Time for Development of Internal Erosion and Piping in Embankment Dams

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Abstract: A method is presented for the approximate estimation of the time for progression of internal erosion and piping, and development of a breach leading to failure in embankment dams and their foundations. The method accounts for the nature of the soils in the dam core, the foundation, and the materials in the downstream zone of the dam. Guidance is also provided on the detectability of internal erosion and piping, taking account of the mechanism of initiation, continuation, and progression to form a breach, for internal erosion and piping in the embankment, the foundation and from the embankment to foundation. It is shown that in many dams which have poor internal erosion and seepage control and are constructed mainly of earthfill, the time for potential development of piping is short, and for these dams continuous monitoring of seepage or surveillance would be needed to detect the piping in time to give warning of possible failure, and to give time to attempt intervention to prevent the failure.

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Introduction

Internal erosion and piping has historically resulted in about 0.5% (1 in 200) embankment dams failing, and 1.5% (1 in 60) experiencing a piping incident. Of these failures and accidents, about half are in the embankment, 40% in the foundations, and 10% from the embankment to foundation (Foster et al. 1998, 2000a,b). Fewer incidents of piping in the foundation, and particularly from embankment to foundation, progress to failure, than for piping in the embankment. About two thirds the failures occur on first filling or in the first 5 years of operation.

As noted by Foster et al. (2000a,b), in a detailed study of piping failures, many piping failures occur rapidly, with the majority less than 6–12 h between the first observation of a concentrated leak, and breach (failure) of the dam. Sherard et al. (1972) and Charles (1997), also noted that piping failures can occur rapidly.

This has important implications for the management of dam safety, because it has been demonstrated [DeKay and McClelland 1993; U.S. Bureau of Reclamation (USBR) 1999], that the potential for loss of life in the event of a dam failure is very dependent on the warning time available to evacuate the population at risk downstream of the dam. USBR (1999), for instance, suggests that an advance warning of failure of as little as 60 min can have a significant impact on reducing the number of lives lost. This has major implications on assessing the consequences of a dam failure, especially when comparing one dam to another in planning remedial works programs.

Many dam owners rely heavily on surveillance, and monitoring of pore pressures and seepage to warn of potential internal erosion and piping problems for many older dams which were not provided with filters designed and constructed to control internal erosion. It has been the authors perception that many may have placed an overreliance on monitoring and surveillance rather than carrying out remedial works, given the potential for rapid failures, and the likelihood that some (or most) modes of initiation of internal erosion may not be easily detectable. Detection may however be possible once erosion has progressed, provided the monitoring is well designed, and read frequently enough.

In this paper, we have set out to define a logical framework to give an approximate estimate of the time for piping to progress and form a breach based on the characteristics of the dam and its foundation. We have trialed this against case studies of dams which have failed or experienced piping incidents, and adjusted the logic to match the case studies so far as practical. We have also set out to discuss the ability of monitoring and surveillance methods to detect internal erosion and piping for the different mechanisms of initiation of erosion, based on an understanding of the internal erosion and piping process and the case studies.

Most of the case studies of failures are prior to 1986, and there is seldom good quality data available about the dam and the incident. As a result, much of what is presented is based on the judgments of the writers. We have sought wide peer review, by seeking to have drafts of the paper reviewed by the representatives of the 17 industry sponsors for the research into internal erosion and piping failure being carried out at the University of New South Wales (UNSW), and other selected colleagues.

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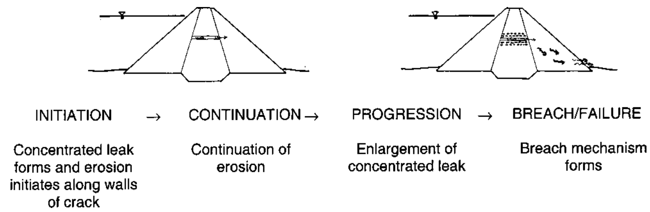

Fig. 1. Model for development of failure by internal erosion and piping—piping in embankment initiated by concentrated leak (Foster and Fell 1999, 2000)

Internal Erosion and Piping Process

It is useful to break up the process of internal erosion and piping into four phases—initiation and continuation of erosion, progression to form a pipe, and formation of a breach. This is shown in Fig. 1 for piping through the embankment initiated by a concentrated leak. Similar processes apply for piping through the foundation, and from the embankment to the foundation. Table 1 summarizes the means by which internal erosion may initiate. The factors affecting the likelihood of initiation of internal erosion are described in Foster and Fell (1999, 2000).

