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Selecting the Safety and Cost Optimized Geo-Stabilization Technique for Soft Clay Slopes

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Abstract

Slope failure poses a serious threat to the built environment as it is currently one of the fundamental contributors to climate change fears across the world, and this threatens the environmental goals of the United Nations Sustainable Development Goals (UNSDGs) for the year 2050. In this research paper, an optimized geo-stabilization numerical model has been developed with a Plaxis 2D code under safety and cost optimization considerations for a 37 m high slope embankment located on a soft clay watershed with an infinite extension. The site was prepared with four monitoring wells installed at 2.5 m, 7.5 m, 12.5 m, and 21.5 m from the foot of the slope to measure the water level conditions, and samples were collected and tested in the laboratory to determine the hydraulic and shear strength and modulus of the soil. Seven (7) different simulation alternatives were considered in terms of the model solutions to be deployed under dry and wet states, which were slope steep (angle) reduction (Alt-1), dewatering (Alt-2), jet grouting (Alt-3), jet grouting/dewatering (Alt-4), slope reduction/jet grouting (Alt-5), slope reduction/dewatering (Alt-6), and slope reduction/jet grouting/dewatering (Alt-7). The finite element model implementation of the alternatives showed that Alt-2, Alt-3, and Alt-4 had FOS of less than 1.5 and were omitted because their stability considerations did not meet the requirements for the normal operating conditions of a slope and also the short-term and long-term stability conditions according to the literature. Alternatives 1, 5, 6, and 7 with FOS above 1.5 were selected for further optimization considerations. Economic and sustainability factors were selected and considered based on the cost in line with current average market prices, constructability, reliability, and the environmental impact needed to achieve the required earthwork, jet grouting, dewatering, and selected combinations. Finally, the Alt-1 (FOS = 1.505), though not the cheapest, was selected as the optimal choice in terms of reliability, constructability, and environmental impact. However, Alt-6 (FOS = 1.520) and Alt-7 (FOS = 1.508) are the most economical but ranked low in reliability and environmental impact considerations.

Keywords: Soft Clay Slopes; Slope Stabilization; Jet Grouting; Finite Element Method; Plaxis 2D Code; Engineering Economy.

1. Introduction

Due to the increasing demand for infrastructure development in urban and rural areas, the number of civil constructions such as highways and especially embankments requires further analysis for their safety [1, 2]. In the specific case of slopes, there are still significant uncertainties regarding the influence of the unsaturated condition [3]. For this reason, more robust analyses are necessary to quantify the effects of suction and changes in slope geometry, as

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well as the inclusion of reinforcements, drains, and vertical columns [2–5]. Finite element methods (FEM) are essential for solving stress-strain problems, particularly in soil-structure interaction and slope stability cases [6]. The behavior of geotechnical materials in FEM is described by an elastoplastic model, according to the Mohr-Coulomb failure criterion. For this reason, it is logical that its use in the case of the safety of civil works is an obligatory consideration. However, the peculiar characteristics of slope problems in unsaturated conditions where suction exerts a significant influence mean that the analysis is not direct, but special care must be taken to reproduce some details [7].

FEM involves basic steps such as discretization, selection of approximate functions, derivation of equations, gathering element properties to form global equations, and calculating primary (e.g., displacements) and secondary (e.g., stresses) quantities. Discretization consists of dividing a continuous medium into an equivalent system of small discrete elements, called finite elements, in which each element is analyzed and treated individually. Each element is assigned physical or constitutive properties, and stiffness matrices are formulated [8]. FEM is a numerical technique for finding approximate solutions to limit value problems for numerous partial differential equations. It theoretically satisfies all the requirements that must be met for a complete solution to a slope stability problem [9]. In addition, slope stability is related to the potential geological conditions of failure and is directly dependent on the shear strength generated along the slip surface [3]. FEM analysis involves the relationship between acting and resisting components, where components can be defined in terms of stresses, forces, and moments. Stability analyses are commonly performed by limiting equilibrium analytical methods through computer programs [10]. Slope stability analysis by three-dimensional limit equilibrium is simple in concept and directly analogous to two-dimensional methods. For the stability analysis to be accurate and to represent with quality the actual behavior and failure mechanisms, or as close as possible, the geomechanical parameters must be carefully defined since the stability analysis results are sensitively dependent on the shear strength. Therefore, the definition of the geomechanical properties is fundamental, and for that, it is necessary to adopt methodologies for estimation to represent the type of mass to be evaluated and the objectives of the analysis [11].

Slope failure is much more complex than what has been modeled by the limit equilibrium method. In practice, failure does not occur simultaneously along a single discrete basal surface, but rather a localized failure progressively develops over a larger failure region. Except for purely structural slope failures, such as those controlled by a discontinuity in a fragile rock mass, the process of internal deformation also plays an essential role in the development of these failures [12]. Thus, stabilizing solutions increase the forces against the massif's sliding or shear resistance, leading to the active stabilization of the slope and its safety factor (FOS). These solutions include resurfacing, balance beams, walls, anchored curtains, reinforcement with geosynthetics, and drainage. Safety factors less than 1.0 represent unstable slope conditions, are more significant than 1.0 stable conditions, and are equal to 1.0 imminence of failure [13]. Several authors, e.g., [14–16], have recommended acceptable safety factors for slope stability values in the literature. For normal operating conditions and long-term stability, safety factors between 1.25 and 2 are recommended, depending on the method, while for short-life slopes, the recommended values vary between 1.3 and 1.5. The recommended values of FOS required for severe load conditions vary between 1.25 and 1.3. The safety factor's accuracy strongly depends on the consistency of the input data, the numerical method, and the numerical modeling used. One of the methods used to calculate the factor of safety in finite elements is Shear Strength Reduction (SSR). In SSR, a reduction factor is gradually imposed on the shear strength parameters of the materials. First, the deformation is calculated according to the parameters defined for the material. The reduction factor is then applied, systematically varying it while the deformations are calculated from altered parameters. This is done until the maximum strain increases significantly, understanding that, at this stage, there has been a rupture. Thus, the safety factor will be equivalent to the reduction factor immediately preceding the one where the great deformation occurred [17].

