

Stability Assessment of Embankments on Soft Soils in Goiana-PE, Brazil

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ABSTRACT: Embankments built on soft soils represent a significant challenge in geotechnical engineering due to the complexity associated with low shear strength, low permeability and high compressibility of the foundation soil. This paper aims to understand and analyze the behavior of two embankments built on soft soils through an integrated approach that combines field tests, laboratory tests, instrumentation and embankment stability control methods. The analysis seeks to correlate the parameters obtained in field and laboratory tests with field instrumentation data to evaluate the performance of the embankments and the instability mechanisms, identifying failure risks and providing subsidies for design and decision making. In the field, standard penetration tests (SPT), vane tests and undisturbed samples collection were performed. In the laboratory, the samples were subjected to physical characterization, oedometric and triaxial (UU) tests. Geotechnical monitoring included the interpretation of data from inclinometers, settlement plates, surface markers and pneumatic piezometers. This paper focuses on presenting the results obtained from the inclinometer measurements. Field and laboratory tests were discussed in an integrated manner. Through the stability control methods employed, an imminent rupture in Embankment 5 was identified, which was later confirmed. It was also possible to observe that Embankment 3 was heading for rupture, which did not occur due to the stoppage of the work after the rupture of Embankment 5. These results were also observed in the stability analyses conducted to determine the embankment's factor of safety. The results reinforce the importance of an integrated approach, which combines field data, laboratory tests and geotechnical monitoring, to accurately assess the behavior of landfills on soft soils. In addition, stability control should be performed through multiple methods, considering the various variables involved.

KEYWORDS: Embankment on soft soil, geotechnical monitoring, stability control.

1 INTRODUCTION

The construction of embankments over soft soils is among the most significant challenges in geotechnical engineering, particularly in large-scale infrastructure projects. The combination of low shear strength and high compressibility, typical of such deposits, poses significant risks to the stability and performance of the structure, potentially resulting in failures, schedule delays, and high remediation costs. This scenario is prevalent in coastal regions and floodplain areas, where these soils directly influence the design and execution of highways and other linear works.

Under such conditions, settlement and stability control require specific strategies that reconcile safety, functionality, and economic feasibility. Geotechnical monitoring, combined with observational methods and established stability control criteria (Coutinho and Bello, 2011; Almeida et al., 2000), has proven to be an essential tool for risk management in this type of project. The systematic interpretation of instrumentation data enables the early identification of instability trends, allowing corrective or preventive interventions to be implemented promptly.

Case studies are a fundamental resource for advancing technical knowledge, as they provide empirical evidence capable of validating, refining, and adapting design and monitoring methodologies to actual field conditions. Furthermore, they allow us to understand structural behavior during the different construction phases, providing a basis for developing more effective guidelines in complex geotechnical contexts.

In the Recife Metropolitan Region (RMR), located in the state of Pernambuco, Northeastern Brazil, the occupation of areas with thick layers of soft soils is compounded by rapid urban expansion. The technical literature presents several studies on the soft clays of this region (Coutinho, 1980; Ferreira et al., 1986; Coutinho and Oliveira, 1994; Cavalcante et al., 1998; Coutinho et al., 2000; Oliveira, 2002; Coutinho, 2007), as well as on the specific geotechnical characteristics of the municipality of Goiana, located to the north of the RMR (Xavier, 2007; Souza, 2012).

This study falls within this context and addresses a practical case related to a highway project in the state of

Pernambuco, carried out under an agreement between the Brazilian Army and the National Department of Transport Infrastructure (DNIT). The project aimed at the duplication and rehabilitation of the BR-101/PE (Lot 6), with approximately 41 km of extension under different geological conditions. In a segment of about 4 km, the duplication involved embankments over soft soils located in the Goiana floodplain, where five such embankments were built.

The focus of the analysis is Embankment 5, which has a length of 320 m. It was constructed in stages and equipped with prefabricated vertical drains (PVDs) to accelerate pore pressure dissipation, but it failed during construction. Additionally, results from Embankment 3 are presented, allowing for a broader understanding of these structures' performance and an assessment of the effectiveness of geotechnical monitoring as a stability control tool.

2 METHODOLOGICAL PROCEDURES

Characterizing materials and systematically monitoring embankment behavior over time are fundamental steps for stability analysis in works executed over soft soils. This section presents the study area, the construction history, and the procedures adopted in the geotechnical investigation, including field tests, laboratory tests, and the instrumentation installed for monitoring.

