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STRESS-STRAIN ANALYSIS OF A REINFORCED SLOPE WITH ACTIVE ANCHORS, USING INDIVIDUAL AND SLAB-TYPE SUPPORT SYSTEMS

Jackson Andrés Gil H[1], Pablo Vélez Velásquez[2] and Francisco Javier Nanclares[3]
[1]Civil Engineering Program, Faculty of Engineering, Surcolombiana University, Neiva, Huila, Colombia
[2]Civil Engineering Program, Faculty of Engineering, EAFIT University, Medellín, Antioquia, Colombia
[3]Civil Engineering Program, Faculty of Engineering, Nacional University, Medellín, Antioquia, Colombia
E-Mail: jackson.gil@usco.edu.co

ABSTRACT

Anchored systems are widely used for slope stabilization in the construction of civil engineering projects in Colombia. These systems transmits a stabilizing force over a support surface (anchor head), inducing normal stresses on the face of the slope to generate an increase in the shear resistance of the soil involved in the failure surface. Regarding the design of the support surfaces it is common to find both, individual and continuous surfaces. The individual support surfaces correspond to isolated concrete blocks in which there is no structural union with adjacent anchor heads, these supports are commonly referred to as "dados" in Colombia; and the continuous support surfaces correspond to reinforced concrete slabs that guarantee the structural union between each of the existing anchor heads. Currently, there is no conceptual clarity as to the actual behavior of each of the support surfaces; therefore, it is not possible to fully evaluate compliance with the design hypotheses. With this in mind, a mathematical modeling was made using Finite Element techniques representing both cases. It was found that there are great differences in the contribution to the stability of the slope generated by each of the systems, which must be considered in the design process.

Keywords: slope stability, finite element method, anchor heads.

1. INTRODUCTION

Research on slope stabilization with active anchors has allowed the development of increasingly demanding projects, resulting in higher slopes and much lower deformations. In Colombia, the use of these systems has become a common practice in engineering projects, mainly due to the experience in construction and design developed in recent years. Nevertheless, regarding to design of these systems, geotechnical engineers usually adopt the design criteria proposed by the United States Department of Transportation (FHWA) in the document "Ground Anchors and Anchored Systems", due to the absence of a state regulation that governs the guidelines for the design of this type of system in Colombia.

The criteria proposed by the FHWA, like any other methodology, are based on the characterization of the environment to be stabilized [1-3]. For this, it is necessary to know the resistance and rigidity parameters of the geological profile of the subsoil, water levels and flow conditions, mechanical behavior of the reinforcement system, and a numerical model that allows an in-depth and thorough analysis of the problem [4-7].

One criterion to be defined during the design of these systems is the type of support surface to be implemented. However, in Colombia there is not clarity about the behavior of this systems; that is, in our environment one can find active anchors supported on individual support surfaces that are designed as large reinforced concrete blocks (see Figure-1), or active anchors supported on continuous support surfaces (see Figure-2).

Figure-1. Anchors supported individually on the slope [8].

Figure-2. Anchorages supported on concrete slabs [8].

Regarding the state of the art on active anchorage bearing surfaces, it can be said that most of the literature is directed towards the design of reinforcement systems supported on continuous bearing surfaces, and little information exists on individual concrete blocks as bearing surfaces and their behavior. Some authors have generated minimum recommendations on the use of individual surfaces, among the most common are: a) individual support surfaces should be used in soils with good bearing capacity to avoid shear failure on the ground during anchorage tensioning; b) a maximum spacing between individual blocks should be calculated to guarantee the arc effect between anchor heads [4].

However, despite some national and international research on the subject, in Colombia there are still no clear criteria on the behavior of the different support surfaces [9]. In Colombia, it is common to find divided opinions among constructors and consultants, about the equivalence of the different support surfaces available for the design, and construction of the reinforcement systems in slopes with active anchors.

Some argue that individual support surfaces are equivalent to reinforced concrete slabs and that, therefore, the use of continuous slabs represents an unnecessary cost overrun on projects; other designers claim that the uses of individual support surfaces do not represent equivalent behavior to the use of continuous slabs, and that individual support surfaces do not allow for adequate erosion control on the face of the slope [10].

In view of these questions, we conclude there is still no clear design criteria on the influence of the different support surfaces on slope stabilization, so this research sought to answer some of the questions raised.

