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INCIDENTS IN DAM AND DIKE BEHAVIOR INDUCED BY INTERNAL EROSION

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1. Introduction

Internal erosion occurs when soil particles within an embankment dam or its foundation are carried downstream by seepage flow.

Internal erosion is a major cause of failure in earthfall dams and dikes. Actually, the most of the failure which occurred on the large dams constructed between 1800 and 1986, showed that 94% of failures were related to erosion; and the internal erosion was responsible for approximately 48% of earthfall dam failures, [1], [2], [3]. If comparing between the slides of embankment dams and the earthquake failure; just 4% represent of the slides and 1.7% of the failure due to the earthquakes, where the internal corrosion represents a much greater threat to the current earthfall dams. This failure occurs by internal erosion introduced from the nature of internal erosion processes, which can develop under case-specific conditions and occur concealed inside the dam's body or its foundation. This makes the erosion process invisible until it has either progressed enough to be visible as sinkholes on the surface of the structure or detected by dam monitoring instruments. However, the failures in the embankment dams make occur after the first filling and the internal erosion remains a threat to existing dams because they not have been designed to resist extreme loads such as extreme water level and earthquakes (cause cracking). Cracking occurs as a result of cycling of water level, differential settlement, and desiccation; as well as the aging causes deterioration, particularly deterioration of conduits, spillways and other structures through dams, at which internal erosion may be initiated, Also they may not be protected against internal erosion by filters, or if filters or transition zones are present, they may not have been designed to modern standards and may be ineffective, [4]. In developing the risk assessment approach researchers have improved understanding of the mechanisms that can result in dam failure by internal erosion. This improved understanding, when added to existing knowledge of seepage forces and hydraulic conditions in an embankment dam and its foundations, makes it possible to assess the ability of a dam to resist the forces imposed on it that may cause internal erosion to initiate, continue and progress to failure.

Recently, the advances in understanding showed the internal erosion occurs in earth water-retaining embankments when the hydraulic forces provisioned by water flowing through openings or seeping through pore size that exceed the ability of the soils in the embankments or their foundations to resist them.

1.1. Importance of Internal Erosion to Dam Safety

The internal erosion is an important safety issue for large and small dams, dikes and levees as shown by the statistics of historic failures and incidents.

The statistics of embankment dam incidents show that internal erosion is a significant cause of incidents and to a lesser extent failure for older dams. Incidents include new or increased seepage and leakage, sinkholes and accelerating settlements of the dam. There is also evidence that incidents and failures are more likely along with the interface between the embankment fill and structures such as culverts and spillway walls. An understanding of internal erosion is important to dam owners as this:

a. Is necessary to understand and interpret the behavior of the dam;
b. Is necessary to assess the safety of the dam, and whether it is safe enough or whether safety works are needed to make it so;
c. Should govern the dam safety surveillance and monitoring regimes.

Many new and potentially useful methods for monitoring and detecting internal erosion and seepage have been developed in recent years. These methods such as visual inspection, leakage measurement and monitoring of pore pressures with piezometers are valuable tools in keeping dams safe by detecting internal erosion early in the process.

2. Description of path failure

Failures and incidents by internal erosion of embankment dams and their foundations are categorized into three general failure modes, as follows:

- ✓ Internal erosion through the embankment, such as conduits associated with outlet works, spillway walls or adjoining a concrete gravity structure supporting the embankment;
- ✓ Internal erosion through the foundation;
- ✓ Internal erosion of the embankment into or at the foundation. Including:

a. seepage through the embankment eroding material into the foundation,
b. seepage in the foundation at the embankment contact eroding the embankment material.

2.1. Phases of internal erosion

There are four phases of internal erosion process, these phases are:

- Initiation of erosion;
- Continuation of erosion;
- Progression to form a pipe or occasionally cause surface instability (sloughing);
- Initiation of a breach.

Figure 1(A) shows the internal erosion through the embankment initiated by a concentrated leak. While Figure 1 (B and C) show the similar processes that apply for piping via the foundation, and from the embankment to the foundation.

2.2. Mechanics of Erosion (Particle Separation)

The first condition for internal erosion to occur is particle detachment. Water seeping through the dam or flowing in cracks must provide enough energy to detach particles from the soil structure.

There are four mechanisms which occur in the erosion initiation, these are:

1) Concentrated leaks;
2) Backward erosion;
3) Contact erosion;
4) Suffusion.

2.2.1. Concentrated leaks

The concentrated leaks may occur through a crack caused by differential settlement during the construction of the dam or in operation by a hydraulic fracture. As well as, it may occur due to the collapse settlement of poorly compacted fill in the embankment, around conduits, and nearby to walls. They may also occur due to the action of animals burrowing into levees and small dams and tree roots rotting in dams and forming holes.

