Calculation of micropiles and anchors to reinforce a slope in emergency situations: application in Málaga, Spain

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ABSTRACT
The importance of preserving affected buildings and infrastructures to landslides is a critical problem in some areas. A system that is less invasive than traditional concrete diaphragm walls or piles is proposed in this work. The proposed system consists of the execution of a row of micropiles and anchors with a methodology of calculation based on the Spencer's limit equilibrium method. Micropiles, as a possible measure for rapid reinforcement of a slope, are always designed in groups. Slope stability analysis automatically employs the pore pressures calculated in groundwater analysis. After a landslide is reinforced, the stability coefficient of the landslide can be increased from 0.907 to 1.504 with the application of our developed model in the application example in Málaga, southern Spain. The results of the proposed model show that a row of micropiles and anchors can effectively enhance the landslide stability in emergency cases. The results and conclusions are helpful in providing a theoretical foundation to clarify the failure mechanism and provide a reference for the design of micropiles and anchors for landslide events.

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Emergencies; row micropiles; landslide; stability analysis; efficient anchors

1. Introduction
Failure within a slope leads to loss of life, buildings, and infrastructures (Acharya et al. 2016a; Acharya et al. 2016b). A landslide event is mostly ascribed to the geological property of dirt; for example, the density, dampness content, particle size, specific gravity, internal friction angle and thickness combined with the force applied on it (Labuz and Zang 2012; Johari and Mousavi 2018). Landslide events can be influenced by different factors, such as manmade activities and heavy rainfall, as well as the geology and geomorphology characteristics of the area Gutiérrez-Martín (2016).

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The use of micropiles as supports to balance dynamic landslides and as a preventive measure for a stable slant has become one of the most important reinforcement techniques in recent times. Micropiles have been applied effectively mainly to settle a slope and improve its stability, and various techniques have been developed for the investigation of reinforcements in situ (Clement et al. 1994; Wan et al. 2016; Chavez-Negrete et al. 2018). In this work, a methodology to employ in cases of emergency and preservation of existing buildings and its application to a practical case has been presented. This methodology is developed in stages and phases, demonstrates the suitability and efficiency of the methodology, and takes into account the European regulations.

One strategy that has been employed to improve the strength of slopes has been the use of micropiles. Micropiles, which are characterised by their small width (usually less than 250 mm), are drilled and grouted replacement piles that are typically reinforced (Bruce and Juran 1997; Johari and Musavi 2018). A micropile is constructed by digging a hole, establishing the reinforcement, and grouting the gap. Innovation in micropiles has developed steadily since their introduction by Fernando Lizzi in the 1950s. Over the course of the last few years, advances in drilling equipment and procedures have expanded the suitability of micropiles to infrastructure repair and seismic retrofit projects (Neuman 1973; Van Genuchten 1980; Juran et al. 1999). In contrast to regular anti-slide piles, micropiles are moderately basic, fast, environmentally friendly, well planned, financially sound and non-invasive, especially for emergency interventions. In addition, micropiles can be rapidly introduced in regions with limited equipment, e.g. for avalanches located in hilly, steep or mountainous territories. The successful use of this strategy in slope adjustment has been described by a few specialists, for example (Ito et al. 1981; Cantoni et al. 1989; Juran and Christopher 1989; Ministry of Development 2005; Slide V5, SLIDE V5 2018).

Anti-slide micropiles have been commonly employed when address in unstable slopes and have been demonstrated to be an operative and efficient reinforcement methodology. For example, Griffiths et al. (2010) analysed the influence of pile reinforcement on the stability of slopes using numerical methods and presented the influence of the length of the micropile on the stability and factor of safety of a slope. Drilled and grouted micropiles are considered active anchors in the lower stable soil layer (in this case, rocky substrate) but are considered passive support in the upper unstable soil layer Griffiths et al. (2010).

Slope failure is a latent and dangerous kind of hazard that can cause sudden destruction that can bury properties. Thus, the study of slope stability becomes critical in geotechnical engineering to forestall this type of catastrophic event. The most employed methodologies in civil engineering for analysing slopes are limit equilibrium methods, such as methods by Janbu (1955), Bishop (1955), Morgenstern, Price (1965), and Spencer (1967). However, these strategies require suppositions on interslice interactions to determine the factor of safety, such as moment or force balance, etc., Yang and You (2013).

