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Emergency repairs downstream of earth and rockfill dams with water spring with indication of internal erosion

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A B S T R A C T

During periodic dam safety assessments, various anomalies are identified through field inspections, project documentation analysis, and structural behavior monitoring. These assessments aim to detect non-conformities, and engineering design firms propose technical solutions to address these issues. The primary goal of these reviews is to evaluate the overall state of conservation and structural safety, ensuring compliance with updated design criteria, revised standards, changing weather conditions, and technological advances. Dam renovations are crucial for enhancing operational capacity and preventive care. Implementing filtering materials within the dam's body establishes a drainage system to relieve internal pressures on the embankments and foundations. This prevents the washing away of soil particles due to internal erosion, known as "piping," a major cause of dam failures. Piping occurs when soil particles are displaced towards the outside of the embankment through the percolation process, particularly in the upstream area near the dam's base, where high hydraulic gradients and flows make it susceptible. This article presents a set of emergency or long-term solutions to address anomalies related to the onset of internal erosion in dams, with a focus on preventing piping. These solutions are vital for safeguarding the structural integrity and safety of these critical infrastructure components.
Keywords: Dams, barrages & reservoirs. Earth and rockfill dam. Water upwelling. Piping. Inverted filter. Relief wells. Intercept dike. Material washout.

Reparos emergenciais a jusante de barragens de terra e enrocamento com indicação de erosão interna

R E S U M O

Durante as avaliações periódicas de segurança de barragens, várias anomalias são identificadas por meio de inspeções de campo, análise da documentação do projeto e monitoramento do comportamento estrutural. Essas avaliações visam detectar não conformidades, e empresas de projeto propõem soluções técnicas para abordar esses problemas. O principal objetivo dessas revisões é avaliar o estado geral de conservação e segurança estrutural, garantindo conformidade com critérios de projeto atualizados, normas revisadas, condições climáticas em mudança e avanços tecnológicos. As reformas em barragens são cruciais para aprimorar a capacidade operacional e os cuidados preventivos. A implementação de materiais filtrantes dentro do corpo da barragem estabelece um sistema de drenagem para aliviar as pressões internas nos aterros e nas fundações. Isso evita a lavagem de partículas de solo devido à erosão interna, conhecida como "piping", uma das principais causas de falhas em barragens. O piping ocorre quando partículas de solo são deslocadas para fora do aterro pelo processo de percolação, especialmente na área a montante, perto da base da barragem, onde gradientes hidráulicos e fluxos elevados o tornam suscetível. Este artigo apresenta um conjunto de soluções de emergência ou a longo prazo para abordar anomalias relacionadas ao início da erosão interna em barragens, com foco na prevenção do piping. Essas soluções são vitais para proteger a integridade estrutural e a segurança desses componentes críticos da infraestrutura.
Palavras-chave: Barragens, diques & reservatórios, Barragem de terra e enrocamento, Surgência de água, Erosão Interna, Filtro invertido, Poços de alívio, Dique intercepto, Carreamento de Materiais.

List of notations

FS - Minimum acceptance safety factor;
γSub- Submerged specific weight, considered as 8 kN/m³;
h- Sand layer thickness (sand boil);
γW - Water specific weight, 10 kN/m³;
Δh - Loss of Load in the sand boil.
ppm: - part per million
mg/l: (milligram per liter)
Q: flow
Qf: contribution flow per well (water loss through the foundation) (cm³/s);
k: permeability coefficient (cm/s);
R: half the distance between wells (cm);
r: well radius (cm); ΔH: total hydraulic load (cm);
2R: distance between wells (cm);
2r: hole diameter (cm);
l/min/m: liters / minute / meter

Introduction

This work details internal erosion and material transport, critical phenomena for the stability of dams. Internal erosion, or "piping," occurs when soil particles are moved along the seepage path, forming an internal erosion. This is concerning in embankments prone to erosion. The downstream toe region is particularly susceptible to piping. The transport of particles can lead to clogging of filter elements, affecting the dam's stability. Water upwelling, or "sand boil," is an anomaly that occurs when water seeps through the dam foundation, potentially resulting in backward erosion. Material transport is discussed, and in the event of solid materials appearing downstream of the dam, it is recommended that the material be collected by a specialized professional. Geotechnical investigation is fundamental in dam projects, as most collapses are caused by internal erosion and material transport. The approach of this work is essential for dam safety, allowing the implementation of effective measures to prevent failures.

Gontijo (2018), highlighted the importance of safety and efficiency of dams as a constant pursuit. This involves the implementation of sustainable and appropriate projects, regular maintenance and careful operation, as well as continuous improvements and adjustments supported by experts, always following the project specifications.

Silva (2022) emphasizes that the damage associated with a dam failure is enormous and must be avoided at all costs, as it can lead to the loss of human lives. Dam accidents have become an increasingly frequent global problem in recent decades. According to CIGB Bulletin 99 (1995), 70% of failures occur within the first ten years of the dam's life. Due to their large-scale structure, a dam failure can result in economic and environmental damage, as well as the loss of human lives.

According to Fernandes (2023), instability problems in slopes and landslides are often the result of design flaws, use of low-quality materials, steep slope gradients, lack of proper drainage, and/or excessive infiltration.

Pereira (2024) highlights the importance of dams in water resources management, emphasizing that, although rare, collapses of these structures can result in tragic accidents. When such catastrophes occur, they cause damage and deaths, leading to extreme situations.

Most dam collapses are caused by the percolation path that moves soil particles as a transport effect towards the outer zone of the embankment, generating the formation of an internal erosion known in the geotechnical field as piping (Freitas, 2019).

According to Sandroni (2021), the washing away of particles can cause clogging of important filtering elements for the stability behavior of the dam, since empty spaces may appear due to a malfunction of the internal drainage.

The region of the downstream foot is a delicate location with more tendency for piping formation, there is a large concentration of hydraulic gradients in this region with very high flows, this event can form the gradual dragging of fine soil particles. It is considered a phenomenon with evolution from downstream towards upstream in the form of piping, which occurs due to an uncontrolled event of water percolation through the massif. There are occurrences that an internal erosion can start due to the existence of roots and vegetal material from the degradation process, or even due to the existence of animal burrows (Zuffo, 2005).

This piping phenomenon is a concern mainly in embankments prone to erosion by concentration of particle washout through cracks or hydraulic fracturing, this can occur shortly after filling the reservoir. Any uncontrolled percolation, added to regions with applications of embankments with dispersive soils, is a warning condition (Sherard, 1973).

For the elaboration of a dam filter project, it is necessary to have as a fundamental guideline the knowledge of the granulometry of the material to be used, considering that the smaller particles are distributed uniformly in the voids in the spaces between the larger particles. This filter system aims to prevent soil washout which can reflect in an internal erosion (piping).

A visual way of monitoring is to check if the waters are clean at the exit of the internal drainage system at the downstream foot of the dam. (FEMA, 2015).

The phenomenon (piping) is a consequence of infiltration forces caused by the movement of waters that percolate through the interior of a dam massif and foundation. This phenomenon begins when there is a dragging of particles and fines. The phenomenon (piping) occurs when soil resistance forces are lower than infiltration forces (FLORES, 2019).

The soils most susceptible to internal erosion event (piping) are sandy materials without compaction, high plasticity clays are materials with greater resistance to this event when well executed (FEMA, 2015).

One of the methods to control the flow in the dam is the use of internal drainage devices in the dam and foundation. If properly dimensioned, these devices can control the flow within the structure. It is important to highlight the assumptions and procedures adopted in the design of the drainage system, as it is directly related to the safety of the structure. The filter material used downstream of the dam core serves to prevent the transport of grains from the neighboring material to be protected, requiring a correct dimensioning of the transition material to ensure the integrity of the dam. The requirements for transition materials are related only to particle size distribution. Since transitions are part of drainage systems, they must comply with containment (non-segregation) and permeability requirements (Pessoa, 2023).

Figure 1 Upper Red Rock Site 20 (USA) demonstrates the consequence caused by internal erosion, with its probable beginning and openings caused by differential settlements of the dam massif, earthquakes, tension openings, or problems during execution with voids left by roots, tree trunks and even holes or burrows dug by animals.