The study area is in the municipality of Goiana, in Pernambuco, Northeastern Brazil. It comprises a segment of the BR-101 highway built over soft soil deposits, where several embankments were constructed. The study focuses on the so-called Embankment 5, located between stakes 3474 and 3490, with an approximate length of 320 m, which experienced a failure in the stretch between stakes 3480 and 3488 (Figure 1). Additionally, results from Embankment 3 are presented to broaden the understanding of structural behavior and evaluate the effectiveness of geotechnical monitoring as a stability control tool.

The field investigation campaign involved 11 standard penetration test (SPT) borings, with an average depth of 20 m, and six field vane shear tests to determine the undrained shear strength at specific depths. Six undisturbed samples were

collected using thin-walled Shelby tube samplers to obtain representative specimens of the soft soils found in the area.

In the laboratory, the samples were subjected to physical characterization tests—including grain size distribution, Atterberg limits, and specific gravity—oedometer (consolidation) tests to determine compressibility properties, and unconsolidated undrained (UU) triaxial tests to assess shear strength. All tests followed the procedures recommended by current technical standards, ensuring the reliability of the results.

Geotechnical monitoring was performed by installing four inclinometers in Embankment 5 (Figure 2) and three in Embankment 3. The equipment was positioned strategically, considering critical stability areas and zones with greater thickness of soft soils, to record horizontal displacements during and after the construction stages. The information obtained was used to compare the actual behavior of the structures with the design predictions, enabling the application of well-established stability analysis methods and reinforcing the importance of monitoring as a risk management tool in projects built over soft soils.

3 RESULTS AND DISCUSSION

3.1 SITE CHARACTERIZATION

The region is part of the Borborema Province and is of Precambrian age. It has a humid tropical climate, with a rainy season concentrated in autumn and winter. Geomorphologically, the studied section is located in a coastal floodplain characterized by the predominant deposition of fine-grained and organic sediments largely associated with fluvio-lagoonal and estuarine environments.

The local geology comprises lithotypes from the Salgadinho and Vertentes complexes, the Beberibe Formation, the Barreiras Group, and alluvial, fluvio-lagoonal, and fluvio-marine deposits. The Barreiras Formation has the largest surface area, while the crystalline basement crops out only in restricted areas in the western portion of the municipality, forming hills.

In the area between the Goiana River, the adjacent mangroves, and the BR-101 highway—where the studied section is located—fluvio-lagoonal deposits predominate, consisting of alluvial, lagoonal, deltaic, and estuarine sediments of varying ages. These materials include significant amounts of clayey and organic soils, with the frequent presence of peat layers in areas of low flow velocity. This is relevant in geotechnical engineering due to their high compressibility and low shear strength.

Figure 3 presents a representative cross-section of Embankment 5, based on SPT boring SP-22, showing the stratigraphy along the embankment axis. It should be noted that there are no documentary records regarding the construction method used for the pre-existing carriageway embankment. However, the geometry inferred from the borehole data suggests the possibility of failures during execution or progressive instabilities over time, possibly associated with continuous loading on the underlying soft soils.



