DSO-04-05

Selected Case Histories

of

Dam Failures and Accidents

Caused

by

Internal Erosion

by

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INTRODUCTION

The vast majority of embankment dams have exhibited good behavior. However, about 50 percent of large embankment dam failures have been attributed to internal erosion. Therefore, a study of case histories of incidents (both accidents and failures) can be instructive.

A. WHY READ CASE HISTORIES?

- To obtain insights into how dams can fail by internal erosion.
- To identify factors that contributed to the internal erosion failure of the dam, if possible.
- To serve as a "reality check" for the risk analyst.

The study of case histories of dam incidents, which includes both accidents and failures, is a very important part of the analysis and design of embankment dams. Case histories contain a wealth of wisdom to supplement the theories and analytical tools provided by a formal engineering education.

Case histories can also help in a risk analysis of a dam. By comparing a dam being studied to similar dams -- that have failed, or have had accidents, or have performed well -- provides a real life basis or "reality check" for the risk analysis.

Engineers, in general, tend to focus on technical aspects of a dam, because they are most knowledgeable about them. The technical factors that cause internal erosion are well know to the dam safety engineering profession. Some of the significant technical factors have been listed by Robert Jansen as the following [1]: defective filters and drains; cracking of the core by settlement; improper preparation of the foundation; open joints or solution channels in the rock foundation; permeable underlying alluvial, glacial, or talus deposits; incorrect shaping of the foundation contacts leaving steep faces or overhangs; and blasting of the foundation for grout caps, which loosens the rock enough to create paths for leakage.

Case histories also illuminate some of the nontechnical causes of failures. Human factors are harder to identify. Steve Vick lists a number of human errors in the case of the Omai Dam failure in Guyana. "Bureaucratic factors" is the term used by James Sherard, who shows how they played a dominant role in the failure of Teton Dam and his paper, "Lessons from the Teton Dam Failure" [2], is included as part of the case history of Teton Dam. George Sowers discusses the Teton Dam failure in his paper [3], "Human Factors in Civil and Geotechnical Engineering Failures." Robert Whitman, in the seventeenth Terzaghi lecture [4], emphasized that "human and organizational factors must be considered as well as design details" in a risk evaluation of a dam. As early as1973, Ralph Peck discussed a wider range of nontechnical factors that can affect the quality of a dam, and his article [5] is included in appendix A. The nontechnical causes of poor quality dams, he said, "are more numerous and more serious than the technical causes . . . Most of these shortcomings originate in the attitudes and actions of the persons most intimately concerned with the creation and completion of the project: the owner, designer, constructor, and the technical consultant."

B. PURPOSE

The purpose of this report is to aid in the risk analyses, in comprehensive facility reviews, and in decisions about modifying existing Bureau of Reclamation (Reclamation) embankment dams.

The goal has been to collect some helpful case histories of dam failures and accidents caused by internal erosion. Also, a few case histories of Reclamation's response to piping incidents at their dams and at one Bureau of Indian Affairs dam have been included. A careful review of a few case histories of dams that are similar to the one under study can result in better assessments of possible failure mechanisms and insights into factors that can contribute to satisfactory or poor performance of embankment dams.

This report will also be used to supplement Reclamation's risk analysis report on internal erosion of embankment dams [6]: "RISK ANALYSIS METHODOLOGY, APPENDIX E - Estimating the Risk of Internal Erosion and Material Transport Failure Modes for Embankment Dams."

C. WHAT MAKES CASE HISTORIES OF DAM FAILURES AND ACCIDENT WORTHWHILE ?

- If the dam is similar to the one being studied
- If the case history is clear and contains sufficient details
- If the authors have critically examined and evaluated what has happened

Over one hundred case histories were read and ten of the most valuable case histories are included. Appendix B contains a list of the case histories that were screened to meet these criteria, with some short comments on each case history.

Not only dam failures, but also accidents are included because they also are important. Dams that have withstood a significant erosion event and have not failed have inherent strengths. These case histories may provide insights to the reader.

D. THE ORGANIZATION OF THE REPORT

The ten case histories chosen are summarized in table 1, which includes some information about the embankment type and construction, the foundation, the reservoir loading, and the incident.

Appendix A contains the article by Ralph Peck on the nontechnical factors that influence the quality of embankment dams. Appendix B contains a list of case histories that were reviewed. Appendix C contains six case histories of Reclamation's response to piping incidents. Appendix D contains a summary list of factors related to the internal erosion of an embankment dam.

Table 1. - Summary of Case Histories of Internal Erosion

Name & Location	Failure or Accident and Mode	Date of Construction and Incident	Height in feet	Foundation Materials	Embankment Type	Reservoir Loading	Comments
Picketberg Dam, South Africa	Failure through embankment near conduit	1986/1986	39	Alluvium - silty sand	Zoned with dispersive clay core. No filters	First filling - 33 ft in 5 weeks	One of the best case histories. Good discussion of a number of contributing factors.
Omai Tailings Dam, Guyana	Failure through embankment, but complex sequence	1993/1995	148	Residual saprolite soils	Tailings dam with sloping core and d/s rock fill	Dam raised ahead of mill effluent	Author Steve Vick's approach is from a background in risk analysis
Ghattara Dam, Libya	Failure through embankment near conduit	1972/1977	92	Alluvium over limestone	Homogeneous. Silty clay core. Chimney drain, filter, and toe drain	Record rains. First filling - 26 ft in 2 days.	Modern dam with chimney drain and filter. No flaws were found in design or construction. Filter beneath conduit?
Stockton Creek Dam, California	Failure through embankment due to cracking	1950/1950	80	Schist - hard and sound	Near homogeneous. Well compacted clayey sand.	Rapid first filling.	Dam on rock with modern construction. Leak through settlement crack near a vertical step in abutment
Lake Francis Dam, California	Failure through embankment due to cracking	1899/1899	52	Sandy clay over rock	Homogeneous. Most fill was compacted dry, some was dumped.	9 in.of rain in 36 hrs. Rapid first filling	Leak through cracks in dumped fill and outlet pipe due to settlement was not surprising.
Walter Bouldin Dam, Alabama	Failure through embankment or from embankment into foundation	1967/1975	164	Jointed sediments of sand, silts, and layers of stiff clay	Nearly homogeneous with thin upstream clay section tied into natural reservoir blanket. No filters.	Normal loading	Peck and Leps believe failure was due to piping of foundation soil rather than the official cause, an upstream slide due to drawdown.

Name & Location	Failure or Accident and Mode	Date of Construction and Incident	Height in feet	Foundation Materials	Embankment Type	Reservoir Loading	Comments
Uljua Dam, Finland	Accident, but near failure. Embankment into foundation	1970/1990	52	Erodible glacial till over fissured bedrock	Zoned. Core of glacial till, filter zones, and supporting rockfill	Several times a day the reservoir fluctuated because of power operations	After 20 years, seepage increased and turned muddy. Only case history in which an erosion tube was traced through core of dam into foundation, which is shown in a figure.
Langborn Dam, Norway	Accident. Erosion through abutment	1958/1958	n/a	Abutment consists of silt, sand, and layers of coarser material	n/a	Slide occurred during first filling.	The probability of several failure modes of the abutment were evaluated. Evaluation followed Reclamation's SEED guidelines.
Teton Dam, Idaho	Failure. Embankment into foundation	1976/1976	305	Jointed rhyolitic welded ash-flow tuff	Zoned. Very erodible, stiff, and brittle silt core. No filters	Rapid first filling.	Sherard's paper gives insights into bureaucratic problems within Reclamation at the time.
Fontenelle Dam, Wyoming	Accident, but near failure. Through embankment or embankment into foundation	1964/1965	139	Interbedded sandstone, siltstone, and shale deposits	Zoned. Erosive core of low plasticity silts and silty sands. No filters	First filing	Peck has suggested there are many similarities between the Fontenelle incident and Teton. Were lessons learned?

In order to relate the case histories to steps used in a risk analysis, each case history has been divided into the stages used by Reclamation to identify internal erosion, which are: initiation, continuation, progression, detection/intervention, and breach mechanism. Foster and Fell [7] have used a table to summarize the factors that contribute to each stage of internal erosion. A modified format is currently used by Reclamation to include factors that not only contribute to, but also resist internal erosion. Factors that contribute to internal erosion are listed in one column as "more likely"; factors that resist internal erosion are listed as "less likely." This table is included with each case history, and the format is shown in table 2.

Headings in the table are briefly described below; a more detailed description can be found in reference 6.

- Initiation. - A concentrated leak develops along a path which leads to migration of fine soil particles.
- Continuation. - A filter to control the migration of soil particles is not present or is deficient which allows migration and exiting of the fine soil particles.
- Progression. - A flow path (pipe) enlarges to the reservoir if the roof of the pipe is supported, if flows are not limited, and if the soil is erodible.
- Detection/Intervention. - Detection of the problem (increasing flows, sand boils, muddy water, sinkholes, whirlpools, etc.) and mitigation of the problem (lower reservoir, place filter berm over seepage point, fill sinkholes, etc.)
- Breach Mechanism. - Type of failure such as enlargement of pipe, crest settlement, sloughing, and slope instability.

Table 2. - Factors Contributing to and Resisting Internal Erosion

INITIATION		CONTINUATION		PROGRESSION		DETECTION/ INTERVENTION UNSUCCESSFUL		BREACH MECHANISM	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY

E. HISTORICAL NOTE

The era during which a dam was designed and constructed has a bearing on the performance of a dam. Before approximately 1930 to 1935, soil mechanics was not accepted as an engineering discipline, empirical methods were the norm, and R. R. Proctor's principles of compaction and construction control [8] were not widely known or followed. During that early era, some embankments were compacted by sheep and cattle and wagons with some moisture control; others were hardly compacted at all and with little or no moisture control; and some were simply built of dumped fill. The case history of Lake Francis Dam, which was constructed in 1899, is an example of this era of construction, and from our modern day perspective it is not surprising that the dam failed.

At Reclamation, the period from about 1935 to 1950 was an era of caution and experimentation, with considerable amount of laboratory research and field studies on compaction and compaction equipment. The period from approximately 1950 to 1976 was an era of generous funding from Congress, with a great amount of design and construction activity. The Teton Dam failure in 1976 forced Reclamation to completely re-examine its dam design and construction practices. From 1976 to the present is a post-dam building era, with only a few dams built, but these have incorporated chimney drains and filters and strict attention to foundation treatment. It is generally accepted that the absence of chimney drains and filters and foundation treatment are the weak links that led to the failure of Teton Dam.

Except for the case history of Lake Francis Dam, the case histories selected have been modern dams, designed and constructed after about 1950. As such, these case histories represent embankment dams that have constructed using modern compaction methods.

F. FAILURE AND ACCIDENT STATISTICS

While the emphasis of this report is on failures and accidents of embankment dams by internal erosion, it should be kept in mind that very few dams have accidents or fail. In the data base complied by Foster and Fell (ERDATA1) [9], the number of accidents and failures for the three types of failure modes for internal erosion are listed in table 3.

Table 3. - Accidents and Failures due to Internal Erosion in ERDATA1 Data Base

Failure Mode	Accidents	Failures	Total
Internal Erosion Through the Embankment	102	51	153
Internal Erosion Through the Foundation	85	21	106
Internal Erosion of the Embankment into the Foundation	31	4	35
Total	218	76	294

There have been only 76 failures and 218 accidents out of 11,192 embankment dams that have been constructed up to 1986 [9]. One way of looking at this is to say that less than 1 percent of the dams in the data base have failed; conversely, the success rate is greater than 99 percent. This is believed to be a very low failure rate when compared to other civil engineering works.

G. INTERNAL EROSION LOCATIONS

Locations where internal erosion can initiate and where a concentrated leak can form are shown on **figure 1**. Fell and Foster have made a statistical analysis of large dams [9] which indicates that failures and accidents usually initiate in the following locations:

- Around or near the conduit (most occurred in this location)
- Over an irregularity in the foundation or abutment leading to cracking of the fill
- Adjacent to a concrete spillway or other structure

Also note that the location where internal erosion has initiated is not known for a large number of cases.

Figure 2 is a bar graph illustrating the number of failures and accidents at various locations for the case histories studied by Fell and Foster [9].

1. Conduits. - Because most accidents and failures by internal erosion are initiated around or near a conduits constructed through an embankment, three case histories are included: Picketberg Dam, Omai Dam, and Ghattara Dam. Why do conduits placed through an embankment cause so many problems? Possible reasons are the following:

- The conduit has cracked, corroded, or joints have opened.
- Stress concentrations, poor compaction of soil adjacent to the conduit, and cracking of the soil adjacent to the conduit have resulted in a zone of weakness in the dam.

This is illustrated in figure 3, taken from reference 10.

Sherard [11] has made the following recommendations for a conduit that is to be placed through an earth dam, and these criteria can be used for purposes of comparison in a risk analysis:

- It is particularly important that the embankment adjacent to the conduit be placed at a relatively high water content and not be a soil susceptible to piping.
- Even in small, homogeneous dams where no chimney drain is installed, it is advisable to provide a drain and filter around the conduit at its downstream end for the purpose of intercepting concentrated leaks which follow the conduit.
- In cases where the soil foundation is thick and compressible, it is not desirable to excavate a trench under the conduit and fill it with compacted earth

2. Transverse cracks. - Two case histories of dams that have cracked are Stockton Creek

Dam and Lake Francis Dam. Transverse cracks through the core of a dam are particularly dangerous because the crack provides a ready path for concentrated seepage to follow. Transverse cracks through the core may be caused by differential settlement, collapse of the foundation, hydraulic fracture, earthquake shaking, or slope instability. Foster and Fell discuss a number of factors that influence the likelihood of transverse cracking in reference 9. Transverse cracks are more likely to occur with decreasing compaction water content and decreasing compaction density; with decreasing plasticity of clayey soils; and with soils containing cementing minerals.

3. Adjacent to a concrete spillway or other structure. - The contact between earthfill and a structure can be a potential zone of weakness in an embankment dam. The contact may provide for a zone of low stress which could lead to a crack and a path for water to flow through. The failure of Walter Bouldin Dam may have been due to poor compaction along the power plant wall.

H. SOME GENERAL OBSERVATIONS

- The reader will benefit the most from a careful reading of the original case histories because of the details that are provided therein.
- Usually, it is a combination of factors, such as weaknesses, defects, and human mistakes, rather than a single one of these factors, that results in an accident or a failure.
- Quite often, incidents are triggered by an unusually high reservoir level or a fast rate of filling of the reservoir.
- For internal erosion to initiate, usually a defect is required that allows a concentrated leak to form.
- It is often the details of design and construction that can lead to internal erosion; unfortunately, these details are not always known or noticed.

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PICKETBERG DAM, SOUTH AFRICA
Failure

This is one of the better case histories because of the clear explanations of internal erosion by piping and the cause of cracks in the fill, which are well illustrated. The authors show how cracking and/or hydraulic fracturing of fill adjacent to the outlet conduit likely initiated a concentrated leak through the entire width of the embankment which led to internal erosion and the breach.

A number of other factors are listed as contributing to the failure:

- dispersive fill
- poor compaction
- collapse potential of the fill and the foundation
- construction over the old dam which resulted in cracking of the new embankment
- incomplete collars*
- encasement details

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* Reclamation's current practice is not to use collars around an embedded conduit because of difficulties in obtaining good compaction around the collars and conduit.

PICKETBERG DAM, SOUTH AFRICA - FAILURE - FIRST FILLING

Factors Contributing to and Resisting Internal Erosion

INITIATION A transverse crack likely developed through the width of the dam next to conduit which provided a path for a concentrated leak		CONTINUATION No filter available to stop internal erosion		PROGRESSION - Erosion pipe enlarges and 5 weeks after first filling, major leakage appeared near d/s conduit		DETECTION/ INTERVENTION UNSUCCESSFUL		BREACH MECHANISM - Gross and rapid enlargement of erosion pipe - less than 1 day	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Incomplete concrete collars around conduit*	Conduit encasement placed on bedrock at 2 locations	No filter around conduit		Dispersive fill material	Part of core treated with gypsum to resist dispersivity	In less than 1 day after major leakage appeared, the dam breached		Entire dam section erodible	Zoned dam
Some fill was low density, nonuniform, and dry of optimum. A few cracks on U/S face of embankment.	Modest fill rate - 33 ft in 5 weeks (about 1 ft/day)	No embank-ment filter		Erosion pipe remains open since concrete around conduit formed a 'roof'	Collars on top & sides of conduit	Major leakage appeared suddenly near outlet conduit		Drawdown capacity likely low	Dam crest remained intact; thus less flow
Loose clayey sand under d/s shell had collapse potential	Compacted fill	Dispersive clay core		Alluvium was erodible	Broadly graded fill	Sinkholes not discovered			
First filling	Pipe encased in concrete				Typical PI = 9				
Some overhangs in concrete encasement	Overhangs not through entire fill				Compaction moisture not excessively low				
Hydraulic fracture possible	Zoned dam								

* Reclamation's current practice is not to use collars around an embedded conduit because of difficulties in obtaining good compaction around the collars and conduit.

OMAI TAILINGS DAM, GUYANA

Failure

The failure of Omai Dam, a tailings dam located in South America, was a complex series of events. It was so complex that any risk analysis would not have identified the actual failure sequence that occurred, according to author Steve Vick. Vick, with a background in risk analysis, goes on to observe that a risk analysis, however, would have identified internal erosion around the outlet conduit and piping of filter sand into the rockfill as major risk contributors instead of focusing just on upstream slope stability.

Vick noted a number of flaws that allowed the failure to occur. These include design errors, construction errors, and human errors. Design errors were the absence of seepage protection around the outlet conduit and a flawed filter design. Construction errors were severe segregation of the transition filter zone and elimination of the zone in some areas. Human errors included not rectifying the absence of the transition filter and elimination of earlier seepage protection around the conduit.

OMAI TAILINGS DAM, GUYANA - FAILURE

Factors Contributing to and Resisting Internal Erosion

INITIATION - Concentrated leak around outlet conduit		CONTINUATION - Gross filter incompatibility between sand filter and rockfill. Longitudinal spreading of seepage resulted in sand filter moving into rockfill. Internal erosion around conduit produced upward-stoping cavities within the core. Underdrains became blocked.		PROGRESSION - Water rose in rockfill and saturated hanging filter which dropped down into rockfill and removed support from the core.		DETECTION/INTERVENTION UNSUCCESSFUL - A 4 PM inspection showed nothing amiss. In the midnight darkness, an alert truck driver noticed water issuing from one end of dam. At dawn, another discharge at the other end occurred with extensive cracking.		BREACH MECHANISM - Core tilted and cracked longitudinally with massive internal erosion and release of reservoir.	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Geometry - a thin, sloping sand filter underlying the core and overhanging the rockfill without proper protection		Downstream portions of the conduit were backfilled with sand that was not filtered at its contact with adjacent rockfill	Filter d/s of core was present	Poor details of conduit design	Powdered bentonite was sprinkled on surface of backfill lifts	Human error - did not recognize effect of rise in water level in rockfill	Rise in water level in rockfill began almost 2 years before failure	Failed area spread rapidly longitud-inally	D/S rockfill section had large flow through capacity
Portions of the backfill around the outlet pipe were undercompacted		Transition rockfill material likely segregated during placement	Mine waste material placed d/s of rockfill except at abutments	Thin core	Gradient across core less than 1	No indication from piezometers in core of impending problems	Dam was well instrumented		Dam crest did not breach
Movement of filter drain material into rockfill		One gradation test during construction showed rockfill coarser than specified				About 1/4 of outflow was contained	Piezometric data revealed rise in water level within rockfill		

GHATTARA DAM, LIBYA

Failure

Ghattara Dam was of modern design. It contained a chimney drain, a blanket filter, and a toe drain. Constructed from 1970 to 1972, it failed in 1977. The author points out that in this semi-arid region cracking of the core was likely, particularly around the conduit where compaction may have been poor. Rapid filling of the reservoir and moderately dispersive fill material also contributed to the failure. It is believed that internal erosion initiated near the downstream end of the conduit and progressed rapidly backwards.

Foster and Fell [8] in their study of this case history raise the question of why the dam failed since it had an embankment filter. It is only one of two cases where an embankment dam failed by piping through the dam despite the presence of an embankment filter. They hypothesize that the inclined filter did not extend into the conduit trench below the level of the general foundation; thus, a continuous path of backfill may have been present with no filter protection against internal erosion.

GHATTARA DAM, LIBYA - FAILURE

Factors Contributing to and Resisting Internal Erosion

INITIATION - Cracking adjacent to or above outlet conduit was possible which provided path for concentrated leak		CONTINUATION - Probably no filter or defective filter around outlet conduit.		PROGRESSION - Erosion pipe enlarges rapidly		DETECTION/ INTERVENTION UNSUCCESSFUL - 10 am, toe dry; 11:30 am muddy water; 12:00 noon erosion of d/s toe; 1:10 PM crest was breached.		BREACH MECHANISM Uncontrolled flow erodes d/s slope back to crest, crest collapses, and breach forms	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Sudden filling of reservoir (2.7 m/day) after 5 years of low reservoir levels	Culvert founded on bedrock	Probably no filter around conduit	Chimney drain, blanket filter, and toe drain	Moderately dispersive soil	Silty clay fill with PI = 23	Failure occurred quickly-infrequent inspections	Technician on site	Homogeneous section at conduit	
Fill susceptible to desiccation cracking during 5 years of low reservoir level		No filter between core and alluvium and rock in cutoff trench		Erodible soil				Moderately dispersive soil	
Compaction of fill around conduit was likely poor	Compacted fill in main part of dam			Cohesive fill able to hold a 'roof'				Erodible soil	
								Outlet too small to lower reservoir rapidly	

STOCKTON CREEK DAM, CALIFORNIA

Failure

Stockton Creek Dam was constructed according to good modern practice in the early 1950s. The cause of the failure is believed to be cracking of the embankment, which led to an initial, concentrated leak and erosion of the low plasticity, clayey sand core.