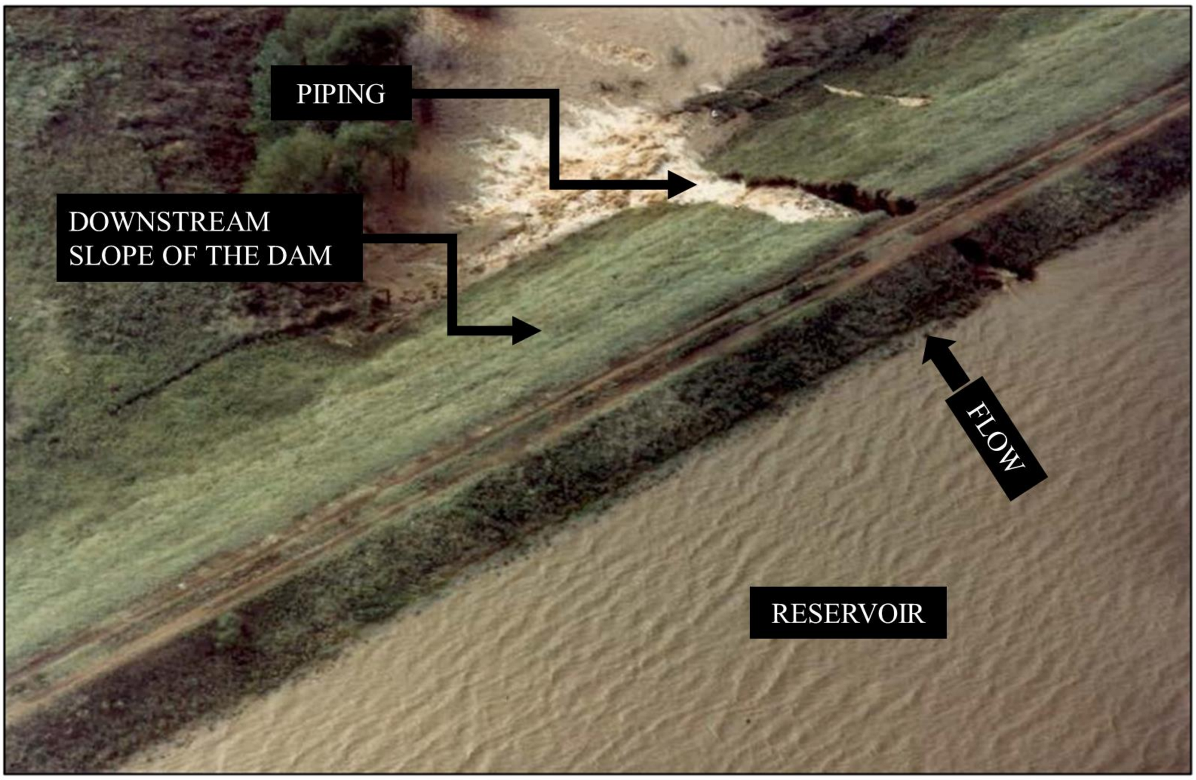

Figure 1. Internal Erosion of a Dam [adapted from FEMA] (2015).

The process of internal erosion has a logical sequence of evolution, which consists of the initial phase, permanence phase, progression phase, and rupture (Fell *et al.* 2005).

Initial Phase: The principle of erosion occurs when the hydraulic gradient flowing through a dam or its foundation is sufficient to separate the particles from each other.

Permanence Phase: The continuation of internal erosion occurs when there is no filtration along the percolation path, with this the soil materials are carried through the material that should be filtering enough to stop the smallest particles.

Progression Phase: At this stage, the erodibility path begins to open more with the formation of a continuous void through the embankment or foundation (piping) without self-recovery.

Rupture Phase: The dam can break in several different ways, such as widening of the piping inducing an internal regressive erosion, loss of the free edge with the collapse of the crest, formation of flow voids, sinking of the downstream slope and collapse of the downstream slope (FEMA, 2015).

Next in Figure 2 is an example of the Fontenelle dam, in 1965 with an incident with an internal erosion process with sinking of the downstream slope.

Comparing in contrast, the accidents caused by internal erosion of the Teton dam and even greater in the Fontenelle Dam where its section is presented in Figure 3, the initial flows of 300 to 400 l/s managed to erode the downstream zones of sandy gravel.

According to Silveira (2023), the Fontenelle Dam, standing 127 feet (38.7 meters) tall, almost failed due to internal erosion during its first filling in 1965. Twenty-four hours after the infiltration was discovered, a hole measuring 23 meters wide, 20 meters deep, and 20 meters long was found. The reservoir was saved through immediate intervention and lowering of the water level.

In 1984, 19 years after the incident, Ralph Peck and Ralph Beene summarized the reasons for the incident, stating that "the lack of multiple defenses against piping in an erosion-prone zone 1 can be considered the basic deficiency of the dam. The original design and construction unjustifiably relied on a thin mortar plug and an injection curtain as defenses against the piping of fine materials. This was inadequate, considering the open joints, fractured rock, unfavorable topography, highly erodible abutment materials, high hydraulic gradient, and the injection curtain. No concrete and grout were applied in the fractures to prevent the erosion of fine material in the rock joints" (Silveira, 2023).

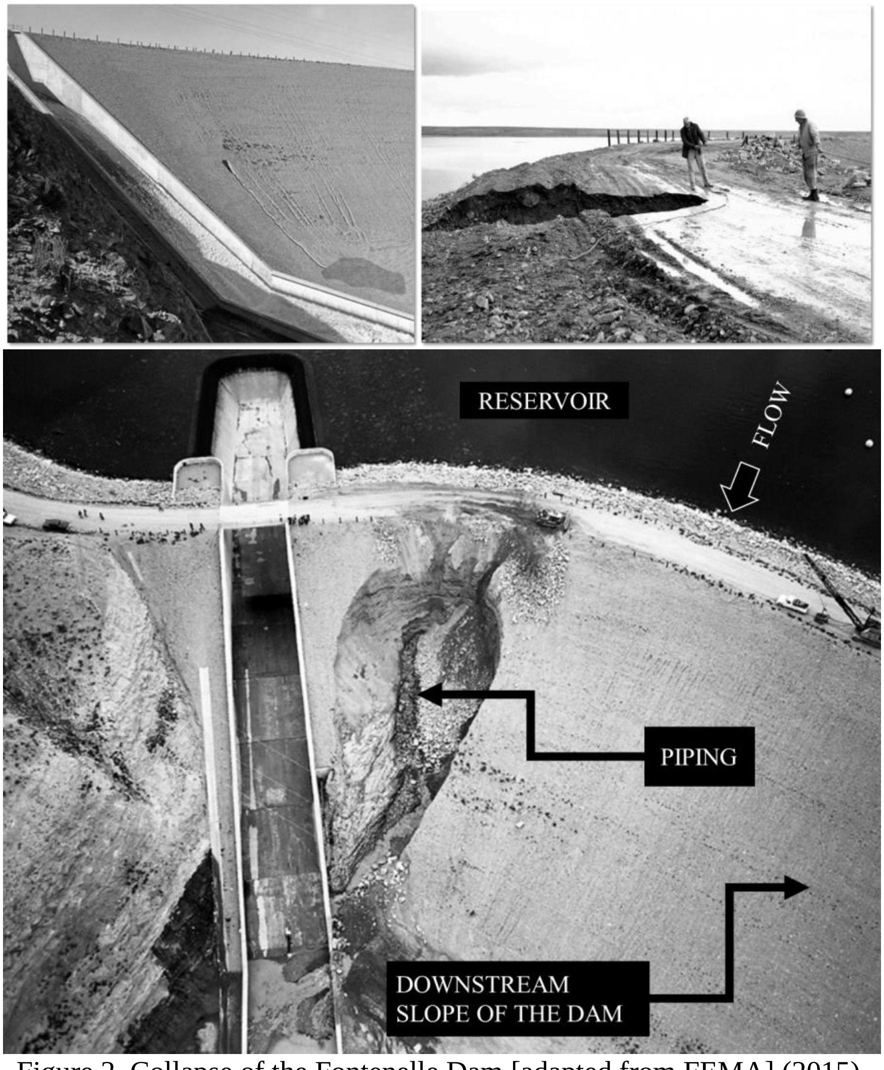

Figure 2. Collapse of the Fontenelle Dam [adapted from FEMA] (2015).

