Use of Geosynthetics to Close a Contaminated Area in Metallurgical Industrly in Bahia - Brazil

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ABSTRACT

The study for closure and monitored natural attenuation/stabilization of industrial waste deposits plays a fundamental role in the process of groundwater quality management, providing information for understanding the contaminants evolution and enabling decision-making, with the purpose of isolating waste, contaminant concentrations, toxicity and mass and/or volume reduction to levels adequate to protect human health and the environment, within a reasonable period of time. The aim of this study was to propose an environmental remediation solution for a contaminated material disposal area using the case study of a metallurgical industry located in Bahia, Brazil. To this purpose, four conditions were provided for compliance: i) control of dust, odor and erosion, ii) control of contaminant release, iii) chemical stabilization of waste and iv) soil recovery. Based on the results obtained in environmental investigation studies and information from the area, the best solution in an attempt to naturally stabilize the area would be the use of geosynthetics as a physical barrier between the contaminated material disposed in the area and the rainwater. In this way, infiltration of rainwater into the landfill and the migration of percolated liquid with risk of contamination to the soil, groundwater table and surface water bodies is avoided. It is still possible to monitor the effectiveness of the proposed solution with the installation of instrumentation such as water level indicators and piezometers.

Keywords: Closure, Contaminated area, environmental remediation, geosynthetics.

1. Introduction

Environmental geotechnics is the branch of geotechnics responsible for investigating and presenting solutions to environmental problems that have arisen due to human actions considering earthworks in mining activities, urban sanitation, generation of industrial waste, among others. According to Nanda and Berruti (2020), Brazil is the third country that generates the most solid waste due to demographic and industrial growth, reaching a projected rate of 330,960 tons per day in 2025. Therefore, aiming to mitigate environmental impacts, proposed remediation of land contaminated with chemical substances in an attempt to mitigate or stabilize the parameters involved, in addition to trying to prevent contamination of groundwater (LANGER, 1995).

A contaminated area is the result of quantities of matter or concentrations of substances, in at least one of the compartments of the environment, capable of causing damage to the assets to be protected (CETESB, 2022).

The Industrial Revolution that began in the 18th century represented changes in the composition of substances deposited in the soil, and contaminants in the environment increased drastically due to industrial and technological development that occurred in the 20th century (SWARTJES, 2011). Therefore, with regard to contaminated land scenarios, the metallurgical industry sector is very present, responsible for the production of metals, considered one of the oldest materials and still widely used, for example, in transport, household utensils and above all in civil construction. However, these industries are considered major sources of emissions of gases that are aggressive to the environment and responsible for the storage of materials, often containing a high level of contaminating chemical substances.

During the years of production, the demand for the closure of industrial units may arise, resulting in the need for studies to manage existing environmental liabilities arising from the packaging of slag and raw materials in the units, for example. The closure considers the cessation of waste disposal and the characterization of the environmental situation of the area in terms of contamination (CETESB, 2022).

Currently, there are several techniques proposed for remediation of contaminated areas (soil, sediments, water resources, atmosphere, etc.). These remediation technologies are very variable, depending on the contaminated matrix, the nature of the contaminant, the level of contamination and the availability of resources (TAVARES, 2013). Therefore, specific studies are developed to characterize the contaminated areas with a view to closing the industrial region, and technologies for remediation can be used, such as the use of capillary barriers, a layer of soil with low permeability, evapotranspiration coverings, cation exchange, phytoremediation, hydraulic barriers, geotechnical capping using geosynthetics, etc. (PENG AND JIANG, 2009).

Therefore, the objective of the present study was to propose an environmental remediation solution using geosynthetics for a contaminated material disposal area using the case study of a metallurgical industry located in Bahia, Brazil.

1.1. Description of the area

The metallurgical industry located in Bahia, northeast Brazil, had iron alloys as its production focus and was built in 1969. Since then, during the unit's operation phase, raw materials and waste were stored in piles and in contact areas. with the natural soil. The waste and raw materials pile has been deactivated and has not received material since the first half of 2021 due to the closure of activities in the metallurgical industry.

Aiming to design the closure of the old waste pile area, geological-geotechnical and environmental investigations were carried out to assess the subsoil: five (05) mixed drilling tests (SM), three (03) standard penetration test (SPT), one (01) vane test (VT) and the collection of one (01) undisturbed block in investigation wells (PI) to support the preparation of geotechnical geological sections aiming to understand the contact between the soil and contaminating material.