Figure 1. General view of the failure in Embankment 5

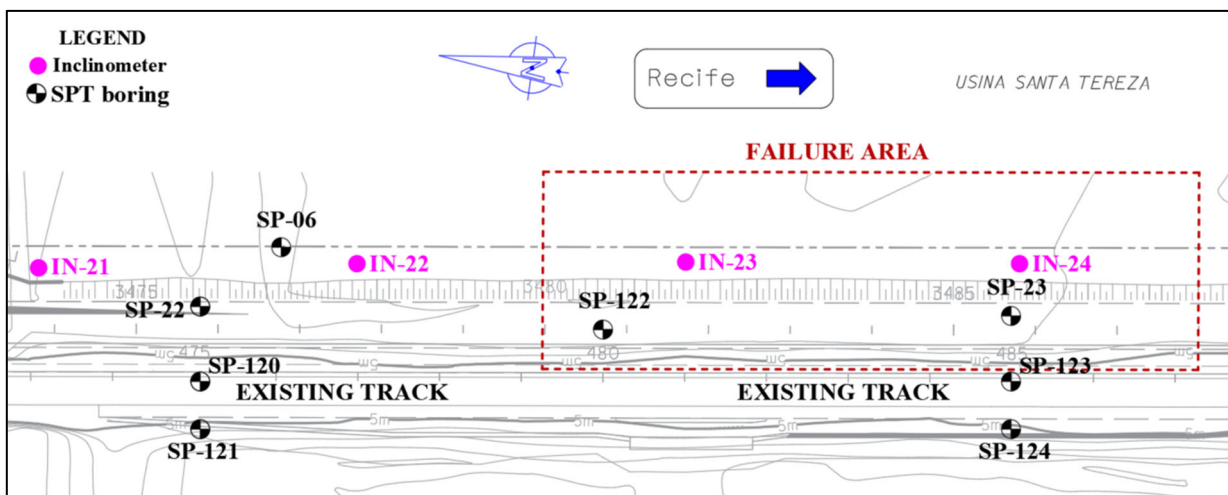


Figure 2. Location of the Geotechnical Instrumentation Installed in Embankment 5

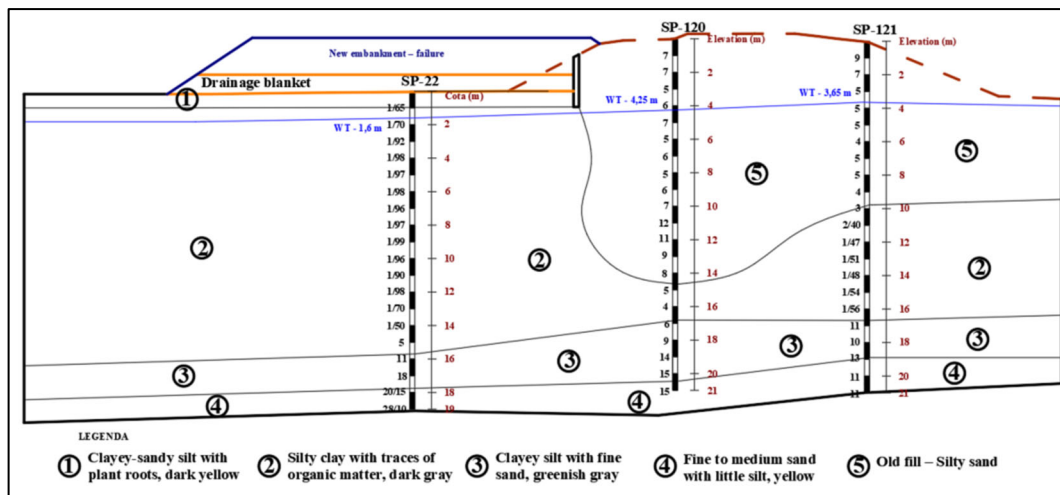


Figure 3. Geological-geotechnical profile – Embankment 5

3.2 Laboratory tests

The physical characterization of the soft soil deposits in the study area was carried out through grain size distribution tests, determination of Atterberg limits (liquid limit and plastic limit), and determination of specific gravity of solids, using procedures recommended by technical standards. The results are presented in Table 1.

Samples were collected at different depths in the embankments analyzed, generally exhibiting similar behavior. In the case of Embankment 5, the sample collected at a depth of 2 m showed clay fraction, natural moisture content (W_n), plasticity index (PI), and void ratio values slightly lower than those observed in the deeper samples. This difference suggests that the surface layer has lower compressibility and plasticity, characteristics that may locally influence settlement behavior and the stability of the structure.

Figure 4 shows the comparison between natural unit weight (γ_{nat}) and natural moisture content (W_n), as well as between liquid limit (LL) and plasticity index (PI), using the geotechnical database of the Recife Metropolitan Region (RMR) as reference. This analysis allowed positioning the results obtained for Goiana-PE, for Embankments 5 and 3, within the regional context. Overall, good agreement was observed between the measured parameters and the characteristic values of the soft soils in the RMR, which provides confidence in the results.

Nevertheless, it is important to emphasize the need to expand the number of specific tests in the Goiana region in order to build a more comprehensive local database. A more robust database will allow more accurate stability analyses, better calibration of numerical models, and the development of more appropriate engineering solutions for works constructed in floodplain areas over highly compressible soils.

Assessing the quality of the samples collected is a critical step when working with soft soils, as disturbances occurring during sampling, transportation, or storage can significantly compromise laboratory test results. Low-quality samples tend to provide inconsistent compressibility, shear strength, and permeability parameters, which can lead to misinterpretations of deposit behavior and, consequently, inadequate design decisions.