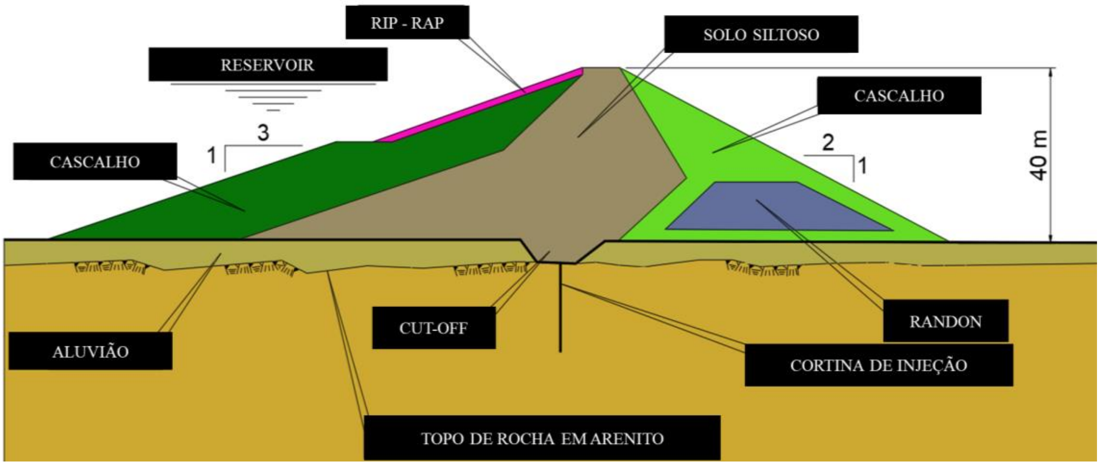

Figure 3. Section of the Fontenelle Dam [adapted from Fell] (2005).

In November 2015, the Fundão tailings dam, located in the municipality of Mariana, State of Minas Gerais, Brazil, suffered a catastrophic failure, resulting in the discharge of approximately 60 million cubic meters of iron ore tailings into the Rio Doce watershed. In this context, under specific conditions, the occurrence of seepages within the dam is possible. These seepages carry the potential to evolve into an internal erosive process, involving material transport (piping), or even initiate a liquefaction process within the tailings, ultimately culminating in the structural collapse. (Barbosa et al., 2023).

Barbosa 2023 highlights that under certain conditions, surges can occur in the dam. These surges can turn into an internal erosion process, with the material being carried away (piping), or even trigger liquefaction of the tailings and result in the collapse of the structure as a whole.

Barbosa 2023 documents that the disaster resulted in the death of 19 individuals, devastated the District of Bento Rodrigues, interrupted the water supply in 39 municipalities in the states of Minas Gerais and Espírito Santo, and destroyed goods and properties along a route of more than 650 km to the Atlantic Ocean. This event is considered the largest environmental disaster in the history of Brazil.

Water Springs

A water spring is described as an anomaly, considering that at the moment when the waters that infiltrate the mass of the dam's landfill and foundations percolate and appear on the surface in unexpected places. The phenomenon of sand boil occurs when the water that percolates through the dam's foundation surfaces with a gradient much higher than the critical gradient of the material (almost always close to 1.0). This phenomenon is dangerous in places with a foundation entirely composed of soil, as it can result in regressive erosion (piping) (FEMA, 2015).

Next, in Figure 4, we observe the transport of material with water coloration indicating suspended particles.

Figure 4. Transport of Suspended Material [adapted from Intertechne] (2022).

It is important to observe the design conditions carefully observing the filtration criteria that are fundamentally based on the studies done by Sherard and Dunningam (1989), which establishes a maximum value for the D15 of the filter in order to protect the adjacent base material.

To avoid occurrences of sand boil, an inverted filter composed of filtering materials can be foreseen, sequentially in contact with the foundation material or contact executing in sequence sand layer, pebble layer, gravel layer and hand stone layer, the thicknesses will be those that allow an adequate executive process, even if in the design of the inverted filter the necessary thicknesses are inferior. One of the functionalities of this protection device is to generate positive effective stresses in the soil, with this the output gradient, will be given by the most permeable material (and no longer by the base material) and will be below the critical gradient in this material of the inverted drain (Massad, 2010).

In FIGURE 5 examples of occurrence of sand boil with transport of solid material are presented, with quicksand type effect.

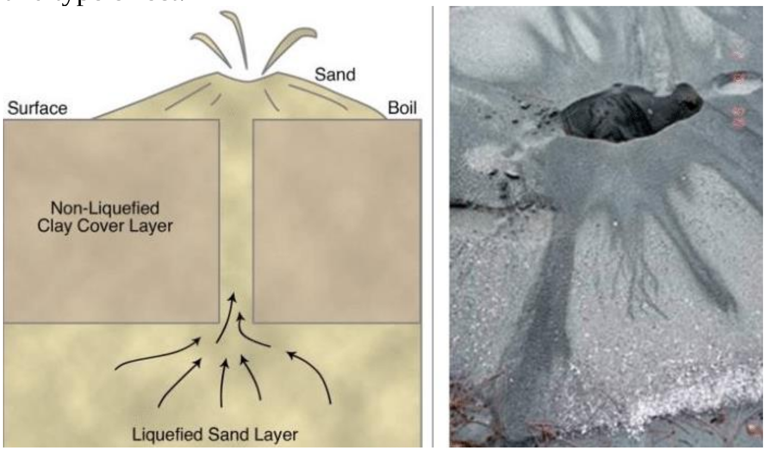

Figure 5. Sand Boil Phenomenon - Quicksand [Larisch] (2019).

The safety factor with respect to sand boil can be calculated by the expression below:

$$FS = \frac{i_{critical}}{i} = \frac{\gamma_{sub} h}{\gamma_w \Delta h} \qquad (1)$$

Where:
FS - Minimum acceptance safety factor;
ΓSub - Submerged specific weight (8 kN/m³)
H - Thickness of the sand layer (sand boil)
Yw - Specific weight of water (10 kN/m³)
Δh - Loss of Load in the sand boil

Opting for the adoption of an inverted filter as a definitive solution in these cases is basically accepting to live with high subpressure values, but eliminating the occurrence of new sand boil points by generating an increase in effective stress on the sandy soil layer and considering a granulometric transition that will prevent the transport of base material. Much of the springs may be linked to clogging and clogging of the internal drainage system or some failures, construction and project detailing. It is possible to visually identify the springs, as they may appear in the form of waterlogging on the slopes or downstream region (ANA, 2012).

This phenomenon can alter the resistance properties of landfills, such as the loss of cohesion between soil particles, which can influence the stability of the massif as a result of internal erosion (ANA, 2016).

In Figure 6 we observe the order of occurrence of the progression of erosion through the foundation, starting with spring along the foundation, continuing erosion in sequence, soon after the progression of erosion in the form of piping until finally resulting in failure mechanism with rupture of the dam structure.

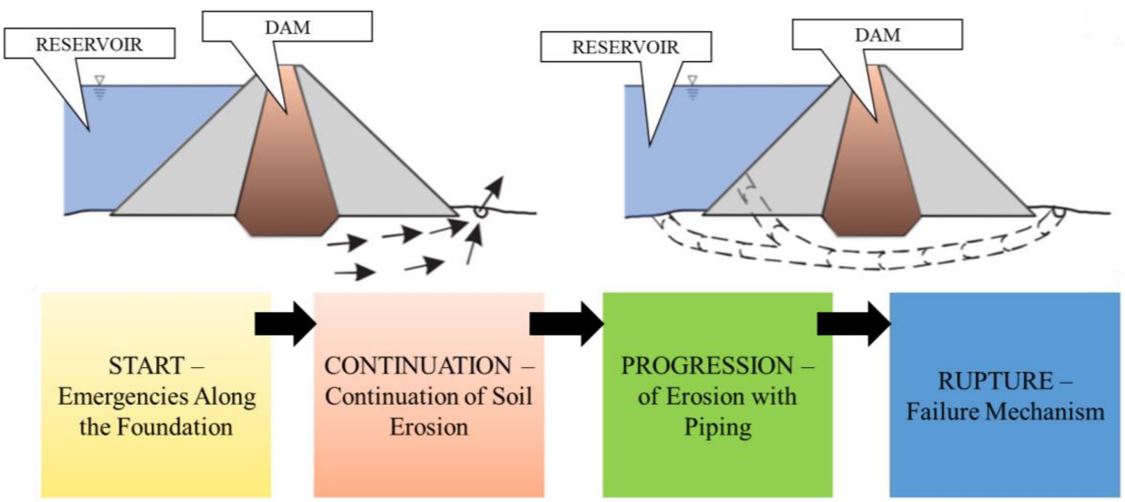

Figure 6. Progression of Erosion [adapted from Fell] (2005).

