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Research Article

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Experimental and finite element analysis of slope stability treated by lime milk (case of El Amir Abdelkader embankment)

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Abstract: This paper presents an experimental stabilization approach of the landslide that threatens a slope located near the city of El Amir Abdelkader, Ain Temouchent, Algeria. Stabilization is assured by the addition of lime milk, and then a numerical validation of the results with respect to the safety coefficient before and after treatment was performed by "Plaxis" software. Experimental results show that the stabilization by lime milk improves compaction parameters, swelling and shear strength, particularly the cohesion and friction angle, the latter permitting appreciation of the sliding surface on which it is necessary to base the calculation of the safety coefficient before and after treatment. Numerical results indicate that the factor of safety increases with the improvement of the mechanical characteristics c and φ, which are improved by increasing lime milk percentage. The numerical validation using "Plaxis" finite element code gives results that are in perfect agreement with the experimental ones, indicating that this software is a good tool for slope stability study.

Keywords: Slope, soil stabilization, lime milk, shear strength, swelling

List of Symbols

C	Cohesion
$\boldsymbol{\varphi}$	Angle friction
$\boldsymbol{\tau_{max}}$	Maximum shear strength
$\boldsymbol{\epsilon_g}$	Swelling amplitude
$\boldsymbol{\sigma_g}$	Swilling pressure
γ_d	Optimum dry weight volume
γ_{sat}	Dry weight volume
$\mathbf{w}_{opm}$	Optimum water content
Fs	Safety factor
E	Young's module
$\boldsymbol{\nu}$	Poisson factor
k	Permeability factor
$\mathbf{C_c}$	Cohesion reduced
$\boldsymbol{\varphi_c}$	Angle friction reduced

1 Introduction

In construction areas, instability may result due to rainfall, increase in groundwater table, and change in stress conditions. Similarly, natural slopes that have been stable for many years may suddenly fail due to changes in geometry, external forces, and loss of shear strength [1].

Evaluating the stability of slopes in soil is an important, interesting, and challenging aspect of civil engineering. Slope instability is a geodynamic process that naturally shapes up the geomorphology of the earth. However, these processes turn out to be a major concern when those unstable slopes can adversely impact the safety of people and property [2].

Estimating actual safety in relation to the risk of rupture is a complex question whose reliable answer is the responsibility of the geotechnical engineer. In-depth study of an embankment includes, in addition to the reconnaissance of the site and the identification of the mechanical characteristics of the soils, a stability calculation to determine on the one hand the rupture curve along which the risk of slipping is the highest, and on the other hand the corresponding value of the safety coefficient [3].

The slope stability analysis is performed with the limit equilibrium (LE) method based on assumptions about the sliding surface shape. These methods remain popular because of their simplicity and the reduced number of parameters they require, which are slope geometry, topography, geology, static and dynamic loads, geotechnical parame-

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ters, and hydrogeologic conditions. However they do not take into account the ground behavior and the safety factors are supposed to be constant along the failure surface [4]. Many methods can be used to evaluate the factor of safety in slope stability analysis. Several researchers used the LE analysis to estimate the factor of safety [4–7].

Some used strength reduction parameters c and φ of the Mohr Coulomb model for evaluation of the slope stability [8–10]. The strength reduction method is based on the reduction of the mechanical characteristics cohesion and friction angle of failed material, determined from laboratory tests [11].

In the present investigation, a series of direct shear box tests and numerical simulation using finite element model have been carried out to investigate the effect of lime milk percentage (0%, 2%, 4%, 6%, and 8%) on the mechanical behavior of soil (maximum shear strength, cohesion, friction angle, and the factor of safety). The objective of this study is to improve the mechanical properties of the studied soil, such as cohesion and friction angle; then, these parameters will be used to calculate factor of safety.

2 Materials and methods

2.1 Study area

The studied slope is an embankment in rubble located on the side of the national road N°35 near El Amir Abdelkader town (related Ain Temouchent city Tlemcen one) situated in the north of Algeria.

This slope has suffered and continues to suffer from disorders that seriously threaten its stability. These disorders are due to the steep slope of the benches that make it up and the surface erosion caused by strong precipitation. So, rapid action will be needed to stabilize this embankment, which is in danger of collapsing at any moment. Figure 1 shows the current situation of the embankment.

