe	14, 60	Spain	1988	Clay core	2b	9	1, 2	2
Elbe-Seitenkanal	20, 33, 45, 46	Germany	1976	Upstream asphaltic membrane	1	1	4	11
Fonte Longa	41	Portugal	1988	Homogeneous earth fill	3	1, 3	5	4
Gostei	41	Portugal	1993	Homogeneous earth fill	3	1	5	4
Gourdon	12, 17, 19	France	1983	Upstream geomembrane, clay blanket on foundation	2b	5	4, 6, 7	6
Greenbooth	10, 11 16	United Kingdom	1961	Central puddle clay core	2b	6	1	2
Grossee	58	Austria	1980	Upstream asphaltic membrane	3	4	2	5
Grundsjoama		Sweden	1972	Central moraine core	2b	7	1, 7	11
Hallby	1, 9	Sweden	1970	Central moraine core	2b	10	1, 2	2
Hyttejuvet	22, 28, 59	Norway	1965	Central moraine core	2b	6	1, 2	2
Ibra	7	Germany	1975	Upstream geomembrane	1	1, 4	4, 7	5, 8, 9, 10
Jukla	23, 26	Norway	1974	Central moraine core	2b	6, 7	2	2, 10, 11
Juktan	29	Sweden	1978	Central moraine core	2b	6, 7	2	1, 11
La Prade	12, 17, 19	France	1982	Wide central clay core	2b	2	4	2, 4
Lavaud-Gelade	12, 17, 18, 19	France	1943	Homogeneous sand fill embankment	3	8	4	10
Lluest Wen	10, 11	United Kingdom	1896	Central puddle clay core	2b	3	1	1, 2
Lovon	24	Sweden	1973	Upstream sloping moraine core	2b	6, 7	1	2, 10
Main-Donau-Kanal	15, 20	Germany	1978	Upstream asphaltic membrane	1	1	4	11
Martin Gonzalo	27	Spain	1987	Upstream geomembrane	2a	4	1, 2	5
Moravka	8	Czech Republic	1965	Upstream asphaltic membrane	2a	4	1, 2	5
Motru	42	Romania	1984	Central clayey core	3	10	2	1
Mysevatn	22, 23	Norway	1973	Moraine core	2b	6	1, 2	2, 10
Nepes	17, 18, 34	France	1945	Reinforced concrete core wall	2b	10	2, 3, 6	2

Dam	Refs	Country	Date built	Watertight element	Problem or incident			
					A	B	C	D
Nyrsko	49	Czech Republic	1970	Upstream reinforced concrete facing	2b	4	2	5
Peruca	13, 37, 48	Croatia	1958	Narrow central clay core	2a	12	1, 2, 3	1, 11
Porjus	25	Sweden	1980	Central moraine core	2b	6, 7	1	2
Rengard		Sweden	1970	Moraine core	2b	6, 7	1, 2, 3	2
Saint Aignan	12, 17	France	1965	Homogeneous earth fill embankment	1	8	4	11
St Julien des Landes	12, 17, 19	France	1969	Homogeneous earth fill embankment	2a	1	5	4, 11
Saint Pardoux	6, 12, 17, 19, 34	France	1975	Homogeneous sand fill embankment	2b	8	4, 7	1, 2
Sapins	6, 12. 17, 18, 19, 34	France	1978	Homogeneous sand fill embankment	2a		4, 9	1, 10
Seitevare	5	Sweden	1967	Central moraine core	2b	10	4	2
Songa	53	Norway	1962	Central moraine core	4	6, 7	2, 3	12
Sorpe	21, 30, 57	Germany	1935	Central concrete core wall	2a	12	1, 2	2, 3
Stenkullafors	38, 39, 40	Sweden	1983	Central moraine core	2b	1, 6, 7	1	10
Suorva	1, 3, 9, 39, 40, 54	Sweden	1972	Central moraine core	2b	6, 7	1, 2, 3	2
Sylvenstein	4, 35	Germany	1958	Central vertical soil-cement core	3	7	2, 7	2
Taibilla	2	Spain	1973	Upstream sloping clay core	2a	9	8	11
Torcy Vieux	52	France	1800	Homogeneous earth fill embankment	2b	11	4, 7	9, 10
Uljua	31, 32, 36, 43, 44	Finland	1970	Central moraine core	2a	10	1, 2, 3	1, 2, 11
Viddalsvatn	22, 56	Norway	1971	Central moraine core	2b	7	1, 2, 3	2
Warmwithens	10, 11	United Kingdom	1870	Central puddle clay core	1	1		12
Winscar	11, 47	United Kingdom	1975	Upstream asphaltic concrete membrane	3	4	2	5
Withens Clough	11	United Kingdom	1894	Central puddle clay core	3	6	2	1, 2