Even if the location of the appearance of a water emergence downstream of a dam is further away, it should be immediately monitored and followed, for this it is important to implement some actions that will help understand its origin. These actions are summarized in checking for a planimetric topographic survey verifying the drainage basin and the drainage exit points, then try by interception and channeling devices to concentrate all the waters at a single point, implementing a flow measurement device at the site. Plan a control and monitoring observing the rainfall and variation of the reservoir level over time, this history is important for a trend analysis and evolution of the flow that percolates through the dam body and foundation (ANA,2012).

In TABLE 1, the maximum height, total length, start year of operation and foundation geology of some Brazilian dams are presented."

Table 1. Geology and Geometry of Brazilian Dams [adapted from Silveira] (2006).

Legend	Dam	Maximum Dam Height (m)	Foundation Geology	Year	Length (m)
A	Água Vermelha (OD)	54	Agglomerate Lava (k =10 -¹ cm/s)	1978	1875
B	Água Vermelha (OE)	63	Agglomerate Lava (k =10 -¹ cm/s)	1978	80
C	Atibainha	35	Saprolitic soils and altered rocks (metamorphosed crystalline rocks, with predominance of biotite-gneiss)	1976	430
D	Rio Verde	16	Residual soil (sandy silt and silty sand) on altered rock	1978	540
E	Paranoá	-	Fractured Quartzite and Phyllite	1981	630

In TABLE 2, total flows and specific flows are observed after the total filling of the reservoirs, as well as interventions in order to allow better monitoring of the waters emerged downstream of each of the dams presented below.

Table 2. Flow observed in Brazilian Dams [adapted from Silveira] (2006).

Legend	Dam	Total flow after reservoir filling (l/min)	Specific flow (l/min/m)	Location	Intervention
A	Água Vermelha (OD)	1500	0.8	Right Shoulder	Execution of Superficial Trenches, Drainage Pipe, Flow Meter
B	Água Vermelha (OE)	2320	29.0	Left Shoulder	Execution of Superficial Trenches, Drainage Pipe, Flow Meter
C	Atibainha	1050	2.4	Left Shoulder	Draining Trenches
D	Rio Verde	-	-	Downstream Berm	Vertical Sand Drains
E	Paranoá	-	-	Right Shoulder - Downstream Slope and Downstream Foot	Drainage Holes and Fishbone Surface Drainage

Barreto (2024) presented the control values calculated by percentiles from the maximum flow data observed through the dams and foundations of 133 Brazilian earth and rockfill dams. The percentiles adopted for the control values tend to be conservative due to the range of data analyzed.

Table 3. Flow control values [Barreto] (2024).

Foundation Rock Origin	Attention (Qe 75%) l/min/m	Alert (Qe 85%) l/min/m	Emergency (Qe 95%) l/min/m
General	2.9	4.5	8.1
Plutonic Igneous	2.7	4.3	5.8
Volcanic Igneous	1.9	2.9	8.0
Metamorphic	3.2	4.7	7.8
Sedimentary	7.8	8.2	9.3
General	2.9	4.5	8.1

Legend: (Qe%): specific flow (percentile) | (l/min/m): liters / minute / meter

It is clear that the estimation of the probability of extreme events has several applications in environmental sciences, being used in the design of hydraulic structures such as culverts, bridges, and dams (ISEBSEE, 2021).

As a result of a statistical analysis using the Multiple Linear Regression method, an equation was obtained through correlations with data from 133 earth dams that allows estimating reference values for specific discharge. The result is represented in the unit l/min/m = liters per minute per meter (Barreto, 2023).

$$Qe = 2{,}006 + 0{,}003 . Hb + 10420{,}168 . kf \quad (2)$$

Where:
Qe = calculated specific flow rate
Hb = maximum height of the dam (m)
kf = foundation permeability (m/s)
l/min/m = liters / minute / meter

Internal Erosion Material Transport in a Dam

In the evolution of detecting new seepages, it is important to immediately adopt corrective measures to stop the anomaly. Firstly, it is important to locate the wet spots and water flow, then try to make the measurements: reservoir level and rainfall control during monitoring to correlate with the flow readings of these seepages. If in doubt about where the infiltration water may be coming from, it is recommended to correlate the measured flows with the data mentioned above (reservoir flow and rainfall). Cases of internal erosion (piping) always bring with them the transport of materials, in the form of a water eye in the region where the water exits, often composed of finer soils (sands or silts).

In the event of the appearance of solid materials downstream of the dam after the reservoir is filled, it is recommended to have a specialized professional to collect the material, record the temperature, and carry out laboratory tests as soon as possible, as it may be a drag of particles coming from the dam. The collection of the material should avoid evaporation or any type of alteration of the material during transport. It is important to check if this material is not leftover material deposited during construction, remnants of cofferdams that were not completely removed, or material superficially eroded from slopes, or brought by installed surface drainage system (Silveira, 2006).

To determine the content of solids (in suspension and in dissolution) the ASTM standard is used, test methods for particles and dissolved matter in water, no. ASTM-D 1888 – 67, 1978 edition. The measurement of the solids content in terms of unit is used (ppm) – part per million = mg/l (milligram per liter), that is: 1l = 1000cm³ 1cm³ = 1000mg 1000mg = 1.0 g

For monitoring the transport of solid particles, it is possible to use a device called a turbidimeter which is a probe for measuring turbidity, this can be coupled together with the flow meter. This device is recommended when the dam presents some anomaly of appearance of solids in drainage waters and also in dams, with a high probability of occurrence of internal erosion (piping) (Silveira, 2006).

It is important that the flow percolated through the foundation and internal drainage system of the dam be measured by a flow meter at a measuring point that can be accessed to obtain readings. The drain foot region always needs to be clean and preserved whenever possible, with easy access (Intertechne, 2022).

Due to factors such as material availability, construction speed, and economic aspects, the preference is for the earth dam category. To ensure safety, the analysis of percolation flow in earth dams must be thorough, considering that the water flow through the embankment and foundation is essential for the design of internal drainage systems. According to Terzaghi and Peck (1962), it is advisable to minimize water percolation from the reservoir through the embankment to its axis, preventing regressive erosion. For this purpose, the use of a vertical sand drain, together with a horizontal drain or drainage mat composed of gravel and sand, complemented by a toe drain made of gravel and sand, is recommended (Lopes, 2024).

There are some dams where there is an accumulation of a material with an aspect of iron-bacteria, with colloidal behavior, usually the smell of this type of material is typical of ferrous material, anyway in this situation it is recommended to be done some type of test with chemical analysis and granulometry that can confirm this information, discarding that it may be some transport of soil particle from the dam. There are historical dams such as, for example, the Rio Grande dam, located in São Paulo, which had their drainage and instrumentation system, mainly piezometers, compromised by accumulation and clogging by the presence of "iron-bacteria" material.

As a reference was published by Cemig energy company the article "Piau Dam — biological clogging of drainage of the downtream toe" and presented at an event organized by ICOLD in Seoul in South Korea in 2004, where it was reported a significant increase in subpressure in some piezometers due to the presence of iron-bacteria phenomenon. It should be noted that iron-bacteria phenomenon can be continuous, which can be a future concern in dams with this type of problem if it starts to present large volumes so it is important that this item starts to be visually monitored routinely. In addition, deposition of this material upstream from flow meter can affect reading giving indication of higher flow than actual so as recommendation it also suggests routine cleaning of this material inside meter boxes before readings (Carim, 2004).

Oliveira (2022) presents two cases of clogging by OCHRE (yellow earth) in earth dams in Poland, where visual inspections and anomalous readings of instrumentation indicated the presence of OCHRE in drainage devices such as toe drains, relief wells, and horizontal drains. Additionally, Oliveira reports the case of clogging by iron bacteria in part of the drainage system at the Rio Grande dam, one of the first documented cases in Brazil. The presence of material with the appearance of iron bacteria, orange in color, ferruginous in aspect, muddy and adhesive impregnated in the filtering layers of the drain, consisting of 79% of iron oxide in hydrated form, was observed.