Filters, or transition zones, if they are present, control the ‘‘continuation’’ phase of the process. If the filters are designed and constructed to satisfy modern filter criteria, e.g., according to Sherard and Dunnigan (1985) and USBR (1999); the internal erosion process will almost certainly not continue. If the filter or transition zone particle size distribution is coarser than required for the ‘‘no-erosion’’ filters designed using these criteria, erosion may continue. Depending on the grading of the filters and soil, some excessive or continuing erosion may occur. Foster and Fell (2001) discuss these concepts and provide criteria to define the excessive and continuing erosion boundaries.

There are three issues affecting the progression of piping through the embankment or foundation (Foster and Fell 1999, 2000): The ability of the soil to support a roof of the pipe, i.e., will the pipe remain open or collapse; enlargement of the hole, i.e., will the pipe enlarge and how quickly; and will flows be limited by ‘‘crack filling’’ from filters upstream of the core, or upstream zones, e.g., fine grained or ‘‘dirty’’ rockfill.

Potential breach mechanisms for piping through the embankment and piping from the embankment to foundation are: Gross enlargement of the pipe hole, crest settlement, or sinkhole on the crest leading to overtopping, unravelling of the downstream slope, and instability of the downstream slope. The first three mechanisms require the formation and the enlargement of a pipe through the dam; the fourth may occur without the formation of a pipe.

Breach from piping in the foundation may occur by slope instability of the embankment and loss of freeboard, or gross enlargement of the pipe, either in the foundation, or in the embankment and foundation; or by enlargement of the pipe, leading to sinkholes, crest settlement and loss of freeboard of the embankment.

Time for Development of Internal Erosion, Piping, and Breach

General Approach Adopted

We have assessed the likely time for the development of internal erosion, piping, and breach by:

Table 1. Means by Which Internal Erosion May Be Initiated in Dam Embankments and Foundations

Location	Means of initiation of erosion
Embankment	• Backward erosion • Concentrated leak - Transverse cracking or hydraulic fracturing due to horizontal or vertical differential settlement, desiccation, earthquake or slope instability - high permeability zone due to poor compaction, layers of coarse soil, ice lenses, desiccation during construction - high permeability zone or cracking associated with conduits and wall - erosion into conduits or cracks in walls • Suffusion (internal instability)
Foundation	• Backward erosion, including that following blowout or heave • Concentrated leak - Transverse cracking due to hydraulic fracture, differential settlement, earthquake and slope instability - High permeability zone due to coarse or structured soils (e.g., laterite), open jointing or solution features in rock, (e.g., karst, limestone, gypsum); ice lenses • Suffusion, and erosion of fine soils into adjacent coarse soils or open joints or solution features in rock.
Embankment to foundation	• Backward erosion, initiated by erosion of the embankment soils into open joints, coarse soils, or solution features in the foundation. This includes erosion (also called scour) at he contact of the embankment and the foundation caused by seepage flow along open joints.

1. Considering each phase of the process.
2. Assessing the likely times to failure accounting for the mechanics of the process, and the factors which affect the likelihood of the process occurring. We have assumed that the rate of each phase of the process is correlated to the likelihood that process will happen. That is, if a phase of the process is very likely, it is also likely to proceed rapidly. If all phases of the process are very likely, then it is also very likely the overall process will be rapid. The times are based on an overall assessment of published literature, case study data, and on preliminary results of laboratory testing of the factors affecting the rates of erosion being carried out at the UNSW.
3. Analyzing the accounts of case studies of piping failures and accidents to assess whether the method the methods developed in point 2 were reasonable, adjusting where necessary, to calibrate the times to failure.

Recognizing that it is not possible to be precise in the assessment of times, we have adopted the qualitative terms in Table 2. Dual descriptors are used to describe intermediate terms, e.g., very rapid—rapid for 6 h. The terms are applied to part (e.g., progression) or the whole process.

