Proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE), and 2nd Latin-American Regional Conference of the International Association for Engineering Geology and the Environment (IAEG), La Serena Chile, 2024.

Technical and economic feasibility assessments of HDPE geomembranes on a hydroelectric generating plant intake channel

Análises de viabilidade técnica e econômica de geomembranas de PEAD em um canal de adução de uma usina hidroelétrica

Felipe Santos, Gregório Araujo & Márcio Farias
PPGG, Universidade de Brasília, Brasil, 231110694@aluno.unb.br

Carlos Larrosa
Diretor, L&S Consultores, Brasil

ABSTRACT: It is common to use and design high-density polyethylene (HDPE) geomembranes for hydraulic channels on Hydroelectric Power Plants (HPPs), as their use brings benefits such as reducing losses from infiltration and roughness. The objective of this article is to present technical and economically feasible assessments of HDPE geomembranes application on the intake channel of Bonfim HPP, located in Perolândia, state of Goiás, Brazil. Permeability data from in-situ and laboratory tests were used to compute hydraulic head loss and water loss through infiltration. The channel was partitioned into segments with a maximum spacing of 20 meters between each segment, and successive approximations were employed to compute losses for every individual segment. The economic and energy analysis has determined that the estimated investment to install the geomembrane would have an investment payback time of approximately 60 years, exceeding the plant's return time of 12 years. Nevertheless, upon evaluating an extended temporal horizon, the geomembrane is a feasible alternative.

RESUMO: É comum o uso de geomembranas de polietileno alta densidade (PEAD) para canais de centrais geradoras hidroelétricas (CGH), uma vez que seu uso traz benefícios como a redução de perdas por infiltração e rugosidade. O objetivo deste artigo é apresentar um estudo de viabilidade técnico-econômico da aplicação de geomembrana de PEAD no canal de adução da CGH Bonfim, localizada em Perolândia, estado de Goiás, Brasil. Nas análises, dados de ensaios de permeabilidade in situ e de laboratório foram utilizados para a estimativa de perda de carga hidráulica e perda de água por infiltração. O canal foi discretizado em segmentos com espaçamento máximo de 20 metros, e aproximações sucessivas foram utilizadas para computar as perdas separadamente. O estudo econômico-energético concluiu que o investimento estimado para a instalação da geomembrana para o caso estudado teria um o tempo de *payback* de aproximadamente de 60 anos, o que excede tanto a vida útil da usina de 50 anos quanto o período de *payback* calculado no projeto básico de 12 anos. No entanto, a longo prazo a geomebrana apresenta-se como uma alternativa viável.

KEYWORDS: geomembrane, HDPE, intake channel, hydroelectric power plant, feasibility study.

1 INTRODUCTION

Since antiquity, canals have served diverse purposes including energy production, water supply, irrigation, flood control, and recreational activities (Vorlet & De Cesare, 2023). The intended function of a canal dictates its specific characteristics, including its geometry, construction methodology, and foundation conditions.

In contrast to irrigation or drainage systems, where water infiltration into the soil is often beneficial, canals designated for human consumption or energy generation must minimize such water loss.

Furthermore, it is crucial to consider the energy dissipation of water due to the roughness of canal walls during conveyance. Specifically, only for hydroelectric generation purposes it is imperative to conserve this energy to mitigate potential long-term financial losses.

In this regard, the utilization of high-density polyethylene (HDPE) geomembranes for lining the intake channels of Hydroelectric Power Plants (HPP) has become common practice due to their ability to reduce water losses through percolation and mitigate load losses resulting from roughness. The Eletrobrás Inventory Manual (MME, 2007) advocates for the adoption of HDPE geomembranes for ground channels. Obidzhonov and Babaev (2023) assert that lining canals with geomembranes not only diminishes water loss but also enhances water quality, irrigation efficiency, and overall project longevity.

The objective of this article is to present a technical and economic feasibility analysis regarding the implementation of HDPE geomembranes in the intake channel of Bonfim HPP, situated in Perolândia, Goiás, Brazil.

2 PROBLEM DESCRIPTION

The layout information of the intake channel of Bonfim HPP was sourced from its Executive Project (Terral, 2022). Illustrated in Figure 1, the adduction channel of Bonfim HPP has undergone earthmoving and rock excavation phases, precluding the possibility of altering its geometric parameters.