Rain is the principal provoking agent of earth movements, becoming a possible threat to society and a motivator to analyze the susceptibility of slopes to landslides [18]. One of the causes that explains their occurrence is the reduction or elimination of a portion of the shear resistance of the soil due to the decrease of the suction portion, also called negative pore pressure, in unsaturated soils generated by the infiltration of rainwater. To analyze the influence of infiltration on the stability of a slope, one must know the hydraulic parameters and soil resistance. Conceptual and numerical models have been developed to determine the hydraulic parameters in unsaturated porous media and use numerical tools that help understand rainfall dynamics and influence slope stability [19]. Xu et al. [20] researched the stability analysis of a 3D vertically cut slope subjected to rain infiltration. The authors adopted an analytical model that directly provides the change in pore water pressure at any depth and time to calculate the time-dependent matrix suction and shear strength of unsaturated soil. It was found that the slope's 3D characteristic is a key factor determining the safety factor and that different patterns of rainfall infiltration led to variations in both the safety factor solutions and the critical failure patterns on the slope. However, at the end of rainfall infiltration, these rainfall patterns with the same accumulated rainfall produced the same result.

Sun et al. [21] studied slope stability analysis in unsaturated conditions, considering unsaturated soils during rainwater infiltration. The authors used a three-phase coupled liquid-gas-solid model and developed the stability analyses in the FLAC 3D software. Sun et al. [21] report that most slope failures are induced by rainfall infiltration. The working model was validated through a water drainage experiment in a sand column, and the results were compared with measured and simulated data from other researchers. The proposed model was used to investigate the characteristics of the two-phase water-air flow and stress fields on a slope of unsaturated soil during rainfall infiltration. The results showed that the safety factor varies over the time of rain application and decreases until it stops. As drainage alternatives, there are deep horizontal drains, crest and crack sealing, drain tips, surface drainage, and drainage tunnels. For cases of deep and large-volume landslides, drainage tunnels are sought, as they have greater drainage capacity, keep the face of the slope free, and entail maintenance inside the tunnel. The other solutions would not be sufficient for stabilization or would be unfeasible, as is the case with deep horizontal drains, requiring a high number of drains arranged on the slope face and more complicated maintenance [22].

Natural reinforcements also help improve slope stability. Studies carried out by Boldrin et al. [23] indicated that different plant species influence soil reinforcement differently, with the functional characteristics of plants, including specific leaf area, root length density, and root-shoot ratio. These showed significant and positive correlations with perspiration-induced suction. The same study also indicated that deciduous species exhibited twice the transpiration efficiency and leaf water vapor conductance of evergreen species.

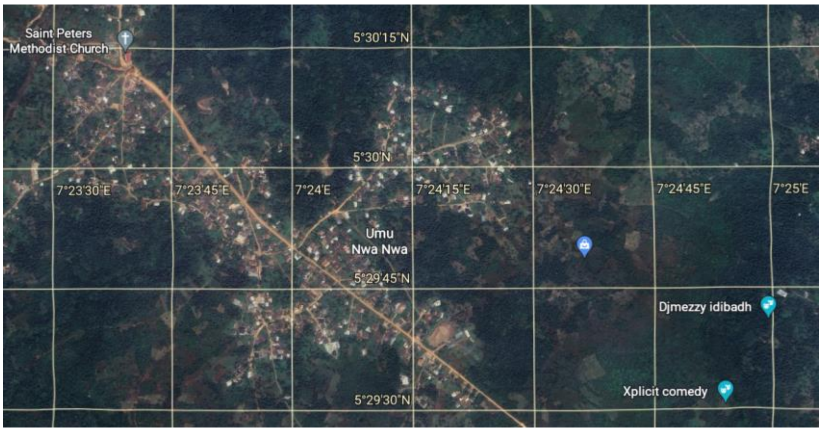
Experimental, laboratory, and field research has enabled in obtaining soil hydraulic parameters. Notably, these methods allow obtaining the characteristic curve but do not obtain conductivity function for unsaturated soils [24]. Drainage tunnels can be excavated below the rupture surface, usually incompetent soil massif, so drainage occurs through the tunnel walls. If necessary, these structures can increase their drainage capacity by applying radial drains excavated from inside the tunnel without intervening on the slope's surface [25]. In addition, although erosion is a natural phenomenon, it can be accentuated by human actions, and all landscapes with some declivity, usually greater than 3°, can suffer erosion. In the same way, some studies e.g., [26, 27] state that erosion occurs more sharply on steeper slopes since higher flow velocities occur, as well as the impact of the raindrop causes the particle splash, so that, the steeper, the terrain, the more soil is spread downhill than uphill. The previous studies cited above have not experimented on the combined effect of slope reduction method, jet grouting and drainage system in solving slope failure problems in collapsible clay embankments. Also, none had applied a cost optimization to determine the cost effectiveness of the techniques in single and combined effects.

Thus, this study aims to employ a finite element method model for a soft clay embankment slope adjacent to a roadway by applying slope angle reduction, jet grouting, and a drainage system approach to improve the safety (FOS) of the slope from less than 1 to above 1.5 considering saturated and unsaturated conditions. In addition, the model also presented the best and most optimized construction cost for the reinforcement (slope angle reduction, jet grouting, and drainage system) options. For this analysis, the Finite Element Method (FEM) was chosen over the Limit Equilibrium method (LEM) since the FEM has some advantages, such as freedom of rupture form, non-predetermination of slopes, and locations application of forces between slices, the calculation of deformations and the robustness of the method. The analysis of slopes with FEM is based on two cases: the first, undrained saturated soil (because it is a silty clay in the rainy season) in a static condition, which implied the definition of the water table, and the second, soil in a saturated state.

2. Methodology

2.1. Case study

The studied watershed is mapped and photographed as represented in Figure 1 from Umunwanwa, Umuahia South of Abia State, Nigeria, on 5.4974˚N, 7.4030˚E coordinates. The average height of the studied embankment was about 37 m, adjacent to a roadway infrastructure. The site, which constitutes a very soft clay region, was prepared with four monitoring wells installed at 2.5 m, 7.5 m, 12.5 m, and 21.5 m from the foot of the slope to measure the water level conditions. The hydraulic conditions of the studied slope site are presented in Table 1. The 2.5 m well (W1) showed a water height below the water table (h_w) of 12.4 m with a depth of water table (d_w) of 2.6 m, the 7.5 m well (W2) showed a height below the water table (h_w) of 22.1 m with a depth of water table (d_w) of 2.9 m, the 12.5 m well (W3) showed a height below the water table (h_w) of 33.55 m with a depth of water table (d_w) of 3.45 m and the 21.5 m well (W4) showed a height below the water table (h_w) of 33.9 m with a depth of water table (d_w) of 3.1 m. The observed water table conditions mapped the phreatic line of the slope pore conditions and separated the phreatic zone of the saturated state and the vadose zone of the unsaturated state. The corresponding saturated porewater pressures (Us) and the unsaturated porewater pressures at ground level (Ug) are estimated based on these water and slope height conditions and also tabulated in Table 1. Further, the unsaturated pore pressure values at point Z below ground level (Pu) are also estimated at 1 m, 2 m and 3 m and tabulated in Table 1. Furthermore, the studied watershed soil samples were tested under laboratory conditions for the shear states, unit weight, hydraulic conductivity and seepage conditions, consistency limits, compaction properties and strength properties (CBR and UCS). The results are represented in Table 2. The hydraulic state conditions and the geometry of the studied embankment slope were used in the finite element method (FEM) modeling of the safety conditions of the slope utilizing different Plaxis 2D and soil reinforcement functions.



