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

Short and long-term analysis of a reinforced embankment over soft soil

M. ABRAMENTO, FAAP, São Paulo, SP, Brazil
G. R. CASTRO, EPUSP, São Paulo, SP, Brazil
S. J. A. M. CAMPOS, IPT, São Paulo, SP, Brazil

ABSTRACT: This paper analyzes how the overall Factor of Safety of a reinforced embankment over soft soil varies considering the simultaneous effects of increase in strength of the soft soil due to consolidation and reduction of strength of reinforcement due to creep. Two conditions are analyzed, namely Short Term (End of Construction - EOC) and Long Term (LT, or Operating) conditions. For EOC, the natural undrained shear strength of the soft soil is considered in the analysis, while for the LT the soft soil was supposed to have a high level of consolidation due to the embankment load and increased undrained shear strength. Polyolefin (PO) and polyester (PET) reinforcements were considered in the analysis, with creep Reduction Factors (RF) estimated from strength retained curves. The results show that, depending on the polymer type, if a reinforcement satisfies the required level of safety for EOC conditions does not necessarily imply that the LT safety conditions are also satisfied.

1 INTRODUCTION

Soft saturated soils are found near harbor areas and most river estuaries. When there is a need for constructing in these areas, traditional foundation options are to excavate (partially or completely) and replace the soft soils, drive deep foundations, stabilize the soft soils (e.g. with additives), or surcharge (normally with vertical drains if the coefficient of consolidation is very low) and wait for consolidation. An alternative method, which has been increasingly used, is to install a high-strength reinforcement over the soft soil and then execute the embankment to the design grade, associated or not with vertical drains. The embankment can then be constructed very rapidly and still guarantee the overall stability, with no need to wait for the soft soil to consolidate.

The design of such basal reinforced embankment is usually carried out considering a "short-term" strength for the soft soil, i.e., without considering any increase in strength due to consolidation, associated with a "long-term" strength for the reinforcement, which includes creep and other reduction factors. No assessment is normally done on the degree of safety considering the actual strength of both soft soil and reinforcement for each construction stage and operating conditions.

This paper presents a study comparing the global factor of safety of a roadway embankment for two conditions, namely "short term" (end of construction) and "long term" (operating) conditions, taking into account the increase in strength of soft soil with consolidation and the decrease in strength of the reinforcement due to creep. The paper focus exclusively on the rotational stability of the embankment. Other failure mechanisms (e.g. lateral sliding of embankment and foundation puncture) are beyond the scope of this paper.

The procedure was used for analyzing a reinforced embankment of BR-116 DNER roadway, which links the cities of Curitiba and São Paulo, Brazil. Parts of BR-116 cross several areas of soft soil (organic clay) deposits, and a reinforcement layer were introduced underneath the embankment.in order to guarantee its overall stability. The same procedure was also used for analyzing all reinforced embankments of a roadway (managed by DERSA authority) which links Dutra and Ayrton Senna roadways, near São José dos Campos city, although these results are not shown in the present paper.

2 GEOMETRY AND INITIAL CONDITIONS

Figure 1 shows the embankment geometry and characteristics of the soft soil. The embankment is 3m high with side slopes of 2H:1V, and is constructed using sandy soil. The soft soil consists in an organic clay, with Liquid Limit 60% and Plasticity Index 20%. A coarse sand with silt, with varied colors, is located underneath the soft soil. The water table is located near the surface.