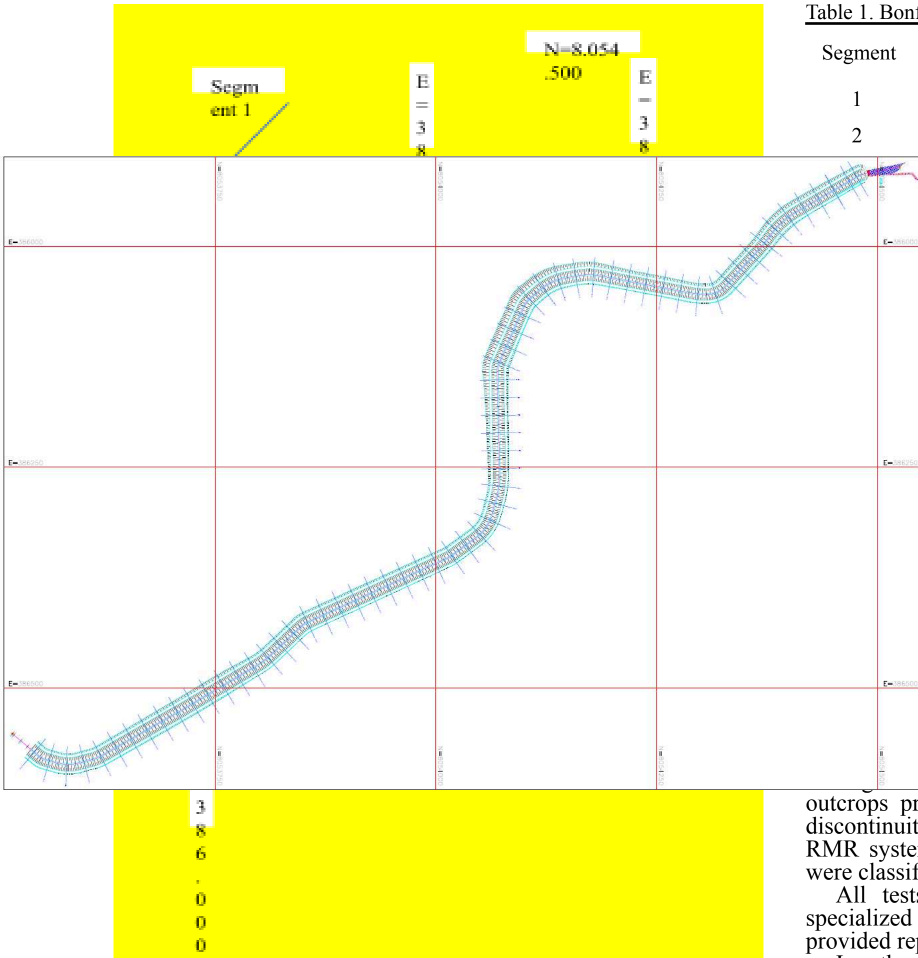

Figure 1. Bonfim HPP intake channel layout. Coordinates: UTM; DATUM: SIRGAS 2000, 22S Fuse (Terral, 2022 - modified).

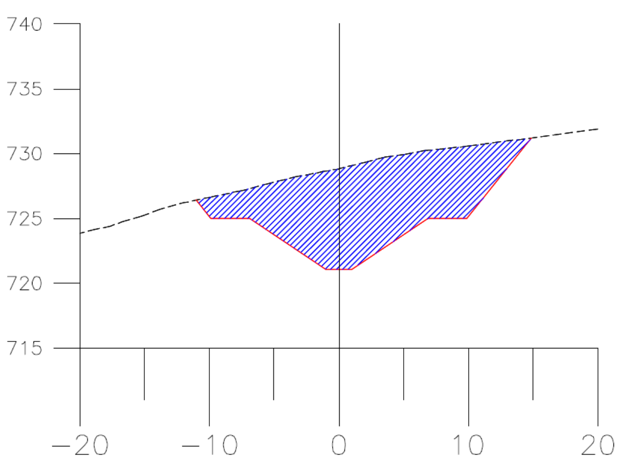

Figure 2. Bonfim HPP intake channel cross section. (Terral, 2022 - modified).

Table 1. Bonfim HPP intake channel segments

Segment	*Beginning Station*	*Ending Station*	*Length (m)*
1	2+00,5	10+00	159,5
2	10+00	20+00	200
	20+00	34+00	280
	34+00	50+00	320
	50+00	67+04,7	344,7

l constitutes a predominantly excavated geotechnical
ιigned to convey water from the reservoir normal
(WL), situated at an elevation of 724.00 m, to the
ber. As illustrated on Figure 2, the canal is
l by a typical trapezoidal cross-section with a base
m and a slope inclination of 1H:1.5V, it features
rms on both sides, located at an elevation of 725 m.
; at station 2+00.5 and extending to station 67+04.68,
; bottom elevation ranges from 721.50 m to 720.50
a total length of 1,304.2 m and exhibiting a bottom
7%.
d into five distinct segments, delineated in Table 1,
ssessment of the foundation material characteristics
ıtinuous rocky outcrops resembling massive slabs
ns 1 and 3. Conversely, sections 2, 4, and 5 comprise
oung basalt residual soil.

ND LABORATORY TESTS

field investigation, it was observed that the rocky outcrops present in sections 1 and 3 exhibited minimal visible discontinuities, a characteristic deemed excellent according to the RMR system (Bieniawski, 1973). Consequently, these segments were classified as impermeable.

All tests and sampling procedures were conducted by a specialized firm, and the ensuing results were derived from the provided report (CONTECH, 2022).

In the remaining sections, both field and laboratory assessments were conducted to ascertain the permeability of the channel walls and bottom. Table 2 delineates the specific locations where undisturbed samples were procured or in situ tests were conducted.

Table 2. Field campaign summary

Segment	*Position (Station)*	*Action*
2	12	Infiltration test
2	15	Undisturbed sample collection
4	38	Undisturbed sample collection
4	42	Infiltration test
4	45	Infiltration test
5	52	Infiltration test
5	60	Undisturbed sample collection

3.1 *Infiltration Tests*

The infiltration tests were conducted in adherence to the guidelines outlined in the ABGE Underground Survey Manual (2013). At designated locations along the excavated slope of the channel, three infiltration tests were performed: the initial test at 1/4 of the slope height, followed by tests at half the height and 3/4 of the height, respectively. Employing the infiltration method, all tests were conducted above the water table. The outcomes of these infiltration tests are graphically represented in Figures3 to 6.

Table 3 provides a summary of the results obtained from the infiltration tests.