APPENDIX 2
CLASSIFICATIONS

A - severity of problem or incident
- A1 Failure
- A2 Serious incident involving emergency action or drawdown
  - (a) Without emergency action, a breach was likely
  - (b) Little danger of immediate breach
- A3 Incident causing concern, major investigation and remedial works
- A4 Symptoms causing concern

B - cause of problem or incident
- B1 Erosion at contact with pipe or structure
- B2 Outlet pipe failure
- B3 Erosion into pipe or culvert
- B4 Upstream membrane failure
- B5 Fracture of clay foundation blanket
- B6 Fracture of core
- B7 Inadequate filter
- B8 Absence of internal drain/filter
- B9 Foundation solubility
- B10 Inadequate foundation treatment
- B11 Rotting tree roots
- B12 Military action

C - symptoms of problem or incident
- Cl Sinkhole
- C2 Excessive or increasing seepage and leakage
- C3 Turbid seepage and leakage
- C4 Wet areas or seepage and leakage on downstream slope
- C5 Leakage into or around culvert
- C6 Piping
- C7 Excessive or increasing pore pressures
- C8 Vortex in reservoir
- C9 Slip

D - remedial works
- Dl Diaphragm wall
- D2 Grouting
- D3 Jet grouting
- D4 Pipe or culvert repair
- D5 Upstream membrane repair
- D6 Clay blanket repair
- D7 Drainage gallery
- D8 Relief wells
- D9 Filters
- D10 Slope flattening or addition of berm
- D11 Partial or total reconstruction
- D12 None

APPENDIX 3
REFERENCES FOR CASE HISTORIES

1. Alemo J, Bronner N & Johansson N (1991). Long term stability of grout curtains. Transactions of 17th International Congress on Large Dams, Vienna, vol 2, pp 1311-1325.
2. Alonso Franco M & Yague Cordova J (1997). Earth materials for cores and homogeneous earth fill dams; singularities. Transactions of 19th International Congress on Large Dams, Florence, vol 2, pp 381-401.
3. Andersson P M (1991). Borehole radar as a tool for detecting dam ageing. Transactions of 17th International Congress on Large Dams, Vienna, vol 5, pp 251-257.
4. Beier H, List F & Lorenz W (1979). Subsequent sealing in the impervious core of the Sylvenstein dam. Transactions of 13th International Congress on Large Dams, New Delhi, vol 2, pp 103-116.
5. Bemell C E (1976). Control of leakage through dams founded on glacial till deposits. Transactions of 12th International Congress on Large Dams, Mexico City, vol 2. pp 937-950.
6. Bister D, Fry J J, Costaz J, Houis J, Dupas J M, Degoutte G, Lino M & Rizzolli J L (1994). Reevaluation de la securite des barrages en remblai exemples d'application. Transactions of 18th International Congress on Large Dams, Durban, vol 1, pp 645-670.
7. Breth H & Romberg W (1984). Failure of an earth dam on Triassic Sandstone: causes of the failure and criteria for reconstruction. Proceedings of International Conference on Safety of Dams, Coimbra, pp 15-20. Balkema, Rotterdam.
8. Brezina P, Satrapa L & Skokan T (1998). The reconstruction of the collapsed bituminous concrete facing of the Moravka dam, Czech Republic. *Rehabilitation of Dams.* Proceedings of symposium held at ICOLD 66th Annual Meeting, November 1998, New Delhi, pp 223-226. Balkema, Rotterdam, 1999.
9. Bronner N. Fagerstrom H & Stille H (1988). Bedrock cracks as a possible cause of leakage in two Swedish dams. Transactions of 16th International Congress on Large Dams, San Francisco, vol 2, pp 1029-1052.
10. Charles J A, Tedd P & Holton I R (1995). Internal erosion in clay cores of British dams. *Research and Development in the Field of Dams.* Proceedings of European Symposium, Crans Montana, pp 59-70. Swiss National Committee on Large Dams.
11. Charles J A, Tedd P, Hughes A K & Lovenbury H T (1996). Investigating embankment dams: a guide to the identification and repair of defects. Building Research Establishment Report BR 303. 81pp.
12. Comité Français des Grands Barrages (1997). Internal erosion: typology, detection repair. 126pp.
13. Croatian Committee on Large Dams (1995). Peruca dam remediation. Proceedings of international conference, Brela, 472pp.
14. De Celix Caballero M R & Sanchez-Albomoz A A (1995). Internal erosion of the Caspe dam. *Research and Development in the Field of Dams.* Proceedings of European Symposium, Crans Montana, pp 47-58. Swiss National Committee on Large Dams.
15. Ferguson H (1979). Germans tight lipped as investigation starts into canal disaster. *New Civil Engineer, 5* April, pp 16-18.
16. Flemming J H & Rossington D T (1985). Repair of Greenbooth dam following localised settlement in the