Analysis of Case Studies

Case studies of piping failures and accidents from the published literature, from sponsors and other direct sources, have been ana-

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Table 2. Qualitative Terms for Times of Development of Internal Erosion, Piping, and Breach

Qualitative term	Equivalent time
Slow (S)	Weeks or months, even years
Medium (M)	Days or weeks
Rapid (R)	Hours (>12 h) or days
Very rapid (VR)	<3 h

lyzed to assess the mechanisms of initiation, continuation, progression, and for failures, breach; and so far as practical, the times for each phase of the process. All failure cases available to the authors with sufficient data, and a selection of the accidents with good quality data, were used. Failures and accidents are defined according to International Commission on Large Dams (ICOLD) (1974). More details of the case studies, and the references from which the data are taken are recorded in Foster and Fell (1999) and Fell et al. (2001).

It will be noted that in most cases it has not been possible to identify the time of initiation of erosion, and the first signs of erosion tend to be at the progression phase, with a concentrated, often muddy leak. Where it is possible, e.g., from increased seepage flows, the time for initiation has been recorded. It should also be noted that for the accidents, the dam did not breach, so the time shown is the time from when progression of the piping began, to when the piping accident ceased, either by self-healing or intervention.

Times for Initiation and Continuation of Erosion

Based on the mechanics of the processes, and the limited case data, the expected usual times for initiation and continuation of internal erosion are summarized in Table 3. We are unable to separate the times for the two processes, which is inherently difficult because one is relying on external observations to assess the initiation of internal erosion. In a general sense, the adequacy of the filter or transition (if present) should have an effect on the time for continuation, with filters which are so coarse as to not satisfy continuing erosion criteria (Foster and Fell 2001) giving more rapid erosion than those satisfying say excessive erosion criteria.

Table 3. Usual Times for Initiation and Continuation of Internal Erosion

Location of internal erosion	Mechanism	Usual time for development	Comment
Embankment	Backward erosion	Slow to rapid/very rapid	The process should be slow in the absence of any concentrated leak, and rapid or very rapid with a concentrated leak. However, the final stage of initiation and continuation where the erosion breaks through to the reservoir is likely to be very rapid or rapid.
	Crack/hydraulic fracture	Rapid or very rapid	The process may develop rapidly once the reservoir level reaches the crack, or reaches the level at which hydraulic fracture is induced.
	High permeability zone	Slow to rapid	The process may develop rapidly once the reservoir level reaches the high permeability zone and/or the critical gradients needed to initiate erosion.
	Suffusion/internal instability	Slow	The process involves a gradual migration of fines within the soil.
Adjacent or into a conduit or wall	High permeability zone, crack, or hydraulic fracture	Rapid or very rapid	The process is likely to develop quickly once the reservoir level reaches the permeable zone adjacent the conduit or wall, or reaches the level at which hydraulic fracture is induced.
	Erosion into open joints or cracks	Slow	Assuming the open joint or crack is not wide.
Foundation	Backward erosion	Slow	The process should be slow in the absence of any concentrated leak. However, the final stage of initiation and continuation where a pipe breaks through to the reservoir is likely to be very rapid or rapid.
	Backward erosion following blowout	Rapid to very rapid	The process is likely to develop quickly once the reservoir level reaches the critical level.
	Backward erosion along a concentrated leak	Slow to rapid	The process may develop quickly once the reservoir level reaches the high permeability zone and/or the critical gradients needed to initiate erosion.
	Suffusion/internal instability	Slow	The process involves a gradual migration of fines within the soil.
Embankment to foundation	Backward erosion initiating at the contact between embankment and foundation, and erosion (scour) at the embankment–foundation contact	Slow to rapid/very rapid	The process is likely to be slow in the absence of any concentrated leak, but rapid to very rapid if a crack or hydraulic fracture forms.

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Table 4. Influence of Factors on Likelihood of Progression of Erosion—Ability to Support Roof (Foster and Fell 1999, 2000)

Factor	Influence on Likelihood of Fill or Foundation Materials Supporting the Roof of a Pipe		
	More likely	Neutral	Less likely
(a) Embankment materials			
Fines content (% finer than 0.075 mm)	Fines content>15%	Fines content<15% and >5%	No fines or fines content<5%
Degree of saturation	Partially saturated (first filling)		Saturated
(b) Foundation materials			
	Piping through soils with cohesive fines Cohesive layer overlying piped material Piping through solution features in rock Piping below rigid structure (e.g., spillway)	Well graded sand and gravel	Homogeneous, cohesionless sands

Time for Progression of Erosion to Formation and Enlargement of Pipe

Tables 4, 5, and 6 summarize the factors which influence this. These are based on literature, and a review of case studies, Foster and Fell (1999). It has been assumed that the rate of progression is independent of the mechanism of initiation and that if most factors in Table 5 indicate enlargement of the pipe is "more likely," erosion will occur rapidly (or very rapidly), if most are "less likely," erosion will occur slowly; and if most are "neutral" or a mix of more likely, neutral and less likely, erosion will occur at an intermediate rate.

