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Permeability, Drainage, and Instrumentation in Massifs: Study and Applications in Dams

Permeabilidade, Drenagem e Instrumentação em Maciços: Estudo e Aplicações em Barragens

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Abstract: This article addresses the influence of permeability and water percolation velocity in soil masses, highlighting their variation according to grain size and sensitivity to the amount of water present. Permeability is directly linked to the medium's porosity, influencing soil drainage. Tables are presented with permeability and drainage characteristics of various types of soil, as well as average consolidated permeability values of common materials used in dam embankments and their foundations. The negative effects of water infiltration in embankment dams are also discussed, such as soil particle displacement and leaching, emphasizing the importance of adequate drainage systems. Additionally, empirical criteria and probabilistic models for the design of drainage and filtration systems for dams are described, aiming to control percolating fluids and ensure the structures' safety. Instrumentation in dams, especially in Brazilian territory, is also addressed, highlighting its fundamental role in the monitoring and control of structures.

Keywords: Permeability; Drainage; Soil masses; Dams; Instrumentation.

Resumo: Este artigo aborda a influência da permeabilidade e velocidade de percolação da água em maciços de solo, destacando sua variação conforme a granulometria e a sensibilidade à quantidade de água presente. A permeabilidade está diretamente ligada à porosidade do meio, influenciando na drenagem do solo. São apresentadas tabelas com características de permeabilidade e drenagem de diversos tipos de solo, assim como valores consolidados médios de permeabilidade de materiais comuns em construção de aterros de barragens e suas fundações. Discute-se também os efeitos negativos da infiltração de água em barragens de aterro, como deslocamento e lixiviação de partículas de solo, ressaltando a importância de sistemas de drenagem adequados. Além disso, são descritos critérios empíricos e modelos probabilísticos para o dimensionamento de sistemas de drenagem e filtração de barragens, visando controlar os fluidos percolantes e garantir a segurança das estruturas. A instrumentação em barragens, especialmente no território brasileiro, também é abordada, destacando seu papel fundamental na monitorização e controle das estruturas.

Palavras-chave: Permeabilidade; Drenagem; Maciços de solo; Barragens; Instrumentação.

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1. Introduction

The design of dams is a complex process that involves multiple criteria and considerations to ensure their stability and safety, including the critical role of internal drainage systems in reducing the risk of failures. Issues such as pollution, environmental degradation, and nature conservation are closely linked to human activities and the lack of proper environmental planning. The need for continuous development of legislation in different countries regarding the construction and monitoring of tailings dams has been emphasized, particularly in the aftermath of the Mariana and Brumadinho disasters. In Brazil, Law 14.066/2020 was enacted to regulate the National Dam Safety Policy, aiming to eliminate accident risks, which may result from various factors.

Awareness of dam failure probabilities remains crucial, despite government efforts, as Brazil still records numerous dam-related incidents annually. Dam safety also has a significant environmental impact, underscoring the importance of incorporating environmental constraints into project development.

From a technological perspective, computational advancements facilitate the processing of instrumentation data, enabling more efficient and safer dam monitoring. Socially, dams play a vital role in economic and social development, providing hydroelectric power, supporting local water supply, flood control, and recreational areas, although competition for water resources is intensifying, especially in arid regions. Economically, Brazil's hydroelectric potential is substantial, and dam insurance serves as an essential financial protection mechanism.

Barreto (2024) highlights those technological advancements, particularly in numerical and computational methods, which have played a fundamental role in ensuring safety during the design, construction, and operation of dams. The choice of dam type is directly related to site characteristics, material availability, and construction methods. Among the most common types, homogeneous earth dams and composite earth-rockfill dams stand out, as their adaptability to topographical conditions and available materials allows construction on versatile foundations suited to resistant soils.

Soil permeability and drainage in embankments are critical aspects of civil engineering projects, particularly in dam construction, as they are essential for the stability and durability of these structures. This article aims to present a detailed analysis of soil permeability and drainage in embankments, highlighting their significance and influence on different types of projects while also addressing the role of instrumentation in dam monitoring.

2. Methodology

This research was conducted based on a literature review of books and scientific articles related to the topic. Authors such as Terzaghi (1996), Lambe and Whitman (1969), among others, were consulted, addressing both theoretical and practical aspects of permeability and drainage in soil embankments. Additionally, tables and consolidated data on the permeability of various materials commonly found in dam construction were analyzed.

For the instrumentation aspect, studies by Gaioto (2003), Eletrobrás (2003), and Silveira (2006), among others, were reviewed, discussing the importance of instrumentation in dam monitoring.

The research was further complemented by an analysis of conclusions from recent studies. It was found that the use of triangular weirs is essential for accurately monitoring flow rates in dams. The proper installation and sizing of these devices ensure reliable results, contributing to the overall safety of the structures.

Lopes (2024) highlights the growing concern regarding the hydraulic stability of earth dams, leading to the application of flow models in porous media and the formulation of numerical models to solve differential equations that describe water percolation flow. The partial differential equations governing water percolation in unconfined or confined aquifers within a three-dimensional domain composed of heterogeneous and anisotropic material describe the transient water flow through the embankment and foundation of earth dams, subjected to a natural hydraulic gradient.

Dam safety, as established by the National Dam Safety Policy, must be considered at all stages of its lifecycle, including design, construction, and operation. During the design phase, proper sizing and consideration of adopted simplifications are crucial. In the construction phase, compliance with the criteria established in the executive project is fundamental, whereas in the operation phase, continuous structural monitoring is the primary focus.

It is important to emphasize the significance of adequate instrumentation in dams, including flow meters, level sensors, piezometers, and other devices, for effective structural monitoring. A detailed analysis of soil embankment permeability and drainage, combined with the use of appropriate monitoring devices, is essential to ensuring dam safety and durability.

Barreto (2024) highlights that the main objective of this research is to consolidate real data from the monitoring history of executed and operational projects in Brazil, contributing to instrumentation analysis by incorporating actual flow rate values observed in flow meters.

Barreto (2024) also discusses a set of solutions aimed at both emergency situations and long-term strategies to mitigate anomalies associated with the onset of internal erosion in dams. Emphasizing piping prevention, the study underscores the importance of these measures in preserving structural integrity and ensuring the safety of these infrastructures. Among the proposed approaches, the use of inverted filters, relief wells, and interceptor dikes stands out, playing a crucial role in controlling water seepage and reducing material transport—key factors in minimizing instability risks in earth and rockfill dams.

2.1 Permeability and drainage

Soil permeability and drainage are intrinsic characteristics of embankments, influenced by their grain size distribution. Soils with a higher void ratio tend to be more porous and, consequently, more permeable. Water present in the soil can percolate through the pores, with its percolation rate varying according to the soil's granulometry.

Soils with a higher void ratio exhibit greater porosity, which in turn results in increased permeability (LAMBE & WHITMAN, 1969).

Table 1 – Soil Permeability and Drainage.

<table>
<tr><th>k (cm/s)</th><th>Permeability</th><th>Drainage</th><th colspan="2">Soil Type</th><th>k (cm/s)</th></tr>
<tr><td>1,00E+02</td><td rowspan="4">High</td><td rowspan="6">Good</td><td colspan="2" rowspan="2">Clean gravels</td><td>1,00E+02</td></tr>
<tr><td>1,00E+01</td><td>1,00E+01</td></tr>
<tr><td>1,00E+00</td><td colspan="2" rowspan="2">Clean sand, clean sand and gravel mixture</td><td>1,00E+00</td></tr>
<tr><td>1,00E-01</td><td>1,00E-01</td></tr>
<tr><td>1,00E-02</td><td rowspan="2">Medium</td><td rowspan="5">Very fine sand, organic and inorganic silt, sandy silt-clay mixture, stratified clay deposit, etc.</td><td rowspan="5">Impermeable soil modified by vegetation and weathering effects</td><td>1,00E-02</td></tr>
<tr><td>1,00E-03</td><td>1,00E-03</td></tr>
<tr><td>1,00E-04</td><td rowspan="2">Low</td><td rowspan="2">Poor</td><td>1,00E-04</td></tr>
<tr><td>1,00E-05</td><td>1,00E-05</td></tr>
<tr><td>1,00E-06</td><td rowspan="2">Very low</td><td rowspan="4">Practically impenetrable</td><td>1,00E-06</td></tr>
<tr><td>1,00E-07</td><td colspan="2" rowspan="3">"Impermeable" soil, homogeneous clays below the weathered zone</td><td>1,00E-07</td></tr>
<tr><td>1,00E-08</td><td rowspan="2">Practically impermeable</td><td>1,00E-08</td></tr>
<tr><td>1,00E-09</td><td>1,00E-09</td></tr>
</table>

Source: Adapted from Terzaghi et al. (1996).

