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Review About Incidents in Dams and Dike Behaviors Induced by Internal Erosion

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Abstract - *Internal erosion is an essential 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 major 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. 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. This article dealt with the study of some important historical cases in which the internal erosion process which occurs that led to failures and incidents on some established embankment occurred, as well as studies related to monitoring the internal erosion process before failures occur, which in turn affects the safety of the dam.*

Key Words: Embankment dam, Failures, Incidents, Internal erosion, Sinkholes.

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. 94% of failures that occurred on the large dams constructed between 1800 and 1986 were related to erosion, while the earthfall dam failures, the internal erosion was responsible for approximately 48%, [1], [2], [3]. If comparing with the slides of embankment dams and the earthquake failure, just 4% represent the slides and 1.7% of the failure due to the earthquakes, that indicate the internal erosion represents a much greater threat to the current earthfall dams. This failure occurs by internal erosion that is 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 progressed enough to be visible as sinkholes on the structure's surface or detected by dam monitoring instruments. However, the embankment dam's failures occur after the first filling. Internal erosion remains a threat to existing dams because they have not been designed to resist extreme loads such as extreme water levels and earthquakes (cause cracking). Cracking occurs because 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. They may be ineffective [4]. In developing the risk assessment approach, researchers have improved their 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, advances in understanding showed the internal erosion occurs in earth water-retaining embankments when the hydraulic forces provisioned by water flow through openings or seep through pore size, which exceed the ability of the soils in the embankments or their foundations to resist them. Understanding internal erosion is important to dam owners to maintain dam safety, as it can be included in three points:

1. It is necessary to understand and interpret the behaviour of the dam.
2. It is necessary to assess the dam's safety and whether it is safe enough or whether safety works are needed to make it.
3. Should control of dam safety surveillance and monitoring regimes.

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:

1. Internal erosion through the embankment includes conduits associated with outlet works, spillway walls, or a concrete gravity structure supporting the embankment.
2. Internal erosion through the foundation.

3. Internal erosion of the embankment into or at the foundation. Including:
    - The seepage through the embankment eroding material into the foundation.
    - The seepage in the foundation at the embankment contact erodes the embankment material.

2.1. Phases of internal erosion

There are four phases of the 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) illustrates the internal erosion through the embankment initiated by a concentrated leak. While (B and C) in the same figure 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 happen is particle detachment. Water seeping through the dam or flowing in cracks must provide enough energy to detach particles from the soil structure. Four mechanisms occur in the erosion initiation, these are:

- Concentrated leaks.
- Backward erosion.
- Contact erosion.
- Suffusion.

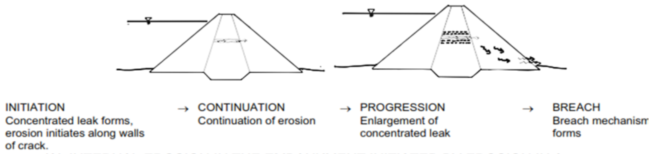
1) Concentrated leaks

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

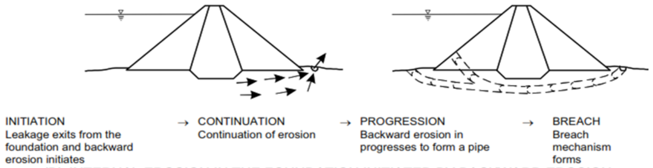
2) Backward erosion

There are two types of backward erosion:

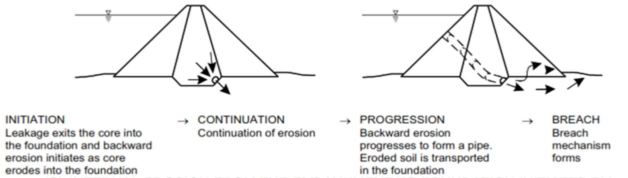
a. Backward erosion piping, at the back (upstream) end of a very small pipe below a "roof," works 'backward' from the toe toward and eventually breaks through the reservoir. It mainly occurs in foundations but may occur within embankments.
b. Global backward erosion, leading to the development of a near-vertical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



(A) INTERNAL EROSION IN THE EMBANKMENT INITIATED BY EROSION IN A CONCENTRATED LEAK



(B) INTERNAL EROSION IN THE FOUNDATION INITIATED BY BACKWARD EROSION



(C) INTERNAL EROSION FROM THE EMBANKMENT TO FOUNDATION INITIATED BY BACKWARD EROSION

Fig -1: Failure development Models for the internal erosion, [2].