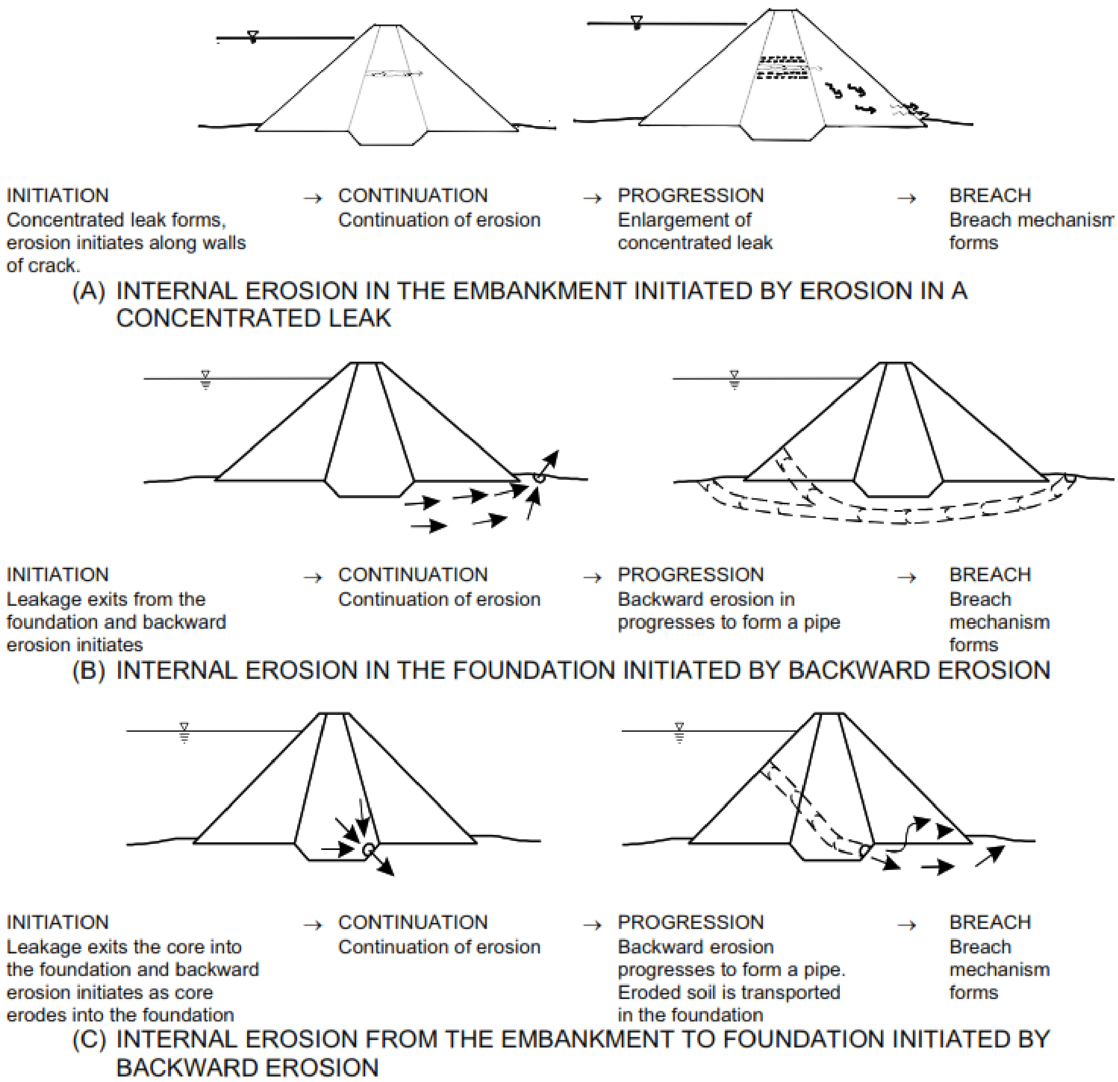


Figure 1. *Models for the development of failure by internal erosion, [2].*

2.2.2. Backward erosion

There are two types of backward erosion:

1. Backward erosion piping, at the back (upstream) end of a very small pipe below a "roof", working 'backwards' from the toe toward, and eventually breaking through, the reservoir. It mainly occurs in foundations but may occur within embankments.
2. Global backward erosion, leading to development of a near-vertical pipe in the core of an embankment.

2.2.3. Contact erosion

Contact erosion occurs where a coarse soil such as gravel is in contact with fine soil, and flow parallel to the contact in the coarse soil erodes the fine soil.

2.2.4. Suffusion

Suffusion occurs when water flows through internally unstable widely graded or gap graded non plastic soils. Some fills and filters in dams also have very broad or gap-gradings and contain excessive fines content.

2.3. Continuation and Filter Action

- ✓ Erosion once initiated will continue unless the eroding forces are reduced, or the passage of the eroded particles is impeded in some way. The filters and transition zones which are coarser than required by design methods based on particle size will often be quite effective in controlling erosion. Even downstream rock fill and sand/gravel zones which were not designed as filters may provide some protection against erosion continuing.