The infiltration of water in embankment dams can cause particle displacement and leaching, making the use of efficient drainage systems essential to prevent such issues.

Presented in TABLE 2 are the empirical design criteria for dam drainage and filtration systems. Additionally, Silveira (1965) proposes a probabilistic model to evaluate a filter's particle retention capacity based on the distribution of particle diameters (ASSIS, 2003).

Table 2 – Drainage and Filtration Systems.

Author	Adjacent Material	Filter Criteria	Main Characteristics
Terzaghi (1922)	Uniform sand	D15/d15 > 4 - 5 and D15/d85 < 4 - 5	Based on the author's experience.
US Bureau of Reclamation (1963)	Cu = 3 - 4 (non-cohesive soils)	5 < D50/d50 < 10 (fine sand)	D100 <75 mu D5> 0,074 mm fine fractions of the filter material and adjacent soil must have parallel gradations.
	Cu > 4 (well-graded soils)	12 < D50/d50<58 and 12 < D15/d15<40 (rounded particles)	
		9 < D50/d50 < 30 and 6 < D15/d15 < 18 (angular particles)	
Vaughan e Soares (1982)	-	$kF < 6{,}7\ .\ 10^{-6}\ .\ \delta\ d^{1,52}$	δ em µm.
Sherard e Dunnigan (1985)	Fine silts and clays (+ 85% < 0,074 mm)	D15/d85 ≤ 9	Fine soil filters (more than 40% < 0,074 mm) must have less than 60% coarser than 4,76 mm and a maximum particle size of 50 mm. For hydraulic conductivity, proposes D15/d85< 3 - 5.
	Silts and clayey sand (40 a 85% < 0,074 mm)	D15 ≤ 0,7 mm	
	Intermediate material (15 a 40% < 0,074 mm)	D15 = (40-*A* / 40-15) . ((4.d85) - 0,7) + 0,7mm	
	Coarse material (- 15% < 0,074 mm)	D15/d85 < 4 - 5	

Source: Assis (2003).

Legend:
Cu = Coefficient of uniformity of the soil, given by the ratio d_{60}/d_{10}.
Dn = Maximum diameter (mm) of the % of the finest particles in the filter materia;
dn = Maximum diameter (mm) of the % of the finest particles in the material adjacent to the filter.
kF = Hydraulic conductivity of the filter.
δ = Equivalent representative diameter of the particles in the soil adjacent to the filter, often $\delta = d_{85}$,
A = Percentage (%) of particles in the material adjacent to the filter that are smaller than 0.074 mm.

2.2 Flow Measurement

Instrumentation has become an essential component in dam projects over the years, primarily aimed at monitoring key parameters of structures subjected to loads and stresses.

For the installation of a triangular flow meter to provide reliable results, certain elements are crucial. These include a metal plate with a triangular opening geometry, installed transversely to the water flow at the end of the spillway basin. Additionally, a flow-stabilizing device is required, which may consist of a dissipation barrier with a cutoff wall or a perforated stainless steel/PVC plate. The finishing should ensure the smoothest possible hydraulic surface. The containment basin of the flow meter must have a length at least 10 times the width of the channel. It is also important to properly position the measuring plate relative to the channel bottom to prevent submerged flow conditions (SILVEIRA, 2006).

Triangular flow meters have a maximum reading capacity of 8,000 L/min, equivalent to 130 L/s. However, it is recommended that they operate within a reading range of 0 L/min to 600 L/min. Specifically, their use is suggested for measurements below 1,800 L/min (30 L/s) (SILVEIRA, 2006).

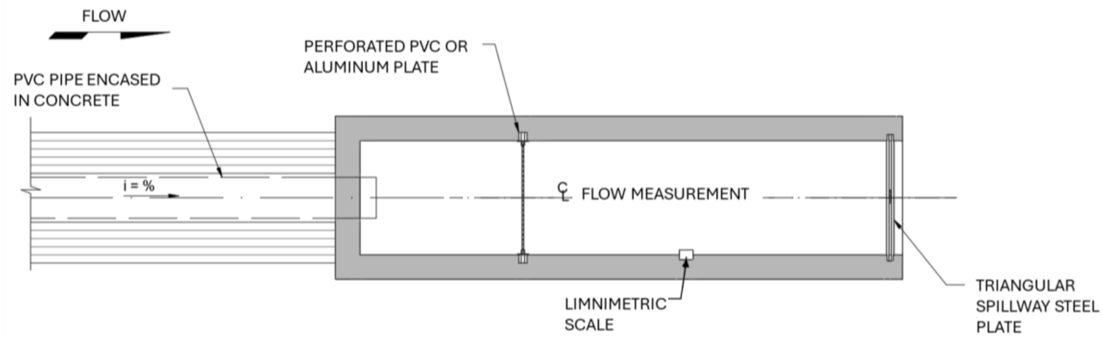


Figure 1 – Flow Measurement (Plan View).
Source: Barreto (2023).

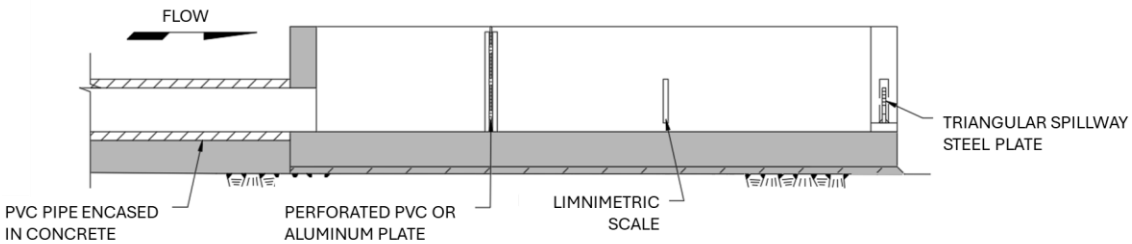


Figure 2 – Flow Measurement (Longitudinal Profile).
Source: Barreto (2023).

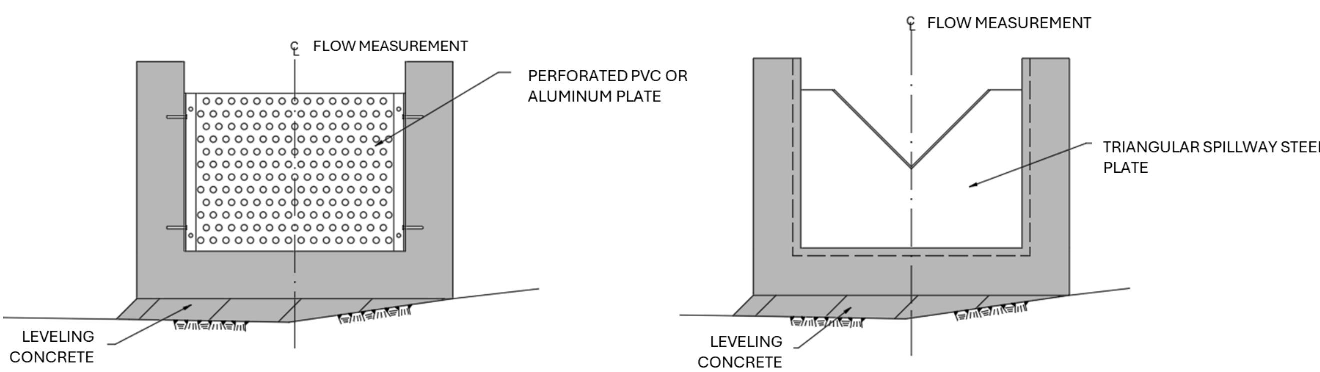


Figure 3 – Flow Measurement (Seccion and Elevation).
Source: Barreto (2023).

