Settlement evolution in railroad embankment over Soft Soil - comparison between instrumentation and bidimensional FEM modelling

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ABSTRACT

This work aims to make a comparison between field data and numerical simulation using the finite elements method (FEM) of the settlement of an embankment in a railroad expansion on soft soil using vertical synthetic drains. The construction was a railroad embankment, next to a pre-existent embankment, in Maranhão, Brazil. In this work can be noticed the influence of the old embankment over-consolidation process in the settlement data collected in the new embankment area. Settlement plates closer to the over-consolidated area presented smaller displacement values. Seeking an improvement of the compatibility between the settlement field's data and numerical simulation results, a second analysis was done decreasing the permeability value of the clay layers above the construction. It provided a satisfactory result in the first analysis, until 259th day, in which the new embankment height increased 2,0 meters. After this period was added 4,7 meters in the embankment that provided mismatched results in terms of settlement, despite the settlement velocity agreement. The results showed the importance of the drainage system in an embankment construction over soft soil through the permeability variation effect. It also refers to the necessity of a careful field's data treatment.

Keywords: embankment on soft soils, settlement prediction

1. INTRODUCTION

Settlement control is an essential theme in geotechnical engineering. Was made a settlement prediction and it was monitored on the field during the work to do a better management of the embankment construction over soft soil. This type of construction depends almost entirely of the soil characteristics.

In construction above thick soft soil's layers the settlement effect act very slowly, it can take years to stop. To embankment construction happen in this condition, some techniques were developed. These techniques aim to improve the embankment stability and accelerate the settlement process (Leroueil et al. 1997). Some of them use geosynthetics for several different functions.

This work shows the case of an embankment on soft soil constructed to an expansion over an 892 kilometers long railroad in Maranhão, Brazil. It makes a comparison between settlement data collected in the field using instruments and data provided by a numerical analysis using finite elements method (FEM), considering the site and laboratory investigation and geometry information of the project.

2. METHODOLOGY

One cross 18 + 880 section was chosen based on quality of the data collected by field investigation, field settlement information reliability and quality, type of embankment stability solution adopted and presence of a thick soft soil layer above the construction.

In this work was used Input data to Hardening Soil constitutive module, for the materials of the equilibrium berms, the embankments, the substitute sand, the layer of thin sand and the drainage mattress. The Soft Soil constitutive model was used to the soft clay layers.

Before the numerical analysis of the new embankment construction was simulated the old embankment, in order to represent the over-consolidation effect caused by the old embankment load. The simulation data considered was the old embankment as stable.

The installation of vertical drains, drainage mattress and geogrid were made before the construction of the new equilibrium berm and the new embankment. To the numerical analysis were considered the periods of time of the embankment elevations according the topography data. The data of the settlement in the field during the embankment construction were collected from elevation of the settlement plates. The 3 settlement plates were installed above the previous berm, which was a stability solution for the previous embankment as can be seen in Figure 2.

In this study two analyses were performed using FEM and their numerical results (analyses 1 and 2) are presented in item 5. In the second analysis the values of soft clay layers permeability were reduced.

3. CASE STUDY

The geometry of the embankment is illustrated in the Figure 1. The two embankments were built on a thick soft soil layer, constituted by 4 sublayers of clay and a deeper layer of fine sand. The layers of Clay A, C and D are 1,5 meters thick and Clay B layer is 2,0 meters thick as the fine sand layer. At first existed the older embankment that had as establishments solution two berms and a substitutive sand landfill under the embankment. After achieving enough stability, the new embankment started to be built. This new one has, in the cross section, 8 vertical drains, a drainage mattress, a geogrid and an equilibrium berm. The vertical drains are distributed as a triangular mesh with 2,7 meters of distance that begins in the drainage mattress and it ends in the Clay (D) layer.

In the new embankment was provided a drainage system. This system had eight vertical fibro-chemical drains that conducted the water from the clay layers to the drainage matters, constituted by sandy soil, and then moving way out the embankment. A geogrid was also installed to function as reinforcement that is his primary function (Koerner et al. 1933).

