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# Behavior with time of reinforced embankments over soft soil

Campos, S.
*Technological Research Institute of São Paulo State IPT, Brazil*

Abramento, M.
*Fiberweb and FAAP & USJT, Brazil*

Castro, G.R.
*EPUSP, Brazil*

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ABSTRACT: This paper analyzes the overall Factor of Safety of a reinforced embankment over soft soil considering the simultaneous effects of increase in strength of the soft soil due to consolidation and reduction of strength of reinforcement due to creep in an optimized design. Behavior with time of reinforced embankments over soft soil are analyzed, since end of construction until end of operating time. For end of construction, the natural undrained shear strength of the soft soil is considered in the analysis, while for the operating time (120 years) the consolidation was considered varing of 10% consolidation degree 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 analyses of Factor of Safety was realized using the software Slope/W and the Bishop Method. The results show that, depending on the polymer type, coefficient of consolidation and the consolidation degree if a reinforcement satisfies the required level of safety for end of construction conditions does not necessarily imply that the operating time safety conditions are also satisfied.

## 1 INTRODUCTION

An usual method to construct embankments over soft soils, which has been increasingly used, is to install a high-strength reinforcement over the soft soil and then execute the embankment, associated or not with vertical drains. 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 for end of construction (EOC) and during consolidation, taking into account the increase in strength of soft soil with consolidation and the decrease in strength of the reinforcement due to creep with focus on an optimized design.

## 2 CASE STUDY

The embankment geometry considered for the analysis is 3 m high, with side slopes of 2H:1V and sandy soil. The soft soil consists in a typical soft clay from Santos, Brazil, with Liquid Limit 60%, Plasticity Index 20% and 10m thick. Three typical values for the coefficient of consolidation were considered ($c_v = 10^{-2}cm^2/s$; $c_v = 10^{-3}cm^2/s$; $c_v = 10^{-4}cm^2/s$). The water table is located near the surface.

Prior to the embankment construction, the undrained strength is denominated $s_{u0}$ and varies with depth according to the following expression:

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

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

For these conditions, the global factor of safety of the embankment considering a rapid construction, without any consolidation of the soft soil, is FS = 0.58. Therefore, a solution of basal reinforcement using a geosynthetic was adopted to satisfy the required safety conditions.

## 3 ANALYSIS

### 3.1 *Operating conditions*

The operating conditions were analyzed for increments of degree of consolidation of 10%, considering the simultaneous effects of the increase in strength of soft soil with consolidation and the available strength of the reinforcement due to creep. The increase in $S_u$ depends on the coefficient of consolidation ($c_v$) and the required global Factors of Safety (FS) for End of Construction and Long Term are, respectively, $FS_{EOC} = 1.2$ and $FS_{LT} = 1.5$.

During operating time, it is assumed that the increase in vertical stresses in the soft soil are due to the embankment load and an undrained failure is considered in the analysis (Ladd, 1991).

### 3.2 *Increase in $S_u$ due to consolidation*

To estimate the increase in undrained strength for the soft soil due to the embankment load, the soft clay was subdivided into five regions, numbered 0 to 4, as shown in Figure 1.

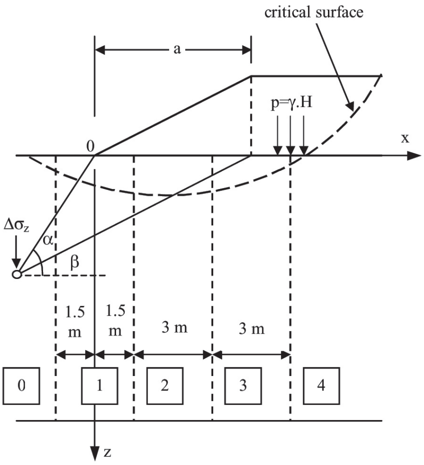

Figure 1. Estimating the increase in $s_u$ for the soft soil.

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

$$\sigma'_{vc0} = \gamma_{sub} \cdot z \tag{2}$$

where $\gamma_{sub}$ = submerged unit weight (considered as 5 kN/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):

$$\frac{s_u}{\sigma'_{vc}} = 0.22\, OCR^{0.8} \tag{3}$$

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

Therefore, for the operating time, the Overconsolidation Ratio $OCR_0$ is calculated as:

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

Considering a submerged unit weight of 5 kN/m$^3$, the resulting EOC overconsolidation ratio ($OCR_0$) varies typically from 18 to 4.6 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.

The EOC yield stress $\sigma'_{p0}$ is calculated as:

$$\sigma'_{p0} = OCR_0 \cdot \sigma'_{vc0} \tag{5}$$

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

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

where p = load under the embankment; a, x, $\alpha$ and $\beta$ are shown in Figure 1.

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

$$\sigma'_{vc} = \sigma'_{vc0} + \Delta\sigma_z \tag{7}$$

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

$$OCR = \frac{\sigma'_p}{\sigma'_{vc}} \tag{8}$$

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

$$s_u = 0.22\,\sigma'_{vc}\, OCR^{0.8} \tag{9}$$

The resulting undrained shear strength considering operating time conditions is shown in Figures 2 and 3 for consolidation degrees of 40% and 90%.

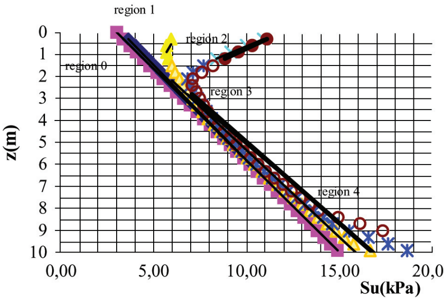

Figure 2. $S_u$ increase at 40% consolidation degree.

