Rstabl: a program for stability analysis of reinforced soil slopes

Ortigao J A R, Alves L S, Brandi V R & Far J

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Abstract

Rstabl is a fast and user-friendly computer program for stability analysis of reinforced soil slopes. It evolved from the well-known Purdue's Stabl program which was modified to accommodate the effect of nails and geosynthetic reinforcement. Nails are assumed to be fixed on the wall face and to contribute with tension only. The effect of these assumption were evaluated by comparison with 3 other programs developed in France. The results indicate that *Rstabl* calculates the factor of safety with reasonable accuracy if Bishop's method is selected for the slip circle search.

Introduction

The research programme on soil reinforcement at the School of Engineering of the Federal University of Rio de Janeiro has led to the construction of a trial wall by the Geo-Rio Foundation (Ortigao et al, 1992), a review of the practice in Brazil (Ortigao and Palmeira, 1992, Ortigao et al, 1993 and 1995) and a survey on the use of geosynthetic bars to replace steel in nails and anchors, presented in a companion paper to this conference (Ortigao, 1995).

At early stages of this research programme, stability analysis was carried out with codes developed at the University of Brasilia (Ortigao et al, 1995) and the Prosper program (Delmas et al, 1986). It was soon realised that a fast and user-friendly computerised method for analysing the stability of reinforced wall was needed.

This paper describes a new computer code named *Rstabl* (*Reinforcement-Stabl*) evolved from the well-known Stabl program developed long ago at Purdue University which has been described in number of publications, *e.g.,* Achilleos (1988), Boutrup (1977), Carpenter (1986), Siegel (1975). Stabl was chosen because of the experience accumulated in this program and it is meant to be a crash-free code, designed to detect errors in the input data and warn the user. Purdue's code accommodates multi-layered soil and enables fast searches circular and polygonal slip surfaces considering either Bishop or Janbu's methods. It handles surface loads and soil anchors.

The work carried out at the Federal University of Rio de Janeiro consisted of introducing the effect of the reinforcement, either nails or geosynthetics. Geobars nails, described in a companion paper to this conference (Ortigao, 1995) can also be easily accommodated.

The method of calculation in *Rstabl* is described followed a series of results of comparison with French programs.

Rstabl calculation method

A full discussion on the methods for stability analysis of soil nailing structures was given by Ortigao et al (1993 and 1995) and will not be repeated here. One important conclusion of that study is that only tension in the reinforcement plays a significant role. Bending and shear of nails are only responsible by a minor share in the calculated factor of safety, less than 3%. As a consequence and for the sake of simplicity, *Rstabl* employs only tension in nails. The soil mass is divided through a slip surface into an *active* and a *passive* zone. The reinforcement force T acting on the active zone is obtained as indicated in Figure 1 as:

$$T = \pi \, D \, q_s \, L_p \qquad (1)$$

where: T is the tensile force in each nail, q_s is the unit friction between soil-nail interface, L_p is the nail length in the passive zone and D is the borehole diameter. An internal check is carried out to ensure that T is less than the strength of the nail material.

The nail tension T at the base of the slice it crosses is then decomposed in a normal and tangential force for each slice. These forces are introduced in the calculation according to Ternier and Morlier (1982).