Table 3. Infiltration tests conductivity values summary

Segment	Position (Station)	*Hole 1 (cm/s)*	*Hole 2 (cm/s)*	*Hole 3 (cm/s)*	*Average (cm/s)*
2	12	1,76E-4	5,63E-4	4,60E-5	2,62E-4
4	42	1,56E-3	1,76E-3	4,97E-3	2,76E-3
4	45	1,88E-4	2,41E-3	2,21E-3	1,60E-3
5	52	1,36E-3	1,92E-3	1,48E-3	1,59E-3

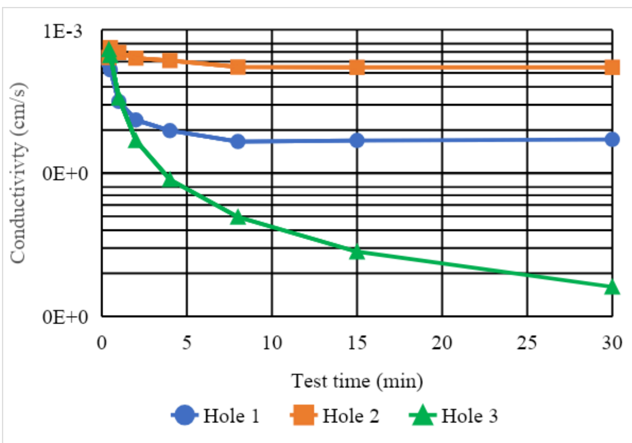

Figure 3. Infiltration tests results from Segment 2 - Station 12.

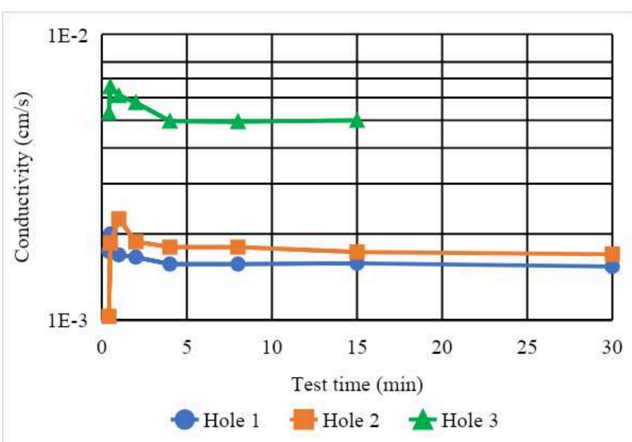

Figure 4. Infiltration tests results from Segment 4 - Station 42.

3.2 *Laboratory conductivity tests*

The acquisition of undisturbed samples utilized for the conductivity analyses was conducted within the slope region of the channel segment, consistently maintaining elevations below the normal operational WL of the channel, set at 724.00 m.

All collected samples exhibited a significant clay content, comprising either silty clays or clayey silts. Consequently, these samples underwent testing under variable loading conditions, conforming to the guidelines stipulated in the NBR 14545 – METHOD B (ABNT, 2021) standard for conductivity assessments. The results derived from these conductivity tests are depicted in Figure 7.

Table 4 provides a succinct summary of the obtained values from the conductivity tests.

Table 4. Variable loading conductivity tests results summary

Segment	Position (Station)	*Average (cm/s)*
2	15	1,44E-6
4	38	9,25E-4
5	60	6,44E-6

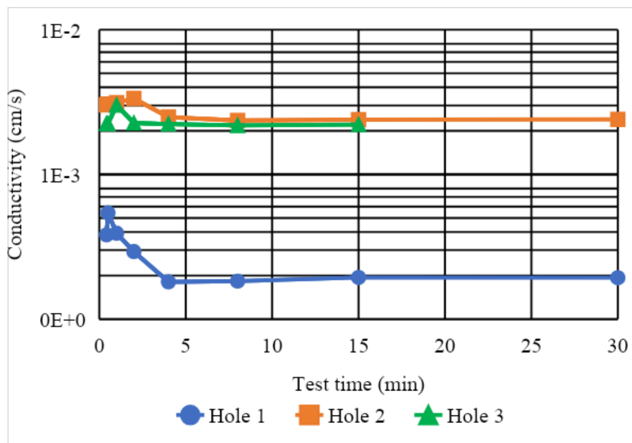

Figure 5. Infiltration tests results from Segment 4 - Station 45.

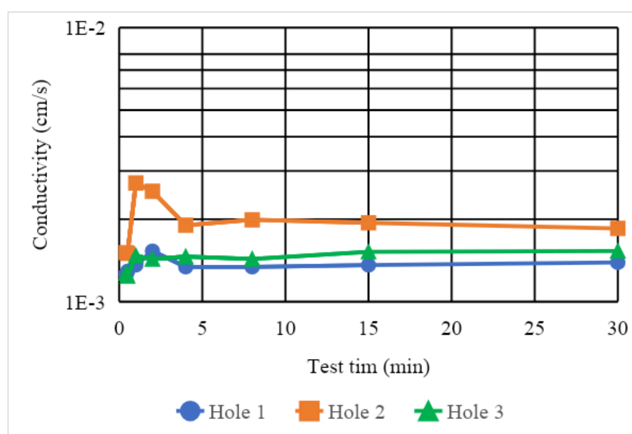

Figure 6. Infiltration tests results from Segment 5 - Station 52.