FIGURE 7 presents photograph of accumulation of solid material transported with reddish coloration as well as some seepages coming from lateral walls of trapezoidal channel located downstream from a dam.

Figure 7. Transport of Solid Material [Intertechne] (2022).

To delimit the region that may be under the effect of the process of fine transport, monitoring can be done in a concrete drainage channel, a half concrete pipe, or some coating that prevents mixing the transported solids with the local surface soil particles. The following is a sequence of works and interventions that can be adopted to control transported solid materials, which are: Cleaning the drainage channel, removing all the fine material that is deposited at its base, followed by the installation of a device for containment of fines that allows the passage of water and retention of material being transported by drag.

This system can be carried out by a kind of sieve in the shape of a frame to be installed inside the drainage channel. This sieve can be equipped with a double # 60 nylon screen, with clearance to create a kind of bag that allows the passage of water and retention of fines. Considering a better observation per section, it is proposed to install more than one sieve along the drainage channel depending on the extension of the section being investigated, aiming to confirm the area where fine transport is occurring (Intertechne, 2022).

Readings can be made at equal spaced periods, with daily readings, this interval can be longer in an evaluation where there is stabilization of material transport, recording the amount of fines retained in the sieve bag and the occurrence of eventual rains, in addition to reading flow monitoring instruments. At the end of each collection cycle of the pre-established period, it is recommended to perform integral granulometry tests (with sedimentation) on collected materials, it is important that collection is done in different places to confirm that it is the same material and from the same origin (INTERTECHNE, 2022).

Figure 8 presents a sketch of this device for collecting transported materials.

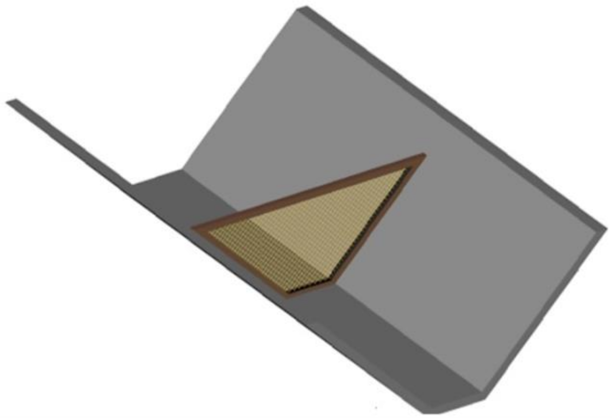

Figure 8. Solid Material Accumulation System [adapted from Intertechne] (2022).

In the event that the drainage system downstream of the dam is underground with perforated concrete or polyethylene drainage pipe, the monitoring of solid materials can be done in the inspection wells installed along the drainage system. It is important to inspect each of the inspection wells to identify the existence of deposited fines and in the process of dragging. It may happen that in some sections the water flow has speeds that make it difficult to confirm the transport of fines, in this case it is proposed to install at the entrance of the tube, located downstream of the wall of each of the inspection wells, a kind of sieve with a bag that allows the accumulation of transported material, in order to have a physical measure.

Prior to the installation of this sieve, cleaning of the tube should be carried out with removal of deposited material as far as possible from the inspection well. The planning of inspection frequency can be adjusted to need and evidence of continuity of solid material accumulation. In sections where material is collected by nylon bag, it is recommended to perform complete granulometry tests (with sedimentation) (IntertechnE, 2022).

Figure 9 presents a sketch of this device for collecting transported materials.

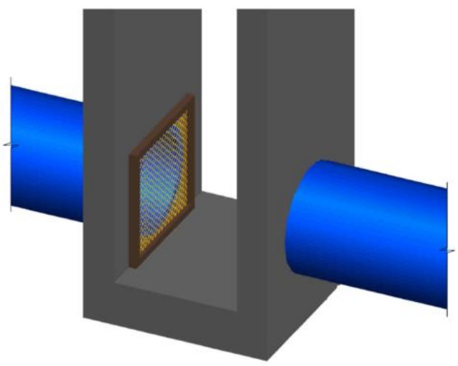

Figure 9. Solid Material Containment Sieve [adapted from Intertechne] (2022).

With the identification of possible sections showing material transport, the research to identify the location of transported materials' deposition can be continued by conducting robotic inspections at each of the sections where material drag has been identified, aiming to define the anomaly location in each affected section, if any. For this activity to be effective and provide reliable information, it is recommended to contract a specialized company for robotic inspections in pipelines; some companies in the sanitation sector frequently perform this work. These inspections may allow for the reasonably accurate localization of any damage occurring in the drainage system, in order to guide the system recovery activities (INTERTECHNE, 2022).

One possibility is that these locations where transported materials accumulate may result from damage due to deformation between adjacent pipes, breakage, or differential deformation, or even from a localized rupture of some pipe segment. With the consolidation of all investigation data, targeted intervention can be carried out at the damaged location, with the potential localized replacement of drainage pipes and/or the adoption of additional measures to prevent material transport.

The condition of the potentially damaged location should be analyzed in light of the information obtained in the investigations, aiming to confirm the feasibility of using the existing project that led to the dam's construction or the possible need to consider adjustments or the inclusion of a complementary solution (Intertechne, 2022).

Methodology

Ensuring the proper functioning and behavior of an earth dam is essential for the safety of the structures and to prevent failures. Therefore, it is essential to carry out meticulous work that involves the implementation of effective measures. Several solutions have been studied to ensure the safety of dams, both during the project phase of the venture and in emergency situations, in conjunction with continuous monitoring.

Among the solutions studied, emergency repair alternatives stand out, which can also be adopted as permanent solutions. An example is relief wells and the inverted filter, which are common operations in cases of suspicion or the appearance of downstream water from an earth dam. These measures help control the pressure in the soil and ensure the stability of the structure, preventing possible landslides and risks to the safety of people and the environment.

Therefore, it is essential to invest in preventive maintenance and actions that ensure the safety and proper functioning of earth dams, aiming to prevent accidents and ensure the protection of the affected areas. Constant monitoring and the adoption of appropriate measures are essential to ensure the stability

Sandbag Intercept Dike

As an emergency and temporary intervention, it is recommended to construct a sandbag intercept dike to direct the water to a single point, then impound the water within this enclosure, forming a larger water body above the water emergence point, reducing the likelihood of erosion (piping), thus preventing an increase in the hydraulic gradient (FEMA, 2015).

Figure 10. Sandbag Intercept Dike [FEMA] (2015).

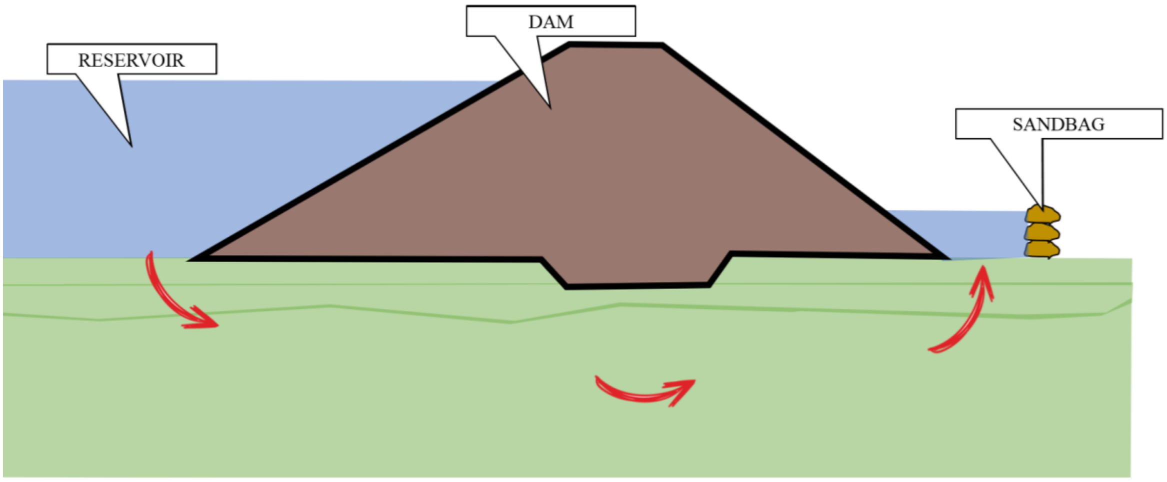

Figure 11. Sandbag Poll [The author] (2024).

