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Failure and Redesign of a Lightweight EPS Embankment on Soft Soil: A Case Study on Buoyancy and Stability from Brazil's BR-101 Highway

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Abstract

This study presents a comprehensive geotechnical evaluation of expanded polystyrene (EPS) as a lightweight fill material for embankments constructed over soft soils. Based on Brazilian case studies, with an emphasis on the duplication project of the BR-101 highway in Pernambuco, the research aims to assess the performance of EPS in terms of mechanical behaviour, settlement control, structural stability, construction efficiency, and cost-effectiveness when compared to conventional fill materials. To achieve this, the methodology incorporates a comprehensive literature review, combined with the analysis of experimental data obtained from field instrumentation (e.g., settlement plates, inclinometers) and laboratory testing (e.g., oedometer, triaxial, and vane shear tests), as well as a comparison with relevant design standards and normative safety criteria. As the results indicate, when properly designed and implemented, EPS can significantly reduce both vertical and horizontal stresses on the foundation soil. Furthermore, it effectively mitigates long-term settlements and improves overall embankment performance. In addition, due to its lightweight nature, EPS allows for faster construction and reduces the need for complex ground improvement techniques, thereby contributing to considerable savings in time and resources. Therefore, the results reinforce the feasibility of EPS and provide valuable field-based evidence for the use of lightweight materials in soft soil embankments, offering a robust and resilient solution for challenging geotechnical contexts.

Keywords: Expanded Polystyrene, Soft Soils, Lightweight Fill, Geotechnical Engineering, Embankment Stability, Settlement Control, BR-101 Highway, Civil Engineering, Ground Improvement, Geosynthetics.

1. INTRODUCTION

The construction of transportation infrastructure, such as highways and railways, frequently encounters challenging ground conditions, particularly the presence of soft, compressible soils. These soils, typically characterized by low shear strength, high water content, and high compressibility, pose significant geotechnical risks, including excessive total and differential settlements, bearing capacity failure, and global instability of embankments (Leroueil et al., 1990). Such issues can compromise the long-term serviceability and safety of the infrastructure, demanding substantial investments in ground improvement techniques. Traditional solutions, such as preloading with vertical drains, deep soil mixing, pile-supported embankments, and soil replacement, have been employed with varying degrees of success. However, these methods are often associated with high costs, extended construction schedules, and significant environmental impact (Duarte et al., 2016).

In response to these challenges, the use of lightweight fill materials has emerged as a technically efficient and economically viable alternative. By reducing the gravitational load imposed on the soft foundation, these materials directly address the root cause of instability and settlement. Among the available options, expanded polystyrene (EPS) geofoam has gained global acceptance over the past decades due to its exceptionally low density (typically 1% to 2% that of soil), high strength-to-weight ratio, and ease of handling (Stark et al., 2004). Its application ranges from embankment construction and slope stabilization to retaining wall backfill and void filling.

Several international case studies have demonstrated the success of EPS. For instance, the 'Almere approach' in the Netherlands involved the construction of embankments for residential roads over highly compressible peat and clay layers, where EPS successfully limited settlements to acceptable levels (Duskov, 1997). Similarly, in Norway, EPS was used for the reconstruction of highway sections over soft marine clays, proving to be a rapid and effective solution (Aabøe & Frydenlund, 2011).

In Brazil, the duplication of the BR-101 highway in the state of Pernambuco serves as a landmark project for the application of EPS in a tropical soft soil environment. The project provided a unique opportunity to evaluate the material's performance under challenging conditions, including a major flood event that acted as an unforeseen full-scale load test. Data from this and other national projects have confirmed the effectiveness of EPS in controlling settlements and ensuring stability (Souza, 2012; 2018). However, the design and implementation of EPS embankments are not without their own challenges, including considerations for long-term creep deformation, buoyancy, and durability when exposed to hydrocarbons (Sakamoto, 2018; Horvath, 1995).

This paper, therefore, aims to provide a critical and detailed evaluation of EPS geofoam as a lightweight fill in embankments over soft soils. Drawing extensively from the well-documented BR-101 case study, the research synthesizes field monitoring data, laboratory test results, and stability analyses to build a comprehensive understanding of the material's in-situ performance. The study critically discusses the design modifications made after a construction-phase failure, offering valuable lessons on risk management, particularly concerning hydraulic actions. By comparing the EPS solution with conventional alternatives in terms of technical performance, construction logistics, and economic cost, this work seeks to provide robust, evidence-based guidelines for geotechnical engineers considering this technology for infrastructure projects in similar challenging soil conditions.

2. METHODOLOGY

The methodology adopted in this study ensures a technically consistent approach aligned with the research objectives, which involve analyzing the applicability of EPS in infrastructure works on soft soils. A systematic literature review was conducted, incorporating peer-reviewed academic works in the field of geotechnical engineering. This qualitative approach is justified by the need to understand, compare, and interpret geotechnical parameters, construction methods, and results obtained from projects using EPS in Brazil.

The sources analyzed provide case studies of embankments built in critical areas, such as BR-101 in Pernambuco. The data extracted include results from vane shear tests, unconfined compression tests on EPS, settlement monitoring, vertical stress measurements, as well as cost and construction time. The information was organized into tables and graphical representations to enable direct comparison between EPS and traditional solutions.