James Sherard, who studied the failure in some detail, concluded that a near-vertical step of about 20 feet in height on the right abutment led to the differential settlement crack. Sherard studied under the guidance of Karl Terzaghi, and over the years has investigated numerous embankment dam failures.

Two articles about the failure by Sherard are included. The earlier and longer account was for his PhD thesis at Harvard. The second account, which was written about 20 years later, summarizes the first and is from a chapter on "Embankment Dam Cracking," Embankment-Dam Engineering, Casagrande Volume [9].

STOCKTON CREEK DAM, CALIFORNIA - FAILURE

Factors Contributing to and Resisting Internal Erosion

INITIATION - Concentrated leakage through a crack caused by differential settlement adjacent to a near-vertical step in right rock abutment		CONTINUATION - No filter or zoned embankment		PROGRESSION - Erosion of fill progresses		DETECTION/ INTERVENTION UNSUCCESSFUL - At 8 PM dam was inspected and OK; at 8 AM next morning, it had breached		BREACH MECHANISM - Erosion led to 40' wide breach	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Near-vertical step in abutment may have caused low stress zone and hydraulic fracture	Rock surfaces were cleaned; fill was compacted against it in a moist state with careful hand compaction	Homo-geneous embank-ment	Rock toe	Fill had low plasticity	Fill material was not highly erodible	Failure occurred at night	Dam was inspected during filling until 8 PM of the night before failure	Homo-geneous section	Rock toe, but only in valley section
Average water content of the fill was about 2-4 percentage points dry of optimum	Good modern construction - fill placed in 6" layers with sheepsfoot roller with control of water content and density	No chimney drain or filter		Fill material was rigid and allowed roof to form	Clayey sand (SC-SM) fill				
Fill material was susceptible to settlement cracking									
Rapid rise (20 feet in one day) in reservoir during initial filling	Reservoir was at a depth of 40 feet for several months below breached area								

LAKE FRANCIS DAM, CALIFORNIA

Failure

Lake Francis Dam, which was constructed in 1899, is an example of a dam that followed empirical construction methods rather than modern engineering design and construction methods. Most of the dam was placed in 6- to 8-inch-thick layers and compacted by the travel of scraper teams passing over the fill. Much of the fill was placed without any moisture because it was difficult to obtain sufficient water to sprinkle the fill. The final section of the embankment was dumped because construction time was running out before the floods came.

Although there is limited information on the details of the failure, this dam is more or less typical of many built in that era and of many that failed. And this is the reason it was included. From our perspective of modern geotechnical engineering and modern construction equipment and construction control, one tends to forget about early methods of dam construction. This case history is one of over 50 case histories studied by James Sherard for his Doctor of Science thesis at Harvard University. All the case histories are included in Reclamation's Technical Memorandum 645 [7].

LAKE FRANCIS DAM, CALIFORNIA - FAILURE - FIRST FILLING

Factors Contributing to and Resisting Internal Erosion

INITIATION - The 1899 embankment, which was constructed dry with very little compactive effort, settled considerably on the initial reservoir filling. A large stream of water came out of the toe of the embankment near a 36" cast-iron outlet pipe. A few minutes later a stream of water broke through a crack near the right abutment.		CONTINUATION - No filter around outlet conduit or within embankment		PROGRESSION - Quick erosion of the fill		DETECTION/ INTERVENTION UNSUCCESSFUL - A few minutes after leak from the outlet pipe, a stream of water broke through a crack, about 20' above the stream bed, near the right abutment		BREACH MECHANISM - The stream of water quickly eroded the d/s slope by backward erosion. The crest collapsed, and the reservoir emptied in an hour forming a 98' wide breach.	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Construction was behind schedule and closure section was not placed in layers but dumped. Closure section was highly permeable.	Non-closure section fill was spread in 6-8" layers, moistened, and compacted by scraper teams	Homo-geneous section		Homo-geneous section	Fill was a mixture of clay, sand, and gravel	Rapid failure		Homo-geneous section	
Soil layer covering abutments and foundation was not removed.		No chimney filter		Closure section erosive	Fill had a LL=35 and a PI=15.				
Not a modern, engineered design or controlled construction				Very dry fill in closure section					
Difficulty in obtaining water, and much of the fill was placed dry									
Rapid filling of reservoir									
Steep abutment									

WALTER BOULDIN DAM, ALABAMA

Failure

The official cause of the failure was an upstream slide, according to three experienced engineering consultants retained by the Alabama Power Company. Ralph Peck, however, disagreed with this cause of failure and said it was the result of subsurface erosion. Thomas Leps, who offered expert testimony during a Federal Power Commission hearing, agreed with Peck and said piping of the foundation soil was the likely cause. Articles by both authors are included with the summary.

WALTER BOULDIN DAM, ALABAMA - FAILURE
Factors Contributing to and Resisting Internal Erosion

INITIATION - Fractures in the Cretaceous Formation due to foundation unloading or due to excessive grouting pressures provided path for concentrated leak		CONTINUATION - No filter within embankment		PROGRESSION - Backward erosion along sides of power plant or through the Cretacious Formation		DETECTION/ INTERVENTION UNSUCCESSFUL - At 9:45 PM, guard inspected dam. At 1 AM, he noticed muddy water; shortly thereafter, the dam failed.		BREACH MECHANISM Rapid enlargement of erosion pipe and collapse of crest into the pipe	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Fractures wider than 1"opened up during construction in the Cretaceous Formation, but were not sealed	Compact-ed embank-ment	No chimney filter within embankment		Two overhangs on the sides of the power plant		Unseen leakage entered tailrace, below tailwater level, on both sides of the powerhouse	Observable leakage was collected and monitored	Homo-geneous dam	
Post-construction grouting may have caused hydraulic fracturing. Post-failure investigations showed extensive grout travel transverse to the dam axis.		The grout curtain was not closed on both sides of the powerhouse		Difficult to compact backfill against power plant		Embankment-Cretacious contact covered by riprap	Regular inspection of dam by on-duty guards		
Forebay's natural earth blanket was non-uniform and allowed seepage to bypass it. Seepage, springs, and sand boils occurred at toes of wing dams.		No subsurface toe drain		Cretacious sediments were highly erodible and pervious		Rapid failure			
Inadequate review of design and construction		Nearly a homo-geneous embankment							

ULJUA DAM, FINLAND - ACCIDENT
Factors Contributing to and Resisting Internal Erosion

INITIATION - After 20 years of clear seepage from bedrock fissures d/s, it became muddy and increased from 5 to 30 l/s.		CONTINUATION - Backward erosion of basal glacial till under dam and glacial core into fissures in rock foundation caused an erosion tunnel to form.		PROGRESSION - Erosion tunnel continued into core and U/S filter and sinkholes formed in reservoir.		DETECTION/ INTERVENTION UNSUCCESSFUL - Muddy water leaked from bedrock fissures at end of tailrace structure. The crest of dam dropped 3 m into the erosion tunnel.		HEROIC INTERVENTION - NO BREACH. Rapid action in following emergency plans prevented failure. Later, foundation was grouted.	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Embankment founded on glacial till		Glacial till in foundation not filter compatible with fissures in bedrock		Glacial till sensitive to erosion	Zoned embankment with filters controlling erosion of fines through embankment.	Erosion of silt into tailrace water was not detected	Dam put under continuous surveillance and reservoir lowered	Within 45 minutes, the first load of till was dumped into sinkhole on crest after crest dropped 3m.	
Open fissures in bedrock foundation below erodible material		No filter or seepage barrier along seepage path		Cor material is erodible glacial till	Glacial till had enough coarse material to keep flow limited		Divers found sinkholes in reservoir and tracer showed conductivity between sinkholes and leakage point. Sinkholes quickly filled with soil.	Reservoir lowered immediately from 77.8 m to 75 m	
2 m fluctuations in reservoir level several times a day							16 days from notice of muddy leakage until crest dropped into erosion tunnel. Many tools used to find cause of leak.	Till and rockfill dumped on U/S and D/S slope	

ULJUA DAM, FINLAND

Accident

Seepage of about 5 l/s had been observed from bedrock fissures at the end of a tailrace tunnel since first filling in 1970. Twenty years later the water turned muddy and increased to 30 l/s, and a number of large sinkholes were found on the lake bottom near the dam. Two weeks later a sinkhole formed near the upstream side of the crest, and part of the crest failed. Only swift action saved the dam from total collapse. Repairs exposed an erosion channel about 3 meters in diameter, which was oriented downward through the core and extended into the glacial fill under the dam.

Of special note is figure 3 in the report that shows the actual erosion channel through the cross-section of the dam. Horizontal, open joints in the rock, and the fluctuation of the water level several times a day for power operations may have contributed to the internal erosion process.

Rapid and heroic efforts in following emergency plans helped avert a failure. A column "Heroic Intervention" is included in the summary table to reflect these efforts.

LANGBORN DAM, NORWAY

Accident

This case history is somewhat unusual because internal erosion was not occurring in the embankment; rather, it was occurring in left abutment itself. A safety evaluation following the guidelines of Reclamation's Safety of Dams program indicated the most serious weakness in the dam was the left abutment. The potential failure mechanism was progressive sliding of the abutment that could lead to failure of the embankment.

Initially, in 1958 during first filling, excessive seepage, erosion, and a slide occurred near the left abutment. Over the years, remedial measures in the form of geotextile filters and drainage ditches had failed to lower the ground water table in the downstream slope of the abutment, and slides continued to take place.

In 1990, sinkholes on the surface of the left abutment were found indicating internal erosion was progressing, probably at the interface of silt material and open-work gravel and cobbles. In 1995, a new slide prompted remedial measures which included horizontal drains and a downstream stability berm.

LANGBORN DAM, NORWAY - ACCIDENT
Factors Contributing to and Resisting Internal Erosion

INITIATION - Seepage flowing through natural coarse layers eroded adjacent silt layers in the abutment. Seepage may have also dissolved minerals in abutment		CONTINUATION - Internal erosion of silt into the coarser layers leads to clogging of geotextile drain/filter at toe of slope due to transport of fines and growth of iron bacteria, thereby increasing water pressures.		PROGRESSION - Internal erosion opens up additional flow paths and dissolves minerals in the abutment and results in progressive caving and the formation of sink holes		DETECTION/ INTERVENTION UNSUCCESSFUL - Continuous measurement and evaluation combined with numerous remedial measures prevented instability of abutment.		BREACH MECHANISM No breach due to remedial measures.	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Abutment consists of silt, sand, and layers of coarser material and cobbles		Slides on the d/s slope of the abutment in 1958, 1966, 1994, and 1995	Drainage ditches and geotextile filters installed at toe of slope in 1958, 1966, 1972, and 1986 provided temporary help	Seepage water is dissolving iron minerals in the abutment			Continuous measurement and evaluation.		
First filling		Ground water pressures gradually increase with clogging	Ground water pressures temporarily decrease with use of filter blankets and shallow ditches	Silt material had an average diameter of 0.4 mm and was erodible			Deposits of silt upstream of measuring weir was observed		
A blanket to protect the abutment was ineffective				Sinkholes had formed since 1990, 32 years after 1st filling			Horizontal drains decreased ground water pressures and berm of free-draining material to stabilize slope in 1995		

TETON DAM, IDAHO

Failure

Much has been written about the Teton Dam failure. It was the highest dam designed by Reclamation when it failed, and the consequences were severe. The primary purpose of the summary is to provide basic information related to the failure. In addition, the seven most likely mechanisms that may have initiated a concentrated leak that led to failure are listed in the summary. A few of the referenced papers are included for further reading. While the exact cause of the failure is not known, it is commonly accepted that a concentrated flow of high pressure reservoir water passed through open cracks in the rock upstream of the key trench on the right abutment and eroded the very erodible silt fill material, which was then carried into large open cracks in the rock downstream of the key trench. This forms the basis of the table of factors contributing to and resisting internal erosion.

A secondary purpose is to recognize that many different factors contributed to the failure. Geologic factors, design decisions, construction control, and human factors were all part of the story. Sherard identified a number of human factors, "the bureaucracy problem," such as: inbreeding; travel restrictions; no consultants; chimney drains and filters were not considered necessary, at that time; lack of cooperation between the construction and the design staff; and no independent review group to challenge designs.

TETON DAM

Dam Type: Compacted, central core, zoned earthfill. Reclamation's design of the late 1960's.

Location: Idaho, USA

Type of event: Failure on first filling. Commonly accepted cause was due to erosion of core material through foundation voids and cracks in the area of the right abutment key trench.

Incident Date: June 5, 1976, During Initial Filling.

Date of construction: 1972 through 1976

Description of Incident: A heavy spring runoff caused a rapid rise in the reservoir level. It was intended that the filling rate would be restricted to one foot per day. During May 1976, the filling rate reached about four feet per day. Only the auxiliary outlet works were in operation, resulting in virtually no control of the reservoir filling rate. The reservoir was just 3 feet below the spillway crest on the morning of failure.

Before June 3, 1976, no springs or other signs of seepage were noticed downstream of the dam. On June 3, clear water springs coming from joints in the right side canyon wall appeared at distances of about 1,300 and 1,600 feet downstream (Fig. 1).

On June 4, a spring of clear water of about 20 gpm was observed flowing from the canyon wall talus about 400 feet downstream of the right abutment groin.

On the morning of June 5, muddy water was flowing at about 20 to 30 cfs from the talus on the right groin, and the flow increased noticeably in the following three hours.

At about 10:30 a.m., a leak of about 15 cfs appeared on the face of the embankment. The new leak increased and appeared to emerge from a "tunnel" about 6 feet in diameter and extending at least 35 feet into the embankment. The tunnel became an erosion gully developing headward up the embankment and curving toward the abutment.

At about 11:00 a.m., a whirlpool appeared in the reservoir opposite the ever-growing gully on the downstream slope of the dam. At 11:55 a.m., the crest of the dam began to collapse, and minutes later the dam was breached.

Only about five hours elapsed from the time observers noticed the small muddy flows to the breaching of the dam. Fourteen people were killed and more than $400 million in damages resulted from the failure.

Description of Geology and Foundation: The dam site is located in a steep-walled canyon. The volcanic rock that forms the canyon walls and foundation is an intensely to moderately jointed rhyolitic welded ash-flow tuff. The welded tuff is characterized by the presence of prominent and abundant open joints and localized fissures, especially in the upper part of the abutment. Horizontal to low angle foliation is common to tuff outcrops.

At the right abutment, the prominent bedrock joint systems are generally flat-lying upstream and approximately vertical downstream. The joints are closely to moderately spaced, conspicuously open, and unfilled, the parting commonly being 1/4 to 2 inches (0.6 to 5 cm). The vertical joints downstream from the dam axis strike across the canyon at an angle of about 45 degrees with the canyon wall, with a bearing of roughly north 20 degrees west. Hence, they provided multiple planes of freely discharging leakage from the right abutment, but practically no such leakage capacity around the left abutment [1].

In the early stages of design, during the test grouting program, it was concluded that the upper 70 feet of rock on both abutments was very open jointed and grouting costs would be excessive; consequently, the deep key-trench design was adopted. The key-trench excavation had steep sides and many local irregularities, including near-vertical faces and occasional overhangs. In the vicinity of Station 14+00, where failure is considered to have started, were several sets of major, through-going joints.

Penman [2], a British geotechnical engineer, raises some thoughtful questions about the choice of the dam site. How was such an unsuitable site chosen for the dam? Eight sites on the Teton River and a tributary were investigated over the years and rejected. Was the ill-fated dam site chosen under pressure from outside sources? Was the inadequate foundation treatment the consequence of a limited budget?

Description of Dam, Design, and Construction:

Height: 305 ft (93 m)

Reservoir Volume: 288,250 acre-feet (355,550 x 10^3 cu meters)

Embankment: Zoned earthfill with a central core and no filters. See figure 2.

Crest length: 3,100 ft (945 m)

Teton Dam was a central core, zoned earthfill structure with a height of 305 feet above the riverbed and 405 feet above the lowest point in the foundation. The crest of the dam was approximately 35 feet wide at an elevation of 5332 feet. No instrumentation was installed other than surface measurement points.

A cutoff trench was excavated through alluvial material to a maximum depth of 100 ft (30 m) so that zone 1 material could be placed on a rock foundation. The cutoff extended up the sides of the abutments and is referred to as a key trench above elevation 5100. The key trench was excavated to a depth of 70 ft (21 m); it had a bottom width of 30 ft (9 m) and steep side slopes of 0.5:1. The key trench was omitted under the spillway; blanket grouting of the welded tuff was used to strengthen the foundation.

Zone 2 material was placed adjacent to zone 1, upstream and downstream. Zone 2 was composed of selected sand and gravel from the Teton River flood plain and compacted to a relative density of at least 70 percent. A filter was not placed downstream of zone 1 material. Zone 2 material did not meet filter criteria with respect to zone 1 material.

A. Zone 1 Material. - Zone 1 soil was a highly erodible, brittle windblown soil, derived from loess deposits, because more suitable material was not readily available. Natural loess is a meta-stable skeleton of silt particles, held together by a thin coating of clay, which forms a strong bond at low water contents. Mineralogical studies have shown the silt preserves a slightly open structure, even under the heavy compaction of sheepsfoot rollers, which allows collapse settlement on wetting [2]. When compacted, the unwetted zone 1 had considerable stiffness and strength resulting from very high suction pore pressures. This is illustrated by the unwetted, steep slopes remaining after the dam failed. While unwetted fill exhibits considerable stiffness, one-dimensional consolidation tests that were wetted to destroy the initial suction showed collapse settlement.

Other important properties of zone 1 material are summarized as follows [3]:

1. The zone 1 silt, ranging from slightly cohesive to cohesionless (plasticity index generally from 1 to 7), is a common type of soil in the Midwestern USA. Many earth dams have been built with practically identical soil over wide geographic areas, such as western Nebraska, including some of the main Reclamation dams.

2. The material is not dispersive; that is, it does not have a high content of dissolved sodium in the pore water, causing repulsive forces between clay particles. Nevertheless, the material is among the most erodible fine-grained soils in nature. Compacted specimens erode in the pinhole test as readily as a highly dispersive clay, an unusual property for a non-dispersive soil. This means that a small concentrated leak with a velocity of only a few centimeters per second will erode the compacted material.

3. Filter tests showed the material could be carried into rock cracks of width only slightly larger that 0.1 mm, and would easily be carried into cracks with widths of 0.2 mm of larger.

4. When compacted in the laboratory at water content near or slightly below Standard Proctor optimum, the material is very stiff and brittle, compared to similarly compacted specimens of other fined-grained impervious soils.

5. There are few impervious soil deposits in nature which are more uniform in visual appearance or have a smaller range in gradation and Atterberg Limits.

Zone 1 material was compacted to at least an average density of 98 percent of Bureau of

Reclamation (Reclamation or USBR) Standard Proctor density, at an average moisture content between 0.5 and 1.5 percent dry of optimum moisture content. The averages of moisture content and density appear to be very good for the entire dam.

B. Low Density Fill and the Wet Seam. - After the failure, however, it was discovered that low density fill was placed, which surprised everyone. This low density fill was placed primarily during May 1975, following the winter shutdown. Found from a detailed study of the compaction control tests, Leonards and Davidson [4] found that layers of fill in the key trench were placed up to 2.2 percent dry of optimum (between El. 5185 and 5200 and Stations 13+90 to 14+40), where failure is thought to have initiated. During investigation of the right abutment shortly after failure, the Independent Panel found an extremely wet layer of fill extending across the full width of the cutoff trench at El. 5215 at Station 13+15 [2].

Leps commented on the low moisture and density layers and raised a serious question [5]:

> "The key deficiency was placement at moisture contents which were excessively dry of optimum, resulting in low density horizons, wherein dry densities in situ of as low as 80 pcf were discovered as compared to the average of 99 pcf for all Zone 1 compacted fill. In-situ dry densities of as low as 85% of laboratory optimum were measured. Hence, it is clear to this discusser that horizons of such low density material were proven to exist, and that their existence was inevitable given the combined effects of (a) permission to place Zone 1 as dry as 3.7% dry of optimum and (b) the reported inefficiencies in moisture conditioning and blending borrow from excessively dry borrow sources, an inadequate construction procedure which guaranteed that sizeable areas of placed fill were to some degree even drier than the limited test data indicated (drying by wind and solar effects).

Incidentally, it is curious that USBR permitted Zone 1 fill placement at moisture contents as dry as 3.5% below optimum when its own laboratory research, performed as long ago as 1942, showed that placement of impervious fill at moisture contents drier than about 2% below optimum would result in abrupt consolidation upon subsequent saturation (Laboratory Report No. E.M.-18.5)."

A wet seam was found during the investigation of the left abutment in October 1977. The wet seam, with a total thickness of about 3 to 4 feet, was not completely continuous but consisted of 3- to 8-inch-thick lenses, covering an area of at least 5 acres [6]. The most likely reasons for the existence of the wet seam include: a rainy period during construction [7]; penetration of reservoir water into the fill which was placed dry of optimum [2]; frost action [8]; and hydraulic fracturing [3].

The Interior Review Group noted additional factors that explain the low density layer: (1) unsuccessful attempts to mix dry fill with wet soil on the fill surface; (2) deficiencies in earthwork control practices, i.e., (a) zone 1 fill placement began on May 1, 1975, but the earthwork inspection staff did not reach full strength until May 12, 1975; (b) frequency for performing earthwork control tests was considerably less than the required minimum. Approximately 52,000 cubic yards of fill were placed between May 1 and 12, and the specifications required one control test for every 2,000 cubic yards of fill placed, or a total of 26 control tests; only 8 tests were performed.