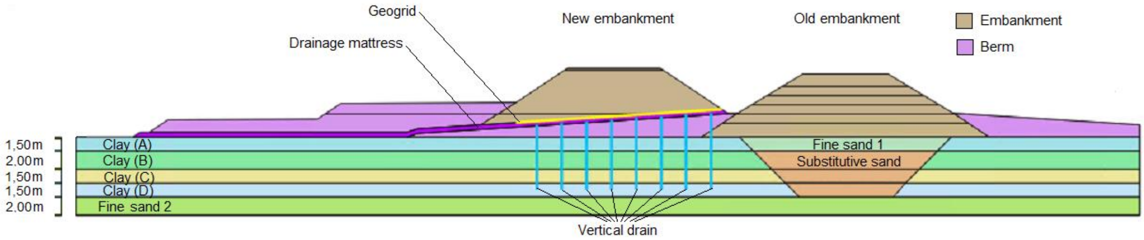


Figure 1. Cross section used in numerical analysis of the embankment (adaptation of Carapiá et al. 2018)

The new embankment construction was done above one of the berms of the older embankment. The new equilibrium berm was built simultaneously. The time in days started to be counted in the first elevation measurement day. The new embankment elevation lasted 423 days, in two different phases (Figure 2). The first phase of 2,0 meters embankment elevation and consolidation process began in the 29^{th} day and last until the 259^{th} day. The second step marked by the beginning of a 4,7 meters elevation executed in 37 days, 26 days after this period was added more 0,2 meter of embankment elevation in 6 days.

In situ tests as SPT, CPTu, Vane test and some laboratory tests were carried out. The results of the investigations used in the simulation are detailed in Carapiá et al. 2018 and briefly cited in Table 1.

4. INSTRUMENTATION RESULTS

The Figure 2 shows the settlement data based on the settlement plates (PR-01, PR-02 and PR-03) and the new embankment height versus time in days.

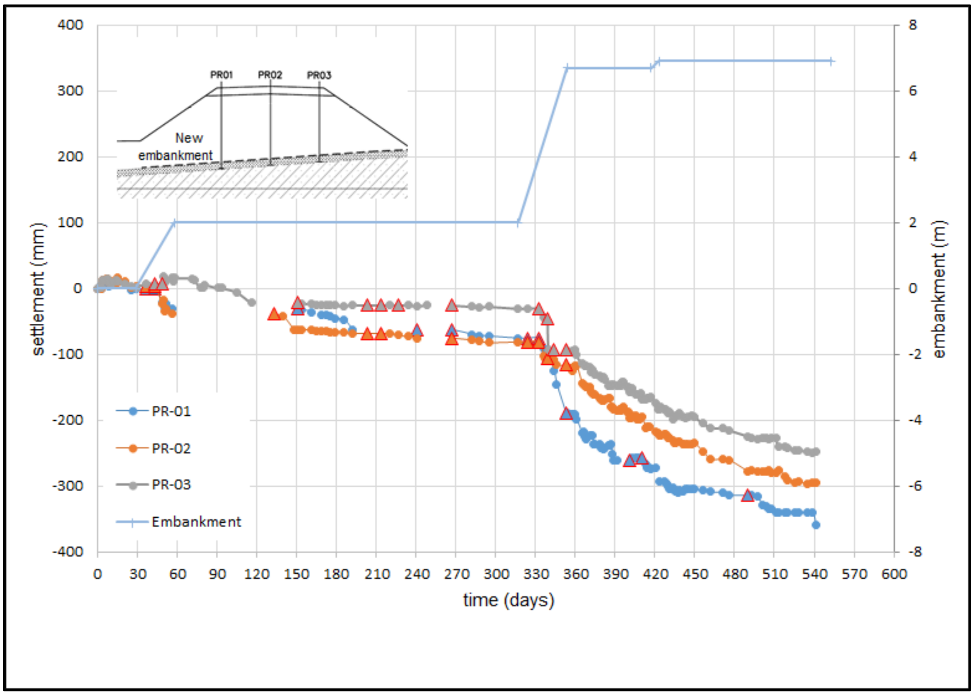


Figure 2. Elevation of the embankment height (m) and settlement (mm) versus time in days.

In the Figure 2 chart, some points are marked with triangle with red border where some corrections were needed. These points indicate elevation measurements considered the same as the previous one. It occurs when the measure seems to be not reliable. In field work, it happens more often in large scale constructions where lots of factors can interfere with the measure gotten. For example, a riser pipe can be installed without accuracy of the pipe's length, vandalism can occur, heavy machines could can damage the instrument during the field work and the level reference could be changed without any warn about it.
Highlighting these events and dates related with the marked points is necessary to do a more reasonable comparison with numerical results.