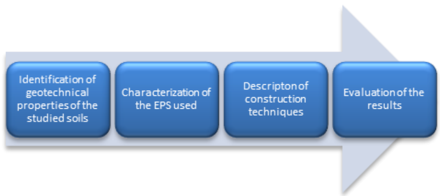

Figure 1 – Data extraction protocol

The analysis followed a four-step data extraction protocol. First, the geotechnical properties of the studied soils were identified to understand the subsurface conditions and their influence on embankment performance. Second, the expanded polystyrene (EPS) used in the project was characterized, including its physical and mechanical properties relevant to geotechnical applications. Third, the construction techniques employed in the field were described, highlighting the execution procedures and technical specifications adopted. Finally, the results were evaluated through a performance assessment of the implemented solution, allowing for a comprehensive analysis of its effectiveness and suitability under the given conditions.

3. CASE STUDY ANALYSIS: BR-101 HIGHWAY

The core of this study is an in-depth analysis of Embankment 3 from the BR-101 highway duplication project. To establish the foundational geotechnical conditions, the analysis began by compiling and interpreting data from the comprehensive site investigation program. This included results from Standard Penetration Tests (SPT), Cone Penetration Tests with pore pressure measurement (CPTu), and field vane shear tests (VST), which were collectively used to determine the soil stratigraphy and define key geotechnical parameters, such as the undrained shear strength (Su) and compressibility characteristics of the soft clay layers. Concurrently, the properties of the expanded polystyrene (EPS) blocks used in the project, were thoroughly reviewed. This characterization included critical design parameters such as density, compressive strength at 10% strain, and long-term creep behavior, based on manufacturer specifications and previous academic research.

To assess the structural integrity of the embankment, its stability was re-evaluated using the limit equilibrium method. The analyses were performed using the commercial geotechnical software GeoStudio SLOPE/W, implementing the rigorous Morgenstern-Price method, which satisfies both force and moment equilibrium. These numerical analyses considered two critical scenarios: the temporary condition at the end of construction with a surcharge, and the final, long-term configuration.

Furthermore, the risk of flotation, highlighted by the 2011 flood event, was also quantitatively assessed to verify the resilience of the revised design.

The analytical predictions were then validated against field performance monitoring data. This crucial step involved analyzing settlement records from settlement plates and horizontal displacement logs from inclinometers to evaluate the actual in-situ performance of the embankment. This empirical data not only confirmed the design assumptions but also allowed for the back-calculation of the soft soil foundation's consolidation parameters.

Finally, a holistic comparative analysis was conducted, where the executed EPS solution was critically compared with other potential solutions considered during the initial design phase, such as stone columns and soil-cement columns. This comparison was based on multiple criteria, including, technical feasibility and performance in terms of settlement and stability, construction time and logistical efficiency, overall project cost, and the associated environmental impact, thereby providing a comprehensive evaluation of the chosen solution's effectiveness.

This detailed, data-driven methodology ensures that the conclusions are robust and well-supported, providing a credible assessment of the performance and viability of EPS embankments over soft soils.

3.1. Study Area and Case Description

The adoption of EPS as an alternative to conventional fill represents an evolution in the concept of load relief in projects on soft soils. The reduction in settlement rates and the shorter execution time make this technique highly competitive, especially when compared to more expensive and time-consuming methods such as stone columns, piles, and complete soil replacement. However, its adoption still faces technical and cultural barriers, partly due to the lack of specific Brazilian standards and limited familiarity among professionals. It is therefore necessary to expand academic studies and technical training programs to consolidate EPS as a reliable engineering solution.

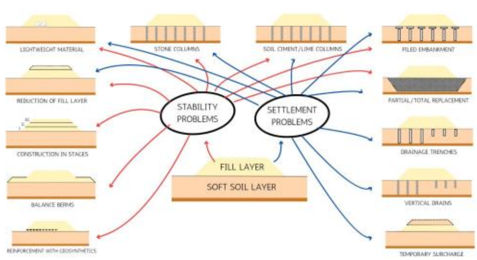

Figure 2 – Classification of Geotechnical Solutions for Embankments over Soft Soils According to Main Design Challenges (Moretti, 2010)

Figure 2 presents a conceptual diagram of geotechnical solutions applied to embankments built over soft soil layers, categorized according to the type of problem they address, stability or settlement. Solutions such as the use of lightweight materials, staged construction, balance berms, and geosynthetic reinforcement are primarily aimed at mitigating stability issues. By contrast, techniques like vertical drains, drainage trenches, and temporary surcharge are more effective in accelerating consolidation and reducing settlements. Some interventions, including stone columns, soil-cement/lime columns, and piled embankments, are shown to address both types of geotechnical challenges. The diagram highlights the complex interaction between soil improvement methods and the mechanical behavior of soft ground, emphasizing the need for integrated design strategies in the construction of stable and durable embankments.

Within the range of geotechnical innovations, the application of expanded polystyrene (EPS) emerges as a prominent solution due to its low density, mechanical efficiency, and ease of installation. In particular, this technique has shown considerable promise in scenarios where the foundation soil lacks sufficient bearing capacity to support conventional loads. Accordingly, studies by Souza (2012) and Sakamoto (2018) highlight that EPS, composed of approximately 98% air and only 2% polymeric matrix, has an exceptionally low unit weight, on the order of 0.2 kN/m³, which makes it nearly one hundred times lighter than typical soil. As a result, this property makes EPS especially suitable for embankment construction in contexts where load reduction is critical, such as bridge approaches, riverbanks, densely urbanized environments, and flood-prone areas. Moreover, as an inert and recyclable material, EPS provides environmental benefits by reducing the ecological footprint of civil engineering works. Finally, practical applications, such as those implemented along the BR-101 highway, exemplify its technical viability and confirm its effectiveness under real-world geotechnical conditions.