(a) The mapping of the Umunwanwa, Nigeria case study on 5.4974° N, 7.4030° E coordinates

(b) Environmental destruction site through slope failure due to erosion in Umunwanwa, Abia State, Nigeria

Figure 1. The studied watershed a) map and b) photographs

Table 1. Measured water table (WT) and pore pressure values of the soil profiles

b (m)	h (m)	d_w (m)	h_w (m)	U_s (kN/m^2)	U_g (kN/m^2)	P_u (Z=1m) (kN/m^2)	P_u (Z=2 m) (kN/m^2)	P_u (Z=3 m) (kN/m^2)
2.5	15	2.6	12.4	210.8	-44.2	-15.696	-5.886	-
7.5	25	2.9	22.1	397.8	-52.2	-18.639	-8.829	-
12.5	37	3.45	33.55	536.8	-55.2	-24.035	-14.225	-4.415
21.5	37	3.1	33.9	542.4	-49.6	-20.601	-10.791	-0.981

Table 2. Properties of the soil multilayered profile of the slope at the erosion watershed

Soil Properties	Layer 1 (Lower)	Layer 2 (Middle)	Layer 3 (Upper)
E (kPa)	1370	1520	1600
υ	0.47	0.48	0.49
Φ (degrees)	20	21	23
C (kN/m^2)	15	12	10
γ (kN/m^3)	17	18	16
K (m/s)	10^{-8}	10^{-7}	10^{-6}
P (cm/hr)	0.045	0.055	0.065
SP (kN/m^2)	371.66	263.23	1101.61
Us (kN/m^2)	210.8	397.8	536.8; 542.4
LL (%)	33	29	27
PL (%)	21	19	20
PI (%)	11	10	7
MDD (g/cm^3)	1.02	1.15	1.28
OMC (%)	23	21	17
CBR (%)	6	7	5
UCS (kN/m^2)	13	14	12.3

2.2. FEM/Plaxis 2D Parametric Study

The research program of this research based on evaluating the performance of the three considered stabilizing techniques (reducing the slope, using jet grouting, dewatering) and combination of them, the characteristics of the studied alternative are listed in Table 3. The used methodology to select the optimum stabilizing technique is divided into two phases. The first one is the safety phase, where the factor of safety (FOS) of all alternatives is calculated using the built-in strength reduction technique in Plaxis-2D software. In order to satisfy the safety requirement, a minimum FOS of 1.5 must be achieved. Alternatives with FOS less than 1.5; Alt-2, Alt-3, and Alt-4 were omitted because the three stability alternatives did not meet the requirements for the normal operating conditions of a slope and also both the short-term and long-term stability conditions according to literature e.g., [14-16].

Table 3. Characteristics of the studied alternatives

Alt.	Technique	Slope	Jet grouting	Dewatering
1	Reducing slope	8º	-	-
2	Dewatering	Natural	-	37 m
3	Jet Grouting	Natural	4 rows × 60 m	-
4	Jet grouting + Dewatering	Natural	4 rows × 60 m	37 m
5	Red. slope + Jet grouting	9º	25 rows × 30 m	-
6	Red. slope + Dewatering	15º	-	37 m
7	Red. slope + grouting + Dewatering	17º	15 rows × 30 m	37 m

The second phase is the optimization phase, where the optimum safe alternative was selected. The performance of each safe alternative is evaluated based on cost, constructability, reliability and environmental impact. Figure 2 graphically presents the research methodology. The relative weights of each one of the previous factors are reasonably assumed based on previous studies [28, 29] and considering the current market condition in a developed country such as Nigeria as shown in Table 4. Also, the used unit prices to calculate the cost of each alternative were the average current prices in the Nigerian market as listed in Table 5.