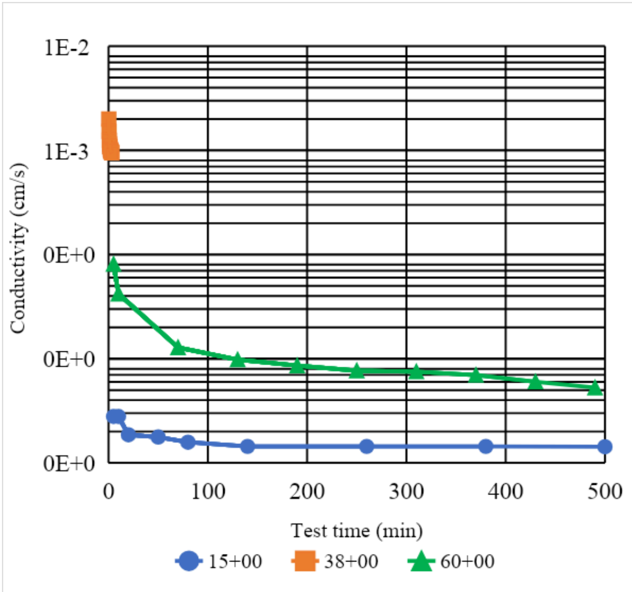

Figure 7. Conductivity tests results

3.3 *Data Analysis*

Initially, considering the three infiltration tests conducted at various elevations along the channel slope, it was observed that all positions exhibited two data points falling within the range of one standard deviation, with all points falling within the range of two standard deviations. This adherence to the empirical rule of standard deviation for normal distribution was confirmed (Portella et al., 2015). Consequently, it was concluded that the adopted averages effectively represent the permeability characteristics of their respective positions.

The conductivity values obtained were deemed high, ranging within the orders of magnitude of 10^{-4} to 10^{-3} cm/s, typical of sandy soils, despite the predominant composition of the samples being silty clays or clayey silts. This phenomenon was attributed to the excavation process itself, as the entire channel was constructed on excavated ground. It is speculated that this excavation process induced microfractures in the soil, rendering it more permeable than anticipated for a compacted sample. Additionally, the auger drilling process during testing may have contributed to such micro fracturing.

Conversely, the conductivity values derived from laboratory tests were considered low, within the orders of magnitude of 10^{-5} to 10^{-6} cm/s, characteristic of silty sands. These laboratory values were notably lower than those obtained from proximity field tests, differing by approximately two orders of magnitude. This discrepancy supports the assertion that the testing procedures themselves induce soil disturbance, consequently increasing conductivity. Similar findings were reported by Nam et al. (2021), who observed in situ test conductivity to be higher than laboratory tests, also differing by approximately two orders of magnitude.

The channel was delineated into six zones of homogeneous conductivity, as detailed in Table 5. This segmentation was based on considering the conductivity values obtained from infiltration tests for the slopes and laboratory tests for the channel bottom.

4 HYDRAULIC ANALYSIS

To assess the economic and energetic viability of implementing HDPE geomembrane, it is imperative to evaluate water and pressure losses within the intake channel, both with and without the geomembrane. Accordingly, a finite differences-based spreadsheet was developed for this purpose. The channel was discretized into segments, each spanning no more than twenty meters, and water and pressure losses were computed for each segment.

The calculated water loss values were utilized to determine the flow rate, while the pressure loss values informed the calculation of water height for subsequent segments. The influence area considered for each segment encompassed the space between it and the adjoining segment. The initial condition considered was the inlet condition of the channel, characterized by an average energy flow rate of 4.65 m^3/s and an initial hydraulic head of 724.00 m, corresponding to the normal Water Level (WL) of the reservoir.

4.1 *Water loss determination*

To quantify water loss via percolation across the slopes and bottom of the channel, each permeable zone within the channel was discretized and modeled using finite element methods implemented in the Seep/W module of GeoStudio software version 2012. An exemplification of this modeling process is depicted in Figure 8, illustrating zone 2 at the 10+00 station location.

All analyses were conducted under steady-state conditions, assuming a stable water table aligned with the channel bottom level. A percolation influence radius of 40 meters on either side from the channel center was considered. Material properties were specified such that the bottom material remained saturated, while the slope material could exhibit unsaturated characteristics. The characteristic curve for unsaturated soil was generated utilizing GeoStudio models for silty soil, incorporating saturated conductivity values derived from infiltration tests and residual volumetric moisture set at 10% of the saturated volumetric moisture.

Table 5. Conductivity zones considered for the channel.

Zone	Beginning Station	Ending Station	*Slopes Conductivity (cm/s)*	*Bottom Conductivity (cm/s)*
1	2+00,5	10+00	0	0
2	10+00	20+00	2,62E-4	1,44E-6
3	20+00	34+00	0	0
4	34+00	43+10	2,76E-3	9,25E-4
5	43+10	50+00	1,60E-3	9,25E-4
6	50+00	67+04,7	1,59E-3	6,44E-6

The consideration of the stable phreatic level at the channel's base was substantiated by observations made during the site visit, indicating a consistent presence of water at the channel bottom, attributed to groundwater percolation.

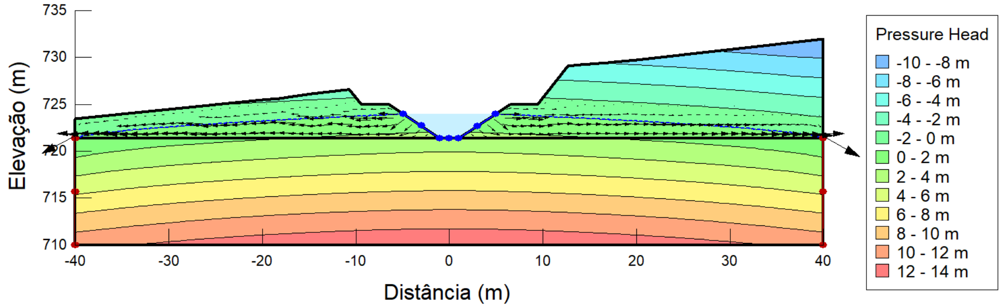

Figure 8. Conductivity analysis result for percolation on zone 2.