Figure 3 – Use of EPS at BR 101 highway, GOIANA-PE

3.2. Technical Background of the BR-101 Case Study

In Brazil, road transport constitutes the predominant mode of transportation, distinguished by its relative operational simplicity when compared with other modalities, such as air, rail, waterway, maritime, and pipeline systems. Although investments in the sector have increased in recent years, the country's road infrastructure still exhibits significant developmental gaps when compared to that of more industrialized nations.

Within this context of the evolving Brazilian highway network, there is a growing demand for more comprehensive and detailed studies regarding design and construction conditions, particularly for embankments built over soft soils. Modern engineering has made it possible to implement technical solutions that were previously unfeasible. Accordingly, this study presents multiple approaches to evaluating the geotechnical solution adopted for the embankment constructed over soft soils along the

BR-101 highway, near the city of Goiana, in the state of Pernambuco. The assessment takes into account both the shear strength parameters of the soft clay and the mechanical properties of expanded polystyrene (EPS), including considerations from the current project regarding the potential for EPS flotation.

Figure 4 – Embankments location (Souza, 2018)

This study aimed to assess the technical feasibility and geotechnical performance of using EPS as a lightweight embankment fill material in the BR-101 duplication project. The project area includes five embankments near the Goiana Waterway (Figure 4), each implemented with a distinct engineering solution. Embankment 1 was the only one entirely built according to the original detailed engineering design, involving total replacement of soft clay with sand, staged construction using vertical drains, and inclusion of geogrids and a sand drainage layer. Embankments 2 and 3 initially employed EPS blocks as lightweight fill. Following a failure caused by flooding in July 2011, revised designs were developed for both embankments, maintaining the use of EPS due to its cost-effectiveness and ease of installation without the need for specialized labor. Although EPS was initially considered for Embankment 4, subsequent hydrological studies, which identified a new maximum flood level of 5.55 m, led to the adoption of a structured embankment supported by steel piles (CS 300-109, Gerdau) arranged in a 2.93 m × 3.06 m grid with cap blocks. Finally, Embankment 5 was constructed using deep soil mixing with cement to form soil–cement columns. The initial Jet Grouting proposal intended to form a monolithic block; however, load tests revealed that the columns functioned effectively only as reinforced soil elements. Each embankment's design was based on comprehensive laboratory and field investigations to ensure compatibility with the local geotechnical profile (Souza, 2012; Souza, 2018).

3.3. Engineering Background and Embankment Design

Above the EPS layers, a 10 cm thick reinforced concrete slab was placed, serving as a protective and structural element for the embankment. This slab was followed by a layer of graded crushed stone (BGS), which functions to improve drainage and provide a stable base for subsequent layers. On top of the BGS, two layers of hot-mix asphalt concrete were applied, together totaling 11 cm in thickness, to ensure a durable and smooth driving surface. At the time of the exceptional flood on July 17, 2011, the construction of the EPS-based embankment solution was only partially completed, having reached up to the reinforced concrete slab stage. The figure below illustrates a typical cross-section of Embankment 03, showing the arrangement and layering of the materials used in its construction.

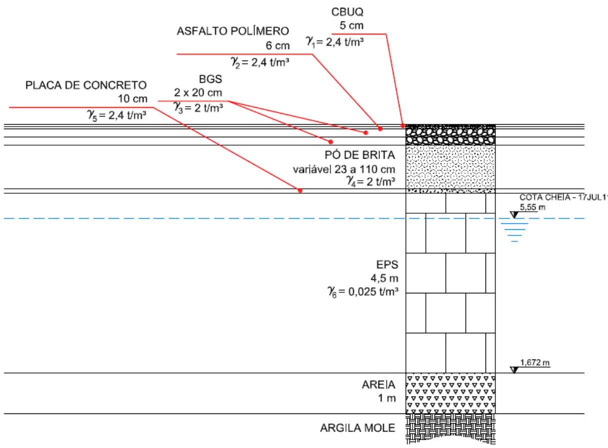

Figure 5 – Cross-section of embankment 3 (Souza, 2018)

In the initial design, the maximum flood elevation considered was 2.818 meters. However, on the date in question, the flood level reached 5.55 meters. As a result, due to several technical factors, the EPS embankment at Embankment 03, which was partially constructed at the time, failed and collapsed. The figures below illustrate the peak flood level and show the failure of Embankment 03.

Figure 6 – Peak flood level and Failure of Embankment 03

After the failure of the embankment constructed with lightweight material, the design for Embankment 3 was revised. In the original project, construction began with a 1.0-meter sand layer reaching elevation 1.672 meters. Above this, an EPS fill layer with a total thickness of 4.5 meters was placed. In the revised design, the thickness of the conventional fill (first-category material) is increased, thereby reducing the thickness of the EPS layer. The new EPS layer will have a thickness of 2.0 meters.

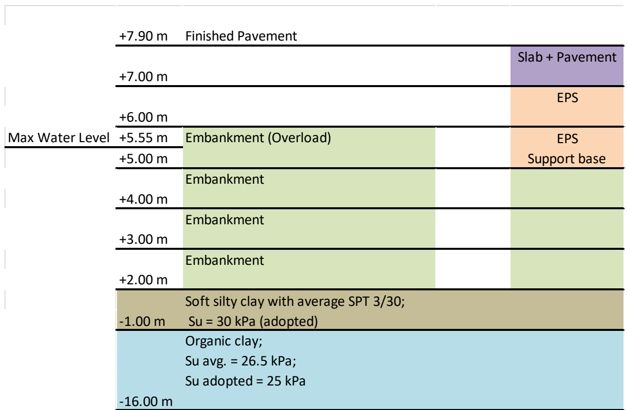

Figure 7 – New cross-section of embankment 03 (Geoprojetos, 2012)