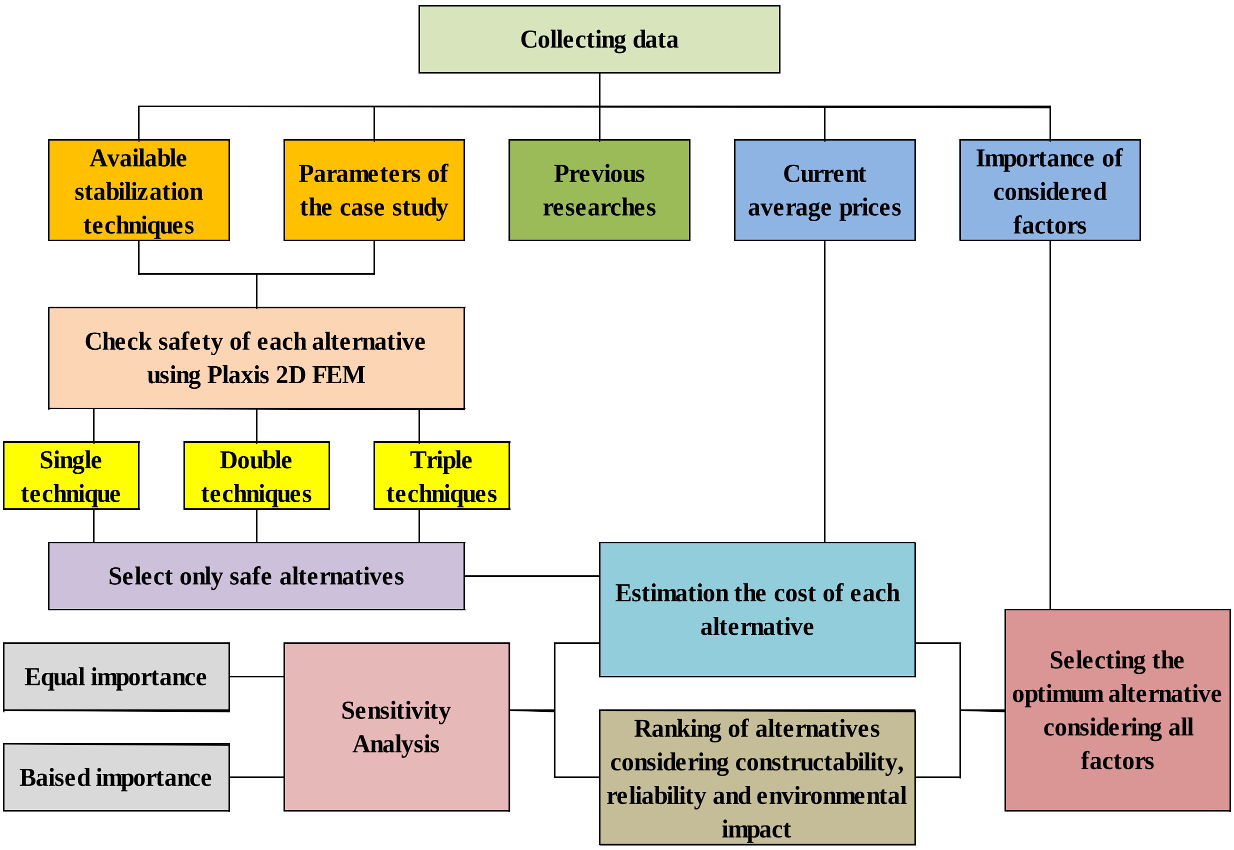


Figure 2. The considered research methodology

Table 4. Relative importance of each considered factor

Factor	Importance (out of 10)	Relative Importance
Cost	10	50%
Constructability	3	15%
Reliability	5	25%
Environmental impact	2	10%
Sum	**20**	**100%**

Table 5. The considered unit prices

Item	Unit	Unit price	Notes
Earth work	(m^3)	5 $	Cutting & transportation
Jet grouting	(m)	10 $	Materials & grouting of 1.0m diameter column
Dewatering	(m^3)	0.30 $	Construction & operation cost for 50 years

All safe alternatives were ranked considering each factor as follows:

The cost of each alternative is calculate based on the considered unit prices and the calculated quantities for each alternative. Constructability means how easy to construct, it includes the required skilled labor, availability of required equipment, site conditions, etc. based on that, reducing the slope got the highest rank (1) because it requires unskilled labor, conventional earthwork equipment [28, 29]. Jet grouting comes next with rank of (2) where it requires unskilled labor and specialized grouting machines. Finally, dewatering comes in the last rank (3) due to the required skilled labor and specialized boring, pumping and piping equipment.

Reliability is the inverse of probability of failure. It means how much trust that the alternative will be fully functional under any conditions [28, 29]. From this point reducing the slope will be the same after construction under any condition, while the jet grout may be slightly affected by the ground water and chemical attack, finally dewatering is the less reliable alternative due to its mechanical parts which need periodic maintenance and replacement besides that, it required a lot of energy to operate the pumps continually which increase its unreliability. Hence the three alternatives have the same ranking as constructability [28, 29]. Finally, the environmental impact was assessed based on used contaminating materials [28, 29]. In this context, reducing the slope has almost no effect on the environment, while jet grouting has very negative impact due to contaminating the soil with grouted materials, and finally dewatering has a slight impact on the planets due to lowering the water level which may compromised by rainfalls. So, the three alternatives may be ranked as (1) for reducing the slope, (2) for dewatering and (3) for jet grouting. For all factors, the factor score is calculated as minimum rank / alternative rank based on the reports of Mahdi et al. [28, 29]. And in case of combination of two or more alternatives, the score is calculated as (minimum rank / sum alternatives rank). Finally, the total score of each alternative in the summation of factor scores multiplied by the factor importance. The alternative with the highest total score is the optimum one.

3. Results and Discussion

3.1. Phase 1: Safety phase theoretical analysis

Seven FEM models were developed using Plaxis-2D software to simulate the behavior of the considered slope after applying each stabilizing alternative. The actual geometrical dimensions were used in all models except the ones with reducing slope technique. The considered material properties and layer thicknesses are the determined values from the site investigation program as shown in Table 6. All models are plane strain using 15-nodes solid elements for both soil mass and grouting. Each model has two stages, the first presents the initial stage in drained condition considering the actual soil shear parameters, while the second is a safety stage which determine the safety factor by gradually reducing the shear parameters of the soil till failure and dividing the actual shear parameters values by those at failure (C-ϕ reduction method). Table 7 shows the characteristics of the studied alternative and the calculated FOS for this alternative, while Figures 3-9 show snapshot of the FEM model of each alternative. As shown in Table 7, the FOS of alternatives number 2, 3 and 4 are less than the minimum requirement (average of 1.50), for the normal operating conditions of a slope and also for both the short-term (1.3 to 1.5) and long-term (1.25 to 2.0) stability conditions according to literature [14-16], hence, they were omitted in further optimization considerations. Accordingly, dewatering (Alt-2), jet grout (Alt-3) and their combination (Alt-4) were omitted. This is because the three stability alternatives did not meet the requirements for the normal operating conditions of a slope and also both the short-term and long-term stability conditions according to literature e.g., [14-16]. Hence, alternatives 1, 5, 6, and 7 were selected having met the safety conditions, which compared sufficiently well with literature e.g., [14-16] for further optimization considerations.

Table 6. Considered material properties

Material	γ ($^{kN}/_{m^3}$)	C ($^{kN}/_{m^2}$)	ϕ (degrees)	E ($^{kN}/_{m^2}$)	υ
Upper layer	16	10	23	1600	0.49
Middle layer	18	12	21	1520	0.48
Lower layer	17	15	20	1370	0.47
Grout	15	510	40	500 000	0.2

Table 7. FOS of each studied alternatives

Alt.	Technique	FOS
1	Reducing slope	1.505
2	Dewatering	0.152
3	Jet Grouting	0.345
4	Jet grouting + Dewatering	0.411
5	Red. slope + Jet grouting	1.510
6	Red. slope + Dewatering	1.520
7	Red. slope + grouting + Dewater.	1.508

