Analysis of solutions for projected landing foundation on soft soil on BR-381: a case study

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Abstract

Soft landfilling is still a major challenge for geotechnical engineering, including road engineering. These soils present great constructive difficulties because of their peculiar characteristics, such as low carrying capacity and high compressibility. Several techniques have been adopted in landfill foundations on soft soils to accelerate and stabilize the settlements, and each one has advantages and disadvantages on its use, depending on the analyzed case. This article presents a case study of a soft soil landfill foundation along highway BR-381 (Fernão Dias) – North Road. The place under study is 120 meters long and had a settlement in the road caused by the presence of compressible soil in its subgrade. To solve the problem, the settlements versus time were analyzed in four geotechnical solutions. After carrying out the analyses and computational studies for proposed solutions, it was concluded that only two of them could be performed for the case studied, mainly, the use of deep drainage of the foundation on the landfill or application of temporary overweight.

Keywords: landfill foundation; soft soil; computational study.

1. Introduction

Due to their physical characteristics, such as low permeability, high compressibility, and low load capacity, when required by landfills, soft soils tend to present problems of instability and settlements. Therefore, soft or compressible soils are still a challenge in road engineering, requiring more detailed geotechnical studies.

The different solutions used for the elaboration of projects on soft soils present distinct characteristics, restrictions, and application conditions, being necessary for the designer to understand and find the best solution for each case and location, observing the technical, economical, and operational points of view. The stabilization of the soil can be by densification where the porosity of treated soils is improved trying to achieve the optimum moisture content required to achieve its maximum dry density or by strength gain required for the construction. (Onyelowe *et al*., 2019).

The main objective of this study is to evaluate the behavior of landfills on compressible soils according to test results and specific knowledge on the subject, studying various solutions. A case study was chosen located on BR-381 (Rodovia Fernão Dias) at Km 571+100. Currently, the segment presents sinking in the roadway due to the presence of compressible soils in the foundation of the existing highway.

1.1 Landfills on soft soils

Among the types of soils identified in the field, there are soft soils, which have fine fractions under saturated conditions in its composition. They have usually clay with consistency indexes less than 0.5, high values of natural moisture, undrained resistance below 25 KPa, low mechanical resistance, high compressibility, little permeability and may contain organic material, which is responsible for its dark color (Zhang *et al*., 2023). Therefore, they offer little security in the laying of foundations or embankments for highways.

Regarding soft soil in Brazil, with marine origin, there were some sedimentation cycles, interspersed by intense erosion process, during the last glaciation of the globe, with two episodes of sea entry, which gave rise to two different types of sediments. The first, is clayey or sandy at its base and sandy at the top (Cananeia Formation); the second is formed by marine sediments, formed by reworking sediments from the first, sand, and clays and sometimes, by sedimentation of static water that had been subjected to rapid and negative oscillations in the sea level (Santos Transgression) (Zhou *et al*., 2021).

Clay minerals are formed by chemical alteration of the rocks, resulting in microscopic particles, with lamellar form, and so, with large surface and very sensitive by the presence of water (Shi *et al*., 2023). The minerals present on its composition influences the behavior of the layer. The more is its presence in the soil the weaker are its geotechnical attributes. Since soft soils are compressible and due to its low strength resistance, many techniques are proposed to minimize the effects of its characteristics. According to Carvalhais (2017), the hydraulic stabilization mechanisms of the foundation soil are based on changing the flow conditions of interstitial water present in the soil mass, while in physical stabilization, the use of lateral elements or even in geometry of the landfill, that creates efforts to compensate the ones induced on the compressible soil. The thicker the layer, longer is the time to consolidate since the water particles must travel a long distance to reach the drainage layer (Garg, 2005).

According to Ugwuanyi *et al*. (2019), stabilization is a technique used in soil mechanics to improve soil properties by various methods and procedures. For greater stability of embankments on soft soils, methods capable of modifying its characteristics are requested as a practice, like the use of materials, such as geosynthetics. (Zahri, Azura, 2019).

Stabilization can be obtained by adding chemicals such as ordinary cement (Saadeldin and Siddiqua, 2013); (Ashraf, 2018), fly ash (Ozdemir, 2016); (Keyu *et al*. 2022), lime (Kamaruddin, 2019); (Saied, 2012) or a combination with enzyme (Eujine, 2017). They can act by two mechanisms: increasing the particles size by cementation, internal friction among the agglomerates, greater shear strength, reduction in plasticity index or by absorption and chemical binding of moisture that facilitates compaction through hydration and calcination reactions. (Zhu, 2017).

There are also methods of physical stabilization, which act on the geometry of the landfill combined with the application of drainage devices that have the function of accelerating the densification of the soil.

1.2 Geotechnical investigations

Regarding soft soil projects, it is necessary, initially, a recognition of the area, followed by investigations of characterization and determination of resistance, such as Standard Penetration Test (SPT) and the Lightweight Dynamic Penetrometer (LDP). In a third phase, specific tests are recommended to define geotechnical parameters, stability, and settlement calculations.

The SPT test (*Standard Penetration Test*) is largely used to characterize the layers of the landfill and evaluate its resistance. Regarding geotechnical engineering, especially in foundations, the wide use of this test, according to Lukiantchuki (2012), is due to its simplicity, robustness and ease application of its results.