In the methodology proposed in this paper, the limit equilibrium technique has been applied due to its versatility, calculation, speed and precision. The use of Spencer’s limit equilibrium method is preferred as it is more precise and considers
the infiltration factor, according to recent publications about it (Clement et al. 1994; Chavez-Negrete et al. 2018). To use this methodology, two balance equations are applied and must be satisfied: force equations and impulse equations (Richards 1931; Sun et al. 2010; Chavez-Negrete et al. 2018). With this methodology, which is detailed in Clement et al. (1994), a safety factor can be obtained. A safety factor determines the stability of the slope and provides a number to decide if a structure is stable or unstable. With the proposed methodology, the value of this number has been corrected by increasing the safety factor with the introduction of supports on the slope. This method is an advantage over other methods and is extensively applied due to its simplicity and interaction between the calculation and speed. By introducing supports, the safety factor \( F_s \) can be corrected to achieve compliance with Spanish and European regulations.

Due to its versatility and extension, we have employed the software program SLIDE V5, which performs a fast and efficient stability analysis using limit equilibrium methods (González de Vallejo et al. 2002; Yang and You 2013). These methods allow the analysis of many common types of landslides, such as translational, rotational, topple, creep, and fall, etc. The stability analysis of this computer program can take into account the pore pressure and simulate the water infiltration into the slope’s soil using the finite element method (FEM) to determine the saturated/unsaturated water flow (Brooks and Corey 1964; Yang et al. 2011).

Due to its versatility, reliability and speed, the SLIDE V5 program will serve as a basic tool in emergency interventions, such as the stabilization of slopes affected by initial instabilities and thus be able to intervene in a non-invasive way avoiding collapses and preserving the buildings and infrastructures that are in them. For the new approach proposed here. In the case study that is presented, the undervaluation, in certain cases, of the impact of the infiltration factor on the stability of the slopes and how it is determinant in some slope landslides is demonstrated. The SLIDE V5 program will be utilised for the analysis and design of emergency corrective measures for slope instability due to excessive infiltration of rainwater. These proposed measures must take into account the delicate state of buildings and infrastructures on a slope due to previous instability and be as non-invasive as possible to avoid the collapse of these structures. Moreover, our approach calculates the necessary passive resistance provided by the micropiles to increase the slip landslide safety coefficient, assuming that the limit state is the micropile failure. In this work, a description of the application of the method to a problem of hillside safety in the province of Malaga (Spain) is presented.

2. Methodology

2.1. Model to increase the shear strength

The slope stability reinforced with micropiles and passive anchors is frequently predicted using pressure-or displacement-based techniques. While finite element/finite difference methods can be a suitable choice for calculating the shear strength reduction Hoek and Bray (1981), there is another method that is based on increasing the shear strength of the slope. This method, where \( \text{FORCE} = \text{PASSIVE} \) (one row of
micropiles and anchors) is introduced, is more suitable for cases of stabilisation in emergency situations due to its fast calculation, among other things. The originality of this method is that it not only simulates the micropile-slope interaction but also calculates the global factor of safety ($F_s$). For stability analyses, we determine the slip surface by the maximum shear force, as shown in Figure 1, by applying our approach.

The calculation model proposed in this work and shown in Figure 1 has been divided into two phases (1 and 2) depending on the value of $F_s$:

![Figure 1. Illustrative example of the theoretical application of the model. (A) No support example, and (B) critical surface with the FORCE introduction.](image-url)
Phase 1: For the mass between points FD, the equilibrium of the acting forces shall be considered toward the path along the slip surface. An initial calculation of $F_s$ is performed with the limit equilibrium method. If $F_s \text{ (initial)} < 1.50$, we determine that the slope is unstable. If $F_s \text{ (initial)} \geq 1.50$, the slope would be stable and it will not be necessary to apply phase 2 of the model.

Figure 2. Algorithm of our approach: Block diagrams.
Phase 2: If $F_s$ (initial) $< 1.50$, then we apply the reinforcement method and increase the shear strength of the slope by introducing $\text{FORCE} = \text{PASSIVE} = \text{SUPPORTED}$. When introducing the support, we increase $F_s$, which in our methodology we denominated reinforced $F_s$ (reinforced) $\geq 1.50$ Burbano et al. (2009). This security coefficient takes into account the European technical regulations and specifically, the technical regulations of the Spanish application in Table 2.1 of the DB-C of The Technical Code of the Building CTE (2007). Figure 2 shows a flowchart of the methodology.

Point E (Figure 1B) determines the maximum shear strength that each micropile in the row must support. Point E coincides with the upper limit of the embedment of the support in the rocky substrate, according to Figure 3.