Figure 1: The actual situation of the slope.

Reworked soil samples were taken from the embankment using the assumption that samples collected represent the studied slope.

2.2 Study analysis

Whatever the objectives of a geotechnical study, it is standard practice to initially identify the soil concerned. This procedure allows us to orient the geotechnical analyses and, more importantly, to classify the materials encountered. Table 1 gathers the results of the physicochemical characteristics of the studied soil; and according to the results, the studied soil is silt clay (classification LCPC). Table 1 summarizes the soil properties used in the present study [12].

Table 1: Soil parameters [12].

Property	Value
Optimum dry volume weight (γd kN/m^3)	17.9
Optimum water content (Wopm%)	15.6
Percentage of element% < 80μ	85
Organic matter (%)	1.63
Liquid limit wl (%)	68.45
Plastic limit wp (%)	26.41
Plasticity index Ip (%)	42.04
Methylene blue value	25.0
Specific surface (m^2/g)	523
$CaCO_3$ Content (%)	23

2.3 Experimental procedures

The methodology adopted in this study is to mix the soil and lime milk at specific percentages (2%,4%, 6%, 8%). Then, reworked samples will be reconstructed, and compacted in press at a slow speed (1.14 mm/min) identical to those of the normal Proctor optimum. The samples are used after 7 days of curing [28].

To study the influence of lime milk and the sample preparation method on shear strength, direct shear tests were carried out at normal stresses 50 kPa, 100 kPa, 200 kPa, and 300 kPa. Tests were performed using a square direct shear box 60 × 60 mm^2. The initial sample height was 25 mm. The test consisted in placing a sample in the shear box and subjecting it to a vertical load N that represented the applied normal stress (50 kPa, 100 kPa, 200 kPa, and 300 kPa) and a horizontal load T which was gradually increased. The direct shear test allowed measuring the peak and residual shear strength corresponding to each normal stress. All the tests were conducted at a constant displacement rate of 1.00 mm/min according to ASTM D3080 [13]. The shear stress was recorded as a function of horizontal displacement up to an average shear strain of 7.5 mm.

To examine the effect of lime milk on the swelling of the studied soil samples, different percentages are prepared (2%, 4%, 6%, 8%.). Immediately after mixing the soil with lime milk, specimens are placed in an oedometric unit 20 mm*50 mm, in which the swelling tests are executed. The method chosen is according to ASTM D-4546-90-method A [14]: this choice is explained by the fact that this method adopts the correction of the reworking effect, by the application of a loading–unloading cycle, and the final constraint of this cycle is equivalent to the soil weight before extraction. The swelling of the sample, obtained by imbibitions, will be followed until stabilization. The swelling pressure will be equal to the pressure that returns the sample to its initial height. The swelling amplitude will correspond to the maximum deformation between the beginning and the end of the swelling phase.

In the following section, the effect of different percentages of lime milk on compacting, swelling pressure, swelling amplitude, and shear strength will be presented. The target is to choose a percentage that gives a better soil improvement.

2.4 Numerical procedures

With the significant development in computer technology, the application of FEM in slope stability analysis has become increasingly common. The primary advantage of this method over FEM is its flexibility. It requires no assumption about the shape or location of the failure surface in advance or about the interslice forces and their directions. This method can be used to analyze slopes with complex configurations. All types of failure mechanism can be virtually modeled using FEM. Most of the general soil material models along with Mohr-Coulomb criterion can be employed. FEM is capable of modeling progressive failure and it can calculate deformations at different slope stress levels [15].

Shear Strength Reduction technique is one of the approaches FEM uses to perform slope stability analyses, which have gained popularity in recent years. In this method, the strength characteristics like cohesion and friction angle are successively reduced by a factor till instability is induced in the system [7].

2.5 Geometry and materials parameters

In order to validate the obtained experimental results, finite element program Plaxis 2D was used to perform the slope stability analyses with an elastoplastic Mohr Coulomb soil model based on eight parameters summarized in Table 2. The numerical study was carried out on the four lime milk mixtures, in order to compare the numerical factor of safety with the theoretical one (LE method).