2. MATERIALS AND METHODS

In this study, a comparison was made between the mechanical behavior of a reinforced slope with an active anchor system supported on continuous slabs versus the behavior of the reinforcement system supported on individual blocks of different dimensions. Two types of reinforcement were considered, type A reinforcement system: active anchors supported on a continuous support surface; and type B reinforcement system: active anchors supported on individual support surfaces.

In order to carry out the modeling to define the behavior of the slope, a two-dimensional analysis was performed in the software Plaxis v8.6. This software is commonly used for the solution of geotechnical problems since it allows the use of different constitutive models, and the results obtained in terms of stress-strain analysis are satisfactory [11].

2.1 Analysis Section and Properties of the Reinforcement System

The slope under study corresponds to a simple homogeneous soil slope whose geometry is shown in Figure-3 and the geotechnical properties and soil parameters used are shown in Table-1. The analysis proposed for the slope consists of a variation of parameters in terms of height, slope gradient and dimensions of the support surface.

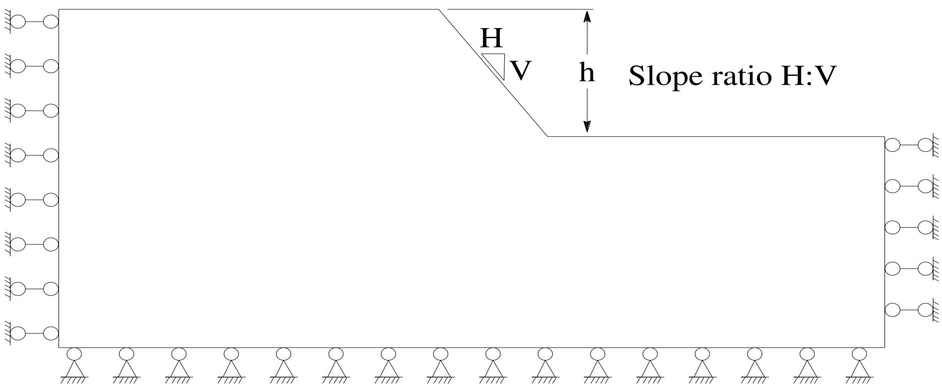

Figure-3. Geometry of analysis with the different support systems.

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Table-1. Effective input parameters for the Hardening Soil model.

Unit weight	γ_h=17,99 [kN/m^2]
Cohesion	C_{ref}=23,3 [kN/m^2]
Angle of friction	$\emptyset$=30^o
Dilatancy angle	ψ=0^o
Reference secant stiffness from drained triaxial test	E_{50}^{ref}=14100 [kN/m^2]
Reference tangent stiffness for oedometer primary loading	E_{oed}^{ref}=14100 [kN/m^2]
Exponential power	Power(m)=0,55
Reference unloading/reloading stiffness	E_{ur}^{ref}=42300 [kN/m^2]
Unloading/reloading Poisson's ration	ν_{ur}=0,25
Reference presure	p^{ref}=100 [kN/m^2]
Coefficient of Earth pressure at rest	K_o^{nc}=0,5
Failure ratio	R_f=0,82

To define the geometric and mechanical properties of the reinforcement system, we considered the materials typically used in Colombia. For the Type A reinforcement system, a 15 cm thick reinforced concrete slab was used and for the type B reinforcement system where individual support surfaces are used, concrete blocks with a thickness of 30cm were considered. In the different support surfaces (continuous type and individual type), a concrete modulus of elasticity of 21000 MPa, Poisson ratio of 0.2, thermal expansion coefficient of 1.1x10-5 per °C and density of 2400 kg/m3 were considered. The anchors used in the two reinforcement systems were stressed with a load of 250kN and the slope with respect to the horizontal was -15° in all cases of analysis [10].

2.2 Analysis Case Modeling

The modeling was carried out by means of a plane deformation analysis assisted by the Plaxis v8.6 software. The modeling of the analysis sections was carried out, looking for the location of the anchor bulb to be located outside the fault surface as shown in Figure 4 [6].

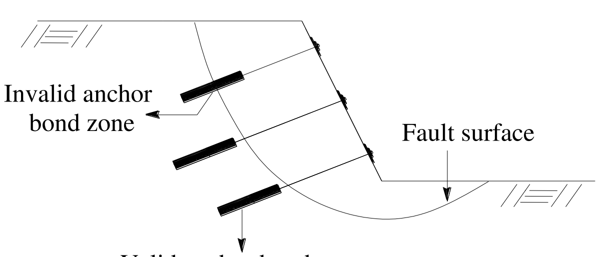

Figure-4. Modeling analysis section [6].