5. NUMERICAL ANALYSIS

The numerical analysis used the finite elements method (FEM) to perform a settlement simulation of the studied cross section while rising the embankment height or level. The cross section was modelled as illustrated in Figure 2.

Numerical analysis parameters

The parameters adopted in the analysis were based in investigations made near the chosen section,18 +880, as shown in Table 1. They are the compressibility parameters (ch, cv, Cc and Cr), the over consolidation ratio (OCR), the natural unit weight (γ_n) and the void ratio (e_0).

Table 1. Other required parameters used in 18+880 section model compared with other section parameters results (from Bouch et al. 2017).

	Depth (m)	18+880 (Project)	18+800 (Test)	18+920 (Test)	19+000 (Test)
Cc	2 a 2,5	1,49	1,49		1,28
	3 a 3,5	1,49			0,72
	4 a 4,5	1,34	1,34		
Cr	2 a 2,5	0,21	0,21		0,15
	3 a 3,5	0,21			0,06
	4 a 4,5	0,2	0,2		
c_h (m²/ano)	2,01	5,68		20,2	
	4,05	5,68		4,7	
	6,01	9,46		16,7	
c_v (m²/ano)	2 a 2,5	2,84	0,18		0,26

	3 a 3,5	2,84		2,27
	4 a 4,5	2,84	0,47	
OCR	2 a 2,5	1,3	2,87	1,13
	3 a 3,5	1,3		
	4 a 4,5	1,2	1,06	
γ_n (g/cm³)	2 a 2,5	1,44	1,44	1,36
	3 a 3,5	1,44		1,53
	4 a 4,5	1,47	1,39	
e_0	2 a 2,5	3,03	3,03	2,68
	3 a 3,5	3,03		2,16
	4 a 4,5	2,99	2,99	

The four soft clay layers were modelled using the Soft Soil module. The respective parameters values used are in **Error! Not a valid bookmark self-reference.**.

Table 2. Soft Soil's parameters used in the Analysis 1

		Clay (A)	Clay (B)	Clay (C)	Clay (D)
γ_{dry} (kN/m³)	Dry soil unit weight	15,7	14,4	14,7	16,2
γ_{wet} (kN/m³)	Wet soil unit weight	15,7	14,4	14,7	16,2
k_x (m/s)	Horizontal permeability	$5,56.10^{-9}$	$2,31.10^{-9}$	$1,97.10^{-9}$	$1,85.10^{-9}$
k_y (m/s)	Vertical permeability	$2,78.10^{-9}$	$1,16.10^{-9}$	$9,95.10^{-9}$	$9,38.10^{-10}$
Cc	Compressibility parameter	0,76	1,49	1,34	0,5
Cs	Compressibility parameter	0,09	0,21	0,2	0,06
e_0	Void ratio	1,89	0,03	2,99	1,63
c'_{ref} (kPa)	Referential "cohesion"	11	11	11	11
φ(°)	Friction angle	18	18	18	18
OCR	Over-consolidation ratio	2	1,3	1,2	1,2

The materials of the berm, the embankment, the substitute sand, the layer of thin sand and the drainage mattress were modelled by the Hardening Soil model. The respective parameters are in Table 3.

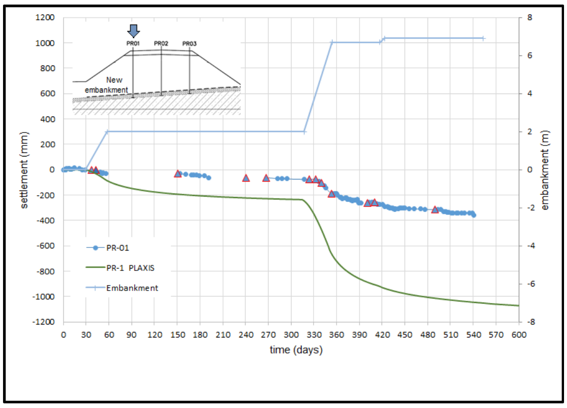
Table 3. Hardening Soil's parameters used in the Analysis 1