Relief Wells

Relief wells also serve as observation wells, but their main purpose is to reduce hydraulic flow at designated points along the flow path. The water discharged from the relief well can be collected and directed through drainage devices, consolidating the water from all relief wells at a single measurement point for monitoring. It is also possible to measure the flow from each well quickly (FEMA, 2015).

It is advisable to periodically schedule a life test program with well flushing since, in dam applications, specific problems associated with the clogging of filter systems or the accumulation of water inside are common (Silveira, 2017).

Relief wells typically require regular maintenance for long-term proper operation, including, in most cases, chemical treatment and disinfection. Although relief wells are not typically installed for the primary purpose of monitoring infiltrating water, their outflow can be collected, measured, and evaluated in a manner similar to open piezometers or observation wells (FEMA, 2015).

Relief wells are effective in reducing foundation pressures, increasing infiltration flow, and thus increasing the head loss in the foundation between the reservoir and the well locations. For uniform foundations, relief wells are typically installed in a line along the dam's downstream drain (Gaioto, 2003).

Regarding the advantages of using relief wells for infiltration control, they include rapid installation, less specialized labor requirements, minimal space, installation, and monitoring, and through the drilling process, the wells can be installed without the need to lower downstream water levels (FEMA, 2015).

As for the disadvantages, potential filter material clogging and transition within the well between the borehole wall and the external tube wall, susceptibility to iron bacteria in some regions where this phenomenon is recurrent due to local geology, and a relatively small influence area per well are notable (FEMA, 2015).

Figure 12 shows a typical installation of a relief well in the downstream foundation of a dam for a confined aquifer.

Please note that some technical terms may have specific variations depending on the context and terminology used in the field.

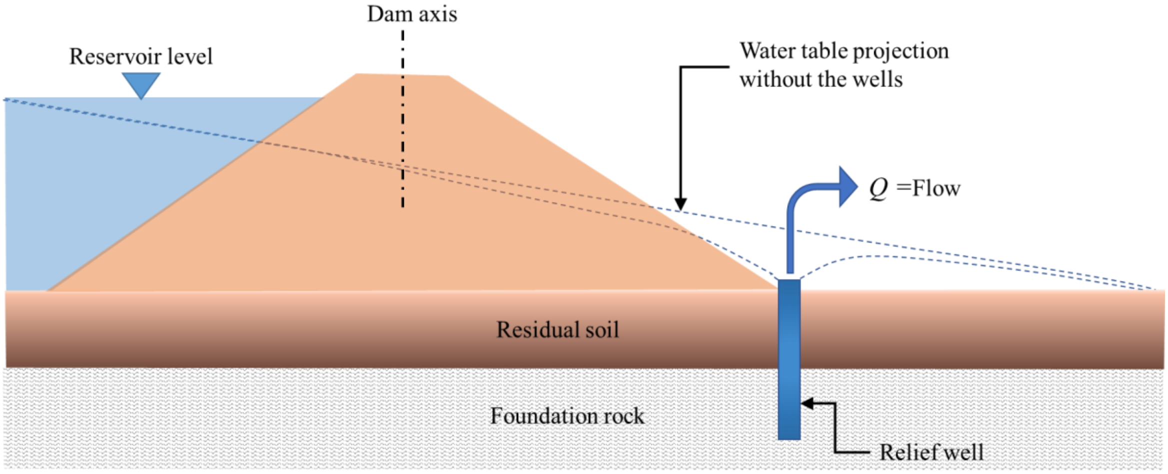

Figure 12. Foundation Relief Well [adapted from FEMA] (2015).

There are ways to predict the flow rate for the design of relief wells, one of which can be achieved through finite element analysis, which may result in flow rates lower than those obtained through commonly used formulas. It is important, for safety reasons, to assess the results and determine which one to adopt for the project, considering that the set of wells to be installed must be sufficient to relieve subsurface hydrostatic pressures. It should be noted that the numerical model is theoretical and assumes a homogeneous medium with constant permeability in all directions. Some geological features that may be responsible for concentrating high flow rates cannot be visualized with mathematical models (USACE, 1992).

Therefore, the quantity, locations, arrangement, and depth of the necessary boreholes may undergo changes during the installation of the wells due to the conditions revealed during the progress of the work. It is possible that even after the wells are put into operation, it may be necessary to expand the system to meet the actual flow requirements observed over time (MASSAD, 2010).

FIGURES 13, 14, 15, and 16 depict some typical details of the relief well installation profile that can be adopted in emergency actions or new project implementations.

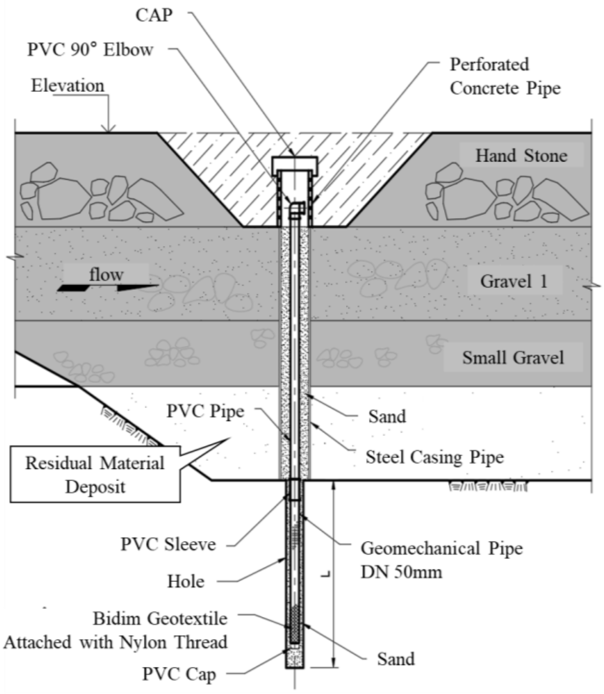

Figure 13. Relief Well Installation [Intertechne] (2022).

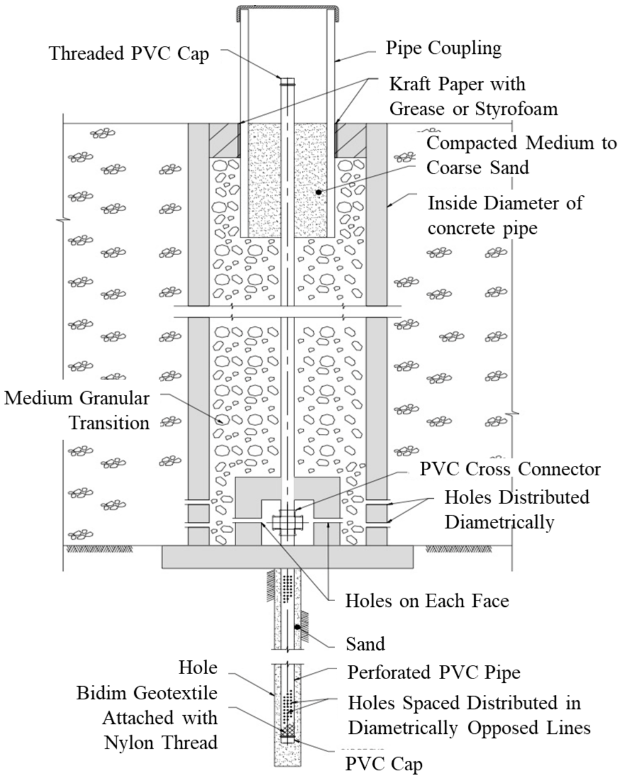

Figure 14. Relief Well with Gauge [Intertechne] (2022).