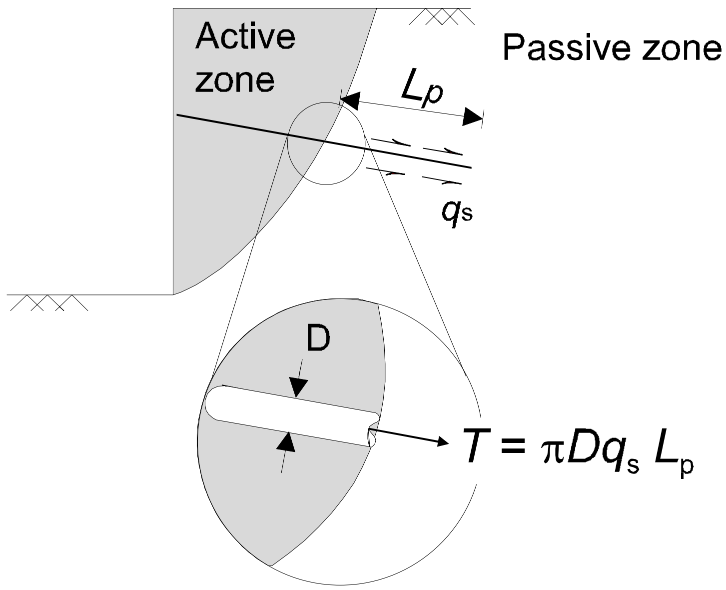

Figure 1 *Rstabl* assumption of tension in nails

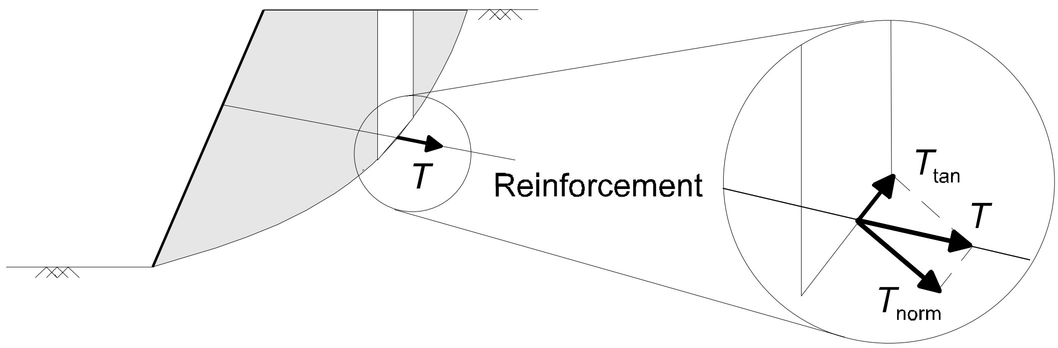

Figure 2 Including the effect of the reinforcement at the base of a slice

The equation used to calculate in Bishop's method is:

$$FS = \frac{\sum \{c\,\Delta l + [W' + T_{\tan}\,\sin\alpha + (T_{norm} - u)\cos\alpha]\ \tan\phi'\}\ m_{\alpha}}{\sum (W'\sin\alpha - T_{norm})} \tag{2}$$

where: c and ϕ' are Mohr-Coulomb's parameters, Δl and W' are respectively the width and the effective weight of each slice in which the soil mass is divided, α is the angle of inclination of the base of each slice, T_{norm} and T_{tan} are the components of T at the base of a slice, as shown in Figure 2. An analogous equation was employed for Janbu's method.

Stability analysis of geosynthetic reinforced walls is discussed elsewhere (*e.g.*, Palmeira, 1992). The reinforcement effect is given by:

$$T = 2\sum_{0}^{L} \sigma'_v\ k \tan\phi'\ \Delta L \tag{3}$$

where σ'_v is the vertical effective stress at the reinforcement level, L is the geosynthetic length in the passive zone, k is the interaction coefficient, defined as the relationship between the friction angle in the soil and at the soil-geosynthetic interface, ϕ' is the soil peak friction angle and ΔL is the interval in which L is divided.