The analyzed sections were contemplated on a vertical axis that passes through the anchor heads as shown in Figure-5. For the simulation of the soil behavior, the constituent model Hardening Soil was used.

This isotropic hardening model with a non-fixed yield surface in the main stress space allows the behavior to be simulated for load-unload conditions, and deformations due to loss of lateral confinement [12-14]. The parameters defined for the soil allow control of creep problems at the soil-bulb interface and guarantee the necessary tensile capacity at each anchorage [1, 3, 15].

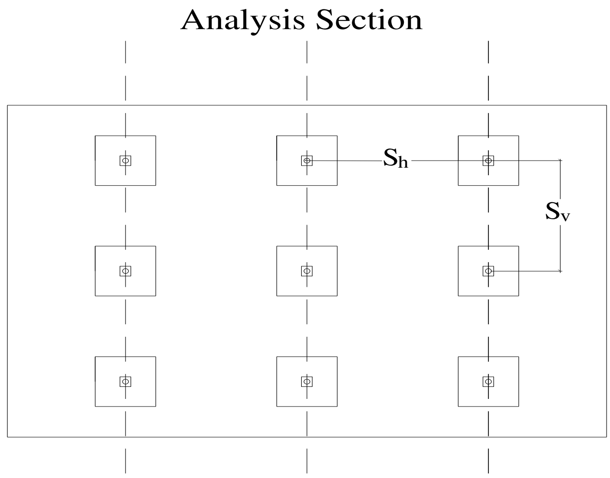

Figure-5. Modeling analysis section.

For this modeling, we employed usual spacings in slope stability projects. We considered a horizontal separation (S_h) between anchors of 2.4m and a vertical separation (S_v) of 3.0m

2.3 Parametric Analysis

For the parametric analysis, we worked with two slope heights (H=10m and H=20m); for each of them a variation in the slope gradient was generated, and the dimensions of the support surfaces. With respect to the slope relations (H:V), three inclinations were analyzed (H:V=1:1, H:V=0.5:1 and H:V=0.75:1) for each of the cutting heights. This results in 6 cases of analysis (see Table-2).

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Table-2. Cases used in the parametric analysis.

Analysis cases	
Case 1	H=10 m; H:V=0,5:1
Case 2	H=10 m; H:V=0,75:1
Case 3	H=10 m; H:V=1:1
Case 4	H=20 m; H:V=0,5:1
Case 5	H=20 m; H:V=0,75:1
Case 6	H=20 m; H:V=1:1

After defining each case of analysis, the two types of reinforcement (Type A, Type B) must be analyzed in each case; and in turn, a variation in the dimensions of the support surfaces must be generated. This results in 7 analysis sections for each case (Table-3 shows all the possible combinations for Case 1). Similarly, the variations were carried out for the other 5 analysis cases, and as a result 42 sections are obtained to be analyzed in terms of stresses and deformations (see Table-4).

Table-3. Variation in the dimensions of the bearing surface, for Case 1 of the analysis with height 10m and slope ratio 1:1. Given as support surface (D) and continuous slabs (CS).

Analysis sections, Case 1
Dice of 0,5 m as support area(D-0,5m).
Dice of 1,0 m as support area (D-1m).
Dice of 1,5 m as support area (D-1,5m).
Dice of 2,0 m as support area (D-2 m).
Dice of 2,5 m as support area (D-2,5m).
Dice of 3,0 m as support area (D-3m).
Continuous display as support surface (CS).

Table-4. Number of sections analyzed.

Cases of analysis	Number of sections analyzed
Case 1, H=10 m; H/V=0,5:1 (C1)	7
Case 2, H=10 m; H/V=0,75:1 (C2)	7
Case 3, H=10 m; H/V=1:1 (C3)	7
Case 4, H=20 m; H/V=0,5:1 (C4)	7
Case 5, H=20 m; H/V=0,75:1 (C5)	7
Case 6, H=20 m; H/V=1:1 (C6)	7
Total of sections analyzed	42

2.4 Safety Factors and Stress-Strain Analysis Associated with Each Analysis Case.

For each of the 42 sections proposed in Table-4, the stress-strain behavior and the respective safety factor were obtained. For the evaluation of the stresses and deformations on the face of the slope, it was necessary to carry out an adequate discretization of the problem, and the program's own tools were used to find the stresses and deformations in the sections of interest.

