SLOPE FACTOR OF SAFETY DURING ROAD CONSTRUCTION

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SLOPE FACTOR OF SAFETY DURING ROAD CONSTRUCTION

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ABSTRACT: Road construction is one of the longitudinal geological-geotechnical works that may consider thousands of kms, where a diversity of embankment slopes and cut slopes are made to implement the way of the desired road. Due to the heterogeneity and variability of the geological and geotechnical surroundings, local slope instabilities are a common geotechnical hazard. To minimize the economic impact and the unavoidable delays due to such happenings it is very important to plan ahead an observation system that insures a safe road construction. One of the key instruments to install is the inclinometer that is used to monitor the evolution of horizontal displacements at specific locations and depths. The purpose of this study is to generalize the procedures developed in 1995 by Salgado (1), assuming initial horizontal ground conditions, to estimate the local factor of safety value at the location of specific inclinometer measurements, to a more realistic and common condition where initial sloping ground conditions prevail. The procedures follow the original work (1) where the boundary conditions between two consecutive inclinometer readings, in depth, are associated to the boundary conditions of the simple shear test. By comparison with the simple shear test results it is possible to assess a factor of safety value based on the level of the shear strain estimated from the inclinometer readings. To extrapolate to different confining stresses the procedures were expanded in 1997 by Carvalho (2) and optimized in 1998 by Salgado & Carvalho (3) considering the hyperbolic stress-strain model formulation. To extrapolate to initial slope ground conditions, new procedures were developed by Salgado (4, 5) to take into account the initial static bias imposed by the *in situ* sloping ground.

Key-Words: *safe road construction, slope cuts, embankment slopes, hyperbolic model, local factor of safety.*

1. INTRODUCTION

The Geotechnical Department of LNEC is often solicited by both Government and private companies to provide consulting work at different levels, namely: a) project review; b) supervision and control of safety, during and after construction; c) diagnosis of geotechnical instability problems and respective solutions.

One of the instruments most widely used in the field monitoring, to evaluate local slope stability, is the inclinometer.

Several types of sensitive inclinometers have been developed (6, 7). The Slope Indicator Company has been optimizing this device as well as the procedures for inclinometer data interpretation (8).

One of the instability cases studied by LNEC researchers underlined the need to improve the procedures for inclinometer data interpretation. In 1994, during the construction of the access embankment of a railroad overpass, a foundation failure occurred in Azambuja ´s underlying soft clay deposit. Using the current procedures for inclinometer data interpretation, it was not possible to forecast that a foundation failure would take place one hour after a reading that was taken in one inclinometer located at the foot of the south embankment. To overcome this shortcoming in inclinometer data interpretation, Salgado (1) proposed a new procedure that allows the estimation of the local factor of safety, FS, based on the estimation of the horizontal shear strain, γ_h, from inclinometer data. Sequentially (2, 3) proposed a new procedure to take into account the effect of the *in situ* confining stress using the concept of the hyperbolic formulation (10, 11). This procedure was used to study the Azambuja case and was successfully applied, in 1997 (10), to sustain as a major slope instability case that developed at one of the main highway access to the city of Lisbon. However, the procedure did not considered the effect of the *in situ* static bias into account in the estimation of the local factor of safety. This expansion of the procedures was later achieved by Salgado (4, 5) as is described in the text of this paper.

2. STANDARD (8) AND NEW (1) INCLINOMETER DATA INTERPRETATION

After installation of the guide casing the probe is lowered to the bottom end and an inclination reading is made. Additional readings are made as the probe is raised incrementally to the top of the casing (Figure 1 a) providing data for determination of the initial casing alignment. The differences between the initial set of readings and a subsequent set define any change in alignment. Provided that the bottom end of the casing is fixed from translation, these differences allow calculation of absolute horizontal deformation at any point along the casing. The standard procedures (8) for the interpretation of inclinometer data consists of two types of plots (Figure 2), namely: i) the "cumulative change plot" given by Σ L Sin (θ) vs depth; and ii) the "change plot" given by L Sin (θ) vs depth, where L = length between readings, θ = inclination angle. In this figure is presented the data obtained at the Azambuja site (1994) where the last reading was taken one hour before foundation failure.