2.2. Selection of the safety factor: reinforced with micropiles row

As previously mentioned, the stability limit equilibrium method proposed in our model for stability calculations is Spencer’s limit equilibrium method, which satisfies the equilibrium conditions of forces and moments in a precise way. The safety factor before considering any slope stability work is defined as follows:
The resisting force $F_r$ oppose sliding divided by $C_0/C_1$

The driving forces $F_d$ induce sliding divided by $C_0/C_1$

\[ F_s (\text{initial}) = \frac{\sum (\text{The resisting force/oppose sliding})}{\sum (\text{The driving forces/induce sliding})} = \frac{F_r}{F_d} \quad (1) \]

$F_s (\text{initial})$, which is classically defined as a ratio of stabilising and destabilising forces, determines the stability of a slope, $F_r$ and $F_d$ are the resisting force and driving force, respectively, of a soil mass (along the critical failure surface), which are determined by the method of slices in the slope stability analysis of a landslide, as shown in Figure 4(1).

In this method, $F_s$ of the whole slope (including the micropiles) is obtained by considering the total resistance provided by micropiles for one unit length of the slope ($F_{\text{rm-p}}$) as follows:
\[ F_{S_{\text{reinforced}}} = \frac{F_r}{F_d} = \frac{(F_r + F_{\text{rm-p}})}{F_d} \quad (2) \]

The \( F_s \) of the supported and unsupported portion of the stabilised slope is obtained as follows (refer to Figure 4(2) for details):

\[ F_{S_{\text{supported}}} = \frac{F_r}{F_d} = \frac{(F_r_{\text{supported}} + F_{\text{rm-p}})}{F_d_{\text{supported}}} \quad (3) \]

\[ F_{S_{\text{unsupported}}} = \frac{F_r}{F_d} = \frac{F_r_{\text{unsupported}}}{F_d_{\text{unsupported}}} + \left[ \frac{(F_d_{\text{supported}} - F_r_{\text{supported}} - F_{\text{rm-p}})}{C_2/C_3} \right] \quad (4) \]

where the supported forces, \( F_r \) and \( F_d \), are the resisting force and the driving force, respectively, of the soil mass along the supported portion of the critical failure surface. Both forces are also obtained using the slope stability method of slices, as shown in Figure 4(2). \( F_{\text{rm-p}} \) in Eqs. (2) and (4) is calculated from Eq. (3) after the desired safety factor of the supported (up-slope) portion of the slope \( (F_{S_{\text{supported}}}) \) is identified. By obtaining \( F_{\text{rm-p}} \), the focus on the load conveyed by each micropile in the micropile column can be assessed \( (F_d = F_{rp} \times S) \). \( F_s_{\text{supported}} \) must be identified with a minimum unit value.

With this methodology, the minimum \( F_s \) \( (F_s_{\text{supported}} = 1.50) \) shows that the stabilising micropile can effectively interact with the sliding mass of the soil. This interaction is achieved by considering a force that is equal to the difference between the driving force and resisting force along the slip surface of the supported portion \( (F_{\text{rm-p}} = F_{d_{\text{supported}}} - F_{r_{\text{supported}}}) \). Therefore, the second sum of the denominator is negligible in Eq. (4). An increasing value of \( F_s \) of the supported portion of the slope should be applied (i.e. transferring more soil pressure through the piles) to reach the decisive safety factor of the stabilised and reinforced slope. This application must be achieved until the maximum interaction between the micropiles and the surrounding soil is observed Acharya et al. (2016). However, in the proposed approach, we indicated a value of \( F_s \) greater than or equal to 1.50 to consider a reinforced and stabilised slope against a landslide (Green and Ampt 1911; Burbano et al. 2009). We must achieve a value of \( F_s \) higher than unity according to the Technical Construction Regulations of several European countries, including Spain.

In the example of the proposed application, with the introduction of the support element (row micropiles), we obtain \( F_s = 1.355 \), which is a considerable improvement in the initial critical safety factor. However, having imposed in the approach \( F_s = 1.50 \), we must introduce another resistant element (supported): Anchors introduced as passive elements or inclined micropiles with respect to the row of vertical micropiles to achieve the necessary reinforcement and value of \( F_s \) for the stability of the slope.

In the model analysis, the force that the sliding mass exerts on a row of micropiles can be expressed as a function of soil strength, micropile diameter and micropile spacing (Labuz and Zang 2012; Herrada et al. 2014). In addition, Spencer’s limit equilibrium method is employed to obtain \( F_s \) of the slopes (Hoek and Bray 1981;
Clement et al. 1994; Herrada et al. 2014). Thus, to determine the maximum shear force on the row of micropiles, the intersection of the slip surface with the micropile (Point E) is determined, as shown in Figure 3. This value of maximum shear strength, which is obtained in the calculation, determines the armour of the projected micropile. Several parameters can affect the interaction between the slope and the micropile and the degree of resistance that the micropile stabiliser can offer to increase F_s of the stabilised slope. Some of these determining factors are the geometry and material properties of the micropile, the soil characteristics, the position of the pile on the slope (i.e. depth of the slip surface at the location of the micropile) and the spacing of the adjacent micropile.

