Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1

Failure mechanism of a geogrid reinforced abutment on soft soil

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ABSTRACT: Geosynthetics can be effectively used to reinforce embankments on soft soils. However, some times basic conditions to be fulfilled for a satisfactory performance of the reinforced structure may be overlooked. This paper describes a case-history where the lack of observation of some basic concepts for this type of work almost yielded to a catastrophic failure of a reinforced abutment on soft clay. The main reasons for that were bad construction practice and insufficient design considerations. Even under these circumstances, the presence of the reinforcement layer minimised the consequences of the failure mechanism developed and showed the influence of reinforcement tensile stiffness on the reduction of the horizontal displacements of the embankment.

1 INTRODUCTION

Soft soil deposits are very common in Brazil, particularly along the country's coast line. Depending on the characteristics of the project, the construction of embankments on soft soils can be very difficult because of the risk of embankment failure and large deformation associated with this type of work. Solutions available for the increase of the soft soil strength or stabilisation of the embankment can be expensive and time consuming. Besides, when the embankment is built close to existing adjacent structures, failure or soft soil displacements can cause severe damages to these structures. Thus, in this type of project deformation limits will have to be imposed in the design and construction monitored by appropriate instrumentation.

Geosynthetics have been used as reinforcement for embankments on soft soils for quite a long time. Its presence in this type of work increases the overall safety factor, allows the use of steeper slopes, reduces construction time and generally yields to cost-effective solutions compared to the alternatives available for soil stabilisation.

The success of the use of geosynthetics as reinforcement can make inexperienced designers and contractors to take the stability of the work for granted, overestimating the reinforcement stabilising effect. Crude stability analyses and careless construction practice can also lead to instability of the embankment or unforeseen large deformations. This paper describes the performance of a reinforced bridge abutment that failed during construction due to the factors mentioned above. A consistent and rather simple analysis of the problem could have predicted and avoided embankment failure.

2 CARACTERISTICS OF THE PROJECT

Several works of highways widening or duplications are underway in Brazil at the present moment, mainly as a result of the necessity of increasing and renewing the country's road infrastructure, responsible for great part of the transportation of goods along its territory. This is the case of the BR-101 highway, which runs along a great extension of the country coast line. Because of the importance of the duplication of this highway, construction has been carried out at a fast pace, yielding to stability problems of some embankments on soft soil, very common in that part of the country. Because of the geotechnical conditions of the region and characteristics of the project, the use of geosynthetic reinforcement was adopted in several cases of embankments on soft soils. The case history described in this paper refers to the abutment built for the crossing of the Santa Luzia river, located 2km far from the city of Tijucas, in the state of Santa Catarina, in the south region of Brazil. Figure 1 shows the location of the case history.

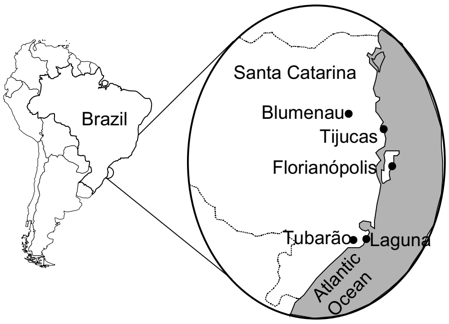
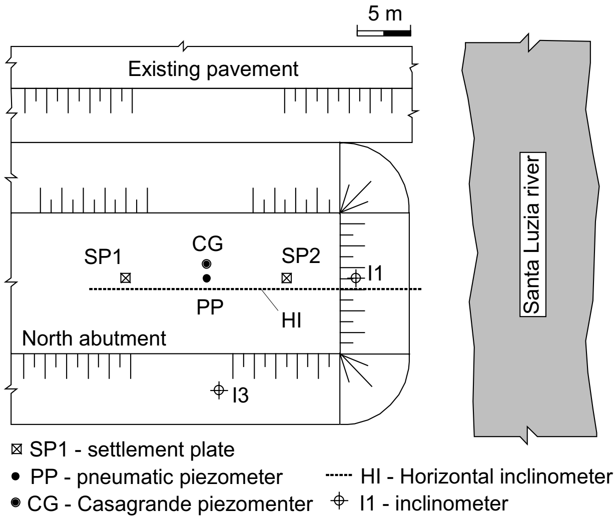