According to NBR 6484 (ABNT, 2001), soft soils can be characterized, preliminarily, those that present penetration resistance index of the SPT test with less than four SPT N-value.

The Lightweight Dynamic Penetrometer (LDC), when it comes to compressible soils, are also very common. According to Alves Filho (2010), they characterize the depths and strengths of foundation soils quickly and efficiently, given the practicality and operability of the equipment used.

Finally, undisturbed samples can be collected to carry out special tests, such as edometric densification and triaxial compression.

2. Experimental

According to Almeida and Marques (2010), the choice of the most appropriate construction method is associated with several issues: geotechnical characteristics, use of the area, including neighborhood, construction deadlines and costs involved. Most methods involves the control of settlements and stability. Among the various techniques adopted in Brazil for construction on soft soils, there are: the total removal with total or partial replacement of soft soils; load transfer to a more resistant soil: conventional piles, columns of sand/gravel; direct construction with soil densification: use of light materials in the embankment, use of vertical drains in the foundation; embankment foundation reinforcement using natural and synthetic fibers, and contour of the stretch with soft soil: variants and viaducts.

These solutions can be designed and executed individually or combined, depending on the characteristics of the projected work.

This case study will compare some solutions, such as: simple removal of the landfill and reconstruction without geotechnical artifices, use of temporary overload combined with deep drainage, use of deep drainage and light landfill with the use of expanded polystyrene (PS).

3. Preliminary project analysis

To support the proposed study, drilling campaigns were programmed to define the thickness of the compressible soil, as well as its resistance and the geotechnical parameters that are necessary for the characterization of the foundation and landfill materials.

The geotechnical studies contemplated the following activities:

- Hand auger drilling;
- Standard Penetration Test -SPT;
- Lightweight Dynamic Penetrometer Test - LDP;
- Extraction of compressible soil samples using Shelby Sampler;
- Characterization laboratory tests: one dimensional and triaxial densification.

Based on the results obtained from the SPT tests, three geological/geotechnical profiles were prepared from the positioning of the SPT holes, based on a horizontal alignment projected on the axis of the north lane of the highway under study.

For the elaboration of this paper, the results from the first section (pile 15 + 0.00) were considered, and from the geological-geotechnical profile (Figure 1) and the geotechnical characteristics of the materials of each layer (Table 1) were made computer analyses to perform different solutions and methods for stabilization and reinforcement of soft soil.