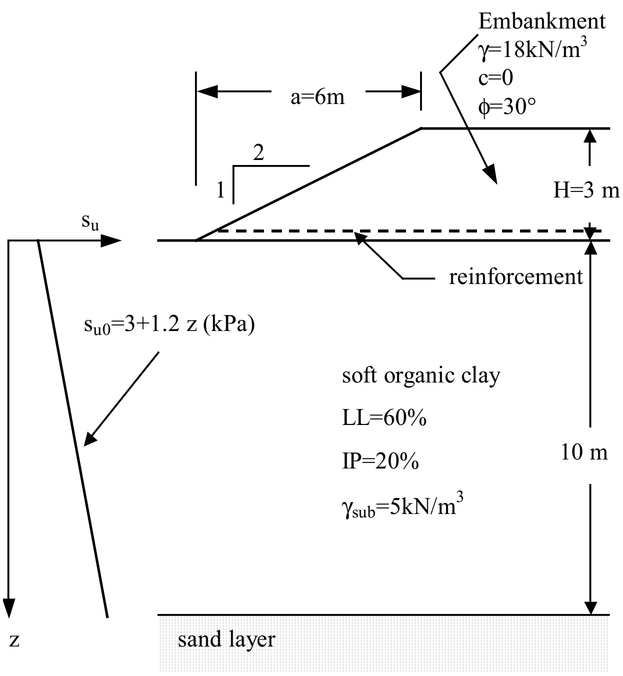

Figure 1. Geometry and initial conditions

The undrained shear strength of the organic clay was determined from field Vane tests, which were corrected using Bjerrum's (1972) formulation. Prior to the embankment construction, the undrained strength is denominated s_{u0} and varies with depth according to the following expression:

$s_{u0}=3+1.2z$ (1)

where: z = depth in meters; s_{u0} is expressed in kPa.

For the conditions shown in Figure 1, the global factor of safety of the embankment considering a rapid construction, without any consolidation of the soft soil, is FS=0.56. Therefore, a solution of basal reinforcement using a geosynthetic was adopted to satisfy the required safety conditions.

3 ANALYSIS

3.1 *Short and Long-Term Conditions*

Two conditions were established for analyzing the embankment shown in Figure 1: Short Term (End of Construction, EOC) and Long Term (LT, or operating) conditions. The required global Factors of Safety FS for these two conditions are, respectively, FS_{EOC}=1.2 and FS_{LT}=1.5, as required by the highway authority.

For the EOC condition, it is assumed that s_u is represented by Equation 1, i.e. neglecting a possible increase in strength due to consolidation during construction process. This hypothesis can be verified calculating the degree of consolidation which occurs during an estimated construction time t = 5 days, and adopting a value for the coefficient of consolidation c_v, which was not measured for this case. For example, considering $c_v=2.0m^2$/year for the 10m thick deposit of Figure 1, which is surrounded by draining layers (i.e., drainage height of H_d=5.0m), the Time Factor can be calculated using Terzaghi's formulation $T=c_v.t/H_d^2=0.002$. This results a degree of consolidation U<5%, which is considered relatively small and is neglected for the EOC stage. For longer construction periods it is recommended a more accurate analysis, calculating the actual value of U as well as the corresponding increase in undrained shear strength.

For the LT condition, it is considered that the soft soil has attained a high degree of consolidation, i.e. U>95% under the embankment load, and the failure is supposed to be undrained.

3.2 *Increase in s_u due to Consolidation for LT Condition*

To estimate the increase in undrained strength for the soft soil due to the embankment load, the organic clay was subdivided into five regions, numbered 0 to 4, as shown in Figure 2.

For each of these five regions, the following sequence of calculations was performed. The initial (EOC) effective vertical stress σ'_{vc0} is given by:

$$\sigma'_{vc0} = \gamma_{sub}.z \quad (2)$$

where γ_{sub} = submerged unit weight (considered as $5kN/m^3$); z = depth in m. It is assumed that the undrained shear strength s_u in either short or long-term conditions can be expressed by the equation proposed by Ladd et al. (1977):

$$\frac{s_u}{\sigma'_{vc}} = 0.22\ OCR^{0.8} \quad (3)$$

where σ'_{vc} = vertical effective consolidation stress; OCR = overconsolidation ratio.