Figure 5 presents the curves of void ratio (e) variation as a function of effective vertical consolidation stress (σ'_v) obtained in the laboratory, along with the field reconstruction curves proposed by Schmertmann (1953) and the curve estimated according to Oliveira (2002). These representations allow the evaluation of clay compressibility under different conditions and the comparison of laboratory-measured behavior with that estimated for the original in situ conditions.

According to the sample quality classification criterion proposed by Coutinho (2007), the material was initially classified as very poor (Table 2). However, after applying the corrections suggested by Schmertmann (1995) and Oliveira (2002)—aimed at reconstructing parameters to approximate them to in situ conditions—an improvement in the classification was observed, reinforcing the importance of this adjustment for a more realistic assessment of soft soil behavior.

The use of such corrections is recommended when it is not possible to obtain high-quality samples, as they help reduce uncertainties associated with the interpretation of laboratory results and provide parameters closer to reality for stability analyses, settlement predictions, and the design of solutions in highly compressible soils. However, it is important to emphasize that the best practice in geotechnical engineering is to adopt field and laboratory procedures that ensure the acquisition of excellent-quality samples, minimizing the need for subsequent corrections.

Tabela 1. Resultados da caracterização física

Embankment	Stake	Depth (m)	Grain size distribution				w_n (%)	WL (%)	PI (%)	γ_{nat} (kN/m ³)
			C	M	SF	SM				
3	3359	6	66	26	8	0	102,41	64,0	34,0	14,54
		10	46	24	28	2	63,74	41,0	21,0	15,73
		14	69	26	5	0	64,80	69,0	36,0	15,71
5	3475	2	62	28	10	0	99,9	64	25	14,4
		6	78	20	2	0	120,4	65	26	13,8
		11	74	20	6	0	126,3	71	30	14,0

C – Clay; M – Silt; SF – Fine sand; SM – Medium sand

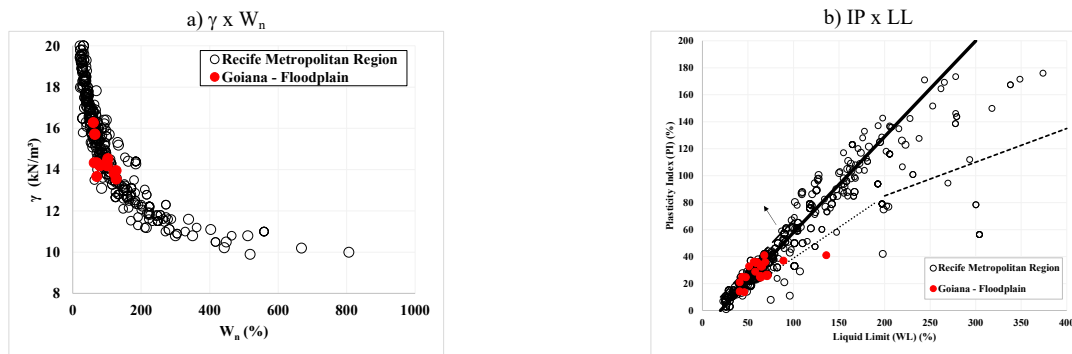


Figure 4. Correlation of geotechnical characterization results with the Recife Metropolitan Region (RMR) database. Source: Souza Neto, 2023

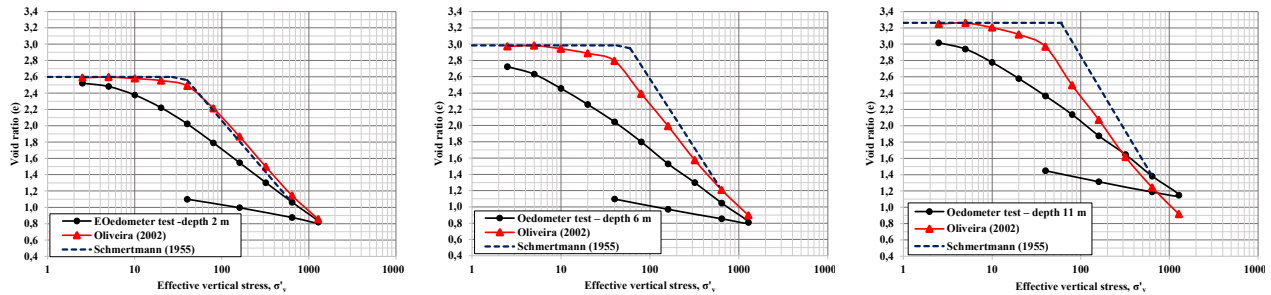


Figure 5. Compressibility curves and corrections proposed by Schmertmann (1953) and Oliveira (2002)