C. Open Cracks and Foundation Treatment. - The open surface cracks on the right abutment undoubtedly played a key role in the failure. Sherard summarized his findings as follows [3]:

> "A major element of the Teton Dam story has to do with the sealing of the open rock foundation cracks under Zone 1 on the right abutment. The wide-open surface cracks were treated by gravity grouting during the first part of the construction. However, this surface crack filling was abandoned near the location where the failure occurred (about Station 14+00). Subsequently the wide surface cracks under Zone 1 embankment were left open and untreated from about Station 14+00 to the right end of the dam . . . These facts support the conclusion that USBR bureaucratic restriction had a major influence on the failure.
>
> When the excavation was made for the 70-ft. deep trench and the rock foundation surface was uncovered upstream and downstream of the trench by excavation of the colluvial overburden, many large cracks in the rock were exposed to view. These were commonly several inches in width, frequently up to 1.0 ft. Some were open (empty), some were silt-filled and some partially filled. During construction of the dam the USBR geologists made an excellent map, showing location, widths and filling of these cracks . . . This map shows literally many dozens of wide-open cracks exposed in the foundation excavation from Station 16+00 to the right end of the dam.
>
> These cracks in the foundation rock under the main Zone 1, many completely open, over several hundred feet of the dam length, were exposed for inspection by all parties for about 2 years before they were covered by the dam. Since there was no provision in the contract for sealing these surface cracks, the inspection forces devised a method of filling them by "gravity" or "slurry" grouting in stages above the rising embankment surface. This consisted of bringing in transit-mix concrete trucks filled with cement-water grout, and pouring the grout by gravity into open cracks, working from the rising embankment surface. No piping or grout pumps were used for this activity.
>
> When the embankment construction reached approximate El. 5200 on the right side, roughly at Station 14+00, this gravity grouting was abandoned. After this date no further sealing of surface rock cracks on the right abutment was carried out during the remainder of the dam construction.
>
> During my site visit of September 1976 I discussed this problem in detail with the responsible inspection staff, trying to understand how this vital piece of work could

> have been stopped . . . The inspectors generally stated that the gravity grouting was stopped on orders from "above" even though there were still many open cracks in the foundation."

Penman commented [2]:

> "It is evident from the specification that the design regarded the bedrock as being free from open fissures and relatively impervious. It called for careful cleaning of the rock surface a few meters in front of the advancing core fill and strickly controlled compaction of a slightly wetter silt against the rock. The actual rough and highly fissured surface of the rock was so completely ignored by the specification that it was difficult to believe that the specification was intended for this dam. . . . It is obvious that a smooth surface should have been provided for the silt contact over a sufficient dam width to ensure that the average total stress across the contact and the hydraulic gradient along it, would have reduced seepage to non-erodible flows. Such a surface could be provided by a thick layer of reinforced concrete placed over and keyed to the bedrock."

Leps would have designed a more conservative key trench, as follows [5]:

1. The side slopes should have been no steeper than 1:1. For this requirement, and including the following concepts, the trench need not have been excavated to such a large depth.

2. The entire rock surface of the trench, side, and bottom, should have been paved with a concrete slab of about 18 inch thickness.

3. The entire paved surface should have received a pattern of consolidation grouting to a depth of say 50 feet.

4. At least one deep grout curtain was needed.

D. The Grout Cap. - The concrete grout cap was only 3 feet wide, and the cracks in the bedrock could transmit water pressure of the almost full reservoir head to the upstream edge of it. Fissures on the downstream side of it could readily conduct water towards the low water table. The resulting very high hydraulic gradient (estimated on the order of 7 to 10) through the silt core resting on the grout cap could be expected to cause erosion, even without consideration of reduction of total stress due to arching in the cutoff trench [2].

Possible Failure Mechanisms: In a 1987 review of the failure, Seed and Duncan [7] listed seven possible trigger mechanisms that led to failure. The paper is included in this section and provides additional details. The possible trigger mechanisms listed are:

1. Flow of water through the grout curtain just below the grout cap, leading to erosion of soil on the base of the key trench.

2. Hydraulic fracturing or differential settlement in the key trench fill leading to cracking across the fill and resulting soil erosion.

3. Hydraulic separation between the key trench and the base of the trench permitting water to flow, with accompanying erosion, from an upstream open joint along the base of the trench, over the grout cap and into a downstream joint.

4. Seepage through the key trench fill, with accompanying erosion, from an open joint upstream, over the grout cap and into a downstream joint. At the time of failure, the hydraulic gradient along such a flow path was probably of the order of 7 to 10.

5. Seepage through the soil near the base of the key trench, facilitated by sloughing of wetted fill into open joints, thereby progressively increasing the hydraulic gradient.

6. The possibility that a dry seam may have existed in the right abutment key trench and that collapse of this seam on wetting may have provided a flow path from open joints on the upstream face of the trench to open joints on the downstream side.

7. The possibility that a wet seam existed in the right abutment key trench permitting seepage directly through the seam and associated internal erosion.

Peck summarized the failure as follows [9]:

> "Upstream of the seepage barrier there was ample opportunity for the reservoir water to reach the barrier in quantity through the joint system in the rock. The physical conditions were fully satisfied for water flowing under high pressure to attack the lower part of the key-trench fill along open joints, some of which were found to transmit water freely through the grout curtain, particularly through the upper part near the grout cap. The attack was fully capable of quickly developing an erosion tunnel breaching the key trench. Arching at local irregularities, loose zones of fill at reentrants, and local cracking may have contributed to the success of the attack and determined the precise location. Hydraulic fracturing, according to analytical studies, may also have been responsible for the initial breaching of the key-trench fill. Conditions were favorable for escape of the water and eroded solids into the joints of the rock downstream, for discharging the water against and along the interface of the right abutment of the dam and the embankment, and for development of the erosion feature that ultimately breached the entire dam.
>
> "The precise combination of geologic details, geometry of key trench, variation in compaction, or stress conditions in fill and porewater that caused the first breach of the key-trench fill is of course unknown and, moreover, is not relevant. The failure was caused not because some unforeseeable fatal combination existed, but because (1) the many combinations of unfavorable circumstances inherent in the situation were not visualized, and because (2) adequate defenses against these circumstances were not included in the design."

It appears that the designers did not anticipate or visualize possible failure mechanisms. Hilf [8] commented that the design concept was that an "impervious plug" would be formed within the key trench. "It was not contemplated that this well-compacted soil would crack. . ."

Clearly many aspects of the site and the embankment design contributed to the failure. The Independent Panel concluded that:

> "The fundamental cause of failure may be regarded as a combination of geological factors and design decisions that, taken together, permitted the failure to develop. The principal geologic factors were (1) the numerous open joints in the abutment rocks, and (2) the scarcity of more suitable material for the impervious zone of the dam than the highly erodible and brittle windblown soils. The design decision included among others (1) complete dependence for seepage control on a combination of deep key trenches filled with the windblown soil and a grout curtain; (2) selection of a geometrical configuration for the key trench that encouraged arching, cracking and hydraulic fracturing in the brittle and erodible backfill; (3) reliance on special compaction of the impervious material as the only protection against piping and erosion of the material along and into the open joints, except some of the widest joints on the face of the abutments downstream of the key trench where concrete infilling was used; and (4) inadequate provisions for collecting and safe discharge of seepage or leakage which inevitably would occur through the foundation rock and cutoff systems."

Lessons Learned: Leps concludes that the lessons to be learned from the failure of Teton Dam do not represent anything new for the profession, but are reminders of points sometimes ignored or forgotten [1].

1. The responsible design engineer should be required to visit the construction site, perhaps monthly.

2. The downstream contact of an impervious embankment zone, whether against foundation material or against a more pervious embankment zone, must be protected against piping by use of filter zones.

3. In grossly pervious foundation bedrock, a single grout curtain should not be relied upon to be adequately effective.

4. Whenever impervious borrow exists at moisture contents severely below optimum, it should be brought to near optimum moisture content in the borrow area.

5. Deep, narrow, key trenches in bedrock should be avoided because they invite arching of backfill.

6. Because of inevitable hydrologic uncertainties, it may be impossible to control the rate of initial reservoir filling. Hence, the dam designer should consider that the reservoir may fill very quickly, regardless of the generally assumed merit of controlling the filling rate.

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TETON DAM, IDAHO - FAILURE - FIRST FILLING

Factors Contributing to and Resisting Internal Erosion

INITIATION - A concentrated flow of reservoir water passed through open cracks in the rock and eroded the silt in the key trench. Hydraulic fracturing, collapse of low-density dry silt, and cracking may have contributed to the initiation of internal erosion.		CONTINUATION - The eroded silt was carried into open cracks downstream of the key trench because the exit seepage was not filtered.		PROGRESSION - Reservoir water under high pressure continued to erode the silt core. An erosion tunnel and a whirlpool formed.		DETECTION/ INTERVENTION UNSUCCESSFUL - Breaching occurred only 5 hours after muddy water was first observed		BREACH MECHANISM Progressive erosion led to collapse of the crest and breaching of the dam	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Gravity grouting of wide cracks in the foundation rock under zone 1 core. Gravity grouting was stopped above El. 5200.	Field inspection crew filled surface cracks in the foundation rock under zone 1 core with gravity grout below El. 5200.	No filter on the D/S side of the erodible zone 1 core, in either the key trench or between zone 1 and 2	Zoned embank-ment	Zone 1 silt was highly erodible - like dispersive clay		Reservoir could not be lowered quickly - outlet works not finished	At 1300& 1500 feet D/S, clear seepage was observed 2 days before failure; at 400 feet D/S 1 day before failure; muddy water at toe 5 hours before failure	Nearly homo-geneous section of erosive silt	
Very steep and deep right abutment key trench with overhangs. Arching of soil in key trench.	A modern, well compacted dam with average moisture content 0.5-1.5% dry of optimum	Zone 2 material did not meet filter criteria with respect to zone 1 material		Stiff silt could form a roof		Failure occurred quickly			
Human errors in design and construction. No defenses in depth. Cracking or concentrated leakage not visualized.	Zoned embankment	Open cracks on the d/s side of the key trench		Silt core had a very small range in gradation and low plasticity		No instru-mentation in embankment, but observation wells showed rapid rise in ground water table in right abutment	Construction workers were at the site		
Rapid first filling - about 4 feet /day.									

FONTENELLE DAM, WYOMING - ACCIDENT - INCIDENT NO. 1
Factors Contributing to and Resisting Internal Erosion

INITIATION - Concentrated flow through untreated joints or through a horizon on the right abutment which solutioned away.		CONTINUATION - Unfiltered exit of seepage allowed continuing erosion of zone 1 core		PROGRESSION - Reservoir water under high pressure continues to erode the fill material forming an erosion tunnel and cavity		DETECTION/ INTERVENTION UNSUCCESSFUL- Seepage was observed coming from the abutments D/S of the dam, but it was not considered dangerous. Details of the monitoring are not known.		HEROIC INTERVENTION - NO BREACH	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Joints in the sedimentary rock abutments were not sealed - no surface treatment	Modern, well-compacted embankment	No filter on the D/S side of the zone 1 core	Zoned embankment with gravel shells	Silty sand fill used by right abutment	Some lean clay used by right abutment	In May, seepage appeared but was not considered dangerous	In June, leakage from spillway rock wetted the fill which sloughed	Lowering of the reservoir reduced the pressure and flow into the cavity	
Grout cap was blasted. High grout pressures were used which may have cracked the sandstone.	Grouting program	Zone 1 core material in contact with open joints		Fill was erodible	Cracks in rock may have limited flow	Oultet works was large, but it took about 1 week to lower reservoir to base of cavity.	In September, leakage increased and large cavity formed and eroded to the crest	Rockfill was available to dump into the cavity on the crest	
Right abutment had steep geometry and overhangs						Large quanity of rockfill dumped into sinkhole forced flow higher and caused further caving.	Large quanity of rockfill that were dumped into cavity from the dam crest may have helped.		
Stress-relief joints were open and pervasive through the abutment							Incident lasted over 3 days		

FONTENELLE DAM, WYOMING

Accident

Fontenelle Dam is included because it experienced two incidents, and the first one was a near failure. Heroic efforts helped avert a failure. A column "Heroic Intervention" is included in the summary table to reflect these efforts.

There are many similarities between Fontenelle Dam and other Reclamation dams that were designed and constructed in the same period. Ralph Peck has observed that Fontenelle Dam and Teton Dam both had unfavorable abutment configurations, jointed rock, untreated rock joints, erodible core, a blasted grout cap, and a single-line grout curtain. Photographs of the first incident and of the construction showing the untreated rock abutment and blasted grout cap are included.

FONTENELLE DAM, WYOMING

Dam Type: Compacted, zoned earthfill. Typical of Reclamation's design of the 1950's.

Location: Wyoming, USA

Construction Date: 1961 through 1964

Incident Dates: 1965 and 1982

Description of Incidents:

Incident No. 1- Accident and near failure: Reservoir filling began in the summer of 1964. When the reservoir depth reached 49 feet, seepage appeared in a borrow area approximately 2,000 feet downstream, but the seepage was not considered to be a threat to the safety of the dam.

On May 6, 1965, when the depth of the reservoir was 85 feet, seepage began to appear from the rock cut for the spillway on the right abutment and from a cliff on the left side of the valley, approximately 0.6 mile downstream. As the reservoir continued to fill, seepage appeared and increased at the downstream borrow area.

The reservoir started to spill on June 15, 1965, at elevation 6513. On June 29, a small slough occurred at about mid-height of the dam on the left side of the spillway. Seepage estimated at 1 cfs flowed from cracks in the rock upon which the spillway rested. The seepage was flowing along a crack in the sandstone parallel to the valley wall and exiting through cracks normal to the valley wall. Part of the seepage saturated the backfill adjacent to the spillway, and caused the fill to slough.

On the morning of September 3, 1965, a wet area was seen about 100 feet left of the previous slough. During the day, leakage increased to about 5 cfs and was accompanied by sloughing and erosion of the embankment. Local officials were alerted to stand by to alert persons living downstream, if a break in the dam were to occur.

By next morning (September 4), flows had increased to about 21 cfs and roughly 10,500 cubic yards of material had eroded to form a cavity extending nearly to the crest. The outlet works were opened. Plan were made to excavate channeels from the canal outlets to the river since canals had not been constructed as yet. An emergency effort was started to fill the hole.

Photograph 1, taken on September 4, 1965, shows water spilling over the spillway, the large erosional cavity, and material being placed at the base of the cavity. **Photographs 2 and 3**, taken on September 5, 1965, reveal the large amounts of material that have been dumped into the hole from the crest of the dam.

On the afternoon of September 5, the leakage was reported to be surging violently and carrying large amounts of earth fill. Dumping of rockfill was stopped temporarily because the rockfill had forced the flow higher, producing further caving.

On September 6, the reservoir level had dropped 8 feet, and the flow from the leak appeared to stabilize at 6 cfs. However, that afternoon the downstream part of the crest suddenly collapsed and dropped over 30 feet. More of the right abutment rock was exposed, and water was observed coming from cracks in the rock. At this time, the reservoir was about 13 feet above the base of the cavity. Rock was again dumped into the hole.

The reservoir continued to drop at a rate of 4 feet per day. **Photograph 4**, taken on September 8, and **photograph 5**, taken the next day, provide an aerial perspective of the dam, spillway, and West Canal outlet works. **Photograph 6**, taken on September 9, 1965, provides a good view of the exposed rock face on the left abutment. The discharge gradually decreased and stopped entirely when the reservoir reached a depth of 66 feet [1]. By the grace of God, failure of the dam was narrowly averted. The left end of the dam was repaired, and 8 lines of holes were used to grout the left abutment.

Incident No. 2:

In late 1982, a small amount of previously unobserved seepage was seen at the toe of the dam near both the left abutment and the central portion of the dam. Study of the design and construction of the embankment indicated inadequate foundation treatment, and the reservoir was restricted to 10 feet below normal. Investigations of the left side of the embankment in 1983 indicated there were numerous, very soft areas near the embankment-foundation contact. As a result, the reservoir was restricted to 25 feet below normal water surface elevation.

In early 1985, it was observed that the water pressure in a piezometer, near the central portion of the embankment where seepage had been noticed in 1982, had risen over 10 feet while the reservoir remained constant. As the pressure in the piezometer continued to rise, and investigations indicated it was valid, the decision was made to lower the reservoir 63 feet below normal water surface elevation [2].

Description of Geology and Foundation: The dam is located in a relatively flat valley nearly a mile wide. The rock foundation and abutments for the dam consist of nearly flat-lying, interbedded, massive to thinly bedded sedimentary deposits of calcareous sandstone, siltstone, shale, and minor beds of limestone. Minor gypsum was found in drill holes above the ground-water table in both abutments. The rock underlying the dam is weathered, fractured, and permeable, and the abutments contain stress relief joints.

Photograph 7, taken on April 12 , 1963, shows the interbedded and massive to thinly bedded sedimentary deposits comprising the left abutment.

The 1955 Reconnaissance Geological Report [3] may have created an image of a tight reservoir which was erroneously carried into the construction stage when it stated: "With impervious formations underlying the reservoir and a ground-water table draining into the basin, it seems certain there will be no seepage from the reservoir."

MacDonald has written a comprehensive analysis of the geologic issues in which he postulates that "an originally extensive bed of soluble material has essentially been solutioned away in the vicinity of the right abutment and in the downstream left bank 'weeping rock' area" [4]. This soluble material is subject to leaching where the ground-water table has risen as a result of Fontenelle Reservoir. Because of the low water table prior to construction of the dam, this pervious horizon was not obvious until after the reservoir was filled and downstream seepage began.

A 1984 geology report from the Regional Office [5] provided evidence for the solution of gypsum-filled joints since the dam was built. It states:

> "Most preconstruction drill holes in the right abutment show the presence of gypsum in the weathered, fractured, permeable rock zone. Recent drilling does not show the presence of gypsum and pump-in permeabilities are an order of magnitude higher than indicated for earlier drill holes."

Also, the report notes that fractured rock extended from the rock surface to a depth of 15 to 60 feet. Observed fracture openings (horizontal and inclined) in boreholes ranged from hairline to one inch. Openings up to 4 inches were noted at Weeping Rock where water is flowing from bedding planes [5].

After the first accident, a geologic appraisal of the right abutment was made by a Reclamation geologist. The following is taken from that report [6].

> "First are the easily split closely spaced bedding planes which are remarkably evident within the platy siltstone and fissile varved shale units. High grout takes west of the spillway centerline were nearly all within the fissile shale and platy siltstone . . . [between elevations 6415 and 64442] undoubtedly entering the voids between the closely spaced and irregular features. It may be that some of the high take at this horizion was caused or aggravated by hydraulically splitting the bedding planes during the grout program. This possibility was indicated by percolation tests during the preconstruction drilling.
>
> Another major type of discontinuity, and in the present case by far the most important, consists of relief joints which occur predominantly within the massive sandstone and within an area bordering the steep abutment. Because of its uniformly massive characteristic, the sandstone responds to stress by breaking along fractures which generally extend the full thickness of the unit and continue laterally for considerable distance. They form in most massive rock due to removal of lateral support but in the present case are aggravated by the underlying shale bed. They result in deep open joints which roughly parallel the abutment and extend at least to the bottom of the massive sandstone. Five of these open joints were encountered in the spillway inlet excavation, and one was exposed in the spillway chute . . . They attain an open width of up to one foot and are generally vertical and roughly parallel to the abutment contours. One relief

joint located about 140 feet left of spillway station 110 shows evidence of water entering the open crack. This may be one of the more important access routes for leakage."

Description of Dam, Design, and Construction:

Height: 139 ft (42 m)

Reservoir: 345,000 acre-ft (425,550,000 cu meters)

Embankment: Compacted, zoned earth and gravel fill

Crest length: 5,450 ft (1,660 m)

The large central core of low plasticity materials (mainly sandy silts and silty sands) is flanked by well graded gravel shells. Material for the right abutment section was excavated from Borrow Area A, and the Preconstruction Material Report indicated the borrow material was primarily clay having a plasticity index (PI) ranging from about 3 to 14 percent. There were a few samples of silty sands and gravel.

During construction work in 1961, the sedimentary rock in the foundation was found to be more fractured than had been expected. Grout takes were very large in the upper 65 feet of the foundation. A second line of grout holes was placed in the vicinity of the outlet and the right abutment. The pressures used for grouting were too high for the horizontally layered rock, and in at least one area there was hydraulic jacking of the foundation [4].

Photograph 8, taken on September 25, 1961, is a view of the grout trench, which was blasted. The specifications allowed for line drilling and light blasting. MacDonald comments that blasting for the grout cap "never should have been allowed in such rock as it was only likely to increase fracturing and loosen any relatively intact rock . . . and increase the potential of zone 1 embankment piping." [4]

The upstream part of the right abutment is nearly vertical and the downstream part is on a slope of 1(V):2(H). There is no mention of foundation treatment in the Final Construction Report [7] except that the soil cover was excavated to firm foundation and the foundation was cleaned. **Photograph 9**, taken on July 14, 1963, indicates that the fill was placed directly against a layer of horizontally stratified rock. Note overhanging rock ledges and jointed rock.

Factors Contributing to Near Failure

Peck has suggested that there were many similarities between the near failure of Fontenelle Dam and the failure of Teton Dam 11 years later [9].

> "I think those of you who have been studying Fontenelle recently, or at some other time, recognize that it had a great many similarities to the failure of Teton. You have the jointed rock and erodible core, untreated joints in the rock, a blasted grout cap, a singleline grout

curtain, and certainly some unfavorable abutment configurations."

The factors that likely contributed to near failure are summarized into three categories, as follows:

<u>Geologic factors</u>

- The right abutment contained open relief joints up to 1 foot in width. It appears that one or more were not filled with grout which allowed reservoir water to move into the joints. The vertical joints were apparently interconnected with horizontal joints, that were smaller in size, ranging from hairline to one inch. Due to possible hydraulic jacking during grouting or other reasons, the reservoir water under high pressure could come into contact with the embankment. In addition, a bed of soluble material may have been present and was leached away by the reservoir water.

- The available material for the core ranged from a silty sand to a lean clay. The silty sand had a low resistance to erosion.

