Stabilization of embankments on inclined surfaces by micropiles

Stabilisation of terrassements appuies sur surfaces inclinées moyen micropieux

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ABSTRACT Embankments constructed on hillsides can have serious problems of stability, generally created by the action of water combined with the inclination of the hillside. In order to increase the stability or correct problems of instability already present, there are various methods that can be used: surface and deep drainage, reinforcements with anchored beams, medium and large diameter piles, etc. Standing out among these systems (for its versatility) is the use of micropiles which "sew" the embankment to a non-unstable area of the hillside. This paper presents research undertaken by means of a finite element code for studying the effect and stress of the micropiles, comparing the results with real measurements taken in the south of Spain.

RÉSUMÉ Les terre-pleins construits à mi-versant peuvent avoir des problèmes de stabilité importants, provoqués généralement par l'action de l'eau, combinée avec l'inclination de ce versant. Pour augmenter la stabilité ou pour réparer les problèmes d'instabilité déjà présents, différentes méthodes peuvent être utilisées: des drainages superficiels et profonds, des renforts avec des poutres ancrées, des pieux de grand et moyen diamètre, etc. Parmi ces systèmes se détache (par sa versatilité) l'emploi de micropieux qui "cousent" le terre-plein à une zone du mi-versant non instable. Dans cet exposé, nous présentons une recherche réalisée au moyen d'un code d'éléments finis pour étudier l'effet et l'effort des micropieux en comparant les résultats avec les mesures réelles prélevées au sud de l'Espagne.

1 INTRODUCTION

The objective of this paper is to present a numerical analysis of the behavior of an embankment located on a hillside, when this construction reaches a critical situation. Under these conditions it wished to analyze the behavior of the embankment-hillside assembly when it is reinforced with a continuous beam supported on micropiles (Figure 1).

This entails various phases of analysis: a) Phase 1: Introduction of the initial state of the ground. b) Phase 2: Addition of the embankment on the hillside under these previously established conditions. c) Phase 3: Modification of the water table, if it has not reached breakage point in the above case. In this phase it is assumed that a "critical situation" will be reached when the embankment slides on the hillside. d) Phase 4: Construction of the reinforcement micropiles along the edge of the embankment.

At the end of Phase 2, if it corresponds to a field case in which it is known that there is a critical situation, a back-analysis would need for to estimate the to geotechnical parameters (safety coefficient around).

In Phase 4 various types of the pile "barrier", different lengths, different stiffness, etc., can be considered. In order to carry out those analyses the PLAXIS finite element code has been selected, in its two-dimensional modality.

2 BASIC HYPOTHESES

The problem lies in simulating the presence of the micropiles. Two major hypotheses were made:

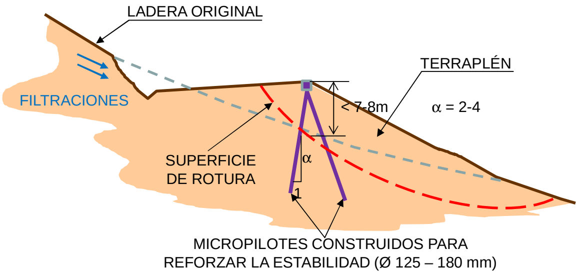

Figure 1. Case of an increase in stability of embankments on a hillside (vertical piles plus various inclinations)

Hypothesis A: Consider the effect of the micros as being that of an injected zone, of better quality than the original (triangular zone).

Hypothesis B: Consider the micros as beam elements, with the rigidity given by the steel pipe and that of the mortar or grout that is introduced.

Both systems have their drawbacks:

In hypothesis A the size of the reinforced zone would have to be defined as a function of the separation of the micros and the reinforcement effect of the injection. Figure 2 shows a possible way of taking that influence into account, based on considering that the effect of an injection ends at a distance of 2.0 m (this has been confirmed in many field cases), with an increase of up to 100% in the cohesion and of 50% in the tangent of the friction angle, tan φ).

In hypothesis B the effect of the injection would have to be taken into account and not just the presence of the reinforcement. As the injection introduces a certain pressure into the nearby terrain, this is equivalent to considering the pile as a cylinder with an additional increment in diameter (De Assis, 2005).

3 INITIAL ANALYSIS

The simulations started by simplifying the problem and were based on data from some field cases with which critical situation:

Phase 1 would be the same as mentioned above.

Phase 2 and 3 or introduction of the embankment and the environmental conditions were combined with the hypothesis of breakage (safety coefficient of the order of 1).

Phase 4 was the construction of micropiles.