### 3.3 *Reinforcement strength available due to creep*

A number of researches have published with results from creep tests of geotextiles and geogrids (e.g. Greenwood et al., 2000; Silva & Vidal, 2002; Constanzi, 2003). Figure 4 shows a general range of retained tensile strength of polymeric reinforcements as a function of time to failure.

For the conditions in this paper the EOC reduction factors were estimated from Figure 4 as varying from 1.25 to 1.4 for polyester and 1.6 to 1.9 for polyolefine

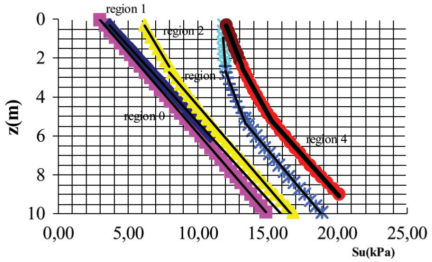

Figure 3. $S_u$ increase at 90% consolidation degree.

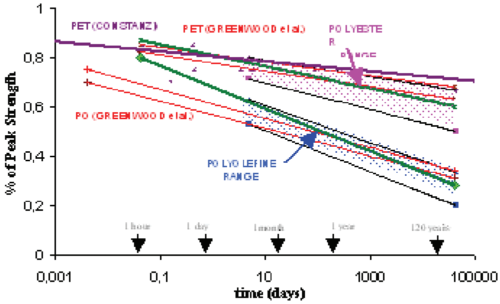

Figure 4. Range of creep retained strength for polymeric reinforcements.

reinforcements. The long term retained strength (for 120 years) was also estimated from Figure 4, with RF varying from 1.5 to 2 for polyester and from 3 to 5 for polyolefines.

For this study, only creep reduction factors were considered; other reduction factors (e.g. installation damage) should be included for a more accurate analysis.

### 3.4 *Modeling*

The computer program Slope/W was used for determining the global factor of safety for the embankment for all stages. The Bishop Method was used in the analyses and the reinforcement was considered as a horizontal single layer. No surcharge over the embankment was considered in this study.

## 4 RESULTS

Figure 5 presents results of global FS for a 3m embankment as a function of Cv and reinforcement polymer. Without reinforcement, the global FS varies from 0.58 (EOC) until 0.92 (long term, or 99% consolidation degree).

In order to achieve a minimum established global FS = 1.2 for EOC, a reinforcement with 180 kN/m of strength is necessary. In this case and for LT conditions the resulting FS varies from 1.51 to 1.60 for PET reinforcements, for the range of RF values considered. Therefore, a PET reinforcement reaches the established target condition of FS = 1.5 at LT conditions. During consolidation process the value of FS for the PET reinforcement is always above the minimum EOC value of 1.2, except for the lower values of Cv.

For the polyolefine reinforcement (PO), and considering the same EOC conditions (FS = 1.2), the Long Term Factor of Safety varies from FS = 1.29 to 1.42, below the required minimum target value of 1.5. As shown in Figure 5, the critical condition may occur during life time for smaller values of coefficient of consolidation. These results shows that because the reduction of retained strength of PO reinforcement due to creep is more significant than the increase in Su, the global FS may decrease during consolidation

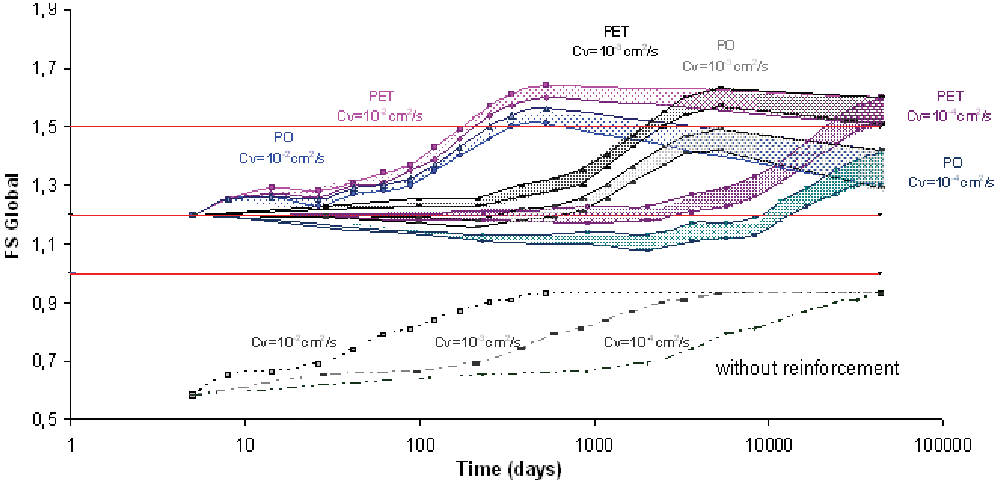

Figure 5. Global FS as a function of construction period, polymer and coefficient of consolidation.

and may be lower than the initial EOC value of FS = 1.2.

## 5 CONCLUSIONS

The following conclusions can be summarized from the analyses:

- The stability of an embankment over soft soil should be analyzed for conditions during operating time, with adequate global safety factors (in general lower for short-term and higher for long-term conditions) with focus in an optimazed design.
- In the example presented in this paper the considered embankment over soft soil may require a basal reinforcement even after full consolidation of soft soil.
- If a reinforcement satisfies the required level of safety for End of Construction (short-term) conditions does not necessarily imply that the operating time and long term safety conditions are also satisfied. This depends on the properties of reinforcement polymer and coefficient of consolidation as shown in this paper. However, other factors like the embankment geometry and overconsolidation ratio of the soft soil as well as drainage conditions may affect the results (Campos, 2002).

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