The foundation where the waste was disposed is composed by approximately 7.0 meters of soft plastic clayey soil and a foundation predominantly made of saprolite. On the west-northwest side of the waste pile area there is a mangrove swamp (a coastal transition ecosystem between terrestrial and marine environments, a humid zone characteristic of tropical and subtropical regions), where the flow is directed.

In addition, samples were collected from surface and underground waters for laboratory analysis to obtain water quality. Is was observed the presence of barium, manganese, cadmium and thallium were detected above the limits of the environmental standard. For groundwater, analytical results above the limit were obtained for dissolved arsenic, indene(1,2,3-cd)pyrene, total metals aluminum, arsenic, boron, lead, iron, manganese and molybdenum. Regarding the physical-chemical parameters of groundwater, obtained in the same period, a pH close to neutrality was identified in most wells, a medium with oxidizing characteristics and varied dissolved oxygen concentrations.

2. Environmental remediation solution for the contaminated area

The waste material is classified as a contaminant material, therefore, the closure design consisted of covering the waste and contaminated soil with the use of geosynthetics and construction of the geotechnical capping to isolate it from leaching and percolation caused by the flow of rainwater. It is noteworthy that, due to the type of waste disposed, the area is considered a Non-Hazardous Waste Landfill (Class II) and, therefore, its closure complied with the recommendations of ABNT NBR 13.896 for non-hazardous waste landfills.

The closure of contaminated areas involves environmental remediation through soil coverings, the solution of which considered four conditions indicated by Peng and Jiang (2009, p. 305): i) control of dust, odor and erosion, ii) control of release of contaminants, iii) chemical stabilization of waste and iv) soil recovery. Below will detail how each item was designed for the case study contaminated slag disposal area:

- Dust, odor and erosion control: The geotechnical capping was based on the premise of monitored natural attenuation/stabilization and adopted as a closure solution for the area.
- Controlling the release of contaminants: After removing the active source of contamination, natural processes begin to act on the chemical substances of interest present in the soil and groundwater.
- Chemical stabilization of waste: The proposed capping solution aimed to implement a waterproofing layer using geosynthetics as a waterproofing and drainage barrier, due to characteristics such as ease of construction, durability, quality control and cost, combined with environmental preservation.
- Soil recovery: After completing the construction of the area's waterproofing system, the appropriate seed mix for germination in the region was created and applied to the final covering soil to reintegrate it into the area.

3. Dimensioning of Solution

Based on the results obtained from geotechnical investigation campaigns and laboratory tests in the area, it was possible to determine the geological-geotechnical section of the pile to define the final geometry of the decommissioned area, with validation by stability analyzes meeting the safety criteria established in standard NBR 13.029 (ABNT, 2017). The region is composed of the waste pile with sandy-silty characteristics with fine to medium sand and the presence of fine to coarse slag boulders, the mangrove with clayey textured material of a plastic nature, the residual soil with clayey-silty characteristics with plastic passages and saprolite being clay-silty with the occurrence of rocky cores. The summary of the investigations is shown in Table 1 and Figure 1.

Table 1. Input data for calculating the GM thickness in the equation proposed by Koerner (1998)

Material	Features	Consis-tancy	Thick-ness
Waste Pile	Sandy-silt with fine sand and coarse waste	Soft	4
Mangrove swamp	Plastic clay texture	Very soft	7
Residual Soil	Clay-silt with plastic passages	Medium to hard	2,5
Saprolite	Clay-silt with rocky cores	Hard	4,6

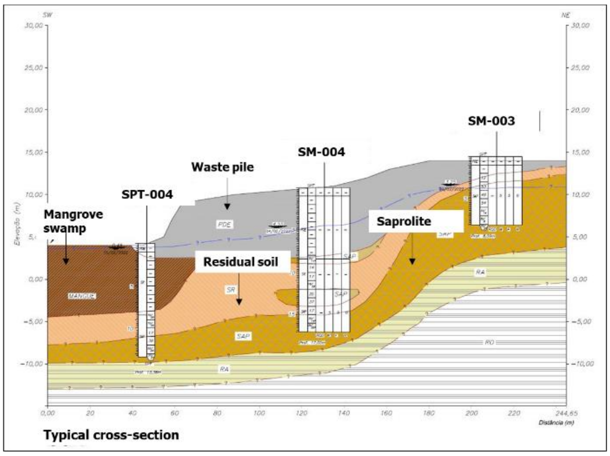

Figure 1. Typical cross-section of the pile area foundation.