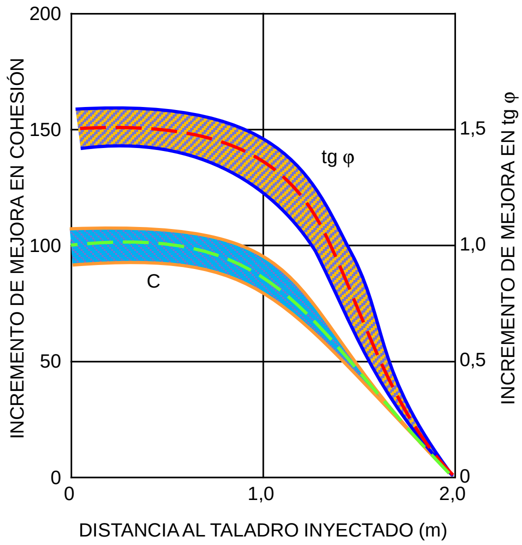

Figure 2. Hypothesis on improvement of the terrain around an injected micro

Taken as a field case was the situation corresponding to Ceuta (Spain) for which data on various unstable embankments on a hillside were available.

The hollowing hypotheses were selected:

Behavior of the ground: Elastoplastic (Mohr-Coulomb).

Triangular elements of 15 nodes with two degrees of freedom each in the PLAXIS code.

The calculation was carried out by progressively reducing the cohesion and the tangent of the friction angle in successive steps, determining the safety coefficient as a ratio between the shear strength at each step and the shear strength at breakage.

The natural ground on the hillside, with an inclination of 28°, consisted of a colluvion of thickness 2 m, parallel to the surface of the slope, supported on phyllites and can include the upper part of the phyllites when they are highly weathered. The embankment had a gradient of 3H:2V. The water table was high (due to heavy rains), affecting the colluvion and running from the inner edge of the embankment (in a small cutting) as far as the foot of the embankment (Figure 3). The failure situation is shown in the same Figure 3. The safety coefficient is 0.95. The parameters of the terrain are shown in Table 1 (natural and improved).

The first way of introducing the reinforcement was by activating the "triangle" of improved terrain clearly marked in Figure 3. It was assumed that the set of micropiles would consist of 2 inclined and 1 vertical.

Table 1. Characteristics of the materials in the simulation with improved terrain.

Material	Specific wt. (t/m^3)	Mod. of deform. (t/m^2)	Poisson Coeff.	Cohesion (t/m^2)	Friction angle
Embankment	1.8	3.500	0.33	1.3	30°
Colluvion	2.1	2.500	0.30	1.4	26°
Phyllites	2.3	30.000	0.28	5	35°
Improved Embankment	1.85	7.000	0.33	3.9	35°
Improved colluvion	2.15	10.000	0.30	4.2	31°
Improved phyllites	2.3	50.000	0.28	6	36°

The failure is as can be see in the Figure 4. The safety coefficient was 1.15 which, after adding drainage, increased to 1.34.

From the described simulation and other similar ones it is revealed that the improvement due to installing micropiles, implying improved ground, can be sufficiently acceptable.

After installing the micropiles, the failure occurs downstream of the embankment (Figure 4), from which it can be deduced that the roadway (the horizontal zone of the embankment) is properly protected, though not the sloping part. Evidently, the bending moment in the micropiles cannot be determined.

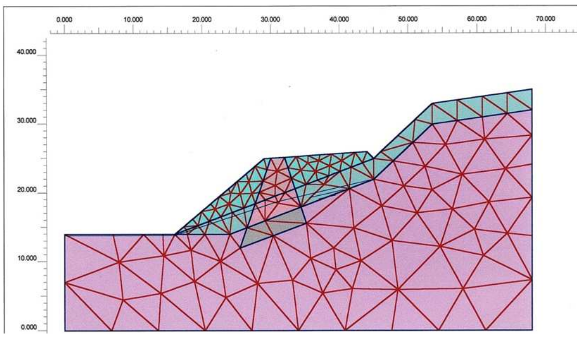

Figure 3. Grid including improved zone

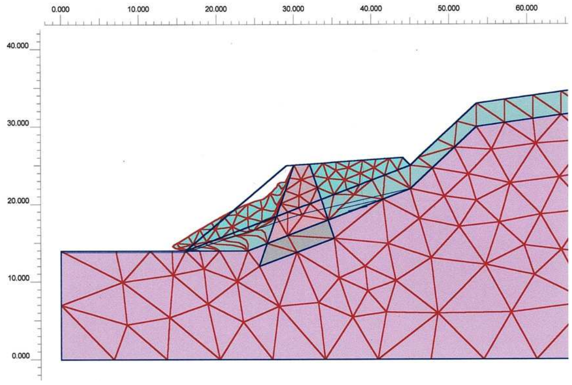

Figure 4. Breakage in the case of the improved zone and lowering of the water table

4 SIMULATION WITH BEAM ELEMENTS

It was introduced another simulation similar to that already used by De la Fuente and Oteo (1999), described by Oteo in 2003, based on representing the micropiles by beam elements, though considering a certain improvement in the terrain around the axis of each beam ("equivalent column" De Assis, 2005).