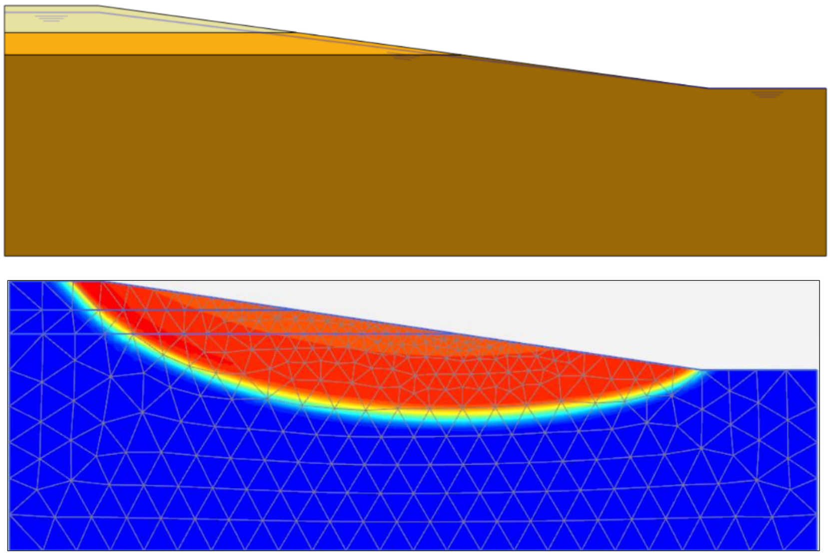


Figure 3. Alt. 1, Reducing slope to 8º; FOS = 1.505

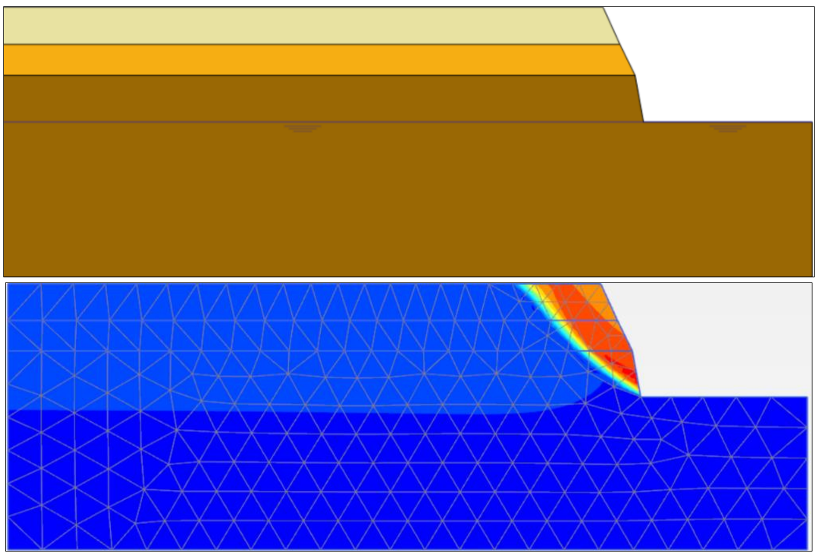


Figure 4. Alt. 2, Dewatering to 37 m; FOS = 0.152

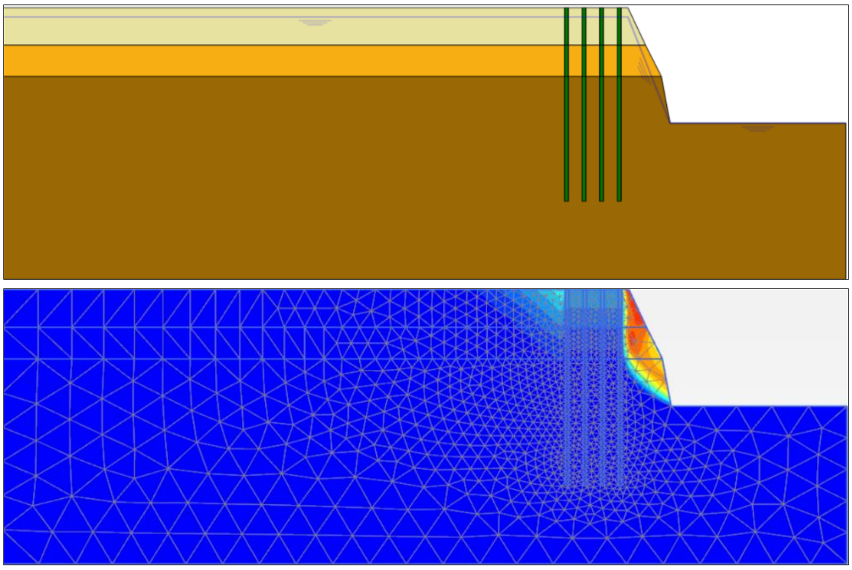


Figure 5. Alt. 3, Jet grouting to 60 m, 4 rows; FOS = 0.354

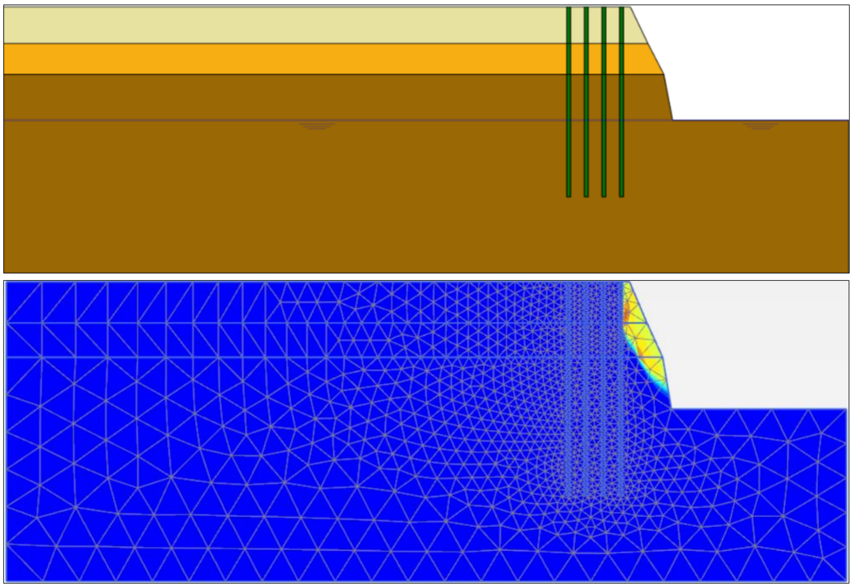


Figure 6. Alt. 4, Jet grouting to 60 m, 4 rows and dewatering to 37 m; FOS = 0.411