Therefore, the EOC Overconsolidation Ratio OCR_0 is calculated as:

$$OCR_0 = \left[\frac{s_{u0}}{0.22\,\sigma'_{vc0}}\right]^{1.25} \quad (4)$$

Considering a submerged unit weight of $5kN/m^3$, the resulting EOC overconsolidation ratio (OCR_0) varies typically from 4 to 8 close to the surface, decreasing to 1.5 at the bottom of the soft soil. The deposit is therefore lightly overconsolidated, probably due to oscillations in the water table.

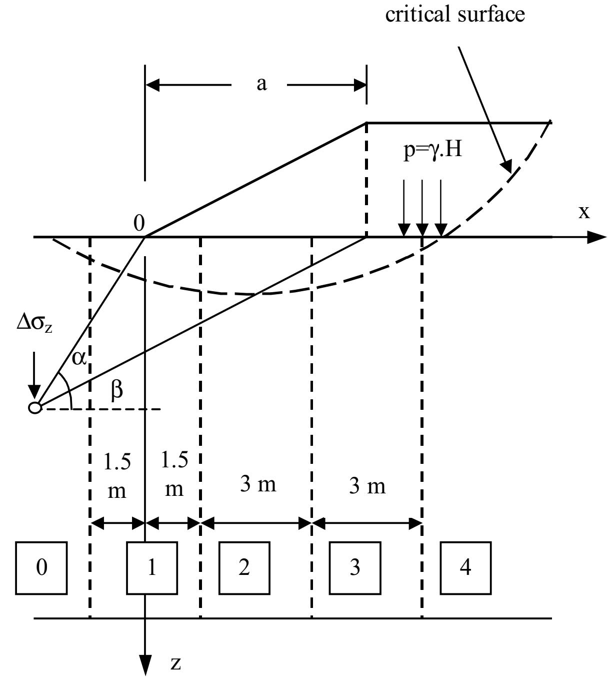

Figure 2. Estimating the increase in s_u for the soft soil

The EOC yield stress σ'_{p0} is calculated as:

$$\sigma'_{p0} = OCR_0.\sigma'_{vc0} \quad (5)$$

The increase in vertical stress $\Delta\sigma_z$ underneath the embankment was estimated using the elastic solution provided by Poulos & Davis (1973):

$$\Delta\sigma_z = \frac{p}{\pi a}(a\beta + x\alpha) \quad (6)$$

where p = load under the embankment; a, x, α and β are shown in Figure 2.

The vertical stress in the soft soil for the LT condition is given by:

$$\sigma'_{vc} = \sigma'_{vc0} + \Delta\sigma_z \quad (7)$$

For this condition, the OCR (limited to 1.0) is then calculated as:

$$OCR = \frac{\sigma'_p}{\sigma'_{vc}} \quad (8)$$

Finally, the undrained shear strength for each region 1 to 4 can be calculated as:

$$s_u = 0.22\ \sigma'_{vc}\ OCR^{0,8} \quad (9)$$

The resulting undrained shear strength considering Long Term conditions is shown in Figure 3.

3.3 *Reduction of Reinforcement Strength due to Creep*

A number of researches have published results from creep testing of geotextiles and geogrids (e.g. Greenwood et al., 2000). Figure 4 shows a general range of retained tensile strength of polymeric reinforcements as a function of time to failure.