Table 1 Comparison between programs (adapted from Gigan and Delmas, 1986)

	Clouage	*Talren*	*Nixesc*	*Prosper*	*Rstabl*
Reference	Gigan, 1986	Blondeau et al, 1984	Rajot, 1983	Delmas et al, 1986	this paper
Method of analysis	Bishop	Bishop Perturbations	Perturbations	Perturbations	Bishop and Janbu
Tension, bending	Tension	Tension and bending	Tension and bending	Tension and bending	Tension
Nail head-wall condition	Fixed	Fixed or free	Fixed or free	Fixed or free	Fixed

Rstabl evaluation

The accuracy of the factor of safety (FS) given by *Rstabl* was checked against several soil reinforcement stability analysis programs developed in France. The work of Gigan and Delmas (1987) was used. They carried out an comparison of 4 French programs Clouage, Talren, Nixesc and Prosper as indicated in Table 1. Three soil nailing cases were run. The geometry and nail data are given in Figure 3 and in Table 2. Soil parameters were unit weight of 20 kN/m^3, cohesion of 10 kPa and a friction angle of 26 degrees. In each case, only the nailing characteristics changed. Geometry and soil data remained constant.

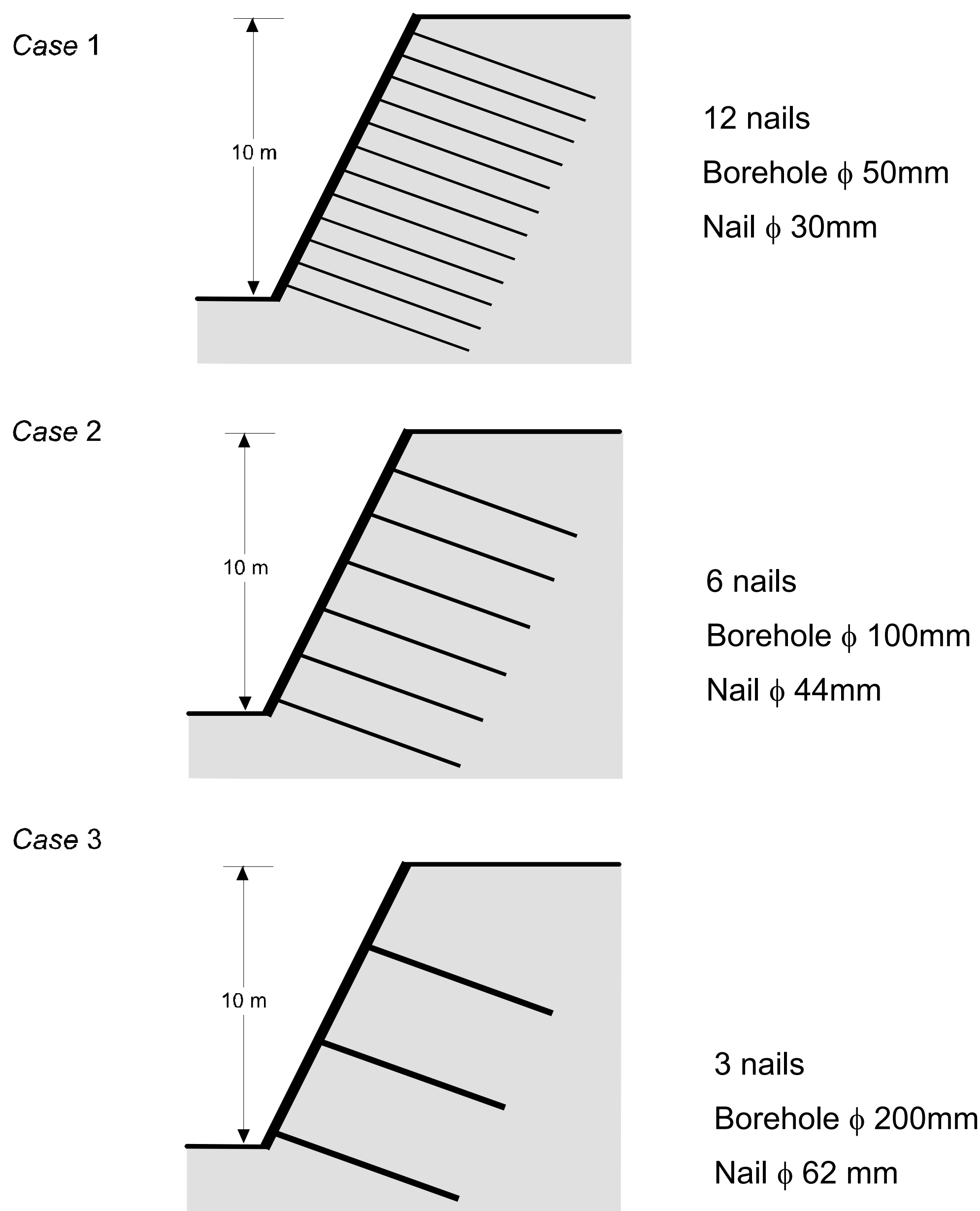

Figure 3 Characteristics of the test cases

Table 2 Characteristics of the test cases

Reinforcement characteristic	***Unit***	***Case 1***	***Case 2***	***Case 3***