The installation of a triangular flow meter in confined areas where the dam is in contact with a concrete structure, downstream of the earth and rockfill dam, can be achieved by constructing a low wall following the dam's slope toe. The flow meter should be installed in the most suitable location for the drainage outlet (SILVEIRA, 2006).

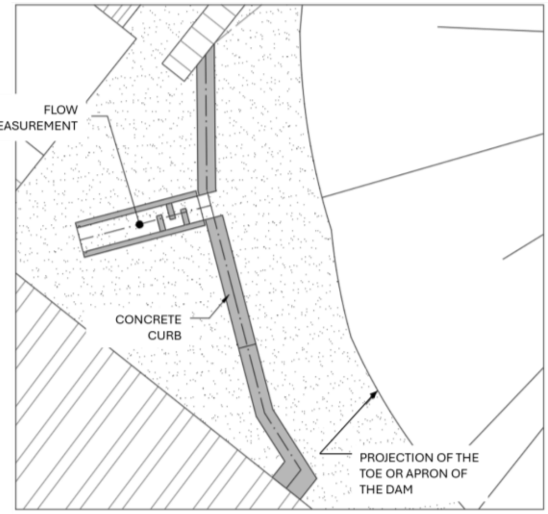


Figure 4 – Flow Meter with External Curb (Plan View).
Source: Barreto (2023).

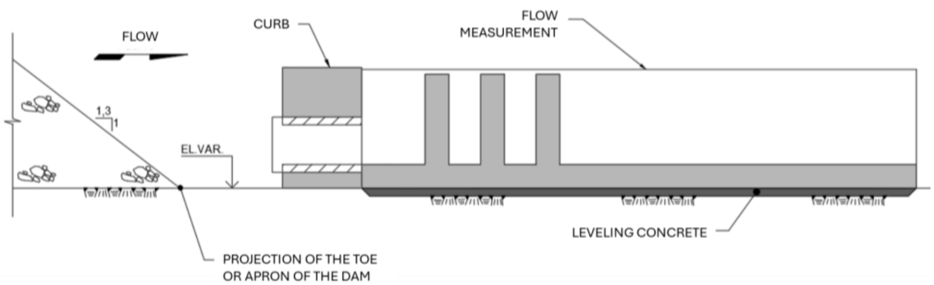


Figure 5 – Flow Meter with External Curb (Longitudinal Profile).
Source: Barreto (2023).

Figure 6 – Flow Meter with External Curb (Implementation).
Source: Barreto (2023).

To calculate flow rates using triangular flow meters, Equation (1) below is applied, considering the dimensions shown in figure 7. For triangular flow meters with a 90° opening, it is possible to obtain the flow rate in liters per second graphically by correlation, based on the presented formulas:

$$Q = \frac{8}{19} \cdot Cd \cdot \sqrt{2g}\, \mathrm{tg}(\alpha / 2) \mathrm{h}^{5/2} \quad (1)$$

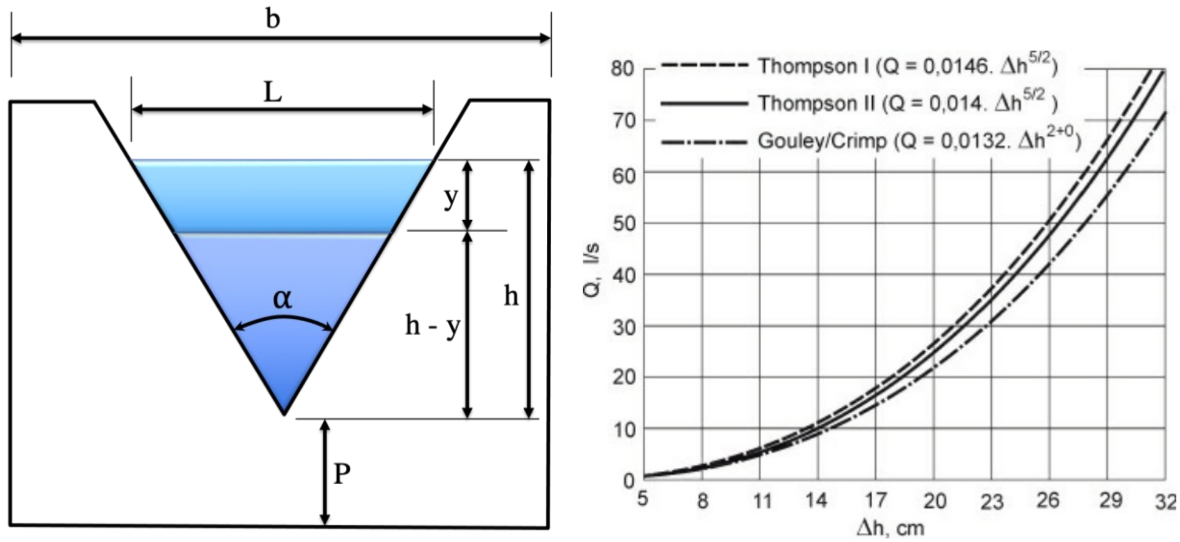


Figure 7 – Diagram of the Triangular Flow Meter.
Source: Adapted from Silveira (2006).

Legend:
Cd = flow coefficient (Bazin, Rehbock, Francis, or Kindsvater & Carter) (Mello Porto, 2001).
g = gravitational acceleration.
α = opening angle of the flow meter;
h = height of the overflowing water sheet relative to the meter's vertex.

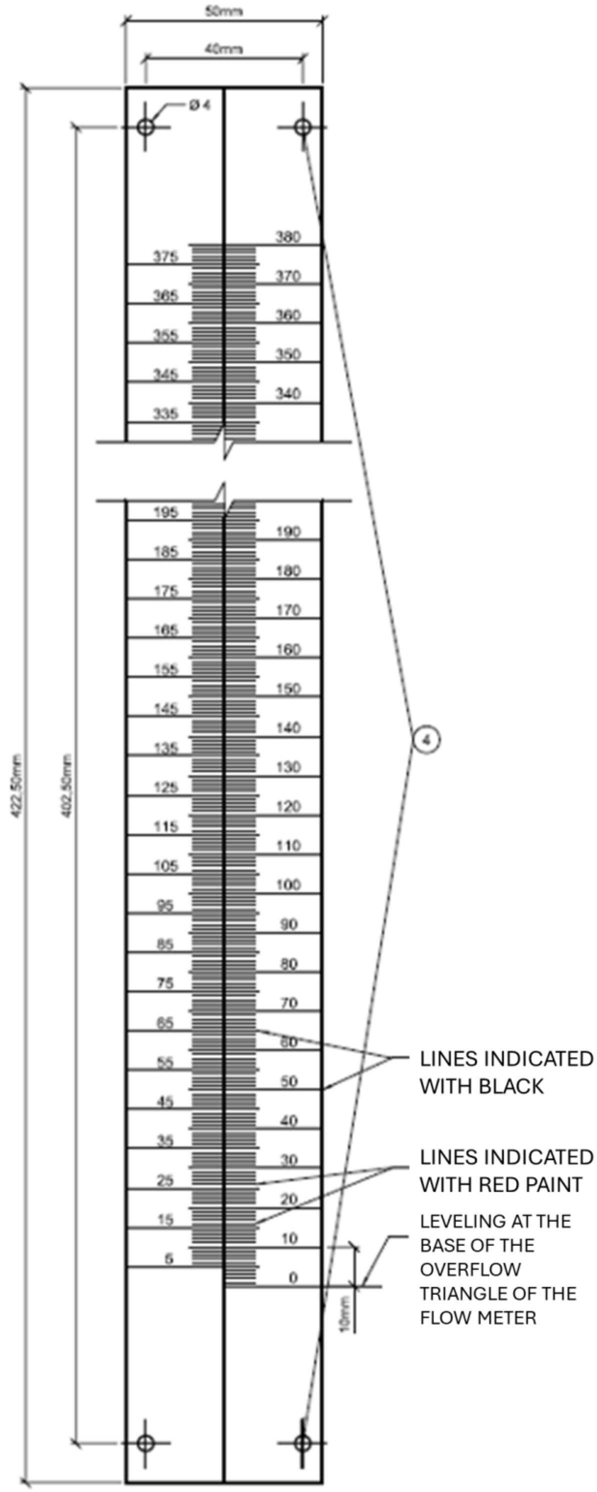
The most used flow meter is the one with a 90° angle on the plate, allowing flow rates to be calculated using the equations of Thompson or Gouley and Crimp.