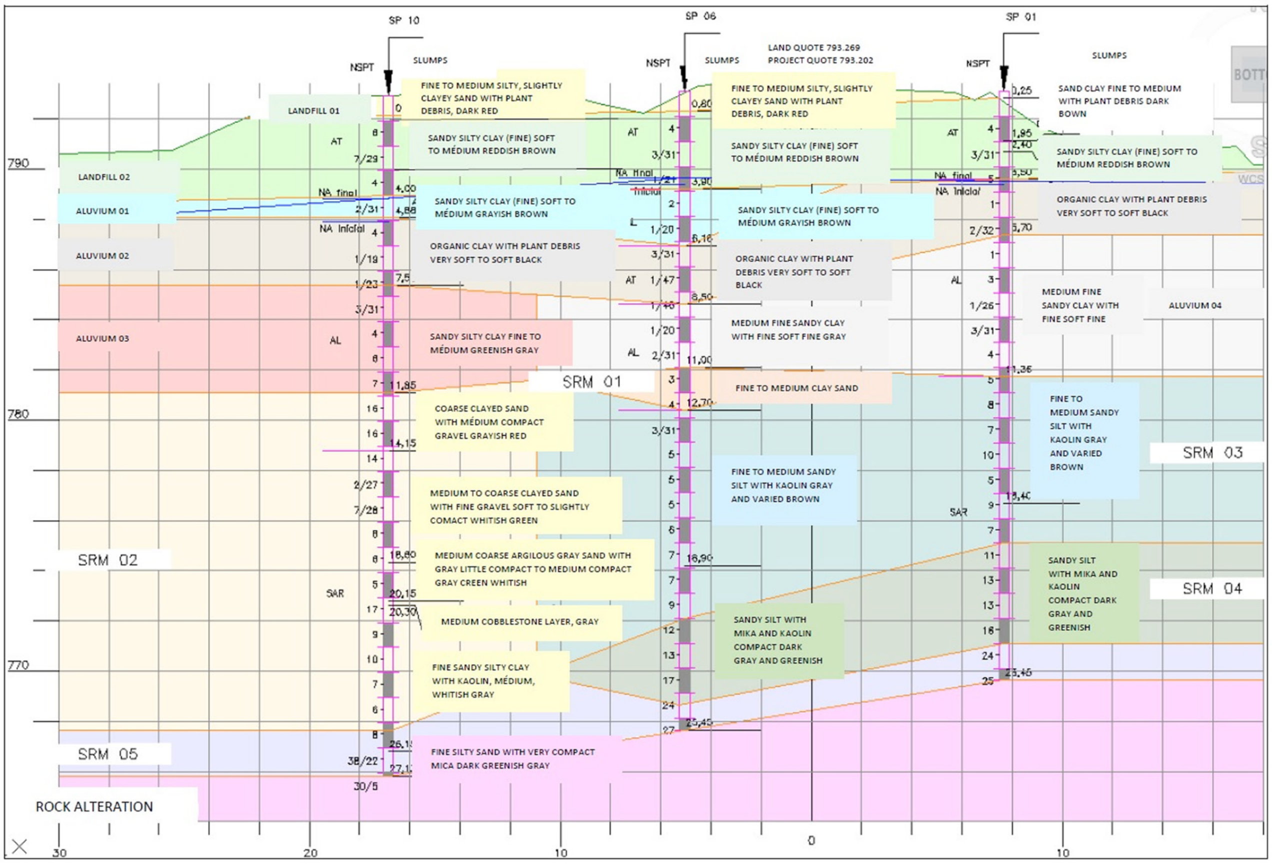

Figure 1 - Geological- Geotechnical profile elaborated from SPT holes SP-10, SP-06 e SP-01. (Author, 2018).

Table 1 - Materials used on the computational analyses of the section.

Name	Material	Hydraulic Properties	Material Model	Elasticicity modulus (Kpa)	Specific Weight (KN/m³)	Poisson Coefficient	Material Category
Embankment 01	Clayey sand with plant debris, dark brown	Effective parameters drained	Elastic Linear	9000	17.00	0.30	-
Embankment 02	Sandy Clay, very soft, red brown	Effective parameters drained	Elastic Linear	7000	15.00	0.30	-
Alluvium 01	Silty sandy clay with mica very soft, grayish brown	Effective parameters with variation of pore pressure	Elastic Linear	3000	15.00	0.33	Soft Clay
Alluvium 02	Organic Clay, very soft, black	Effective parameters with variation of pore pressure	Elastic Linear	3000	15.00	0.33	Soft Clay
Alluvium 04	Sandy Clay with fine gravel, very soft, light gray	Effective parameters with variation of pore pressure	Elastic Linear	464	11.89	0.33	Soft Clay
SRM 01	Fine to medium clayey sand, soft, light gray	Effective parameters with variation of pore pressure	Elastic Linear	7000	17.00	0.35	Fine Sand
SRM 03	Sandy silt with fine gravel, soft, gray, and reddish brown	Effective parameters with variation of pore pressure	Elastic Linear	14000	19.00	0.30	Clayey Silt
SRM 04	Sandy silt with fine gravel, little compact, greenish gray	Effective parameters with variation of pore pressure	Elastic Linear	29000	19.00	0.30	Clayey Silt
SRM 05	Fine silty sand, very stiffy, gray	Effective parameters with variation of pore pressure	Elastic Linear	18000	17.50	0.33	Fine Sand

4. Computational analysis

The landfill observed is carrying out settlements, and as the tests over time, as well as the original 1993 Project, did not indicate the existence of previous services that could accelerate the occurrence of settlements on this segment of the road. Live with the problem could be a solution, however, it is not recommended since periodic maintenance should be carried out with the application of asphalt on the track to restore the leveling due to the settlements.

Considering that the study site has a compressible soil layer with an average thickness of 10 meters and based on the laboratory tests results carried out on the site's soil, as well as on the current situation of deformation of the landfill, four stabilization and reinforcement solutions for the soft soil of this foundation were simulated.

The total removal of the compressible material and subsequent filling with a material with minimal geotechnical characteristics is a discarded solution, as it would generate a high volume of soil to be removed, in addition to the risk of rupture of the old track (South Track), which would result in the total interruption of the traffic on the highway. The use of this technique is limited to the maximum of 4.0 meters of soft soil layer thickness.

4.1 Reconstruction of the landfill without deep drainage

The first solution studied was the reconstruction of the landfill without the use of deep drainage to accelerate the densification in the soft soil layer. It consists of the removal of the current landfill, the execution of sand mattress drainage, followed by the reconstruction of the embankment in layers. In this simulation, it was also possible to evaluate the settlements that would still happen, in the upcoming years, considering the hypothesis of no treatment at the landfill foundation.

To perform the analyses, the software GeoStudio 2018 was used. After the development of computational analysis, the model was generated, indicating in meters, the reached densification. On the point where is the major settlement, can be observed on Figure 2, that the landfill will take an average of 1600 days to stabilize with a value near to 10.90 cm, as shown in Figure 3.

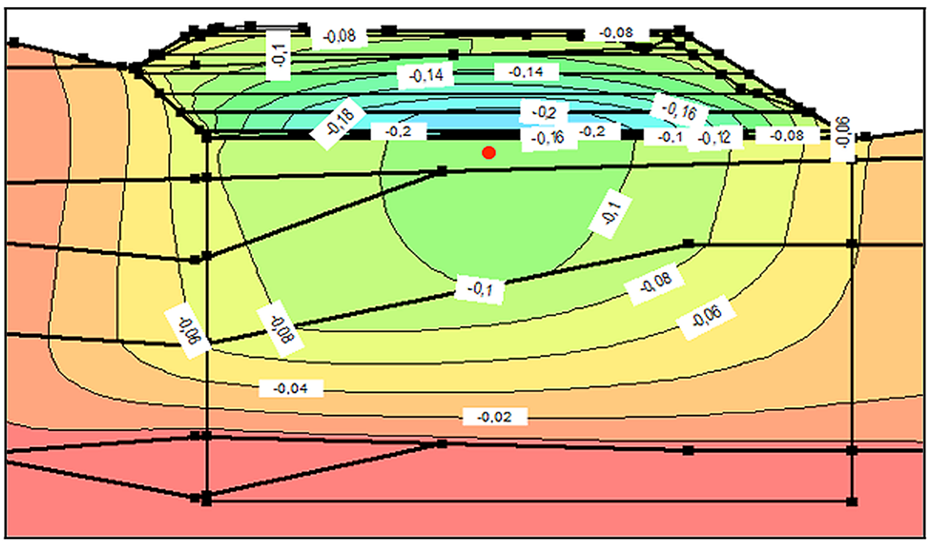

Figure 2 - Settlements after 10 years from the reconstruction of the landfill.