To determine the factor of safety, the finite element model uses the Strength Reduction Method (SRM). This method reduces the parameters that control the shear strength of the soil: cohesion (C) and angle of friction (∅), by varying the factor of safety (FS) as indicated in equation (1) and (2).

$$\varphi' = arctan\left(\frac{\tan\varphi}{F_s}\right) \qquad (1)$$

$$C' = \frac{c}{F_s} \qquad (2)$$

3. RESULTS AND DISCUSSIONS

3.1 Results of the Evaluation of 10m and 20m Slopes

The 10m and 20m high slopes were evaluated for different slopes and bearing surface dimensions. The dimensions of the blocks varied from 0.5m to continuous slabs on the face of the slope (see Table-3). It was found that the safety factors increased as the dimensions of the concrete blocks increased, but in no case do they equal the safety factor found when using the continuous slabs (CS). This behavior can be seen in Figure-6, where the variation of the factor of safety vs. the percentage of length covered by the support surfaces is presented. To determine the % of length covered, the relationship between the length of the support surfaces with respect to the analysis axis and the total length of the slope face is taken.

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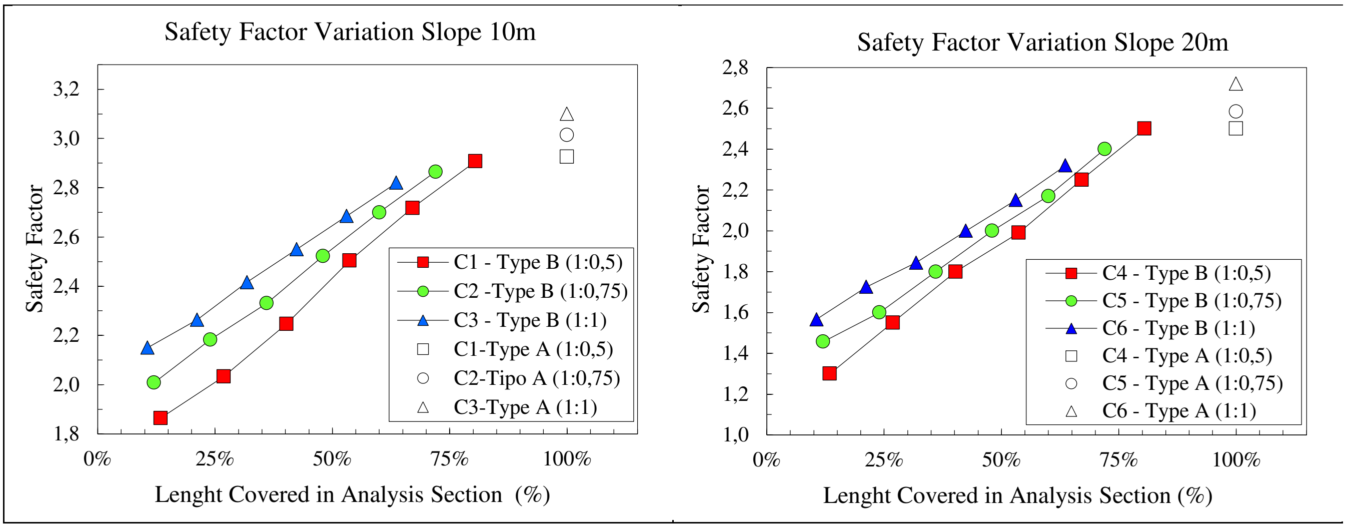

Figure-6. Variation of the safety factor vs. the % of area covered by the individual concrete blocks.

Variation of horizontal forces. Figure-7 presents how the horizontal stresses on the face of the slope vary for two analysis cases: individual support surfaces (Type B) with 0.5m concrete blocks (D-0.5m) and a continuous type support surface (Type A (CS) reinforcement system).

According to the results it was found that the use of continuous slabs does not guarantee a uniformly distributed load, but allows the entire surface of the slope to be subjected to normal confinement stresses; and in the cases of individual concrete blocks the load is concentrated under the support surface, leaving areas of the slope face without any type of confinement.