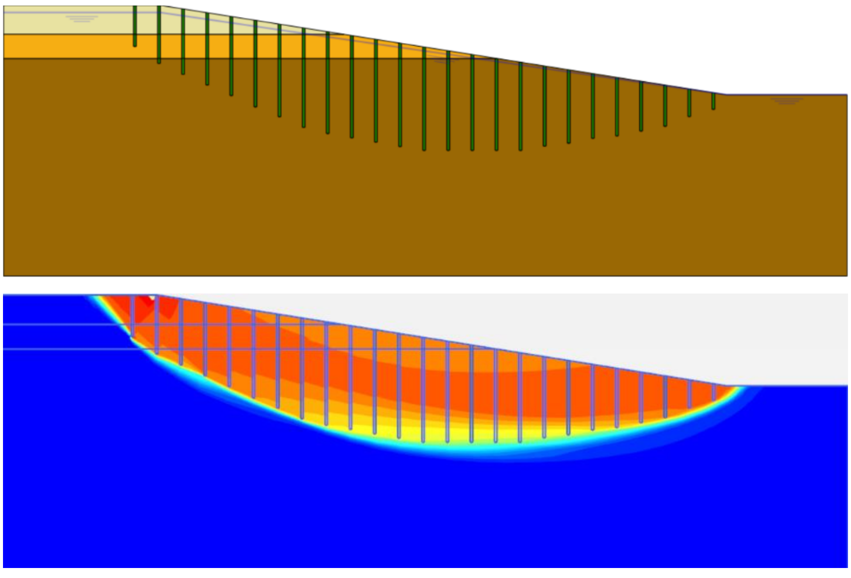
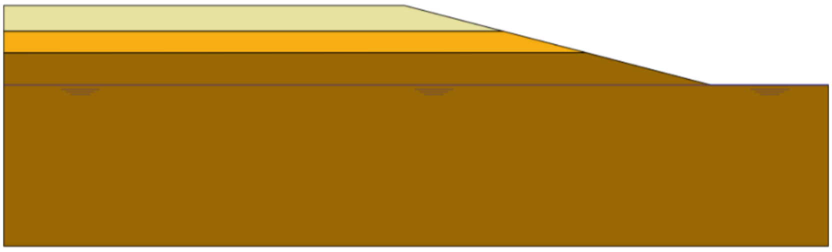


Figure 7. Alt. 5, Jet grouting to average depth 30 m, 25 rows and reduce slope to 9^o, FOS = 1.510



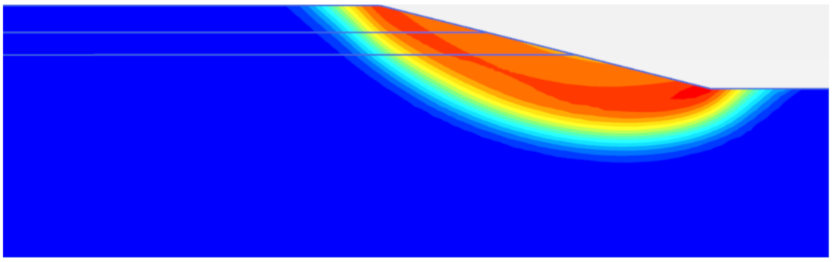
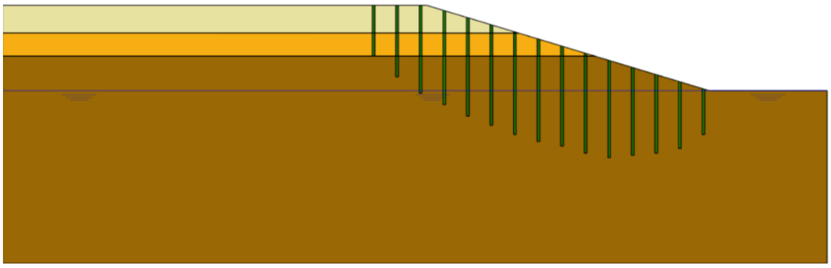


Figure 8. Alt. 6, Dewatering to 37 m and reduce slope to15 º; FOS=1.520



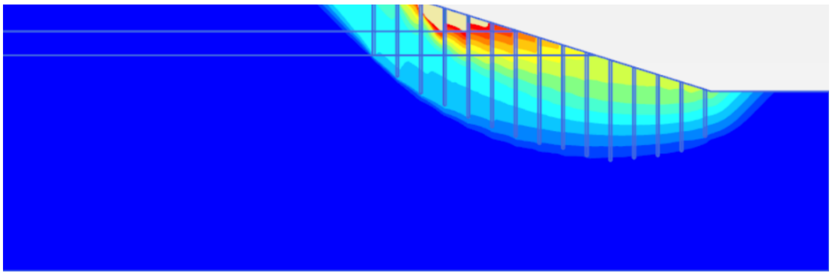


Figure 9. Alt. 7, Dewatering to 37 m, Jet grouting to average depth of 30 m in 15 rows and reduce slope to 17º; FOS=1.508

3.2. Phase 2: Slope Stabilization and Cost Optimization

For each safe alternative, quantities of each item were calculated to estimate the alternative cost as shown in Table 8. Then, the score of each factor was calculated for each alternative as shown in Table 9. Finally, the total score of each calculated was computed as shown in Table 10. As shown in Table 10, Alt-1 (reducing the slope) is the optimum one with total score of 0.785. The next one is Alt-6 (reducing the slope + dewatering) with total score of 0.633. Alt-7 (reducing the slope + dewatering + grouting) comes in the third rank with total score of 0.510, and finally, Alt-5 comes lastly with total score of 0.393, which compares closely with previous studies [14-16, 28, 29].

Table 8. Cost of safe alternatives / m

Alt.	Earthwork (m^3)	Grout (m)	Dewatering (m^3)	Total Cost ($)
1	4715	0	0	23 575
5	4160	750	0	28 300
6	2400	0	4760	13 428
7	2030	450	4080	15 874

Table 9. Factors' scores for safe alternatives

Alt.	Cost	Constructability	Reliability	Environmental impact
1	13428 / 23575 = 0.57	1 / 1 = 1.00	1 / 1 = 1.00	1 / 1 = 1.00
5	13428 / 28300 = 0.47	1 / 3 = 0.33	1 / 3 = 0.33	1 / 4 = 0.25
6	13428 / 13428 = 1.00	1 / 4 = 0.25	1 / 4 = 0.25	1 / 3 = 0.33
7	13428 / 15874 = 0.85	1 / 6 = 0.17	1 / 6 = 0.17	1 / 6 = 0.17

Table 10. Total scores for safe alternatives

Alt.	Total score
1	(0.57x0.5) + (1.00x0.15) + (1.00x0.25) + (1.00x0.10) = 0.785
5	(0.47x0.5) + (0.33x0.15) + (0.33x0.25) + (0.25x0.10) = 0.393
6	(1.00x0.5) + (0.25x0.15) + (0.25x0.25) + (0.33x0.10) = 0.633
7	(0.85x0.5) + (0.17x0.15) + (0.17x0.25) + (0.17x0.10) = 0.510

3.3. Sensitivity Analysis

This section aims to study the effect of changing the factors' relative importance values on the optimum alternative. Five scenarios were tested in this section, the first one, when all factors have the same relative importance of 25%. In the rest of the four scenarios, one factor has a major relative importance of 70%, and the other factors equally share the rest of the 30%. The same calculations shown in Table 10 were applied to figure out the optimum alternative for each scenario. Table 11 summarizes the results of the sensitivity analysis.