Table 2: Mohr coulomb parameters for unreinforced soil (0% lime milk).

Parameters	Value
γ_{unsat}	17.9 KN/m^3
γ_{sat}	19.7 KN/m^3
kx	10^{-7} m/day
ky	10^{-7} m/day
E	800 kPa
ν	0.3
c	70 kPa
φ	7°

Figure 2 shows the geometry, meshing, and boundary conditions of the slope object of the present study. The slope height is about 25 m and the length is about 60 m. The soil properties of different mixtures (0%, 2%, 4%, 6%, and 8% lime of milk) were obtained from soil experimental tests.

A 15-node triangular element was used to mesh the slope.

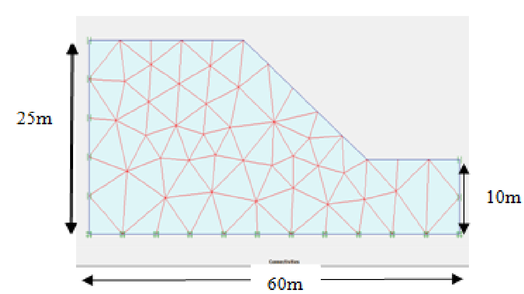

Figure 2: The Plaxis finite element model (geometry, meshing and boundary conditions) of El Amir Abdelkader embankament.

Standard fixities were applied as a boundary condition in Plaxis. The mesh generation is done automatically; the initial conditions require the generation of the initial hydraulic conditions (phreatic level) and the initial stresses. The Phi-c reduction approach, which was proposed in the literature [16], is adopted for calculation phase. In this approach the strength parameters tan Φ and c of the soil are successively reduced until failure of the structure occurs. The strength of structural objects like plates and anchors is not influenced by Phi-c reduction. When using Phi-c reduction in combination with advanced soil models, these models will actually behave as a standard Mohr-Coulomb model. The Phi-c reduction approach resembles the methods of calculating safety factors as conventionally adopted in slip-circle [17]. This approach is based on the reduction of the strength parameters c and φ of the Mohr-Coulomb model, and it is represented by the named factor of safety. An equation for calculating factor of safety is available in the literature [18]:

$$\text{Safety factor} = \frac{S}{S_c} = \frac{C + \sigma' \cdot \tan\varphi}{C_c + \sigma' \cdot \tan\varphi_c} \quad (1)$$

where S is the shear strength; and S_c is the reduction shear strength. Note that c and φ are the cohesion and friction angle, respectively, with C_c and φ_c representing the reduced value of the cohesion and friction angle, respectively.

3 Results and discussion

3.1 Lime milk effect on compaction parameters

Figure 3 illustrates the variation of optimum dry weight volume (γ_d) and optimum water content (w_{opm}) as a function of lime milk percentage. It is clear from this figure that the use of lime milk leads to an increase of the optimal water content and optimum dry weight volume, and this increase is due to the fact that the lime milk occupies the interparticle void between the soil particles. Thus, a large part of water will be absorbed by the lime milk, and therefore, the reduction of void causes an increase in the final dry density of the samples [19].

The reduction in dry unit weight is probably due to the immediate reactions between lime and soil, which is represented by flocculation [16] and the formation of agglutinating products which lead to the increase of soil resistance capacity [20] According to Mateos and Davidson [21], and as confirmed by Babouri [22], the principal agglutinating products are calcium silicates and aluminates.

In addition, the higher pH environment in the treated soil changed the surface charge distribution in the soil particles, resulting in an increase in repulsion between particle layers. This, along with changes in the particle size distribution, caused a decrease in maximum dry unit weight [23, 24].