3) Contact erosion

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

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 coarser than required by design methods based on particle size will often effectively control erosion. Even downstream rockfill 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 the development of a pipe.
b. The erosion process extends upstream from the point of initiation for backward erosion. 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 forms. 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, particularly case, lead to the development of a pipe in the finer soil.

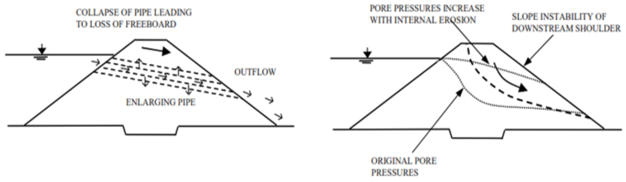
For suffusion, some of the finer fraction is eroded, leaving the coarse matrix of the soil. No pipe is formed, but the permeability of the soil may be increased significantly.

2.5. Breach

In these situations, the entire process of internal erosion has concluded, detection and intervention have failed. The dam may be breached by one of the five mechanisms 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. It was overtopping (e.g., due to the settlement of the crest from suffusion 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 is a slope instability that may include increased pore pressure and collapse in the eroded zone.

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



Breach by pipe enlargement *Breach by slope instability*

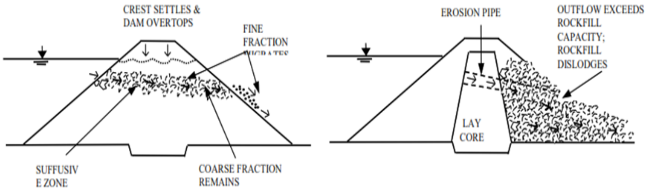
Fig -2: Potential breach (failure) phenomena-pipe enlargement and slope instability, [4].

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, see Figures (5 and 7). The dam has not been rebuilt, and its remains can still be seen at the site.



Breach by overtopping by settlement *Breach by unraveling of the downstream face*

Fig -3: Potential breach (failure) phenomena-overtopping by settlement and unraveling of the downstream face, [4].

The dam has a 93 m high earth zoned embankment. Sections are shown in Figure 4 on the valley floor and in Figure 6 in the right abutment, around the location where the leakage was first seen, and the failure commenced, [5]. 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 valley floor and key trenches in the upper parts of the core contact zone (above El 5,100-ft).

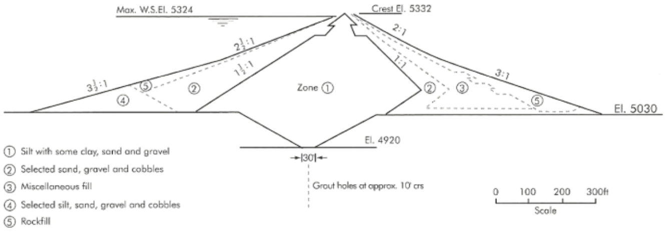


Fig -4: Schematic diagram of the Teton Dam: Section in valley bottom showing fill zones and cut-off through alluvium, [6].

Mr. Chadwick's reviewed the cause of 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 Zone 1, fill in the right abutment key trench at approximately the location is shown in Figure 8.