The influence radius was determined using Eq. 1 (Sichardt, 1930):

$$R = 3000 \cdot \Delta H \cdot \sqrt{k} \quad (1)$$

Considering the maximum water height ($\Delta H = 1.85\, m$) and the maximum conductivity ($k = 2.76 \cdot 10^{-3}\, m/s$), the calculated radius of influence extends to 29.16 m. When adding half of the base to this radius, an axis distance of 30.16 m is obtained.

Consequently, the assumptions employed in the section modeling are deemed conservative as they aim to maximize the percolated flow.

The unit flow outcomes for each zone are provided in Table 6. These results align with the specified conductivities; notably, zone 2, characterized by the lowest permeability, exhibits the least water loss, while zones 4 and 5, possessing the highest permeabilities, demonstrate the greatest water loss. The maximal disparity in water loss, between zones 2 and 5, approximates 50-fold.

Table 6. Unitary water loss for each zone

Zone	Beginning Station	Ending Station	*Unitary water loss (m³/s/m)*
1	2+00,5	10+00	0
2	10+00	20+00	2,57E-7
3	20+00	34+00	0
4	34+00	43+10	1,15E-5
5	43+10	50+00	1,32E-5
6	50+00	67+04,7	2,37E-6

4.2 *Water height determination*

The hydraulic potential of each section was determined utilizing Eq. 2, which leverages Bernoulli's principle (Porto, 2006) for open channel flow:

$$H = z + \frac{v^2}{2g} \quad (2)$$

In Eq. 2, H represents the hydraulic potential, z denotes the elevation of the fluid surface (water level), v signifies the velocity of the fluid, and g represents the gravitational constant.

The hydraulic potential of each section is required to be equivalent to the potential of the preceding section reduced by the pressure drop. The head loss for each section is calculated using Eq. 3 (Strickler, 1923):

$$h_f = \left(\frac{n \cdot v}{R_h^{\frac{2}{3}}} \right)^2 \quad (3)$$

In Eq. 3, h_f denotes the unit head loss, n represents the roughness coefficient, v stands for the flow velocity, and R_h represents the hydraulic radius of the section. The roughness coefficients utilized are outlined in Table 7.

Table 7. Utilized roughness coefficients (MME, 2007, translated)

n	*Surface type*
0,035	For rock channels
0,025	For ground channels
0,014	For concrete-lined channels
0,010	For geomembrane-lined channels

4.3 *Hydraulic assessments results*

Two studies were conducted on the intake channel of Bonfim HPP, one with and one without the installation of HDPE geomembrane in the soil sections. In both scenarios, rock segments are regarded as impermeable with a roughness coefficient of 0.035. In the absence of the geomembrane, unit water losses from Table 6 were utilized, with a roughness coefficient of 0.025 for the soil sections. Conversely, with the geomembrane installed, the sections are deemed impermeable with a roughness coefficient of 0.010. It was assumed that no holes were present in the geomembrane, although limited holes were permitted.

Although calculations were performed for each station, Tables 8 and 9 present summarized results categorized by homogeneous zones due to space constraints. Figure 9 illustrates the hydraulic profiles for scenarios both without and with the geomembrane.

The total water loss in the scenario without the geomembrane was 0.005 m³/s, representing merely 0.1% of the initial flow rate of 4.65 m³/s. This minimal water loss can be attributed to several factors, including a significant portion of the channel being comprised of solid rock where water loss was negligible, and the soil being clayey silt, which possesses low conductivity.

Table 8. Hydraulic assessments results: alternative without geomembrane

Zone	Station	*Length (m)*	*Bottom Initial El. (m)*	*WL (m)*	*Height (m)*	*Area (m²)*	*Flow (m³/s)*	*Velocity (m/s)*	*Water loss (m³/s)*	*Total head (m)*	*Head loss (m)*
1	2+00,5	157,5	721,498	724,000	2,502	14,394	4,650	0,323	0,000E+0	724,005	1,301E-2
2	10+00	200	721,377	723,988	2,610	15,443	4,650	0,301	4,997E-5	723,992	6,794E-3
3	20+00	280	721,224	723,982	2,758	16,925	4,650	0,275	0,000E+0	723,986	1,409E-2
4	34+00	190	721,009	723,968	2,959	19,055	4,650	0,244	2,177E-3	723,971	3,734E-3
5	43+10	130	720,863	723,965	3,102	20,635	4,648	0,225	1,714E-3	723,968	1,745E-4
6	50+00	344,7	720,764	723,963	3,200	21,756	4,646	0,214	8,161E-4	723,966	4,424E-3
	67+04,7		720,499	723,959	3,460	24,879	4,645	0,187		723,961	

Table 9. Hydraulic assessments results: alternative with geomembrane

Zone	Station	*Length (m)*	*Bottom Initial El. (m)*	*WL (m)*	*Height (m)*	*Area (m²)*	*Flow (m³/s)*	*Velocity (m/s)*	*Water loss (m³/s)*	*Total head (m)*	*Head loss (m)*
1	2+00,5	157,5	721,498	724,000	2,502	14,394	4,650	0,323	0,000E+0	724,005	1,301E-2
2	10+00	200	721,377	723,988	2,610	15,443	4,650	0,301	0,000E+0	723,992	1,082E-3
3	20+00	280	721,224	723,987	2,764	16,984	4,650	0,274	0,000E+0	723,991	1,396E-2
4	34+00	190	721,009	723,974	2,965	19,119	4,650	0,243	0,000E+0	723,977	5,912E-4
5	43+10	130	720,863	723,974	3,111	20,737	4,650	0,224	0,000E+0	723,977	3,374E-4
6	50+00	344,7	720,764	723,974	3,210	21,881	4,650	0,213	0,000E+0	723,976	6,970E-4
	67+04,7		720,499	723,974	3,475	25,059	4,650	0,186		723,976	