2.3. Design methodology of micropiles and anchors passive: development of the simplified model

The computer software SLIDE V5 Pinyol and Alonso (2012) is a two-dimensional (2D) slope stability analysis software that applies limit equilibrium methods. This software has been utilised in our methodology to implement the presented technique for micropile stabilised slopes, including slope stability analysis (with no micropiles-support) using Spencer’s limit equilibrium method. We have performed a 2D simulation due to its simplicity and speed in the calculation, which offers an efficient calculation result. To define the support pattern, the starting and ending points on the peripheral slope boundary must be introduced. However, if the method Force Application = PASSIVE is considered, valid safety factors can be calculated for these surfaces, as PASSIVE support does not decrease the driving force; instead, it increases the resisting force in the F_s calculation of the slope.

When a support element intersects a slip surface, a force is applied at the point of intersection between the slip surface and the mentioned support (i.e. applied to the base of a single slice). The applied force is simply a linear load, the units of which are FORCE per unit width of the slope. In general terms, F_s is calculated as the resistant forces against the driving forces. The former is due to cohesion and friction, while the latter includes the mass of the soil and the effect of water on the subsoil.

Passive Support is included in the SLIDE V5 analysis, as shown in Eq. (5).

\[
F_s = \frac{\text{resisting force} + T_n \tan \phi \ T_S}{\text{driving force} - T_S} \tag{5}
\]

where \( T_n \) is the normal component and \( T_S \) is the shear component of the force applied to the base of a slice by the support. Duncan and Wright (2005) offer the following guidelines for active and passive support capacities employed in limit equilibrium slope stability analysis. According to these researchers, the method of Force Application = PASSIVE is preferable as the soil strength and reinforcement forces have different causes of uncertainty Pinyol and Alonso (2012) and factoring them separately enables these differences to be reflected Hayek (2016). When a support intersects a slip surface (Point E to Figure 1B), a force is applied at the point of intersection of the slip surface with the support (i.e. to the base of a single slice). As the exact sequence of loading and movement on a slope is never known in advance in an
emergency, in our approach, we propose use of the Passive Force Application, which simulates the row of micropiles and passive anchors.

### 2.4. Effect of micropile spacing (D)

As the micropile spacing decreases, the micropiles resemble a continuous micropiles wall and the integrity of the soil and micropiles increases. The lateral load capacity of the reinforced slope significantly improved; however, the affected area becomes enlarged (i.e. reflected in the critical length of the micropile). Moreover, as the micropile spacing increases, the bearing capacity of a single micropile also increases. In our model, we have proposed the separation indicated in Spanish regulations Labuz and Zang (2012), which indicates a separation of 5 times D (D is the diameter of the micropile), with a maximum of 1.00 m. of separation between the axes of micropiles in the row.

### 3. Validation and application of the developed approach

Similar methodologies have been conducted by previous researchers (Van Genuchten 1980; Ashour and Ardalan 2012) but the originality of the proposed approach is to model an algorithm for the case of emergencies where a previous landslide has occurred. In our approach, we utilise commercial software, such as SLIDE V5 Pinyol and Alonso (2012).

Richards (1931), to which we introduce the infiltration factor in the calculations. The slope model considered by Spencer (1967) is employed in this paper. We propose a calculation model and intervention proposal for emergencies that involve unstable,
landslide-affected buildings. The proposal consists of implementing corrective stabilising measures, which involve the use of two row micropiles and anchors, to minimise damage. We present the results obtained with the proposed calculation model for a real case in Estepona, Malaga, Spain.

To study the effect of micropiles and anchors against landslides, an existing embankment landslide in the province of Malaga, with several buildings that are accessed by road MA 8301 between Jubrique and Estepona, in southern Spain is presented as an example. The situation of the accident is indicated in Figure 5; its coordinates are 36°2739.7N50°937.7W.