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

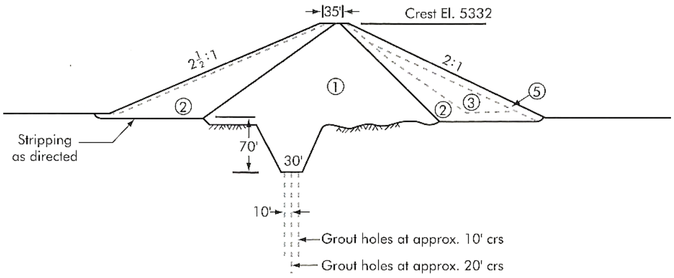


Fig -6: Schematic diagram of the Teton Dam: Section with a deep cut-off trench at failure position in right abutment, [6].

Fig -7: Photograph of Teton Dam: leak has enlarged and widened, crest (bridge) has collapsed, the outflow exceeds 28,300 m3/s eroded all the dam fill, [5].

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 could 'hold a roof' of the considerable span, like the photographs, Figure 5 shows. As the erosion 'pipe' enlarged and discharge increased, the hole exposed in miter at the junction between the dam's downstream face and the rock abutment enlarged and rose 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. After that, the escaping water-eroded dam fills rapidly, deepening and widening the initial breach, less or more removing all traces of the dam fills from the side, and exposing the foundations. [5]. There have been many subsequent examinations of the failure, and many papers written about it, which continues to the day. A preliminary trial by Merino [8] of its benchmark approach to analyzing internal erosion examined the Teton case, which USBR reviewed. One result 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 June 5th, 1976.

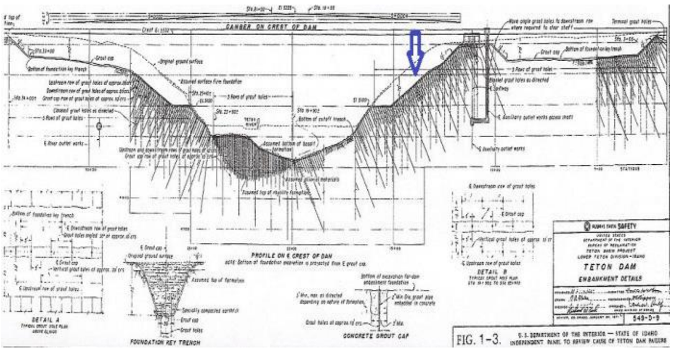


Fig -8: Longitudinal section along cut-off trench showing (arrow) approximate location in the right bank key trench where concentrated leak erosion leading to failure initiated, [7].

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 been initiated. Therefore, it is 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 finished in 1958 in Ontario, Canada, [9]. 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 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. [5]. 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.

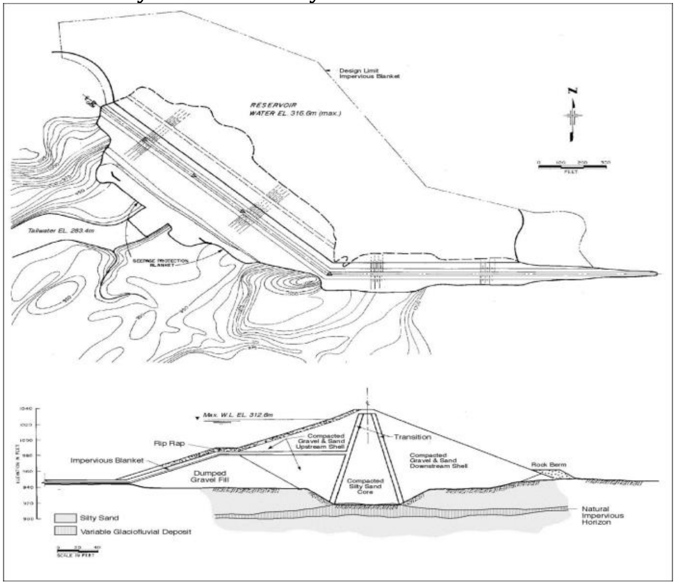


Fig -9: Shikwamkwa Dam: Section and plan showing the extent of the upstream blanket [9].

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 see Figures 10 and 11. 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 repairing, incidents continued, however, possibly because the foundation was seriously damaged by removing and disturbing large volumes of material by piping over 40 or more years, [5]. 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.