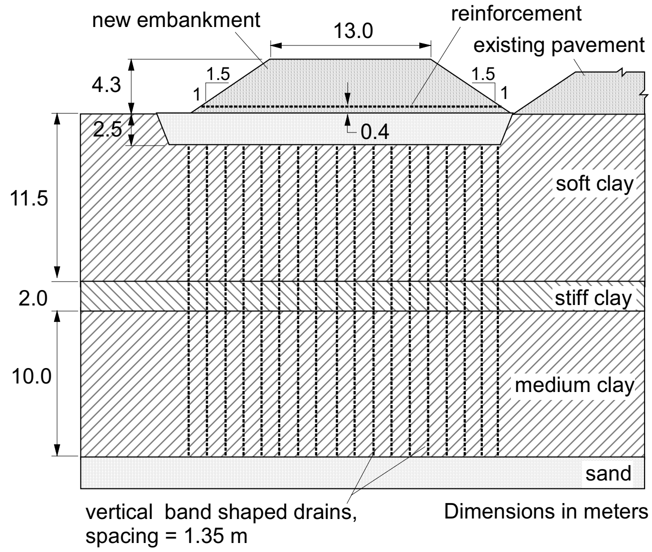
Figure 1. Case-history location.

The project involved the construction of a new embankment, 4.3 m high, adjacent to the existing embankment, as part of the duplication of the highway. Figures 2 (a) and (b) show the proposed initial general geometrical characteristics of the project, with respect to the north abutment, the one considered in this paper. The first 2.5 m depth of the soft soil below the new embankment was substituted by compacted fill material because of the very low shear strengths of the foundation soil at its surface. The inclination of the embankment slopes with the horizontal direction were 1.5:1 (H:V).

The embankment rests on a 23.5m thick clay foundation. The upper half of the foundation soil is composed of a soft clay layer with undrained strengths ranging from 5 to 40 kPa. The lower half of the foundation soil is composed of stronger and stiffer clay layers. Figure 3 presents the variation of undrained shear strength of the foundation soil with depth, obtained from different types of in-situ tests, such as cone penetration tests (CPT and CPTU) and vane shear tests. A rather large scatter of undrained strength values with depth can be observed in Figure 3, as is common in this type of soil deposit.



(a) Plan view



(b) Cross-section

Figure 2. Geometrical characteristics of the reinforced abutment.

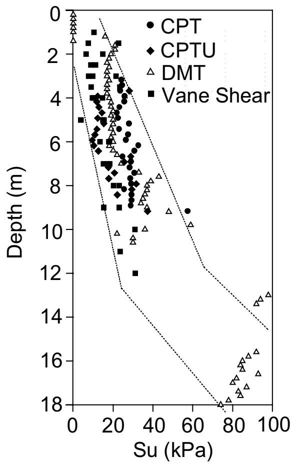


Figure 3. Undrained strength of the soft soil foundation versus depth.

A very heterogeneous fill material was used in the abutment, with grain size distribution ranging from fine sand grains to large blocks of rock. Typical geotechnical parameters for this material were: unit weight equal to 21 kN/m^3, cohesion equal to zero and friction angle equal to 32^o.

To reinforce the embankment, the designers prescribed the installation of a single layer of an uniaxial geogrid reinforcement along its base, 0.4 m above the original foundation surface. The geogrid used is made of polyester fibres protected by a polypropylene cover. The tensile strength of the reinforcement along its longitudinal direction (coincident with the embankment axis) was equal to 200 kN/m and along its transversal direction (normal to the embankment axis) was equal to 15 kN/m. As will be seen later in this work, this difference in tensile strengths and lack of proper consideration on this in the design played a major role in the embankment failure.

Vertical band shaped drains were installed in the clayey foundation to accelerate consolidation settlements. The vertical drains were 100 mm wide and 5 mm thick and were distributed on a square pattern with a spacing equal to 1.35 m.

The geotechnical instrumentation of the abutment consisted of two vertical inclinometers (one at the embankment slope facing the river and the other at the embankment lateral slope), one horizontal inclinometer for settlement measurements, settlement plates and Casagrande and pneumatic piezometers. Figure 2 (a) shows the location of the instruments in the north abutment.

Additional information on materials and project characteristics can be found in Fahel (2002).

3 EMBANKMENT BEHAVIOUR

The embankment was lifted at a rate of approximately 0.35 m/day, as shown in Figure 4. After 10 days of construction, when the embankment height reached 3.6m, large cracks were observed along the embankment surface, parallel to its longitudinal axis, as shown in Figure 5 (a). The contractor and designers then decided to stop the construction and to remove a significant part (2.5 m) of the embankment height in order to build a berm (1.1 m high) for the stabilisation of its lateral slope. The reinforcement capacity to increase embankment stability at such a fast rate of construction was certainly overestimated. It was then decided to leave the embankment with a height of 1.1 m for approximately 4 months for the soft soil to gain strength due to consolidation before construction restarts. A similar failure mechanism and remedial measures to avoid embankment collapse was also observed in other reinforcement abutment in the region and it is described elsewhere (Fahel et al. 2000). Figure 5 (b) shows a pit excavated in the fill to locate the region where the reinforcement failed in tension.