Unit friction between soil nail interface q_s	kPa	40	40	40
Horizontal spacing	m	1	1	1
Number of nails		12	6	3
Nail density $d = \frac{T}{\gamma s_v}$		0.340	0.340	0.340
Diameter of steel section of nails	m	0.030	0.044	0.062
Borehole diameter	m	0.050	0.100	0.200
Tensile strength of nails f_y	MPa	500	500	500
Length	m	8	8	8
Inclination	degrees	20	20	20

where:

T = Nail maximum tension
γ = soil unit weight
s_v = vertical spacing between reinforcement layers

The results are summarised in Table 3 and in Figure 4. The following conclusions are obtained. As expected, the influence of bending and shear is very small in the calculated FS, even for the stiffer nail used in Case 3. Therefore, the assumption of tension only in *Rstabl* is reasonable for practical applications.

Rstabl run with Bishop method gives values of FS that are close to most French programs. On the other hand, *Rstabl* with Janbu method gives lower FS values. This difference seems to increase with nail bending stiffness, higher in Case 3.

Table 3 Calculated FS

Method	***Program***	***Case 1***	***Case 2***	***Case 3***
Only tension in nails	*Rstabl* (Bishop)	1.42	1.50	1.73
	Rstabl (Janbu)	1.27	1.32	1.44
	Clouage	1.30	1.36	1.52
	Talren *T*	1.40	1.48	1.64
	Nixesc *T*	1.39	1.48	1.63
Tension, bending and shear	Talren *T&B*	1.45	1.56	1.80
	Nixesc *T&B*	1.42	1.50	1.73