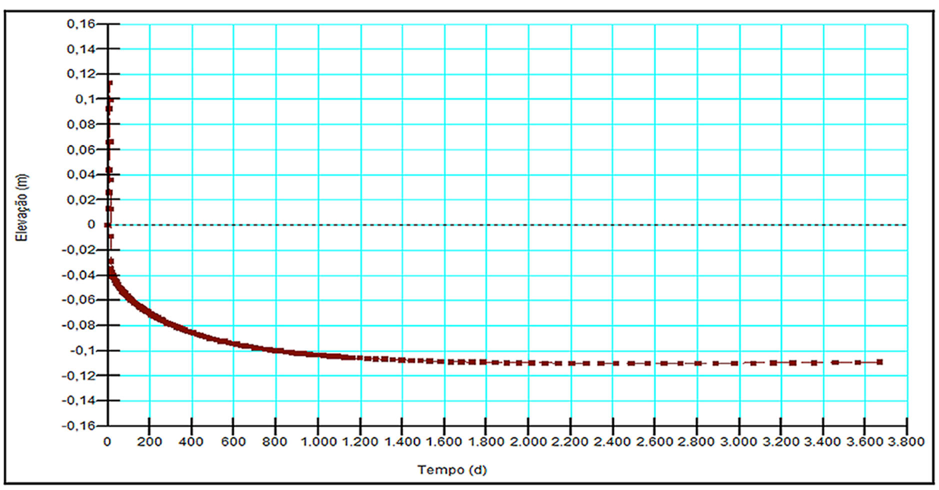

Figure 3 - Settlement versus Time for the reconstruction of the landfill. (Author, 2019).

Another inconvenience that can be observed is that over 1600 days, there will be a slowly variation of approximately 7.00 cm, that can generate great instability on the runway for a period of more than four years. With this simulation, it is proved that the main responsible for the densification of the runway is the compressible material located below the landfill and the non-intervention in the foundation will cause new settlements in the coming years.

4.2 Use of temporary overload with deep drain execution

Using overload with deep drainage, for design purposes, considers the total weight of the landfill plus an overload of 3.0 meters in height to accelerate and increase the densification of the entire massif. The proposal is to stabilize the landfill with the implementation of deep drainage composed of a mesh of geodrains and a drainage mattress, followed by the reconstruction of the landfill of the highway and execution of the temporary load aiming accelerate the densification.

The executive project was developed considering the following steps: the removal of the existing landfill until the soft soil layer; execution of deep drainage with geodrains, sand mattresses and drainage; reconstruction of the landfill with an addition of 3.0 meters of overload; overload removal up to the specified grade in the project.

Due to the thick layer of compressible soil and the low hydraulic conductivity average factor of this layer (K=1.09 x cm/s), initially, the inclusion of a mesh of vertical drains was indicated so that 90% of the settlement occurs, considering, for the purposes of the study, 50 days of overload on the new built landfill. Therefore, the mesh indicated by the study was the equilateral triangular one, with spacing L=0.87 m and D=0.91 m, applied along the entire length of the embankment on the compressible soil.

In soft and poorly permeable clayey segments, the use of drains reduces the time for densification and contributes to increasing the shear strength of the soil and its bearing capacity.

After the setting of the geodrains in the critical terrain of the landfill, a sand mattress and a drainage mattress with 0.20 m and 0.50 m thickness, respectively, was simulated, so that the reconstruction phase of the landfill projected on design and also the construction of the overload landfill. For calculation purposes, it was established that the landfill would be carried out in two layers of 0.25m each day, in approximately 10 days.

To prepare the project considering the use of temporary overload as a solution, the analyses were carried out with the parameters obtained from the results of the triaxial and edometric density tests, as well as the correlations with the results obtained in SPT soundings from the number of and the type of soil found at each depth. Therefore, based on technical experiences disseminated on literature, it was possible to define values of specific weight (Y), effective cohesion (c'), effective friction angle (Φ') and effective elasticity modulus (E') for all layers of soil identified in the sections of the geological- geotechnical profiles used for the computational modeling of the settlements analysis. These correlations, with established parameters, are regularly used in studies and academic practices.

Using the software GeoStudio 2018, it was possible to analyze all stages of the temporary overload construction project. It is important to say that during the development of the project, arose the need of simulate the temporary overload action on the landfill considering different periods of permanence.

The values obtained in the studies are represented, in meters versus days, in the predicted settlement graphs along the entire area of the landfill in the different stages of the process, from the removal of the existing landfill and the construction of the new landfill, until the construction of the overload landfill, its maintenance for the determined period and its subsequent removal.