Tabela 2. Sample quality classification by Coutinho (2007). Source: Souza Neto (2023)

Stake	Depth. (m)	e_0	$\Delta e/e_0$ (Oliveira)	Classification (laboratory)	Classification (after correction)
3475 + 14,21	2	2,59	0,17	Very poor	Very good to excellent
	6	2,98	0,32	Very poor	Good to fair
	11	3,26	0,31	Very poor	Very poor

3.3 Geotechnical monitoring

The monitoring of embankment stability was qualitative, based on horizontal displacements measured by inclinometers installed in the field. In Embankment 5, data were obtained from inclinometer IN-23 (Figure 5), while in Embankment 3, monitoring was performed using inclinometer IN-12 (Figure 6).

It should be noted that inclinometer readings provide essential information on the behavior of embankments over soft soils. Still, they reflect only the specific conditions at the point where the equipment is installed. Factors such as subsurface stratigraphic variability, differences in loading rates, and the relative position of the shear plane may cause the displacements recorded at a single point not to represent the global behavior of the structure with accuracy.

Despite these limitations, inclinometry is essential for identifying movement trends and preliminarily assessing the stability of embankments built over soft soils. When integrated with other geotechnical monitoring methods—such as piezometers for pore pressure measurement—this technique enhances the reliability of interpretations and allows the adoption of preventive or corrective measures, significantly reducing the risks of failure or excessive settlements during construction and throughout the service life of the structure.

Figure 7 presents the stability control analysis of Embankment 5, based on the methods of Coutinho and Bello (2011) and Almeida et al. (2000). According to Coutinho and Bello method, the divergent behavior observed in Figure 7a—characterized by the progressive increase in horizontal displacements over time—indicates that the structure was approaching a critical condition, potentially evolving into failure. This interpretation is reinforced by Figure 7b, in which

the methodology of Almeida et al. (2000) shows a significant increase in distortion rate during the last monitoring cycles.

In the last reading recorded, the distortion rate was in the intermediate range, varying between 0.5% and 1.5% per day, a value that, according to the Almeida et al. (2000) criterion, is classified as an alert condition for embankment stability. This analysis reinforces the importance of continuous geotechnical monitoring in embankments over soft soils, enabling the early detection of instability signs and adopting preventive or corrective measures before failure occurs.

Figure 8 shows the stability control analysis of Embankment 3, based on the methods of Coutinho and Bello (2011) and Almeida et al. (2000). Up to the interruption of construction activities, Figure 8a indicates divergent behavior, suggesting proximity to an instability condition. After the loading suspension, a transition to convergent behavior was observed, characterized by the gradual stabilization of displacements, consistent with load interruption and pore pressure dissipation over time.

Two depth intervals were analyzed using Almeida et al. (2000) method: (i) 9.0 to 9.5 meters and (ii) 9.5 to 10.0 meters. At the most critical points, the distortion rate reached the alert zone in the penultimate loading stage and, after the placement of the last embankment layer, advanced into the range indicative of a trend toward instability. Subsequently, with load suspension and pore pressure dissipation, these values decreased to the attention zone, reflecting a stabilization trajectory.

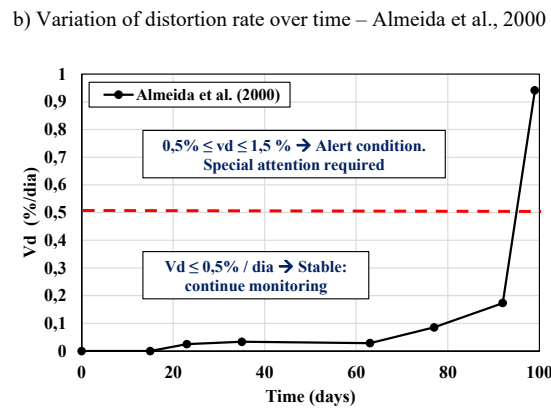
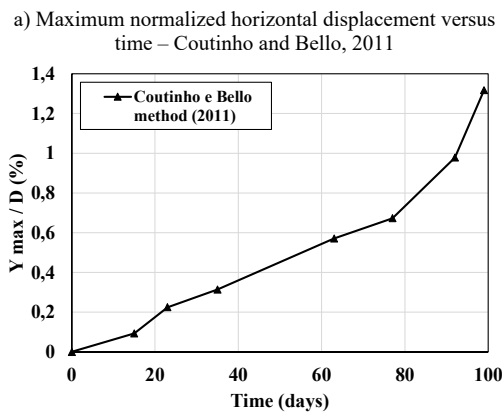