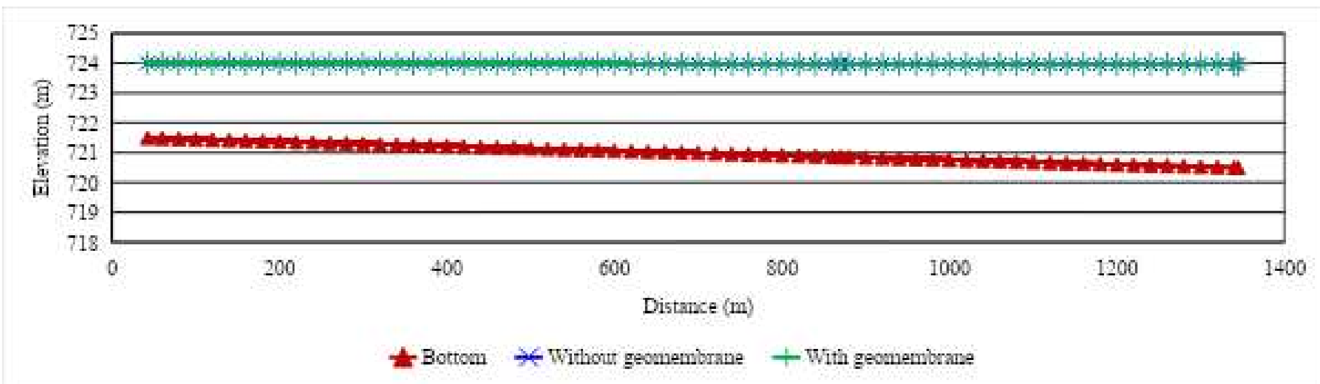

Figure 9. Canal hydraulic profile.

Conversely, the total head loss for the scenario without the geomembrane was 4.1 cm, while with the geomembrane it was 2.6 cm, resulting in a difference of 1.5 cm. Relative to the gross head drop of 42.31 m, the head losses without and with the geomembrane were 0.10% and 0.06%, respectively. The low head loss can be attributed to a significant portion of the channel being situated in solid rock, thereby unaffected by the presence of the geomembrane. Furthermore, the mean water flow rate (4.65 m³/s) falls considerably below the designated flow rate (7.35 m³/s), resulting in velocities below 0.35 m/s. The permissible average velocity for silt-clay soils, as stipulated by the Eletrobrás Design Criteria (2003), ranges from 0.76 to 0.84 m/s. However, it is noteworthy that despite the small difference in relation to the gross head drop, this disparity accounts for 39% of the pressure loss in the channel without the geomembrane, indicating that adopting more appropriate velocities could yield a more substantial reduction in pressure loss.

Furthermore, the potential for particle entrainment should be considered in the scenario without the geomembrane, although it is unlikely due to the low flow velocities. Nonetheless, such low velocities have the potential to induce sedimentation within the channel, whereby particles from the reservoir may accumulate.

5 ECONOMIC AND ENERGETIC ASSESMENTS

To assess the economic and energetic viability of installing HDPE geomembrane into the intake channel of Bonfim HPP, the energy losses stemming from water and pressure losses within the plant's intake channel will be initially computed. Subsequently, these energy losses will be translated into revenue losses and juxtaposed with the investment needed for geomembrane installation to ascertain the attractiveness of such an investment.

5.1 *Energy loss determination*

The electric power generated at any given moment is determined by Eq. 4 (MME, 2007):

$$P = \gamma_w \cdot \eta_{r-g} \cdot (H - \Delta H) \cdot (Q - \Delta Q) \quad (4)$$

where P represents the generated power, γ_w denotes the specific weight of water, η_{r-g} signifies the efficiency of the turbine/generator set, H denotes the gross head, ΔH represents the head loss, Q stands for the inlet flow rate, and ΔQ indicates the water loss.

A Eq. 4 can be rewritten as follows:

$$P = \gamma_w \cdot \eta_{r-g} \cdot f_{hl} \cdot H \cdot f_{wl} \cdot Q \quad (5)$$

In Eq. 5, f_{hl} represents the head loss factor defined in Eq. 6, while f_{wl} denotes the water loss factor defined in Eq. 7:

$$f_{hl} = \left(1 - \frac{\Delta H}{H}\right) \quad (6)$$

$$f_{wl} = \left(1 - \frac{\Delta Q}{Q}\right) \quad (7)$$

Hence, Eq. 5 can be reformulated for a reference power as follows:

$$P = f_{hl} \cdot f_{wl} \cdot P_{ref} \quad (8)$$

The reference power must be computed excluding hydraulic losses and can be determined utilizing Eq. 9:

$$P_{ref} = \gamma_w \cdot \eta_{r-g} \cdot H \cdot Q \quad (9)$$

Due to fluctuations in both turbine flow and head, as dictated by the water regime, the Basic Project of Bonfim HPP (Terral, 2020) included hydrological studies estimating the mean power output at 1.65 MW. This calculation was derived from a gross head of 42.31 m and an average flow rate of 4.65 m³/s. The turbine and generator efficiencies, as provided by manufacturers' estimates, were 92.8% and 90% respectively, resulting in a combined efficiency of 83.52%.