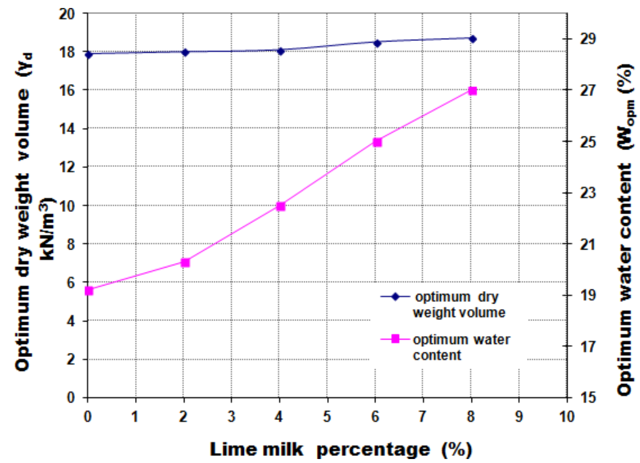

Figure 3: Evolution of compaction characteristics as a function of lime milk percentage.

3.2 Lime milk effect on shear parameters (cohesion, angle of friction and maximum shear strength)

Adding lime milk to the soil leads to a modification of the angle of friction and cohesion. The increase in the internal friction angle depends on lime milk percentage added; for example, 8% of lime milk increases cohesion to 80 kpa.

Figure 4 gives the evolution of the angle of friction and the cohesion as a function of lime milk percentage. These high cohesions are due to the texture of clays improved by the addition of lime milk that behaves, during shearing, like a soil made up of hard lumps. Improvement in this parameter is attributed to the process of reorganization induced by flocculation [25].

Figure 5 shows significant improvement in maximum shear strength based on lime milk addition. This parameter

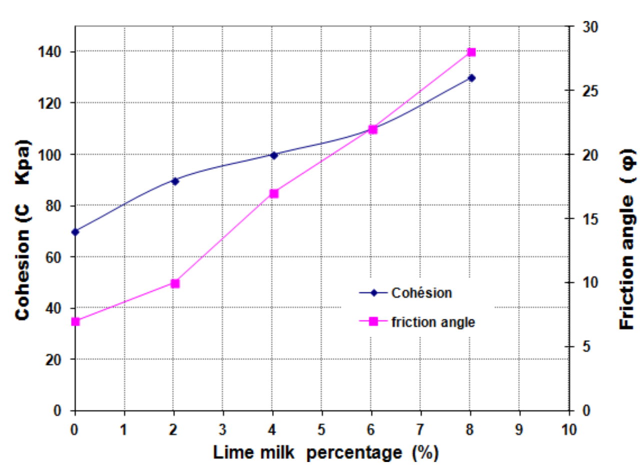

Figure 4: Variation of the angle of friction and the cohesion according to the lime milk percentage.

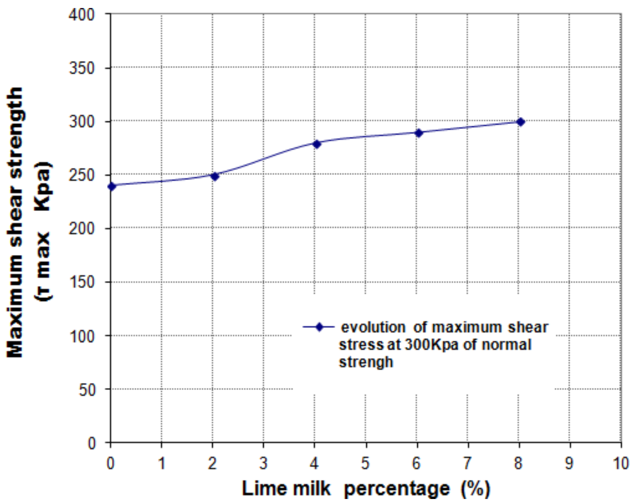

Figure 5: Evolution of maximum shear strength with respect to lime milk percentage.

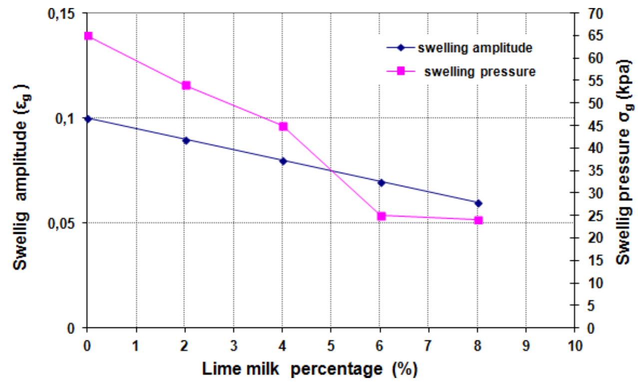

Figure 6: Evolution of amplitude and swelling pressure depending on lime milk percentage.

is significantly improved after adding 8% of lime milk (an increase from 247 kpa without lime milk to 300 Kpa with 8% of lime milk). The reason for this improvement is the sample preparation, compaction, and remolding, which are done after curing period (7 days).

