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Analysis by Numerical Simulation of the Stabilization of Slope Sites under Building Loads

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Abstract

This study evaluates the effects of the initial situation of the site (slope and quality of the soil with its resistance characteristics), building loads, support and drainage/non-drainage on the safety and stability of sloping sites. The objective is to contribute to the stabilization of sloping sites under building loads. Considering a sloping site under building loads in the city of Bujumbura in Burundi facing the problem of instability, an experimental study of the site's soils is first carried out in the laboratory. Secondly, an analysis by numerical simulation of stability is carried out based on 3 main simulation cases: By first considering an initial situation (unloaded), then a loaded situation without support and a loaded situation with support. The calculation is carried out in a drained state and in an undrained state, with a water table blocked at depth to simulate the reality on the ground. Three buildings of different levels are designed according to the existing buildings and their loads are determined for the loaded case simulations. The results of the analysis thus make it possible to assess the effect on safety and stability of: 1) the slope of the unloaded site and the quality of the soil with its resistance characteristics, 2) the loads of the buildings or their intensive increase, 3) the drained or undrained state of the soil on the site, 4) the support or non-support of the unloaded or loaded, drained or undrained sloping site.

Keywords

Numerical Simulation, Stabilization, Sites on Loaded Slopes, Bujumbura

1. Introduction

Construction on sloping sites is a common practice taking into account the topographical conditions of the environment or, as pointed out by Cuervo Y. [1] or Antoine P. *et al.* [2], taking into account the constant demographic development of cities which favors the increasing concentration of people in mountainous regions.

This is the case of Bujumbura, a city overlooked by mountains along its eastern part and with a population growth rate of 4.02%; *i.e.* a population ranging from 7,862,226 to 13,379,000 inhabitants between 2007 and 2024 [3].

This practice of building on sloping sites generally gives a fairly pleasant architectural view but at the same time presents a disadvantage if particular attention is not paid to it because it can be the basis of the risks of land movements (slides, landslides, creep, etc.) and collapse or destruction of structures. Indeed, sloping ground can be naturally stable but a disturbance of its structure, that is to say an increase in stresses and a modification of its mechanical characteristics (loss of resistance by rearrangement) or hydraulic (appearance of a flow: rainwater, melting snow, runoff water, etc.; rapid emptying of an earth dike) can lead to its instability [4]-[6].

Thus slopes have always been a subject of discussion [7]-[9], their stability being of major importance, since their collapse can cause the loss of inestimable and precious human lives.

In Bujumbura, this problem has become a common reality. Data received at the General Directorate of Civil Protection and Disaster Management indicate that in the space of less than 5 years (between 2019 and 2024), six cases of sloping sites under load from building constructions occurred where ground movements and dozens of building collapses caused material and human losses. These phenomena are often observed during the rainy season, and the questions we ask ourselves are, among others: *Are these phenomena caused by rain? or by construction loads and rain is only a trigger? Or are these sites unsuitable for construction? or what can be done to improve the stabilization of these sites?*

As Coquillay S. points out [10], one of the objectives of geotechnical research is to improve the prediction of movements induced in a soil mass by the loadings it undergoes, particularly during the construction of a book.

It is with this in mind that this study is carried out on a sloping site under building construction loads in the Gasekebuye district in the city of Bujumbura where these phenomena occurred. This complements other studies carried out on the same site, in this case, that of Gerard P. *et al.* aimed at understanding the effects of infiltration and evaporation on the stability of slopes [11].

The approach pursued herein consists of carrying out, on the one hand, geotechnical investigations in order to identify the type of soil on the site and to study its mechanical parameters and on the other hand, with the results of geotechnical studies in the laboratory as well as the topographical data of the site, carry out a numerical analysis with a calculation code based on the finite element method, with the aim of evaluating according to the simulation cases adopted, the variation of the safety coefficient (factor of security) of the site, the deformations of the soil and the effective stresses induced in the soil.

When we submit the soil, like any other material in general, to stress, deformations occur. These formations of soil will act on the structures and can cause disorders jeopardizing the proper use, or even the safety, of the structures [12]. Calculating the state of stress in the soil under the action of the self-weight or the loads transmitted by the foundations requires the use of a behavioral law (model). There are several behavioral models to represent soils [10] [13] [14] and their understanding is necessary for adequate modeling of geotechnical problems. Thus, this allows us to choose a model to implement in the calculation code, in order to significantly improve the results of this study. The behavioral model retained is the Mohr-Coulomb elastoplastic model.