2.4. Progression

Progression is the phase of internal erosion where:

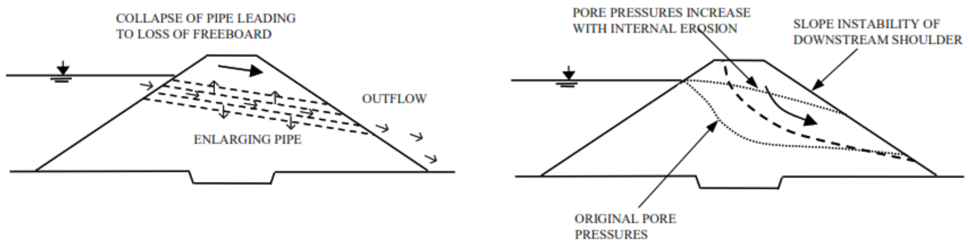
a. For concentrated leak erosion, the erosion in the crack or concentrated leak leads to development of a pipe.
b. For backward erosion the erosion process extends upstream from the point of initiation, and a network of small erosion channels forms beneath the soil or embankment providing the roof to the erosion pipes. If these small erosion channels reach the reservoir or river, then a pipe form. In global backward erosion, sinkholes (vertical pipes) form.
c. For contact erosion the erosion of the finer soil into the coarser soil continues. This may in particular cases lead to development of a pipe in the finer soil.
d. For suffusion, some of the finer fraction is eroded leaving the coarse matrix of the soil. No pipe is formed but the permeability of the soil may be increased significantly.

2.5. Breach

In these situations, the entire process of internal erosion has concluded, detection and intervention have failed. The dam may breach by one of five mechanisms as listed below, while the internal erosion process will stabilize. The breach phenomena are listed in order of their observed frequency of occurrence.

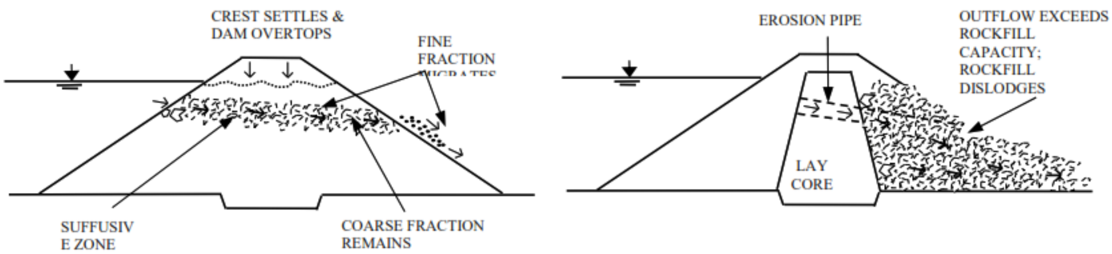
a. Gross enlargement of the pipe.
b. Overtopping (e.g. due to the settlement of the crest from suffusion and/or due to the formation of a sinkhole from a pipe in the embankment).
c. Slope instability of the downstream slope.
d. Unraveling of the downstream face.
e. Static liquefaction which is a form of slope instability which may include the increase of pore pressure and sudden collapse in the eroded zone.

The first four are shown schematically in Figures 2 and 3.



BREACH BY PIPE ENLARGEMENT BREACH BY SLOPE INSTABILITY

Figure 2*. Potential breach (failure) phenomena-pipe enlargement and slope instability*.



BREACH BY OVERTOPPING BY SETTLEMENT BREACH BY UNRAVELING OF THE DOWNSTREAM FACE

Figure 3. *Potential breach (failure) phenomena-overtopping by settlement and unraveling of the downstream face,* [5]*.*

3. Case Histories

3.1. Failures and incidents from concentrated leak erosion

- **Failure in dam body and into foundation: (Teton Dam):**

Teton dam it's a dam constructed in Idaho, USA. the first failed during the first filling on June 5th, 1976. The water level was about one meter below the spillway weir crest. There was no sign of malfunction until the sediment-laden leak was seen flowing from the right abutment, Figure 4. The leakage and erosion accelerated until the dam had failed, as shown in Figures (5 and 7). The dam has not been rebuilt and its remains can still be seen at the site.

The dam has a 93 m high earth zoned embankment. Sections are shown in Figure 4 in the valley floor and in Figure 6 in the right abutment, around the location where the leakage was first seen, and the failure commenced. [6]

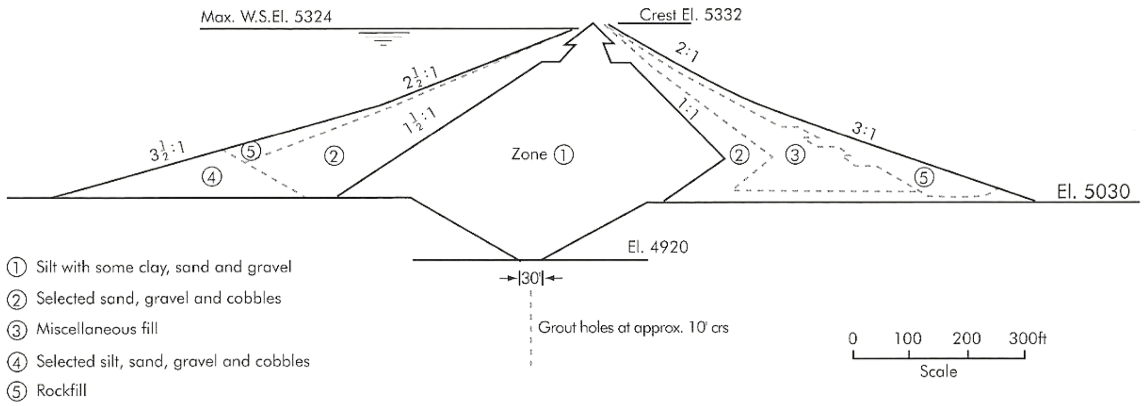


Figure 4. *Schematic diagram of the Teton Dam: Section in valley bottom showing fill zones and cut-off through alluvium,* [6].