The new procedures were developed by Salgado (1) considering the analogy between the boundary conditions of the simple shear test and the correspondent to the inclinometer between two consecutive readings of the same data set (Figure 1b). Considering the difference in displacements between two consecutive readings (d_i-d_{i+1}) it is possible to compute the correspondent horizontal shear strain, γ_h, as shown in Figure 1b, where γ_h (%) = 100 . (d_i-d_{i+1}) / L cos (θ). The correspondent factor of safety can be obtained using the data from a simple shear test as is shown in Figure 3 (Salgado (1)), where: γ_1 is the horizontal shear strain correspondent to inclinometer data set nº 1, τ_1 is the correspondent mobilized shear stress and the factor of safety is computed from the ratio between the peak shear resistance, cup, and τ_1 (Salgado (1)).

To take into account the effect of in situ confining stress the original procedure was expanded (2, 3) using the hyperbolic formulation (9, 10), expressed by eq. 1. The factor of safety is given by eq. 2 and the shear strain at failure, γ_f, is obtained from eq. 2, by inputting FS=1 and computing γ_f from eq. 3:

$$\tau = \gamma / (1/ G_i + \gamma R_f / \tau_r) \qquad (1)$$

$$FS = (\tau_r + G_i \gamma R_f) / (G_i \gamma) \qquad (2)$$

$$\gamma_f = (\tau_r / G_i) (1/ (1- R_f) \qquad (3)$$

where γ is the maximum shear strain, G_i isthe initial shear modulus and R_f is the failure ratio equal to the ratio between the resistance shear stress, τ_r, and τ_{ult} , the asymptotic value of τ_r.

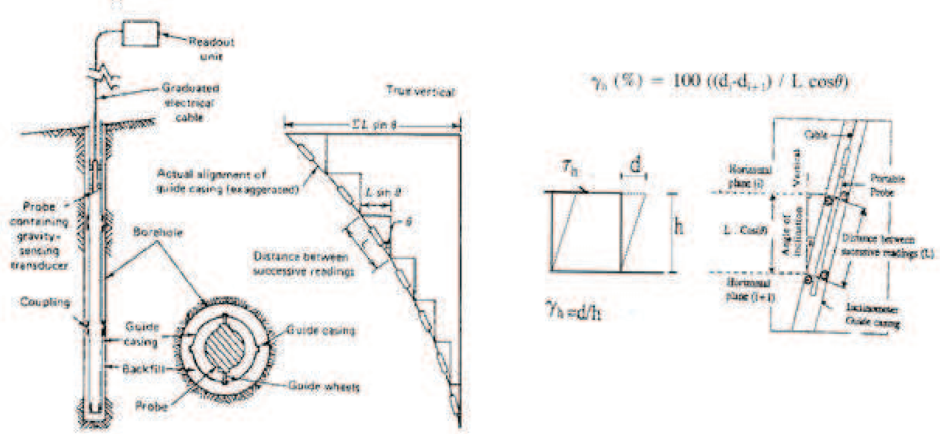


Figure 1 – a) Principle of inclinometer (8) ; b) analogy between the boundary conditions of the simple shear test and the correspondent to the inclinometer between two consecutive readings(1)

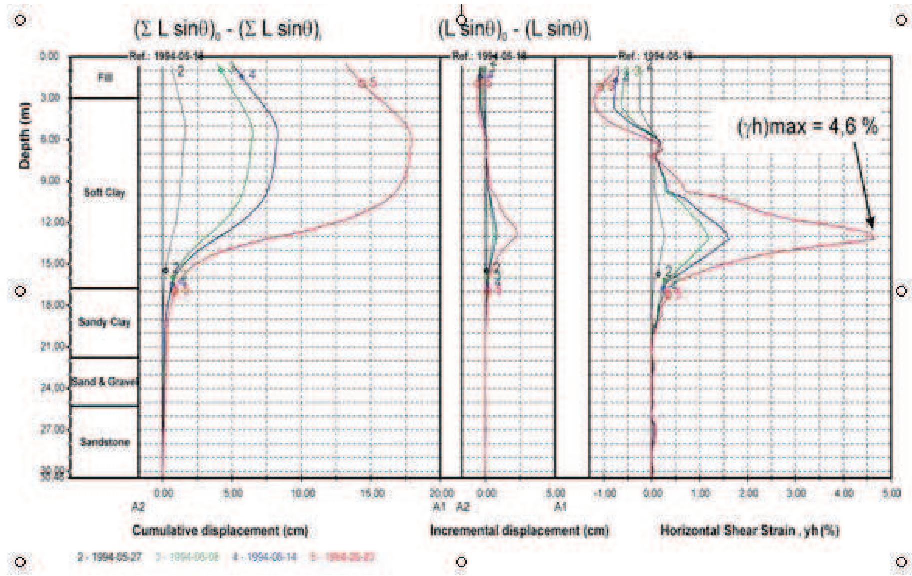


Figure 2 – Procedures for inclinometer data interpretation: a) standard procedures; b) new procedures (Salgado (1))

Where simple shear conditions prevail, i.e., when the horizontal shear strain equals the maximum shear stress, then, γ_h can be used in eq. (1) to compute *FS* (Figure 3).