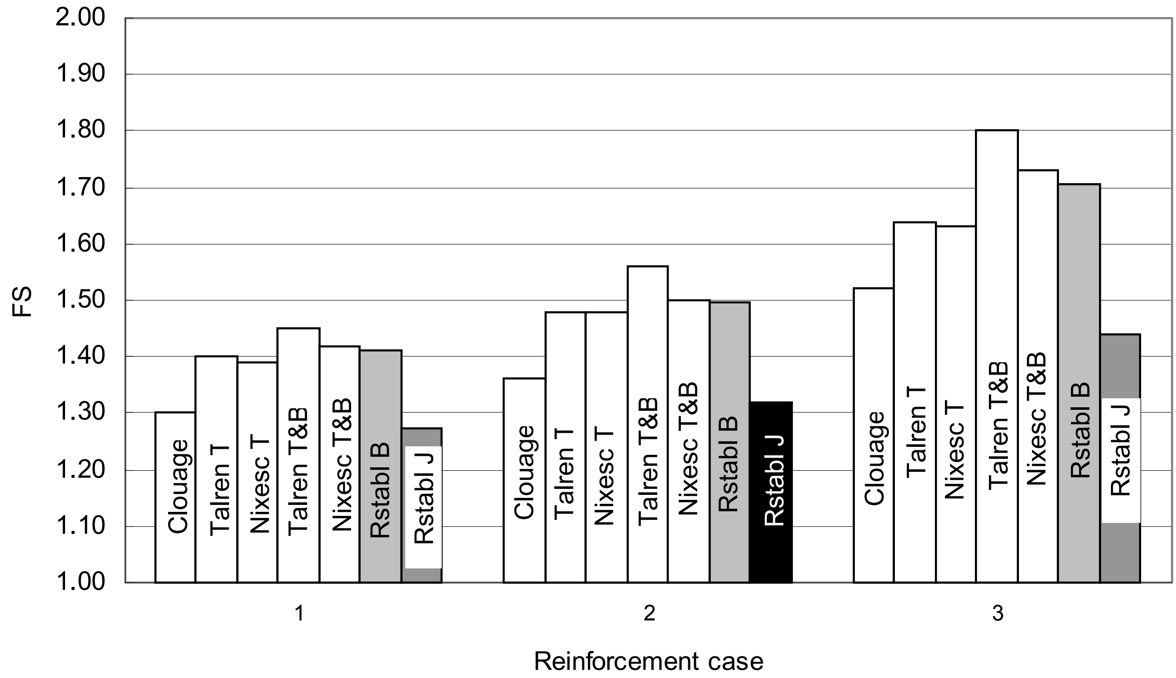

Figure 4 Calculated FS

Rstabl analysis of a mixed soil nailed structure

Mixed soil nailed structures employing nails and soil anchors have been used to increase the structure stiffness and, consequently, to reduce deformation (Clouterre, 1991, Ortigao et al, 1995). The ability of *Rstabl* to handle such problems is demonstrated in two examples.

The wall in Figure 5 is 16 m high soil wall was considered for an excavation in residual loose silty sand soil in Rio de Janeiro. Soil parameters were estimated as: unit weight 18 kN/m^3, cohesion was taken as 10 kPa and friction angle equal to 26 degrees. The

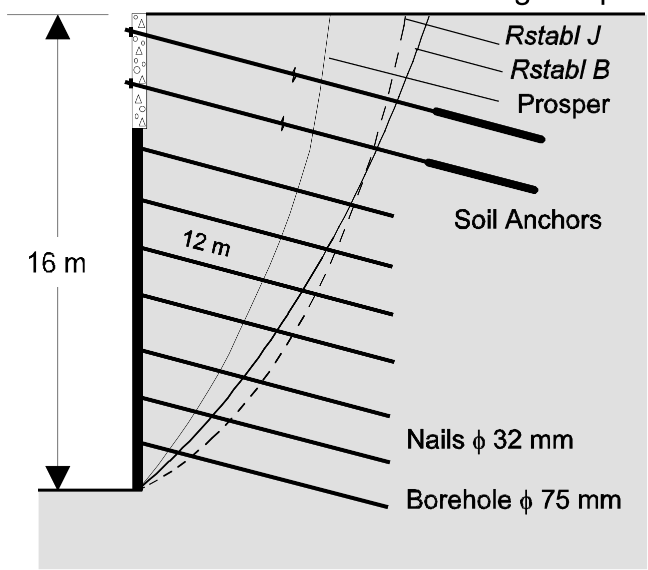

Figure 5 Mixed soil nailing structure proposed for an excavation in medium sandy-silt

excavation took place close to an existing road , therefore, as a safety measure to reduce deformation at the top of the wall, the design included two lines of tiebacks.

Table 4 Stability analyses of mixed soil nailed wall

Condition	***Calculated FS***			
	Rstabl		***Prosper***	
	Bishop	Janbu	FS	δ (mm)
No reinforcement	0.480	0.498	0.69	0
Nails only	1.481	1.478	1.50	16
Nails and soil anchors	1.499	1.483	1.50	11

Rstabl results in Table 4 were compared with Prosper. Computed FS values with Bishop and Janbu's methods are close.