Table 11. Results of the sensitivity analysis

Scen. ID	Relative importance				Total score				Opt. Alt.
	Cost	Const.	Reliab.	Env.	Alt-1	Alt-5	Alt-6	Alt-7	
1	0.25	0.25	0.25	0.25	**0.893**	0.345	0.458	0.340	Alt-1
2	**0.70**	0.10	0.10	0.10	0.699	0.420	**0.783**	0.646	Alt-6
3	0.10	**0.70**	0.10	0.10	**0.957**	0.336	0.333	0.238	Alt-1
4	0.10	0.10	**0.70**	0.10	**0.957**	0.336	0.333	0.238	Alt-1
5	0.10	0.10	0.10	**0.70**	**0.957**	0.288	0.381	0.238	Alt-1

4. Conclusions

This research presents a multi-criteria approach to determining the optimum stabilization technique for a soft clay slope. A case study of a 37.0 m height slope located in Umunwanwa, Umuahia, Nigeria, was used to demonstrate the proposed approach. The criteria (factors) considered in this study were cost, constructability, reliability, and environmental impact. Seven alternative techniques were studied, including reducing slope angle, using jet grouting, dewatering, and combinations of two or three of these techniques. The original study was based on reasonably assumed relative importance values for each criterion and used the current prices in the Nigerian market. In addition, a sensitivity analysis was carried out to figure out the effect of changing the assumed relative importance on the selected alternative. The results of this research could be summarized in the following points:

- The results of phase-1; the safety phase showed that not all alternatives satisfy the minimum required safety limits because the existing slope is too steep to achieve the minimum required FOS even after dewatering. On the other hand, grouting equipment can't stand on such a steep slope to construct grouted columns within the slope; hence, the grouted columns were constructed on the flat surface as close as possible to the slope; unfortunately, this location didn't prevent the slope failure.
- In phase-2, which is the optimization phase, a multi-criteria selection procedure was applied to the four safe alternatives (1, 5, 6, and 7) to determine the optimum one. The results of this phase indicated the following: Considering the current market conditions and unit prices in Nigeria and the reduction of slope angle, Alt-1 is the optimal choice, although it is not the cheapest. Using dewatering with a reduction of slope angle, Alt-6 is the cheapest alternative, however it is not the optimum one due to its lack of reliability. Combining jet grout with a reduction in slope angle, Alt-5 is the worst choice. It is the most expansive one despite its negative environmental impact and low constructability rank. Finally, the combination of the three stabilization techniques in Alt-7 reduces the construction cost, but still suffers from a lack of reliability and a negative environmental impact.
- The outcomes of the sensitivity analysis indicated that the relative importance values of constructability, reliability, and environmental impact had a neglected effect on the optimum choice, as the optimum choice still maintained Alt-1, although the relative importance changed between 0.1 and 0.7. On the other hand, the relative importance of the cost had a significant impact on the optimal choice, as it changed from Alt-1 for a relative importance of 0.1 to Alt-6 for a relative importance of 0.7.
- The proposed multi-criteria selecting procedure can be successfully used to determine the optimum stabilizing technique for soft clay slopes considering many different criteria, both quantitative like cost and qualitative like constructability, reliability, and environmental impact.
- The selected choice in the case study is based on the current market condition and unit prices in Nigeria; hence, it must be adopted for other countries or different market conditions.

5. Declarations

5.1. Author Contributions

Conceptualization, K.C.O.; methodology, A.M.E.; formal analysis, J.A.B.; writing—review and editing, K.C.O., A.M.E., H.A.M., and J.A.B.; supervision, H.A.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. Nomenclature

E	Elastic Modulus	υ	Poisson ratio
Φ	Friction angle	C	Cohesion
γ	Unit weight of soil	γ_w	Unit weight of water
K	Hydraulic gradient	P	Permeability
SP	Seepage pressure	U_s	Saturated pore pressure, ($\gamma_{w*}h_w$)
U_g	Unsaturated pore pressure at the ground level, ($-\gamma_{w*}d_w$)	P_u	Unsaturated pore pressure at points, Z below ground level, ($\gamma_w(Z_u - d_w)$)
Z_u	Points below ground level within the vadose zone	b	Width measured from slope foot to borehole
h	Height of borehole from datum	d_w	Depth of water table (WT) within the vadose zone
h_w	Height below the water table (WT) within the phreatic zone	Scen.	Scenario
Const.	Constructability	Reliab.	Reliability
Env.	Environmental impact	Alt.	Alternatives
Opt.	Optimum or Optimal or Optimized	LL	Liquid Limit
PL	Plastic Limit	PI	Plasticity Index
MDD	Maximum Dry Density	OMC	Optimum Moisture Content
CBR	California Bearing Ratio	UCS	Unconfined Compressive Strength

7. References

[1] Onyelowe, K. C., Sujatha, E. R., Aneke, F. I., & Ebid, A. M. (2022). Solving geophysical flow problems in Luxembourg: SPH constitutive review. Cogent Engineering, 9(1). doi:10.1080/23311916.2022.2122158.

[2] Song, L., Yu, X., Xu, B., Pang, R., & Zhang, Z. (2020). 3D slope reliability analysis based on the intelligent response surface methodology. Bulletin of Engineering Geology and the Environment, 80(2), 735–749. doi:10.1007/s10064-020-01940-6.

[3] Onyelowe, K. C., Mojtahedi, F. F., Azizi, S., Mahdi, H. A., Sujatha, E. R., Ebid, A. M., Darzi, A. G., & Aneke, F. I. (2022). Innovative Overview of SWRC Application in Modeling Geotechnical Engineering Problems. Designs, 6(5), 69. doi:10.3390/designs6050069.

[4] Sun, C., Chai, J., Ma, B., Luo, T., Gao, Y., & Qiu, H. (2019). Stability Charts for Pseudostatic Stability Analysis of 3D Homogeneous Soil Slopes Using Strength Reduction Finite Element Method. Advances in Civil Engineering, 2019. doi:10.1155/2019/6025698.

[5] Sui, Z. F., Yuan, W., Yi, W., & Yang, W. (2021). Stability analysis of ecological slopes based on a 3D finite element model. Advances in Materials Science and Engineering, 2021. doi:10.1155/2021/3785943.

[6] Cala, M., & Flisiak, J. (2020). Slope stability analysis with FLAC and limit equilibrium methods. FLAC and Numerical Modeling in Geomechanics, 111–114. doi:10.1201/9781003077527-18.

[7] Johari, A., & Gholampour, A. (2018). A practical approach for reliability analysis of unsaturated slope by conditional random finite element method. Computers and Geotechnics, 102, 79–91. doi:10.1016/j.compgeo.2018.06.004.