Figure 5. *Photograph of Teton Dam: approaching mid-day, the leak has enlarged further and widened under crest,* [7].

Following practice at the time, no filters were provided to prevent erosion in the windblown non-plastic to slightly plastic Zone 1 core fill. The means provided to stop erosion were grouting of the foundation from a grout cap under the core in a cut-off trench through the alluvium in the floor of the valley and in key trenches in the upper parts of the core contact zone (above El 5,100-ft).

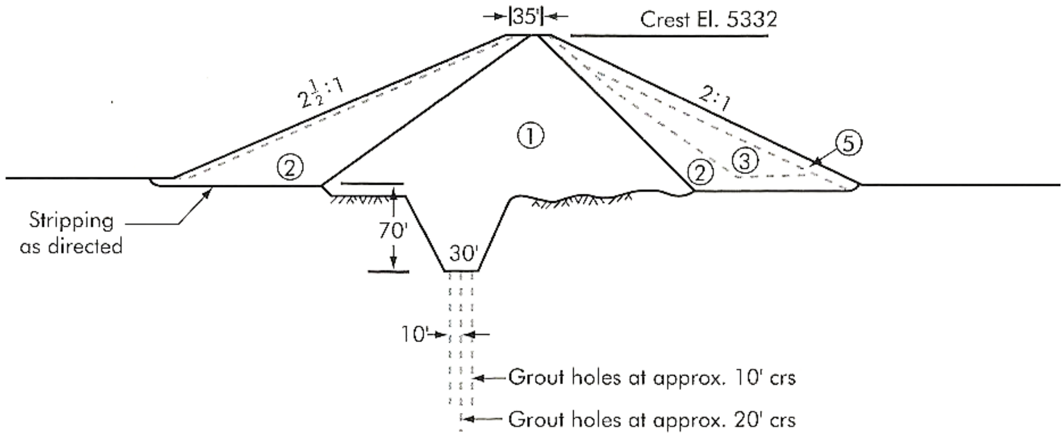


Figure 6. *Schematic diagram of the Teton Dam: Section with a deep cut-off trench at failure position in right abutment,* [6].

Figure 7. *Photograph of Teton Dam: leak has enlarged and widened, crest (bridge) has collapsed, the outflow exceeds 28,300 m^3/s eroded all the dam fill entirely,* [7].

Mr. Chadwick's review the cause the Teton Dam failure and summarized that the failure at Teton followed what is now recognized as the four phases of internal erosion leading to failure, as follows:

- **Initiation**: in this case by erosion in concentrated leaks through the Zone 1 fill in the right abutment key trench at approximately the location is shown in Figure 8. The cracks and openings probably formed by one or both of the following: from below by water flowing through open joints in the trench foundation not sealed by dental concrete, slush grouting or the grout cap and grout curtain; and through hydraulic fractures resulting from low total stresses caused by 'arching' in the deep steep-sided key trench and possibly from unfavorable foundation profiles in the base of the trench. Water flowing in the open joints in the foundation rock would then enter the openings and readily initiate erosion of the erodible Zone 1 fill.

- **Continuation**: through open joints in the foundation rock at first, not blocked in the cut-off trench by grouting or arrested by filters there.
- **Progression**: progressing upwards through the Zone 1 fill and above the grout cap (which afterward was found to have been washed out at the failure position). The fill was easily eroded, non-plastic and much was probably not saturated. It was plainly able to 'hold a roof' of the considerable span, like the photographs, Figure 5, show. As the erosion 'pipe' enlarged and discharge increased, the hole exposed in miter at the junction between the downstream face of the dam and the rock abutment, enlarged, and rose up the slope, gradually approaching the dam crest. A small sinkhole was seen in the crest shortly before the (bridge) across it collapsed, and at this late stage, whirlpools were first seen in the reservoir water above the upstream face, presumably above the upstream end(s) of the erosion pipe.
- **Breach**: the erosion (pipe) broke through into the reservoir soon before the crest (bridge) collapsed. Thereafter the escaping water eroded the dam fills rapidly, deepening and widening the initial breach, less or more totally removing all traces of the dam fills from the site and exposing the foundations. [6]