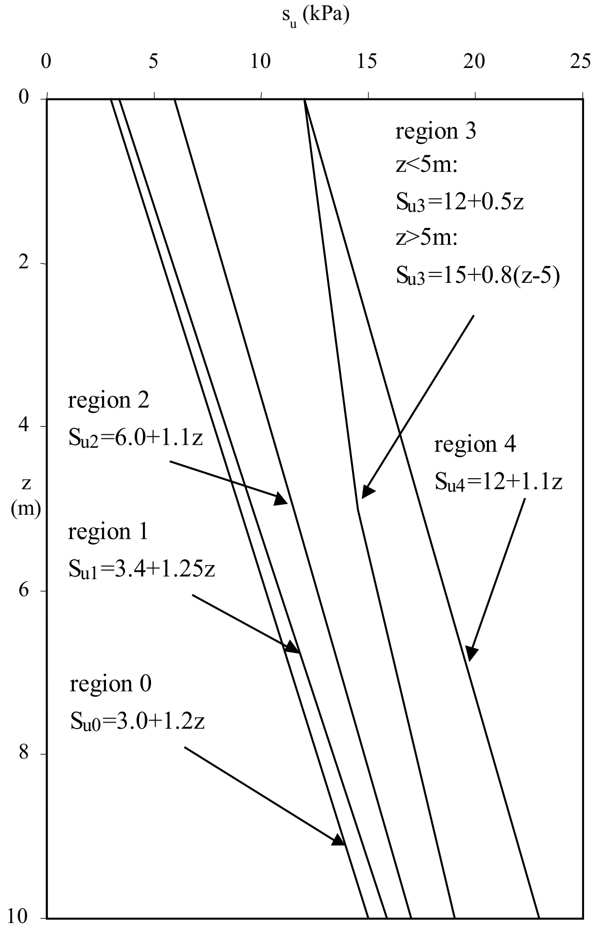

Figure 3: Undrained shear strength for the Long Term condition

The retained strength for the construction time considered in the present analysis (EOC, around five days) ranges approximately from 70 to 80% for polyester reinforcements and from 50 to 60% for polyolefine reinforcements. For the LT condition the retained strength corresponding to 120 years is considered in the analysis, and ranges from 50 to 65% for polyester and from 20 to 35% for polyolefine reinforcements.

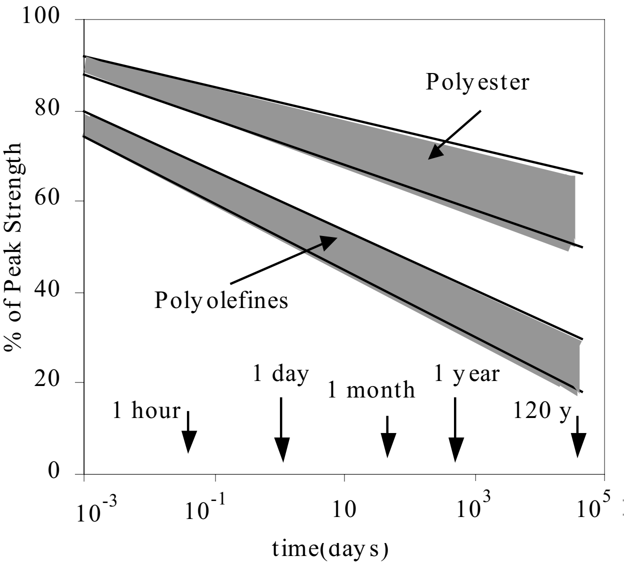

Figure 4. Range of creep retained strength for polymeric reinforcements

For the present study, only the reduction factor due to creep is considered; other reduction factors (e.g. installation damage) should be included for a more accurate analysis.

3.4 *Modeling*

A limit equilibrium computer program was used for determining the global factor of safety for the embankment at both EOC and LT conditions. The Spencer (1967) algorithm was used in the analyses.

The reinforcement was considered as a horizontal single layer and its rotation at the intersection point with the potential failure surface was not allowed. This procedure generally yields higher reinforcement strength; however, its influence in the relative variation in the overall safety factor for the conditions analyzed is considered to be small and is neglected in this study.

To simplify the analyses, no surcharge over the embankment was considered in this study.