The stability analysis of a slope carried out by the limit equilibrium methods of the slices or the sliding block makes it possible to evaluate the Factor of security [6] [15]. This latter is chosen by the engineer between several definitions and can be a ratio of forces, moments, quantities in relation to a limiting quantity [16] and its expression depends on the cases of rupture [17] [18].

The calculation methods which make it possible to evaluate the displacements, not only of the structure studied, but also of the terrain and the structures located nearby, are not numerous: this is one of the advantages of the finite element method., which allows, a priori, to deal with almost any configurations (in terms of geometry and construction phasing) and to calculate the displacements of the entire domain taken into account in the discretization [10] [19].

In this perspective, researchers, who want to evaluate the stability of slopes and embankments, have used the finite element method and obtained interesting results [20] [21].

The finite element code that we used is the Plaxis code (2D-version 8.6) with which much of the work was carried out, notably that of Mats Kahlström M. [22], Sellami S. *et al.* [23], Adel L. [24], Terrasol [25], etc.

2. Methodology

To achieve the objective assigned to this study, the methodology pursued is an experimental approach followed by an analysis as described below:

Initially, after reviewing the literature, an experimental study is carried out in the laboratory with the aim of identifying the type of soil in the study area, studying its mechanical parameters as well as determining the necessary parameters to be introduced into the calculation code during modeling. Secondly, an analysis by numerical simulation of stability is carried out based on 3 main simulation cases:

- Case A: Initial situation (unloaded and unsupported).
- Case B: Loaded situation without support.
- Case C: Loaded situation with support.

Knowing that pore pressures significantly influence the response of the soil, each of these case scenarios is carried out in the state where the soil is drained and then in the state where it is undrained in order to assess the contribution of water on safety and stability of the site. The water table being blocked at depth to simulate the reality on the site.

In drained behavior, no excessive pore pressure is generated. This is the case for dry soils or for simulations of long-term soil behavior. The undrained behavior, for its part, is used for a complete development of excessive pore pressures. Pore water flow can sometimes be neglected due to low permeability and/or high loading rate.

Three buildings of different levels are designed in accordance with the existing buildings on the ground in order to calculate their loads which must be introduced into the calculation code for the simulation of the last two scenario cases.

Finally, a presentation and discussion of the results are carried out last before the conclusion.

Model Description

As its name suggests, the Plaxis 2D software is software that allows users, particularly researchers, to carry out 2D studies. This is for example the case for the research work of the authors indicated above who used it in their studies. In order to allow us to study the nature of slope failures, soils, or building interactions, the 2D model used in this study was carried out following section C1 - C2 (**Figure 1** and **Figure 2**) since it crosses the location where the failures and collapse of buildings occurred in our study area.

Figure 1. Materialization of buildings and cutting plan for 2D modeling.

The numerical model is therefore chosen in accordance with the ruptures observed on the ground. Therefore, the location of the buildings (B1, B2, B3) in the model and the distances separating them are carried out in accordance with the real situation on the ground (**Figure 2**), that is to say at the place where the ruptures accompanied by the collapse of the buildings occurred. The distances between the buildings are 25 m between building B1 and building B2 and 15 m between building B2 and building B3.