		Embankment	Berm	Substitutive sand	Fine Sand 1	Fine Sand 2	Drainage Mattress
γ_{dry} (kN/m³)	Dry soil unit weight	20,00	18	18	19,5	19,5	19,5
γ_{wet} (kN/m³)	Wet soil unit weight	20,00	18	18	19,5	19,5	19,5
k_x (m/s)	Permeability parameter	$2,00.10^{-5}$	$2,00.10^{-5}$	$3,00.10^{-5}$	$2,00.10^{-5}$	$2,00.10^{-5}$	$2,00.10^{-5}$
k_y (m/s)	Permeability parameter	$2,00.10^{-5}$	$2,00.10^{-5}$	$3,00.10^{-5}$	$2,00.10^{-5}$	$2,00.10^{-5}$	$2,00.10^{-5}$
E^{50}_{ref} (kN/m²)	Secant stiffness in standart drainaded triaxial test	25000	20000	10000	35000	35000	25000
E^{oed}_{ref} (kN/m²)	Tangent stiffness for primary oedometer loading	25000	20000	10000	35000	35000	25000
m	Power for stress level dependency of stiffness	0,50	0,5	0,7	0,5	0,5	0,5
c' (kPa)	Effective cohesion	2,00	1	0	0	0	0
φ'(°)	Effective friction angle	35	32	29	37	37	37
ψ(°)	Dilatancy angle	2	0	0	4	4	4
E^{ur}_{ref} (kN/m²)	Unloading/ reloading stiffness	75000	60000	20000	105000	105000	75000
p_{ref} (kN/m²)	Reference pressure to stiffnes	100,00	100	224	159,5	288,5	100

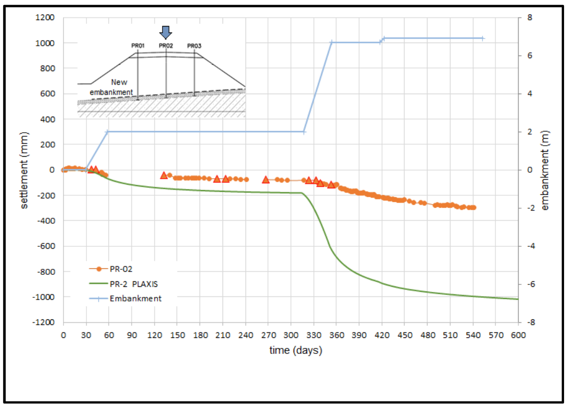
Using these parameters and the geometry showed in the Figure 1, the first analysis was carried out. Other different analysis was simulated as well. In the second analysis the value of soft clay layers permeability was changed, reducing it 20 times. The second analysis was based on the first one. The results are illustrated in the following charts (Figure 3 and Figure 4).

5.1 First analysis results

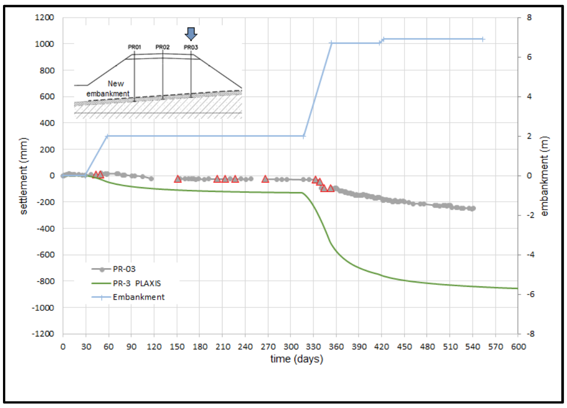
PR01 is the settlement plate that is further from the old embankment (Figure 3a), while PR03 is the closest one (Figure 3 c) and the PR02 in the middle of them (Figure 3b). The graphs show the new embankment level using the right vertical axis scale and the full blue line. They show the settlement of the respective plate using the scale of the left vertical axis and the dots, with different colours for each plate. The horizontal axis indicates the time in days, starting in the beginning of the first settlement measurement.



a) Plate PR 01



b) Plate PR 02



c) Plate PR 03

Figure 3. Elevation of the embankment height (m) and settlement (mm) versus time in days - First analysis

The highest settlement values were observed in the left side of the new embankment where is located the furthest plate, whereas the lowest ones were in the right. The over consolidation effect of the old embankment can be pointed as the main cause of this kind of settlement behaviour.