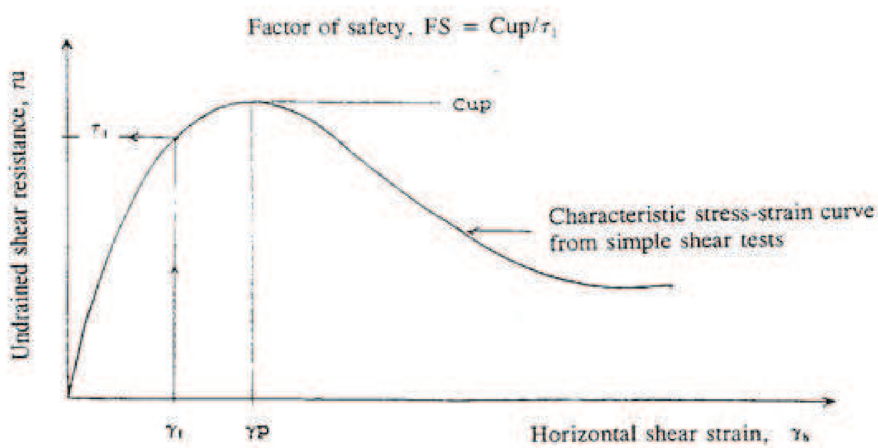


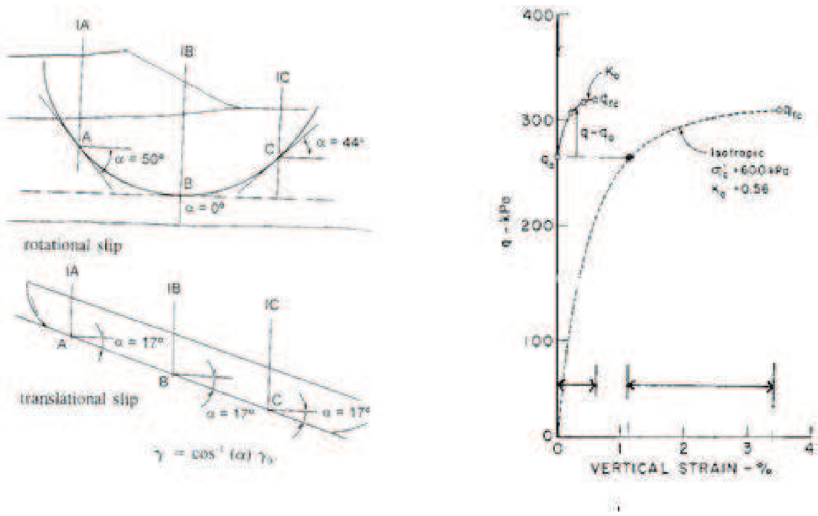
Figure 3 – Estimation of factor of safety from the estimated horizontal shear strain based on simple shear test data and inclinometer reading data (1)

For the cases where $\gamma_h \neq \gamma$, the simple procedure, developed by Salgado and Carvalho (3), shown in Figure 4a can be applied to infer γ from γ_h, where $\gamma_h$is estimated from the inclinometer reading data obtained at the locations of inclinometers IA, IB and IC, using the value of the angle α of the slope at the inclinometer location with eq. 4.

$$\gamma = \cos^{-1}(\alpha)\ \gamma_h \qquad (4)$$

However, for sloping ground the effect of the static bias must be taken into account as developed by Salgado (4, 5). Based on the work carried out by Byrne et al. (12) the hyperbolic eq. 1 can be modified as presented in eq. 5 and in Figure 4b, where τ_{st} is the in situ static shear stress.

$$(\tau - \tau_{st}) = \gamma / (1/G_i + \gamma\, R_f / \tau_r - \tau_{st}) \qquad (5)$$



a) b)

Figure 4 – a) procedures to infer γ from γ_h; b) stress strain behavior of Haney clay (12)