Figure 5 shows the grid used for this simulation with the initial instability, with the final situation of the micropiles (beam element). With the water table high (Fig. 5), the safety coefficient was 0.97, virtually unity, so it was therefore decided – as in the previous tests – not to vary those parameters. The improvement around the micro was applied solely in the embankment and the weathered zone and not in the healthy substrate. Just two micros of different inclination were considered (the minimum number). The water table had not been lowered. The failure occurred in front of the micropiles and the safety coefficient was 1.17.

If the beam elements are maintained but in addition the water table is lowered by 2-3 m, the breakage continues to occur in front of the micropiles and the safety coefficient rises to 1.37.

Figure 6 shows the bending moment in the rearmost micropile and how the maximum moments are to be found in the area of the colluvion, since the micro penetrates into the area with the healthiest terrain (as if it had been embedded there).

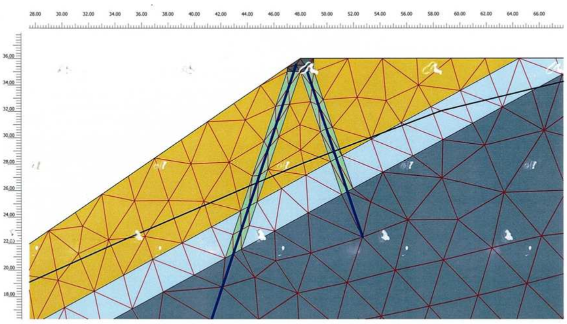

Figure 5. Mesh with beam element. High water table (F=1.15).

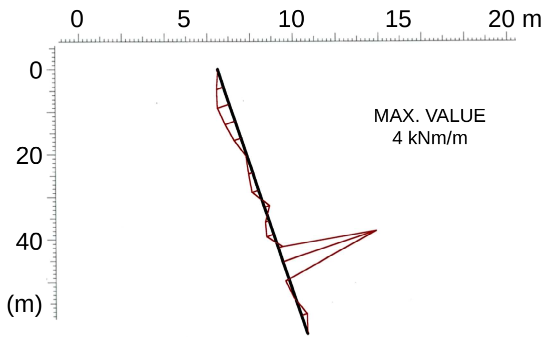

Figure 6. Law of bending moments in the pile furthest from the slope of the embankment.

5 COMPARISON OF RESULTS FOR THE FIRST SIMULATIONS

The effect of lowering the water table is very important and, in the simulations that were conducted, this was able to raise the coefficient of safety towards sliding of the embankment by 0.20.

The effect of the micropiles, as this was simulated, can imply an increase in that safety coefficient of around 1.15-1.20. The embedding in the resistant substrate has to be of the order of 3 m, at least.

Although this influence of the micros is less than that of the water table, the latter can always vary if the drainage is not properly maintained. For that reason, in relation to real situations of failure that allow a good estimate of the shear strength parameters (following the “back-analysis” implied by the methodology used), the increase in the safety coefficient of around 1.15-1.17 by means of the micropiles can be acceptable. It is an increment that can be regarded as “real”.

The simulation with beam elements can provide a higher safety coefficient than the simulation using reinforced ground but, above all, it allows the bending stresses in the piles to be estimated.

The micropile needs to be properly introduced into the resistant ground for various reasons: A) So that the injection can be more effective in the failure zone (which is to be found in the upper, weathered part of the substrate). B) In order to achieve a kind of “equivalent fictitious embedding”, as in the case of piles subjected to a horizontal load. In these a length of pile is needed of the order of several times its elastic length $\left(L_e = 1{,}2\sqrt[4]{3E_p \cdot I_p / E_s}\right)$, where $E_p{\cdot}I_p$ is the rigidity to bending of the pile and Es is the modulus of deformation of the terrain. 5-6 elastic lengths have to be introduced, as shown by the calculations made using different lengths of piles.