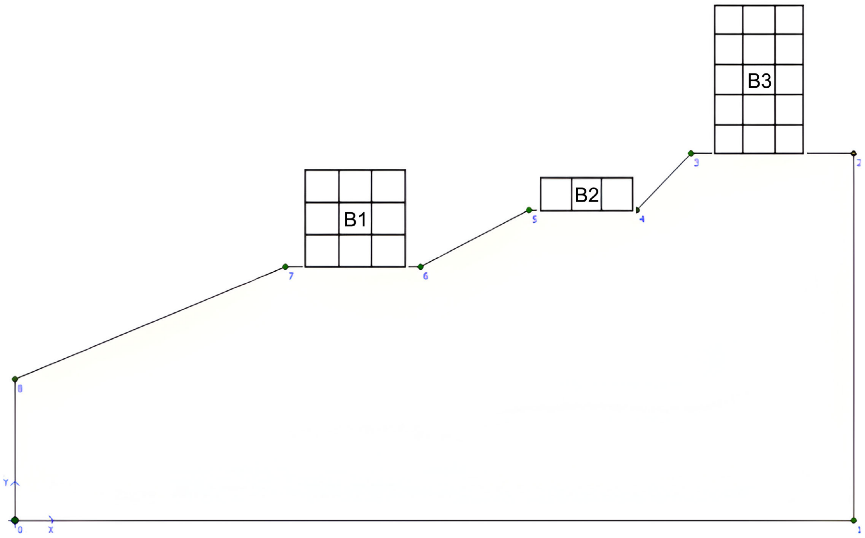
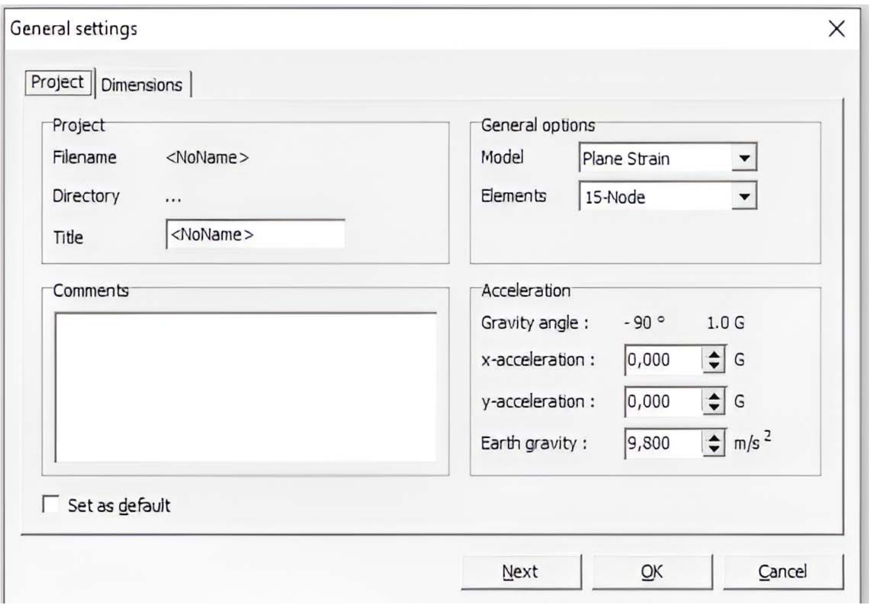


Figure 2. Land section plan and location of buildings in the model: loaded situation.

The 3 main cases of scenarios retained and considered in the Plaxis 2D software are carried out over a distance of 130 m. The height difference between the lowest and highest points of the area considered in the modeling is 40 m.

The planar type model and the 15-node triangular element type with fine mesh were adopted in the modeling and calculation (**Figure 3**).