The waterproofing system proposed for the plateau (Figure 2) and for the slopes (Figure 3) consisted of 06 (six) elements: regularization layer, non-woven geotextile, geomembrane, drainage geocomposite, geocell (on the slopes) and layer of covering soil.

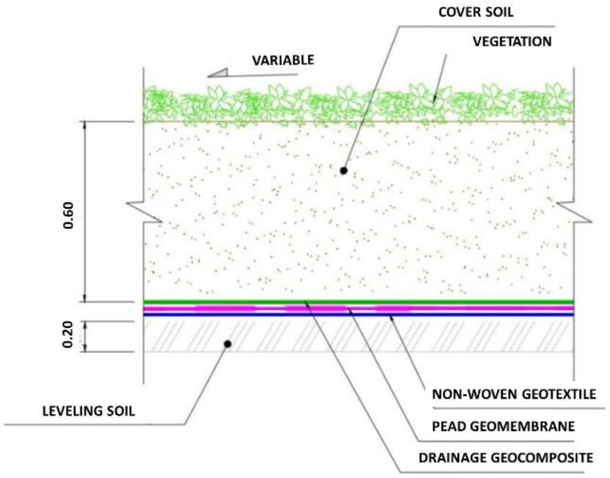

Figure 2. Proposed waterproofing system on the plateau.

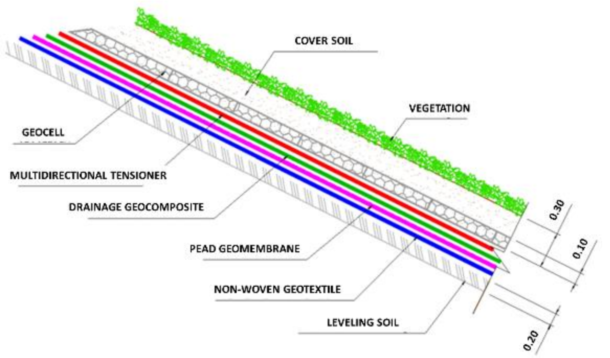

Figure 3. Proposed waterproofing system on slopes.

3.1. Regularization layer

The layer of compacted soil had the function of regularizing the surface, keeping it free from piercing materials, and providing the roof with the final geometry and slopes. To protect the waterproofing geosynthetic in the capping system, the entire storage area received a layer of leveling fill with a thickness of at least 20 cm. The material planned for the regularization layer included soils with a clayey-silty or clayey-sandy matrix, free of boulders or materials that could cause punctures in the geotextile/geomembrane assembly.

3.2. Non-woven geotextile

Since geomembranes are installed in earthmoving works, where they are in direct contact with different types of soil, which can have variable particle sizes and irregular surfaces. Therefore, it is possible for the geomembrane structure to suffer a puncturing effect, deteriorating the total tightness of the system. It was then planned to cover the slopes and plateaus of the entire area with geotextile, after the regularization layer. The most suitable geotextile in the context of application for protection is based on puncture resistance. In this way, the pressure that acts on the geotextile was determined, under certain conditions, and then it was checked whether the selected material resists the punching that could be generated, for example, by a sharp rocky material. To use Geotextile as a protective material for the geomembrane, the methodology presented by Wilson-Fahmy, Narejo and Koerner was used, exposed in 1996 through technical work by GRI (Geosynthetic Research Institute) and updated in 2016 due to technical work by GRI. in its 2012 GTI 12 test standard (apud WAVIN, 2022). Therefore, the geotextile must have a CBR punching resistance greater than 0.9 kN.

3.3. Geomembrane

The geomembrane is a product manufactured from relatively thin sheets of polymers such as HDPE and PVC, suitable for coating or barrier with very low permeability, being applicable in conjunction with any type of related material and applied to geotechnical engineering, to control the fluid migration. The sizing of the thickness and type of geomembrane to be used in the waterproofing system of the area in question were calculated as presented in the following items.