<u>Design and construction</u>

- The concept of using multiple lines of defense was apparently not used for the design. Foundation treatment (such as removal of overhangs, slush grouting, and dental concrete) was not required. Erodible core material was placed against open cracks in the right abutment. Filters were not used at critical locations, and too much reliance was placed on the narrow grout cap and grout curtain.

<u>Human factors</u>

- Apparently, misconceptions about the foundation and abutment geology were carried into the design stage.

- An independent review of the design and construction by consultants was not required.

- Based upon success in building large dams at more suitable sites, the designers may not have anticipated problems or possible failure modes.

A more complete list of factors that likely contributed to the near-failure of the dam were contained in the 1984 Safety Evaluation of Fontenelle Dam [9].

> 1. Tabular openings, one-half inch to three-fourths inch wide, were noted along several bedding planes upstream of the dam. The layers were broken by many steeply inclined intersecting joints and relief cracks trending in various directions.
>
> 2. A crack, which had transmitted water recently, was discovered at the upstream end of the canal inlet. The crack's direction was toward the area of the initial leak.
>
> 3. During the excavation for repair, a "soft spot" was discovered in the embankment roughly between elevations 6458 and 6450.
>
> 4. The relief joints were larger on the upstream side of the grout cap than on the

downstream side. In fact, 10 to 20 feet downstream of the grout cap they seemed to disappear.

5. An open relief joint about 15 feet long and one-half to three-fourths inch wide was discovered 85 to 100 feet upstream of the grout cap at elevation 6471.4. Frank D. Carlson, who was resident engineer in charge of construction, stated that the joint was definitely not like that (as large) when the embankment was placed against the abutment.

6. A clean sand and gravel deposit was discovered in the embankment 21 feet upstream of the grout cap opposite station 15+34 at elevation 6453.7.

7. Inspection of bore holes with a television bore-hole camera indicated that relief joints that were once filled with debris had been cleaned out.

8. The steep abutment made shallow grouting difficult because low pressures were necessary to prevent movement in the foundation.

9. The steep abutment encouraged differential settlement and cracking of the embankment.

10. The steepness of the abutment, along with irregularities and overhangs in the rock, made it difficult to achieve a good abutment-embankment bond.

11. Lack of slush grouting and dental concrete allowed a substantial amount of water to seep along the embankment-abutment contact.

12. Zone 1 soil was highly erodible.

Factors That Helped To Resist Failure

The width of the cracks in the right abutment is believed to be one of the key factors that prevented the failure of Fontenelle Dam. The size of the cracks limited the flow of water from the reservoir against the zone 1 fill. Okeson, a Bureau employee who visited the site after the near failure, made a similar observation [8]:

> "I believe that the reservoir water simply moved along the cracks and came out of the rock under the impervious embankment and made it a loblolly. After a few months the water caused slumping of the downstream toe. Then, within a few hours the seepage path became much shorter, and the quantity of water increased rapidly until the rate of flow was restricted only by the size of the cracks in the abutment."

The heroic efforts by Reclamation personnel to quickly lower the reservoir and to fill the cavity with rockfill was a second key factor in saving the dam.

A Comparison Between Fontenelle Dam and Teton Dam

One of the reasons that accidents have been included in this report is to recognize that these dams have withstood a significant errosion event and have not failed. Since Fontenelle Dam and Teton Dam are similar in many respects, it is only appropriate to ask why one failed and the other one did not.

The tables included with each case history (which summarize factors contributing to and resist internal erosion) are valuable in pointing out some of the differences between the two dams. At the same time, it is recognized that each dam had unique characteristics, and the factors listed are our best attempt to explain what happend, and may not be the complete story. Nevertheless, there are differences worth noting. These differences are listed in table 1 and described briefly below.

As mentioned earlier, the width of the cracks in the right abutment is believed to be one of the key factors that prevented the failure of Fontenelle Dam, since the flow of water from the reservoir against the zone 1 fill was limited. At Teton Dam, the width of the joint openings in the rock adjacent to the erodible core was believed to be many times larger, perhaps 10 or more times larger than at Fontenelle Dam.

The difference in the reservoir head is believed to also be significant. The reservoir head acting at the elevation where internal erosion initiated is a measure of the potential energy to erode the soil in the core of the dam. Assuming a direct connection between the reservoir and the point of erosion, at Fontenelle Dam the reservoir head was close to 55 feet of water (about 3,400 psf of pressure). At Teton Dam, erosion is believed to has started somewhere between a depth of 121 and 136 feet below the water surface of the reservoir. Using an average of 128.5 feet of water (about 8,000 psf of pressure), the presssure is estimated to have been about 2-1/3 times greater at Teton Dam than at Fontenelle Dam.

Efforts to prevent failure at the two dams were both heroic in nature. At Fontenelle Dam, the reservoir could be lowered fairly quickly through the large-capacity outlet works, althought it took 17 days before the leakage stopped. Unfortunately, Teton reservoir could not be lowered because the outlet works were not operational.

The reservoir filling history and rate of filling deserve mention, as do the characteristics of the fill material. It was the first filling for Teton Dam and the rate of filling was greater than for Fontenelle Dam, which had been partially filled the previous year. Both dams had erodible core material, although Teton Dam core material was the more erodible of the two.

Table 1

Factor	Fontenelle Dam - Accident	Teton Dam - Failure
Width of joint openings in rock adjacent to fill	Hairline to an inch	Several inches to a foot
Approximate reservoir head acting at location of internal erosion	About 55 feet	Between 121 to 136 feet
Intervention efforts	Reservoir lowered at a maximum rate of 4 ft/day. Rockfill dumped into cavity	Reservoir could not be lowered in time. Fill dumped into cavity.
Zone 1 material placed against rock	Erodible. Mostly CL and CL-ML with PI of 4 to 15	Highly erodible silt with PI of 1 to 7
Reservoir filling history and rate of filling	Reservoir filling began in April 1964 (the year prior to the accident) and was filled to about El.6458. Prior to the accident, the rate of filling was about 0.8 ft/day (April 7 to June18, 1965).	First filling began in Oct. 1975 at 1 ft/day and then increased to 2 ft/day in April 1976. For short periods it was greater with the maximum rate of 4.3 ft/day on May 18, 1976.

References:

[1] International Commission on Large Dams, "Lessons from Dam Incidents," Paris, France, 1974.

[2] "Lessons from Dam Incidents. USA-II," USCOLD, American Society of Civil Engineers, New York, 1988.

[3] Reconnaissance Geological Report of the Fontenelle Dam and Reservoir Site, Seedskadee Project, Wyoming, Bureau of Reclamation, January 1955.

[4] MacDonald, Robert, "Analysis of Geological Issues," SEED Report, Bureau of Reclamation, Denver, Colorado, 1983.

[5] Grundvig, D. and J. Roberts, "Summary of Geologic Investigations, Geologic Factors, and Site Conditions - Fontenelle Dam, Seedskadee Project, Wyoming," Report No. G-367, Bureau of Reclamation, Salt Lake City, Utah, January 1984.

[6] Calder, L., "Geologic Appraisal of Right Abutment Area, Fontenelle Dam, Seedskadee Project, Wyoming," Report No. G-219, Bureau of Reclamation, Salt Lake City, Utah, September 1965.

[7] "Final Construction Report on Fontenelle Dam, Wyoming," Bureau of Reclamation, January 1966.

[8] Okeson, C. J., Travel Report, Bureau of Reclamation, October 29, 1965.

[9] Peck, R., Taped remarks in a class presented to Reclamation employees, Denver, Colorado, 1985.

[10] "Final Safety Evaluation of Fontenelle Dam, Seedskadee Project, Wyoming," Bureau of Reclamation, Denver, Colorado, July 20, 1984.

APPENDIX A

APPENDIX B

APPENDIX C

INTERNAL EROSION OF THE EMBANKMENT - **FAILURES**

Dam Name and Location	Date of Const. / Failure	Ht. Ft.	Comments	Value Guide
Ahraura, India	1953/1953	75	Whirlpool, failure along outlet works and masonry wall	
Apishapa, CO	1920/1923	112	Settlement, cracking, leaking	
Ash Pond, LA	?	10	Settlement, hydraulic fracturing	
Avalon II, NM	1894/1904	?	Overtopping, no compaction	
Beloeil, Quebec	1985	13	Paper in French	
Bila Densa, Czechoslovakia	1915/1916	59	Leak near outlet works; cause of failure unknown.	
Bilberry, U.K.	1845/1852	66	Masonry outlet works leak, narrow puddle core	
Blackbrook, U.K.	36652	92	Narrow puddle core, internal erosion, settlement, overtopped	
Flood Levies on Rhone R., France	1994?	15	16 breaches caused by backward erosion and burrowing animals	***
Dale Dike, U.K.	1864/1864	95	Narrow puddle core, uncompacted fill, settlement, and hydraulic fracturing	

Ghattara (Wadi Qattarah), Libya	1972/1977	125	Piping near conduit, poor compaction near conduit, cracking of clay, dispersive clay	***
Gouhou, China	1988/1993	233	Concrete face cracked, fill was impervious, high phreatic line.	
Hatchtown, UT	1908/1914	65	No compaction, leak by outlet conduit, backward sloughing to crest.	
Hebron, NM	1913/1914	56	Rodent hole led to piping.	
Horse Creek, CO	1912/1914	56	Uncompacted fill, high phreatic line, leak near conduit	
Ibra, Germany	1997/1977	33	Failure teaches about improper use of geomembranes.	*****
Kaihua, Finland	1959		No details of failure in paper.	
Kantalai, Sri Lanka	612,1875, 1952/1986	88, 45?	Geologic paper, other factors not explained	
Kedarnala, India	1964/1964	70	Settlement, drain dug through width of dam and piping, and sudden filling of res.	
Kelly Barnes, GA	1899/1977	42	Intense rainfall, slide on steep d/s slope, possible piping around old penstock.	
La Escondida, Mexico	1970/1972	43	50 pipes and 8 breaches, 1st filling, dispersive clay.	
Lake Francis, CA	1899/1899	52	Most of fill placed dry, last part dumped, settled on first filling and cracked	**

Lawn Lake, CO	1903/19 82	28	Deteriorated lead caulking at outlet gate valve may have led to piping along pipe.	
Lyman, AZ	1913/19 15	65	Puddle clay, rapid filling, settlement	
Mafeteng, Lesotho	1988/19 88	75	Spillway wall, placed on compressible fill, tilted and water flowed through crack. Fill had sand and gravel layers and was dispersive.	*****
Mena/Valparaiso, Chile	1885/18 88	56	No details in paper	
Mill River, MA	1865/18 74	43	Leakage beneath masonry core wall led to slide. Poor design, workmanship, and no inspection.	***
Mohawk, OH	1914/19 15	18	Settlement of uncompacted fill resulted in cracks to the concrete facing, leakage, and erosion.	
14 in Oklahoma and Mississippi	?/1957-70	23-65	Rapid first filling, settlement, cracking, and dispersive clay.	
Omai, Guyana	1993/19 95	148	Internal erosion along conduit, filter sands moved into rockfill, and the sloping core was lost.	****
Pampulha, Brazil	1941/19 54	54	Deformation, concrete face cracked, seepage, and internal erosion.	
Panshet, India	1961/19 61	168	An early monsoon, incomplete outlet works vibrations led to settlement of fill over the conduit and overtopping.	****
Piketberg, South Africa	1986/19 86	39	Reduced stresses by vertical sides of the outlet pipe caused cracks, concentrated leakage, and piping erosion. Good discussion of internal and piping erosion.	*****

Ramsgate, South Africa	1984/19 84	46	Dispersive clay, poor compaction, core not continued by 2nd contractor, rapid filling, settlement, cracks, piping tunnels.	
Ropptjern, Norway	?/1976	26	Combination of factors including erosion along outlet pipe	
St. Ajgnan, ?	1965/19 84	26	External suffusion turned into piping, poor soil and construction, no inspection.	
Senekal, South Africa	1974/19 74	26	Combination of factors caused initial leak leading to piping of dispersive clays.	***
Sheep Creek, North Dakota	1969/19 70	60	Combination of factors caused spillway pipe to leak and dam to fail.	
Smartt Sindicate, South Africa	1912/19 61	92	Spillway washed away. Possible piping along old and new crests.	
Stockton Creek, California	1949/19 50	80	Cracking of embankment at near-vertical step in abutment led to erosion.	***
Trial Lake (dike), Utah	1925/19 86	15	Piping along foundation contact which contained organics and root holes.	
Utica, New York	1873/19 02	70	No stripping, no compaction, or design.	
Walter Bouldin, Alabama	1967/19 75	164	Piping although some disagreement by other investigators.	****
Warmwithens, England	1860/19 70	35	Seepage along an old or new tunnel may have contributed to the failure.	
Zoeknog, South Africa	1992/19 93	125	No foundation treatment or grout curtain, poor compaction, and piping by conduit.	****

PIPING THROUGH FOUNDATION - **ACCIDENTS AND FAILURES**

Dam Name and Location	Date of Const. and Accident / Failure	Ht.	Comments	Value Guide
Addicks, TX	1948/1977 Accident	49 Ft.	Seepage path through foundation sands exposed by excavation leading to sand boils and erosion.	
Baldwin Hills, CA	1951/1963 Failure	232 Ft.	Fault movement in foundation led to rupture of asphalt reservoir lining and under drains.	***
Bastusel, Sweden	1972/1972 Accident	40 m	On first filling, leakage led to sinkhole at crest due to internal erosion.	
Beaver, AK	1966/1984 Accident	10 m	Grouted karstic foundation leaked after first filling. 18 years later muddy springs appeared.	
Bent Run Dike, PA	1969/1971 Accident	35 m	On filling of the reservoir, leakage and piping through asphalt lining and open joints occurred 4 times.	****
Black Lake, ??	1967/1986 Accident	23 m	Note about material piping through the toe drain.	

Black Rock, NM	1907/19 09 Accident - failure	7 0 ft	Piping through alluvial sands beneath lava cap led to spillway settlement and breach through abutment.	
Bloemhoek, South Africa	1978/19 78 Accident	2 1 m	During first filling, seepage through termite galleries in foundation and boils; sediment found in toe drains.	** *
Borga, Sweden	1951/19 51 Accident	2 7 m	On first filling, muddy leakage and piping through a sand layer in foundation.	
Cedegren Example 2, CA	Failure	?	Piping under fish ladder resulted in underground channels and dam failure.	**
Como, MT	1910/19 83 Accident	7 0 ft	Seepage and boils downstream and sinkholes in right abutment.	
Corpus Christi, TX	1930/19 30 Failure	6 1 ft	Seepage beneath sheetpile walls led to piping under or adjacent to spillway and breach. Discussion by Terzaghi.	** *
Denison, TX/OK	1994/19 92 Accident	1 6 5 ft	Hole in corroded CMP toe drain led to erosion of fine sand and silt foundation material into toe drain pipe.	
Dudhawa, India	1962/19 62 Accident	2 5 m	During first filling, sand boils found downstream due to lack of positive cutoff of sand layer beneath clay cover.	
Goczalkowice, Poland	1956/? Accident	1 7 m	Excess pore pressure in foundation d/s of dam led to a huge pot-hole	

Great Salt Plains, AK	? Accident	22 m	During first filling, seepage emerged at d/s toe; corrected by relief wells	
Grenada (B), MS	1954/1954 Accident	26 m	Sink holes over the collector pipe and piping of foundation sands through pipe joints	
Hackberry Site 1, NM	1967/ 70's & 1982 Accident	26 ft	Sinkholes u/s, d/s, and in embankment, settlement, cracking and erosion, erosion of gypsum, and seepage.	**
Helena Valley, MT	1958/ Numerous accidents	76 ft	Hundreds of small sinkholes were observed in reservoir bed	
Inglis, FL	1973/1973 Accident	43 ft	A major boil (2,200 gpm) under D/S slope led to initiation of slope instability	
Julesberg - (A) (Jumbo), CO	1905/1906 Accident	60 ft	After first filling, a concentrated leak of 1 to 1.5 cfs of clear water emerged at an outcrop of porous limestone in the foundation. For next 3 years the leak increased slightly and large fish occasionally were washed under the dam.	**
Julesberg - (B) (Jumbo), CO	1905/1910 Failure	60 ft	A 400-ft-long section of embankment centered on the above leak washed out. Solution cavities and channels up to 2 feet in diameter found in limestone.	**
Keban, Turkey	1973/1975 Accident	208 m	After a large vortex was observed u/s of the left abutment and spring discharge d/s reached 25 cu m/s, the reservoir was lowered to reveal a large cavity in the karstic foundation.	

Koronowo, Poland	?/? Accident	2 3 m	Excess pore pressure in foundation led to sand boils and cavities in u/s and d/s slopes	
Lafage, ?	Around 1980 Accident	1 1 m	Possible piping in marl foundation	
Laguna, Mexico	1908/19 69 Failure	1 7 m	Seepage was measured since 1927, but too much reliance was placed on total seepage and visual observations. Piping was through weathered volcanic tuff.	***
Lake Invernada, Chile	1957/19 58 Accident	3 0 m	Sinkholes appear during yearly reservoir filling in same area due to abrupt soil and underlying basalt changes.	
Lake Toxaway, NC	1902/19 16 Failure	1 9 m	Seepage at foot of dam (through rock fissures) since it was built, turned muddy about 7 hours before failure.	
Langalda, Iceland	1966/19 71 Accident	1 0 m	A large fracture in lava foundation opened under the dam and reservoir emptied in 3 or 4 days.	
Langbjorn, Norway	1958/19 90 Accident		Sink holes, build up of water pressure and internal erosion on left abutment led to repairs.	****
Logan Martin, AL	1964/19 64 Accident	3 0 m	On first filling muddy leakage; later boils and a sinkhole. Piping through limestone foundation.	
Meeks Cabin, WY	1971/19 86 Accident	5 7 m	Bureau design had seepage through left abutment and sinkholes since first filling. Glacial till assumed to be impervious but contained openwork gravels in contact with core of dam.	***

Messaure, Sweden	1963/? Accident	100m	Excavation of rock foundation led to uplift and dilation of joints and increased foundation permeability.	
Mill Creek Lake, WA	1941/1945 Accident	44m	Excessive seepage and piping of 750 cu yards of silt.	**
Mohawk, OH	1937/1969 Accident	34m	After flood in 1969, flood-control dam had seeps, springs, and boils.	
Nanak Sagar, India	1962/1967 Failure	16m	Piping through pervious foundation led to settlement and overtopping during storm.	
Nepes, ?	1945/1988 Accident	13m	Piping through gravel layers below cutoff of dam.	
Paloma, Chile	1967/1973 Accident	85m	Hazy seepage at right abutment, which is composed of fluvial materials.	
Phewa, Nepal	?/1975 Failure	20m	No investigation of failure or details given	
Prezczyce, ?	?	?	No details	
Red Bluff, Texas	1936/1974 Accident	34m	Sink holes and major seepage due to solutioning of gypsum beds.	

Roxboro, NC	1955/1984 Failure	7 m	Piping beneath spillway with no under drains progressed to failure.	
Ruahihi Canal, New Zealand	?/1981 Failure	?	Seepage through canal lining caused subsurface erosion and collapse of brittle and erosive volcanic soils.	***
Sarda Sagar, India	1960/1968 Accident	18 m	Under seepage resulted in sand boils, sloughing of d/s slope of dam	
Sardis, MS	1940/1974 Accident	35 m	Relief wells were being plugged by piping of sand through well screens	
Seitevare, Sweden	1967/1967 Accident	106 m	During first filling, springs observed at d/s toe. Concentration of flow at juncture of grout curtain and abutment	****
Tarbella, Pakistan	1974/1974 Accident	145 m	During first filling, 400 sinkholes formed in u/s 'impervious' blanket due to openwork gravel in foundation	**
Three Sisters, Alberta, Canada	1952/1974 Accident	21 m	During first filling, seepage and sand boils near d/s toe. 130 sinkholes in reservoir in 9-year period. Sinkhole on d/s slope behind powerhouse after 29 years. Internal erosion of sand and sandy silt into open-work gravels in foundation	***

Uljua, Finland	1970/19 90 Accident	1 6 m	Seepage of 5 L/min observed since first filling. After 20 years, leakage turned muddy, flow increased to 30 L/s, and 2 sinkholes formed by u/s toe. 2 weeks later, sinkhole on crest and 100 L/s leak. Piping of glacial till into fractured bedrock. Erosion tunnel discovered.	** **
Walter F. George Lock and Dam, GA	1963/19 82 Accident	5 2 m	Piping through ungrouted construction piezometer holes u/s of power station.	
West Hill, MA	1961/19 79 Accident	1 7 m	Sand boils near d/s toe	
Western Turkey	1959/19 68 Accident	7 7 m	Seepage suddenly increased by 300% due to a crack in the impervious blanket in the reservoir.	
Wheao Canal, New Zealand	1982/19 82 Failure	?	Interface between canal earth lining wingwall may have opened up allowing piping to develop.	**

A SUMMARY LIST OF FACTORS RELATED TO INTERNAL EROSION

While reading through the case histories, I wondered which factors were the most important and how many combinations of factors were necessary to cause an internal erosion accident or failure. Foster and Fell and others have pointed out that it usually is not a single factor, but a combination of factors that causes an incident. My conversations with a safety engineer about industrial accidents indicated that accidents usually occurred when faulty equipment and when human error, such as haste and carelessness, happened at the same time.

Initially, I subdivided the factors that affect internal erosion into the following categories:

- Performance. - How well the dam has performed, especially with regard to seepage and sinkholes and cracking.
- Geology. - The type of foundation (soil or rock), foundation treatment, and site geology
- Design and Construction. - Design and construction aspects, especially seepage control measures, properties of the core material, and construction quality.
- Outlet-Works Conduit. - Location, type, condition, and age of outlet works and other structures in contact with to the dam

After reading Dr. Peck's article about the influence of nontechnical factors on the quality of dams [4], I included a human factors category. While this category is important, it is difficult to quantify. Later, Fell and Foster [9] reported that nearly 50 percent of failures due to internal erosion occurred on first filling of the dam. Therefore, another category was added to reflect the age of the dam, the era of construction, and the reservoir load history.