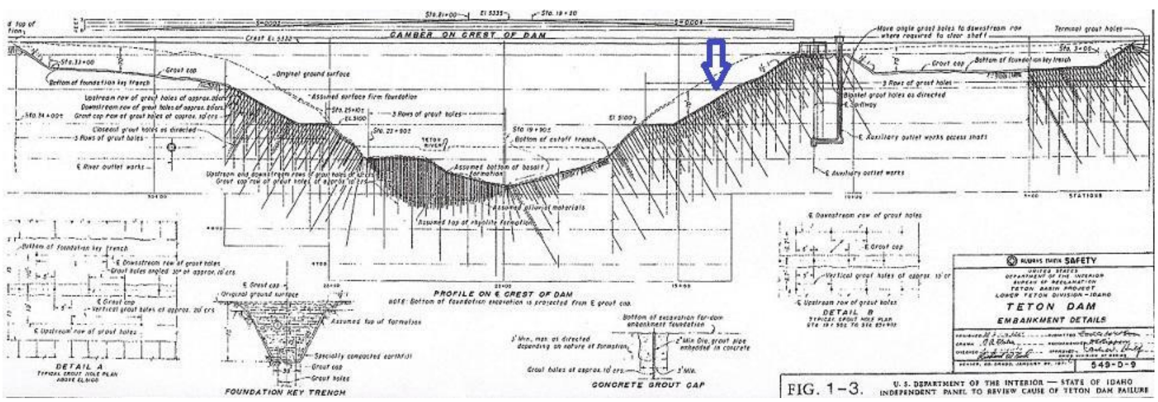


Figure 8. *longitudinal section along cut-off trench showing (arrow) approximate location in the right bank key trench where concentrated leak erosion leading to failure initiated, [8].*

There have been many subsequent examinations of the failure, and many papers written about it, which continues to this day.

A preliminary trial by Merino, [9] of its benchmark approach to analyzing internal erosion examined the Teton case, which USBR reviewed. One result that analysis was indicated that erosion may have initiated before the eroding opening and the discharge through it had become large enough to cause and continued undetected for several days the leakage seen in the miter of the dam on 5th June 1976. This may provide incentives to develop monitoring devices capable of detecting otherwise indiscernible leakage or openings in the body of a dam. However, for the present, it confirms that there are no reliable indicators that internal erosion potentially leading to failure is occurring until it has initiated. It is therefore advisable to investigate, analyze and assess the vulnerability of dams to internal erosion and remediate if necessary, to protect them against it.

3.2. Failures and Incidents from Backward Erosion and Global Backward Erosion

- **backward erosion pipes breaking through upstream blankets from below of Shikwamkwa Dam:**

Shikwamkwa dam was completed in 1958 in Ontario, Canada, [10]. The cross-section is shown in Figure 9. It was a 35 m zoned earthfall dam with a central impervious core constructed using a fine silt material (rock flour). The dam was founded on a deep, permeable and highly variable interbedded glaciofluvial and glaciolacustrine overburden deposits that ranged from cohesionless silts to coarse deposits of nested cobbles and boulders. The primary defense against foundation seepage was a relatively short (about six times the head) and thin (about 3% of the hydraulic head) impervious blanket that connected to the central core and what was thought to be a relatively continuous layer of relatively impervious silty sands in the dam foundation. [6]