Vertematti (2015) emphasizes that geomembranes must survive the rigors of installation so that they can have a performance compatible with the desired design. Therefore, using the minimum values of properties to guarantee the survival of geomembranes indicated by Koerner (1998) and presented in Table 1, we have the minimum properties of the geomembrane:

- Thickness (ASTM D 5193): 1.0 mm
- Tensile ASTM D 882 (25 mm strip): 13.0 kN/m
- Tear (D1004 - mold C): 90 N
- Punch (ASTM D 4833): 200.00 N
- Impact (modified ASTM D 3998): 20 J

Table 2. General formatting styles

Test property and method	Required degree of installation survival			
	Low[1]	Medium[2]	High[3]	Very High[4]
Thickness (ASTM D 5193) (mm)	0,63	0,75	0,88	1
Traction ASTM D 882 (tira de 25 mm) (kN/m)	7	9	11	13
Tear (D1004 - molde C) (N)	33	45	67	90
Puncture (ASTM D 4833) (N)	110	140	170	200
Impact (ASTM D 3998 modificada) (J)	10	12	15	20

The dimensioning of the thickness of the HDPE geomembrane (GM) was based on the methodology of Koerner (1998), presented in the Brazilian Manual of Geosynthetics (VERTEMATTI, 2015), as indicated in Equation 1, whose

1 L - Low: manual, careful placement on a well-graded, very uniform subgrade with light loads of a static nature, typical of vapor barriers below floor slabs.
2 M - Medium: refers to manual or mechanical placement on subgrades with medium loads, typical of channel lining.
3 A - High: refers to manual or mechanical placement, in subgrades with poor texture, with high loads, typical of barriers and landfill covers.
4 M -Very High: refers to manual or mechanical placement in subgrades of very poor texture, with very high loads, typical of leach heap barriers and reservoir covers.

properties are illustrated in the free body diagram of the Figure 3.

$$t = \frac{\sigma_n x(\tan\delta_U + \tan\delta_L)}{(\sigma_r/FS)(\cos\alpha - \sin\alpha\tan\delta_L)} \quad (1)$$

In which:

t	geomembrane thickness (m).
T	normal tension due to the weight of the stored material (kPa);
x	mobilization length (m);
δ_U	angle of friction between the geomembrane and material on it (°);
δ_L	angle of friction between the geomembrane and material beneath it (°);
σ_r	geomembrane rupture stress (kPa);
α	GM mobilization angle with horizontal tension (°);
σ_n	normal stress applied by overload (kPa);
FS	Fator de Segurança (adimensional).

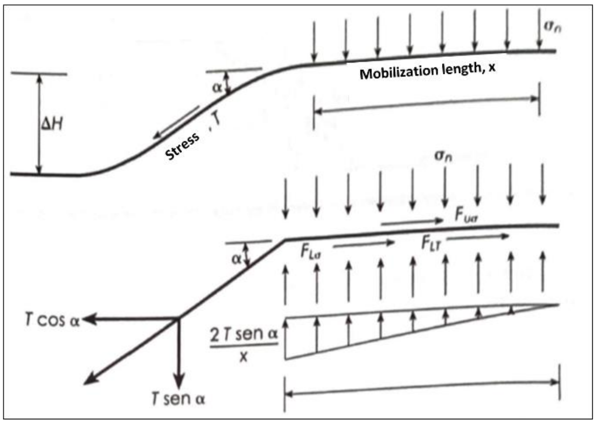

Figure 4: Free-body diagram of the geomembrane indicating the variables in Equation 1 (KOERNER, 1998 apud de VERTEMATTI, 2015).

Table 3 presents the input values considered to calculate the thickness of the HDPE geomembrane planned for the solution.

Table 3. Input data for calculating the GM thickness in the equation proposed by Koerner (1998).

Property	Input
Specific weight of the covering soil in the geomembrane (kN/m3):	16.0
Height of the covering layer in meters (h):	0.6
Stress applied by the weight of the material in kPa (σ_n):	9.6
Membrane mobilization length in meters (m):	0.40
Angle of friction between GM and material on it (δ_U) in degrees (°):	15.0
Angle of friction between GM and material beneath it (δ_L) in degrees (°):	15.0
GM Breakdown Voltage (kPa):	14,000
Mobilization angle (a) of GM with horizontal tension (°):	18.4
Safety Factor	1.50

Substituting the values from Table 2 into Equation 1, we will have the GM thickness results as shown in Table 3.

Table 3. Result of GM thickness calculated using the equation proposed by Koerner (1998).

Thickness Condition	Thickness
Minimum geomembrane thickness (m):	0,00029
Required geomembrane thickness (mm):	0,26
Final thickness of the geomembrane (mm):	2,00

According to EPA (2004), the thickness of a GM used in a roofing system is selected based on several factors, the most important of which are durability and seam capacity. GMs must be adequately thick to resist construction damage and punctures.