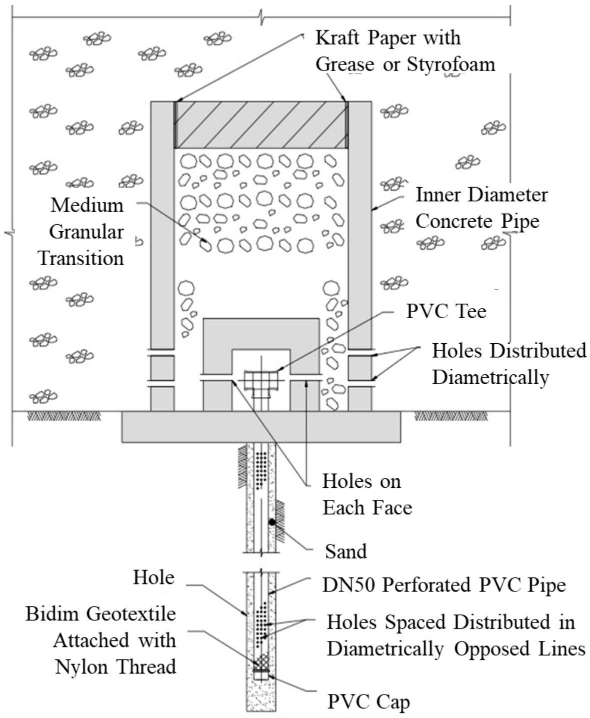

Figure 15. Recessed Relief Well [Intertechne] (2022).

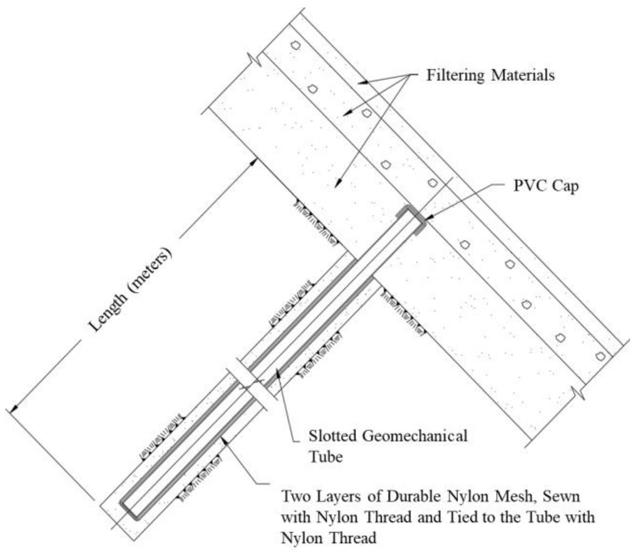

Figure 15. Relief Well Installation on a Slope [Intertechne] (2022).

For the design of the relief well system, it is possible to consider a single equivalent well to represent the entire system. To do this, it should be assumed that these wells are located in parallel with standardized spacing and diameters (Massad, 2010).

The total contribution flow rate is defined by equation (2), as proposed by Cedergren (1967) and cited in Massad (2006), for drawdown in a gravitational aquifer with a circular source:

(You may insert the equation here if needed, or I can help explain it further.)

The safety factor with respect to sand boil can be calculated by the expression below:

$$Qf = \frac{\pi \times k \times D \times \Delta H}{\ln(R/r)} \quad (3)$$

$$\Delta H = h1 - h2 \quad (4)$$

$$D = h2 \quad (5)$$

Where:
Qf: Contribution flow rate per well (water loss through the foundation) (cm^3/s).
k: Permeability coefficient (cm/s).
R: Half the distance between wells (cm).
r: Well radius (cm).
ΔH: Total hydraulic head (cm).
2R: Distance between wells (cm).
2r: Borehole diameter (cm).

The equation appears to describe the contribution flow rate (Qf) in the context of a well system's design for groundwater drawdown, where various parameters, such as permeability, distances between wells, and well characteristics, are taken into account.

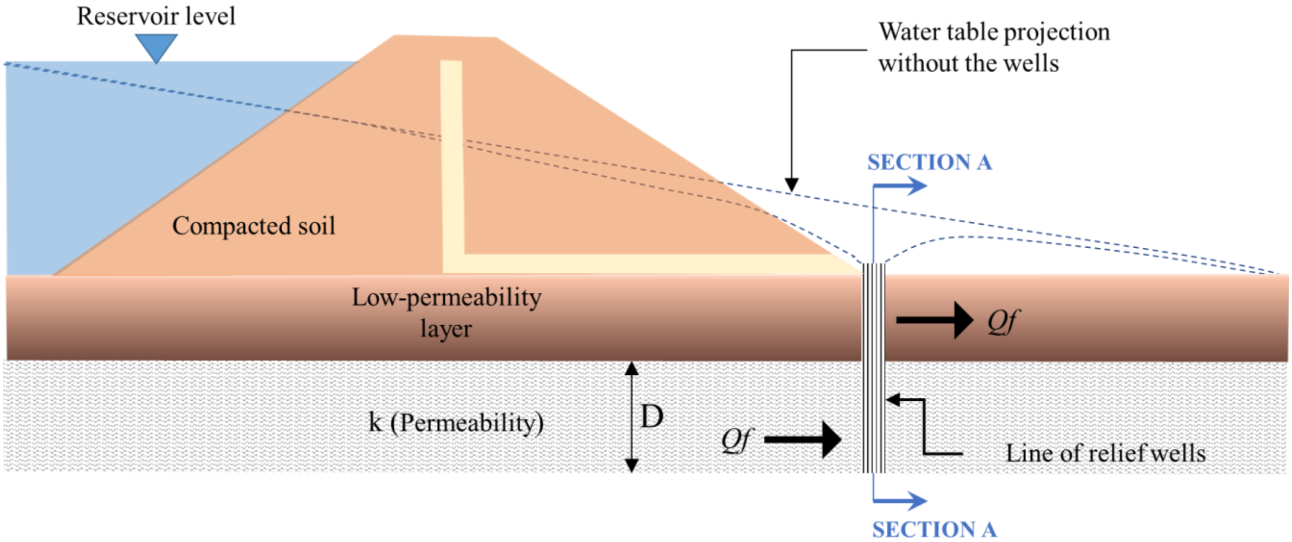

Figure 17. Relief Well for Water Outflow Control [adapted from Massad] (2010).

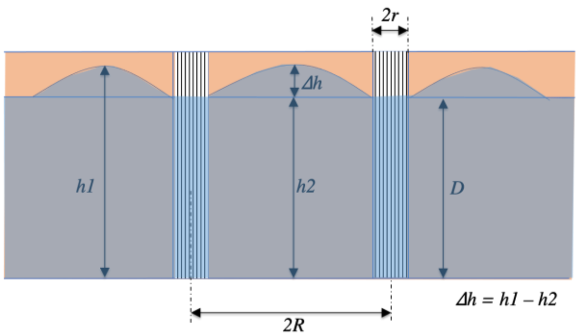

Figure 18. Relief Well Section A [adapted from Massad] (2010).

Inverted Filter

Massad (2010) describes the inverted filter as generally being considered a berm with a sandwich of granular filter materials between them. This device, whether of an emergency nature or not, can be placed immediately at the foot of the downstream embankment slope. Its primary function is to allow water to pass through it, while preventing the transportation of foundation materials or the embankment mass.

The combined effect of the weight of the material and its permeability simultaneously aids in combating geotechnical phenomena known as "sand boil" and "blow out," respectively. These phenomena are associated with the risk of soil liquefaction and soil uplift (Massad, 2010).

This solution is commonly used right after filling a reservoir and can be combined with other methods applied to rock-filled earth dams, one of which is the use of relief wells (Silva, 2016).

FIGURE 19 below schematically illustrates the application of an inverted filter in a dam.