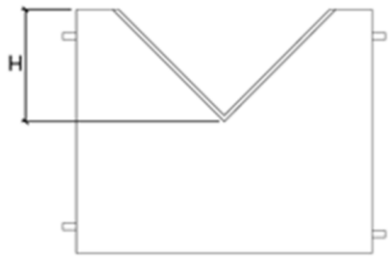
$$\text{Thompson I: } Q = 1{,}46.\, h^{5/2} \quad (2)$$

$$\text{Thompson II: } Q = 1{,}40.\, h^{5/2} \quad (3)$$

$$\text{Gouley e Crimp: } Q = 1{,}32.\, h^{5/2} \quad (4)$$

For the results to be evaluated, they must satisfy the following criteria:
$0{,}05 < h < 0{,}38m$
$P > 3h$
$b > 6h$
Figure 8 illustrates an example of calculation using Thompson's formula, with tabulated results correlated with measurements obtained through the reading of the limnimetric scale to determine the discharge of the triangular weir.





TRIANGULAR WEIR FLOW RATE

ALTURA H	Q	ALTURA H	Q
cm	l/s	cm	l/s
1	0,01	20	26,12
2	0,08	21	29,51
3	0,23	22	33,14
4	0,47	23	37,04
5	0,82	24	41,20
6	1,29	25	45,63
7	1,89	26	50,33
8	2,64	27	55,30
9	3,55	28	60,67
10	4,62	29	66,12
11	5,86	30	71,97
12	7,28	31	78,12
13	8,90	32	84,57
14	10,71	33	91,34
15	12,72	34	98,41
16	14,95	35	105,81
17	17,40	36	113,53
18	20,07	37	121,58
19	22,97	38	129,96

CALCULATED USING THOMPSON'S FORMULA

Figure 8 – Staff Gauge Reading (Thompson).
Source: Intertechne (2022).

During the flow measurement campaign in a dam's flow meters, it is essential to observe the color of the water—whether it is clear or turbid. In addition to monitoring increases in flow rates, attention should be given to the sediment content, as it may indicate the potential transport of solids originating from the dam's core (Silveira, 2006).

FIGURE 9 presents an example of a flow meter in operation, specifically constructed with concrete retaining walls and a half-round channel downstream to direct water to the storm drainage system.

Figure 9 – Triangular Flow Meter.
Source: Intertechne (2022).

In figure 10, an example of a flow meter with an automated reading system for data transmission is presented, allowing remote monitoring of flow measurements. This type of device has been commercialized by companies specializing in dam monitoring systems.

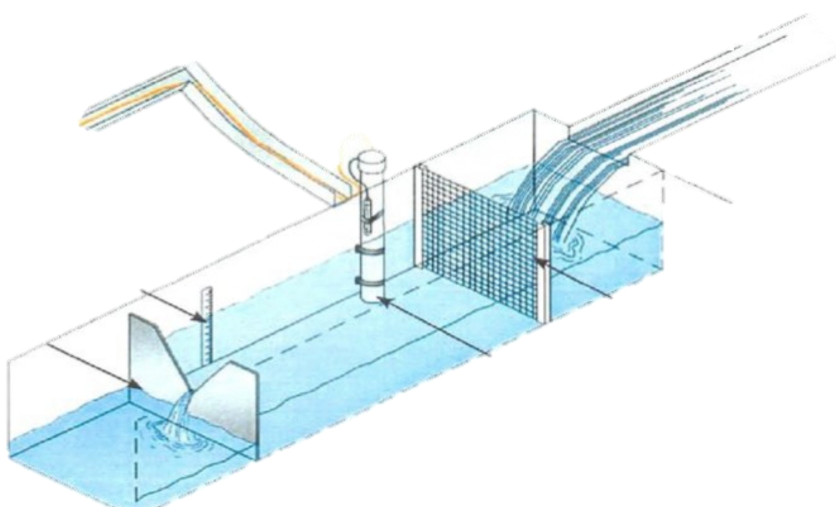


Figure 10 – Diagram of the Triangular Flow Meter.
Source: FEMA (2015).

Regarding the maintenance of instruments, certain actions must be taken during routine inspections of the project. In the case of flow meters, they must be completely cleaned of sediment buildup and any vegetation that may accumulate in the measurement box to prevent impacts on measurements and flow. Additionally, ensuring that all flow meters are properly identified facilitates inspections and readings (ANA, 2016).

2.3 Intercepting Dike

The measurement of infiltration flow through the foundation and the dam body is a critical parameter to be monitored during the reservoir filling phase and throughout the operational period. Observations of sudden increases in percolated water and the potential detection of fine material transport indicate possible anomalies within the area influenced by the flow meter. The positioning of flow meters in a dam requires a prior assessment of the contribution area intended for monitoring (SILVEIRA, 2006).

Figure 11 schematically illustrates how, depending on the foundation topography, the contribution sections can be divided for measuring dam flow rates.

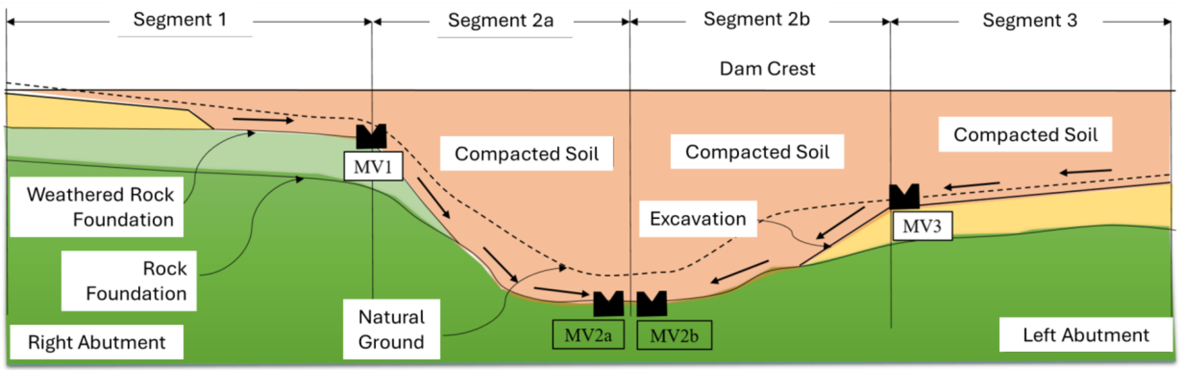


Figure 11 – Example of Contribution Sections.
Source: Barreto (2023).

The flow meter is specifically designed to provide data and information for assessing infiltration that may occur through the embankment and foundation. To delineate contribution areas and define measurement sections, it is necessary to construct interceptor dikes made of compacted soil. These structures typically cut through and interrupt the drainage blanket to channel the collected water toward the flow meter's collection basin (SILVEIRA, 2006).

Figure 12 and figure 13 present an example of the interceptor dike seal, which connects the compacted embankment sealing layer to the downstream toe of the dam. This design aims to retain water within a specific contribution basin at the foundation-embankment interface (BARRETO, 2023).