General settings

Project | Dimensions

Project
Filename <NoName>
Directory ...
Title <NoName>

Comments

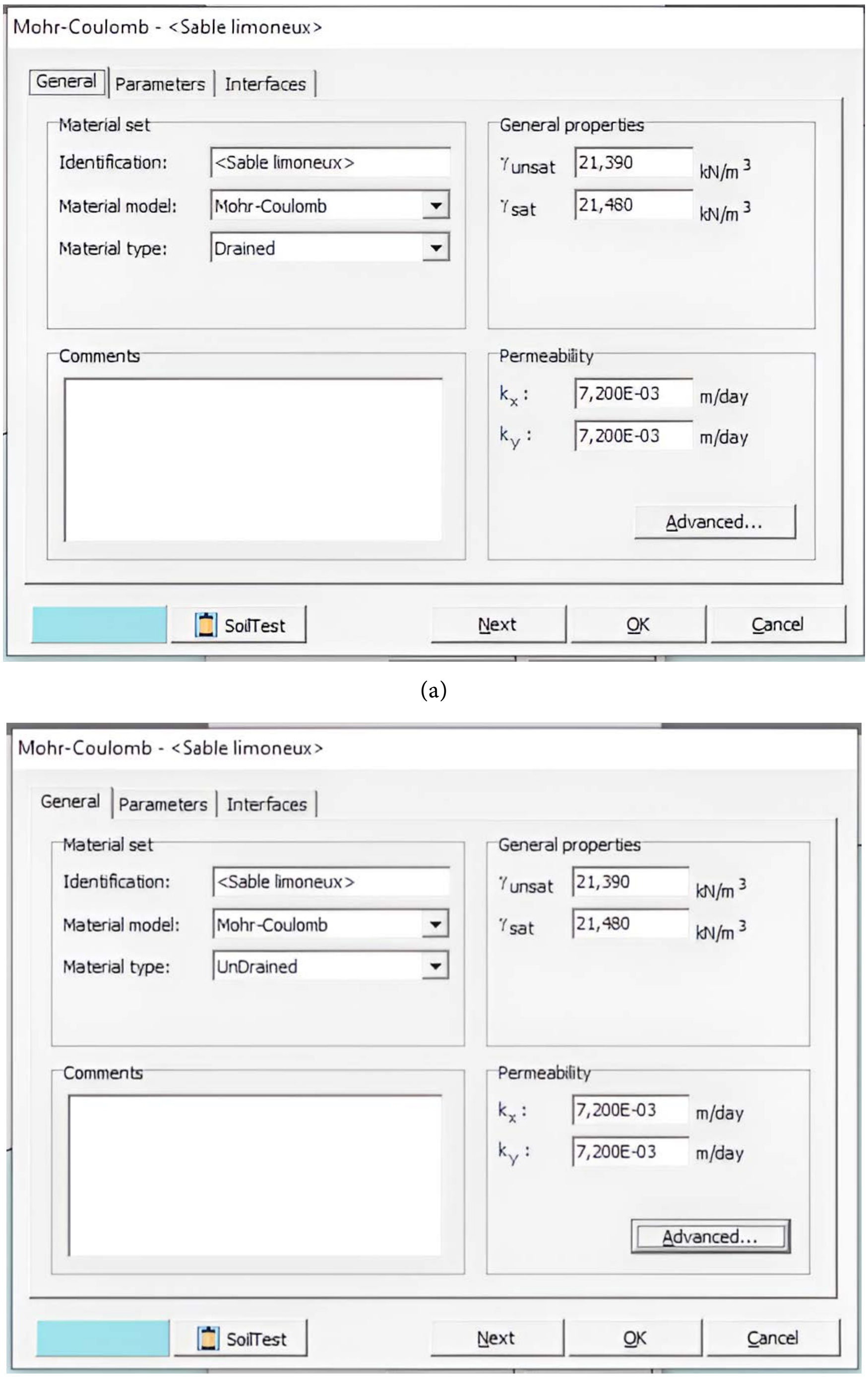
General options
Model: Plane Strain
Elements: 15-Node

Acceleration
Gravity angle : - 90 ° 1.0 G
x-acceleration : 0,000 G
y-acceleration : 0,000 G
Earth gravity : 9,800 m/s ^{2}

☐ Set as default

Figure 3. Window of general settings.

Knowing that pore pressures significantly influence the response of the soil, each of these case scenarios is carried out in the state where the soil is drained (**Figure 4(a)**) and then in the state where it is undrained (**Figure 4(b)**) in order to assess the contribution of water on safety and stability of the site. The water table is blocked at depth to simulate the reality on the site. In drained behavior, no excessive pore pressure is generated. This is the case for dry soils or for simulations of long-term soil behavior. The undrained behavior, for its part, is used for the complete development of excessive pore pressures. Pore water flow can sometimes be neglected due to low permeability and/or high loading rate.



Mohr-Coulomb - <Sable limoneux>

Material set
Identification: <Sable limoneux>
Material model: Mohr-Coulomb
Material type: Drained

General properties
γ_{unsat} 21,390 kN/m^3
γ_{sat} 21,480 kN/m^3

Permeability
k_x : 7,200E-03 m/day
k_y : 7,200E-03 m/day

(a)

Mohr-Coulomb - <Sable limoneux>

Material set
Identification: <Sable limoneux>
Material model: Mohr-Coulomb
Material type: UnDrained