Considering that the EPS must support at least 0.80 meters of pavement and 0.10 meters of reinforced concrete slab, the final design load, encompassing the combined weight of the EPS, concrete slab, and pavement layers, must remain lower than the load initially anticipated in the original embankment design. This requirement ensures that the lightweight fill continues to effectively reduce stresses transmitted to the underlying soft soils, preventing excessive settlement or instability. However, the revised design proposes an increase in the thickness of the conventional fill while simultaneously reducing the EPS layer thickness, thereby altering the load distribution within the embankment structure. Due to this change, it becomes necessary to implement a temporary surcharge of 1.0 meter of compacted material atop the embankment. This surcharge serves a critical role: it accelerates consolidation and settlement of the soft soil foundation, promoting stability before the final configuration is established. After allowing sufficient time for these settlements to occur, the excess surcharge material is carefully removed down to the planned EPS installation elevation, ensuring that the final load applied matches the design criteria. This staged construction approach balances the need for settlement control with the structural benefits provided by the lightweight EPS fill, demonstrating a thoughtful and adaptive engineering solution tailored to challenging ground conditions.

4. RESULTS AND DISCUSSION

4.1. Geotechnical Characterisation and Stability Evaluation

The strength parameters adopted for the soft soil layer were based on the arithmetic average of vane shear tests (Vane Tests) conducted on site. Between stakes 3349 and 3364, results were obtained at various depths from four tests: VT-3360-LD on 01/16/2009, VT-3360 on 06/21/2009, VT-3335 on 01/30/2008, and VT-3335 on 06/20/2009. (Moretti, 2012). After applying the corrections proposed by Bjerrum and disregarding inconsistent results, it was possible to estimate the average undrained shear strength of the soft soil layer.

The results obtained from the tests were plotted on a Su vs. Depth graph, shown below.

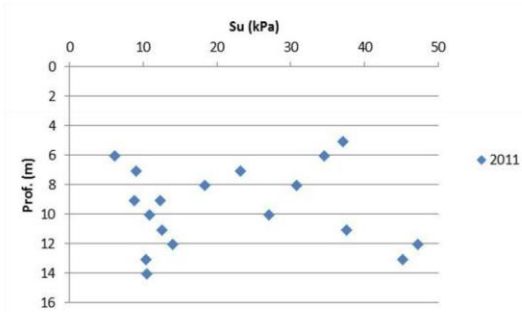

Figure 8 – undrained shear strength profile (Geoprojetos, 2012)

The analysis of the graph provided crucial insights that supported the determination of the soft soil layer parameters, which are essential for accurate geotechnical modeling and design. Among the key parameters identified was the estimated undrained shear strength (Su), determined to be 26.5 kPa. This value reflects the soil's resistance to shear stresses without drainage and is a critical factor in evaluating the stability and deformation characteristics of the soft soil deposit under embankment loading. Accurately estimating Su is fundamental to predicting settlement behavior and ensuring the embankment's structural integrity throughout its service life. By adopting this parameter, the engineering team was able to simulate realistic soil responses, guiding the choice of lightweight fill materials and the overall embankment configuration. This careful calibration of soil parameters highlights the importance of integrating detailed soil investigation data into engineering decision-making, particularly in challenging soft soil environments.

4.1.1 Global Stability Evaluation

The stability analyses were carried out in terms of total stresses, considering potential planar failure surfaces. The calculation method employed in the analyses was that of Morgenstern-Price, which is based on Limit Equilibrium Theory. The geotechnical parameters of the soil adopted in the stability analyses are presented in Table 1, having been determined based on SPT surveys and Vane Tests conducted.

Table 1 – Adopted geotechnical parameters (Geoprojetos, 2012).

SOIL	Su (kPa)	γ_{nat} (kN/m^3)	γ_{sat} (kN/m^3)	c' (kPa)	ϕ (°)
FILL	-	18.0	-	10.0	27
SOFT SILTY CLAY	30.0	-	15.0	-	-
SOFT CLAY	25 / 26.5	-	13.0	-	-

The results of these analyses are presented in Figures 9 and 10 below, providing a visual representation of the geotechnical behavior and stability assessment of the embankment. The focus was placed exclusively on the section exhibiting the greatest embankment height, as shown in Figure 7, since this represents the most critical and potentially vulnerable portion of the structure. Evaluations were conducted under two distinct conditions: the surcharge load condition, which simulates the temporary loading applied during construction, and the end-of-construction condition, reflecting the final state of the embankment after all materials have been placed and settlements have occurred. By concentrating on this critical section and these loading scenarios, the analysis ensures a conservative and robust assessment of stability. The calculated Safety Factors for these analyses, which provide quantitative measures of the embankment's resistance to failure, are summarized in the tables below. These values are instrumental in verifying that the design meets required safety standards and can withstand the expected loading throughout its lifespan.

Table 2 - Stability analysis under surcharge load condition (Geoprojetos, 2012).

FILL	PILE	Fill Thickness (m)	Surcharge Fill Thickness (m)	Safety Factor
#3	3350+10	3.00	1.00	1.7

Table 3 - Stability analysis at end-of-construction condition (Geoprojetos, 2012).

FILL	PILE	Fill Thickness (m)	EPS Thickness (m)	Traffic Surcharge (kPa)	Safety Factor
#3	3350+10	3.00	2.00	20	1.4

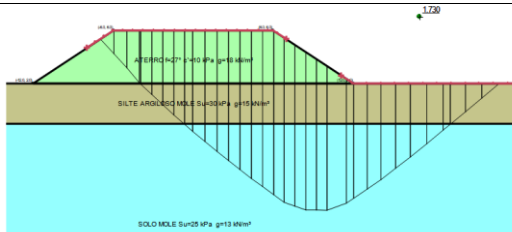

Figure 9 – Stability analysis under surcharge load condition (Geoprojetos, 2012).