The analysis of the Ceuta cases allows a comparison to be made of the movements measured with inclinometers and the calculated movements (Figure 7).

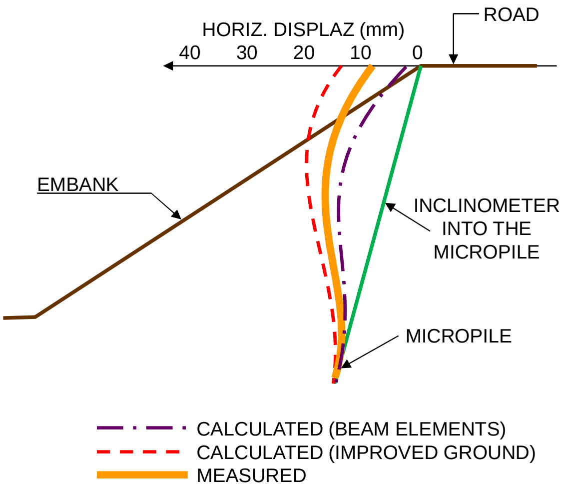

Figure 7. Comparison of calculated and measured movements in Ceuta.

The measured and calculated values are sufficiently similar. The deformation moduli are those initially considered and have not been altered.

6 MORE REALISTIC SIMULATION

A more realistic simulation can be carried out based on the following hypothesis: a) The potentially sliding mass, is completely ignored. b) The stratigraphy of the ground is similar to some of the earlier simulations. There is a colluvion of thickness 3 m. Below there appears a neighboring substrate of phyllite. c) The barrier of micropiles consists of two inclined elements 1(H):3(V). d) The rigidity of the pile capping can be introduced. e) The micros are separated by 0.50 m or 1.00 m within the same alignment. f) The embedding of the micros in the resistant substrate can be between 1.5 and 7.0 m. g) The model of the ground is the “Hardening” type. h) The parameters assumed in the ground are those of Table 2: i) The micropiles considered had a steel pipe of Ø 90 mm and thickness 6.5 mm (surface area = 17.05 cm^2 and moment of inertia of the steel pipe of 149.51 cm^4).

Table 2. Geotechnical parameters in the new simulation

Unit	γ_{ap} (KN/m^3)	γ_{sat} (KN/m^3)	E_{50} (KN/m^2)	E_{ur} (KN/m^2)	C' (KN/m^2)	φ' (^{0})
Embankment	18	18.5	20,000	60,000	15	30
Colluvial	21	21.5	25,000	75,000	15	29
Phyllites	23	23.5	30,000	90,000	50	35

Figure 8 shows the result of the final calculation, with the water table “high”. In it, given that the ground in front of the micros barrier has been eliminated, the potential breakage surface affects the embankment, the micropiles and the weathered ground. In this case, the micros also have an inclination 1(H):3(V) and are separated by 0.5 m within each alignment. The weight of the eliminated wedge is considered as acting on the substrate.

The maximum safety coefficients and bending moments increase by having the embedding between 1.5 and 3.5 m, though there is no practical increase by increasing the length of the micros (Figures 9 and 10). The embedding of 3.5 m complies with the condition of about 6 elastic lengths. The front micropiles have a bending moment about three times greater than that of the rear micropiles.

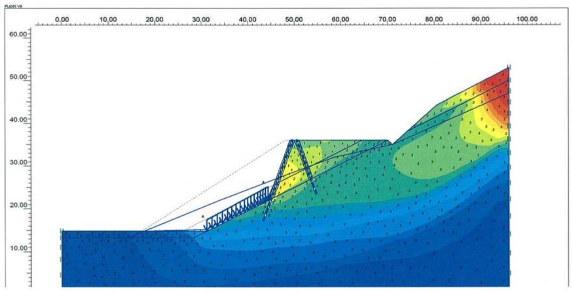

Figure 8. Elimination of the mass of ground in front of the row of micropiles. Embedding in the substrate: 3.5 m.

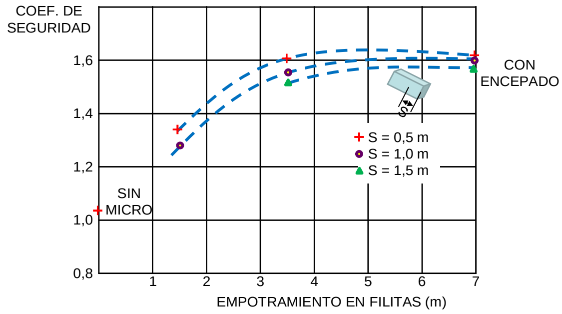

Figure 9. Influence of embedding in the substrate on the safety coefficient.

