



La importancia de evaluar la permeabilidad del suelo mediante redes de flujo en la instrumentación de una presa de relaves

The importance of evaluating soil permeability using flow nets in the instrumentation of a tailings dam

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INFORMACIÓN

Palabras clave:

- *Caracterización*
- *Jales*
- *Permeabilidad*
- *Red de flujo*
- *Instrumentación*

Key words:

- *Characterization*
- *Tailings*
- *Permeability*
- *Flow net*
- *Instrumentation*

RESUMEN

Este artículo establece un marco metodológico para la caracterización e integración del análisis de redes de flujo con la instrumentación geotécnica de campo, específicamente con piezómetros, como una herramienta fundamental para el control de infiltraciones en presas de jales. El objetivo es garantizar la estabilidad y seguridad a largo plazo de estas estructuras críticas. La metodología propuesta permite predecir el gasto de infiltración y la distribución de presiones de poro dentro del cuerpo de la presa y su cimentación, para posteriormente verificar y calibrar estas predicciones mediante mediciones directas. Las conclusiones clave demuestran que esta sinergia entre el modelo teórico y el monitoreo es indispensable para un programa de seguridad proactivo, permitiendo la detección temprana de anomalías que podrían comprometer la integridad estructural y asegurando el cumplimiento de la normativa aplicable.

ABSTRACT

This article establishes a methodological framework for the characterization and integration of flow net analysis with field geotechnical instrumentation, specifically piezometers, as a fundamental tool for controlling seepage in tailings dams. The objective is to ensure the long-term stability and safety of these critical structures. The proposed methodology allows for the prediction of seepage flow rate and the distribution of pore pressures within the dam body and its foundation, for subsequent verification and calibration of these predictions through direct measurements. The key conclusions demonstrate that this synergy between the theoretical model and monitoring is indispensable for a proactive safety program, enabling the early detection of anomalies that could compromise structural integrity and ensuring compliance with applicable regulations.

1 OBJECTIVE

To define the technical and normative requirements for determining hydraulic and mechanical parameters in tailings dams, in order to generate accurate Flow Net Models. These models will serve as the basis for the strategic placement of piezometric instrumentation, allowing for the calculation and periodic monitoring of the seepage flow rate (Q) to ensure the physical and environmental stability of the structure.

2 INTRODUCTION

Seepage control is critically important for the safety of any tailings dam. Uncontrolled water flow through the embankment body and its foundation can generate excessive pore pressures, reduce the shear strength of the materials and, ultimately, provoke instability. Phenomena such as piping (progressive internal erosion), siphoning, and slope failures are directly linked to deficient seepage management (Marsal y Reséndiz, 1979). The analysis and control of seepage is, therefore, one of the central tasks in the design and supervision of these structures (USACE, 1993).

This technical document addresses the problem from a comprehensive geotechnical engineering perspective, articulating the geological characterization of the site, the determination of material properties through field and laboratory tests, and the application of flow principles in porous media. The ultimate goal is to provide a robust methodology that allows for the design of effective monitoring systems to ensure the structural safety of the dam and compliance with environmental regulations, such as the Mexican Official Standard NOM-141-SEMARNAT-2003, which establishes the requirements for the project, construction and operation of tailings dams.

The basis of any geotechnical analysis and, therefore, of any flow model, resides in a clear and detailed understanding of the geological environment

3 GEOLOGICAL MODEL

The conceptual geological model is the first step in defining the boundary conditions of the flow net. The development of a detailed geological-geotechnical model is the indispensable foundation for any seepage analysis. This model conceptualizes the spatial distribution of the different subsurface materials and their structures, allowing for an understanding of potential water flow paths and identifying zones of higher permeability or weakness that require rigorous monitoring. Without a robust geological model, the selection of locations for instrumentation would be arbitrary and its effectiveness, questionable

3.1 Lithology

Three main lithological units must be clearly differentiated in the reservoir and embankment.

- Foundation: Bedrock or alluvial soils that determine losses through the subsoil.
- Coarse Tailings (Beach): Silty sands (SM) deposited near the crest, with higher permeability. Marsal & Reséndiz (1979).
- Fine Tailings (Pond/Slimes): Silts and clays (ML-CL) in the center of the reservoir, acting as a low-permeability barrier but with high compressibility.