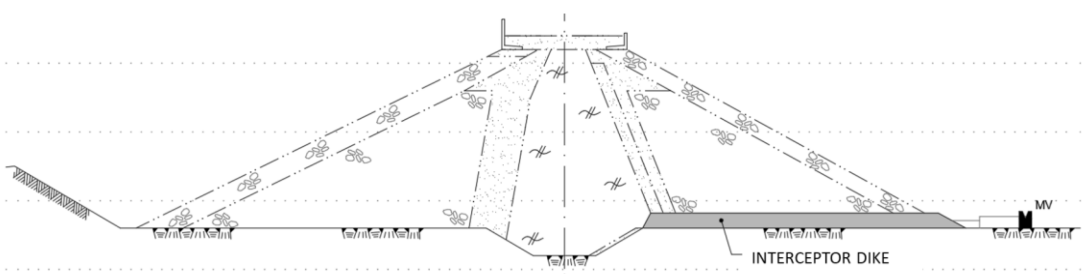


Figure 12 – Interceptor Dike in Earth Dam.
Source: Barreto (2023).

The connection of the interceptor dike outlet must be properly executed along the sealing core to prevent water leakage to the outer edge of the internal basin intended for collection. The height of the interceptor dike should be sufficient to cut through the horizontal drainage layer or material placed downstream of the dam axis. The interceptor dike may follow the terrain, provided that its alignment does not include a depression capable of causing overflow of the structure (FEMA, 2022).

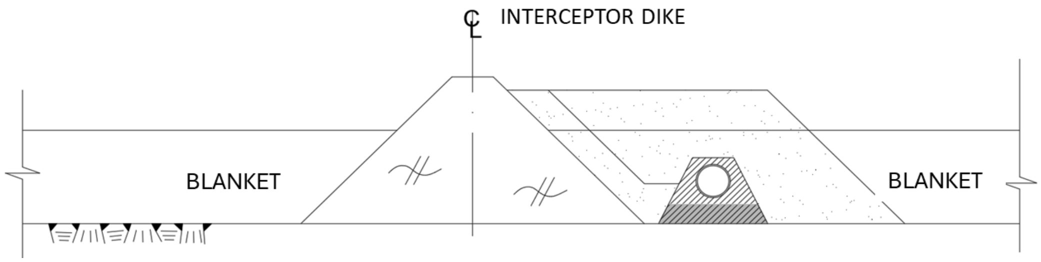


Figure 13 – Typical Detail of Interceptor Dike.
Source: Adapted from Intertechne (2022).

For small-scale dams, when the downstream water level does not reach the toe of the downstream slope, it is possible to install a single device, as illustrated in FIGURE 14, to measure the contribution from both abutments. It is essential to verify the downstream water level during the rainy season before installation or to check whether the location of the flow meter is not in a depression or an area of water accumulation, which could submerge the device, making measurements difficult or even impossible (ANA, 2016).

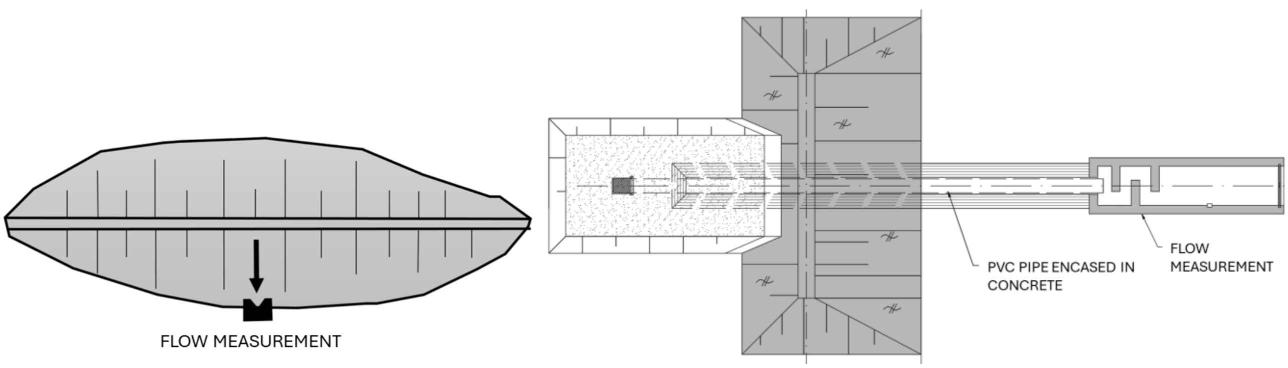


Figure 14 – Location of the Single Flow Meter.
Source: Adapted from Silveira (2006).

Based on the author's experience in various projects, emphasis is placed on the importance and specific precautions regarding the flow meter's collection area. It is recommended that the intake pipe be surrounded by protective material to prevent clogging or the entry of solids that could obstruct the pipeline. The pipe inlet should be safeguarded with filtering material, such as a nylon mesh or Bidim geotextile. Additionally, in the water intake region, it is advisable to construct a collection basin using granular material (medium transition) (INTERTECHNE, 2022).

For dams requiring a single flow meter to monitor a divided contribution basin, two flow meters can be installed by constructing a central interceptor dike, as illustrated in figure 15. This division allows for a more precise assessment of which side of the dam may be experiencing water concentration from the dam body or foundation (SILVEIRA, 2006).

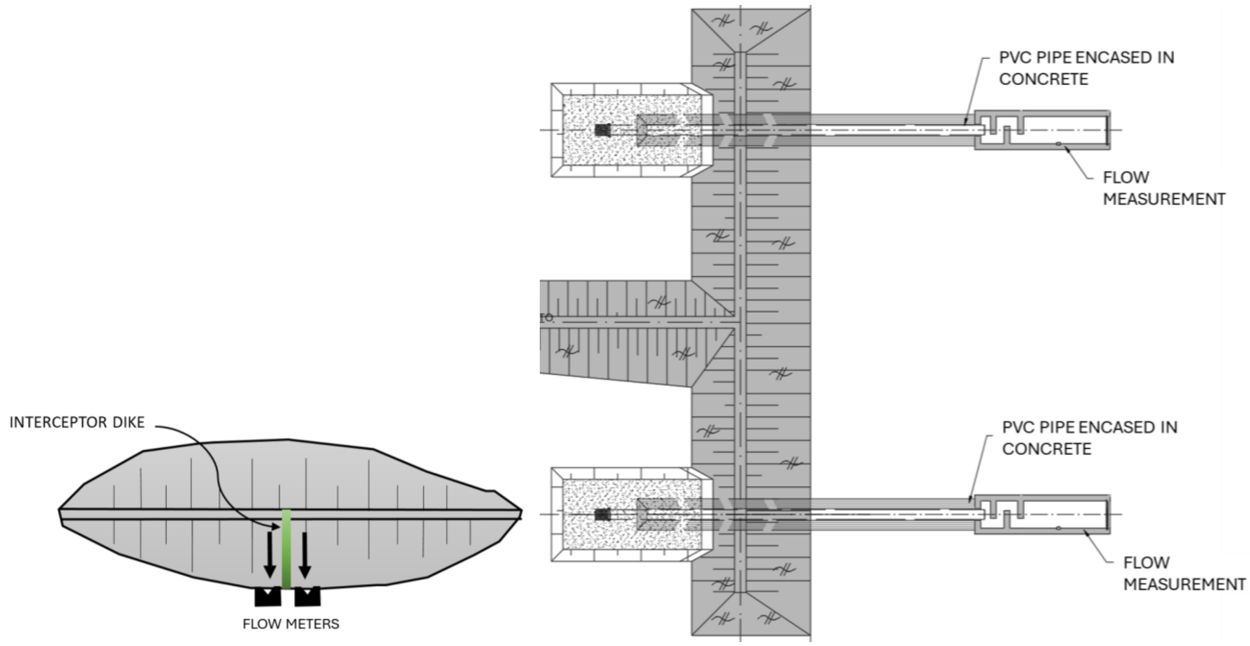


Figure 15 – Location of Flow Meter with Central Intercept Dike.
Source: Adapted from Silveira (2006).

In dam structures where a cofferdam is present in the riverbed, or even when the normal downstream water level is in contact with the downstream slope, as illustrated in FIGURE 16, flow meters are typically limited to the riverbanks, measuring only the contributions from the left and right margins of the dam (SILVEIRA, 2006).