The following pages should be helpful in summarizing data for use in a risk analysis or a review of a dam.

PERFORMANCE SUMMARY

1. Seepage/Leakage

- location: ______________________________
- amount: ______________________________
- history: ______________________________
- rate of change: ______________________________
- color: ______________________________
- sandboils: ______________________________
- sinkholes: ______________________________
- other: ______________________________

2. Instrumentation interpretation

- piezometers (e.g., pore pressure increase, hydraulic gradient): ______________________________
____

- other:

3. Other observations (e.g., cracking, settlements):

4. Comments:

5. Conclusions:

6. Evaluation of performance:

DSO-04-05

Selected Case Histories of Dam Failures and Accidents Caused by Internal Erosion

by

David Miedema

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F. Keechelus Dam, Washington

Appendix D - A Summary List of Factors Related to Internal Erosion

INTRODUCTION

The vast majority of embankment dams have exhibited good behavior. However, about 50 percent of large embankment dam failures have been attributed to internal erosion. Therefore, a study of case histories of incidents (both accidents and failures) can be instructive.

A. WHY READ CASE HISTORIES?

- To obtain insights into how dams can fail by internal erosion.
- To identify factors that contributed to the internal erosion failure of the dam, if possible.
- To serve as a "reality check" for the risk analyst.

The study of case histories of dam incidents, which includes both accidents and failures, is a very important part of the analysis and design of embankment dams. Case histories contain a wealth of wisdom to supplement the theories and analytical tools provided by a formal engineering education.

Case histories can also help in a risk analysis of a dam. By comparing a dam being studied to similar dams -- that have failed, or have had accidents, or have performed well -- provides a real life basis or "reality check" for the risk analysis.

Engineers, in general, tend to focus on technical aspects of a dam, because they are most knowledgeable about them. The technical factors that cause internal erosion are well know to the dam safety engineering profession. Some of the significant technical factors have been listed by Robert Jansen as the following [1]: defective filters and drains; cracking of the core by settlement; improper preparation of the foundation; open joints or solution channels in the rock foundation; permeable underlying alluvial, glacial, or talus deposits; incorrect shaping of the foundation contacts leaving steep faces or overhangs; and blasting of the foundation for grout caps, which loosens the rock enough to create paths for leakage.

Case histories also illuminate some of the nontechnical causes of failures. Human factors are harder to identify. Steve Vick lists a number of human errors in the case of the Omai Dam failure in Guyana. "Bureaucratic factors" is the term used by James Sherard, who shows how they played a dominant role in the failure of Teton Dam and his paper, "Lessons from the Teton Dam Failure" [2], is included as part of the case history of Teton Dam. George Sowers discusses the Teton Dam failure in his paper [3], "Human Factors in Civil and Geotechnical Engineering Failures." Robert Whitman, in the seventeenth Terzaghi lecture [4], emphasized that "human and organizational factors must be considered as well as design details" in a risk evaluation of a dam. As early as1973, Ralph Peck discussed a wider range of nontechnical factors that can affect the quality of a dam, and his article [5] is included in appendix A. The nontechnical causes of poor quality dams, he said, "are more numerous and more serious than the technical causes . . . Most of these shortcomings originate in the attitudes and actions of the persons most intimately concerned with the creation and completion of the project: the owner, designer, constructor, and the technical consultant."

B. PURPOSE

The purpose of this report is to aid in the risk analyses, in comprehensive facility reviews, and in decisions about modifying existing Bureau of Reclamation (Reclamation) embankment dams.

The goal has been to collect some helpful case histories of dam failures and accidents caused by internal erosion. Also, a few case histories of Reclamation's response to piping incidents at their dams and at one Bureau of Indian Affairs dam have been included. A careful review of a few case histories of dams that are similar to the one under study can result in better assessments of possible failure mechanisms and insights into factors that can contribute to satisfactory or poor performance of embankment dams.

This report will also be used to supplement Reclamation's risk analysis report on internal erosion of embankment dams [6]: "RISK ANALYSIS METHODOLOGY, APPENDIX E - Estimating the Risk of Internal Erosion and Material Transport Failure Modes for Embankment Dams."

C. WHAT MAKES CASE HISTORIES OF DAM FAILURES AND ACCIDENT WORTHWHILE ?

- If the dam is similar to the one being studied
- If the case history is clear and contains sufficient details
- If the authors have critically examined and evaluated what has happened

Over one hundred case histories were read and ten of the most valuable case histories are included. Appendix B contains a list of the case histories that were screened to meet these criteria, with some short comments on each case history.

Not only dam failures, but also accidents are included because they also are important. Dams that have withstood a significant erosion event and have not failed have inherent strengths. These case histories may provide insights to the reader.

D. THE ORGANIZATION OF THE REPORT

The ten case histories chosen are summarized in table 1, which includes some information about the embankment type and construction, the foundation, the reservoir loading, and the incident.

Appendix A contains the article by Ralph Peck on the nontechnical factors that influence the quality of embankment dams. Appendix B contains a list of case histories that were reviewed. Appendix C contains six case histories of Reclamation's response to piping incidents. Appendix D contains a summary list of factors related to the internal erosion of an embankment dam.

Table 1. - Summary of Case Histories of Internal Erosion

Name & Location	**Failure or Accident and Mode**	**Date of Construction and Incident**	**Height in feet**	**Foundation Materials**	**Embankment Type**	**Reservoir Loading**	**Comments**
Picketberg Dam, South Africa	Failure through embankment near conduit	1986/1986	39	Alluvium - silty sand	Zoned with dispersive clay core. No filters	First filling - 33 ft in 5 weeks	One of the best case histories. Good discussion of a number of contributing factors.
Omai Tailings Dam, Guyana	Failure through embankment, but complex sequence	1993/1995	148	Residual saprolite soils	Tailings dam with sloping core and d/s rock fill	Dam raised ahead of mill effluent	Author Steve Vick's approach is from a background in risk analysis
Ghattara Dam, Libya	Failure through embankment near conduit	1972/1977	92	Alluvium over limestone	Homogeneous. Silty clay core. Chimney drain, filter, and toe drain	Record rains. First filling - 26 ft in 2 days.	Modern dam with chimney drain and filter. No flaws were found in design or construction. Filter beneath conduit?
Stockton Creek Dam, California	Failure through embankment due to cracking	1950/1950	80	Schist - hard and sound	Near homogeneous. Well compacted clayey sand.	Rapid first filling.	Dam on rock with modern construction. Leak through settlement crack near a vertical step in abutment
Lake Francis Dam, California	Failure through embankment due to cracking	1899/1899	52	Sandy clay over rock	Homogeneous. Most fill was compacted dry, some was dumped.	9 in.of rain in 36 hrs. Rapid first filling	Leak through cracks in dumped fill and outlet pipe due to settlement was not surprising.
Walter Bouldin Dam, Alabama	Failure through embankment or from embankment into foundation	1967/1975	164	Jointed sediments of sand, silts, and layers of stiff clay	Nearly homogeneous with thin upstream clay section tied into natural reservoir blanket. No filters.	Normal loading	Peck and Leps believe failure was due to piping of foundation soil rather than the official cause, an upstream slide due to drawdown.

Name & Location	Failure or Accident and Mode	Date of Construction and Incident	Height in feet	Foundation Materials	Embankment Type	Reservoir Loading	Comments
Uljua Dam, Finland	Accident, but near failure. Embankment into foundation	1970/1990	52	Erodible glacial till over fissured bedrock	Zoned. Core of glacial till, filter zones, and supporting rockfill	Several times a day the reservoir fluctuated because of power operations	After 20 years, seepage increased and turned muddy. Only case history in which an erosion tube was traced through core of dam into foundation, which is shown in a figure.
Langborn Dam, Norway	Accident. Erosion through abutment	1958/1958	n/a	Abutment consists of silt, sand, and layers of coarser material	n/a	Slide occurred during first filling.	The probability of several failure modes of the abutment were evaluated. Evaluation followed Reclamation's SEED guidelines.
Teton Dam, Idaho	Failure. Embankment into foundation	1976/1976	305	Jointed rhyolitic welded ash-flow tuff	Zoned. Very erodible, stiff, and brittle silt core. No filters	Rapid first filling.	Sherard's paper gives insights into bureaucratic problems within Reclamation at the time.
Fontenelle Dam, Wyoming	Accident, but near failure. Through embankment or embankment into foundation	1964/1965	139	Interbedded sandstone, siltstone, and shale deposits	Zoned. Erosive core of low plasticity silts and silty sands. No filters	First filing	Peck has suggested there are many similarities between the Fontenelle incident and Teton. Were lessons learned?

In order to relate the case histories to steps used in a risk analysis, each case history has been divided into the stages used by Reclamation to identify internal erosion, which are: initiation, continuation, progression, detection/intervention, and breach mechanism. Foster and Fell [7] have used a table to summarize the factors that contribute to each stage of internal erosion. A modified format is currently used by Reclamation to include factors that not only contribute to, but also resist internal erosion. Factors that contribute to internal erosion are listed in one column as "more likely"; factors that resist internal erosion are listed as "less likely." This table is included with each case history, and the format is shown in table 2.

Headings in the table are briefly described below; a more detailed description can be found in reference 6.

- Initiation. - A concentrated leak develops along a path which leads to migration of fine soil particles.
- Continuation. - A filter to control the migration of soil particles is not present or is deficient which allows migration and exiting of the fine soil particles.
- Progression. - A flow path (pipe) enlarges to the reservoir if the roof of the pipe is supported, if flows are not limited, and if the soil is erodible.
- Detection/Intervention. - Detection of the problem (increasing flows, sand boils, muddy water, sinkholes, whirlpools, etc.) and mitigation of the problem (lower reservoir, place filter berm over seepage point, fill sinkholes, etc.)
- Breach Mechanism. - Type of failure such as enlargement of pipe, crest settlement, sloughing, and slope instability.

Table 2. - Factors Contributing to and Resisting Internal Erosion

INITIATION		CONTINUATION		PROGRESSION		DETECTION/ INTERVENTION UNSUCCESSFUL		BREACH MECHANISM	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY

E. HISTORICAL NOTE

The era during which a dam was designed and constructed has a bearing on the performance of a dam. Before approximately 1930 to 1935, soil mechanics was not accepted as an engineering discipline, empirical methods were the norm, and R. R. Proctor's principles of compaction and construction control [8] were not widely known or followed. During that early era, some embankments were compacted by sheep and cattle and wagons with some moisture control; others were hardly compacted at all and with little or no moisture control; and some were simply built of dumped fill. The case history of Lake Francis Dam, which was constructed in 1899, is an example of this era of construction, and from our modern day perspective it is not surprising that the dam failed.

At Reclamation, the period from about 1935 to 1950 was an era of caution and experimentation, with considerable amount of laboratory research and field studies on compaction and compaction equipment. The period from approximately 1950 to 1976 was an era of generous funding from Congress, with a great amount of design and construction activity. The Teton Dam failure in 1976 forced Reclamation to completely re-examine its dam design and construction practices. From 1976 to the present is a post-dam building era, with only a few dams built, but these have incorporated chimney drains and filters and strict attention to foundation treatment. It is generally accepted that the absence of chimney drains and filters and foundation treatment are the weak links that led to the failure of Teton Dam.

Except for the case history of Lake Francis Dam, the case histories selected have been modern dams, designed and constructed after about 1950. As such, these case histories represent embankment dams that have constructed using modern compaction methods.

F. FAILURE AND ACCIDENT STATISTICS

While the emphasis of this report is on failures and accidents of embankment dams by internal erosion, it should be kept in mind that very few dams have accidents or fail. In the data base complied by Foster and Fell (ERDATA1) [9], the number of accidents and failures for the three types of failure modes for internal erosion are listed in table 3.

Table 3. - Accidents and Failures due to Internal Erosion in ERDATA1 Data Base

Failure Mode	Accidents	Failures	Total
Internal Erosion Through the Embankment	102	51	153
Internal Erosion Through the Foundation	85	21	106
Internal Erosion of the Embankment into the Foundation	31	4	35
Total	218	76	294

There have been only 76 failures and 218 accidents out of 11,192 embankment dams that have been constructed up to 1986 [9]. One way of looking at this is to say that less than 1 percent of the dams in the data base have failed; conversely, the success rate is greater than 99 percent. This is believed to be a very low failure rate when compared to other civil engineering works.

G. INTERNAL EROSION LOCATIONS

Locations where internal erosion can initiate and where a concentrated leak can form are shown on **figure 1**. Fell and Foster have made a statistical analysis of large dams [9] which indicates that failures and accidents usually initiate in the following locations:

- Around or near the conduit (most occurred in this location)
- Over an irregularity in the foundation or abutment leading to cracking of the fill
- Adjacent to a concrete spillway or other structure

Also note that the location where internal erosion has initiated is not known for a large number of cases.

Figure 2 is a bar graph illustrating the number of failures and accidents at various locations for the case histories studied by Fell and Foster [9].

1. Conduits. - Because most accidents and failures by internal erosion are initiated around or near a conduits constructed through an embankment, three case histories are included: Picketberg Dam, Omai Dam, and Ghattara Dam. Why do conduits placed through an embankment cause so many problems? Possible reasons are the following:

- The conduit has cracked, corroded, or joints have opened.
- Stress concentrations, poor compaction of soil adjacent to the conduit, and cracking of the soil adjacent to the conduit have resulted in a zone of weakness in the dam.

This is illustrated in figure 3, taken from reference 10.

Sherard [11] has made the following recommendations for a conduit that is to be placed through an earth dam, and these criteria can be used for purposes of comparison in a risk analysis:

- It is particularly important that the embankment adjacent to the conduit be placed at a relatively high water content and not be a soil susceptible to piping.
- Even in small, homogeneous dams where no chimney drain is installed, it is advisable to provide a drain and filter around the conduit at its downstream end for the purpose of intercepting concentrated leaks which follow the conduit.
- In cases where the soil foundation is thick and compressible, it is not desirable to excavate a trench under the conduit and fill it with compacted earth

2. Transverse cracks. - Two case histories of dams that have cracked are Stockton Creek

Dam and Lake Francis Dam. Transverse cracks through the core of a dam are particularly dangerous because the crack provides a ready path for concentrated seepage to follow. Transverse cracks through the core may be caused by differential settlement, collapse of the foundation, hydraulic fracture, earthquake shaking, or slope instability. Foster and Fell discuss a number of factors that influence the likelihood of transverse cracking in reference 9. Transverse cracks are more likely to occur with decreasing compaction water content and decreasing compaction density; with decreasing plasticity of clayey soils; and with soils containing cementing minerals.

3. Adjacent to a concrete spillway or other structure. - The contact between earthfill and a structure can be a potential zone of weakness in an embankment dam. The contact may provide for a zone of low stress which could lead to a crack and a path for water to flow through. The failure of Walter Bouldin Dam may have been due to poor compaction along the power plant wall.

H. SOME GENERAL OBSERVATIONS

- The reader will benefit the most from a careful reading of the original case histories because of the details that are provided therein.
- Usually, it is a combination of factors, such as weaknesses, defects, and human mistakes, rather than a single one of these factors, that results in an accident or a failure.
- Quite often, incidents are triggered by an unusually high reservoir level or a fast rate of filling of the reservoir.
- For internal erosion to initiate, usually a defect is required that allows a concentrated leak to form.
- It is often the details of design and construction that can lead to internal erosion; unfortunately, these details are not always known or noticed.

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PICKETBERG DAM, SOUTH AFRICA
Failure

This is one of the better case histories because of the clear explanations of internal erosion by piping and the cause of cracks in the fill, which are well illustrated. The authors show how cracking and/or hydraulic fracturing of fill adjacent to the outlet conduit likely initiated a concentrated leak through the entire width of the embankment which led to internal erosion and the breach.

A number of other factors are listed as contributing to the failure:

- dispersive fill
- poor compaction
- collapse potential of the fill and the foundation
- construction over the old dam which resulted in cracking of the new embankment
- incomplete collars*
- encasement details

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* Reclamation's current practice is not to use collars around an embedded conduit because of difficulties in obtaining good compaction around the collars and conduit.

PICKETBERG DAM, SOUTH AFRICA - FAILURE - FIRST FILLING
Factors Contributing to and Resisting Internal Erosion

INITIATION A transverse crack likely developed through the width of the dam next to conduit which provided a path for a concentrated leak		CONTINUATION No filter available to stop internal erosion		PROGRESSION - Erosion pipe enlarges and 5 weeks after first filling, major leakage appeared near d/s conduit		DETECTION/ INTERVENTION UNSUCCESSFUL		BREACH MECHANISM - Gross and rapid enlargement of erosion pipe - less than 1 day	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Incomplete concrete collars around conduit*	Conduit encasement placed on bedrock at 2 locations	No filter around conduit		Dispersive fill material	Part of core treated with gypsum to resist dispersivity	In less than 1 day after major leakage appeared, the dam breached		Entire dam section erodible	Zoned dam
Some fill was low density, nonuniform, and dry of optimum. A few cracks on U/S face of embankment.	Modest fill rate - 33 ft in 5 weeks (about 1 ft/day)	No embank-ment filter		Erosion pipe remains open since concrete around conduit formed a 'roof'	Collars on top & sides of conduit	Major leakage appeared suddenly near outlet conduit		Drawdown capacity likely low	Dam crest remained intact; thus less flow
Loose clayey sand under d/s shell had collapse potential	Compacted fill	Dispersive clay core		Alluvium was erodible	Broadly graded fill	Sinkholes not discovered			
First filling	Pipe encased in concrete				Typical PI = 9				
Some overhangs in concrete encasement	Overhangs not through entire fill				Compaction moisture not excessively low				
Hydraulic fracture possible	Zoned dam								

* Reclamation's current practice is not to use collars around an embedded conduit because of difficulties in obtaining good compaction around the collars and conduit.

OMAI TAILINGS DAM, GUYANA

Failure

The failure of Omai Dam, a tailings dam located in South America, was a complex series of events. It was so complex that any risk analysis would not have identified the actual failure sequence that occurred, according to author Steve Vick. Vick, with a background in risk analysis, goes on to observe that a risk analysis, however, would have identified internal erosion around the outlet conduit and piping of filter sand into the rockfill as major risk contributors instead of focusing just on upstream slope stability.

Vick noted a number of flaws that allowed the failure to occur. These include design errors, construction errors, and human errors. Design errors were the absence of seepage protection around the outlet conduit and a flawed filter design. Construction errors were severe segregation of the transition filter zone and elimination of the zone in some areas. Human errors included not rectifying the absence of the transition filter and elimination of earlier seepage protection around the conduit.

OMAI TAILINGS DAM, GUYANA - FAILURE

Factors Contributing to and Resisting Internal Erosion

INITIATION - Concentrated leak around outlet conduit		CONTINUATION - Gross filter incompatibility between sand filter and rockfill. Longitudinal spreading of seepage resulted in sand filter moving into rockfill. Internal erosion around conduit produced upward-stoping cavities within the core. Underdrains became blocked.		PROGRESSION - Water rose in rockfill and saturated hanging filter which dropped down into rockfill and removed support from the core.		DETECTION/INTERVENTION UNSUCCESSFUL - A 4 PM inspection showed nothing amiss. In the midnight darkness, an alert truck driver noticed water issuing from one end of dam. At dawn, another discharge at the other end occurred with extensive cracking.		BREACH MECHANISM - Core tilted and cracked longitudinally with massive internal erosion and release of reservoir.	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Geometry - a thin, sloping sand filter underlying the core and overhanging the rockfill without proper protection		Downstream portions of the conduit were backfilled with sand that was not filtered at its contact with adjacent rockfill	Filter d/s of core was present	Poor details of conduit design	Powdered bentonite was sprinkled on surface of backfill lifts	Human error - did not recognize effect of rise in water level in rockfill	Rise in water level in rockfill began almost 2 years before failure	Failed area spread rapidly longitud-inally	D/S rockfill section had large flow through capacity
Portions of the backfill around the outlet pipe were undercompacted		Transition rockfill material likely segregated during placement	Mine waste material placed d/s of rockfill except at abutments	Thin core	Gradient across core less than 1	No indication from piezometers in core of impending problems	Dam was well instrumented		Dam crest did not breach
Movement of filter drain material into rockfill		One gradation test during construction showed rockfill coarser than specified				About 1/4 of outflow was contained	Piezometric data revealed rise in water level within rockfill		

GHATTARA DAM, LIBYA

Failure

Ghattara Dam was of modern design. It contained a chimney drain, a blanket filter, and a toe drain. Constructed from 1970 to 1972, it failed in 1977. The author points out that in this semi-arid region cracking of the core was likely, particularly around the conduit where compaction may have been poor. Rapid filling of the reservoir and moderately dispersive fill material also contributed to the failure. It is believed that internal erosion initiated near the downstream end of the conduit and progressed rapidly backwards.

Foster and Fell [8] in their study of this case history raise the question of why the dam failed since it had an embankment filter. It is only one of two cases where an embankment dam failed by piping through the dam despite the presence of an embankment filter. They hypothesize that the inclined filter did not extend into the conduit trench below the level of the general foundation; thus, a continuous path of backfill may have been present with no filter protection against internal erosion.