The embankment was constructed nearly 40 years ago and had an approximate height of 25 m with an inclination of 15° (Figure 10). An embankment landslide occurred after several storm rainfalls. The instabilities at Finca La Cala de Estepona (Malaga) resulted from landslides that were triggered by abnormally high rainfall in the area, which caused a decrease in the soil's matrix suction due to continuous infiltration of rainwater into the ground (Green and Ampt 1911; Lizzi 1978; Pearlman et al. 1992; Hassiotis et al. 1997; Gutiérrez-Martín 2016, 2020; Gutiérrez-Martín et al. 2019). As a result, we were forced to propose an action methodology to avoid the collapse of not only buildings but also infrastructures. This methodology was applied in the emergency slope stabilisation project conducted by the first author of the paper and resulted in the design and calculation of a row of micropiles and anchors. Intervention in emergencies of this type demand both the avoidance of further damage to the affected buildings and the preservation of the safety of the people involved. We designed this intervention methodology to achieve the following outcomes:

1. Guarantee the safety of damaged buildings.
2. Minimise vertical and horizontal movements.
3. Avoid the occurrence of new landslides, which may increase the initial damage to the constructions and/or cause collapse.

### 3.1. Background

The analysis and information compiled for the preparation of this article is mostly derived from a similar case study for a similar emergency intervention in the Stabilisation Construction Project and conducted by the consultancy General de Micropiles S.L. This applied methodology implied an innovation for the containment of emergencies and prevented the collapse of buildings, buildings that everyone considered lost.

The proposed emergency containment system in the case study was anchored to the resistant rock substrate by means of micropiles and a strand at the resistance level. The row of micropiles was projected with two different depths by the morphology of the geotechnical substrates: at 25 and 21 m, as indicated in Figure 6. We focus on the calculation of row number 1 (shown in black), as this row is the most unfavourable in its calculations and design.
3.2. Methodology or the calculation

We proceed to simplify and determine the geotechnical levels based on the geotechnical report to determine the stratigraphic column and geotechnical parameters associated with the subsoil. For the calculation of the stability and shear stress of the mass of slipped earth, we apply Eq. (6):

$$\tau_f = c + \sigma_f \tan \phi$$

(6)

$\tau_f$ is the shear strength along the failure surface at the time of failure, $\sigma_f$ is the normal stress that acts on the failure surface, $c$ is the cohesion and $\phi$ is the residual angle of friction. The last two parameters are the actual shear strength parameters. This methodology is based on the Mohr-Coulomb failure criterion Juran et al. (1996) and is the
basic expression for the determination of the shear resistance, i.e. the resistance of the soil to sliding.

This work explores the design of one row of micropiles and their anchors by applying the methods of limit equilibrium and the evaluation of their $F_s$ Braja (1999) with software that has reputed reliability, SLIDE V5, which was developed by the company Geosciences Slide. From the various possible limit equilibrium methods, we have chosen Spencer's limit equilibrium method Sun et al. (2010), which satisfies all equilibrium conditions—of horizontal and vertical forces and the sum of moments with respect to a common point.

A geotechnical field campaign is proposed, which consists of four rotation probes and various laboratory tests, to obtain the cut parameters of the slope. The prescribed geotechnical study must adequately consider the dimensions of the intervention and the steps prescribed by the technical regulations of application. In Spain, the Technical Code of Construction, CTE SE-C (2007) determines the number of surveys
based on the type of building and type of terrain. Our study involves a type C-1 building and group of T-3 terrain, according to Table 3.4 of the referred technical document CTE (2007). Taking into account the obtained geotechnical data, a typical geotechnical profile with the design and calculations of the proposed containment system was constructed and is plotted in Figure 7.

It is a novelty in this methodology, for emergency cases, to use the soil cohesion parameter with a value that is equal to zero. This value has been selected to address any deviation in the values and considers that this slope stabilisation-mitigation

Figure 8. Study example: State of the building after the previous landslide.
A procedure is proposed to intervene in landslides that occurred because of significant rainfall and infiltration into the rocky matrix of the slope. Therefore, note that the interstitial pressure in the rocky matrix decreases considerably during this important infiltration of rainfall, which contributes to a reduction of the matrix suction (1, 2) and cohesion. This process occurs in porous, permeable rocks, which allows water to flow in and cause saturation. The real cohesion value should not be zero; as an example, the cohesion value of schist in healthy rock is on the order of 2500 N/cm², and sandstone has a cohesion value of 3 MPa or 300 N/cm² Cantoni et al. (1989). In our approach, considering the rainwater infiltration and the emergency (requires a fast approach and solution); we set the cohesion value to zero to be conservative in the calculation. This type of rock has important surface meteorization substrates, which means that we must use this value to consider the infiltration in the rocky substrate.

In this methodology, before prescribing any emergency containment intervention, it is important to determine the constructive and structural state of the buildings after the previous landslide.

As shown in Figure 8, after the initial slip there has been a clear tilting forward of the main building, and its collapse is imminent. After performing a preliminary analysis of the state of the building, we considered the need to use the emergency corrective methodology proposed in this article to avoid further damage and prevent the final collapse of the buildings.