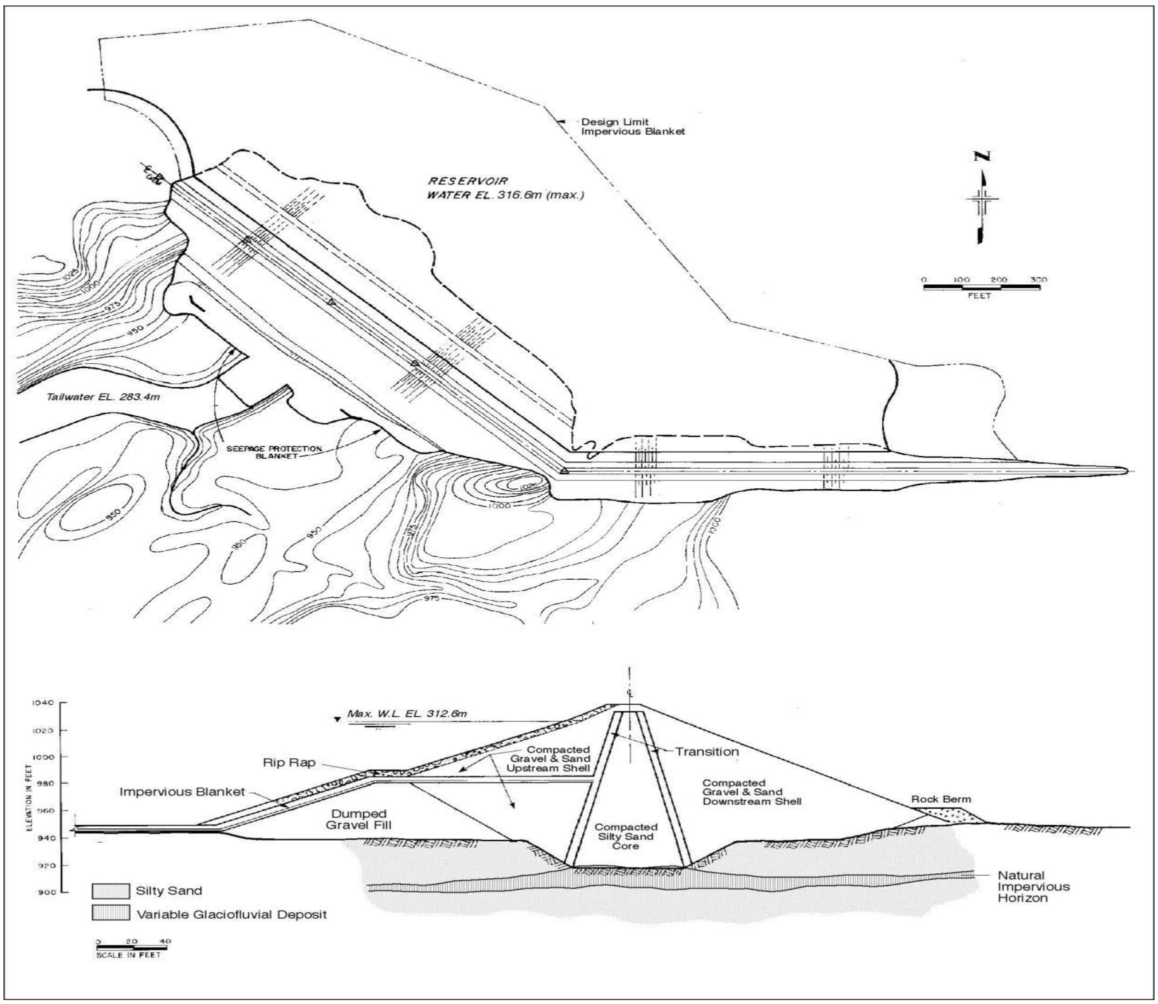


Figure 9. *Shikwamkwa Dam: Section and plan showing the extent of upstream blanket, [10].*

During impounding in 1958 numerous seepage incidents occurred with leakage up 1.0 m3/s and local instability on the downstream slope. Toe berms and additional blankets were added, and the dam performed satisfactorily for about ten years. Then downstream sand boils, piping incidents and sinkholes re-commenced, including one sinkhole which in 1971 opened up at the toe of the upstream slope, causing a slope failure, which fortunately did not break through the dam crest. A record of this event (which after repair left a depression in the crest) and the many sinkholes, seepage routes, sand boils and other damage which occurred is shown in Figures 10 and 11.

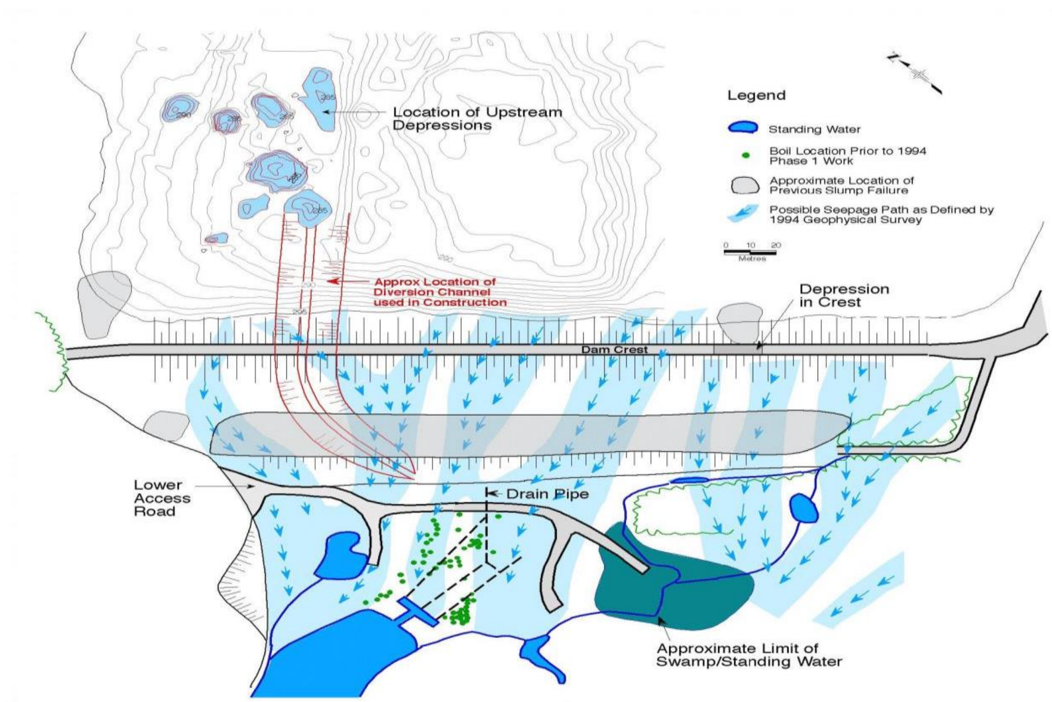


Figure 10,Shikwamkwa Dam: a record of upstream sinkholes, erosion pipe routes, downstream sand boils and the depression left in the crest after slope failure caused by sinkhole opening up at upstream toe , *[10]*