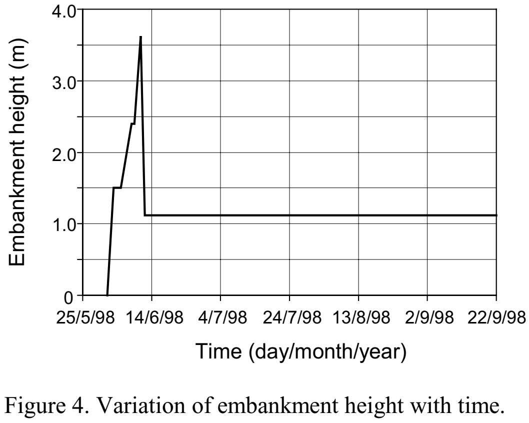


Figure 4. Variation of embankment height with time.

Figure 6 shows the evolution of embankment settlement profiles along the embankment axis at different construction stages, obtained from horizontal inclinometer measurements. A consistent pattern of settlement variation with time can be observed up to the embankment height of 2.4m. When the height of 3.6 m was reached a sudden increase of settlements was observed, caused mainly by the failure mechanism of the lateral slope. After almost 3 months after the reduction of the embankment height to 1.1 m, the settlements had increased 10% due to consolidation of the soft soil (Fig. 6).

(a) Cracks on the embankment surface.

(b) Excavation to locate geogrid failure.

Figure 5. Embankment failure.

Figures 7 (a) and (b) present the horizontal displacement profiles as measured in inclinometers I1 and I3 (Fig. 2a). The horizontal displacements beneath the embankment slope facing the river increased significantly after the embankment has reached a height of approximately 2.4 m (Fig. 7a). Figure 7 (b) shows that the horizontal displacements beneath the lateral embankment slope started increasing at a greater rate for embankment heights above 1.5 m. At the embankment height of 3.6 m the maximum horizontal displacement observed in the lateral embankment (weaker reinforcement direction) height was almost twice that value for the slope facing the river (stronger reinforcement direction). As expected, horizontal displacements of the foundation soil also increased due to consolidation.

The variation of the maximum horizontal displacement in the foundation with the embankment height can be visualised in Figure 8. It is clear that a more significant yielding of the soft soil under the lateral embankment slope started after the its height reached 1.3 m, while a more steady and consistent evolution of maximum horizontal displacements with embankment height can be observed for the slope facing the river.

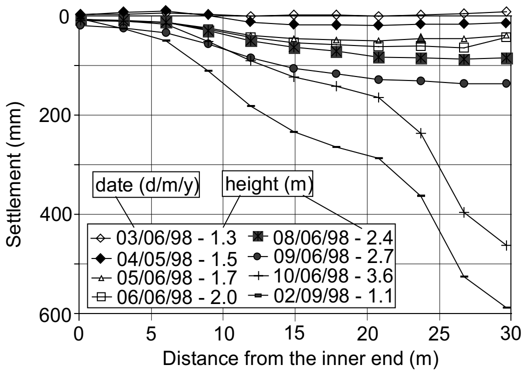
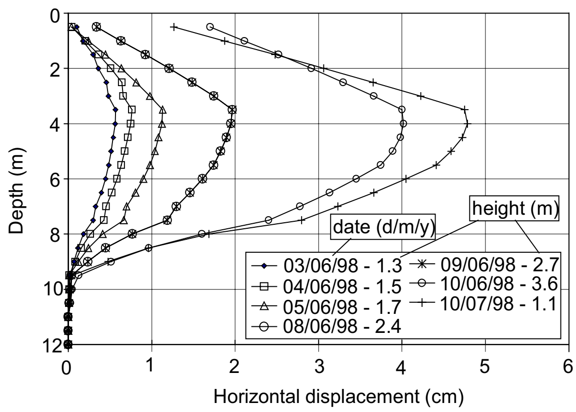
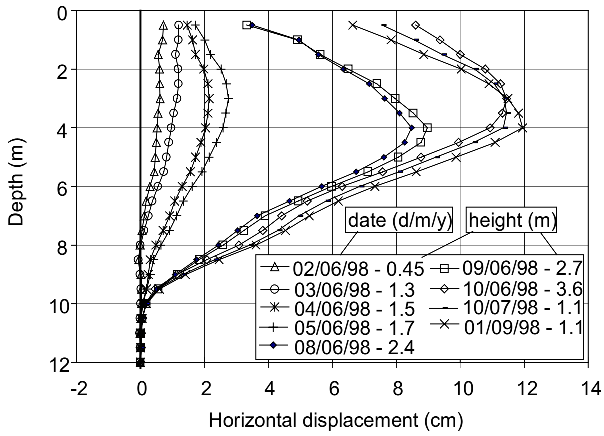


Figure 6. Embankment settlement along its longitudinal axis.