3.2 Structural Geology

The presence of faults, fractures, or discontinuities in the bedrock foundation can govern regional flow. It is imperative to identify discontinuity sets that can hydraulically connect the reservoir to the exterior, bypassing drainage systems. González V. L. (2002).

4 FIELD WORK

Field investigations constitute the process by which the geological model is validated, representative samples of subsurface materials are obtained, and data on their properties are collected. This stage is essential for reducing the uncertainty inherent in geotechnical design and for providing the necessary parameters for stability and seepage analyses (Marsal y Reséndiz 1979; USACE, 1993.).

The exploration campaign must comply with CFE B.2.3 (1969), regulations. Standard Penetration Tests (SPT) are required in the embankments and beach tailings to evaluate relative density, and cored drilling in the foundation to determine RQD and perform permeability tests (Lugeon or Lefranc).

The samples obtained and data collected during field investigations are subsequently analyzed in detail in the laboratory.

5 LABORATORY WORK

Precise characterization of materials is vital for feeding the numerical or graphical flow net model. Laboratory tests aim to quantify the physical, mechanical, and dynamic properties of the soil and rock samples recovered in the field. These parameters are the direct inputs for the construction of the geotechnical model and for the execution of slope stability and water flow analyses.

5.1 Index Properties

Classification of materials according to the Unified Soil Classification System USCS. Tailings show granulometric segregation that varies with the distance from the discharge point, table 1.

Table 1. Typical Index Properties Results in Tailings Dams.

Material	USCS Classification	Dry Unit Weight γ_d kN/m ³	Specific Gravity G _s	Fines Content %
Beach Tailings (Embankment)	SM / SP	17.5-19.0	2.7-3.5	15-35
Pond Tailings (Slimes)	ML / CL	14.0-16.0	2.7-3.0	70-95
Borrow Material (Core)	CL / SC	18.0-20.5	2.6-2.7	40-60

5.2 Mechanical Properties

Shear strength parameters necessary to verify stability under the established flow conditions (table 2). Source typical values referenced. (Marsal & Reséndiz 1979).

Table 2. Typical Shear Strength Parameters (Drained Condition).

Geotechnical unit	Effective cohesion c' kPa	Effective friction angle ϕ' °	Failure criterion
Beach Tailings (Compacted)	0 - 5	32 - 38	Mohr-Coulomb
Pond Tailings (Normally Consolidated)	0	24 - 30	Mohr-Coulomb
Rock Foundation	N/A	40 - 55 (Joints)	Barton-Bandis / Hoek-Brown

5.3 Dynamic Properties

Given the susceptibility of loose and saturated tailings to seismic liquefaction (table 3), dynamic moduli must be evaluated. CFE Diseño por Sismo Manual (1969).

Table 3. Dynamic Properties (Typical Range).

Material	Shear Wave Velocity, V_s m/s	Maximum Shear Modulus, G_{max} MPa	Damping Ratio D %
Tailings (Vadose Zone)	180 - 250	60 - 120	2 - 5
Tailings (Deep saturated)	220 - 350	90 - 200	1 - 3

6 ROCK MASS CLASSIFICATION

For the foundation, secondary permeability due to fracturing is critical.

6.1 Definition of Geotechnical Units

The RMR, (Bieniawski, 1989) or Q system (Barton, 2002), is used to zone the foundation.

- UG-1. Sound rock, RQD > 75%, $K < 10^{-7}$ m/s.
- UG-2. Fractured/weathered rock, RQD < 50%, $K > 10^{-6}$ m/s (Grout curtain required).

7 HYDRAULIC PROPERTIES: THE CORE OF SEEPAGE ANALYSIS

Permeability (K) is the fundamental variable for Darcy's Law (v). Anisotropy ($K_h > K_v$) is common in tailings due to horizontal stratification during deposition, see the following equations. (Juárez V. E., Rico R. A. 1974, US Army Corps of Engineers 1993).

$$v = Ki \tag{1}$$

$$K_v = \sum_{i=1}^n \left(\frac{L_i}{K_i} \right) \tag{2}$$

$$K_h = \sum_{i=1}^n \left(\frac{K_i L_i}{L_i} \right) \tag{3}$$

$$K = \sqrt{k_h \cdot k_v} \tag{4}$$

where: v = fluid velocity; K = equivalent permeability; hydraulic gradient (i); K_h = horizontal permeability; and K_v = vertical permeability.