GHATTARA DAM, LIBYA - FAILURE

Factors Contributing to and Resisting Internal Erosion

INITIATION - Cracking adjacent to or above outlet conduit was possible which provided path for concentrated leak		CONTINUATION - Probably no filter or defective filter around outlet conduit.		PROGRESSION - Erosion pipe enlarges rapidly		DETECTION/ INTERVENTION UNSUCCESSFUL - 10 am, toe dry; 11:30 am muddy water; 12:00 noon erosion of d/s toe; 1:10 PM crest was breached.		BREACH MECHANISM Uncontrolled flow erodes d/s slope back to crest, crest collapses, and breach forms	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Sudden filling of reservoir (2.7 m/day) after 5 years of low reservoir levels	Culvert founded on bedrock	Probably no filter around conduit	Chimney drain, blanket filter, and toe drain	Moderately dispersive soil	Silty clay fill with PI = 23	Failure occurred quickly- infrequent inspections	Technician on site	Homogeneous section at conduit	
Fill susceptible to desiccation cracking during 5 years of low reservoir level		No filter between core and alluvium and rock in cutoff trench		Erodible soil				Moderately dispersive soil	
Compaction of fill around conduit was likely poor	Compacted fill in main part of dam			Cohesive fill able to hold a 'roof'				Erodible soil	
								Outlet too small to lower reservoir rapidly	

STOCKTON CREEK DAM, CALIFORNIA

Failure

Stockton Creek Dam was constructed according to good modern practice in the early 1950s. The cause of the failure is believed to be cracking of the embankment, which led to an initial, concentrated leak and erosion of the low plasticity, clayey sand core.

James Sherard, who studied the failure in some detail, concluded that a near-vertical step of about 20 feet in height on the right abutment led to the differential settlement crack. Sherard studied under the guidance of Karl Terzaghi, and over the years has investigated numerous embankment dam failures.

Two articles about the failure by Sherard are included. The earlier and longer account was for his PhD thesis at Harvard. The second account, which was written about 20 years later, summarizes the first and is from a chapter on "Embankment Dam Cracking," Embankment-Dam Engineering, Casagrande Volume [9].

STOCKTON CREEK DAM, CALIFORNIA - FAILURE

Factors Contributing to and Resisting Internal Erosion

INITIATION - Concentrated leakage through a crack caused by differential settlement adjacent to a near-vertical step in right rock abutment		CONTINUATION - No filter or zoned embankment		PROGRESSION - Erosion of fill progresses		DETECTION/ INTERVENTION UNSUCCESSFUL - At 8 PM dam was inspected and OK; at 8 AM next morning, it had breached		BREACH MECHANISM - Erosion led to 40' wide breach	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Near-vertical step in abutment may have caused low stress zone and hydraulic fracture	Rock surfaces were cleaned; fill was compacted against it in a moist state with careful hand compaction	Homo-geneous embank-ment	Rock toe	Fill had low plasticity	Fill material was not highly erodible	Failure occurred at night	Dam was inspected during filling until 8 PM of the night before failure	Homo-geneous section	Rock toe, but only in valley section
Average water content of the fill was about 2-4 percentage points dry of optimum	Good modern construction - fill placed in 6" layers with sheepsfoot roller with control of water content and density	No chimney drain or filter		Fill material was rigid and allowed roof to form	Clayey sand (SC-SM) fill				
Fill material was susceptible to settlement cracking									
Rapid rise (20 feet in one day) in reservoir during initial filling	Reservoir was at a depth of 40 feet for several months below breached area								

LAKE FRANCIS DAM, CALIFORNIA

Failure

Lake Francis Dam, which was constructed in 1899, is an example of a dam that followed empirical construction methods rather than modern engineering design and construction methods. Most of the dam was placed in 6- to 8-inch-thick layers and compacted by the travel of scraper teams passing over the fill. Much of the fill was placed without any moisture because it was difficult to obtain sufficient water to sprinkle the fill. The final section of the embankment was dumped because construction time was running out before the floods came.

Although there is limited information on the details of the failure, this dam is more or less typical of many built in that era and of many that failed. And this is the reason it was included. From our perspective of modern geotechnical engineering and modern construction equipment and construction control, one tends to forget about early methods of dam construction. This case history is one of over 50 case histories studied by James Sherard for his Doctor of Science thesis at Harvard University. All the case histories are included in Reclamation's Technical Memorandum 645 [7].

LAKE FRANCIS DAM, CALIFORNIA - FAILURE - FIRST FILLING

Factors Contributing to and Resisting Internal Erosion

INITIATION - The 1899 embankment, which was constructed dry with very little compactive effort, settled considerably on the initial reservoir filling. A large stream of water came out of the toe of the embankment near a 36" cast-iron outlet pipe. A few minutes later a stream of water broke through a crack near the right abutment.		CONTINUATION - No filter around outlet conduit or within embankment		PROGRESSION - Quick erosion of the fill		DETECTION/ INTERVENTION UNSUCCESSFUL - A few minutes after leak from the outlet pipe, a stream of water broke through a crack, about 20' above the stream bed, near the right abutment		BREACH MECHANISM - The stream of water quickly eroded the d/s slope by backward erosion. The crest collapsed, and the reservoir emptied in an hour forming a 98' wide breach.	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Construction was behind schedule and closure section was not placed in layers but dumped. Closure section was highly permeable.	Non-closure section fill was spread in 6-8" layers, moistened, and compacted by scraper teams	Homo-geneous section		Homo-geneous section	Fill was a mixture of clay, sand, and gravel	Rapid failure		Homo-geneous section	
Soil layer covering abutments and foundation was not removed.		No chimney filter		Closure section erosive	Fill had a LL=35 and a PI=15.				
Not a modern, engineered design or controlled construction				Very dry fill in closure section					
Difficulty in obtaining water, and much of the fill was placed dry									
Rapid filling of reservoir									
Steep abutment									

WALTER BOULDIN DAM, ALABAMA

Failure

The official cause of the failure was an upstream slide, according to three experienced engineering consultants retained by the Alabama Power Company. Ralph Peck, however, disagreed with this cause of failure and said it was the result of subsurface erosion. Thomas Leps, who offered expert testimony during a Federal Power Commission hearing, agreed with Peck and said piping of the foundation soil was the likely cause. Articles by both authors are included with the summary.

WALTER BOULDIN DAM, ALABAMA - FAILURE
Factors Contributing to and Resisting Internal Erosion

INITIATION - Fractures in the Cretaceous Formation due to foundation unloading or due to excessive grouting pressures provided path for concentrated leak		CONTINUATION - No filter within embankment		PROGRESSION - Backward erosion along sides of power plant or through the Cretacious Formation		DETECTION/ INTERVENTION UNSUCCESSFUL - At 9:45 PM, guard inspected dam. At 1 AM, he noticed muddy water; shortly thereafter, the dam failed.		BREACH MECHANISM Rapid enlargement of erosion pipe and collapse of crest into the pipe	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Fractures wider than 1"opened up during construction in the Cretaceous Formation, but were not sealed	Compact-ed embank-ment	No chimney filter within embankment		Two overhangs on the sides of the power plant		Unseen leakage entered tailrace, below tailwater level, on both sides of the powerhouse	Observable leakage was collected and monitored	Homo-geneous dam	
Post-construction grouting may have caused hydraulic fracturing. Post-failure investigations showed extensive grout travel transverse to the dam axis.		The grout curtain was not closed on both sides of the powerhouse		Difficult to compact backfill against power plant		Embankment-Cretacious contact covered by riprap	Regular inspection of dam by on-duty guards		
Forebay's natural earth blanket was non-uniform and allowed seepage to bypass it. Seepage, springs, and sand boils occurred at toes of wing dams.		No subsurface toe drain		Cretacious sediments were highly erodible and pervious		Rapid failure			
Inadequate review of design and construction		Nearly a homo-geneous embankment							

ULJUA DAM, FINLAND - ACCIDENT

Factors Contributing to and Resisting Internal Erosion

INITIATION - After 20 years of clear seepage from bedrock fissures d/s, it became muddy and increased from 5 to 30 l/s.		CONTINUATION - Backward erosion of basal glacial till under dam and glacial core into fissures in rock foundation caused an erosion tunnel to form.		PROGRESSION - Erosion tunnel continued into core and U/S filter and sinkholes formed in reservoir.		DETECTION/ INTERVENTION UNSUCCESSFUL - Muddy water leaked from bedrock fissures at end of tailrace structure. The crest of dam dropped 3 m into the erosion tunnel.		HEROIC INTERVENTION - NO BREACH. Rapid action in following emergency plans prevented failure. Later, foundation was grouted.	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Embankment founded on glacial till		Glacial till in foundation not filter compatible with fissures in bedrock		Glacial till sensitive to erosion	Zoned embankment with filters controlling erosion of fines through embankment.	Erosion of silt into tailrace water was not detected	Dam put under continuous surveillance and reservoir lowered	Within 45 minutes, the first load of till was dumped into sinkhole on crest after crest dropped 3m.	
Open fissures in bedrock foundation below erodible material		No filter or seepage barrier along seepage path		Cor material is erodible glacial till	Glacial till had enough coarse material to keep flow limited		Divers found sinkholes in reservoir and tracer showed conductivity between sinkholes and leakage point. Sinkholes quickly filled with soil.	Reservoir lowered immediately from 77.8 m to 75 m	
2 m fluctuations in reservoir level several times a day							16 days from notice of muddy leakage until crest dropped into erosion tunnel. Many tools used to find cause of leak.	Till and rockfill dumped on U/S and D/S slope	

ULJUA DAM, FINLAND

Accident

Seepage of about 5 l/s had been observed from bedrock fissures at the end of a tailrace tunnel since first filling in 1970. Twenty years later the water turned muddy and increased to 30 l/s, and a number of large sinkholes were found on the lake bottom near the dam. Two weeks later a sinkhole formed near the upstream side of the crest, and part of the crest failed. Only swift action saved the dam from total collapse. Repairs exposed an erosion channel about 3 meters in diameter, which was oriented downward through the core and extended into the glacial fill under the dam.

Of special note is figure 3 in the report that shows the actual erosion channel through the cross-section of the dam. Horizontal, open joints in the rock, and the fluctuation of the water level several times a day for power operations may have contributed to the internal erosion process.

Rapid and heroic efforts in following emergency plans helped avert a failure. A column "Heroic Intervention" is included in the summary table to reflect these efforts.

LANGBORN DAM, NORWAY

Accident

This case history is somewhat unusual because internal erosion was not occurring in the embankment; rather, it was occurring in left abutment itself. A safety evaluation following the guidelines of Reclamation's Safety of Dams program indicated the most serious weakness in the dam was the left abutment. The potential failure mechanism was progressive sliding of the abutment that could lead to failure of the embankment.

Initially, in 1958 during first filling, excessive seepage, erosion, and a slide occurred near the left abutment. Over the years, remedial measures in the form of geotextile filters and drainage ditches had failed to lower the ground water table in the downstream slope of the abutment, and slides continued to take place.

In 1990, sinkholes on the surface of the left abutment were found indicating internal erosion was progressing, probably at the interface of silt material and open-work gravel and cobbles. In 1995, a new slide prompted remedial measures which included horizontal drains and a downstream stability berm.

LANGBORN DAM, NORWAY - ACCIDENT
Factors Contributing to and Resisting Internal Erosion

INITIATION - Seepage flowing through natural coarse layers eroded adjacent silt layers in the abutment. Seepage may have also dissolved minerals in abutment		CONTINUATION - Internal erosion of silt into the coarser layers leads to clogging of geotextile drain/filter at toe of slope due to transport of fines and growth of iron bacteria, thereby increasing water pressures.		PROGRESSION - Internal erosion opens up additional flow paths and dissolves minerals in the abutment and results in progressive caving and the formation of sink holes		DETECTION/ INTERVENTION UNSUCCESSFUL - Continuous measurement and evaluation combined with numerous remedial measures prevented instability of abutment.		BREACH MECHANISM No breach due to remedial measures.	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Abutment consists of silt, sand, and layers of coarser material and cobbles		Slides on the d/s slope of the abutment in 1958, 1966, 1994, and 1995	Drainage ditches and geotextile filters installed at toe of slope in 1958, 1966, 1972, and 1986 provided temporary help	Seepage water is dissolving iron minerals in the abutment			Continuous measurement and evaluation.		
First filling		Ground water pressures gradually increase with clogging	Ground water pressures temporarily decrease with use of filter blankets and shallow ditches	Silt material had an average diameter of 0.4 mm and was erodible			Deposits of silt upstream of measuring weir was observed		
A blanket to protect the abutment was ineffective				Sinkholes had formed since 1990, 32 years after 1st filling			Horizontal drains decreased ground water pressures and berm of free-draining material to stabilize slope in 1995		

TETON DAM, IDAHO

Failure

Much has been written about the Teton Dam failure. It was the highest dam designed by Reclamation when it failed, and the consequences were severe. The primary purpose of the summary is to provide basic information related to the failure. In addition, the seven most likely mechanisms that may have initiated a concentrated leak that led to failure are listed in the summary. A few of the referenced papers are included for further reading. While the exact cause of the failure is not known, it is commonly accepted that a concentrated flow of high pressure reservoir water passed through open cracks in the rock upstream of the key trench on the right abutment and eroded the very erodible silt fill material, which was then carried into large open cracks in the rock downstream of the key trench. This forms the basis of the table of factors contributing to and resisting internal erosion.

A secondary purpose is to recognize that many different factors contributed to the failure. Geologic factors, design decisions, construction control, and human factors were all part of the story. Sherard identified a number of human factors, "the bureaucracy problem," such as: inbreeding; travel restrictions; no consultants; chimney drains and filters were not considered necessary, at that time; lack of cooperation between the construction and the design staff; and no independent review group to challenge designs.

TETON DAM

Dam Type: Compacted, central core, zoned earthfill. Reclamation's design of the late 1960's.

Location: Idaho, USA

Type of event: Failure on first filling. Commonly accepted cause was due to erosion of core material through foundation voids and cracks in the area of the right abutment key trench.

Incident Date: June 5, 1976, During Initial Filling.

Date of construction: 1972 through 1976

Description of Incident: A heavy spring runoff caused a rapid rise in the reservoir level. It was intended that the filling rate would be restricted to one foot per day. During May 1976, the filling rate reached about four feet per day. Only the auxiliary outlet works were in operation, resulting in virtually no control of the reservoir filling rate. The reservoir was just 3 feet below the spillway crest on the morning of failure.

Before June 3, 1976, no springs or other signs of seepage were noticed downstream of the dam. On June 3, clear water springs coming from joints in the right side canyon wall appeared at distances of about 1,300 and 1,600 feet downstream (Fig. 1).

On June 4, a spring of clear water of about 20 gpm was observed flowing from the canyon wall talus about 400 feet downstream of the right abutment groin.

On the morning of June 5, muddy water was flowing at about 20 to 30 cfs from the talus on the right groin, and the flow increased noticeably in the following three hours.

At about 10:30 a.m., a leak of about 15 cfs appeared on the face of the embankment. The new leak increased and appeared to emerge from a "tunnel" about 6 feet in diameter and extending at least 35 feet into the embankment. The tunnel became an erosion gully developing headward up the embankment and curving toward the abutment.

At about 11:00 a.m., a whirlpool appeared in the reservoir opposite the ever-growing gully on the downstream slope of the dam. At 11:55 a.m., the crest of the dam began to collapse, and minutes later the dam was breached.

Only about five hours elapsed from the time observers noticed the small muddy flows to the breaching of the dam. Fourteen people were killed and more than $400 million in damages resulted from the failure.

Description of Geology and Foundation: The dam site is located in a steep-walled canyon. The volcanic rock that forms the canyon walls and foundation is an intensely to moderately jointed rhyolitic welded ash-flow tuff. The welded tuff is characterized by the presence of prominent and abundant open joints and localized fissures, especially in the upper part of the abutment. Horizontal to low angle foliation is common to tuff outcrops.

At the right abutment, the prominent bedrock joint systems are generally flat-lying upstream and approximately vertical downstream. The joints are closely to moderately spaced, conspicuously open, and unfilled, the parting commonly being 1/4 to 2 inches (0.6 to 5 cm). The vertical joints downstream from the dam axis strike across the canyon at an angle of about 45 degrees with the canyon wall, with a bearing of roughly north 20 degrees west. Hence, they provided multiple planes of freely discharging leakage from the right abutment, but practically no such leakage capacity around the left abutment [1].

In the early stages of design, during the test grouting program, it was concluded that the upper 70 feet of rock on both abutments was very open jointed and grouting costs would be excessive; consequently, the deep key-trench design was adopted. The key-trench excavation had steep sides and many local irregularities, including near-vertical faces and occasional overhangs. In the vicinity of Station 14+00, where failure is considered to have started, were several sets of major, through-going joints.

Penman [2], a British geotechnical engineer, raises some thoughtful questions about the choice of the dam site. How was such an unsuitable site chosen for the dam? Eight sites on the Teton River and a tributary were investigated over the years and rejected. Was the ill-fated dam site chosen under pressure from outside sources? Was the inadequate foundation treatment the consequence of a limited budget?

Description of Dam, Design, and Construction:

Height: 305 ft (93 m)

Reservoir Volume: 288,250 acre-feet (355,550 x 10^3 cu meters)

Embankment: Zoned earthfill with a central core and no filters. See figure 2.

Crest length: 3,100 ft (945 m)

Teton Dam was a central core, zoned earthfill structure with a height of 305 feet above the riverbed and 405 feet above the lowest point in the foundation. The crest of the dam was approximately 35 feet wide at an elevation of 5332 feet. No instrumentation was installed other than surface measurement points.

A cutoff trench was excavated through alluvial material to a maximum depth of 100 ft (30 m) so that zone 1 material could be placed on a rock foundation. The cutoff extended up the sides of the abutments and is referred to as a key trench above elevation 5100. The key trench was excavated to a depth of 70 ft (21 m); it had a bottom width of 30 ft (9 m) and steep side slopes of 0.5:1. The key trench was omitted under the spillway; blanket grouting of the welded tuff was used to strengthen the foundation.

Zone 2 material was placed adjacent to zone 1, upstream and downstream. Zone 2 was composed of selected sand and gravel from the Teton River flood plain and compacted to a relative density of at least 70 percent. A filter was not placed downstream of zone 1 material. Zone 2 material did not meet filter criteria with respect to zone 1 material.

A. Zone 1 Material. - Zone 1 soil was a highly erodible, brittle windblown soil, derived from loess deposits, because more suitable material was not readily available. Natural loess is a meta-stable skeleton of silt particles, held together by a thin coating of clay, which forms a strong bond at low water contents. Mineralogical studies have shown the silt preserves a slightly open structure, even under the heavy compaction of sheepsfoot rollers, which allows collapse settlement on wetting [2]. When compacted, the unwetted zone 1 had considerable stiffness and strength resulting from very high suction pore pressures. This is illustrated by the unwetted, steep slopes remaining after the dam failed. While unwetted fill exhibits considerable stiffness, one-dimensional consolidation tests that were wetted to destroy the initial suction showed collapse settlement.

Other important properties of zone 1 material are summarized as follows [3]:

1. The zone 1 silt, ranging from slightly cohesive to cohesionless (plasticity index generally from 1 to 7), is a common type of soil in the Midwestern USA. Many earth dams have been built with practically identical soil over wide geographic areas, such as western Nebraska, including some of the main Reclamation dams.

2. The material is not dispersive; that is, it does not have a high content of dissolved sodium in the pore water, causing repulsive forces between clay particles. Nevertheless, the material is among the most erodible fine-grained soils in nature. Compacted specimens erode in the pinhole test as readily as a highly dispersive clay, an unusual property for a non-dispersive soil. This means that a small concentrated leak with a velocity of only a few centimeters per second will erode the compacted material.

3. Filter tests showed the material could be carried into rock cracks of width only slightly larger that 0.1 mm, and would easily be carried into cracks with widths of 0.2 mm of larger.

4. When compacted in the laboratory at water content near or slightly below Standard Proctor optimum, the material is very stiff and brittle, compared to similarly compacted specimens of other fined-grained impervious soils.

5. There are few impervious soil deposits in nature which are more uniform in visual appearance or have a smaller range in gradation and Atterberg Limits.

Zone 1 material was compacted to at least an average density of 98 percent of Bureau of

Reclamation (Reclamation or USBR) Standard Proctor density, at an average moisture content between 0.5 and 1.5 percent dry of optimum moisture content. The averages of moisture content and density appear to be very good for the entire dam.

B. Low Density Fill and the Wet Seam. - After the failure, however, it was discovered that low density fill was placed, which surprised everyone. This low density fill was placed primarily during May 1975, following the winter shutdown. Found from a detailed study of the compaction control tests, Leonards and Davidson [4] found that layers of fill in the key trench were placed up to 2.2 percent dry of optimum (between El. 5185 and 5200 and Stations 13+90 to 14+40), where failure is thought to have initiated. During investigation of the right abutment shortly after failure, the Independent Panel found an extremely wet layer of fill extending across the full width of the cutoff trench at El. 5215 at Station 13+15 [2].

Leps commented on the low moisture and density layers and raised a serious question [5]:

> "The key deficiency was placement at moisture contents which were excessively dry of optimum, resulting in low density horizons, wherein dry densities in situ of as low as 80 pcf were discovered as compared to the average of 99 pcf for all Zone 1 compacted fill. In-situ dry densities of as low as 85% of laboratory optimum were measured. Hence, it is clear to this discusser that horizons of such low density material were proven to exist, and that their existence was inevitable given the combined effects of (a) permission to place Zone 1 as dry as 3.7% dry of optimum and (b) the reported inefficiencies in moisture conditioning and blending borrow from excessively dry borrow sources, an inadequate construction procedure which guaranteed that sizeable areas of placed fill were to some degree even drier than the limited test data indicated (drying by wind and solar effects).

Incidentally, it is curious that USBR permitted Zone 1 fill placement at moisture contents as dry as 3.5% below optimum when its own laboratory research, performed as long ago as 1942, showed that placement of impervious fill at moisture contents drier than about 2% below optimum would result in abrupt consolidation upon subsequent saturation (Laboratory Report No. E.M.-18.5)."

A wet seam was found during the investigation of the left abutment in October 1977. The wet seam, with a total thickness of about 3 to 4 feet, was not completely continuous but consisted of 3- to 8-inch-thick lenses, covering an area of at least 5 acres [6]. The most likely reasons for the existence of the wet seam include: a rainy period during construction [7]; penetration of reservoir water into the fill which was placed dry of optimum [2]; frost action [8]; and hydraulic fracturing [3].