The likelihood of upstream flow limitation by, for example, fine grained or dirty rockfill zones, or concrete facing, or potential crack filling by filters or similar materials upstream of the dam core is assessed using Table 6. Where flow limitation is likely, the time for progression is likely to be longer than if there is no flow limitation. In some cases, the flow limitation may stop the erosion process, or have it reach an equilibrium prior to breach of the dam. Flow limitation and crack filling can also occur in piping in the foundation, or from embankment to the foundation.

Time for Formation of Breach Leading to Failure of Dam

The factors which influence the likelihood of breaching for different modes of failure are discussed in (Foster and Fell 1999, 2000). It has been assumed that dams which have factors making it more likely for a breach to form are likely to breach more quickly than those with neutral or less likely factors. We have found that the time of development of a breach is difficult to separate from the progression phase, and that in many cases it might not be practical to consider each breach mode separately, so

Table 5. Influence of Factors on Progression of Erosion—Likelihood of Pipe Enlargement (Erodibility) [Adapted from Foster and Fell 1999(a), 2000]

Factor	Influence on Likelihood of Pipe Enlargement		
	More likely	Neutral	Less likely
Embankment and foundation			
Hydraulic gradient across core[b]	High	Average	Low
Soil type	Very uniform, fine cohesionless sand (PI<6)[c] or well graded cohesionless soil (PI<6)	Well graded material with clay binder (6<PI<15)	Plastic clay (PI>15)
Clay fraction % (passing 0.002 mm)	Low clay % (e.g. <5%)		High clay % (e.g. >50%)
Pinhole dispersion Test[d]	Dispersive soils, pinhole D1, D2	Potentially dispersive soils, pinhole PD1, PD2	Nondispersive soils, pinhole ND1, ND2
Embankment			
Compaction density ratio	Poorly compacted, <95% standard compaction density ratio[a]	95–98% standard compaction density ratio	Well compacted, ⩾98% standard compaction density ratio
Compaction water content	Dry of standard optimum water content (approximately 3% or less)	Approximately 1–2% drier than standard optimum water content	Standard optimum or wet of standard optimum water content
Saturation	As-compacted, partially saturated		Saturated after compaction
Foundation			
Relative density or	Loose	Medium dense	Dense
Consistency	Soft	Stiff	Very stiff

[a]<93% Standard, dry of optimum water content, much more likely.
[b]Even dams with very low gradients, e.g., 0.05, can experience piping failure.
[c]PI=Plasticity index.
[d]Using Sherard Pinhole Test.
[e]Based on tests at University of New South Wales.

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Table 6. Influence of Factors on Progression of Erosion in Embankment—Limitation of Flows by Upstream Zones (Foster and Fell 1999, 2000)

Factor	Influence on Likelihood of Upstream Flow Limitation: Unlikely	Neutral	Likely
Filling of cracks by washing in of material from upstream	Homogeneous zoning. Upstream zone of cohesive material		Zone upstream of core capable of crack filling (cohesionless soil)
Restriction of flow by upstream zones or concrete element in dam	Homogeneous zoning. Very high permeability zone upstream of core e.g., coarse grained rockfill	Medium to high permeability zone upstream of core	In zoned dam, medium to low permeability granular zone upstream of core, e.g., fine grained, or dirty rockfill. Central concrete corewall and concrete face rockfill dams

we have adopted Table 7 as a guide to the breach time. Table 7 reflects the fact that the breach time is controlled largely by the ability of the downstream zone to handle increased seepage flows. This is controlled by the permeability and erodibility of the material forming the downstream zone. For piping through the foundation, we have found it useful to assess both the foundation and embankment using Table 7.

Method for Assessing Time from First Signs of Piping, to Breach, Piping in Embankment, Foundation, and Embankment to Foundation

The method for estimating the time from the first signs of piping (usually a major increase in seepage, often muddy, and from a single point), to breach, is given in Table 8. Most of the case studies against which the method was trialed are for failure by gross enlargement, so Table 8 is best applicable to cases where the mechanism is gross enlargement. It is considered to be reasonably applicable to cases where the final breach is by slope instability, following development of a pipe. For cases where the primary breach mechanism is by sinkhole leading to crest settlement, the rate of erosion should be assessed from Table 5, and consider the other factors in Table 6. Breach by crest settlement is usually slow to medium, although unless addressed, it can lead to overtopping with a resultant rapid breach. For unravelling or sloughing, the rate of erosion should be assessed from Table 5, and consider the other factors in Table 6. These processes are expected to be slow to medium, but may be rapid if the erosion rate is rapid.