Safety Criterion, the exit hydraulic gradient (i_s) must be less than the critical gradient (i_c) to prevent piping. CFE B.2.3 (1969), see eq. 5.

$$FS = \frac{i_c}{i_s} \geq 3 \tag{5}$$

7.1 Permeabilities

Values must be obtained from tests and calibrated in the laboratory (table 4). (Marsal 1979a, b, Reséndiz & CFE B.2.3 Estructuras de Tierra 1969).

Table 4. Design Permeability Coefficients.

Stratum / Zone	Vertical Permeability K_v , m/s	Horizontal Permeability K_h , m/s	Anisotropy Ratio K_h-K_v	Lugeon Units
Pond Tailings	1.0×10^{-8}	5.0×10^{-8}	5 - 10	< 1
Beach Tailings	5.0×10^{-6}	1.0×10^{-5}	2 - 5	5 - 10
Filters / Drains	1.0×10^{-3}	1.0×10^{-3}	1	N/A
Foundation (Untreated)	1.0×10^{-6}	1.0×10^{-6}	Variable	10 - 20

Regarding the permeability range in an anisotropic medium (K_h-K_v) indicated in table 4, the following histogram is presented in figure 1.

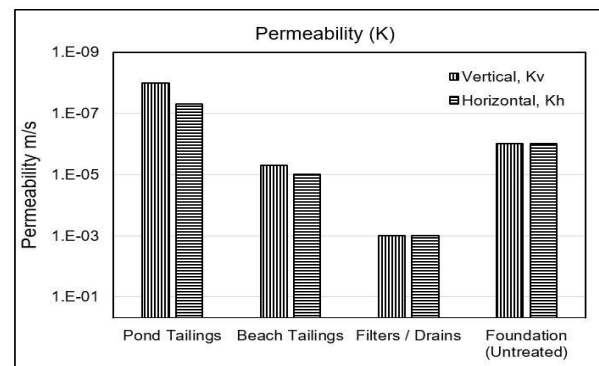


Figure 1. Histogram of permeability of graded materials (fine tailings, coarse tailings, and drains).

7.2 Water Levels and Boundary Data

To generate the flow net, the following are required:

- Upstream Water Level (UWL), Current elevation of the water surface in the reservoir.
- Downstream Water Level (DWL), Generally the elevation of the dam toe or the regional phreatic level.
- Boundary Conditions, Dam-foundation contact and location of chimney or finger drains.

8 DETERMINATION OF THE FLOW NET

A flow net is a graphical or numerical solution of Laplace's equation, which describes the steady-state flow of water through a porous medium that can behave homogeneously (isotropic) or heterogeneously (anisotropic). The net consists of two families of curves that intersect orthogonally: flow lines and equipotential lines.

Flow lines represent the trajectory that water particles would follow as they move through the porous medium, from the upstream boundary to the downstream boundary.

Equipotential lines are curves that connect all points having the same total hydraulic head (sum of pressure head and elevation head).

The seepage flow rate through the dam section can be calculated directly from the flow net (equation 2), In equation 6 considers the possibility of anisotropic permeability. (Juárez V. E., Rico R. A. 1974; US Army Corps of Engineers 1993; Chable J. 2025).

$$Q = K \cdot H \frac{N_f}{N_d} \quad (6)$$

where: H = total hydraulic head, N_f = Number of flow channels, N_d = number of equipotential drops.

9 APPLICATION OF THE FLOW NET IN INSTRUMENTATION

The flow net guides the optimal location of piezometers for continuous seepage monitoring. The following describes the analysis of the flow net for four typical sections and its application in instrumentation.

9.1 Flow Net Analysis

The flow net analysis not only allows for the calculation of total seepage discharge, but, crucially, it predicts the distribution of pore pressure (or piezometric head) at any point within the dam embankment and its foundation. This knowledge serves as the basis for a rational and effective dam instrumentation and safety program. For this reason, four typical sections were

analyzed using the flow net method: two downstream and two upstream.