Figure 6. Stability control of Embankment 5

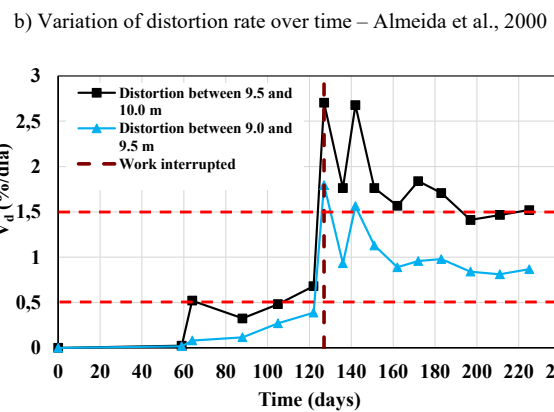
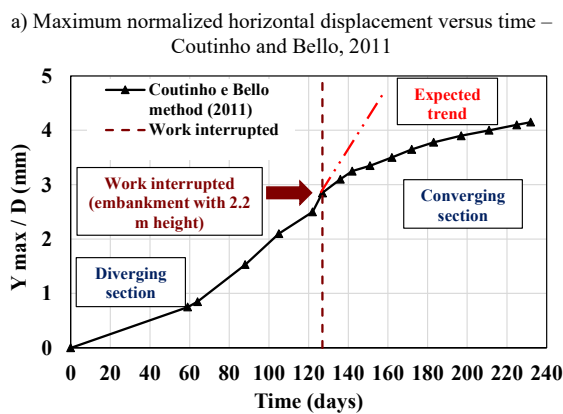


Figure 7. Stability control of Embankment 3

3.4 Stability analysis

Although instrumentation had previously indicated the failure of Embankment 5, the design assumed that the structure would maintain safe conditions throughout construction, particularly at the height of 1.8 m—the stage at which the failure occurred.

In the analyses carried out by the designer, the initial stability, without considering prefabricated vertical drains (PVDs), was evaluated with an undrained shear strength (S_u) of 18.3 kPa, resulting in a Factor of Safety (FS) of 1.37. With the installation of PVDs, it was estimated that, after 60 days, there would be a strength gain to 22.3 kPa, raising the FS to 1.65.

Strength gain over time is expected in embankments built on soft soils using PVDs; however, in the design predictions, this gain was considered progressive and nearly immediate relative to the construction stages, resulting in overestimated strength values for the stage at which the failure occurred.

In the analysis presented in this study, for the height of 1.8 m, the corrected undrained shear strength of 7.92 kPa was adopted, applying Bjerrum correction factor (μ) equal to 0.8. Under this condition, and without considering strength gains associated with PVDs, the FS obtained was 1.066 (Figure 8).

The comparison between analyses indicates that, while the design predicted that at this stage the embankment would present an adequate FS due to the estimated strength gain, the analysis with corrected parameters resulted in a value close to unity, consistent with the occurrence of failure.

The depth of the failure surface estimated in the stability analysis performed with the software was 13.4 m, which is very close to the depth indicated by the inclinometer, which is approximately 14.0 m. This agreement, within a margin considered acceptable for geotechnical studies, reinforces the

reliability of the interpretation and highlights the importance of integrating instrumentation data with numerical analyses to assess the behavior of embankments on soft soils.

Technical experience accumulated from similar studies and projects indicates that obtaining consistent and reliable results depends on a set of interconnected factors: the collection of high-quality samples capable of faithfully representing in situ conditions; expertise in analyzing and interpreting field and laboratory results; the presence of a qualified monitoring team, able to perform accurate readings, identify trends, and promptly communicate any sign of instability; and the execution of a rigorous stability study that contemplates different scenarios and realistic variations of geotechnical parameters.

Combining these elements strengthens the ability to predict and prevent instabilities, enhancing operational safety and the performance of embankments constructed over soft soils.