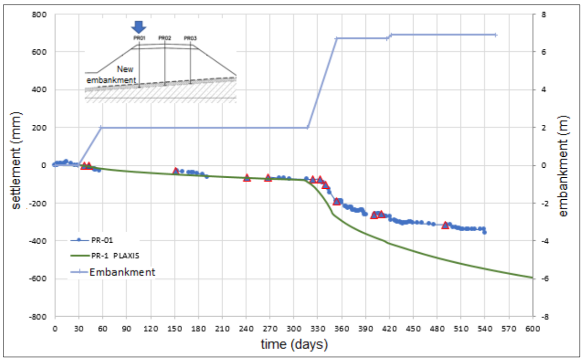
For the three plates (PR 01, PR 02 and PR 03) it was possible to observe a relatively good agreement between field measurements and numerical analysis in phase 1 (initial part of each curve). However, in phase 2, numerical analysis provided larger settlements than those measured in the field (final part of each curve).

5.2 Second analysis results

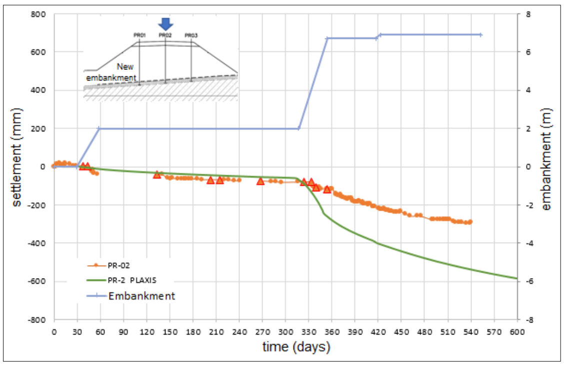
In the second analysis, the permeability of the soft clay layers was decreased by 20 times.

Table 4. Permeability of the soft clay layers used in the second analysis

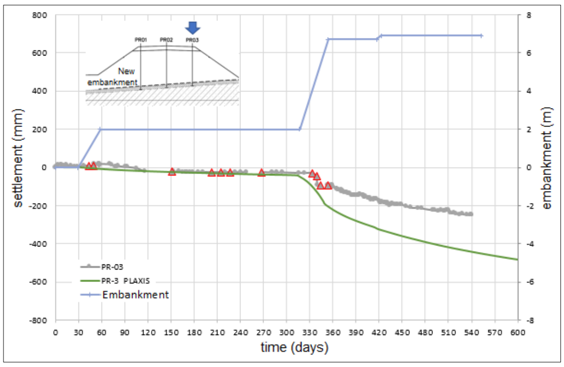
	Clay (A)	Clay (B)	Clay (C)	Clay (D)
k_x (m/s)	$2{,}78.10^{-10}$	$1{,}16.10^{-10}$	$9{,}84.10^{-11}$	$9{,}26.10^{-11}$
k_y (m/s)	$1{,}39.10^{-10}$	$5{,}79.10^{-11}$	$4{,}98.10^{-11}$	$4{,}69.10^{-11}$



a) Plate PR 01



b) Plate PR 02



c) Plate PR 03

Figure 4. Elevation of the embankment height (m) and settlement (mm) versus time in days - Second analysis

In the second analysis it can be noticed a greater compatibility of the numerical results with the field measurements than in the first analysis. It presents a great agreement in the first phase. In the second phase can be seen an improvement of compatibility of the settlement values and velocity. However, even observing this improvement, the second analysis doesn't indicate ideal adjustment between numerical analyses and and field measurements related to the second phase. This lack of agreement can be caused by problems to get the real settlement values during the two periods of greater elevation of the embankment (first and second phase) as a lot of soil movements during construction occurs which could have damaged the instruments. If this type of event occurred, possibly measurements have been affected and the final adjustment, in fact, will be inadequate.

6. CONCLUSION

This article presents the case of an embankment on soft soil constructed to an expansion railroad in State of Maranhão, Brazil, including a comparison between instrumented settlement data collected in the field and results provided by numerical analysis using finite elements method (FEM), according site and laboratory investigation and geometry information of the project. The influence of existing old embankment in the vicinity of the new one and the soft soil permeability, possibly related to the performance of drainage system, were assessed.

The settlement distribution along the cross section (settlement: PR 01 > PR 02 > PR 03) shows the influence of the over consolidation effect of the old embankment. The two different analyses (1 and 2) indicated the importance of influence of the permeability in numerical analysis in terms of the consolidation process velocity

In conclusion, second numerical analysis was compatible with field measurements, considering the first phase of the embankment. However, considering the second phase of the embankment, none of the analyses were compatible with the field measures. The reasons are not accurate, and the inaccuracy of field measurement can be considered. These field instrumentation values were collected without academic or specialized monitoring or follow-up and collected almost simultaneously in other different cross sections of a long road in construction.

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