The graphs below show the behavior of the settlement versus time, considering an overload of 30 and 50 days, for a period of 10 years after its removal.

Analyzing the graphs on Figures 4 and 5, we can see that the longer is the period observed, the greater is the value of the settlement reached in the foundation soil, and longer is the time to achieve stabilization of the settlement (Table 2).

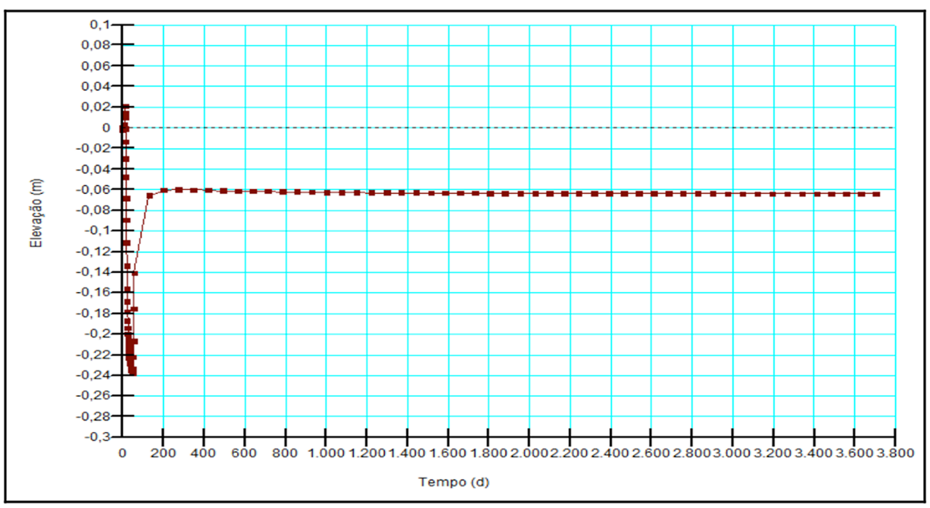

Figure 4 - Graph Settlement (m) versus Time (days) after 3708 days, considering 30 days of overload.

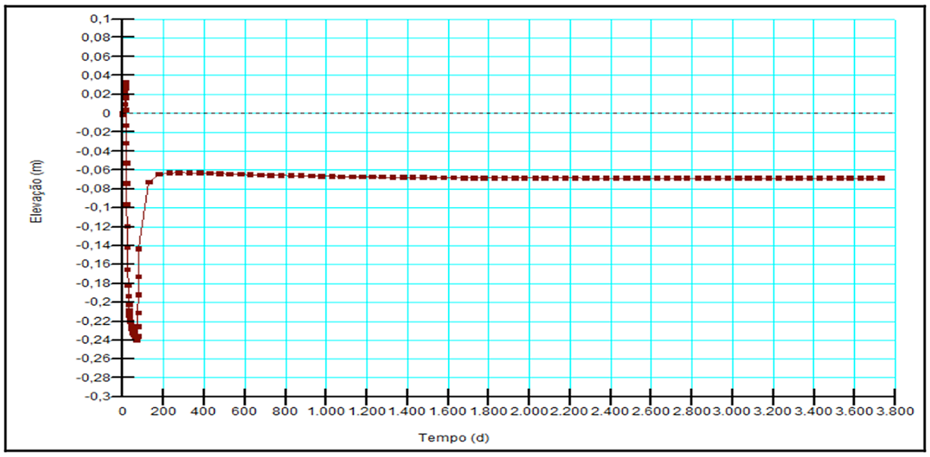

Figure 5 - Graph Settlement (m) versus Time (days) after 3708 days, considering 50 days of overload.

Table 2 - Comparative of estimated settlements. (Author, 2019).

Overload period (days)	Settlement after Overload Period (cm)	Settlements 6 days after the start of overload removal (cm)	Settlement variation 5 days after overload removal (cm)	Settlement Stabilization (cm)
30	23.82	14.02	9.80	6.41
50	24.19	14.10	10.09	6.52

It is also noticed that the tendency for the two stipulated deadlines is to suffer approximate settlement variation, due to the relief after the removal of the embankment built as temporary overload. Thus, it is concluded that the increase in the number of days of action of the overload on the landfill would not have considerable effects from a geotechnical point of view, and would keep the traffic interrupted for a longer period of time.

It is important to mention that the settling value reached is not decisive in this analysis, and its fast stabilization is essential, in order not to suffer further slump. In the analyzed periods, a rapid trend towards stabilization is noticed after 6 days of starting the removal of the load, with small variations over the next 1 to 2 years. For this point of the landfill, the complete stabilization of this settlement take place when reaches a value around 6.50 cm, as indicated in the graphs with a projection for 10 years.

We can also conclude that the increase in overload would generate a delay, in days, in the stabilization of the landfill, since a longer time would have to be spent reaching a greater value of settlement, so that later, this tension could be relieved until the stabilization point.

From these observations, claims the need for looking for an alternative solution, considering only the inclusion of deep drainage geodrains and execution of sand mattress and drainage mattress, without temporary overload.