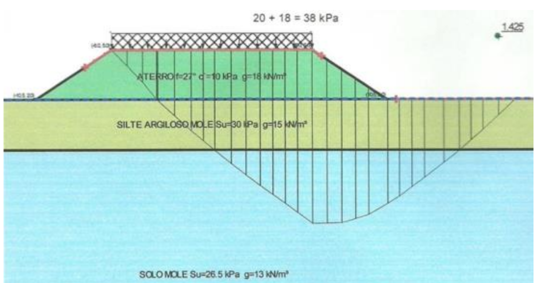

Figure 10 – End-of-construction stability (Geoprojetos, 2012).

The end-of-construction analysis yielded a safety factor (SF) of 1.4, which, although slightly below the commonly accepted threshold of 1.5, is deemed acceptable in the context of this project. The undrained shear strength parameter used in the analysis was conservatively estimated based on in situ vane shear tests, without incorporating strength gains from subsequent consolidation. This conservative approach likely underestimates the post-construction strength, thereby justifying the SF value observed. Similar behavior has been reported by Coutinho et al. (2010), who found that EPS embankments constructed over soft soils maintained long-term performance even with initial SF values close to 1.4.

4.1.2 Evaluation of Stability against Uplift Pressure

Only the section with the greatest embankment height (Figure 7), critical situation for the embankment in question, was evaluated with respect to water pressures due to submersion, under the end-of-construction condition. For this purpose, the maximum flood level elevation of 5.55 m was adopted, according to the exceptional flood that occurred on July 17, 2011. The table below shows the minimum elevation of the EPS blocks and the reported maximum elevation:

Table 4 – Elevation Data for Uplift Pressure Evaluation

EMBANKMENT	Base of Blocks (m)	Maximum River Level (m)
#3	5.00	5.55

According to the table above, the possibility of flotation must be evaluated due to the submersion of 0.55 m of embankment with EPS.

The Factor of Safety against flotation will be equal to:

$$SF = \frac{T_{v1}}{T_{v2}} \geq 1{,}50$$

where:

$$T_{v1} - \text{Vertical downward stress (weight of the materials)}$$
$$T_{v2} - \text{Vertical upward stress (pore water pressure)}$$

The weights of the materials and their respective thicknesses are:

Table 5 - weights of the materials and their respective thicknesses

MATERIALS	Thickness (m)	Specific Weight (t/m³)
Graded pavement gravel	0.45	2.0
Fill (soil)	0.35	1.8
Concrete	0.10	2.2
EPS	2.0	0.02

Vertical downward stress (T_{v1}– weight of the materials above the water table):

$$T_{v1} = 0.45x2.0 + 0.35x1.8 + 0.1x2.2 + 2.0x0.02 = 1.79\ t/m^2$$

Vertical upward stress (T_{v2} – pore water pressure):

$$T_{v2} = (5.55 - 5.00)x1.0 = 0.55\ t/m^2$$

Therefore:

$$SF = \frac{1.79}{0.55} = 3.254$$

Therefore, the Safety Factor is acceptable and there is no risk of flotation.

However, it is important to note that the geometry of the solution may lead to the accumulation of rainwater inside the embankments, which could result in the formation of additional negative pore pressure due to infiltration. To minimize this possibility, the project includes the installation of horizontal drainage lines, using geodrain or a similar system, along the embankment, as shown in the project drawings.

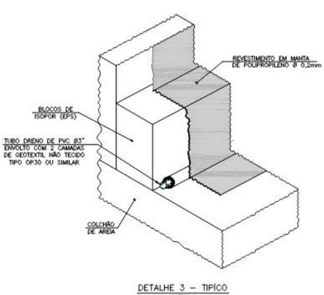

Figure 11 – Detail of geodrain (Geoprojetos, 2012)

4.2 Comparative Analysis of Engineering Solutions

A comparison was carried out among possible engineering solutions for the development of an executive project following a flood, aimed at the stabilization and foundation improvement of Embankment 3. Based on the technical characteristics of each solution, Table 6 was structured according to Moretti (2010), presenting the advantages and disadvantages of each alternative.

Table 6– Advantages and Disadvantages of Each Solution (Moretti, 2010).

METHOD	ADVANTAGES	DISADVANTAGES
STONE COLUMNS	1) Permeable columns; 2) Easy to execute; 3) Gain in undrained shear strength of soft soil after pore pressure dissipation.	1) Long-term stability is difficult to predict; 2) Variability in column diameter; 3) Soft soil bulging during installation; 4) Limited material availability in the region.
SAND COLUMNS WITH GEOSYNTHETIC	1) Permeable columns; 2) Easy to execute; 3) Gain in undrained shear strength of soft soil after pore pressure dissipation, due to column confinement by the geosynthetic.	1) Limitation in column diameter due to geosynthetic geometry; 2) Soft soil bulging during installation; 3) Lack of technical experience in the field regarding column performance.
COMPACTION GROUTING	1) Permeable columns; 2) Easy to execute and non-destructive technique; 3) Gain in undrained shear strength of soft soil after pore pressure dissipation.	1) Soft soil bulging during installation; 2) Lack of technical experience in Brazil.
SOIL-CEMENT COLUMNS	1) Greater number of contractors available; 2) Material availability; 3) Improvement of soft soil geomechanical properties.	1) Lack of specialized labor; 2) High cement consumption.
EPS EMBANKMENT	1) Use of conventional labor; 2) Shorter construction time compared to other methods; 3) Reduction of vertical stresses induced by the embankment.	1) Existing fill must be removed; 2) Lack of technical experience in Brazil.