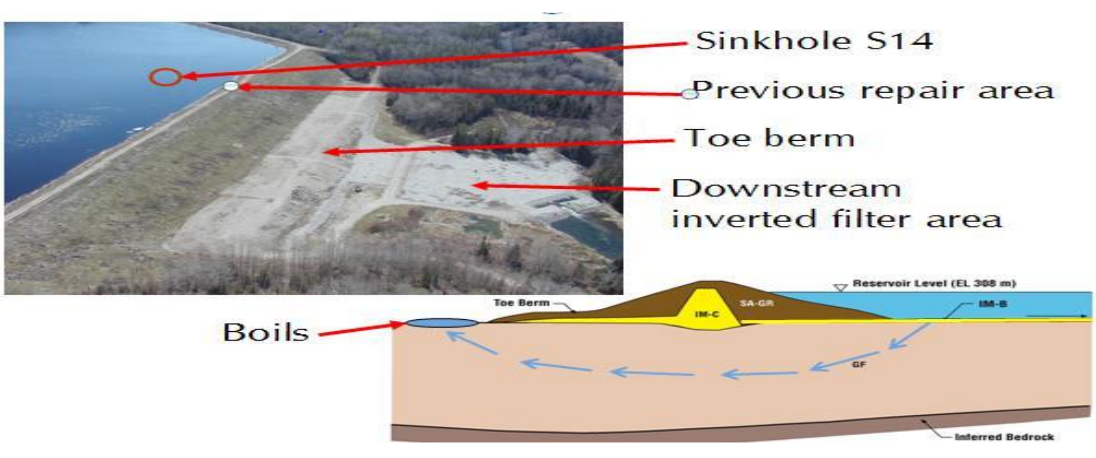


Figure 11. *Shikwamkwa Dam: showing damage, filtered toe berm and section of erosion pipes [10]*

Repairs were conducted to allow the life of the dam to be extended. The repairs program included a downstream filter blanket and a fully automated monitoring system consisting of piezometers, weirs and a turbidity meter.

Over the years following the installation of the remedial works, the dam was inspected and assessed monthly, identifying vulnerable zones and carrying out repairs in phases, carefully monitoring each repair before commencing another. despite the continuous of repairing, incidents continued, however, possibly because the foundation was seriously damaged by the removal and disturbance of large volumes of material by piping over 40 or more years. [6]

The upstream blanket may have been thin and may have cracked as settlement across the old river channel occurred, but the downstream sand boils, the piping and the upstream depressions, confirm that what is now known as backward erosion was occurring. It does not appear to be forward erosion through concentrated leaks, cracks and openings, in the blanket and foundation.

The upstream blankets can be ineffective in reducing the overall hydraulic gradient that initiates backward erosion, almost certainly in this case because the blanket materials were fine and vulnerable to backward erosion from below.

If upstream blankets are erodible, the outcomes are unpredictable and may be serious.

At Shikwamkwa, the emerging upstream end of one of the erosion pipes was at the upstream toe of the dam, causing instability of the slope, but fortunately not cutting through the crest, thereby narrowly avoiding failure by overtopping.

Upstream blanket materials should be plastic or sands and gravels too coarse to be vulnerable to backward erosion from below.

3.3. Failures and Incidents from contact Erosion

- **Sinkhole incidents on zoned dikes, River Rhone, France**

Some twenty cases of leakage associated with development of a sinkhole or subsidence have been reported in the dikes on the River Rhone. The dikes are embankments constructed with fine alluvium (clayey silt to silty sand often covered by shoulders of coarse alluvium (sandy gravel) on the upstream and downstream slopes. The dikes are often on alluvium foundations (a thin layer of fine alluvium on a thick layer of gravelly alluvium). [6]

Contact erosion occurs when high river levels cause high velocities in the gravel foundation, sufficient to cause erosion at the contact with the silty fill of the dikes. The erosion of the fine fill seems to result in slow settlement of the dikes in such a manner that failure by overtopping is not expected. As Figure 12, shows, contact erosion results in most cases in sinkholes,

a) cause piping in extreme cases (but never observed on site)
b) leads to instability
c) the fine particles accumulate and clog the gravel foundation at the toe,
d) possibly causing hydraulic fracture and heave.