The method was trialed against 28 failures and 7 accidents, for piping in the embankment (including along a conduit); 8 failures and 3 accidents for piping in the foundation; and 3 failures and 3 accidents piping trialed from the embankment to the foundation. Table 9 summarizes the estimated versus actual times from the first sign of piping to breach. It can be seen that the method is most reliable for piping in the embankment, but if anything has a bias toward estimating a slower time than actual. The two cases where the rate was estimated as slow when it was rapid or very rapid were Bilberry, which failed by overtopping, due to crest settlement which had developed slowly by internal erosion, and Dale Dyke, where piping had been slow developing and known for some months, but was rapid when the reservoir rose suddenly. For piping in the foundation, the two cases where the rate was estimated as medium or medium-slow and it was rapid to very rapid were where a concrete corewall had an incomplete cutoff in the foundation which was not allowed for in the estimate. Details are given in Fell et al. (2001).

The authors caution however, against over-reliance on these figures. They are only approximate, and hidden or unknown details within a dam or its foundation may give shorter or longer times.

There are some points of detail worth noting:

1. There does not seem to be any particular relationship between the time for progression and breach, and the presence or absence of a conduit. The conduit does however make it more likely that piping will occur (Foster et al. 2000a).
2. There does not seem to be a difference in the behavior of dams which fail on first filling (or the first 5 years), and older dams.
3. Piping may initiate in the foundation and progress into the embankment. We have found that assessing breach times for both the foundation and embankment, and using the shorter of the two, gives the best correlation with actual performance.
4. The flow limiting benefits of a concrete face (or other face membrane) may be lost or reduced, if the connection between the face and foundation is not founded on nonerodible rock.
5. Pipes which have developed and are reasonably stable under normal reservoir may progress rapidly under higher reservoir levels.
6. It is notable that most of the failures are for homogeneous dams, earthfill with (a small) rock toe, concrete face earthfill, and puddle core. All of these types of dams have little ability to stop erosion from continuing, (that is, they have no filters or transition zones) and have poor breach resistance in the downstream zone. Most accidents, by contrast, are dams with some control on internal erosion (even if not satisfying filter criteria), or have high permeability downstream zones. These features will often at least slow the progression and breach formation, even if they do not prevent failure.
7. Very poorly compacted soil, e.g. $<90\%$ density ratio, standard compaction, appears to be rapidly erodible regardless of the type of soil. Soils of glacial origin also appear to be often rapidly erodible—more rapid than indicated by Table 5.
8. Most foundation failures appear to be initiated by backward erosion. These may take many years to develop, and then progress rapidly or very rapidly. However, in the case of blowout or heave, the process may all occur in a short period of time.

Table 7. Influence of Material in Downstream Zone of Embankment, or in Foundation, on Likely Time for Development of Breach

Material description	Likely breach time
Coarse grained rockfill	Slow–medium
Soil of high plasticity (liquid limit $>50\%$) and high clay size content including clayey gravels	Medium–rapid
Soil of low plasticity (liquid limit $<35\%$) and low clay size content, all poorly compacted soils, silty sandy gravels	Rapid–very rapid
Sand, silty sand, silt	Very rapid

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Table 8. Method for Approximation Estimation of Time for Progression of Piping and Development of Breach, for Breach by Gross Enlargement, and Slope Instability Linked to Development of Pipe

Factors Influencing the Time for Progression and Breach				Approximate likely time—qualitative	Approximate likely time—quantitative
Ability to support a roof [a]	Rate of erosion[b]	Upstream flow limiter[c]	Breach time[d]		
Yes	R or VR	No	VR or R–VR	Very rapid	<3 h
Yes	R	No	R	Very rapid to rapid	3–12 h
Yes	R–M	No	VR		
Yes	R	No	R–M	Rapid	12–24 h
Yes	R–M, or M	No	R		
Yes	R	Yes	R or VR		
Yes	R	No	M or S	Rapid to medium	1–2 days
Yes	R–M, or M	No	M or M–S		
Yes	R or R–M	Yes	R or R–M		
Yes	M or R–M	No	S	Medium to slow	2–7 days
Yes	R–M or M	Yes	S		
Yes	M	Yes or No	S	Slow	Weeks–even months or years

Notes: VR=Very Rapid; R=Rapid; M=Medium; S=Slow.
[a]Estimated using Table 4.
[b]Estimated using Table 5.
[c]Estimated using Table 6.
[d]Estimated using Table 7.