Next, we analysed the stability of the affected building after sliding by analysing the angular distortion limit values for the foundations in load-bearing walls. We were able to measure the values of angular distortion in the foundation higher than 1/2000. This limit is considered the maximum limit for the state of service according to the Spanish regulations in Table 2.3 of the DB SE-C of the Technical Code of the Building of Spain CTE (2007). These high values of angular distortion for the foundation of the building confirmed the need for an emergency containment intervention to avoid collapse of the affected buildings, since the values were close to the ultimate limit state of building stability.
Once the damaged buildings were analysed, we divided the methodology into the following stages:

a. Procedure and method of calculation
b. Stability analysis
c. Calculation of one row of micropiles and the anchors

The used calculation method is based on Spencer’s limit equilibrium method and takes into account the stability of the slope and the infiltration factor of water in the ground by applying interstitial pressure Spencer (1967). The method also contemplates the influence of loads, overloads and external actions on the analysed slope. The calculation procedure has the following stages: (1) Geometric definition of the slope, including the introduction of loads and overloads, as well as interstitial pressure; (2) Definition of the different depths and layers of soil; (3) Definition of type and depth for one row of micropiles and anchors based on the calculation data of the mechanical capacity required for stability.

In the calculation methodology proposed in this paper, we will employ the software application SLIDE V5, version 5.033 Pinyol and Alonso (2012) and Spencer’s limit equilibrium method in two-dimensional analysis. Once the geometry of the slope and the layers and depths of the geotechnical strata have been defined, we proceed with the computer application for the discretisation of the terrain in slices to consider different sliding surfaces and discover the critical break curve.

As previously indicated in Section 3.1 of this document, the method for calculating stability is based on the Mohr-Coulomb breakage criterion and defined by the geotechnical parameters of the different layers of the ground: internal friction angle and cohesion. The proposed calculation procedure, using the Slide software application, includes two phases: (1) Stability analysis of slope; (2) Emergency corrective measures to be applied.
When applying the emergency control procedure, the initial analysis of the stability of the slope is intended to determine the critical safety factors. A previous stability analysis using Spencer’s limit equilibrium method is shown in Figure 9 that calculates the global $F_s$ of the residual material of 1.043.

In this case, the influence of the infiltration water on the stability of the slope is decisive due to unusual rains during the hydrological period Gutiérrez-Martín (2016). Of special interest is the reduction in the matrix suction in the partially saturated subsoil due to an increase in the rainfall regime Ghotbi et al. (2011). For these emergency cases, in which the infiltration of water in the slope is decisive, Spencer’s limit equilibrium method is ideal for quickly and effectively analysing the stability.

In SLIDE V5, the groundwater influence is calculated with a finite element analysis. To conduct these calculations, a mesh is required; however, SLIDE V5 constructed this mesh in a friendly environment. The slope stability analysis will automatically employ the pore pressures calculated from the groundwater analysis by the Van Genuchten method (Spencer 1967; Wei and Cheng 2009; Yang and You 2013).

We have performed a hydrological analysis of the slope by calculating finite elements in the stationary state of groundwater in the slope, that is, we have calculated the pore pressure and its influence on stability. With this hydrological calculation, we have obtained $F_s = 0.907$, that is, $F_s < 1.00$, which makes the slope unstable Herrada et al. (2014) (see Figure 10). These results suggest that the infiltration in the slope produced by the extraordinary rains caused the landslide that produced the initial damage to the structures.

The European technical regulations, and specifically, the technical regulations of the Spanish application in Table 2.1 of the DB-C CTE (2007) indicate that the sliding safety coefficient for a permanent state in the stability calculations should be $F_s = 1.500$ (Ayala-Carcedo and Corominas 2002; CTE 2007; Burbano et al. 2009). The slope of the case study is less than this value.

The substandard $F_s$ of the slope indicated that corrective measures were necessary. As an initial corrective measure, the execution of one row of micropiles was proposed to reach a stabilization force that would oppose or resist shearing. While types of diaphragm walls would have produced the collapse of existing damaged buildings, one row of micropiles is less invasive taking into account the structural state of the constructions. The micropiles row is introduced in the computational calculation as a resistant element in the terrain, which is defined by the resistance to shear stress in the terrain.

The final design of the micropiles row is obtained via repetitive calculations in SLIDE V5 by introducing different resistances in the terrain and noting the obtained $F_s$. The calculations are performed per linear meter, according to Table 1.

In the calculation of stability, to obtain the highest shear stress and increase the safety coefficient, a discontinuous row of micropiles is introduced into the slope by means of resistant elements (micropiles) every 45 cm between axes, which are capable of withstanding a shear stress of 600 kN.