[8] Johari, A., & Talebi, A. (2019). Stochastic Analysis of Rainfall-Induced Slope Instability and Steady-State Seepage Flow Using Random Finite-Element Method. International Journal of Geomechanics, 19(8). doi:10.1061/(asce)gm.1943-5622.0001455.

[9] Kamchoom, V., & Leung, A. K. (2018). Hydro-mechanical reinforcements of live poles to slope stability. Soils and Foundations, 58(6), 1423–1434. doi:10.1016/j.sandf.2018.08.003.

[10] Wang, L., Wu, C., Gu, X., Liu, H., Mei, G., & Zhang, W. (2020). Probabilistic stability analysis of earth dam slope under transient seepage using multivariate adaptive regression splines. Bulletin of Engineering Geology and the Environment, 79(6), 2763–2775. doi:10.1007/s10064-020-01730-0.

[11] Suhatril, M., Osman, N., Azura Sari, P., Shariati, M., & Marto, A. (2019). Significance of Surface Eco-Protection Techniques for Cohesive Soils Slope in Selangor, Malaysia. Geotechnical and Geological Engineering, 37(3), 2007–2014. doi:10.1007/s10706-018-0740-3.

[12] Nguyen, T. S., Likitlersuang, S., & Jotisankasa, A. (2020). Stability analysis of vegetated residual soil slope in Thailand under rainfall conditions. Environmental Geotechnics, 7(5), 338–349. doi:10.1680/jenge.17.00025.

[13] Zhou, T., Zhang, L., Cheng, J., Wang, J., Zhang, X., & Li, M. (2022). Assessing the rainfall infiltration on FOS via a new NSRM for a case study at high rock slope stability. Scientific Reports, 12(1), 11917. doi:10.1038/s41598-022-15350-z.

[14] Chen, X., Zhang, L., Chen, L., Li, X., & Liu, D. (2019). Slope stability analysis based on the Coupled Eulerian-Lagrangian finite element method. Bulletin of Engineering Geology and the Environment, 78(6), 4451–4463. doi:10.1007/s10064-018-1413-4.

[15] Lin, S., Zheng, H., Han, C., Han, B., & Li, W. (2021). Evaluation and prediction of slope stability using machine learning approaches. Frontiers of Structural and Civil Engineering, 15(4), 821–833. doi:10.1007/s11709-021-0742-8.

[16] Wang, Z., Liu, B., Han, Y., Wang, J., Yao, B., & Zhang, P. (2020). Stability of inner dump slope and analytical solution based on circular failure: Illustrated with a case study. Computers and Geotechnics, 117. doi:10.1016/j.compgeo.2019.103241.

[17] Dar, L. A., & Shah, M. Y. (2021). Deep-Seated Slope Stability Analysis and Development of Simplistic FOS Evaluation Models for Stone Column-Supported Embankments. Transportation Infrastructure Geotechnology, 8(2), 203–227. doi:10.1007/s40515-020-00134-7.

[18] Reichenbach, P., Rossi, M., Malamud, B. D., Mihir, M., & Guzzetti, F. (2018). A review of statistically-based landslide susceptibility models. Earth-Science Reviews, 180, 60–91. doi:10.1016/j.earscirev.2018.03.001.

[19] Liu, X., & Wang, Y. (2021). Probabilistic simulation of entire process of rainfall-induced landslides using random finite element and material point methods with hydro-mechanical coupling. Computers and Geotechnics, 132. doi:10.1016/j.compgeo.2020.103989.

[20] Xu, J., Zhao, X., Li, P., & Zhang, M. (2021). Stability of a 3D unsaturated vertical cut slope subjected to variable rainfall infiltration. Computers and Geotechnics, 134. doi:10.1016/j.compgeo.2021.104110.

[21] Sun, D. mei, Li, X. min, Feng, P., & Zang, Y. ge. (2016). Stability analysis of unsaturated soil slope during rainfall infiltration using coupled liquid-gas-solid three-phase model. Water Science and Engineering, 9(3), 183–194. doi:10.1016/j.wse.2016.06.008.

[22] Jimenez Fernandez, J. C., Castanon-Jano, L., Gaute Alonso, A., Blanco-Fernandez, E., Gonzalez Fernandez, J. C., Centeno Gonzalez, V., Castro-Fresno, D., & Garcia-Sanchez, D. (2022). 3D numerical simulation of slope-flexible system interaction using a mixed FEM-SPH model. Ain Shams Engineering Journal, 13(2). doi:10.1016/j.asej.2021.09.019.

[23] Boldrin, D., Leung, A. K., & Bengough, A. G. (2017). Correlating hydrologic reinforcement of vegetated soil with plant traits during establishment of woody perennials. Plant and Soil, 416(1–2), 437–451. doi:10.1007/s11104-017-3211-3.

[24] Xiang, G., Wang, C. L., Bai, M. Z., Xu, Z. Y., & Yan, J. J. (2013). Stability analysis of slope under the condition of rainfall infiltration. Applied Mechanics and Materials, 405–408(9), 256–261. doi:10.4028/www.scientific.net/AMM.405-408.256.

[25] Shaghaghi, T., Ghadrdan, M., & Tolooiyan, A. (2020). Design and Optimisation of Drainage Systems for Fractured Slopes Using the XFEM and FEM. Simulation Modelling Practice and Theory, 103. doi:10.1016/j.simpat.2020.102110.

[26] Egbueri, J. C., Igwe, O., & Unigwe, C. O. (2021). Gully slope distribution characteristics and stability analysis for soil erosion risk ranking in parts of southeastern Nigeria: a case study. Environmental Earth Sciences, 80(7). doi:10.1007/s12665-021-09605-7.

[27] Geitner, C., Mayr, A., Rutzinger, M., Löbmann, M. T., Tonin, R., Zerbe, S., Wellstein, C., Markart, G., & Kohl, B. (2021). Shallow erosion on grassland slopes in the European Alps – Geomorphological classification, spatio-temporal analysis, and understanding snow and vegetation impacts. Geomorphology, 373. doi:10.1016/j.geomorph.2020.107446.

[28] Mahdi, I. M., Ebid, A. M., & Khallaf, R. (2020). Decision support system for optimum soft clay improvement technique for highway construction projects. Ain Shams Engineering Journal, 11(1), 213–223. doi:10.1016/j.asej.2019.08.007.

[29] Mahdi, I. M., Arafat, H., Ebid, A. M., & El-Kadi, A. F. (2021). Decision model to identify the optimum retaining wall type for restricted highway projects sites. International Journal of Construction Management, 1–8. doi:10.1080/15623599.2021.1974151.