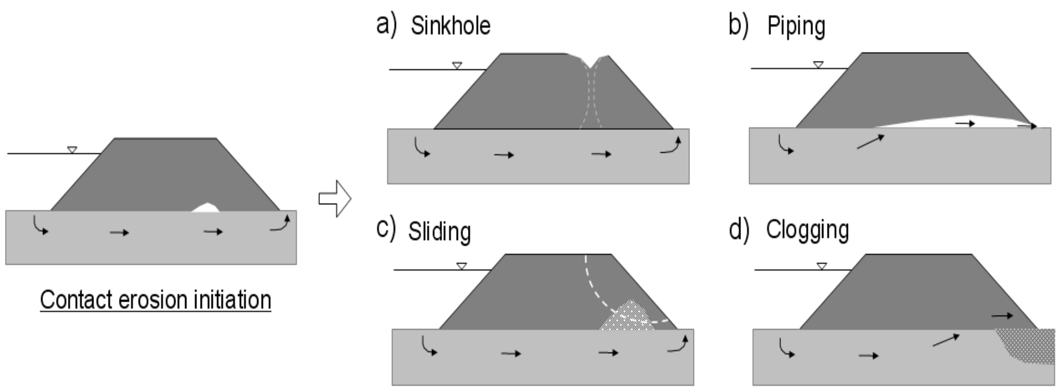


Figure 12. *Consequences of contact erosion. Black arrows indicate a groundwater flow through a more permeable layer (light grey) under a less permeable dam (dark grey). a) sinkhole daylights b) beginning of backward erosion piping c) creation of a weaker zone initiating instability d) clogging of the permeable layer and increase of pore water pressure* [11].

No incidents in collapse and failure of the dike were recorded. This may be explained cause the Darcy velocities were less than the critical limits (0.02 m/s), and the erosion was not continuous.

Interrupted erosion may occur after paving when fine silt particles are eroded leaving coarse particles that filter and retain the oncoming newly eroded fine particles under constant water level and constant Darcy velocity no longer high enough to carry continuous erosion,

or the Darcy velocity does not remain high enough for periods long enough to carry continuous erosion. The sinkholes form as fine soils is drawn in to replenish material lost through intermittent erosion above the foundation areas where the critical flow velocity is reached in the gravel.

Following the incidents, diaphragm walls were installed through the embankments and into the gravel foundations over the affected lengths to limit groundwater flow velocities in the gravel to be below critical at the interface with the fine soil in the fill.

3.4. Failures and Incidents from suffusion.

- **Suffusion in residual soil fill: Saint Pardoux Dam:**

Saint Pardoux dam (Figure 13) is a 19 m high homogeneous (unzoned) dam constructed using residual soil of decomposed granite as filled with a layer of coarser material on the downstream slope and a horizontal foundation toe blanket for drainage. [6]

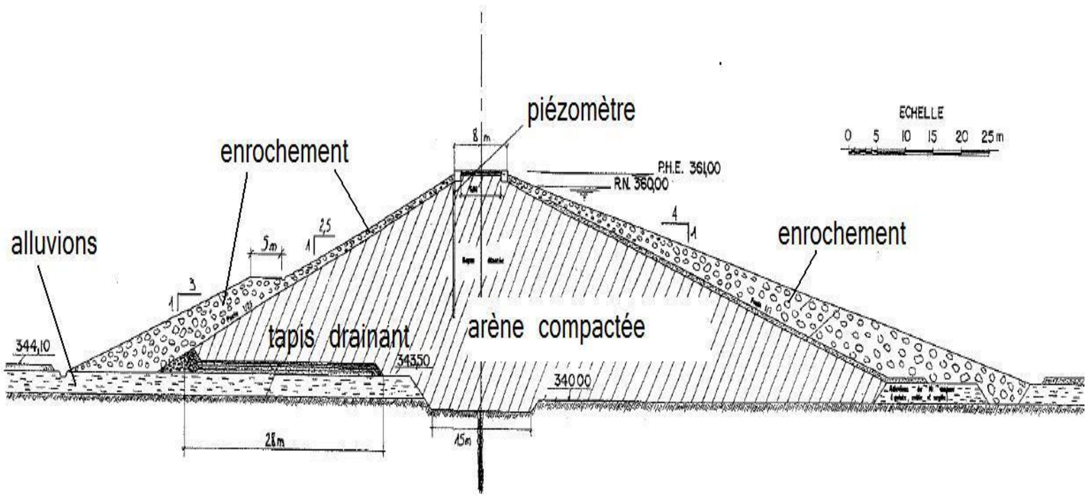


Figure 13. Saint Pardoux dam: decomposed granite fill with coarser material on the upstream and downstream slopes, and a horizontal downstream drain.

The dam was completed, and the reservoir filled in 1976. An expert assessment in 1991 found high and increasing pore pressures in the downstream slope, wet areas on the slope and leakage emerging on to the slope and at the abutments. There was also an increase in the seepage collected from below the upstream slope.

The progression of piping could be taken to mean gradual loss of fines and increase of seepage, indicates that suffusion was occurring in the fill and that there was preferential drainage through some sandy layers included in the fill.

To correct the situation, a diaphragm wall was installed from the crest, the foundation grout curtain was made deeper and wider and drainage added, and other works were completed in the abutments. [6]

4. Conclusions

1. Internal erosion initiates when the hydraulic forces exceed the ability of the materials in the dam and foundation to resist them.

2. Internal erosion may be arrested in zoned dams if any filters are effective. Inhomogeneous dams there are no zones, consequently, if erosion initiates, it cannot be arrested

3. The ability of a dam to resist erosive forces is not constant over time. This is because cracking from a settlement, or from hydraulic fracture, or zones of low stress, may create sites where erosion can initiate even at water levels previously experienced.

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