3.3 Lime milk effect on swelling parameters (amplitude and swelling pressure)

Figure 6 presents the evolution of the pressure, and the amplitude of the swelling as a function of lime milk percentage added to the tested soil. In general, a continuous decrease of the swelling pressure and amplitude is observed. The important diminution of the swelling is attributed mainly to the reduction of the water absorption capacity at the end of the cationic exchange, which is the more accentuated, as the percentage in lime milk is important (progressive replacement of the sodium cations Na^+ in the interfoliar space which have a high hydration energy by the calcium cations (Ca^{2+}) brought from lime milk which have a low hydration energy [22].

The net result is a substantial decrease in swelling characteristics of the soils. In addition, the pozzolanic reaction between lime and soil, which usually occurs after a sufficiently long time, forms a cementitious matrix [16]. Overall, when lime is added to soil, reduction in swell potential occurs primarily because of alteration in clay structure [26–28].

3.4 Numerical results

Figure 7a and b shows the deformed mesh and total displacement of the untreated slope (0% lime milk); we observe that the most critical displacement zone is located at the inclination of the slope. It can be shown from Figure 7b that the total displacement of unreinforced slope is important. Figure 7c shows that the factor of safety of the unreinforced slope was observed as 0.789, which indicated that the slope was unstable at 0% lime milk.

Figure 8a–c shows the effect of 8% lime of milk on the numerical analysis of the slope.

It is observed from Figure 8a and b that the total displacement is reduced compared to the unreinforced slope (0% lime of milk), and this reduction is due to the increase in the cohesion and the friction angle, which are improved by the addition of 8% of lime milk. It is observed from Figure 8c that the increase of the lime of milk from 0% to 8% improves the value of the factor of safety from 0.789 (unreinforced soil) to 2.371 (reinforced soil with 8% lime milk).

In order to compare numerical safety factor (found from numerical simulation), this later was calculated using Mohr coulomb method based on the following equation:

$$\text{Safety factor} = \frac{c'}{\gamma_{sat} H \cos^2\beta \tan\beta} + \frac{\gamma'' \tan\varphi'}{\gamma_{sat} \cdot \tan\beta} \qquad (2)$$

It is clear from Figure 9 that safety factor found from the numerical simulation results increases from 0.789 to 2.371 with the addition of lime milk (0%, 2%, 4%, 6%, and 8%). Simulation results are in good agreement with the theoretical ones (– which were computed based on LE method).

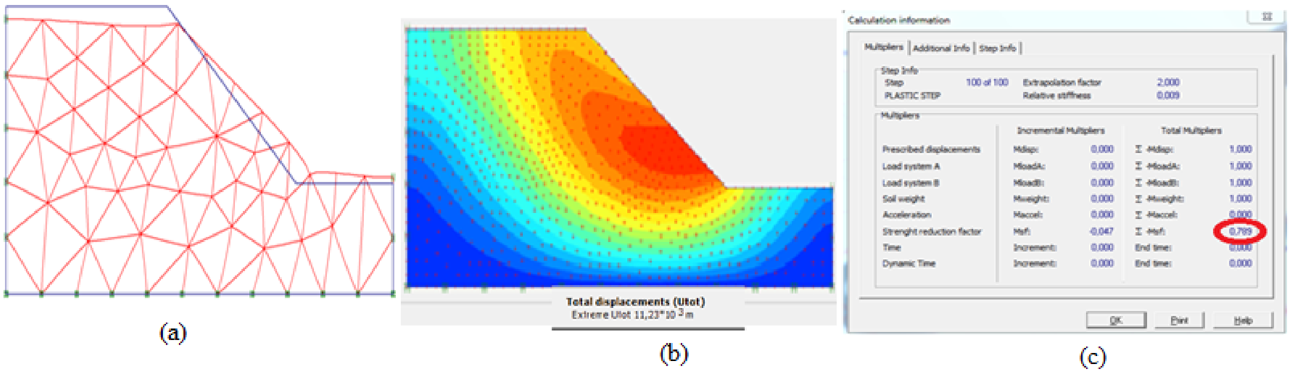

Figure 7: Slope stability analysis Results of untreated soil (0% lime milk) **(a)** deformation mesh, **(b)** total displacement direction, **(c)** value of the factor of safety (Plaxis 8.2).