To ensure no water leakage occurs along the lateral closure section, the alignment of the intercept dike, projected along the downstream slope toe of the dam, should intersect the topography at the contour line immediately adjacent to the abutment, maintaining the same elevation as the crest of the intercept dike (INTERTECHNE, 2022).

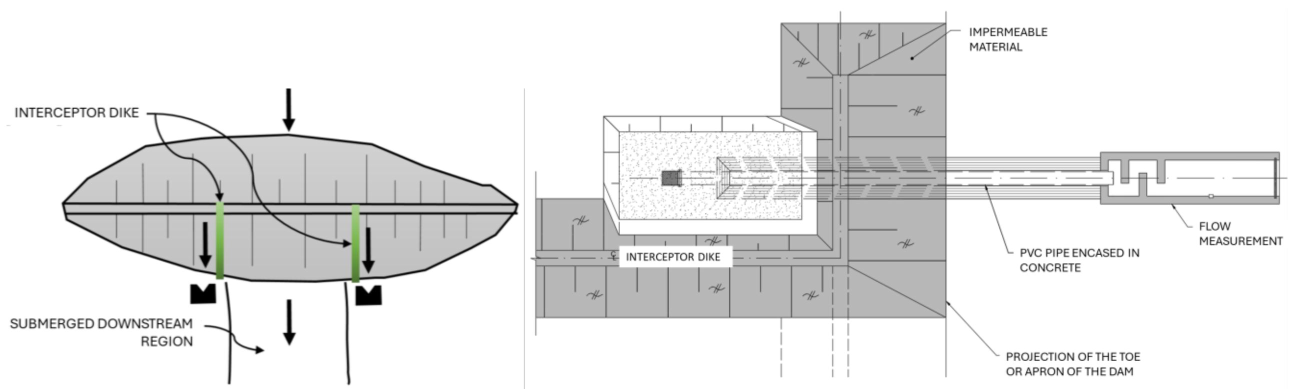


Figure 16 – Location of Flow Meters Limited to the Downstream Flooded Area.
Source: Adapted from Silveira (2006).

According to the section representation in FIGURE 17, depending on the slope of the abutments, it is possible to construct the interceptor device by aligning it with the compacted fill layer along the abutment, cutting through the drainage blanket at the defined elevation for water collection to the flow meter. At the chosen elevation for the sealing, the compacted fill layer is interrupted, leaving a gap of approximately 1 m in thickness without the drainage blanket (INTERTECHNE, 2022).

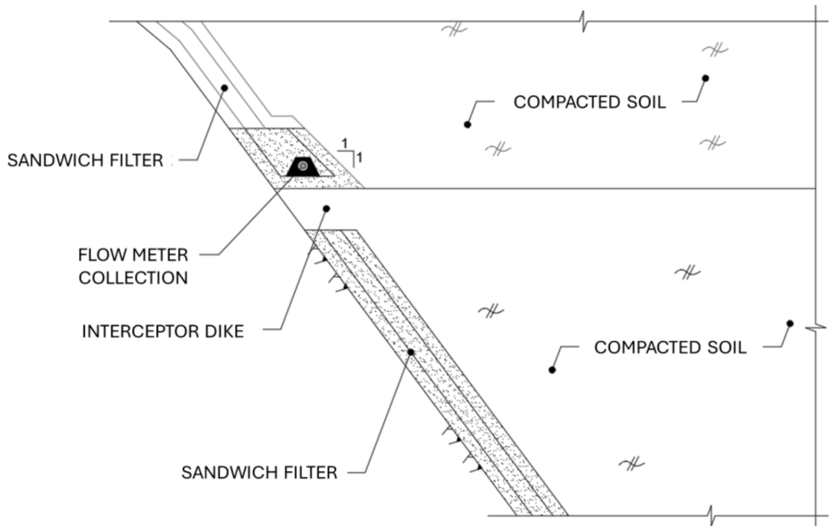


Figure 17 – Detail of the Interceptor Seal in Abutments.
Source: Adapted from Intertechne (2022).

To prevent damage to the rigid PVC or steel piping, a concrete encasement can be implemented, similar to the example shown in FIGURE 18. The length of this encasement should extend from the collection basin to the inlet of the stilling box of the flow meter (INTERTECHNE, 2022).

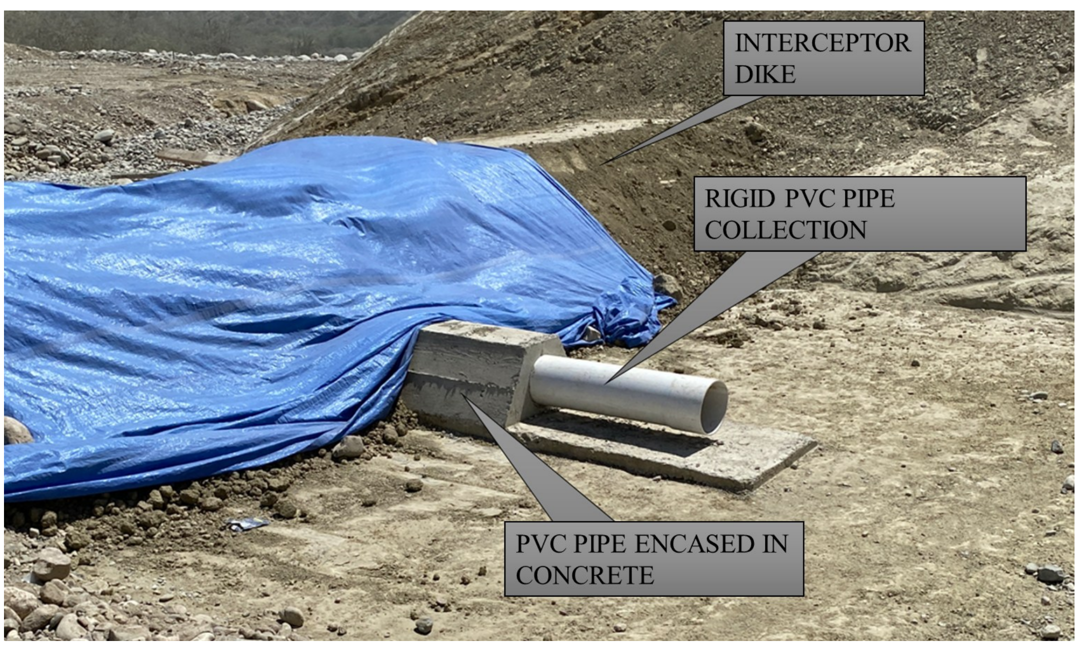


Figure 18 – Piping in the Collection Area.
Source: Adapted from Intertechne (2022).

2.4 Behavior Analysis

The analysis of dam behavior involves measuring the infiltration volume passing through the structure, generating surface and subsurface flow downstream of the dam. Establishing an effective long-term forecast of dam behavior typically requires an analytical study of a significant and measurable amount of data collected over time. This includes compiling records of readings taken within the periodically defined by the project's instrumentation plan. The interpretation of these data can be performed using statistical and/or probabilistic methods (MAXWELL, 2022).

The total volume of water emerging from the ground and discharged into a drainage system can be measured directly. Meanwhile, water appearing on the ground surface downstream of the dam can be measured using flow meters (US ARMY CORPS OF ENGINEERS, 2004).

For the analysis and monitoring of flow rates, it is common to develop graphs relating to discharge versus time, based on historical measurements taken during reservoir filling and the initial operational phase, following the periodicity established in the project. Reservoir level variations play a significant role, as they can influence the flow rates observed in the installed flow meters (SILVEIRA, 2006).

Flow meters are directly affected by rainfall during wet periods. This information can be incorporated into discharge versus time graphs to correlate with periodically measured data (SILVEIRA, 2006).

Table 3 – Occurrences and Flow Behavior.