- Conventional (downstream)
- Chimney-Blanket (downstream)
- Spigot type (upstream)
- Cycloned Sand (upstream)

The flow net analysis (figures 1 to 4) was performed according to the average permeability parameters indicated in table 4, considering a maximum hydraulic head column at the NAMO (Maximum Operating Water Level). (NOM-141-SEMARNAT 2003; US Army Corps of Engineers, 1993; Chable J. 2025).

9.2 Conventional downstream section

The Conventional Downstream design (Graded or Zoned Section) is a safety standard, as it adheres to the principles of earth and rockfill dams. It utilizes selected borrow materials (core, filters, shell/embankment fill) to construct a stable and wide embankment, with the tailings subsequently deposited against the upstream face or used as fill material within a pre-established zone. This section exhibits an average seepage discharge of $1.5 \times 10^{-4} \text{ m}^3/\text{s}$, which is a moderate flow, considering a maximum hydraulic head column at the NAMO level, shown in the following figure.

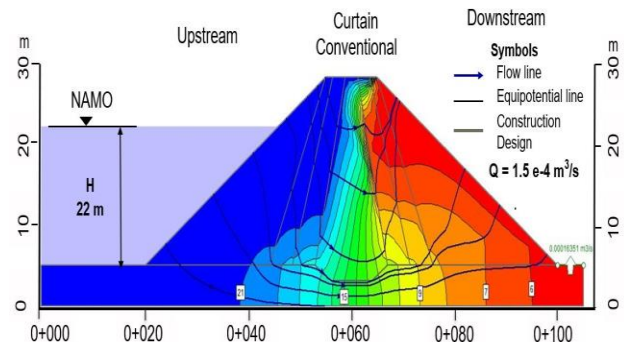


Figure 2. Flow net of the Conventional downstream section.

9.3 Chimney-Blanket downstream section

This specific Downstream design is the most robust because, based on the flow net analysis, the phreatic line is maintained at a low level thanks to a high-capacity internal drainage system (chimney and blanket drains). Furthermore, these drains make it possible to optimally collect and channel the water for reuse in the mining processes. This section exhibits an average seepage discharge of $3.4 \times 10^{-4} \text{ m}^3/\text{s}$, which is considered an optimal flow rate given that the water will be conveyed (or channeled), see figure 3.

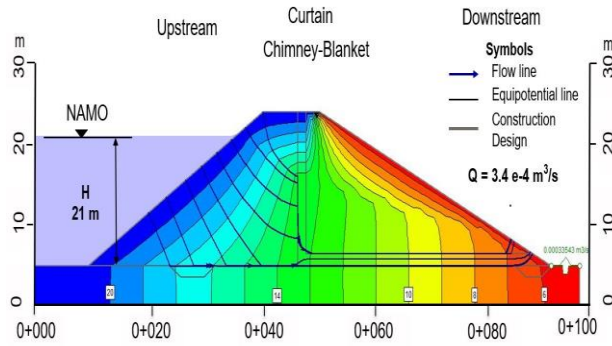


Figure 3. Flow net of the Chimney-Blanket downstream section.

9.4 Spigot Design upstream section

This type of design presents a particular challenge in terms of seepage control because the embankment rests on fine, saturated tailings. The Upstream design generates significant heterogeneity: the coarse material is deposited near the discharge point (the beach), and the fine material accumulates beneath the pond. The Upstream design is highly sensitive to hydraulic control. If the basal drainage is not efficient, the phreatic line can rise through the beach tailings, compromising stability and potentially leading to collapse due to shear failure or liquefaction. The average seepage discharge for this design is $4 \times 10^{-4} \text{ m}^3/\text{s}$ which is considered an optimal flow rate given that it is located upstream of the Relaves Dam, see figure 4.

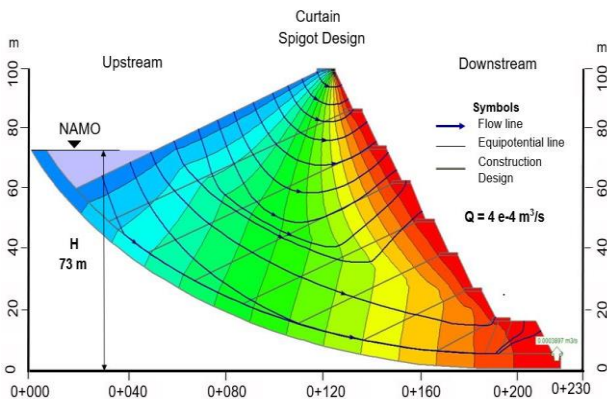


Figure 4. Flow net of the Spigot Design upstream section.