In line with German technical regulations, which require a minimum thickness of 2.0 mm for HDPE GMs (KOERNER, 2005), for application in the area, the use of a 2.00 mm thick HDPE geomembrane was envisaged, with textured faces, manufactured with virgin High Density Polyethylene resin, with 2 to 3% carbon black and a density of 0.94 g/c.

The recommended geomembranes are covered to provide additional protection against oxidation, ultraviolet degradation, high temperatures, puncture and tearing by angular materials, and even against damage during and after construction work.

3.4. Drainage geocomposite

The drainage geocomposite was added with the aim of capturing and conveying percolated water not absorbed by the vegetation, preventing it from remaining accumulated/retained in the substrate, generating additional loads for the system. Furthermore, the presence of this layer of drainage geocomposite also works as a layer of reinforcement for the covering soil, which can significantly reduce the efforts transferred to the geomembrane installed on the surface.

According to the geometric characteristics of the slope, the values of the coefficient of k = 5x10-6 m/s and hydraulic capacity of θi2 = 4.24x10-3 m²/s, resulting in a required drainage geocomposite with a minimum required transmissivity of 3.00 l/m.s, for i = 0.20 (slope 5H:1V).

3.5. Geocell

Geocells are 3D panels, made from synthetic materials such as HDPE, resistant to weathering and resistant to the effects of water. The geocell, applied to slopes, aimed to guarantee the stability of the soil layer necessary for the establishment of vegetation in the medium and long term, thus guaranteeing its permanence on surfaces where revegetation would be practically impossible, such as on geomembranes.

The geocell is superimposed and fixed on the multidirectional tensioner, which aims to resist the active loads generated both by the weight of the coating and by overloads resulting from earthquakes, precipitation, construction processes, among others, as well as serving as an anchor, offering greater flexibility to the system. Finally, to guarantee the mechanical union and transmission of the forces generated between the geocells and the tensioners, fasteners with a minimum resistance of 50 kg and stabilization against UV rays were used.

3.6. Cover soil

The covering soil was added to protect the underlying geosynthetic layers and promote the necessary environment for the growth of the superficial protective vegetation layer.

According to EPA (2004), the root systems of shallow grass roots do not penetrate deeper than 0.15m underground, while grasses with deeper root systems may have roots that penetrate depths of 0.30 to 0.50m. Therefore, the thickness of the covering soil on the plateau was proposed as a minimum thickness of 0.60 m, with 0.10m of superficial vegetation cover (organic soil) and 0.50m of the protective layer. For the cover soils located on the slopes, the indicated thickness was 0.30m, with 0.10m of vegetable surface cover (organic soil) and 0.20m of the protection layer.

4. Stability Analysis

The proposed geotechnical capping was validated through 2D stability analysis, using the Spemcer limit equilibrium method using Rocscience's Slide2 software.

The C-C section in Figure 4 was chosen because it is the most critical condition in terms of the soft soil layer found in the foundation, according to the available field investigations.

Two scenarios were evaluated considering the pile in its final form and the waterproofing cover in place:

- scenario 1: normal permanent water level (from boreholes and/or monitoring);
- scenario 2: permanent critical water level (hypothetical maximum elevation corresponding to a FS of 1.3).

The minimum Safety Factor of 1.5 was considered for the normal and 1.3 critical condition, according to standard NBR 13.029 (ABNT, 2017).

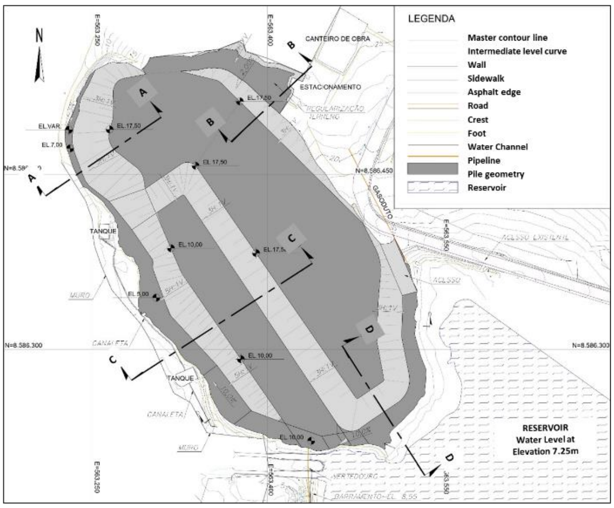

Figure 4: Location of the cross sections assessed for geotechnical stability for the Pile.

The water level of the foundation and inside the pile was defined based on the records presented in the profiles of the borings carried out in the area of the deposit and the field observations made during the on-site inspection.