Structure	Occurrence
Atibainha Dam	(Oliveira et al., 1976) presented the variation of drainage flows and the reservoir level of the Atibainha Dam over time. At the end of the reservoir filling process, the total discharge reached 1,050 l/min. Considering the dam length as the contribution area, this resulted in a specific flow rate of 2.4 l/min/m.
Left Bank Dam - Água Vermelha	Two months after the filling of the left bank earth dam at Água Vermelha, the total discharge exceeded the estimated control value from the design phase, which was 2,300 l/min—this being the highest recorded flow during this period. On the left abutment, it was determined that the permeability of the agglomerate lava layer was 10^{-1} cm/s (SILVEIRA, 2006). A drainage outlet was installed around stake 191 + 00, where a "flow meter" device was placed. This device was used not only for flow readings from the drainage outlet but also for water sampling from both the reservoir and the drain. These samples were collected during the reservoir filling process to determine the concentration of suspended and dissolved solids (SILVEIRA, 2014).
Santa Clara HPP Dike	The loading chamber dike of the Santa Clara Hydropower Plant (HPP), despite being a rockfill dam with a concrete face, underwent flow monitoring during the filling of its own reservoir chamber. The effluent from a drainage trench installed in the structure was monitored using triangular flow meters (INTERTECHNE, 2006). This concern arose due to the fact that the substation yard is located at a lower elevation than the dike, posing a risk of seepage through the slope separating the two structures. Monitoring was conducted for eight months following reservoir filling, and the historical flow records demonstrated satisfactory dike behavior. The highest recorded flow rates reached 11 l/s at EL. 805.50. However, during the first drawdown of the chamber reservoir level to EL. 798.00, the recorded discharge was null (INTERTECHNE, 2006).

Source: Adapted from Barreto (2023).

In figure 19, a photograph of the loading chamber dike is shown, while FIGURE 20 illustrates the behavior of the flow meter installed for monitoring.

Figure 19 – Loading Chamber Dike of UHE Santa Clara.
Source: Intertechne (2006).

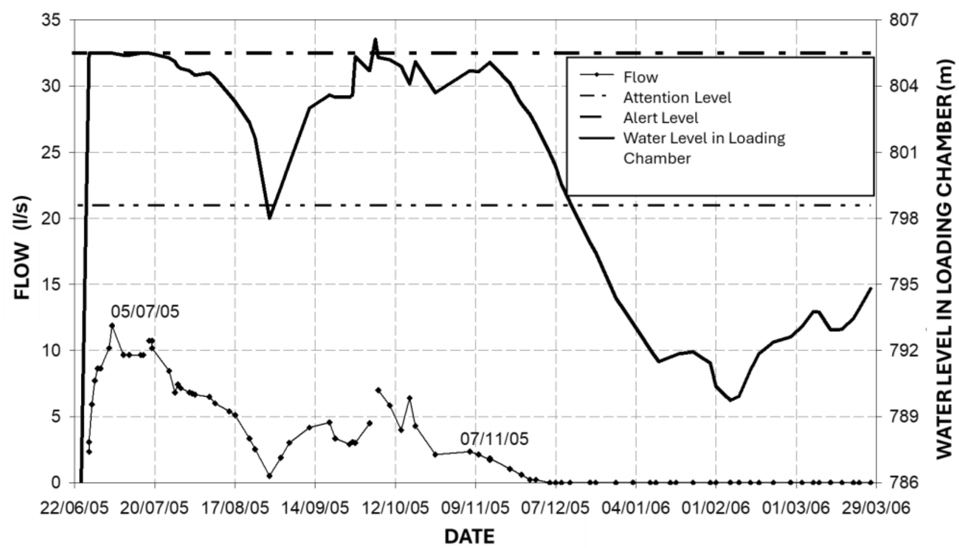


Figure 20 – Flow Meter of the Loading Chamber Dike at UHE Santa Clara.
Source: Intertechne (2006).

2.5 Sudden Increases in Flow

To identify sudden increases in flow, it is essential to define the reading frequency of a dam's monitoring program. The current recommendation is that, during reservoir filling, measurements should be taken daily, transitioning to a weekly frequency once the dam is in operation. In some cases, the reading periodicity has been changed to biweekly due to contractual labor constraints. However, the history of dam anomalies suggests that this biweekly interval may not be adequate.

Examples of this include the Pampulha Dam in Brazil and the Teton Dam in the United States, where failure events were caused by internal erosion. If flow readings had been taken at shorter time intervals, the sudden increase in water discharge could have been identified in time (SILVEIRA, 2006).

By comparing dam failures caused by internal erosion at the Teton Dam and, on a larger scale, at the Fontenelle Dam, it is evident that initial discharges of 300 to 400 l/s were sufficient to erode the downstream zones composed of sandy gravel. These events highlight the importance of parameters such as particle size distribution of fine-grained materials and low permeability, which are critical for the behavior of these structures (FELL, 2005).

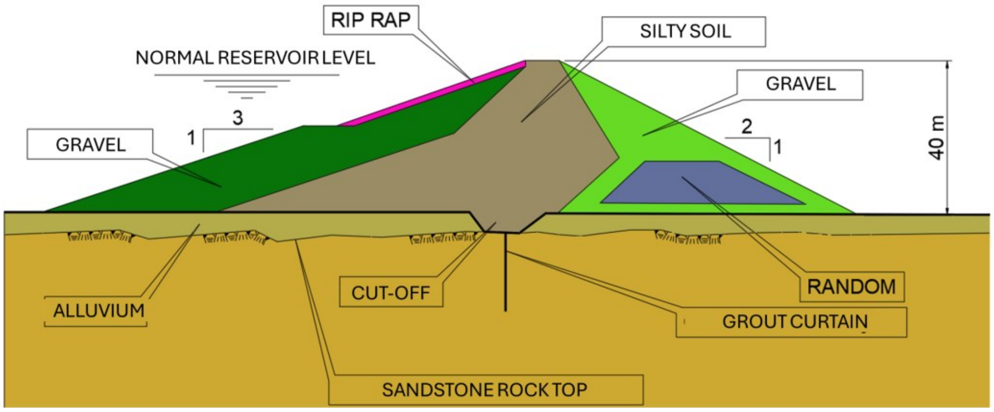


Figure 21 – Fontenelle Dam Section.
Source: Adapted from Fell (2005).

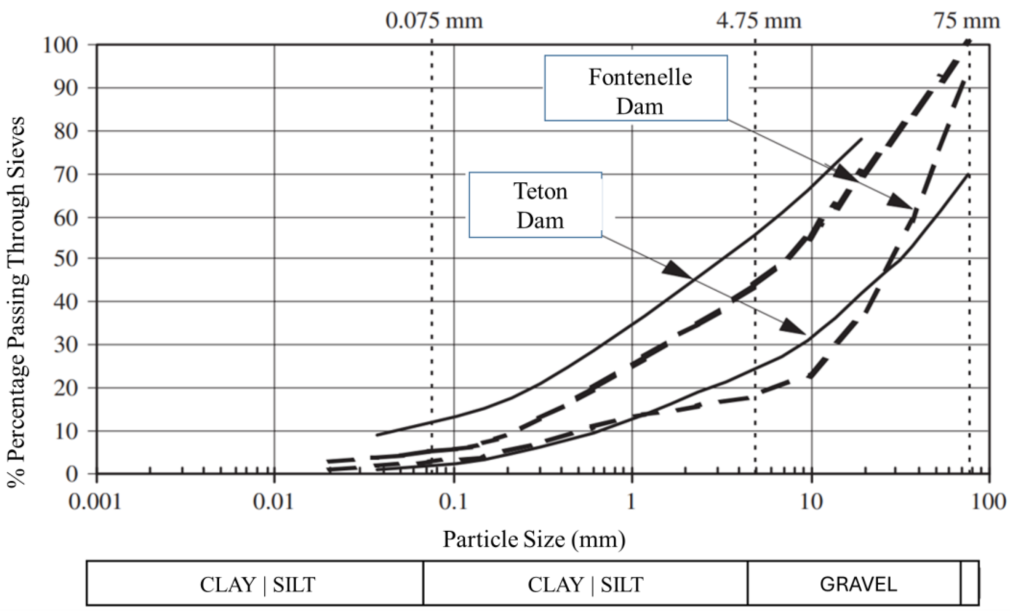


Figure 22 – Downstream Materials of Teton and Fontenelle Dams.
Source: Adapted from Fell (2005).