4.3 Reconstruction of the landfill using deep drainage

This solution does not consider a construction of a temporary overload, with the exclusive role of deep drainage as the main problem solver. |It involves three steps:

- Removal of the existing landfill;
- Placement of deep drainage (vertical geodrains), sand mattress and drainage mattress.
- Reconstruction of the landfill to the level specified on geometric design.

For the removal of the existing landfill, was estimated a period of 10 days. The geodrains are presented with the same characteristics specified on item 4.2, in this article, and were inserted in a depth of 10.0 meters of drained soil. The implementation of vertical geodrains and vertical sand drained mattress were foreseen within 2 days after the removal of the existing landfill. The reconstruction of the landfill takes place between the 12th and 16th days.

Computer simulations were performed, using the software GeoStudio 2018 (Sigma/W). The graph that indicates the settlement as function of time was constructed considering a period of 10 years after the reconstruction of the landfill to demonstrate the settling values achieved from the beginning of the process is showed on Figure 6.

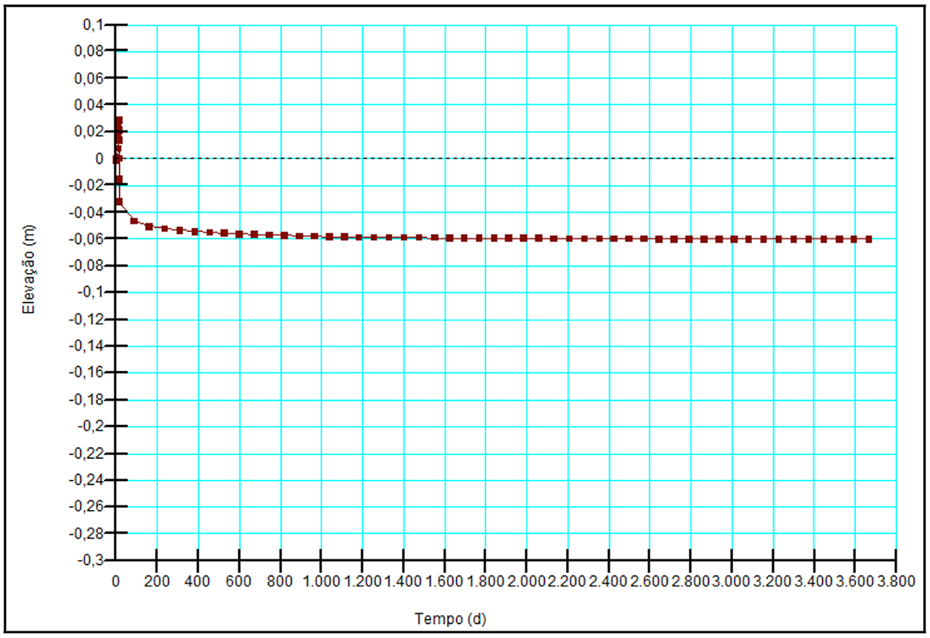

Figure 6 - Settlement (m) versus time (days) after 3666 days, using deep drainage. (Author, 2019).

4.4 Lightweight landfill with expanded Polystyrene (EPS) core

Although landfills made with Expanded Polystyrene (EPS) or popularly known as "Styrofoam", a registered trademark from Knauf Isopor Ltde., are not frequently used on Brazil, it is widely spread and used abroad due to its low specific weight and makes the technique known as ultralight landfill.

According to Sakamoto (2018), EPS is a polymeric cellular material composed of spherical shaped particles, which give the structure about 98% of air, that guarantees a specific weight of 1% of the traditional compacted landfills and allow satisfactory mechanical properties.

The execution of landfills using EPS is able of reduce the structure settlements, improve the stability of the landfill, ensuring safety and lightness to it, and with greater agility of the work.

One more advantage is that there is no need of changing the route or current grade of the highway, and so, maintaining the geometry design. As negatives aspects for the using of EPS,

we can mention the difficulty in finding experienced professionals to perform and supervise the technique, risks of chemical attacks, such as fuel and solvents, fluctuation of the EPS due to its lightness, possibility of rutting due to plastic deformation of the EPS and, finally, the price added to the transport of the material.

As a solution to the problems mentioned above, such as risks of chemical attacks, flotation or rutting, it is suggested the construction of a layer of soil to confine the EPS and spread the tensions that could be absorbed by the EPS and counteract the hydrostatic thrust. To reduce the price of transport, it is suggested to look for providers of EPS near the site and so, make the solution feasible.

The strength and characterization parameters suggested for the EPS blocks, considered in the execution of the landfill, were extracted from studies carried out by Avesani Neto (2008) and Sakamato (2018) and are shown in Table 3.

Table 3 - EPS Properties. Adapted from Avesani Neto (2008) and Sakamoto (2018).

Characteristics	Adopted values
Specific weight	0.15 a 0.30 KN/m³
Compressive Strength resistance	55 a 265 KPa
Modulus of Elasticity	2000 a 10000 KPa
Poisson's Ratio	0.05 a 0.20
Friction Angle	30° a 41°
Coesion	Non-existent

The specific weight of the EPS is much lower if compared to other materials used in road landfills, since expanded styrene is a kind of foam, lightweight, rigid, with closed-cell insulation.