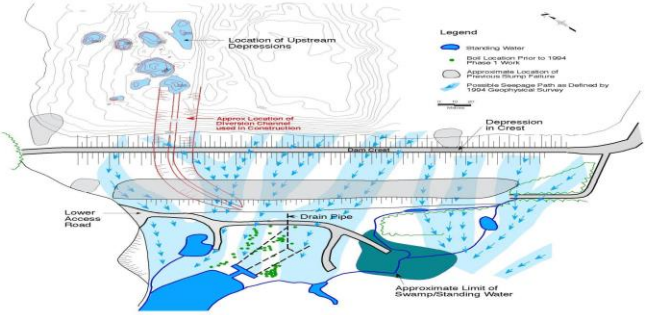


Fig -10: Shikwamkwa Dam: a record of upstream sinkholes, erosion pipe routes, downstream sand boils, and the depression left in the crest after slope failure caused by sinkhole opening at the upstream toe, [9].

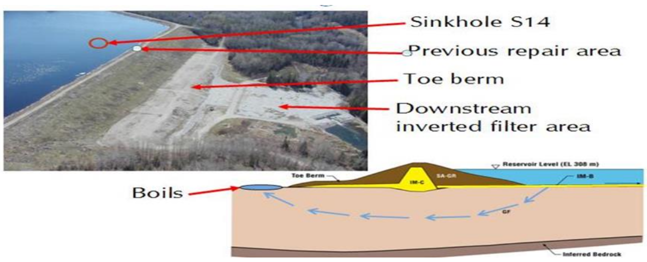


Fig -11: Shikwamkwa Dam: showing damage, filtered toe berm, and section of erosion pipes [9].

3.3. Failures and Incidents from contact Erosion

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

Some twenty cases of leakage associated with the 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), [5]. 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 in Figure 12, which illustrate the consequences of contact erosion, where the black arrows indicate groundwater flow through a more permeable (light grey) layer 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, [10].

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 a hydraulic fracture and heave.

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 grave 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.

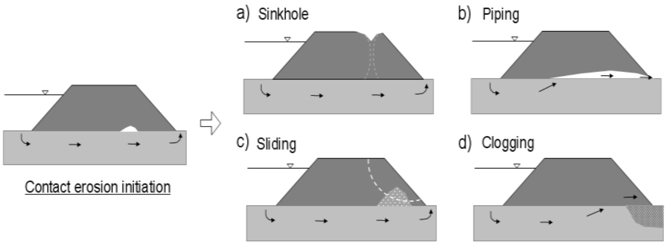


Fig -12: The contact erosion in most cases in sinkholes, [10].

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, [5]. The dam was finished, and the reservoir was 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 onto the slope and at the abutments. There was also an increase in the seepage collected from below the upstream slope. The piping progression could mean gradual loss of fines and increase of seepage, indicating 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 was added, and other works were completed in the abutments, [5].

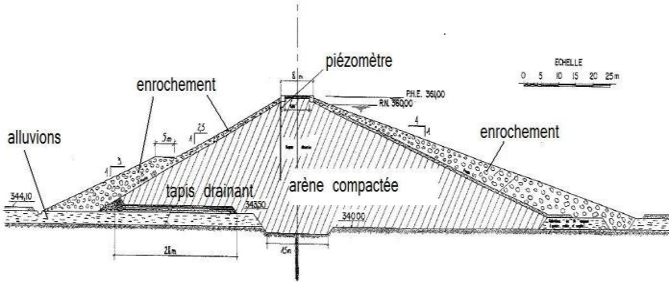


Fig -13: Saint Pardoux dam: decomposed granite fill with a coarser material on the upstream and downstream slopes and a horizontal downstream drain.

4. CONCLUSIONS

Through mentioned from previous studies and literature review on the causes and types of internal erosion, the following can be concluded:

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 hydraulic fracture, or zones of low stress, may create sites where erosion can initiate even at water levels previously experienced.

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