In addition to the consistency between the results obtained by back-analysis and instrumentation, this study reinforces the need to adopt more conservative design criteria for embankments on soft soils, particularly in contexts where strength gains induced by prefabricated vertical drains are assumed to occur immediately in stability predictions. The failure of Embankment 5 demonstrates that such estimates may overestimate actual safety, leading to misinterpretations of the safety factor and, consequently, to high-risk design decisions.

Therefore, this study's main contribution is not only to demonstrate the effectiveness of integrating instrumentation and back-analysis but also to highlight the urgency of revising current design practices by introducing more robust correction factors, continuous instrumentation protocols, and early warning methodologies as mandatory elements in embankments on soft soils.

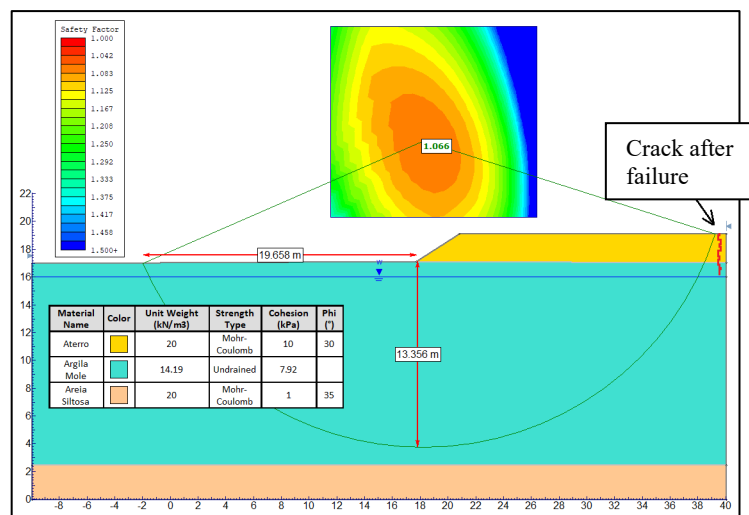


Figure 8. Stability Analysis of Embankment 5 Considering the Undrained Shear Strength Corrected According to Bjerrum (1973) Proposal

4 FINAL CONSIDERATIONS

The study demonstrated that the integration of geotechnical investigation, laboratory testing, and instrumentation-based monitoring is decisive for the stability control of embankments on soft soils. The combined analysis of these data made it possible to identify critical behavioral trends and to guide preventive actions prior to failure.

Monitoring with inclinometers was crucial to detect the evolution of horizontal displacements, confirming the imminence of failure in Embankment 5 and indicating, in Embankment 3, an instability that was reversed by the suspension of construction activities.

The depth of the failure surface obtained in back-analysis (13.4 m) showed strong agreement with the estimate derived from instrumentation data (14 m), reinforcing the reliability of the method.

The results also highlighted that undisturbed samples' quality directly influences geotechnical parameters' representativeness. The initial classification as very poor (Coutinho, 2007) and the improvements obtained after corrections (Schmertmann, 1995; Oliveira, 2002) indicate the need for rigorous sampling, transportation, and testing procedures in order to avoid underestimation of strength and distortions in settlement predictions.

It was also found that the adoption of multiple methods of stability evaluation, combined with trained teams for immediate reading and interpretation of monitoring data, is fundamental to reducing uncertainties and increasing the safety of projects in complex geotechnical contexts.

This research also contributed to updating the regional database on soft soils in the Recife Metropolitan Region and in Goiana-PE, strengthening the knowledge base for future projects and reinforcing that multidisciplinary approaches are the best strategy to combine safety, cost-effectiveness, and reliability in this type of work.

The results show that the failure in Embankment 5 was not merely an isolated event. Still, rather concrete evidence of the limitations of designs that overestimate strength gain in soft soils. The back-analysis integrated with instrumentation data demonstrated that slight differences in parameters can significantly alter the safety factor, leading to interpretations that are inconsistent with field reality. This finding underscores that continuous critical analysis must accompany all construction stages; otherwise, both the structure and the population may be exposed to high levels of risk.

In this context, the present study consolidates evidence that integrating site investigation, laboratory testing, and monitoring cannot be treated as an ancillary activity, but as an indispensable condition. The documented case thus becomes a valuable technical reference for projects on soft soils in different contexts, serving as a warning to designers and managers regarding the need to adopt more cautious approaches, capable of ensuring stability and the efficiency and durability of interventions.

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