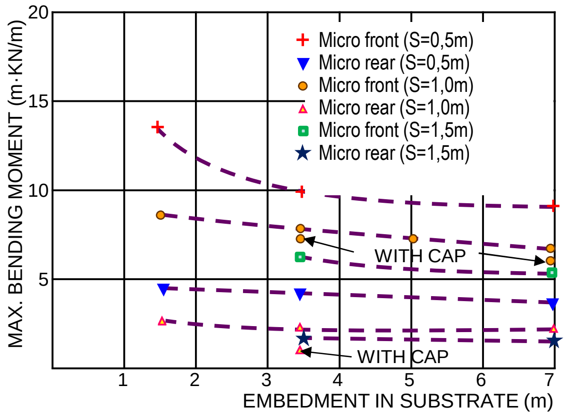

Figure 10. Relation between maximum moments and embeddings

7 COMPARISON WITH ANOTHER FIELD CASE

For the purposes of comparing with another case of embankment on hillside in schists, the results of the instrumentation of a field case in the Casasola Reservoir (Jaén, Spain) have been used. The upper part is highly weathered with thickness of 2 m (Fig. 11).

The simulation was carried out considering an inclination of the hillside equal to 18^0, the embankment represented by a cohesion of 0.5 T/m^2 and friction of 26^0 and the highly weathered schists by a cohesion of 0.2 T/m^2 and a friction of 21^0, with the water table at a depth of 2 m. With this, a safety coefficient of 1.014 is obtained.

Under these circumstances, with a thickness of 2 m of highly weathered schists, the linear elements which represented the micropiles were activated.

Represented in Figure 12 are the measured and the calculated movements. At the head, the micropile becomes inclined backwards according to the calculations, while the measurements show that this upper zone is where the displacement is greatest.

This can be due to various reasons: a) The theoretical simulation takes into account the presence of the pile capping in the upper part of the micros (which locally increases their rigidity). b) The pile capping is on the edge of the embankment slope and this maintains its shape. In reality, the excavation was done in front in order to carry out the pile capping, which causes this zone to become weakened.

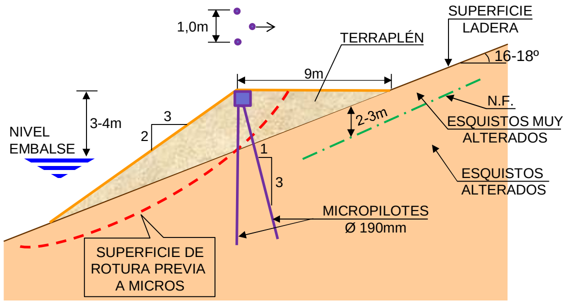

Figure 11. Case of the Casasola reservoir.

8 CONCLUSIONS

The micropiles can be introduced as structural elements, or a reinforced zone.

The micropiles presence allows the stability of the roadbed sought to be protected to be assured.

In the front micros the bending moment can be as much as three times greater than in the rear micros.

The micropiles increase the safety coefficient by a magnitude of the order of 0.15-0.20, while the drainage can do so by 0.20.

The comparisons with field cases (horizontal movements) back up the results obtained.

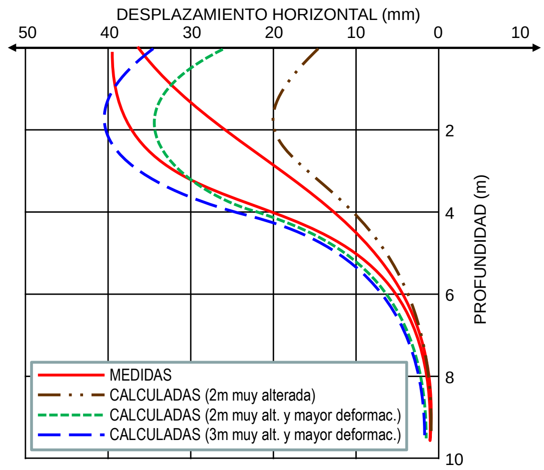

Figure 12. Comparison of real and calculated measurements (horizontal movements)

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REFERENCES

Oteo, C. 2003. Criterios para el diseño de micropiles. *Jornadas Técnicas SEMSIG-AETESS. Micropiles*. Madrid. pp 21-41.

Oteo, C., De la Fuente, P. and De Assis, S. 2007. Jet-grouting walls as protection to the buildings near urban tunnels. *XIV European Conf. on Ground mechanics and Geot. Eng.* Madrid