(a) Inclinometer I1.



(b) Inclinometer I3.

Figure 7. Horizontal displacements from inclinometer readings.

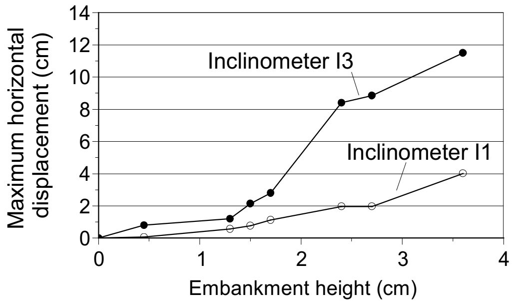


Figure 8. Maximum horizontal displacements in the foundation soil.

The results presented in Figure 8 also shows that the horizontal displacements in the foundation soil were considerably smaller in the stronger/stiffer reinforcement direction (embankment longitudinal direction). This suggests a significant effect of the combination of reinforcement and vertical drains in reducing lateral displacements of the foundation soil, which is particularly relevant in cases of presence of adjacent structures (bridges, for instance). The effect of the reinforcement on the reduction of lateral displacements of the soft soil for a similar case history is also reported in Palmeira and Fahel (2000).

The variation of porepressure from the pneumatic piezometer showed only a small increase close to embankment failure, which suggests the the piezometer must have malfunctioned.

In spite of the deformations in the new embankment no damage was observed in the existing highway embankment. Based on their experience with the construction of the north abutment, the designers increased the stability of the south abutment with a lateral berm and lowered the construction speed.

4 BACK-ANALYSIS OF THE EMBANKMENT STABILITY

In order to assess if the failure mechanism of the reinforced embankment might be anticipated by current design tools, a slope stability analysis was carried out using a limit equilibrium method. A computer code for the analysis of reinforced soil structures developed at the University of Brasilia (Palmeira, 1988) was used to calculate the factor of safety of the embankment at the height of 3.6m using Bishop's method. Soil and reinforcement properties presented in previous sections of this paper were used in the analysis. The average variation of soft soil undrained shear strength with depth from vane and CPT tests was used in the calculations. Both the factor of safety for the slope facing the Santa Luzia river and the lateral embankment slope were calculated. Table 1 summarises the results obtained. For an embankment height equal to 3.6 m, the factor of safety obtained for the embankment lateral slope was equal to 1.07 and for the slope facing the river was equal to 1.23, showing the influence of the value of reinforcement tensile strength in each case. It should be noted the value of safety factor equal to 1.05 for the embankment under unreinforced conditions. These results show that the failure mechanism observed in the embankment lateral slope could have been anticipated and avoided with the use of routine slope stability analysis and also that the slope facing the river was also in unsatisfactory stability conditions.

CONCLUSIONS

This paper described the performance of a case-history of reinforced bridge abutment on soft foundation soil. The embankment presented a failure mechanism and almost collapsed before its planned final height has been reached. Two main reasons for the instability of the embankment can be clearly identified. Firstly a uni-axial geogrid was used as reinforcement, with very different tensile strength values along its longitudinal and transversal directions. As the slopes of the embankment had the same inclination to the horizontal, its lateral slope was not reinforced according to the stability requirements. Even the embankment slope facing the river had just enough reinforcement to avoid failure. Secondly, the fast rate of construction was also detrimental to the stability of the embankment because the drainage system was not able to dissipate a significant proportion of the the pore pressures generated during construction in such a short construction time.

It was also observed that had the designers performed appropriate stability analysis using current design tools the design and construction methodology could have been altered in order to avoid failure of the embankment during construction and the associated disruptions of construction activities and delays.

The results obtained suggest that the use of reinforcement and vertical drains had a significant influence on the reduction of lateral displacements of the foundation soil caused by embankment construction. This reduction is certainly beneficial when there are structures adjacent to the embankment, but still difficult to be accurately quantified routine works. Further analyses are under way for a better understanding on the effects of the use of geosynthetic reinforcement as well as on its required tensile properties values for the reduction of lateral displacements of embankments on soft foundation soils.

Table. Stability analysis results.

Embankment slope	Reinforcement force available (kN/m)	FS(1) for h(2) = 3.6 m
Lateral slope	15.0	1.07
Slope facing the river	200.0	1.23
Unreinforced case	0	1.05

Notes: (1) FS = factor of safety from Bishop's method (slip circle analysis), (2) h = embankment height.

ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian National Highways Department (DNER) for the authorisation to report the results and analyses presented in this paper. The authors are also indebted to the following institutions, whose support made this work possible: CNPq/Brazilian Research Council, CAPES/Brazilian Ministry of Education, FAP-DF/Federal District Research Sponsoring Agency, FINATEC-UnB and the University of Brasilia.

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