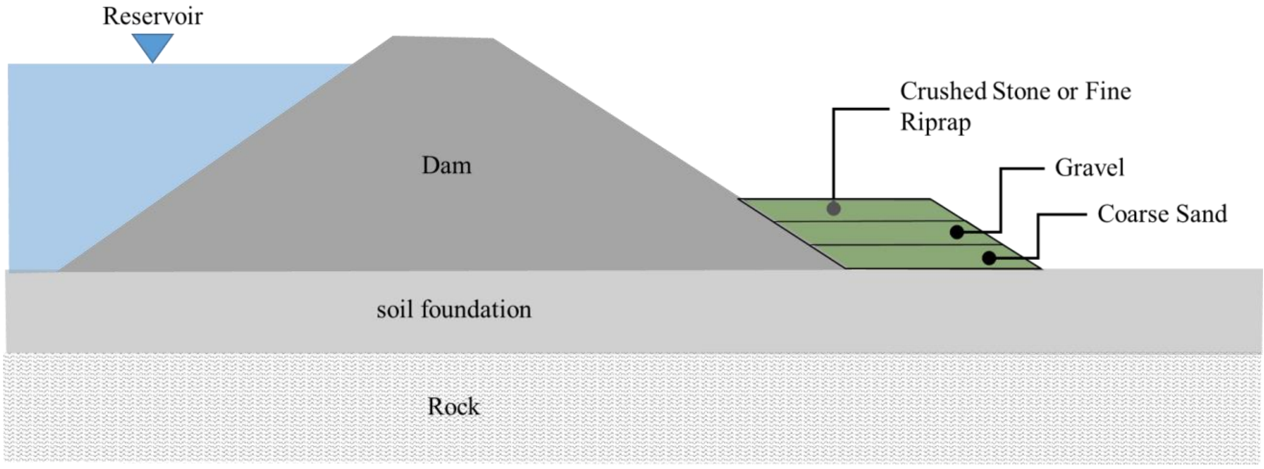

Figure 19. Inverted Filter [adapted from Massad] (2010).

In situations where the dam structure is already showing signs of instability due to the internal erosion phenomenon and there is a higher likelihood of destabilization, it is advisable to have a contingency plan in place. This plan should include stocking materials near the foot of the downstream slope of the dam to expedite the implementation of the inverted filter if necessary.

In some cases, when dams are undergoing repairs to restore their geometry or drainage system, it may be necessary to plan the execution in segments to avoid undermining the dam's foot all at once. It is important to specify the particle size distribution for granular materials used in the inverted filter. However, all materials must meet the criteria for filtration, permeability, and uniformity when applicable. This validation is crucial for the proper functioning of the system, preventing material transportation or clogging of adjacent materials (Intertechne, 2022).

Cardozo (2017) emphasizes that drainage systems, present in all construction methods, are essential to control pore pressure caused by water flow in the dam. Pore pressure forces facilitate movement, and inefficiency of the drainage system can result in the phenomenon of piping. This phenomenon occurs due to internal erosion that removes soil particles, forming empty "pipes" that lead to collapses and lateral landslides.

FIGURE 20 demonstrates the implementation of an inverted filter alongside the toe drain of a dam.

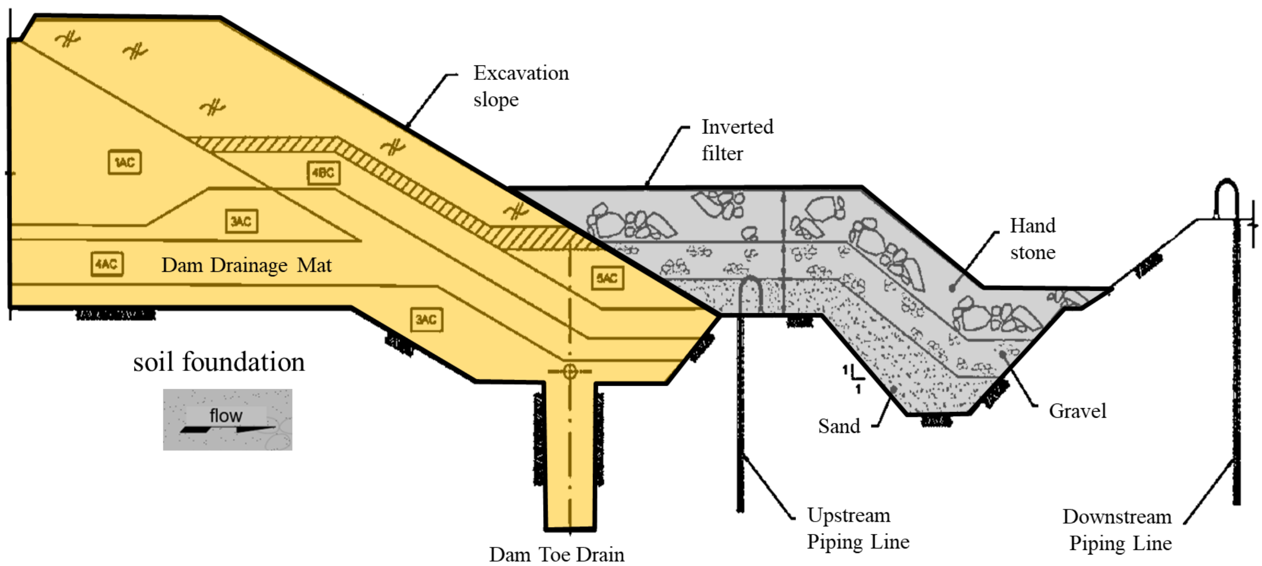

Figure 20. Inverted Filter - Detail [adapted from Intertechne] (2022).

The importance and necessity of internal drainage of a dam, designed by filter and drainage system, also apply to the concept of inverted filters. This technique, used successfully for years, began in Brazil in the 1930s in dam reservoirs in the Northeast. Initially, drainage devices, in the form of vertical sand and/or dry stone drains, were inserted immediately downstream of thin impermeable walls of mortar or concrete, intercepting the flow through the dam body and capturing any water flows due to cracks or construction defects in the impermeable elements.

By the mid-1930s, such impermeable walls were no longer used, but internal drainage systems, provided by sand and/or dry stone filters and mats, continued to be used. Historically, these devices preceded, by about 15 years, the internal drainage system designed by Karl Terzaghi for the Vigário dam and embankment project, a solution that was later widely adopted (Guidiccini, 2023).

Conclusions

In conclusion, the findings of this study emphasize the critical importance of regular assessments and proper maintenance of dam structures to prevent internal erosion and ensure their long-term safety and functionality. By implementing the proposed solutions for addressing internal erosion, such as the installation of filtering materials and establishing drainage systems, dam owners and managers can mitigate the risks associated with piping formation and potential failures. Furthermore, the study underscores the significance of understanding soil composition and thermal management techniques in optimizing the performance of horizontal heat exchangers for sustainable geothermal applications. Overall, effective dam safety requires a holistic approach that considers various factors and employs both structural and non-structural measures to maintain the integrity and stability of these crucial infrastructures.

Based on the presented article, we can conclude that dam safety is of paramount importance. Regular assessments of these structures are essential to identify and rectify anomalies, ensuring their conservation and structural safety. Internal erosion, known as "piping," is one of the primary causes of dam failures. This phenomenon occurs when water percolation displaces soil particles towards the outer part of the embankment, resulting in internal erosion.

The upstream region, especially near the base of the dam, is particularly susceptible to "piping" formation due to high hydraulic gradients and flow rates. To address this problem, several solutions are proposed, including the installation of filtering materials within the dam body to establish a drainage system capable of relieving internal pressures on the materials used in embankments and their foundations.

This article presents a set of solutions that can be implemented to address anomalies associated with the onset of internal erosion in dams. These solutions can be applied in both emergency situations and as permanent measures to ensure the safety and operability of dams.

The study found that for the red latosol, horizontal heat exchangers should be installed at a depth of 2.40 m to prevent surface thermal disturbances. The choice between PVC or copper for the heat exchanger material did not significantly affect the heat transfer rate. However, the soil composition emerged as a limiting factor, indicating that PVC exchangers may be preferable due to their lower cost and easier handling.

Temperature difference between the circulating water in the exchanger and the surrounding soil emerged as the key factor influencing heat transfer rate. This highlights the importance of understanding the soil conditions for effective and sustainable thermal management.

Based on our findings, in a red latosol, it is recommended that parallel tubes of horizontal heat exchangers maintain a minimum distance of 0.60 m to minimize mutual thermal interference and maximize system efficiency.

According to Ferreira (2022), the risk posed by a dam is rarely caused by a single factor, but is the result of a combination of scenarios with adverse conditions. These risks include contributions from the site, the design, the construction and maintenance methods, the geotechnical characteristics of the region and the implementation, as well as precipitation conditions, among others. In this sense, dam safety is a multidisciplinary process that may involve structural and non-structural activities, aimed at maintaining the operational conditions for which the dam was designed. One of the major concerns regarding the safety of dam structures is the stability of the downstream slope. The structure may be threatened due to increased loading and/or deficiencies in the internal drainage system, which can raise the water table to levels higher than those acceptable for the structure, as well as the formation of piping (Ferreira, 2022).

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