The average annual reference energy is determined by multiplying the reference power by the plant's operational duration over one year, as described in Eq. 10:

$$E_{ref} = P_{ref} \cdot t_{op} \quad (10)$$

The Basic Project of Bonfim HPP (Terral, 2020) assumed continuous generation without idle hours, owing to the presence of multiple generating units. Any necessary forced stops or maintenance can be scheduled during the dry season when water availability is insufficient to operate all machinery. Consequently, the average reference energy is determined to be 14,463.9 MWh/year.

The energy loss ΔE can therefore be defined as a fraction of the average reference energy and can be represented by Eq. 11:

$$\Delta E = \left(1 - f_{hl} \cdot f_{wl}\right) \cdot E_{ref} \quad (11)$$

In the non-geomembrane scenario, the water loss is 0.005 m³/s, and the head loss is 4.1 cm, yielding f_{hl} of 99.89% and f_{wl} of 99.90%. Consequently, the resulting energy loss is calculated to be 29.6 MWh/year. Conversely, for the geomembrane scenario, with water loss reduced to 0 m³/s and a head loss of 2.6 cm, f_{hl} is 99.94%, and f_{wl} is 100%, leading to an energy loss of 8.9 MWh/year.

Relative to the average energy, the losses without and with geomembrane are 0.20% and 0.06%, respectively. Although as observed on the hydraulic losses, the energy losses are minimal compared to the average energy, a comparison between the scenarios reveals that the disparity accounts for 71% of the energy loss observed in the non-geomembrane scenario.

5.2 *Income losses determination*

The determination of energy prices in Brazil is contingent upon various factors, with three primary markets prevailing: the regulated market, characterized by energy auctions overseen by the Brazilian National Electric Energy Agency (ANEEL); the free market; and distributed generation. The average energy sale price in the most recent auction was reported as US$23.83/MWh (Agência Gov., 2023). Conversely, establishing an average price for the free energy market proves challenging due to its high volatility and variability.

The distributed generation market centers on self-generation, wherein consumers produce their own energy but remunerate the utility company for transmission line usage. This market segment is typically advantageous as it operates on a cost-loss basis, meaning the tariff paid to the energy producer aligns with that the consumer pays to the utility company, which is considerably higher than market prices. To mitigate the necessity of matching consumption with generation, it is customary to engage in plant lease agreements, where a large consumer leases one or more plants, paying a lower rate for the energy generated compared to the utility company tariff but higher than the market rate. Bonfim HPP has entered into a lease agreement for the plant under the distributed generation modality, with a tariff set at US$77.22/MWh, serving as the basis for calculating income losses.

Consequently, for Bonfim HPP, the average annual revenue loss for the non-geomembrane channel alternative amounts to US$2,282.13, while for the geomembrane-installed channel, it is US$659.95. Thus, it can be deduced that implementing the geomembrane would yield a revenue gain of US$1,622.18/year.

5.3 *Geomembrane installation price determination*

To ascertain the price of HDPE geomembrane, the expenditures associated with the installation of a geomembrane in a channel at another hydroelectric power plant, possessing comparable dimensions to the Bonfim HPP, also situated in the state of Goiás, Brazil, were utilized as a benchmark. The incurred costs are detailed in Table 10.

The estimated area of geomembrane required for installation, encompassing the slopes of the channel at Bonfim HPP, amounts to 16,300 m². Consequently, the approximate installation cost is US$96,822.

Table 10. Unit Cost Composition utilized for geomembrane installation in the channel.

Item	*Cost (US$/m²)*
HDPE geomembrane (e = 1.5 mm)	4.92
Installation Devices, Parts & Accessories	0.38
Labor - Wages	0.43
Labor - Food and Accommodation	0.19
Electricity (generator 100 kVA)	0,01
Munck Truck	0,01

Total	**5.94**

5.4 *Assessment of the economic and energetic feasibility of installing HDPE geomembrane*

Hydroelectric power plants are conventionally engineered with a service life exceeding 50 years, potentially extending beyond a century with appropriate design and maintenance (Vorlet & De Cesare, 2023). Conversely, the payback period specified for Bonfim HPP in its Basic Project (Terral, 2020) - denoting the duration within which an investor anticipates recovering their investment - is 12 years.

The payback period for a particular investment can be computed using Eq. 12:

$$t_{pb} = \frac{Investment}{Revenue} \quad (11)$$

Based on the conducted studies, considering an investment of US$96,822 and an annual return of US$1,622.18, the payback period for the installation of the geomembrane is calculated to be 59.7 years, exceeding both its anticipated service life and its stipulated payback duration. Table 11 provides a summary of all the steps leading to this outcome. Consequently, it is inferred that the installation of the geomembrane is not economically viable in this instance. However, it is noteworthy that should the decision be made to proceed with the installation, this investment would eventually recoup its costs.

It is pertinent to mention that the comparisons conducted herein pertain to a pre-designed and executed section that underwent minimal interventions. In this context, conducting a study involving diverse cross-sections aimed at reducing excavated rock volume and increasing flow velocities could potentially yield different results from those obtained here.