The types of EPS blocks used in the construction activities along the BR-101 highway were categorized into three distinct formats, defined according to their geometric dimensions. This variation in block sizing was necessary to accommodate the specific geometric and structural requirements of each embankment section, ensuring efficient material placement and overall embankment stability. The selection of block types was based on optimizing spatial distribution and minimizing voids during installation. Table 7 presents the dimensions of the EPS blocks employed in the project.

Table 7 – Dimension of EPS Blocks Used on BR-101

Block Type	Dimensions (A × B × C) [m]
Type A	1.25 × 1.00 × 4.00
Type B	1.25 × 0.50 × 4.00
Type C	1.00 × 0.625 × 4.00

Table 8 – Quantity and Volumes of EPS Blocks Used on embankment 3

TYPE	Quantity	VOLUME [m³]
Type A	1000	5000
Type B	-	-
Type C	340	850
Total Volume	—	5850

Tables 9 and 10 present the minimum technical specifications of the materials used in the lightweight embankment solution applied to Embankment 3. Table 9 summarizes the mechanical and physical properties of the expanded polystyrene (EPS) blocks, including density, compressive strength, and flexural and shear resistance, based on standardized tests (Moretti, 2010). Table 10 details the properties of the geomembrane employed as a protective and sealing layer over the EPS, including tensile behavior, puncture and tear resistance, carbon black content, and burst strength, also according to relevant ASTM standards (Moretti, 2010). These material properties were essential to ensure performance under operational and environmental conditions in the soft soil context of the BR-101 project.

Table 9 – Characteristics of the EPS used (Moretti, 2010)

PROPERTY	TEST STANDARD	UNIT	TYPE 5
Nominal apparent density	NBR 11949	kg/m³	22.5
Minimum apparent density	NBR 11949	kg/m³	20
Compressive strength at 10% deformation	NBR 8082	kPa	110
Minimum flexural strength	ASTM C-203	kPa	220
Minimum shear strength	EM-12090	kPa	110

Table 10 – Characteristics of the geomembrane used (Moretti, 2010)

PROPERTY	TEST STANDARD	UNIT	1.0 mm
Thickness	ASTM D1599	mm	nominal
Minimum apparent specific mass	ASTM D1505/D792	g/cm³	0.94
Tensile strength at yield (avg. min.)	ASTM D6693 Type IV	kN/m	15
Elongation at yield (avg. min.)	ASTM D6693 Type IV	%	12
Tensile strength at break (avg. min.)	ASTM D6693 Type IV	kN/m	27
Elongation at break (avg. min.)	ASTM D6693 Type IV	%	700
Minimum tear resistance	ASTM D1004	N	125
Minimum puncture resistance	ASTM D4833	N	320
Carbon black content	ASTM D1603	%	2 to 3
Burst strength	ASTM D3786	kPa	150

The performance data collected from EPS-based embankment projects demonstrated clear advantages in terms of global stability and differential settlement control. EPS's low specific weight significantly reduces the vertical stresses transmitted to soft foundation soils, which, in turn, decreases primary settlement and improves the long-term structural performance of the pavement layers. This benefit is particularly relevant for organic or highly compressible clays, as found in the BR-101 project. These findings are consistent with those of Galdino et al. (2018) and Souza (2012), who reported settlement reductions exceeding 60% and noted improvements in stability and load distribution. Therefore, EPS emerges as a technically sound solution for critical infrastructure built over weak subgrades.

A market study was previously conducted in July 2010 by a company contracted by DNIT, which identified the EPS embankment as the most economically advantageous solution.

Table 11 - GLOBAL STABILITY ANALYSIS (Moretti, 2010)

SOLUTION	SAFETY FACTOR (SF)
Gravel columns	1.47
Sand columns confined by geosynthetics	1.51
Compaction grouting	1.56
Graded gravel columns treated with cement	1.52
Soil-cement columns	1.49
Lightweight fill material	It was verified that the existing stresses (14.2 kPa) were of the same order as those with the use of EPS (14.1 kPa) No fluctuation issues were observed for the maximum groundwater level over a 100-year return period (elevation 2.85 m)

Therefore, in this study, a new price survey was carried out using July 2025 as the reference date, with the aim of verifying whether the EPS embankment remains the most cost-effective alternative.

Table 12 - Geometric and Geotechnical Comparison of the Solutions (Moretti, 2010)

SOLUTION	TRIANGULAR SPACING (m)	COLUMN DIAMETER (m)	NUMBER OF COLUMNS PER m²	Ac/Ae Ratio (%)
Sand Columns	1.70	0.80	5.50	14
Gravel Columns	2.10	0.78	8.15	25
Compaction Grouting	1.60	0.60	9.38	29
Soil-Cement Columns	1.60	0.80	7.07	19
Graded Gravel Columns Treated with Cement	1.60	0.50	7.86	7

Table 12 presents a comparative assessment of five ground improvement solutions based on their geometric configurations and geotechnical efficiency. The solutions include sand columns, gravel columns, compaction grouting, cement-stabilized soil, and Graded gravel columns treated with cement.

To estimate the cost of each engineering solution, several boundary conditions were established to accurately reflect the logistical and technical realities of the segment under analysis. The disposal site distance was set at 5 km, corresponding to the nearest suitable areas for receiving excavated material from the experimental section. The EPS embankment was designed with a slab thickness of 10 cm and a reinforcement ratio of 50 kg/m³, both based on the executive design prepared by Moretti in 2010. Additionally, the specific mass of the EPS blocks was considered to be 25 kg/m³, following the same design reference. Construction losses were estimated at 10% to account for material wastage during execution. The unit price for EPS includes delivery to the construction site, identified as the most logistically viable option for the Brazilian Army. Similarly, the unit cost for the soil-cement solution encompasses equipment mobilization, site setup, labor, and cement consumption, which also represent the preferred logistical approach for the Brazilian Army in this project. Based on these assumptions, the values in the tables are presented per meter of section for each solution.