4 RESULTS

Table 1 shows values of global factor of safety for the embankment of Figures 1 and 2 for both EOC and LT conditions. The necessary tensile strength of the reinforcement was initially calculated as 183kN/m in order to satisfy FS=1.2 at EOC (5 construction days) for both polyester and polyolefine reinforcements. For this construction time, the retained geosynthetic strength was estimated from Figure 4, yielding the Reduction Factors shown in Table 1. The necessary peak tensile strength was then backcalculated, for both reinforcements. The Long Term retained strength (for 120 years) was also estimated from Figure 4 for both reinforcements, yielding the values shown in Table 1.

Figure 5 shows schematically the evolution of global FS for the embankment for both EOC and LT conditions. The evolution of the overall factors of safety are shown in dashed lines since they do not necessarily follow a straight line.

For the unreinforced embankment, the global FS increases from 0.56 at End of Construction to 0.92 at Long Term conditions, demonstrating the need of reinforcement even for full consolidation of the soft soil.

Supposing that the embankment is constructed with a polyester reinforcement such that FS=1.2 for EOC, Figure 5 shows that the resulting FS for LT conditions varies from FS=1.49 to 1.60. Therefore, for PET reinforcements the LT condition target of FS=1.5 is attained. For the polyolefine reinforcement however, starting with FS=1.2 at EOC, the global FS at LT conditions varies from 1.25 to 1.35 and, therefore, the LT condition target of FS=1.5 is not attained. These results show that because the loss of strength due to creep is more significant for PO reinforcements, the Long Term global FS requirements may not be always satisfied.

For the polyolefine reinforcement, limit equilibrium analyses demonstrate that the necessary retained strength at LT conditions should be 135kN/m in order to satisfy FS=1.5. Using the average reduction factors from Figure 4, the peak and End of Construction strength values (Tpeak and T_{EOC}) are backcalculated as 540kN/m and 310kN/m, respectively. Figure 5 shows that the global factor of safety for the embankment at EOC using a PO reinforcement must be FS=1.64 in order to satisfy the required value of FS=1.5 at LT conditions.

Possible paths for the evolution of FS during consolidation of soft soil considering the simultaneous effect of creep are shown schematically in the same Figure 5 as dashed lines with question marks, demonstrating that the lowest or highest possible values of FS may occur anytime during the consolidation process, depending on the rate of consolidation and other factors.

The analysis presented in this paper does not consider the presence of vertical drains (which accelerate the rate of consolidation) or the reduction of reinforcement strength by chemicals and mechanical attacks during construction.

It should be pointed out that the geosynthetic "creep retained strength" shown in Figure 4 is conventionally obtained for reinforcements under constant load. For the real case of a reinforced embankment over a consolidating soil, however, this may not be the case because the increase in strength for the soft soil due to consolidation probably leads to a load reduction in the geosynthetic. The analysis presented in this paper considers a simplified limit equilibrium approach for both short and long term conditions. It is possible to carry out a more accurate analysis considering the rheology of both soft soil and reinforcement using numerical procedures. These analyses, however, are beyond the scope of this paper.

Table 1. Results for EOC and LT construction periods

Condition	Parameter		Reinforcement PET	Reinforcement PO
EOC	Required Global FS		1.2	1.2
	T necessary (kN/m)		183	183
	RF* @ EOC	Average	1.33	1.75
		Range	1.25 – 1 .40	1.60 – 1.90
	Tpeak (kN/m)	Average	245	320
		Range	230 – 250	290 – 350
LT	Required Global FS		1.5	1.5
	RF* @ LT	Average	1.75	4.0
		Range	1.5 – 2.0	3.0 – 5.0
	T calculated (kN/m)	Average	140	80
		Range	130 – 155	70 – 95
	Calculated Global FS	Average	1.53	1.29
		Range	1.49 – 1.60	1.25 – 1.35