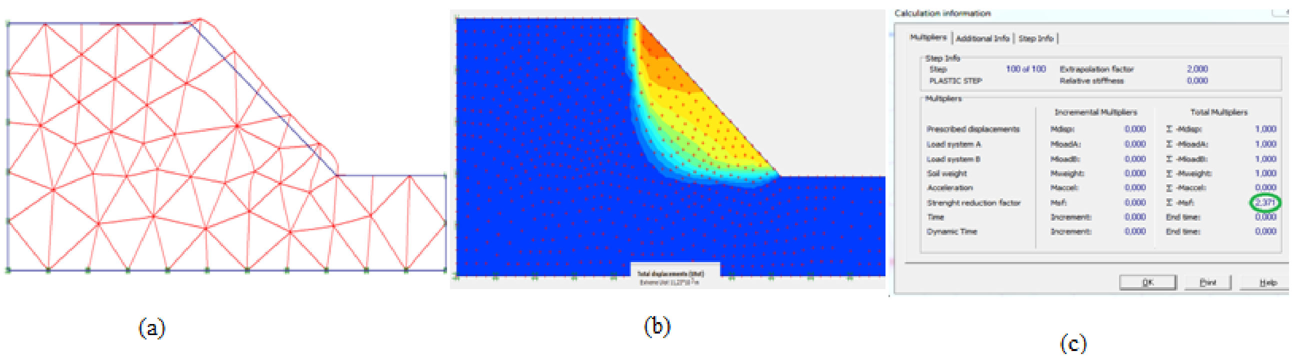

Figure 8: Slope stability analysis results of treated soil (8% of lime milk) **(a)** deformation mesh, **(b)** total displacement direction, **(c)** value of the factor of safety (Plaxis 8.2).

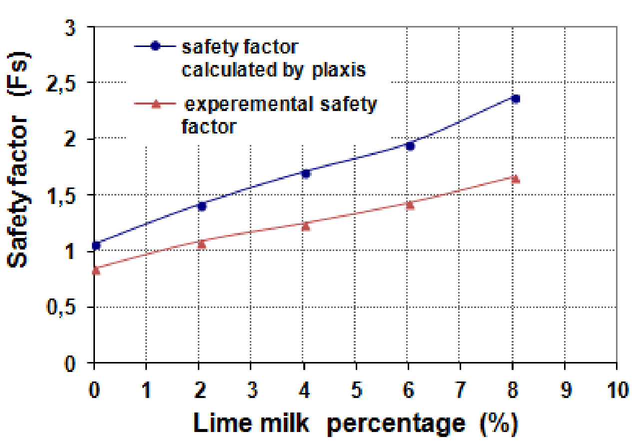

Figure 9: Effect of lime milk on safety factor value.

4 Conclusion

In the present paper, the soil of El Amir Abdelkader embankment has been treated by adding different lime milk percentages (2%, 4%, 6%, and 8%). The study has led us to reach the following conclusions:

- The addition of lime milk modifies the compaction characteristics of the treated soil and reduces its adsorption capacity.
- The treatment increases the dry density.
- The maximum shear strength, as well as the cohesion and friction angle, have shown clear improvement with the addition of lime milk.
- A small percentage of lime milk has the effect of decreasing the amplitude and pressure of swelling.

Furthermore, finite element method simulations were performed using the Plaxis 2D software to calculate the slope safety factor. The numerical safety factor results are in perfect agreement with the theoretical ones. Numerical simulation results indicate that the improvement of the cohesion and of the friction angle by lime milk addition leads to an enhancement of the safety factor from 0.789 for the untreated soil to 2.371 for the treated soil with 8% of lime milk.

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