4.2. Discussion: Performance, Failure, and Lessons Learned

The performance of the EPS embankment at the BR-101 site, both before and after the redesign, provides several crucial insights. The primary advantage of the EPS was the drastic reduction in net stress applied to the soft foundation. A conventional soil embankment of the same height would have induced settlements on the order of metres; the EPS solution limited the predicted and measured long-term settlements to a few centimetres, well within the tolerable limits for a highway pavement.

The failure event of 2011, while unfortunate, served as an invaluable lesson. It highlighted that for lightweight structures in flood-prone areas, the hydraulic actions can become the most critical design load, surpassing the gravitational loads. The failure was not one of bearing capacity or internal stability of the soil mass, but rather a flotation-induced failure of the EPS block assembly. This underscores the absolute necessity of incorporating robust anti-flotation measures in the design, a consideration that is now a standard of practice but was less emphasized at the time. The revised design, which effectively used the upper soil layers as a permanent ballast, is a simple yet effective approach to mitigate this risk.

Comparing the BR-101 experience with international cases, the challenges and solutions are remarkably similar. The need for a protective layer or slab on top of the EPS to distribute traffic loads and protect against fuel spills is a common feature in designs from the USA, Japan, and Europe (Stark et al., 2004). Furthermore, the observation of reduced horizontal pressures against the bridge abutment at Embankment 3 is consistent with findings from instrumented retaining walls backfilled with EPS, which report a significant reduction in lateral earth pressures (Horvath, 1995).

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Table 13 – Crushed stone column

Description	Unit	Unit Price (R$)	Quantity/m	Total Price (R$/m)
Crushed stone delivered to site	m³	205,15	73,75	15128,87
Execution of granular column with closed-end vibratory tube (Ø≈80cm)	unit/m	323,67	146,71	47486,60
Pre-drilling in embankment layer for granular column (Ø≈80cm)	m	215,78	16,30	3517,52
Pavement execution	m	5394,43	1	5394,43

Site facilities	%	6.00%		4291,65
Mobilization	%	2.66%		1902,64
TOTAL				77721,70

Table 14 – Sand column

Description	**Unit**	**Unit Price (R$)**	**Quantity/m**	**Total Price (R$/m)**
Sand delivered to site	m³	129,47	49,75	6451,74
Execution of granular column with closed-end vibratory tube (Ø≈80cm)	m	323,67	98,97	32034,61
Geosynthetic resist. 100/200kN/m (M=98.00m)	m	364,12	98,97	36038,92
Pre-drilling in embankment layer for granular column (Ø≈80cm)	m	215,78	16,30	3517,52
Labor for pavement execution	m	5394,43	1	5394,43
Site facilities	%	6.00%		4961,53
Mobilization	%	2.66%		1833,89
TOTAL				90232,63

Table 15 – Compaction Grouting

Description	**Unit**	**Unit Price (R$)**	**Quantity/m**	**Total Price (R$/m)**
Execution of compaction grouting column (Ø≈60cm)	m³	539,44	168,87	91097,06
Pre-drilling in embankment layer for compaction grouting	m	53,94	12,76	688,41
Pavement execution	m	5394,43	1	5394,43
Site facilities	%	6.00%		3478,49
Mobilization	%	2.66%		2593,64
TOTAL				103252,03

Table 16 – Cement-treated graded crushed stone column

Description	**Unit**	**Unit Price (R$)**	**Quantity/m**	**Total Price (R$/m)**
Drainage layer with sand, thickness 0.5m	m²	106,19	11	1167,95
Polyethylene geogrid, resist. transverse 200kN/m, longitudinal 200kN/m	m²	142,49	15	2137,41
Graded gravel treated with cement (5% cement)	m³	391,10	27	10559,60
Execution of granular column with closed-end vibratory tube (Ø≈50cm)	m	269,72	141,53	38173,68
Pre-drilling in embankment layer for granular column (Ø≈50cm)	m	215,78	16,3	3517,52
Pavement execution	m	5394,43	1	5394,43
Mobilization	%	2.66%		2017,41
Site facilities	%	6.00%		4703,94
TOTAL				67671,93

Table 17 – Cement-soil Column

Description	**Unit**	**Unit Price (R$)**	**Quantity/m**	**Total Price (R$/m)**
Drainage layer with sand, thickness 0.5m	m²	106,19	11	1167,95
Polyethylene geogrid, resist. transverse 200kN/m, longitudinal 200kN/m	m²	142,49	15	2137,41
Execution of cement-soil column (Ø≈80cm)	m	778,77	127,31	99146,03
Pavement execution	m	5394,43	1	5394,43
TOTAL				107845,82

Table 18 – Lightweight Embankment

Description	Unit	Unit Price (R$)	Quantity/m	Total Price (R$/m)
Excavation, transport of material (1st CAT, DMT 3000 to 5000m/load)	m³	42,43	18,27	775,26
Compaction of embankments at 95% Proctor Normal	m²	7,50	9,93	74,52
Structural concrete FCK=15MPa – casting according to general specifications	m³	764,09	1,29	986,94
Steel supply CA-50	Kg	16,08	56,72	909,07
Spreading and compaction of backfill	m²	50,52	19,39	979,12
EPS blocks (5000x1250x1000mm)	m³	113,31	44,94	5848,91
Nonwoven geotextile, PEAD, textured geomembrane 1.0mm	m²	21,44	101,31	2172,42
Pavement	m	5394,43	1	5394,43
Embankment execution	m	40,54	44,94	1821,73
Site facilities	%	6.00%		4260,39
Mobilization	%	2.66%		1846,16
TOTAL				76302,54

Finally, the economic analysis confirmed the cost-effectiveness of the EPS solution. While the material cost per cubic metre of EPS is higher than that of conventional soil fill, the overall project cost is reduced due to several factors like elimination or reduction of costly ground improvement Works, faster construction, leading to lower equipment and labor costs and earlier opening of the highway to traffic and reduced transportation costs, as one truck of EPS replaces dozens of trucks of soil. This holistic economic advantage, demonstrated in Figure 12, is a key driver for the adoption of this technology.