For the development of this solution, the results of geotechnical investigations as well as the current geometry of the runway, such as lane widths, and planialtimetric positioning were maintened. Considering the EPS blocks parameters, it was possible to simulate the solution of the landfill execution and analyze the predicted settlements for the site, using the Sigma/W module of the GeoStudio 2018 software.

The parameters considered for the EPS blocks were:

- Specific weight: 0.30 KN/m³
- Compressive strength resistance: 220 KPa
- Modulus of Elasticity: 9000 KPa
- Poisson's Ratio: 0.10
- Friction Angle: 37º

- Coesion: nonexistent

The block adopted had 4.0 meters x 0.5 meters x 1.2 meters. Thus, it was possible to design three layers of EPS, totaling 1.5 meters in height and 13.20 meters in width as shown on Figure 7.

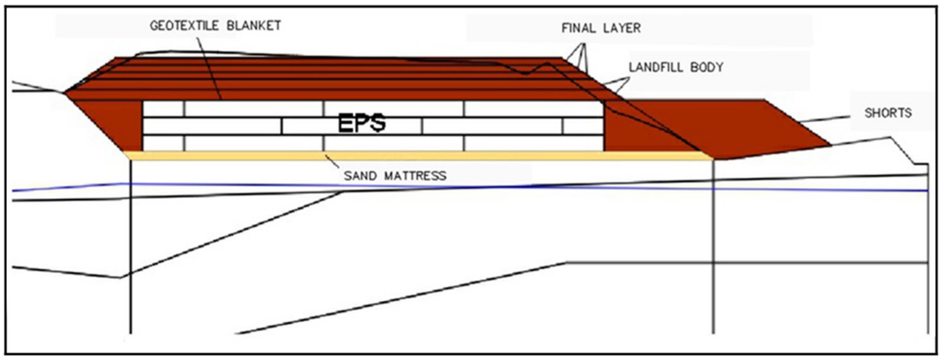

Figure 7 - Transversal section using EPS. (Author, 2019).

The soil used for enveloping and confining the EPS blocks was a clay available in the region, presenting the following characteristics:

- Specific Weight: 17.5 KN/m³
- Modulus of Elasticity: 18000 KPa
- Poisson's Ratio: 0.3

In addition to the use of these materials, a regularization sand mattress was disposed prior to the placement of the EPS blocks and a geotextile blanket over the EPS blocks.

After the computational modeling of the solution with three layers of EPS a different result from expected was obtained, analyzing the settlements as function of time. When filling part of the interior of the landfill with light material, it was expected that the settlement in the foundation would be smaller or nonexistent, and the soil would support the entire weight of the load.

However, from the moment the landfill was rebuilt, an unexpected situation occurs. Overtime, settlements do not continue to reduce or stabilize, on the contrary, they continue to increase, and took a long time to stabilize. (Figure 8).

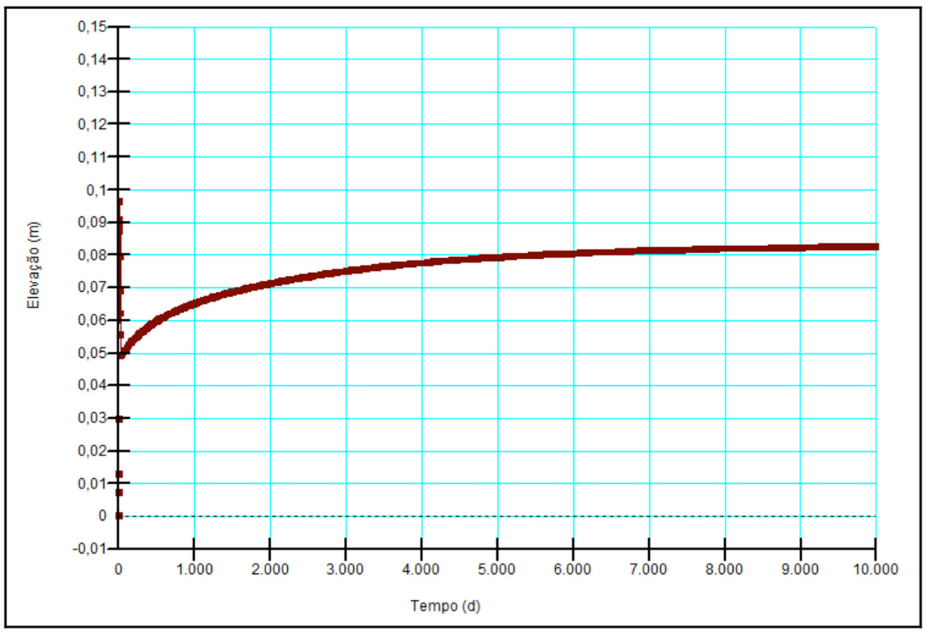

Figure 8 - Solution with 3layers of EPS after 10.000 days. (Author, 2019).

It was concluded that the stress relief that occurred due to the excavation of the existing landfill continues even after the construction of the new embankment. One of the reasons that can lead to this result is the low specific weight of EPS used in the center of the embankment, incapable of generating a counterweight in relieving soil tensions.

Based on this conclusion, the same study was carried out reducing the EPS layers in the center of the landfill, and, consequently, increasing the landfill with clayed soil. The results found considering two and one layers of EPS are shown on Figures 9 and 10, respectively.