A management model that allows for more frequent reading intervals is the automation of the monitoring system within the project. This approach can detect anomalies that might not be identified in weekly or biweekly measurements. An example of this is the Songa Dam in Norway, where three sudden flow increases were recorded between 1976 and 1991. The dam settlement remained within normal limits, approximately 0.6% of the dam height. Between 1964 and 1991, variations in flow rates were observed, as shown in the table below. Notably, there were significant increases in flow; however, when evaluated in terms of specific discharge conditions, the maximum recorded flow rates reached 0.3 l/min/m, which is considered an acceptable value (SILVEIRA, 2006).

Table 4 – Sudden Flow Increase at Songa Dam.

Dam	Observation Period	Contribution Region	Initial Measured Flow (l/min)	Final Measured Flow (l/min)
Songa Dam, Norway	1964 to 1991	Right Abutment	30	60
	1964 to 1991	Central Section	180	240
	1964 to 1991	Left Abutment	42	60
	6,3 hours only	Sudden increase on 08/11/1994	75	6420

Source: Adapted from Silveira (2006).

What analytically allowed the observation and recording of this sudden flow increase within a short interval of only 6.3 hours was the automation system of the instrumentation implemented in the project (SILVEIRA, 2006).

2.6 Reservoir Variation

It is also possible to analyze flow data by comparing it with reservoir level fluctuations, as this represents another approach to monitoring drainage flows through a dam. This can be achieved using flow versus reservoir water level graphs. The advantage of this graphical analysis method is that it helps identify anomalous seepage events through the dam body, as sudden variations directly impact the readings.

With an accumulation of measurements, behavioral trends can be observed more clearly by correlating downstream flows with reservoir level variations. The causes of gradual increases in flow need to be identified and investigated, while corrective measures must be urgently implemented if a sudden and abrupt increase in flow continues (SILVEIRA, 2006).

Reservoir level variations are generally minimal since dams are designed to maintain a constant normal maximum water level. However, careful investigation of the behavioral trend of these variations is necessary (DRIP, 2018). The following figure illustrates a projection of behavior that may be considered anomalous, showing an abrupt elevation increase outside a normal trend pattern.

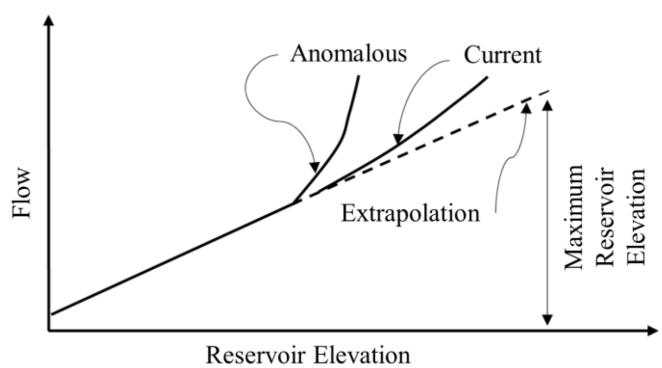


Figure 23 – Flow versus Reservoir Level.
Source: Adapted from DRIP (2018).

Figure 24 (Left) illustrates a behavioral analysis considering the correlation between flow versus time as the reservoir water level increases. Figure 24 (Right) illustrates a behavioral analysis considering the correlation between flow versus time when the reservoir water level remains constant, which is more common during the operation of the project. These are more appropriate methods that demonstrate the correct trend in the correlation between flow and reservoir level, making them useful for interpretation (DRIP, 2018).

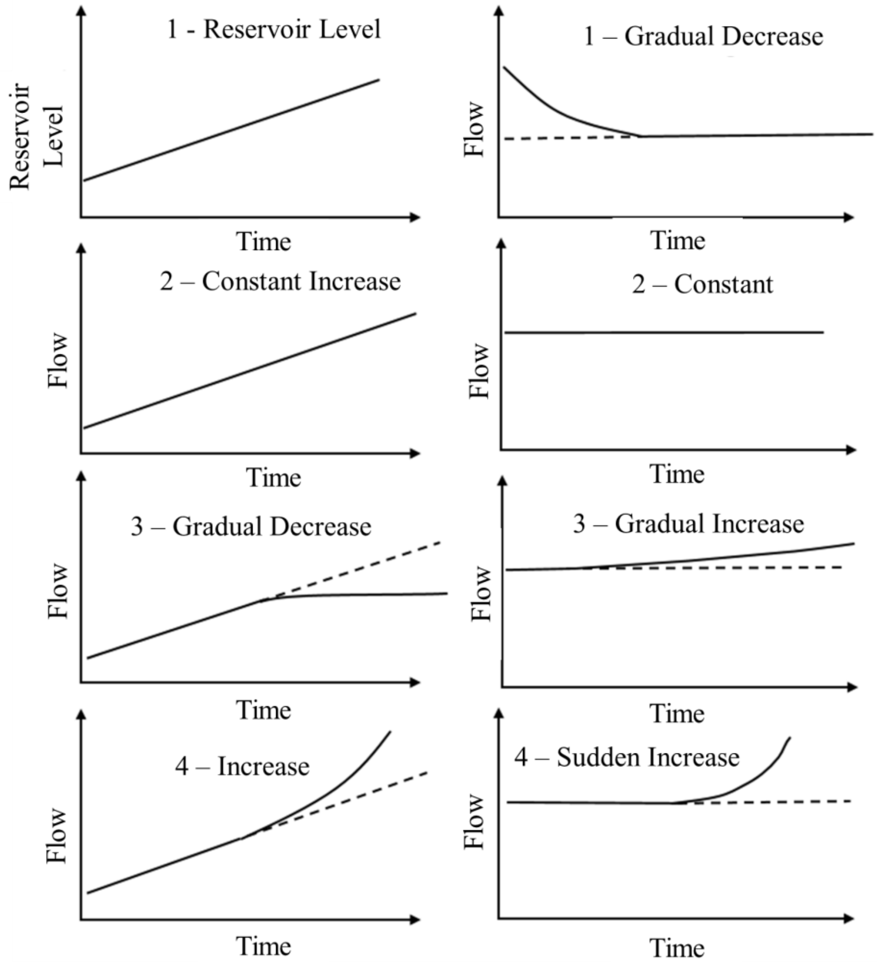


Figure 24 – Flow vs. Time (Reservoir).
Source: Adapted from DRIP (2018).

3. Final considerations

The use of triangular weir flow meters is of great importance for accurately monitoring discharge in dams, ensuring reliable results and contributing to the safety of these structures. Proper instrumentation in dams, including flow meters, level sensors, and piezometers, is fundamental for effective structural monitoring. A detailed analysis of soil permeability and embankment drainage, combined with the use of appropriate monitoring devices, is essential to ensure dam safety and longevity by properly controlling water infiltration and drainage within the embankments.

The ability of soil to allow water flow is directly related to its grain size distribution, as more porous soils tend to be more permeable. Water infiltration in dams can lead to issues such as particle displacement and leaching, making effective drainage systems crucial.

Empirical criteria have been developed over time for designing dam drainage and filtration systems, which are fundamental for ensuring structural safety and stability by properly managing water infiltration and drainage within embankments. The correct application of these criteria and models contributes to the safety and efficiency of dams, positively impacting socio-economic and environmental development.

The proper installation and maintenance of flow meters are essential to ensure accurate measurements, contributing to dam safety and efficiency, as well as to the effective management of water resources. The automation of monitoring systems emerges as a key tool for the early detection of sudden flow increases, significantly enhancing dam safety.

Analyzing reservoir level variations in relation to drainage flows is essential for monitoring dam integrity, allowing for prompt and effective actions to ensure structural safety. Flow meters play a crucial role in monitoring seepage through the foundation and internal drainage system of the dam, providing valuable references for interpreting structural behavior.

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