Examples of Application of the Method

The following are two examples of application of the method to estimate the time for progression and development of a breach.

Case A. A zoned earthfill dam (''USBR type'') with the upstream zone (the core) constructed of sandy clay of low plasticity (liquid limit 30%, plasticity index 12%, clay size 15%), and pinhole dispersion PD1; and a downstream zone of gravelly silty sand, with 15% fine passing 0.075mm. All zones were compacted to 98% standard maximum dry density at optimum water content. The dam has been in operation for some years. The likely failure mode is the initiation of erosion in cracks near the crest.
In Table 8:

- Ability to hold a roof—Yes for core and downstream zone;
- Rate of erosion—Core. Neutral (N) hydraulic gradient; N soil type. N clay fraction %; N pinhole dispersion, N compaction density and water content; more likely (ML) saturation. Overall Neutral giving medium rate;
- Upstream flow limiter—No;
- Breach time—Rapid to very rapid;
- Approximate likely time for progression and development of breach—Rapid to very rapid, i.e., about 12 h.

Case B. A homogeneous earthfill dam, constructed of sandy clay of low plasticity, (liquid limit 25%, plasticity index 8%, clay size 10%), and pinhole dispersion of D1, compacted to 95% standard maximum dry density, 3% dry of standard optimum water content). First filling (e.g., a flood control structure or levee bank).
In Table 8:

- Ability to hold a roof—Yes;
- Rate of erosion—N hydraulic gradient; N-ML soil type; ML-N clay fraction %; ML pinhole dispersion; ML compaction density and water content; ML saturation. Overall more likely, giving rapid to very rapid rate;
- Upstream flow limiter—No;
- Breach time—Rapid to very rapid;
- Approximate likely time for progression and development of breach—Very rapid, i.e., less than 3 h.

Table 9. Summary of Estimated versus Actual Times from First Signs of Piping to Breach

	Estimated versus Actual Time				
Piping mode	Faster	Equal	Half scale slower	One scale slower	>One scale slower
Embankment	0	10	14	2	2
Foundation	1	3	2	0	2
Embankment to foundation	2		1		

Note: Scales for times are given in Table 2.

Detection of Internal Erosion and Piping

We have assessed the methods and ease of detection of internal erosion and seepage by: Reviewing the case studies to assess what methods of detection were used, and how obvious it was that piping had initiated or progressed, and considering the mechanisms involved in initiation, continuation, progression and breach, and the ability of standard methods of surveillance and monitoring to detect internal erosion and piping either directly or indirectly.

From the case studies, and a general understanding of the mechanics of internal erosion and piping, it can be concluded that:

1. Monitoring of seepage, either by visual surveillance, or measurement, is the most common means of identifying that internal erosion and piping have occurred.
2. It is not common to have sufficient change in the seepage, or in other factors such as pore pressure changes, or settlement, to identify conclusively that internal erosion has initiated and is continuing. It is more common to recognize when the erosion has progressed to the stage that a pipe has developed; or that there are changes in pore pressures, seepage, or settlement which may be related to internal erosion, but this is not conclusive and it may reflect other factors. These changes may be a precursor to a higher likelihood of internal erosion and piping, so it is important they are observed, and when they occur, investigated.

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3. The inability to detect that internal erosion has been initiated relates to the common mechanisms of initiation. For piping in embankment failures, initiation is most commonly cracking, high permeability zone or hydraulic fracture, in the embankment, or around a conduit. These mechanisms could be expected to initiate very rapidly or rapidly once the reservoir level reaches the critical level at which erosion begins in cracks or high permeability zones; or the critical level at which hydraulic fracture initiates. Initiation of erosion by suffusion/internal instability is likely to be a more slowly developing process, accompanied by more gradual increases in seepage, and changes in pore pressure with time.