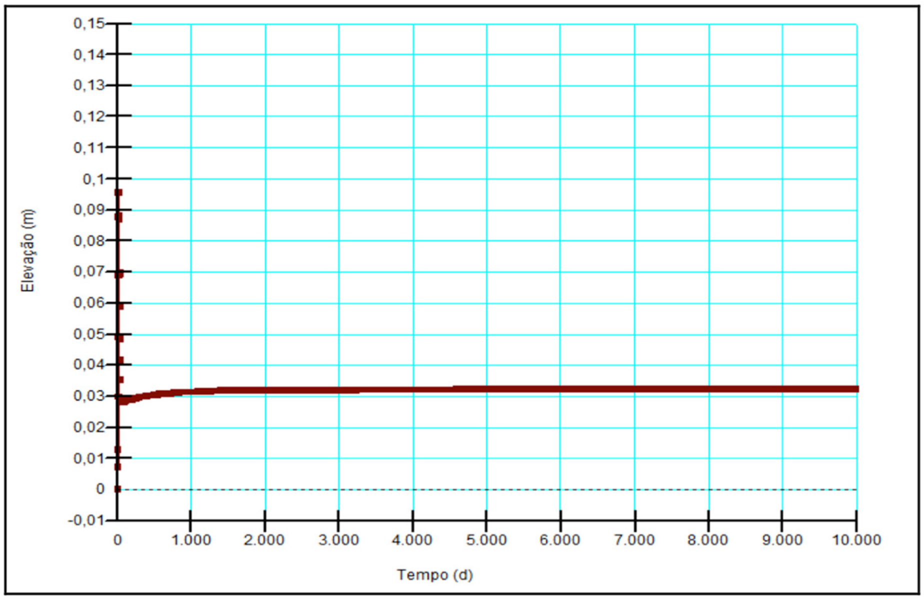

Figure 9 - Solution with 2 layers of EPS after 10.000 days. (Author, 2019).

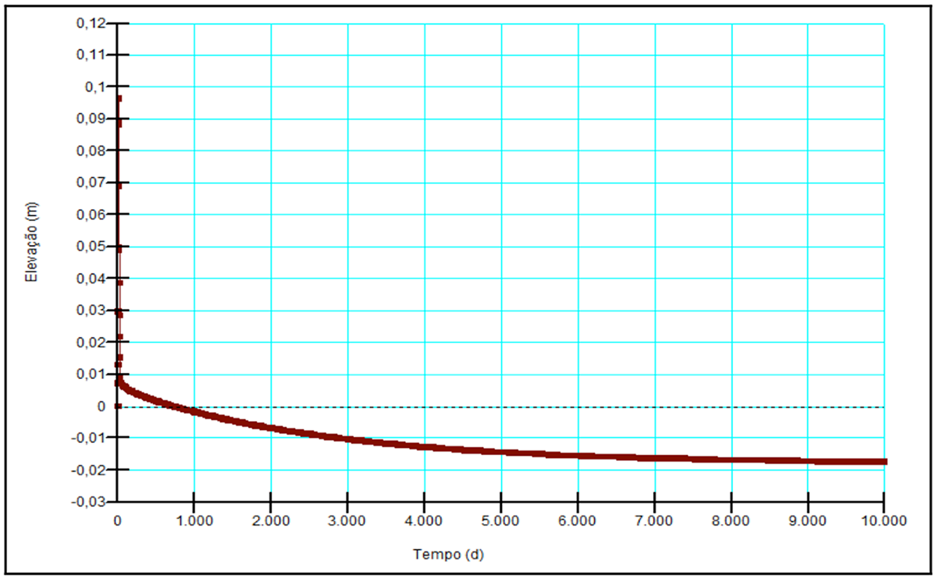

Figure 10 - Solution with one layer of EPS after 10.000 days.

As can be seen, the use of EPS does not meet the expectations for the case study, since settlements will continue to occur slowly until they stabilize. This is due to the initial excavation of the existing landfill and the consequent stress relief caused by it. The very light material is not capable of generating the necessary stresses so that the landfill ceases to suffer relief, causing this stress relief to generate positive settlements over years.

5. Conclusions

After carrying out the analyses and computational studies for proposed solutions, it was concluded that only two of them could be performed for the case studied, the use of deep drainage on foundation of the landfill and application of temporary overweight, and mainly the use of deep drainage in the landfill foundation.

Therefore, considering technical, economic and time aspects, after the simulations of the solutions, it can be concluded, based on the parameters adopted and analyses carried out, that the best solution for the site is the execution of the landfill considering the use of deep drainage.

The use of EPS was discarded due to its behavior. The use of deep drainage associated with an overload of 3.0 meters proved to be technically feasible, once it can stabilize the settlements in the foundation of the landfill, however, it demands a longer period of interdiction of the North Lane to traffic. The use of overload generates greater safety for the geotechnical designer, since it guarantees that the settlement achieved is greater. If the application of temporary overload is the chosen solution, it is recommended to adopt it for a maximum of 30 days.

It is worth to mention, that most of the parameters used in the development of this paper were obtained through correlations with SPT soundings, which generates greater uncertainty for the designer. It is necessary in the geotechnical environment applied to road engineering a greater request for special tests along the problematic extension to characterize the soil under study with greater reality, despite the costs of these tests.

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