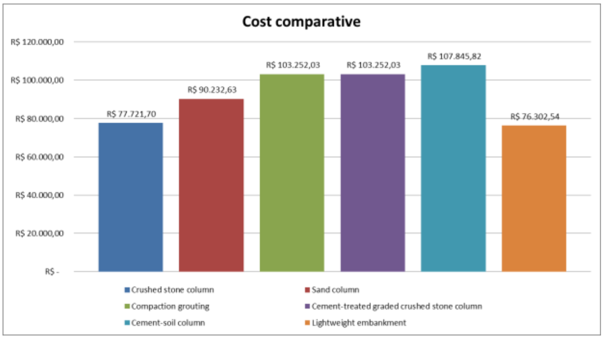

Figure 12 – Solutions cost comparative

5. CONCLUSION

The use of expanded polystyrene (EPS) as an alternative material in embankments on soft soils has proven to be a technically, economically, and environmentally viable solution. The data presented in this study, indicate that EPS effectively reduces load on low-strength subgrades, significantly limits settlements, and enhances overall system stability. In addition, the construction process is simplified and fast, making EPS a favorable alternative when compared to conventional methods. This approach aligns with the demands of modern engineering, which seeks to combine structural performance with resource efficiency and reduced environmental impact.

Case studies such as the BR-101 in Goiana (PE) demonstrated concrete benefits with EPS application. Settlement reductions exceeding 60%, global cost savings of up to 20%, and execution times cut in half were recorded when compared to conventional solutions (Souza, 2018). EPS also showed good compatibility with various types of soft soils and was applicable even in critical areas with water presence or differential displacements. Another positive aspect was its environmental performance, since EPS is recyclable, inert, and contributes to reducing the extraction of natural resources used in traditional embankments.

Despite these benefits, EPS application requires specific care regarding project design and execution. The lack of detailed Brazilian technical standards on the use of EPS places greater responsibility on the design engineer, who must have adequate technical knowledge. Aspects such as fire resistance, resistance to biological agents, and chemical stability must be properly addressed. Additionally, training skilled labor and encouraging applied research are fundamental steps toward large-scale adoption of this technology in Brazil. The national experience is still recent, but promising, especially when associated with good practices in project development, supervision, and instrumentation.

Due to its low specific weight, EPS is inherently vulnerable to buoyant forces, especially in flood-prone zones. The failure of Embankment 3 was directly linked to an exceptional flood event, which exceeded design flood levels by more than 2.5 meters. This highlights the critical importance of adopting robust anti-flotation measures, such as ballast layers, anchoring systems, or scheduling construction during dry periods, in the design of EPS embankments. This consideration is especially relevant in tropical regions with unpredictable precipitation patterns and underscores the need for conservative hydraulic design criteria when employing ultralight materials.

Based on the results of this study and the analysis of Brazilian case histories, the following recommendations are proposed to ensure the effective and safe implementation of EPS in soft soil embankments.

The set of recommendations herein referenced encompasses strategic directives aimed at advancing the technical, operational, and environmental performance of EPS-based solutions in geotechnical engineering. These directives advocate for the development and institutionalization of standardized national design guidelines, with emphasis on resistance to uplift pressures, fire performance criteria, and long-term material durability. In scenarios characterized by high groundwater levels or susceptibility to inundation, the incorporation of ballast layers or anchorage mechanisms, such as geogrids or micropiles, is recommended to ensure the stability and confinement of EPS blocks, thereby mitigating flotation risks.

Furthermore, the implementation of comprehensive geotechnical monitoring systems, including settlement plates, piezometers, and inclinometers, is essential for the accurate assessment of embankment behavior both during the construction phase and throughout its operational lifespan. Regarding construction logistics, it is advised that EPS installation be scheduled during dry climatic periods to reduce the likelihood of flood-induced displacement or structural compromise, particularly in regions with pronounced seasonal rainfall variability.

In parallel to these engineering measures, the recommendations underscore the critical role of professional capacity-building initiatives and the systematic dissemination of successful case studies as mechanisms to consolidate technical expertise and promote broader institutional acceptance of EPS technologies within infrastructure development frameworks. Additionally, the evaluation of environmental performance indicators, through comparative analysis with conventional fill materials, is vital to support evidence-based decision-making aligned with sustainable infrastructure objectives.

EPS constitutes a technically feasible and sustainable solution for embankment construction on soft soils, demonstrating substantial benefits in terms of settlement control, execution time, and cost reduction. Its successful application in national infrastructure projects reinforces its potential for broader implementation, contingent on appropriate engineering design and regulatory development. Its use can be strategically incorporated into the portfolio of geotechnical solutions, provided it is supported by technical studies, numerical simulations, field monitoring, and progressive standardization. Continued research and widespread dissemination of knowledge are essential steps for EPS to become a reference solution in sustainable and resilient infrastructure design in Brazil.

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