   ''Blowout'' or ''heave'' in dam foundations where seepage forces create a zero-effective stress condition is a situation which should be able to be detected readily by carefully positioned, and well monitored piezometers. Often these low effective stresses occur below lower permeability layers which act to confine the seepage flow, and it is important that piezometers are installed to measure pore pressures in these areas. These pressures are usually directly related to reservoir levels and it is important to monitor the relationship between the pore pressures and reservoir levels. Most often these conditions will occur on first filling or at historic high reservoir water levels, but we are aware of cases where pressures have increased with time possibly due to suffusion, or blockage of drains and pressure relief walls.
4. Failures from piping in the foundation and from the embankment to the foundation are mostly from backward erosion, or backward erosion following hydraulic fracture, blowout or heave. These would not necessarily be expected to be preceded by large increases in seepage during the time the erosion is gradually working back from the downstream exit point. When the erosion has progressed to within a short distance of the reservoir/foundation interface, it breaks through rapidly or very rapidly.
5. In the vast majority of cases of piping through the embankment, the reservoir was either at a historic high level, or within 1 m of the historic high level, when progression of erosion to form a pipe occurred. This is an important factor in dam safety management, and it shows that enhanced surveillance and monitoring should be carried out on dams which have potential internal erosion and piping problems, when the reservoir is at or near historic high levels. This will usually mean during floods and of course on first filling. It might also be concluded that the initiation of erosion, continuation, and progression to form a pipe is less likely if the reservoir is held below its historic levels—e.g., as an interim dam safety management measure while remedial works are planned and constructed. However care should be exercised in this, since lowering the reservoir might promote drying and cracking of the core—increasing the likelihood of initiation of erosion when the reservoir level is again raised, or if a flood occurs.

For piping in the foundation, or from embankment to foundation, there is a lesser correlation of the timing of the incident to the reservoir level. However, for most modes of initiation, we would expect the likelihood of failure to be highest when the reservoir level is high.

Summary and Conclusions

The methods proposed for assessing the rate of development of internal erosion and piping are very approximate and should be only used as a general guide to performance. Where the consequences of failure of the dam are large, a cautious approach should be adopted in making these estimates.

It should be recognized that the time for progression and development of a breach does not include the time for the dam to be emptied of water, i.e., it does not include the time for breach enlargement which is used in estimates of dam-break floods. It also does not equal the available warning time to evacuate persons at risk, since this is dependent on whether the dam is under surveillance at the time of piping, and the measures set in place to advise persons downstream of an impending dam failure.

The frequency at which seepage is measured can be related to the likelihood that a dam may fail or experience an accident by internal erosion and piping, the consequences of failure, and the likely time for internal erosion to progress to form a pipe and the dam breach. It might also be related to the reservoir level, with enhanced measurements at times of high reservoir level. The seepage monitoring system needs to be capable of being calibrated to separate out the effects of rainfall or snowmelt, e.g., by prior observation and monitoring; and coupling seepage measurements to rainfall and snowmelt measurements at the dam. Seepage monitoring systems that are set up to monitor different portions of the dam can be helpful. Also, seepage monitoring systems that can monitor for sediment transport can provide important information on the progression phase of the failure mode. It should, however, be recognized that there are many situations where it will be unlikely that seepage will be detected, e.g., at night when visual surveillance is being relied upon; if the toe of the dam is submerged or if seepage occurs high on the dam abutments, it may bypass measuring weirs; in winter when the dam is covered by snow.

There are clearly many dams which may have progression and breach times of the order of hours. These dams particularly include some older dams which have no filter or transitions, dams without downstream rockfill zones to stop or slow the erosion process, and/or those dams on erodible foundations without well designed and constructed cutoffs or filters to intercept the foundation seepage. For these dams, an effective seepage monitoring program would virtually require continuous monitoring. Daily, or even twice daily inspections, or measurements, may be inadequate depending on the consequences of failure.

The likelihood of success of intervention measures will be dependent on the detailed circumstances for a dam. Factors which will influence this include the likely time from progression of internal erosion to form a pipe and breach, the mechanism of piping involved, the zoning of the dam, the size of the reservoir and whether the reservoir level can be drawn down rapidly, and the resources readily available to carry out intervention measures. It will be particularly dependent on whether the piping would be inherently likely to stop progressing to develop a breach because the erosion eventually is controlled by the filters or transition zones, the inherent low likelihood of the downstream zone to develop a breach mechanism (e.g., if it was free draining rockfill), or the erosion is self-limiting (e.g., in a rock foundation with erodible joints of limited width).

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