*RF = Reduction Factor, from Figure 4.
T= reinforcement tensile strength

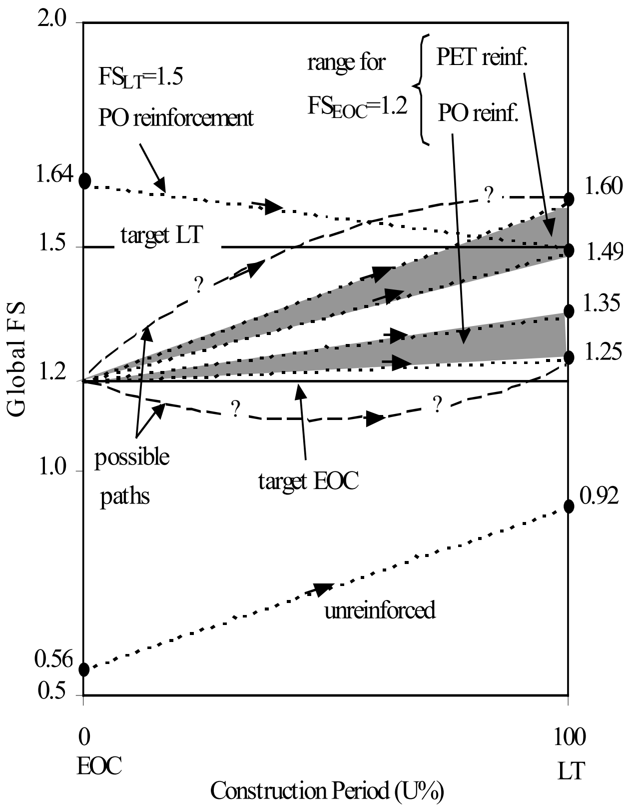

Figure 5. Global FS as a function of construction period and polymer

5 CONCLUSIONS

The following conclusions can be summarized from the analyses:

- The stability of an embankment over soft soil should be analyzed for both short and long-term conditions, with adequate global safety factors (in general lower for short-term and higher for long-term conditions).
- An embankment over soft soil may require a basal reinforcement for both short and long-term conditions, even considering that the soft soil attains a high level of consolidation.
- If a reinforcement satisfies the required level of safety for End of Construction (short-term) conditions does not necessarily imply that the long term safety conditions are also satisfied. This depends on the properties of reinforcement polymer, as shown in this paper. However, other factors like the embankment geometry, overconsolidation ratio and consolidation parameters of the soft soil as well as drainage conditions may affect the results (Campos, 2002).
- For example, relatively thick deposits (e.g. 20m) of plastic organic soils with relatively low c_v values (say 0.6m2/year), without vertical drains, would reach 90% consolidation at t=170 years and, therefore, later than the available values of retained strength presented in the literature.
- As a general conclusion, it is suggested that the global factor of safety for a reinforced embankment over soft soil be calculated for different stages of consolidation, comparing the actual increase in strength of the soft soil and the reduction of strength of the reinforcement due to creep.

REFERENCES

Bjerrum, L. 1972. Embankments on soft ground: SOA Report. *Proc. Speciality Conference on Performance of Earth and Earth-Supported Structures*, ASCE, 2, 1-54.

Campos, S.J.A.M. 2002. *Short and long-term analysis of reinforced embankments over soft soils*. M.Sc. Thesis, Escola Politécnica da USP (in Portuguese).

Greenwood, J.H. Kempton, G.T. Watts, G.R.A. & Bush, D.J. 2000. Twelve year creep tests on geosynthetic reinforcements. *II European Geosynthetics Conference*, Bologna, 1, 333-336.

Ladd, C.C., Foott, R., Ishihara, K., Schlosser, F. & Poulos, H.G. 1977. Stress-deformation and strength characteristics: state-of-the art report. *Proc. 9th Intern. Conf. on Soil Mechanics and Foundation Engineering*, 2, Tokyo, 421-494.

Poulos, H.G. & Davis, E.H. 1973. *Elastic solutions for soil and rock mechanics*. J. Wiley and Sons.

Spencer, E 1967. A method of analysis of the stability of embankments assuming parallel inter-slice forces. *Geotéchnique*, v. 17, n.1, 11-26.