The Interior Review Group noted additional factors that explain the low density layer: (1) unsuccessful attempts to mix dry fill with wet soil on the fill surface; (2) deficiencies in earthwork control practices, i.e., (a) zone 1 fill placement began on May 1, 1975, but the earthwork inspection staff did not reach full strength until May 12, 1975; (b) frequency for performing earthwork control tests was considerably less than the required minimum. Approximately 52,000 cubic yards of fill were placed between May 1 and 12, and the specifications required one control test for every 2,000 cubic yards of fill placed, or a total of 26 control tests; only 8 tests were performed.

C. Open Cracks and Foundation Treatment. - The open surface cracks on the right abutment undoubtedly played a key role in the failure. Sherard summarized his findings as follows [3]:

> "A major element of the Teton Dam story has to do with the sealing of the open rock foundation cracks under Zone 1 on the right abutment. The wide-open surface cracks were treated by gravity grouting during the first part of the construction. However, this surface crack filling was abandoned near the location where the failure occurred (about Station 14+00). Subsequently the wide surface cracks under Zone 1 embankment were left open and untreated from about Station 14+00 to the right end of the dam . . . These facts support the conclusion that USBR bureaucratic restriction had a major influence on the failure.
>
> When the excavation was made for the 70-ft. deep trench and the rock foundation surface was uncovered upstream and downstream of the trench by excavation of the colluvial overburden, many large cracks in the rock were exposed to view. These were commonly several inches in width, frequently up to 1.0 ft. Some were open (empty), some were silt-filled and some partially filled. During construction of the dam the USBR geologists made an excellent map, showing location, widths and filling of these cracks . . . This map shows literally many dozens of wide-open cracks exposed in the foundation excavation from Station 16+00 to the right end of the dam.
>
> These cracks in the foundation rock under the main Zone 1, many completely open, over several hundred feet of the dam length, were exposed for inspection by all parties for about 2 years before they were covered by the dam. Since there was no provision in the contract for sealing these surface cracks, the inspection forces devised a method of filling them by "gravity" or "slurry" grouting in stages above the rising embankment surface. This consisted of bringing in transit-mix concrete trucks filled with cement-water grout, and pouring the grout by gravity into open cracks, working from the rising embankment surface. No piping or grout pumps were used for this activity.
>
> When the embankment construction reached approximate El. 5200 on the right side, roughly at Station 14+00, this gravity grouting was abandoned. After this date no further sealing of surface rock cracks on the right abutment was carried out during the remainder of the dam construction.
>
> During my site visit of September 1976 I discussed this problem in detail with the responsible inspection staff, trying to understand how this vital piece of work could

have been stopped . . . The inspectors generally stated that the gravity grouting was stopped on orders from "above" even though there were still many open cracks in the foundation."

Penman commented [2]:

> "It is evident from the specification that the design regarded the bedrock as being free from open fissures and relatively impervious. It called for careful cleaning of the rock surface a few meters in front of the advancing core fill and strickly controlled compaction of a slightly wetter silt against the rock. The actual rough and highly fissured surface of the rock was so completely ignored by the specification that it was difficult to believe that the specification was intended for this dam. . . . It is obvious that a smooth surface should have been provided for the silt contact over a sufficient dam width to ensure that the average total stress across the contact and the hydraulic gradient along it, would have reduced seepage to non-erodible flows. Such a surface could be provided by a thick layer of reinforced concrete placed over and keyed to the bedrock."

Leps would have designed a more conservative key trench, as follows [5]:

1. The side slopes should have been no steeper than 1:1. For this requirement, and including the following concepts, the trench need not have been excavated to such a large depth.

2. The entire rock surface of the trench, side, and bottom, should have been paved with a concrete slab of about 18 inch thickness.

3. The entire paved surface should have received a pattern of consolidation grouting to a depth of say 50 feet.

4. At least one deep grout curtain was needed.

D. The Grout Cap. - The concrete grout cap was only 3 feet wide, and the cracks in the bedrock could transmit water pressure of the almost full reservoir head to the upstream edge of it. Fissures on the downstream side of it could readily conduct water towards the low water table. The resulting very high hydraulic gradient (estimated on the order of 7 to 10) through the silt core resting on the grout cap could be expected to cause erosion, even without consideration of reduction of total stress due to arching in the cutoff trench [2].

Possible Failure Mechanisms: In a 1987 review of the failure, Seed and Duncan [7] listed seven possible trigger mechanisms that led to failure. The paper is included in this section and provides additional details. The possible trigger mechanisms listed are:

1. Flow of water through the grout curtain just below the grout cap, leading to erosion of soil on the base of the key trench.

2. Hydraulic fracturing or differential settlement in the key trench fill leading to cracking across the fill and resulting soil erosion.

3. Hydraulic separation between the key trench and the base of the trench permitting water to flow, with accompanying erosion, from an upstream open joint along the base of the trench, over the grout cap and into a downstream joint.

4. Seepage through the key trench fill, with accompanying erosion, from an open joint upstream, over the grout cap and into a downstream joint. At the time of failure, the hydraulic gradient along such a flow path was probably of the order of 7 to 10.

5. Seepage through the soil near the base of the key trench, facilitated by sloughing of wetted fill into open joints, thereby progressively increasing the hydraulic gradient.

6. The possibility that a dry seam may have existed in the right abutment key trench and that collapse of this seam on wetting may have provided a flow path from open joints on the upstream face of the trench to open joints on the downstream side.

7. The possibility that a wet seam existed in the right abutment key trench permitting seepage directly through the seam and associated internal erosion.

Peck summarized the failure as follows [9]:

> "Upstream of the seepage barrier there was ample opportunity for the reservoir water to reach the barrier in quantity through the joint system in the rock. The physical conditions were fully satisfied for water flowing under high pressure to attack the lower part of the key-trench fill along open joints, some of which were found to transmit water freely through the grout curtain, particularly through the upper part near the grout cap. The attack was fully capable of quickly developing an erosion tunnel breaching the key trench. Arching at local irregularities, loose zones of fill at reentrants, and local cracking may have contributed to the success of the attack and determined the precise location. Hydraulic fracturing, according to analytical studies, may also have been responsible for the initial breaching of the key-trench fill. Conditions were favorable for escape of the water and eroded solids into the joints of the rock downstream, for discharging the water against and along the interface of the right abutment of the dam and the embankment, and for development of the erosion feature that ultimately breached the entire dam.
>
> "The precise combination of geologic details, geometry of key trench, variation in compaction, or stress conditions in fill and porewater that caused the first breach of the key-trench fill is of course unknown and, moreover, is not relevant. The failure was caused not because some unforeseeable fatal combination existed, but because (1) the many combinations of unfavorable circumstances inherent in the situation were not visualized, and because (2) adequate defenses against these circumstances were not included in the design."

It appears that the designers did not anticipate or visualize possible failure mechanisms. Hilf [8] commented that the design concept was that an "impervious plug" would be formed within the key trench. "It was not contemplated that this well-compacted soil would crack. . ."

Clearly many aspects of the site and the embankment design contributed to the failure. The Independent Panel concluded that:

> "The fundamental cause of failure may be regarded as a combination of geological factors and design decisions that, taken together, permitted the failure to develop. The principal geologic factors were (1) the numerous open joints in the abutment rocks, and (2) the scarcity of more suitable material for the impervious zone of the dam than the highly erodible and brittle windblown soils. The design decision included among others (1) complete dependence for seepage control on a combination of deep key trenches filled with the windblown soil and a grout curtain; (2) selection of a geometrical configuration for the key trench that encouraged arching, cracking and hydraulic fracturing in the brittle and erodible backfill; (3) reliance on special compaction of the impervious material as the only protection against piping and erosion of the material along and into the open joints, except some of the widest joints on the face of the abutments downstream of the key trench where concrete infilling was used; and (4) inadequate provisions for collecting and safe discharge of seepage or leakage which inevitably would occur through the foundation rock and cutoff systems."

Lessons Learned: Leps concludes that the lessons to be learned from the failure of Teton Dam do not represent anything new for the profession, but are reminders of points sometimes ignored or forgotten [1].

1. The responsible design engineer should be required to visit the construction site, perhaps monthly.

2. The downstream contact of an impervious embankment zone, whether against foundation material or against a more pervious embankment zone, must be protected against piping by use of filter zones.

3. In grossly pervious foundation bedrock, a single grout curtain should not be relied upon to be adequately effective.

4. Whenever impervious borrow exists at moisture contents severely below optimum, it should be brought to near optimum moisture content in the borrow area.

5. Deep, narrow, key trenches in bedrock should be avoided because they invite arching of backfill.

6. Because of inevitable hydrologic uncertainties, it may be impossible to control the rate of initial reservoir filling. Hence, the dam designer should consider that the reservoir may fill very quickly, regardless of the generally assumed merit of controlling the filling rate.

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TETON DAM, IDAHO - FAILURE - FIRST FILLING
Factors Contributing to and Resisting Internal Erosion

INITIATION - A concentrated flow of reservoir water passed through open cracks in the rock and eroded the silt in the key trench. Hydraulic fracturing, collapse of low-density dry silt, and cracking may have contributed to the initiation of internal erosion.		CONTINUATION - The eroded silt was carried into open cracks downstream of the key trench because the exit seepage was not filtered.		PROGRESSION - Reservoir water under high pressure continued to erode the silt core. An erosion tunnel and a whirlpool formed.		DETECTION/ INTERVENTION UNSUCCESSFUL - Breaching occurred only 5 hours after muddy water was first observed		BREACH MECHANISM Progressive erosion led to collapse of the crest and breaching of the dam	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Gravity grouting of wide cracks in the foundation rock under zone 1 core. Gravity grouting was stopped above El. 5200.	Field inspection crew filled surface cracks in the foundation rock under zone 1 core with gravity grout below El. 5200.	No filter on the D/S side of the erodible zone 1 core, in either the key trench or between zone 1 and 2	Zoned embank-ment	Zone 1 silt was highly erodible - like dispersive clay		Reservoir could not be lowered quickly - outlet works not finished	At 1300& 1500 feet D/S, clear seepage was observed 2 days before failure; at 400 feet D/S 1 day before failure; muddy water at toe 5 hours before failure	Nearly homo-geneous section of erosive silt	
Very steep and deep right abutment key trench with overhangs. Arching of soil in key trench.	A modern, well compacted dam with average moisture content 0.5-1.5% dry of optimum	Zone 2 material did not meet filter criteria with respect to zone 1 material		Stiff silt could form a roof		Failure occurred quickly			
Human errors in design and construction. No defenses in depth. Cracking or concentrated leakage not visualized.	Zoned embankment	Open cracks on the d/s side of the key trench		Silt core had a very small range in gradation and low plasticity		No instru-mentation in embankment, but observation wells showed rapid rise in ground water table in right abutment	Construction workers were at the site		
Rapid first filling - about 4 feet /day.									

FONTENELLE DAM, WYOMING - ACCIDENT - INCIDENT NO. 1
Factors Contributing to and Resisting Internal Erosion

INITIATION - Concentrated flow through untreated joints or through a horizon on the right abutment which solutioned away.		CONTINUATION - Unfiltered exit of seepage allowed continuing erosion of zone 1 core		PROGRESSION - Reservoir water under high pressure continues to erode the fill material forming an erosion tunnel and cavity		DETECTION/ INTERVENTION UNSUCCESSFUL- Seepage was observed coming from the abutments D/S of the dam, but it was not considered dangerous. Details of the monitoring are not known.		HEROIC INTERVENTION - NO BREACH	
MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY	MORE LIKELY	LESS LIKELY
Joints in the sedimentary rock abutments were not sealed - no surface treatment	Modern, well-compacted embankment	No filter on the D/S side of the zone 1 core	Zoned embankment with gravel shells	Silty sand fill used by right abutment	Some lean clay used by right abutment	In May, seepage appeared but was not considered dangerous	In June, leakage from spillway rock wetted the fill which sloughed	Lowering of the reservoir reduced the pressure and flow into the cavity	
Grout cap was blasted. High grout pressures were used which may have cracked the sandstone.	Grouting program	Zone 1 core material in contact with open joints		Fill was erodible	Cracks in rock may have limited flow	Oultet works was large, but it took about 1 week to lower reservoir to base of cavity.	In September, leakage increased and large cavity formed and eroded to the crest	Rockfill was available to dump into the cavity on the crest	
Right abutment had steep geometry and overhangs						Large quanity of rockfill dumped into sinkhole forced flow higher and caused further caving.	Large quanity of rockfill that were dumped into cavity from the dam crest may have helped.		
Stress-relief joints were open and pervasive through the abutment							Incident lasted over 3 days		

FONTENELLE DAM, WYOMING

Accident

Fontenelle Dam is included because it experienced two incidents, and the first one was a near failure. Heroic efforts helped avert a failure. A column "Heroic Intervention" is included in the summary table to reflect these efforts.

There are many similarities between Fontenelle Dam and other Reclamation dams that were designed and constructed in the same period. Ralph Peck has observed that Fontenelle Dam and Teton Dam both had unfavorable abutment configurations, jointed rock, untreated rock joints, erodible core, a blasted grout cap, and a single-line grout curtain. Photographs of the first incident and of the construction showing the untreated rock abutment and blasted grout cap are included.

FONTENELLE DAM, WYOMING

Dam Type: Compacted, zoned earthfill. Typical of Reclamation's design of the 1950's.

Location: Wyoming, USA

Construction Date: 1961 through 1964

Incident Dates: 1965 and 1982

Description of Incidents:

Incident No. 1- Accident and near failure: Reservoir filling began in the summer of 1964. When the reservoir depth reached 49 feet, seepage appeared in a borrow area approximately 2,000 feet downstream, but the seepage was not considered to be a threat to the safety of the dam.

On May 6, 1965, when the depth of the reservoir was 85 feet, seepage began to appear from the rock cut for the spillway on the right abutment and from a cliff on the left side of the valley, approximately 0.6 mile downstream. As the reservoir continued to fill, seepage appeared and increased at the downstream borrow area.

The reservoir started to spill on June 15, 1965, at elevation 6513. On June 29, a small slough occurred at about mid-height of the dam on the left side of the spillway. Seepage estimated at 1 cfs flowed from cracks in the rock upon which the spillway rested. The seepage was flowing along a crack in the sandstone parallel to the valley wall and exiting through cracks normal to the valley wall. Part of the seepage saturated the backfill adjacent to the spillway, and caused the fill to slough.

On the morning of September 3, 1965, a wet area was seen about 100 feet left of the previous slough. During the day, leakage increased to about 5 cfs and was accompanied by sloughing and erosion of the embankment. Local officials were alerted to stand by to alert persons living downstream, if a break in the dam were to occur.

By next morning (September 4), flows had increased to about 21 cfs and roughly 10,500 cubic yards of material had eroded to form a cavity extending nearly to the crest. The outlet works were opened. Plan were made to excavate channeels from the canal outlets to the river since canals had not been constructed as yet. An emergency effort was started to fill the hole.

Photograph 1, taken on September 4, 1965, shows water spilling over the spillway, the large erosional cavity, and material being placed at the base of the cavity. **Photographs 2 and 3**, taken on September 5, 1965, reveal the large amounts of material that have been dumped into the hole from the crest of the dam.

On the afternoon of September 5, the leakage was reported to be surging violently and carrying large amounts of earth fill. Dumping of rockfill was stopped temporarily because the rockfill had forced the flow higher, producing further caving.

On September 6, the reservoir level had dropped 8 feet, and the flow from the leak appeared to stabilize at 6 cfs. However, that afternoon the downstream part of the crest suddenly collapsed and dropped over 30 feet. More of the right abutment rock was exposed, and water was observed coming from cracks in the rock. At this time, the reservoir was about 13 feet above the base of the cavity. Rock was again dumped into the hole.

The reservoir continued to drop at a rate of 4 feet per day. **Photograph 4**, taken on September 8, and **photograph 5**, taken the next day, provide an aerial perspective of the dam, spillway, and West Canal outlet works. **Photograph 6**, taken on September 9, 1965, provides a good view of the exposed rock face on the left abutment. The discharge gradually decreased and stopped entirely when the reservoir reached a depth of 66 feet [1]. By the grace of God, failure of the dam was narrowly averted. The left end of the dam was repaired, and 8 lines of holes were used to grout the left abutment.

Incident No. 2:

In late 1982, a small amount of previously unobserved seepage was seen at the toe of the dam near both the left abutment and the central portion of the dam. Study of the design and construction of the embankment indicated inadequate foundation treatment, and the reservoir was restricted to 10 feet below normal. Investigations of the left side of the embankment in 1983 indicated there were numerous, very soft areas near the embankment-foundation contact. As a result, the reservoir was restricted to 25 feet below normal water surface elevation.

In early 1985, it was observed that the water pressure in a piezometer, near the central portion of the embankment where seepage had been noticed in 1982, had risen over 10 feet while the reservoir remained constant. As the pressure in the piezometer continued to rise, and investigations indicated it was valid, the decision was made to lower the reservoir 63 feet below normal water surface elevation [2].

Description of Geology and Foundation: The dam is located in a relatively flat valley nearly a mile wide. The rock foundation and abutments for the dam consist of nearly flat-lying, interbedded, massive to thinly bedded sedimentary deposits of calcareous sandstone, siltstone, shale, and minor beds of limestone. Minor gypsum was found in drill holes above the ground-water table in both abutments. The rock underlying the dam is weathered, fractured, and permeable, and the abutments contain stress relief joints.

Photograph 7, taken on April 12 , 1963, shows the interbedded and massive to thinly bedded sedimentary deposits comprising the left abutment.

The 1955 Reconnaissance Geological Report [3] may have created an image of a tight reservoir which was erroneously carried into the construction stage when it stated: "With impervious formations underlying the reservoir and a ground-water table draining into the basin, it seems certain there will be no seepage from the reservoir."

MacDonald has written a comprehensive analysis of the geologic issues in which he postulates that "an originally extensive bed of soluble material has essentially been solutioned away in the vicinity of the right abutment and in the downstream left bank 'weeping rock' area" [4]. This soluble material is subject to leaching where the ground-water table has risen as a result of Fontenelle Reservoir. Because of the low water table prior to construction of the dam, this pervious horizon was not obvious until after the reservoir was filled and downstream seepage began.

A 1984 geology report from the Regional Office [5] provided evidence for the solution of gypsum-filled joints since the dam was built. It states:

> "Most preconstruction drill holes in the right abutment show the presence of gypsum in the weathered, fractured, permeable rock zone. Recent drilling does not show the presence of gypsum and pump-in permeabilities are an order of magnitude higher than indicated for earlier drill holes."

Also, the report notes that fractured rock extended from the rock surface to a depth of 15 to 60 feet. Observed fracture openings (horizontal and inclined) in boreholes ranged from hairline to one inch. Openings up to 4 inches were noted at Weeping Rock where water is flowing from bedding planes [5].

After the first accident, a geologic appraisal of the right abutment was made by a Reclamation geologist. The following is taken from that report [6].

> "First are the easily split closely spaced bedding planes which are remarkably evident within the platy siltstone and fissile varved shale units. High grout takes west of the spillway centerline were nearly all within the fissile shale and platy siltstone . . . [between elevations 6415 and 64442] undoubtedly entering the voids between the closely spaced and irregular features. It may be that some of the high take at this horizion was caused or aggravated by hydraulically splitting the bedding planes during the grout program. This possibility was indicated by percolation tests during the preconstruction drilling.
>
> Another major type of discontinuity, and in the present case by far the most important, consists of relief joints which occur predominantly within the massive sandstone and within an area bordering the steep abutment. Because of its uniformly massive characteristic, the sandstone responds to stress by breaking along fractures which generally extend the full thickness of the unit and continue laterally for considerable distance. They form in most massive rock due to removal of lateral support but in the present case are aggravated by the underlying shale bed. They result in deep open joints which roughly parallel the abutment and extend at least to the bottom of the massive sandstone. Five of these open joints were encountered in the spillway inlet excavation, and one was exposed in the spillway chute . . . They attain an open width of up to one foot and are generally vertical and roughly parallel to the abutment contours. One relief

joint located about 140 feet left of spillway station 110 shows evidence of water entering the open crack. This may be one of the more important access routes for leakage."

Description of Dam, Design, and Construction:

Height: 139 ft (42 m)

Reservoir: 345,000 acre-ft (425,550,000 cu meters)

Embankment: Compacted, zoned earth and gravel fill

Crest length: 5,450 ft (1,660 m)

The large central core of low plasticity materials (mainly sandy silts and silty sands) is flanked by well graded gravel shells. Material for the right abutment section was excavated from Borrow Area A, and the Preconstruction Material Report indicated the borrow material was primarily clay having a plasticity index (PI) ranging from about 3 to 14 percent. There were a few samples of silty sands and gravel.

During construction work in 1961, the sedimentary rock in the foundation was found to be more fractured than had been expected. Grout takes were very large in the upper 65 feet of the foundation. A second line of grout holes was placed in the vicinity of the outlet and the right abutment. The pressures used for grouting were too high for the horizontally layered rock, and in at least one area there was hydraulic jacking of the foundation [4].

Photograph 8, taken on September 25, 1961, is a view of the grout trench, which was blasted. The specifications allowed for line drilling and light blasting. MacDonald comments that blasting for the grout cap "never should have been allowed in such rock as it was only likely to increase fracturing and loosen any relatively intact rock . . . and increase the potential of zone 1 embankment piping." [4]

The upstream part of the right abutment is nearly vertical and the downstream part is on a slope of 1(V):2(H). There is no mention of foundation treatment in the Final Construction Report [7] except that the soil cover was excavated to firm foundation and the foundation was cleaned. **Photograph 9**, taken on July 14, 1963, indicates that the fill was placed directly against a layer of horizontally stratified rock. Note overhanging rock ledges and jointed rock.

Factors Contributing to Near Failure

Peck has suggested that there were many similarities between the near failure of Fontenelle Dam and the failure of Teton Dam 11 years later [9].