Table 11. Economic and energetic assessments results

Alternative	*Without geomembrane*	*With geomembrane*	*Difference*
Water loss (m³/s)	0,005	0,000	0,005
Head loss (cm)	4,1	2,5	1,6
f_{hl}	99,89%	100,00%	
f_{wl}	99,90%	99,94%	
Average energy loss (MWh/year)	29,6	8,5	71%
Annual revenue loss	US$2,282.13	US$659.95	US$1,622.18
Geomembrane installation surface (m²)	0	16.300	16.300
Geomembrane installation cost	-	US$96,822	US$96,822
Payback period (years)			59,7

6 CONCLUSIONS

During the course of this studies, the technical and economic viability of installing HDPE geomembrane in the intake channel of Bonfim HPP was thoroughly assessed. This study contributes to elucidating the requisite steps for such an evaluation, encompassing field and laboratory data collection, hydraulic analyses, and the subsequent determination of economic and energy viability. The conclusions drawn from these analyses are outlined as follows:

Laboratory and *in situ* tests revealed disparate conductivity values for the same soil sampled from closely situated locations, differing by two orders of magnitude. This variation is consistent with previous studies and can be attributed to soil disturbance induced by the excavation process, which creates preferential percolation pathways.

Hydraulic studies indicated marginal increases in water and pressure losses when comparing the alternative without geomembrane to that with geomembrane (0.005 m³/s and 1.6 cm difference in losses, respectively, compared to a turbine flow of 4.65 m³/s and a gross head of 72.31 m). This outcome can be primarily attributed to three factors: the presence of a substantial rock segments, which homogenized parameters across approximately one-third of the channel; the low conductivity of the foundation soil; and the adoption of low velocities in the channel design, leading to significant reductions in head losses.

The adoption of higher velocities in the channel would yield a more pronounced reduction in head drop. The utilization of these reduced velocities resulted in increased excavation costs. A recommendation for future research involves conducting an economic-energy comparison between a channel design featuring reduced excavations, higher velocities, and geomembrane installation versus the current design characterized by low velocities and no geomembrane.

Economic-energy analyses corroborated hydraulic findings, revealing a payback period of 59.7 years for geomembrane installation, exceeding both the 12-year payback period stipulated for Bonfim HPP and the plant's estimated 50-year service life. Consequently, it is concluded that installing the geomembrane in this instance is not economically viable. However, it is important to note that altering channel geometry could yield different outcomes.

7 ACKNOWLEDGEMENTS

We extend our sincere appreciation to Terral Engenharia for their collaboration in this feasibility study and their consent to share their data for inclusion in this article.

Furthermore, we express our gratitude to Engineer Henrique Santos for his informative lecture on the Brazilian energy market.

8 REFERENCES

ABGE. 2013. Manual de Sondagens. ABGE, São Paulo, SP, 5ª Edição. 203 p.

ABNT. 2021. NBR 14545 – Solo – Determinação do coeficiente de permeabilidade de solos argilosos à carga variável. ABNT, Rio de Janeiro, RJ, 2ª Edição. 22 p.

Bieniawski Z.T. 1973. Engineering Classification of Jointed Rock Masses. The Civil Engineer in South Africa. December 1973, 335-343.

Brasil. Ministério de Minas e Energia. 2007. Manual de Inventário Hidroelétrico de Bacias Hidrográficas. CEPEL, Rio de Janeiro, RJ. 684 p.

Brasil. Agência Gov. 2023. Leilões de Energia Existente A-1 e A-2 movimentam R$ 1,325 bilhão em contratos e garantem suprimento seguro e barato. Disponível online em https://q.eletrobras.com/pt/AreasdeAtuacao/geracao/Manuais%20para%20Estudos%20e%20Projetos%20de%20Gera%C3%A7%C3%A3o%20de%20Energia/Crit%C3%A9rios%20de%20Projetos.pdf. Acessado em 28/02/2024.

CONTECH. 2022. CGH Bonfim – Relatório Técnico de Ensaios. Goiânia, GO. 20 p.

Eletrobrás. 2003. Critérios de Projeto Civil de Usinas Hidroelétricas. Eletrobrás. 278 p. Disponível online em https://agenciagov.ebc.com.br/noticias/202312/leiloes-de-energia-existente-a-1-e-a-2-movimentam-r-1-325-bilhao-em-contratos-e-garantem-suprimento-seguro-e-barato#:~:text=J%C3%A1%20para%20o%20Leil%C3%A3o%20de,a%2031%2F12%2F2026. Acessado em 29/02/2024.

Nam S., Gutierrez M., Diplas P. and Petrie J. 2021. Laboratory and In Situ Determination of Hydraulic Conductivity and Their Validity in Transient Seepage Analysis. *Water* 13, 1131. 20 p.

Obidzhonov A. and Babaev A. 2023. Hydraulic efficiency of coated and uncoated open channels. *Universum: technical sciences: electron.* 10 (115), 64-68.
Kyrieleis W. and Sichardt W. 1930. Lowering of groundwater during foundation work. Springer: Berlin/Heidelberg, Germany.
(In German)
Portella, A. C. F., Nascimento, I. R., Alves, A. F., Scheidt, G. N. 2015. Estatística Básica para os Cursos de Ciências Extas e Tecnológicas. EDUFT/UFT, Palmas, TO. 168 p.
Porto, R. M. 2006. Hidráulica Básica. EESC/USP, São Carlos, SP. 4ª Edição. 519 p.
Strickler A. 1923. Contributions to the question of velocity formula and roughness data for streams, channels and close pipelines, Translated by T. Roesgen e W. R. Brownlie, W.M. Keek Laboratory of Hydraulics and Applied Science, California Institute os Technology, 1981.
Terral. 2020. CGH Bonfim – Projeto Básico. Goiânia, GO.
Terral. 2022. CGH Bonfim – Projeto Executivo do Canal de Adução. Goiânia, GO.
Vorlet S.I. and De Cesare G. 2023. A comprehensive review on geomembrane systems application in hydropower. *Renewable and Sustainable Energy Reviews.* 189(2024), 16p.