As shown in Table 1, with the introduction of this resistant element, we obtain $F_s = 1.355$, which improves the initial safety coefficient of the sliding slope by more
than 35%. In Figure 11, we have analysed how the \( F_s \) of the slope varies according to the passive resistance to shear, which simulates a row of micropiles.

The introduction of the passive elements (row of micropiles) considerably increased \( F_s \) but the minimum \( F_s \) of 1.500 for the overall stability of the slope was not reached.

We self-impose this value of global stability compared to stability in the calculation of the containment of landslides in emergencies. To increase \( F_s \) to 1.500 and satisfy this imposed condition, it is decided to introduce a new resistant element in the field via the application of permanent anchors as elements of traction in SLIDE V5. The placement of permanent anchors every 2.50 m was proposed and tested at 90 tons, and \( F_s \) of 1.500 were attained.

The necessary depth of the anchors to guarantee penetration in this substrate depends on the layer of healthy phyllites recognized in the drilling. As indicated in Figure 12, to guarantee the stability of the row of micropiles and the slope, an embedment of 10.50 meters is required when taking into account a sliding safety coefficient of 1.500.

To size the row of micropiles, we calculate the total pressure in non-draining conditions; thus, we apply the geotechnical parameters in undrained conditions (Bustamante 1986; GDRS 2001, 2009). To calculate the Total Vertical Pressures exerted by the terrain, the following formula is applied (7):

| Geotechnical soil parameters | Shear stress (kN) | Safety factor (Fs) |
|-----------------------------|------------------|------------------|
| Apparent density = 20.00 kN/m³ | 100              | 1.097            |
| Saturated density = 22.00 kN/m³ | 200              | 1.150            |
| Internal friction angle = 15° | 300              | 1.201            |
| Cohesion = 0.00 kN/m³        | 400              | 1.254            |
|                             | 500              | 1.304            |
|                             | 600              | 1.355            |

Figure 11. Relationship graph (Safety Factor-Shear Resistance) (kPa and kN).
To calculate the Total Horizontal Pressure exerted by the terrain on the row of micropiles, the following expression is applied.

\[ R_v = \frac{k_a c}{\gamma z + q} \]  

(7)

To calculate the Total Horizontal Pressure exerted by the terrain on the row of micropiles, the following expression is applied.

\[ \Sigma_v = k_a (\gamma z + q) - 2c k_a^\frac{1}{2} \]  

(8)

To provide the necessary safety coefficient to the micropiles row, anchors were calculated at a height of 1.15 meters from the coronation once perforation of the micropiles was completed and the crowning beam was constructed.

In the case study, the anchors were introduced in the stratum of healthy shale and drilled at an inclination of 20° with the horizontal. Anchors formed by Ø 0.6” strands of steel Y1860S7 (f_{max} = 1860 N/mm², f_{yk} = 1767 N/mm²) were dimensioned. For the service load, the tension is limited to 60% of the load of the elastic limit so that each anchor will be formed by 9 strands of Ø 0.6”.

In the proposed methodology, we calculate the anchors using the Bustamante method and consider the guidelines of the General Direction of Roads of Spain (GDRS 2001, 2009), taking into account that the bulb is embedded in its entirety in sound rock. In the shale residues of the case study, the free length of the anchor is assumed to be in the residual material.

The minimum required length of the anchor head is calculated by an empirical method, which is based on the effect of the tensile force to which the anchor is subjected until the ground in its movement tends to drag it. For the calculation of the anchor extraction limit force, Eq. (9) is applied.

\[ \sigma_v = \gamma z + q \]  

To calculate the Total Horizontal Pressure exerted by the terrain on the row of micropiles, the following expression is applied.
where $P_{nd}$ is the rated charge; $D_n$ is the nominal diameter of the bulb; $L_b$ is the bulb calculation length and $A_{adm}$ is the adherence admissible against the uprooting of the ground surrounding the bulb.

$$A_{adm} = \frac{a_{lim}}{F_3}$$

The $a_{lim}$ values are obtained by applying the empirical methods of limit adhesion obtained from Table 3.3 of the Spanish Guide for the Design and Execution of Anchors (GDRS 2001; Wei and Cheng 2009). For friction (granular) soils, graphs from the same guide provide the limit of adhesion. Conservatively considering $N_{spt} = 100$ hits, the value obtained for the adhesion is 5.00 kg/cm$^2$.

Therefore, the average resistance to sliding of the bulb $\approx 10.00$ m, with $a_{lim} = 5.00$ kg/cm$^2$; $a_{adm} = 5.00/1.65 = 3.00$ kg/cm$^2$ and $L_b \geq 90.000$ kg $\times 1.50/ (\pi \times 15$ cm $\times 3$ kg/cm$^2$) $\approx 10.00$ m.