> "I think those of you who have been studying Fontenelle recently, or at some other time, recognize that it had a great many similarities to the failure of Teton. You have the jointed rock and erodible core, untreated joints in the rock, a blasted grout cap, a singleline grout

curtain, and certainly some unfavorable abutment configurations."

The factors that likely contributed to near failure are summarized into three categories, as follows:

Geologic factors

- The right abutment contained open relief joints up to 1 foot in width. It appears that one or more were not filled with grout which allowed reservoir water to move into the joints. The vertical joints were apparently interconnected with horizontal joints, that were smaller in size, ranging from hairline to one inch. Due to possible hydraulic jacking during grouting or other reasons, the reservoir water under high pressure could come into contact with the embankment. In addition, a bed of soluble material may have been present and was leached away by the reservoir water.

- The available material for the core ranged from a silty sand to a lean clay. The silty sand had a low resistance to erosion.

Design and construction

- The concept of using multiple lines of defense was apparently not used for the design. Foundation treatment (such as removal of overhangs, slush grouting, and dental concrete) was not required. Erodible core material was placed against open cracks in the right abutment. Filters were not used at critical locations, and too much reliance was placed on the narrow grout cap and grout curtain.

Human factors

- Apparently, misconceptions about the foundation and abutment geology were carried into the design stage.

- An independent review of the design and construction by consultants was not required.

- Based upon success in building large dams at more suitable sites, the designers may not have anticipated problems or possible failure modes.

A more complete list of factors that likely contributed to the near-failure of the dam were contained in the 1984 Safety Evaluation of Fontenelle Dam [9].

1. Tabular openings, one-half inch to three-fourths inch wide, were noted along several bedding planes upstream of the dam. The layers were broken by many steeply inclined intersecting joints and relief cracks trending in various directions.

2. A crack, which had transmitted water recently, was discovered at the upstream end of the canal inlet. The crack's direction was toward the area of the initial leak.

3. During the excavation for repair, a "soft spot" was discovered in the embankment roughly between elevations 6458 and 6450.

4. The relief joints were larger on the upstream side of the grout cap than on the

downstream side. In fact, 10 to 20 feet downstream of the grout cap they seemed to disappear.

5. An open relief joint about 15 feet long and one-half to three-fourths inch wide was discovered 85 to 100 feet upstream of the grout cap at elevation 6471.4. Frank D. Carlson, who was resident engineer in charge of construction, stated that the joint was definitely not like that (as large) when the embankment was placed against the abutment.

6. A clean sand and gravel deposit was discovered in the embankment 21 feet upstream of the grout cap opposite station 15+34 at elevation 6453.7.

7. Inspection of bore holes with a television bore-hole camera indicated that relief joints that were once filled with debris had been cleaned out.

8. The steep abutment made shallow grouting difficult because low pressures were necessary to prevent movement in the foundation.

9. The steep abutment encouraged differential settlement and cracking of the embankment.

10. The steepness of the abutment, along with irregularities and overhangs in the rock, made it difficult to achieve a good abutment-embankment bond.

11. Lack of slush grouting and dental concrete allowed a substantial amount of water to seep along the embankment-abutment contact.

12. Zone 1 soil was highly erodible.

Factors That Helped To Resist Failure

The width of the cracks in the right abutment is believed to be one of the key factors that prevented the failure of Fontenelle Dam. The size of the cracks limited the flow of water from the reservoir against the zone 1 fill. Okeson, a Bureau employee who visited the site after the near failure, made a similar observation [8]:

> "I believe that the reservoir water simply moved along the cracks and came out of the rock under the impervious embankment and made it a loblolly. After a few months the water caused slumping of the downstream toe. Then, within a few hours the seepage path became much shorter, and the quantity of water increased rapidly until the rate of flow was restricted only by the size of the cracks in the abutment."

The heroic efforts by Reclamation personnel to quickly lower the reservoir and to fill the cavity with rockfill was a second key factor in saving the dam.

A Comparison Between Fontenelle Dam and Teton Dam

One of the reasons that accidents have been included in this report is to recognize that these dams have withstood a significant errosion event and have not failed. Since Fontenelle Dam and Teton Dam are similar in many respects, it is only appropriate to ask why one failed and the other one did not.

The tables included with each case history (which summarize factors contributing to and resist internal erosion) are valuable in pointing out some of the differences between the two dams. At the same time, it is recognized that each dam had unique characteristics, and the factors listed are our best attempt to explain what happend, and may not be the complete story. Nevertheless, there are differences worth noting. These differences are listed in table 1 and described briefly below.

As mentioned earlier, the width of the cracks in the right abutment is believed to be one of the key factors that prevented the failure of Fontenelle Dam, since the flow of water from the reservoir against the zone 1 fill was limited. At Teton Dam, the width of the joint openings in the rock adjacent to the erodible core was believed to be many times larger, perhaps 10 or more times larger than at Fontenelle Dam.

The difference in the reservoir head is believed to also be significant. The reservoir head acting at the elevation where internal erosion initiated is a measure of the potential energy to erode the soil in the core of the dam. Assuming a direct connection between the reservoir and the point of erosion, at Fontenelle Dam the reservoir head was close to 55 feet of water (about 3,400 psf of pressure). At Teton Dam, erosion is believed to has started somewhere between a depth of 121 and 136 feet below the water surface of the reservoir. Using an average of 128.5 feet of water (about 8,000 psf of pressure), the presssure is estimated to have been about 2-1/3 times greater at Teton Dam than at Fontenelle Dam.

Efforts to prevent failure at the two dams were both heroic in nature. At Fontenelle Dam, the reservoir could be lowered fairly quickly through the large-capacity outlet works, althought it took 17 days before the leakage stopped. Unfortunately, Teton reservoir could not be lowered because the outlet works were not operational.

The reservoir filling history and rate of filling deserve mention, as do the characteristics of the fill material. It was the first filling for Teton Dam and the rate of filling was greater than for Fontenelle Dam, which had been partially filled the previous year. Both dams had erodible core material, although Teton Dam core material was the more erodible of the two.

Table 1

Factor	Fontenelle Dam - Accident	Teton Dam - Failure
Width of joint openings in rock adjacent to fill	Hairline to an inch	Several inches to a foot
Approximate reservoir head acting at location of internal erosion	About 55 feet	Between 121 to 136 feet
Intervention efforts	Reservoir lowered at a maximum rate of 4 ft/day. Rockfill dumped into cavity	Reservoir could not be lowered in time. Fill dumped into cavity.
Zone 1 material placed against rock	Erodible. Mostly CL and CL-ML with PI of 4 to 15	Highly erodible silt with PI of 1 to 7
Reservoir filling history and rate of filling	Reservoir filling began in April 1964 (the year prior to the accident) and was filled to about El.6458. Prior to the accident, the rate of filling was about 0.8 ft/day (April 7 to June18, 1965).	First filling began in Oct. 1975 at 1 ft/day and then increased to 2 ft/day in April 1976. For short periods it was greater with the maximum rate of 4.3 ft/day on May 18, 1976.

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APPENDIX A

APPENDIX B

APPENDIX C

INTERNAL EROSION OF THE EMBANKMENT - **FAILURES**

Dam Name and Location	Date of Const. / Failure	Ht. Ft.	Comments	Va lue Gu ide
Ahraura, India	1953/19 53	75	Whirlpool, failure along outlet works and masonry wall	
Apishapa, CO	1920/19 23	112	Settlement, cracking, leaking	
Ash Pond, LA	?	10	Settlement, hydraulic fracturing	
Avalon II, NM	1894/19 04	?	Overtopping, no compaction	
Beloeil, Quebec	1985	13	Paper in French	
Bila Densa, Czechoslovakia	1915/19 16	59	Leak near outlet works; cause of failure unknown.	
Bilberry, U.K.	1845/18 52	66	Masonry outlet works leak, narrow puddle core	
Blackbrook, U.K.	36652	92	Narrow puddle core, internal erosion, settlement, overtopped	
Flood Levies on Rhone R., France	1994?	15	16 breaches caused by backward erosion and burrowing animals	***
Dale Dike, U.K.	1864/18 64	95	Narrow puddle core, uncompacted fill, settlement, and hydraulic fracturing	

Ghattara (Wadi Qattarah), Libya	1972/1977	125	Piping near conduit, poor compaction near conduit, cracking of clay, dispersive clay	***
Gouhou, China	1988/1993	233	Concrete face cracked, fill was impervious, high phreatic line.	
Hatchtown, UT	1908/1914	65	No compaction, leak by outlet conduit, backward sloughing to crest.	
Hebron, NM	1913/1914	56	Rodent hole led to piping.	
Horse Creek, CO	1912/1914	56	Uncompacted fill, high phreatic line, leak near conduit	
Ibra, Germany	1997/1977	33	Failure teaches about improper use of geomembranes.	*****
Kaihua, Finland	1959		No details of failure in paper.	
Kantalai, Sri Lanka	612,1875, 1952/1986	88, 45?	Geologic paper, other factors not explained	
Kedarnala, India	1964/1964	70	Settlement, drain dug through width of dam and piping, and sudden filling of res.	
Kelly Barnes, GA	1899/1977	42	Intense rainfall, slide on steep d/s slope, possible piping around old penstock.	
La Escondida, Mexico	1970/1972	43	50 pipes and 8 breaches, 1st filling, dispersive clay.	
Lake Francis, CA	1899/1899	52	Most of fill placed dry, last part dumped, settled on first filling and cracked	**

Lawn Lake, CO	1903/19 82	28	Deteriorated lead caulking at outlet gate valve may have led to piping along pipe.	
Lyman, AZ	1913/19 15	65	Puddle clay, rapid filling, settlement	
Mafeteng, Lesotho	1988/19 88	75	Spillway wall, placed on compressible fill, tilted and water flowed through crack. Fill had sand and gravel layers and was dispersive.	*****
Mena/Valparaiso, Chile	1885/18 88	56	No details in paper	
Mill River, MA	1865/18 74	43	Leakage beneath masonry core wall led to slide. Poor design, workmanship, and no inspection.	***
Mohawk, OH	1914/19 15	18	Settlement of uncompacted fill resulted in cracks to the concrete facing, leakage, and erosion.	
14 in Oklahoma and Mississippi	?/1957-70	23-65	Rapid first filling, settlement, cracking, and dispersive clay.	
Omai, Guyana	1993/19 95	148	Internal erosion along conduit, filter sands moved into rockfill, and the sloping core was lost.	****
Pampulha, Brazil	1941/19 54	54	Deformation, concrete face cracked, seepage, and internal erosion.	
Panshet, India	1961/19 61	168	An early monsoon, incomplete outlet works vibrations led to settlement of fill over the conduit and overtopping.	****
Piketberg, South Africa	1986/19 86	39	Reduced stresses by vertical sides of the outlet pipe caused cracks, concentrated leakage, and piping erosion. Good discussion of internal and piping erosion.	*****

Ramsgate, South Africa	1984/1984	46	Dispersive clay, poor compaction, core not continued by 2nd contractor, rapid filling, settlement, cracks, piping tunnels.	
Ropptjern, Norway	?/1976	26	Combination of factors including erosion along outlet pipe	
St. Ajgnan, ?	1965/1984	26	External suffusion turned into piping, poor soil and construction, no inspection.	
Senekal, South Africa	1974/1974	26	Combination of factors caused initial leak leading to piping of dispersive clays.	***
Sheep Creek, North Dakota	1969/1970	60	Combination of factors caused spillway pipe to leak and dam to fail.	
Smartt Sindicate, South Africa	1912/1961	92	Spillway washed away. Possible piping along old and new crests.	
Stockton Creek, California	1949/1950	80	Cracking of embankment at near-vertical step in abutment led to erosion.	***
Trial Lake (dike), Utah	1925/1986	15	Piping along foundation contact which contained organics and root holes.	
Utica, New York	1873/1902	70	No stripping, no compaction, or design.	
Walter Bouldin, Alabama	1967/1975	164	Piping although some disagreement by other investigators.	****
Warmwithens, England	1860/1970	35	Seepage along an old or new tunnel may have contributed to the failure.	
Zoeknog, South Africa	1992/1993	125	No foundation treatment or grout curtain, poor compaction, and piping by conduit.	****

PIPING THROUGH FOUNDATION - **ACCIDENTS AND FAILURES**

Dam Name and Location	Date of Const. and Accident / Failure	Ht.	Comments	Value Guide
Addicks, TX	1948/1977 Accident	49 Ft.	Seepage path through foundation sands exposed by excavation leading to sand boils and erosion.	
Baldwin Hills, CA	1951/1963 Failure	232 Ft.	Fault movement in foundation led to rupture of asphalt reservoir lining and under drains.	***
Bastusel, Sweden	1972/1972 Accident	40 m	On first filling, leakage led to sinkhole at crest due to internal erosion.	
Beaver, AK	1966/1984 Accident	10 m	Grouted karstic foundation leaked after first filling. 18 years later muddy springs appeared.	
Bent Run Dike, PA	1969/1971 Accident	35 m	On filling of the reservoir, leakage and piping through asphalt lining and open joints occurred 4 times.	****
Black Lake, ??	1967/1986 Accident	23 m	Note about material piping through the toe drain.	

Black Rock, NM	1907/1909 Accident - failure	70 ft	Piping through alluvial sands beneath lava cap led to spillway settlement and breach through abutment.	
Bloemhoek, South Africa	1978/1978 Accident	21 m	During first filling, seepage through termite galleries in foundation and boils; sediment found in toe drains.	***
Borga, Sweden	1951/1951 Accident	27 m	On first filling, muddy leakage and piping through a sand layer in foundation.	
Cedegren Example 2, CA	Failure	?	Piping under fish ladder resulted in underground channels and dam failure.	**
Como, MT	1910/1983 Accident	70 ft	Seepage and boils downstream and sinkholes in right abutment.	
Corpus Christi, TX	1930/1930 Failure	61 ft	Seepage beneath sheetpile walls led to piping under or adjacent to spillway and breach. Discussion by Terzaghi.	***
Denison, TX/OK	1994/1992 Accident	165 ft	Hole in corroded CMP toe drain led to erosion of fine sand and silt foundation material into toe drain pipe.	
Dudhawa, India	1962/1962 Accident	25 m	During first filling, sand boils found downstream due to lack of positive cutoff of sand layer beneath clay cover.	
Goczalkowice, Poland	1956/? Accident	17 m	Excess pore pressure in foundation d/s of dam led to a huge pot-hole	

Great Salt Plains, AK	? Accident	2 2 m	During first filling, seepage emerged at d/s toe; corrected by relief wells	
Grenada (B), MS	1954/19 54 Accident	2 6 m	Sink holes over the collector pipe and piping of foundation sands through pipe joints	
Hackberry Site 1, NM	1967/ 70's & 1982 Accident	2 6 ft	Sinkholes u/s, d/s, and in embankment, settlement, cracking and erosion, erosion of gypsum, and seepage.	**
Helena Valley, MT	1958/ Numero us accidents	7 6 ft	Hundreds of small sinkholes were observed in reservoir bed	
Inglis, FL	1973/19 73 Accident	4 3 ft	A major boil (2,200 gpm) under D/S slope led to initiation of slope instability	
Julesberg - (A) (Jumbo), CO	1905/19 06 Accident	6 0 ft	After first filling, a concentrated leak of 1 to 1.5 cfs of clear water emerged at an outcrop of porous limestone in the foundation. For next 3 years the leak increased slightly and large fish occasionally were washed under the dam.	**
Julesberg - (B) (Jumbo), CO	1905/19 10 Failure	6 0 ft	A 400-ft-long section of embankment centered on the above leak washed out. Solution cavities and channels up to 2 feet in diameter found in limestone.	**
Keban, Turkey	1973/19 75 Accident	2 0 8 m	After a large vortex was observed u/s of the left abutment and spring discharge d/s reached 25 cu m/s, the reservoir was lowered to reveal a large cavity in the karstic foundation.	

Koronowo, Poland	?/? Accident	2 3 m	Excess pore pressure in foundation led to sand boils and cavities in u/s and d/s slopes	
Lafage, ?	Around 1980 Accident	1 1 m	Possible piping in marl foundation	
Laguna, Mexico	1908/19 69 Failure	1 7 m	Seepage was measured since 1927, but too much reliance was placed on total seepage and visual observations. Piping was through weathered volcanic tuff.	***
Lake Invernada, Chile	1957/19 58 Accident	3 0 m	Sinkholes appear during yearly reservoir filling in same area due to abrupt soil and underlying basalt changes.	
Lake Toxaway, NC	1902/19 16 Failure	1 9 m	Seepage at foot of dam (through rock fissures) since it was built, turned muddy about 7 hours before failure.	
Langalda, Iceland	1966/19 71 Accident	1 0 m	A large fracture in lava foundation opened under the dam and reservoir emptied in 3 or 4 days.	
Langbjorn, Norway	1958/19 90 Accident		Sink holes, build up of water pressure and internal erosion on left abutment led to repairs.	****
Logan Martin, AL	1964/19 64 Accident	3 0 m	On first filling muddy leakage; later boils and a sinkhole. Piping through limestone foundation.	
Meeks Cabin, WY	1971/19 86 Accident	5 7 m	Bureau design had seepage through left abutment and sinkholes since first filling. Glacial till assumed to be impervious but contained openwork gravels in contact with core of dam.	***

Messaure, Sweden	1963/? Accident	100 m	Excavation of rock foundation led to uplift and dilation of joints and increased foundation permeability.	
Mill Creek Lake, WA	1941/1945 Accident	44 m	Excessive seepage and piping of 750 cu yards of silt.	**
Mohawk, OH	1937/1969 Accident	34 m	After flood in 1969, flood-control dam had seeps, springs, and boils.	
Nanak Sagar, India	1962/1967 Failure	16 m	Piping through pervious foundation led to settlement and overtopping during storm.	
Nepes, ?	1945/1988 Accident	13 m	Piping through gravel layers below cutoff of dam.	
Paloma, Chile	1967/1973 Accident	85 m	Hazy seepage at right abutment, which is composed of fluvial materials.	
Phewa, Nepal	?/1975 Failure	20 m	No investigation of failure or details given	
Prezczyce, ?	?	?	No details	
Red Bluff, Texas	1936/1974 Accident	34 m	Sink holes and major seepage due to solutioning of gypsum beds.	

Roxboro, NC	1955/1984 Failure	7 m	Piping beneath spillway with no under drains progressed to failure.	
Ruahihi Canal, New Zealand	?/1981 Failure	?	Seepage through canal lining caused subsurface erosion and collapse of brittle and erosive volcanic soils.	***
Sarda Sagar, India	1960/1968 Accident	18 m	Under seepage resulted in sand boils, sloughing of d/s slope of dam	
Sardis, MS	1940/1974 Accident	35 m	Relief wells were being plugged by piping of sand through well screens	
Seitevare, Sweden	1967/1967 Accident	106 m	During first filling, springs observed at d/s toe. Concentration of flow at juncture of grout curtain and abutment	****
Tarbella, Pakistan	1974/1974 Accident	145 m	During first filling, 400 sinkholes formed in u/s 'impervious' blanket due to openwork gravel in foundation	**
Three Sisters, Alberta, Canada	1952/1974 Accident	21 m	During first filling, seepage and sand boils near d/s toe. 130 sinkholes in reservoir in 9-year period. Sinkhole on d/s slope behind powerhouse after 29 years. Internal erosion of sand and sandy silt into open-work gravels in foundation	***

Uljua, Finland	1970/19 90 Accident	1 6 m	Seepage of 5 L/min observed since first filling. After 20 years, leakage turned muddy, flow increased to 30 L/s, and 2 sinkholes formed by u/s toe. 2 weeks later, sinkhole on crest and 100 L/s leak. Piping of glacial till into fractured bedrock. Erosion tunnel discovered.	** **
Walter F. George Lock and Dam, GA	1963/19 82 Accident	5 2 m	Piping through ungrouted construction piezometer holes u/s of power station.	
West Hill, MA	1961/19 79 Accident	1 7 m	Sand boils near d/s toe	
Western Turkey	1959/19 68 Accident	7 7 m	Seepage suddenly increased by 300% due to a crack in the impervious blanket in the reservoir.	
Wheao Canal, New Zealand	1982/19 82 Failure	?	Interface between canal earth lining wingwall may have opened up allowing piping to develop.	**

A SUMMARY LIST OF FACTORS RELATED TO INTERNAL EROSION

While reading through the case histories, I wondered which factors were the most important and how many combinations of factors were necessary to cause an internal erosion accident or failure. Foster and Fell and others have pointed out that it usually is not a single factor, but a combination of factors that causes an incident. My conversations with a safety engineer about industrial accidents indicated that accidents usually occurred when faulty equipment and when human error, such as haste and carelessness, happened at the same time.

Initially, I subdivided the factors that affect internal erosion into the following categories:

- Performance. - How well the dam has performed, especially with regard to seepage and sinkholes and cracking.
- Geology. - The type of foundation (soil or rock), foundation treatment, and site geology
- Design and Construction. - Design and construction aspects, especially seepage control measures, properties of the core material, and construction quality.
- Outlet-Works Conduit. - Location, type, condition, and age of outlet works and other structures in contact with to the dam

After reading Dr. Peck's article about the influence of nontechnical factors on the quality of dams [4], I included a human factors category. While this category is important, it is difficult to quantify. Later, Fell and Foster [9] reported that nearly 50 percent of failures due to internal erosion occurred on first filling of the dam. Therefore, another category was added to reflect the age of the dam, the era of construction, and the reservoir load history.

The following pages should be helpful in summarizing data for use in a risk analysis or a review of a dam.

PERFORMANCE SUMMARY

1. Seepage/Leakage
   - location: ____
   - amount: ____
   - history: ____
   - rate of change: ____
   - color: ____
   - sandboils: ____
   - sinkholes: ____
   - other: ____
2. Instrumentation interpretation
   - piezometers (e.g., pore pressure increase, hydraulic gradient): ____

____

- other: ____

3. Other observations (e.g., cracking, settlements): ____________

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4. Comments:

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5. Conclusions: ______________________________

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6. Evaluation of performance:

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