9.5 Cycloned Sand Design upstream section

The key to this design is the control of the beach slope formed by the cycloned sand, which is generally steeper than the beach formed by spigot discharge. Although the cycloned sand buttress has better permeability and bearing capacity than the deposited tailings, the design remains an Upstream type. This

means that each new embankment rests on the fine, saturated tailings of the previous pond, necessitating constant piezometric monitoring to ensure that the pore pressure does not exceed the critical stability limits. According to the section analysis, the flow lines converge in the central, downstream part of the section. Given that this is a Tailings Dam, this condition can be analyzed and used favorably with constant piezometer monitoring to channel the water flow in that zone. The average seepage discharge for this type of section is $3.3 \times 10^{-4} \text{ m}^3/\text{s}$, which is also considered an optimal flow rate, taking into account the critical conditions and the fact that it is an upstream configuration, see figure 5.

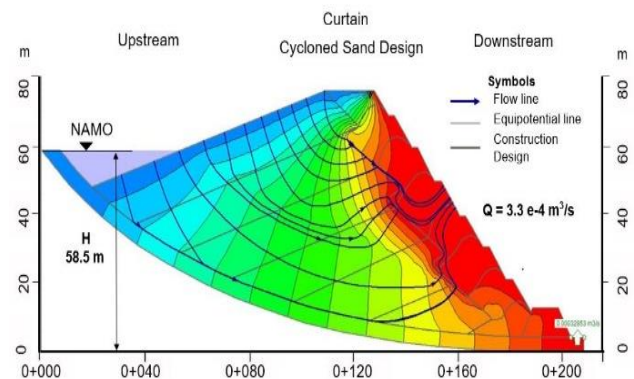


Figure 5. Flow net of the Cycloned Sand Design upstream section.

According to the results obtained in the flow net analysis, the maximum infiltration rates for each design are described below, table 5.

Table 5. Maximum infiltration rate (Q) for each curtain design, according to the flow net criteria.

Curtain Design	Curtain Direction	Maximum Head Height, H (NAMO) m	Maximum rate, Q m³/s
Conventional	Downstream	22	1.5×10^{-4}
Chimney-Blanket	Downstream	21	3.4×10^{-4}
Spigot	Upstream	73	4.0×10^{-4}
Cycloned Sand	Upstream	58.5	3.3×10^{-4}

9.6 Periodic Control Methodology

In summary, the following control should be implemented, see table 6.

- Read piezometric levels monthly.
- Adjust the Flow Net (Back-analysis) if observed levels differ from theoretical ones.
- Recalculate the expected Flow Rate (Q) with the new calibrated net.

- Compare Q calculated vs Q measured. A divergence implies possible undetected leaks or drain clogging. (CFE B.2.5 Instrumentación en Suelos, 1969).

Table 6. Flow Net-Based Piezometric Instrumentation Plan.

Location in the Flow Net	Recommended Instrument Type	Monitoring Objective
High equipotential lines (Core/Fine Tailings)	Vibrating Wire Piezometer	Verify waterproofing efficiency and pore pressure during construction.
Gradient change zone (Dam Toe)	Open Piezometer (Casagrande) or Pneumatic	Monitor the actual phreatic level vs. theoretical.
Flow Outlet (Drains)	Flow Meter (Thomson/Cipolletti Weir)	Measure actual Q and compare with calculated Q.

10 CONCLUSIONS AND RECOMMENDATIONS

Model Validation. The flow net is not static; it must be updated with the evolution of the dam (embankment raises) and instrumentation data. (AIMMGM 1993).

Hydraulic Safety. Flow rate control through the comparison of Theoretical Model vs. Piezometric Measurement is the best defense against failure due to internal erosion.

Regulatory framework. Strict compliance is required with the safety factors against piping. (CFE Manuals 1969 & CNA Manual 1999).

Operational Recommendation: Install settlement cells alongside piezometers to correlate deformation with changes in permeability and pore pressure.

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