4. Results and discussion

During the execution of the micropiles row, the tensions and lengths proposed in this methodology and the containment emergency calculation were checked on site. Satisfactory results were obtained.

After introducing the row of micropiles and the anchors as corrective measures, we proceeded to recalculate the stability of the slope where the damaged constructions were located by Spencer’s limit equilibrium method, with the conditioning factors and methodology proposed in this document. In the computer calculations in the study example, $F_s = 1.504$ has been obtained by introducing these passive containment elements in the slope (Figure 13).

This value of $F_s \geq 1.500$, which was obtained with the introduction of the proposed containment elements, satisfies the self-imposed parameters in this
Figure 14. Image A: Construction process of the calculated containment elements (micropiles row and anchors); current state of the main building after the emergency intervention. The effectiveness of the methodology against landslides is confirmed.
methodology to satisfy the overall stability. With this non-invasive, emergency methodology, we would have stabilized the slope and avoided further damage and movement in the affected buildings (Zheng et al. 2009; Yang et al. 2011). Figure 14 shows the row of micropiles and anchors that are designed and executed with this proposed methodology and the state in which the main building was left after this emergency intervention and its overhaul.

This proposed calculation model innovates by applying a hydrological variable of pore pressure to the slope, which comprises data that are not always considered in calculations in civil engineering and emergency interventions. This emergency containment method is very useful for this type of increasingly common problem in overcrowded construction areas, such as the Costa del Sol (Gutiérrez-Martín 2016; Gutiérrez-Martín et al. 2019). This methodology considers the need to introduce adequate safety factors, to avoid unforeseen difficulties in the stability of the slope and the application of corrective measures, and prevent material and even personal damage to the slopes (Zhou and Cheng 2013).

5. Conclusions

In this study, the embedded lengths of micropiles for slopes reinforced with one row of micropiles and passive anchors are analysed by a 2D shear strength increased method with the introduction of a passive force and the application of Spencer’s limit equilibrium method. The following conclusions can be obtained:

a. In emergencies, the slope stability can be enhanced with micropiles and passive anchors, and as expected, the $F_s$ increase with an increase in the micropile length and tend to remain constant when the micropile length exceeds the critical length.

b. In practice, with a single row of piles, achieving a restrained head condition would be difficult unless the pile is strongly anchored, as the proposal of passive anchors indicated in our model proposal.

c. The force due to the infiltration hydrological factor has been determinant in the landslide; thus, the hydrological factor of our approach must be taken into account not only for the initial analysis but also for the reinforcement of the final slope.

d. In practice, the stability of the slope has been analysed using Spencer’s limit equilibrium method (Spencer 1967; Ito et al. 1979; Clement et al. 1994), which introduces water infiltration that simulates a stationary rainfall regime, with an initial result of $F_s = 0.970$, that is, $F_s < 1.000$, which makes the slope unstable. In the procedure, we introduce a passive force in the slope (micropile row) and manage to increase the $F_s = 1.335$. Later, we introduce another force in this active case (line of passive anchors), which increases the factor $F_s = 1.504$. This finding shows that our slope stabilization methodology in emergencies is a useful tool for in-situ reinforcement slopes/embankments and landslide stabilization with soil strengthening and protection.
e. The $F_s$ of the slope that is analysed with our methodology is increased by 55.04% for this type of geotechnics.

Our results show that Spencer’s limit equilibrium method, with the hydrological factors proposed in this paper, is an ideal method for circumstances described in the approach application example. This method allows us to calculate necessary emergency corrective measures more precisely for slope instability caused by vertical infiltration and enables the preservation of affected buildings, infrastructures and the people in them. This methodology of repair and stabilization in emergencies is not only useful for the correction of damage incurred but also effective in preventing instabilities in the project and design phase of hillside buildings.

**Data availability statement**

Some or all data, models, or approach that support the findings of this study are available from the corresponding author upon reasonable request:

1. Field data. The properties to shear stress of the analysed soil have been obtained. In this case the rocky substratum of phyllite
2. We have developed an algorithm to stabilize landslides in case of emergencies, in a non-invasive way to be able to preserve the existing building and without having to demolish it. The data are contrasted in the case study.
3. Reinforced with micropiles row. A simplified calculation model is used, evaluated with highly efficient software such as Slide V5. The data is available.
4. A deterministic method such as the Spencer method and a hydrological evaluation by the Van Genuchten method is used for the evaluation of the landslide problem and for later the calculation of the containment.

**Disclosure statement**

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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