Prosper deals with the reinforcement in a alternate way. Nails are treated according to the Winkler model, as a beam supported by non-linear springs. Tension, bending and shear are considered. The FS calculation iterates until the necessary nail deformation δ is calculated to give a specified FS equal to 1.50. The resulting δ values in Table 4 are small, indicating that the proposed wall is acceptable. The calculated slip surface is different from *Rstabl* run.

Another example is shown in Figure 6, and consisted of a cut in gneissic residual soil. It was built in 1984 and described in more detail by Ortigao et al (1993 and 1995). It is the highest wall in Brazil, 35 m high, located at Icarai Beach, Niteroi, near Rio de Janeiro. The lower 18 m of the cut was supported with tiebacks. The upper part was nailed. *Rstabl* analyses employed the following estimated soil parameters: cohesion of 40 kPa, friction angle of 35 degrees and unit weight 18 kN/m^3. The results are summarised in Figure 6

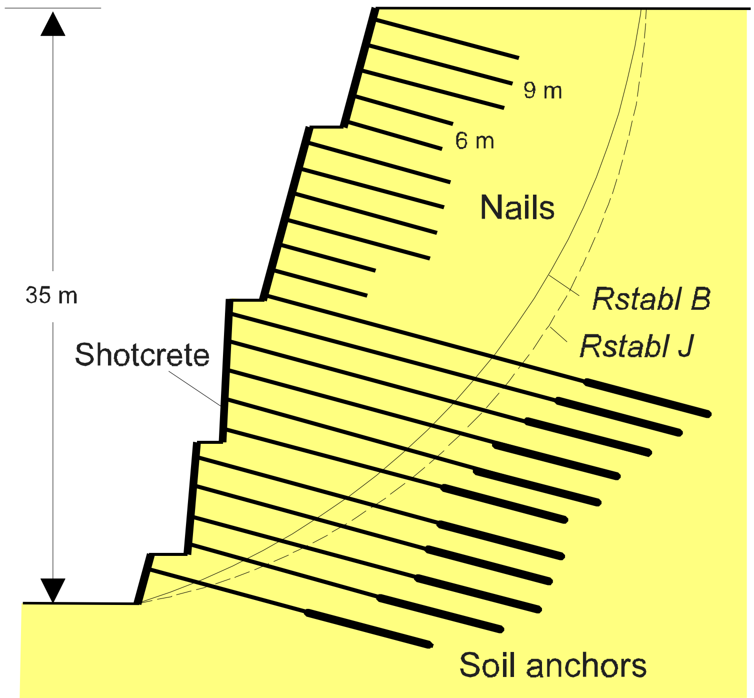

Figure 6 Highest wall in Brazil at Icaraí Beach, Niteroi

and Table 5.

Table 5 Stability analyses of mixed soil nailed wall

Condition	***Calculated FS***	
	Bishop	Janbu
No reinforcement	1.048	1.062
Nails and soil anchors	1.502	1.593

The resulting FS value is close to 1.5. It is argued that if the designers back in 1984 of this had a powerful tool like *Rstabl*, the reinforcing and anchoring design would probably be different and better optimised.

Conclusions

The fast and crash-free *Rstabl* computer program for stability analysis of soil reinforced structures was developed, evolving from the well-known Purdue's Stabl. The program performs fast slip surface searches using Bishop and Janbu's simplified methods. Data preparation is easy and facilitated by error checking routines.

The stabilising effect of nails is assumed to be tension only. Nails are considered to fixed on the wall face. A series of studies were carried out to evaluate *Rstabl* results. Comparison with several programs developed in France that consider tension and bending have shown that *Rstabl* assumptions lead to accurate results if Bishop's method is selected. Lower and conservative FS values may result from Janbu's method.

The ability of *Rstabl* to handle reinforced walls that combine nails and soil anchors was demonstrated in two examples.

A user-friendly Windows environment shell for *Rstabl* is underway. It is expected to be finished by mid 1995.

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