For the critical water level elevation scenario, corresponding to a critical situation, an elevation was imposed in order to simulate the fully saturated condition of the pile.

The geotechnical parameters of the materials in Table 4 were defined on the basis of field and laboratory investigations and the geological-geotechnical model was interpreted in the field and laboratory investigations. The pile configuration was developed on the premise that the capping could be adjusted/extended if contaminated soil layers were detected beyond the design perimeter, according to observations during the work.

Table 4. Geotechnical parameters considered in stability analyses.

Material	γ (kN/m³)	Resistance parameters (kPa) c'	ø'	Source
Cover material	17	5	26	Estimated
Slag	18	5	28	Estimated
Residual soil	17	7	30	Triaxial Test CiU (SPT-TEC3-009)
Saprolite	18	20	24	Triaxial test CiU (block PI-IV-B)

Material	γ (kN/m³)	S_U (design) Prof. (m)	S_U (base)	ΔS_U (depth)	Source
Soft clay	16	1,0 a 3,0	7,9	3,9	Vane and triaxial UU tests
		>3,0	16,2	0,5	

Although the waterproofing cover provides a certain gain in shear strength from the tensile strength of the geomembrane and geotextiles, this contribution was not taken into account in the stability analyses.

The results obtained in the stability analyses for the global slope were satisfactory in accordance with the Brazilian standard NBR 13.029 (ABNT, 2017). For the scenario and methodology applied in this study, considering the available research data, the results of the global stability analyses of the C-C section (Figure 5) showed that the 5H:1V slope setback and inclination were important and sufficient to guarantee the stabilization of the pile in its most critical region.

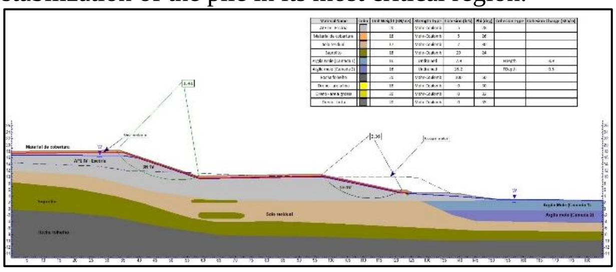

Figure 5: Stability analysis section C - Critical water level.

5. Conclusion

The work for geotechnical capping was proposed based on the premise of combined use of the waste deposit closure method (geotechnical capping) and monitored natural attenuation/stabilization, as the remediation methods applicable to the area.

The geotechnical capping consisted of an artificial waterproofing system considering a 2.0 mm thick HDPE geomembrane, protected on its lower face by a non-woven geotextile implanted on a compacted regularizing embankment. The drainage system is composed of a triplanar geosynthetic drainage composite. The entire capping system is protected by a clayey soil cover capable of promoting the necessary conditions for the growth of the covering vegetation.

Considering the points recommended in NBR 13.896 (ABNT, 1997), the investigation campaigns carried out in the area allowed the dimension of the horizon of contaminating material, as well as the geotechnical-geological characteristics of the deposit.

The final geometry was established seeking the best mass balance, acceptable safety factors given the uncertainties of the foundation, best geometric conformation for implementing the waterproofing system and seeking the best access routes for maintenance and future monitoring.

As for natural attenuation/stabilization, it is important to emphasize that it depends on processes that occur naturally and reduce the pollutant load present in the subsoil and groundwater. Natural attenuation/stabilization is present in most contaminated areas, whether by adsorption, chemical transformation of substances under local hydrochemical changes, transformation by microbiological activities, dilution, physical transformations (precipitation, volatilization) among others. However, specific conditions must exist in the subsoil and groundwater so that the Chemical Substances of Interest are attenuated/stabilized over time, and the time required for the transformations.

If specific local conditions are not stabilized or sufficient to attenuate/stabilize contaminants within the expected time, a new action plan must be established, considering the area's environmental liability management strategy.

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Addressing the following comments will make this manuscript useful to many readers. - Title: bahia -> Bahia in India - mangrove? - non-woven --> nonwoven - specify length and angle of the slopes - Fator de Segurança --> Factor of safety - Table 2: Voltage? - Table 3: Unit of minimum geomembrane thickness. m -> mm. - Figure 1, 2: Resolution is insufficient. The text in these figures should be shown clearly. - Fig. 3 needs to be translated. - ...drainage layer working as reinforcement? what? - there is no stability analysis for geocells on slope. - References: Please check formats. Follow the paper template.