crest. Transactions of 15th International Congress on Large Dams, Lausanne, vol 4, pp 875-897.

17. Fry J-J (1995). Developpements concernant les risques d'erosion interne et des seismes relatifs aux remblais. *Research and Development in the Field of Dams.* Proceedings of European Symposium, Crans Montana, pp 35-46. Swiss National Committee on Large Dams.
18. Fry J-J, Brun P & Royet P (1994). Internal erosion problems in some old embankment dams in France. *Reservoir Safety and the Environment.* Proceedings of 8th Conference of British Dam Society, Exeter, pp 23-34. Thomas Telford, London.
19. Fry J-J, Brun P, Lautrin D, Albalat **C,** Droux J M, Mercier A, Riesterer J M, Thareau L & Degoutte G (1997). Typologie de 1'erosion interne et detection. Transactions of 19th International Congress on Large Dams, Florence, vol 2, pp 819-844.
20. Hager M (1982). Stand der Risikobewertung bei durchstromten, gewachsenen und geschutteten nichtbindigen Dammbaustoffen im Kanalbau. Vortrage der Basugrundtagung in Braunschweig, DGEG e V Essen.
21. Heitefuss C, Krug H-J & Ruhnke H (1998). Die Sanierung des Sorpes-Dammes mit einer HDI-Dichtwand (Rehabilitation of Sorpe dam with a jet grout curtain), *Wasserwirtschaft,* vol 88, pll.
22. Hoeg K, Valstad T, Kjaemsli B & Johansen P M (1993). Norwegian experience with embankment dams. *Maintenance of older dams: accidents, safety assessment and repairs.* Proceedings of European Technical Symposium, Chambery, vol 1, pp 41-61. Comite Francais des Grands Barrages.
23. Hoff T & Nilsen K Y (1985). Erosion and leakage problems on some Norwegian dams. Transactions of 15th International Congress on Large Dams, Lausanne, vol 4, pp 573-586.
24. Johansson S (1996). Seepage monitoring in embankment dams by temperature and resistivity measurements. *Repair and Upgrading of Dams,* Proceedings of Symposium, Stockholm, June 1996, pp 288-297.
25. Johansson B, Johansson S & Nilsson R (1996). Investigations and repair of the embankment dam at Porjus power station. *Repair and Upgrading of Dams.* Proceedings of European Symposium, Stockholm, pp 218-227. Royal Institute of Technology, Stockholm.
26. Johansen P M & Eikevik J H (1997). Internal erosion and rehabilitation of Jukia rockfill dams. Transactions of 19th International Congress on Large Dams, Florence, vol 2, pp 245-253.
27. Justo J L (1988). The failure of the impervious facing of Martin Gonzalo rockfill dam. Transactions of 16th International Congress on Large Dams, San Francisco, vol 5, pp 252-262.
28. Kjaemsli B & Torblaa I (1968). Leakage through horizontal cracks in the core of Hyttejuvet dam. Norwegian Geotechnical Institute publication no 80, pp 39-47.
29. Kjellberg R, Norstedt U & Fagerstrom H (1985). Leakage in and reconstruction of the Juktan earth and rockfill dams. Transactions of 15th International Congress on Large Dams, Lausanne, vol 4, pp 553-572.
30. Koenig H W (1967). Damage of the Sorpe dam by vibrations and repair work. Transactions of 9th International Congress on Large Dams, Istanbul, vol 4, pp 485-498.
31. Kuusiniemi R (1991). Internal erosion of the Uljua earth dam. Transactions of 17th International Congress on Large Dams, Vienna, vol 5, pp 257-262.
32. Kuusiniemi R & Loukola E (1996). Repairing works of earth dams owned by the state in Finland. *Repair and Upgrading of Dams.* Proceedings of European Symposium, Stockholm, pp 195-206. Royal Institute of Technology, Stockholm.