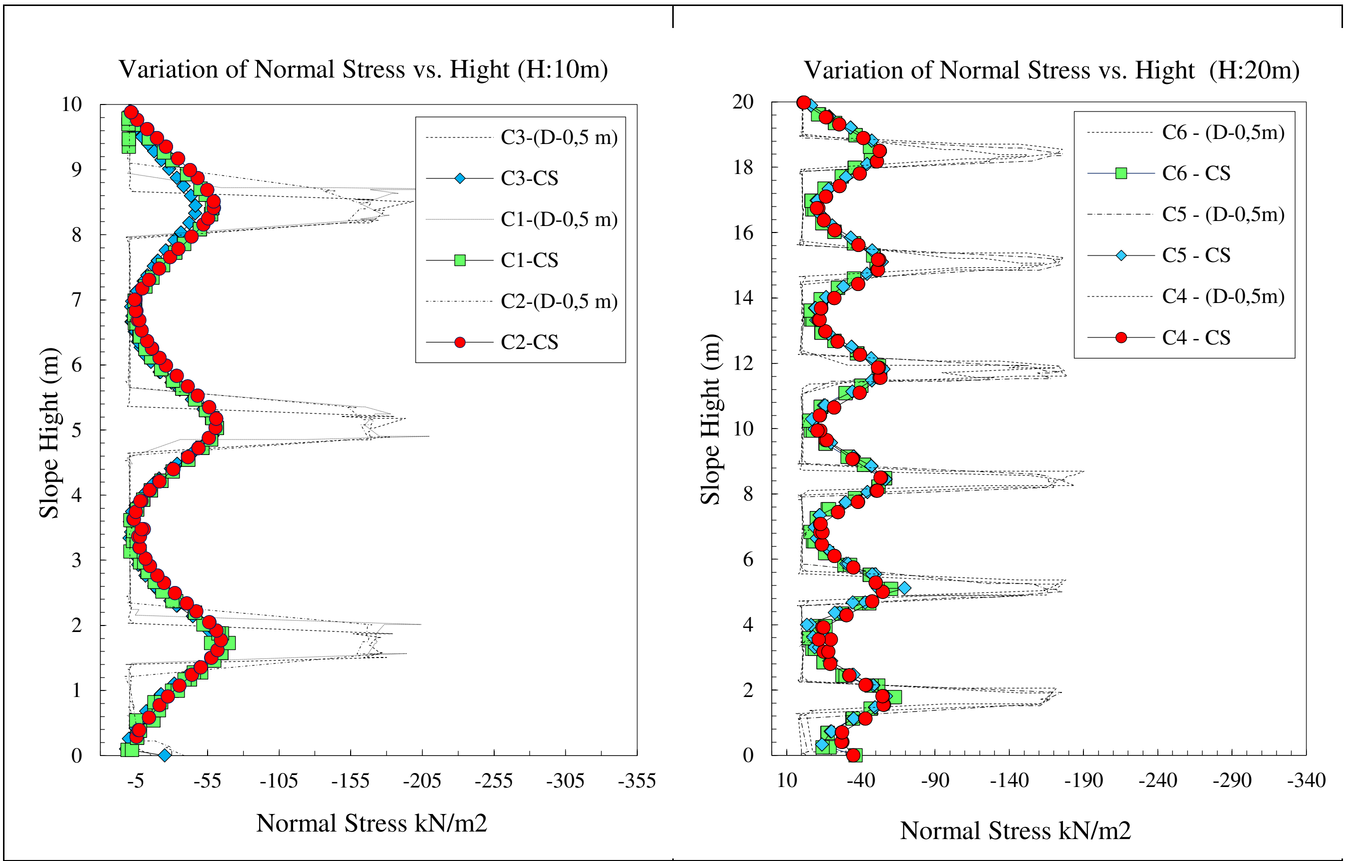

Figure-7. Variation of normal stresses on the face of the slope for the 6 analysis cases.

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CONCLUSIONS

A detailed analysis of the behavior of slopes reinforced with active anchors supported on continuous and individual surfaces was carried out. The analysis allowed different doubts to be clarified regarding the equivalence of these systems and their behavior.

The analysis showed that the continuous and individual support surfaces are not equivalent. The behavior of the systems shows great differences in terms of stresses and deformations on the face of the slope; there are also great variations in terms of safety factors.

The safety factor of a reinforced slope with active anchors is directly proportional to the area covered by the anchor heads on the face of the slope; that is, as the dimensions of the anchor support surfaces increase, the confined areas on the face of the slope increase, and this in turn allows for more soil to be involved during the time of failure.

The use of a continuous slabs as a support surface for active anchors allows for better performance in terms of stresses and deformations, compared to the performance of individual support surfaces.

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