From eq. 5, for *FS* = 1 it implies that $\tau = \tau_r$ and $\gamma = \gamma_f$, therefore:

$$\gamma_f = ((\tau_r - \tau_{st}) / G_i)\ (1/(1 - R_f)) \qquad (6)$$

3. APPLICATION OF THE PROCEDURES TO HISTORIC DATA CASES

3.1 Azambuja case (2, 3)

When the 1^{st} set of readings was taken (Fig. 2) the embankment was already 5 m high. This means that a static bias was already in place and eq. 6 should be used instead of eq. 1. However, the representative static shear stress correspondent to the location of the inclinometer and depth of the failure surface was not known. Based on detailed F.E. analysis, Carvalho (2) computed that at the time of the first inclinometer set of readings a maximum shear strain value, γ = 5% was already in place. However, from Fig. 2, one hour before failure a value of γ_h = 4.6 % is obtained. Knowing that α = 25 º then, from eq. 4 an additional value of γ = 5.1 % is computed totalizing a value for γ = 10.1%. Knowing from (2) that τ_r = 26 kPa, G_i = 3800 kPa and R_f = 0.86, then a value of *FS* = 0.93 is computed one hour before failure.

3.2 Lisbon Case (3, 4, 5, 11)

During a new railroad construction to access Lisbon from the South of Tagus River the foot of an existing slope was partially cut and triggered a highly instable situation where displacement rates of about 2,0 to 2.5 mm/day were mobilized at IN1 and IN3 (Fig. 5).

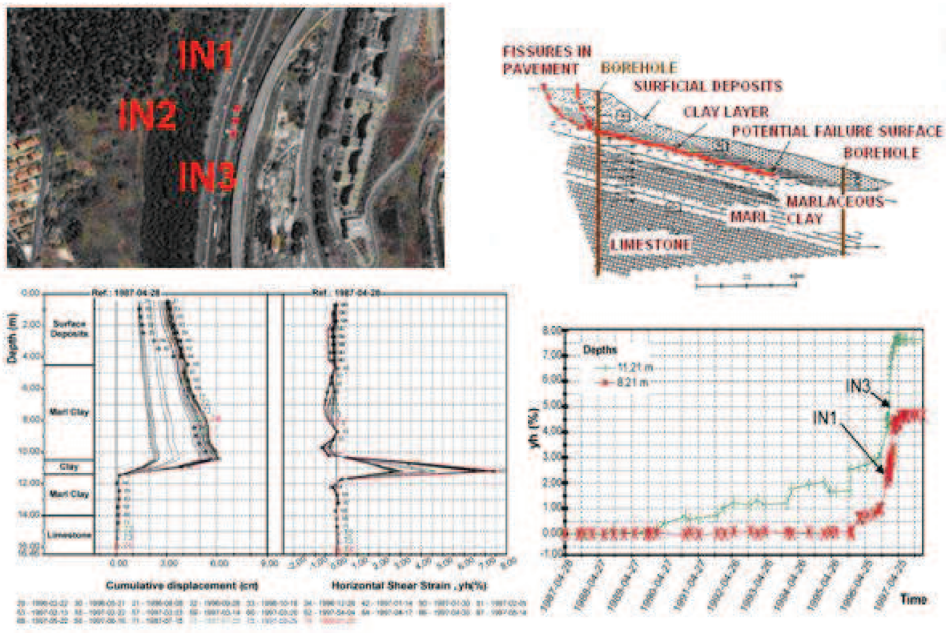


Figure 5 – Site location, cross section, inclinometer data (IN3), inferred γ_h data and evolution of γ_h for IN1 and IN3.

Using laboratory and field data the following parameters were estimated (4, 5, 11): α = 12.5 º, τ_{st} = 39 kPa, τ_r = 70 kPa, Gi = 3780 kPa and R_f = 0.86. Entering these values into eq. 6 a value of γ_f = 6,0 % is computed. It may be seen that at IN3 and IN1 values of γ_h = 7.5 % and 4.0 % were estimated, corresponding to mobilized maximum shear strains, γ of 7.7% and 4.1% respectively. This means that at IN3 the factor of safety was lower than 1 and at IN1 was slightly higher than 1, given an overall global factor of safety close to 1.

4. CONCLUSIONS

New procedures for inclinometer data reduction have been presented trough which it is possible to estimate values of local factor of safety. The procedures were applied to a foundation embankment failure and to a slope instability case located in the South highway access of Lisbon. Based on the work carried out by LNEC, the Government Authorities immediately reacted and the unstable area was rapidly reinforced (11).

AKNOWLEDGEMENTS

To the Government Authorities that, at the time of the instability (1996), namely JAE, GNFL and Lusoponte, accepted LNEC´s advices and promptly promoted all the required measures to insure safety. This avoided a long and chaotic traffic situation, since there was, at the time, a daily traffic flow of about 150,000 vehicles, as well as, a long delay in the construction of the new railroad.

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