33. Lackner E & Hager M (1980). Der Schadensfall an der Unterfuhrung Luneburg/Nutzfelde des Elbe-Seitenkanals und seine Folgerungen. Jahrbuch der Hafenbautechnischen Gesellschaft e V 37 Band, Springer-Verlag.
34. Lino M, Degoutte G, Goguel B, Chassard G, Saint-Marcel A, Gouvenot D & Delmas F (1994). Mesures prises pour ameliorer 1'etancheite des barrages et de leurs fondations et reduire Ie risque d'erosion interne. Transactions of 18th International Congress on Large Dams, Durban, vol 1, pp 731-761.
35. List F & Strobi T (1991). Changing of tightness in the grout curtain and core of the Sylvenstein dam by ageing. Transactions of 17th International Congress on Large Dams, Vienna, vol 5, pp 1295-1309.
36. Loukola E & Slunga E (1982). Observations on the seepage control through and under dams made of glacial till. Transactions of 14th International Congress on Large Dams, Rio de Janeiro, vol 1, pp 293-304.
37. Megia T, Rupcic J, Petricec M, Sever **Z,** Macan J, Vilovic M, Kuk V, Herak D, Herak M, Dadic V, Grbec B, . Salkovic A, Dujmic D, Nonveiller E & Grgic P (1993). The Peruca dam, Croatia. Proceedings of International Workshop on Dam Safety Evaluation, Grindelwald, Supplementary volume, 71pp. Dam Engineering, Sutton, Surrey, England.
38. Nilsson A & Norstedt U (1991). Evaluation of ageing processes in two Swedish dams. Transactions of 17th International Congress on Large Dams, Vienna, vol 2, pp 23-47.
39. Norstedt U, Eriksson H & Nilsson A (1993). Research and development programs in Sweden. *Maintenance of older dams: accidents, safety assessment and repairs.* Proceedings of European Technical Symposium, Chambery, vol 1, pp 359-383. Comite Francais des Grands Barrages.
40. Norstedt U & Nilsson A (1997). Internal erosion and ageing in some of the Swedish earth and rockfill dams. Transactions of 19th International Congress on Large Dams, Florence, vol 2, pp 307-319.
41. Oliveira Lemos F & Machado do Vale J (1997). Culverts buried in earthfill dams; some cases and problems. Transactions of 19th International Congress on Large Dams, Florence, vol 2, pp 421-429.
42. Popovici A, Sarghiuta R, Abdulamit A & Teodorescu C (1998). Study concerning the excessive leakage from a large reservoir. *Rehabilitation of Dams.* Proceedings of Symposium held at ICOLD 66th Annual Meeting, November 1998, New Delhi, pp 425-433. Balkema, Rotterdam. 1999.
43. Rathmayer H & Polla J (1998). Finnish dam safety code prohibited collapse of the Uljua earth dam. *Dam Safety* (ed L Berga). Proceedings of International Symposium on New Trends and Guidelines on Dam Safety, Barcelona, vol 2, pp 903-910. Balkema, Rotterdam.
44. Ravasaka 0 (1997). Piping susceptibility of glacial till. Transactions of 19th International Congress on Large Dams, May, Florence, vol 2, pp 455-471.
45. Reina P & Marshall T (1976). German canal fails after only 6 months. *New Civil Engineer,* 22 July, p6.
46. Reina P (1976). Six-man team wades into Luneburg collapse. *Ne\v Civil Engineer,* 29 July, pp 16-18.
47. Routh C D (1988). The investigation, identification and repair of the asphaltic concrete facing of Winscar dam. Transactions of 16th International Congress on Large Dams, San Francisco, June 1988, vol 2, pp 655-677.