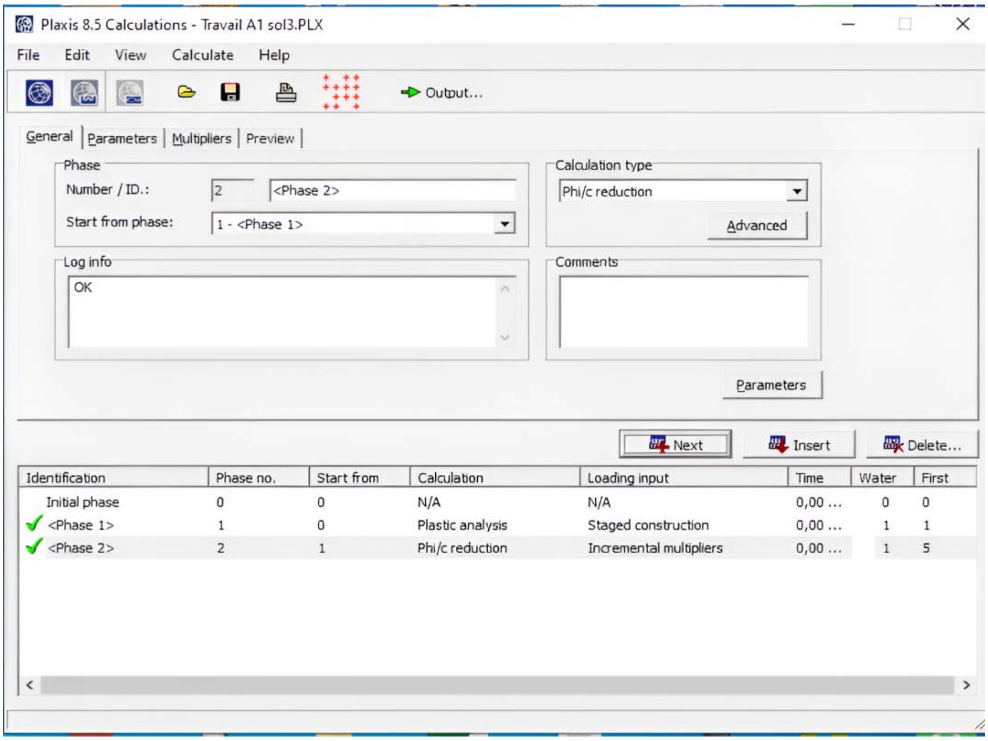
General properties
γ_{unsat} 21,390 kN/m^3
γ_{sat} 21,480 kN/m^3

Permeability
k_x : 7,200E-03 m/day
k_y : 7,200E-03 m/day

(b)

Figure 4. Configuring drained state (a) and undrained state (b).

Two calculation phases are carried out for each simulation case (**Figure 5**).



Phase
Number / ID.: 2 <Phase 2>
Start from phase: 1 - <Phase 1>

Calculation type: Phi/c reduction

Log info: OK

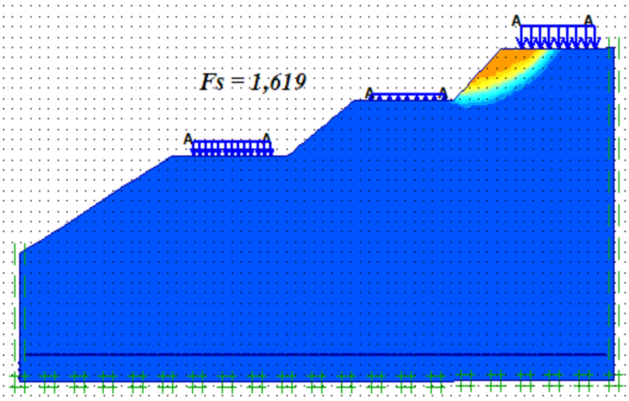
Identification	Phase no.	Start from	Calculation	Loading input	Time	Water	First
Initial phase	0	0	N/A	N/A	0,00 ...	0	0
✓ <Phase 1>	1	0	Plastic analysis	Staged construction	0,00 ...	1	1
✓ <Phase 2>	2	1	Phi/c reduction	Incremental multipliers	0,00 ...	1	5

Figure 5. Calculation phases.

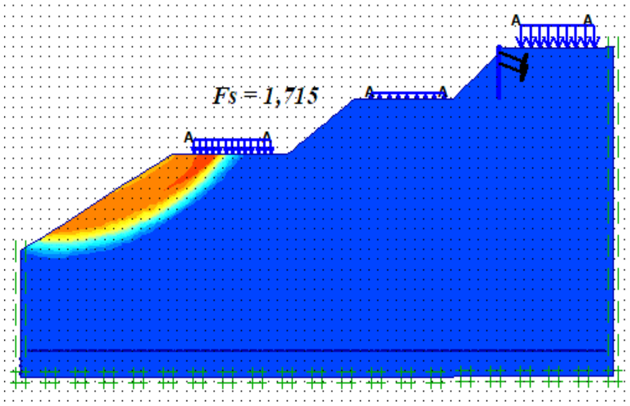
- The plastic analysis phase for the analysis of total deformations and effective stresses;
- The Phi-c reduction analysis phase for calculating the safety coefficient.

The designed retaining wall is placed at the most stressed location to maximize stability, *i.e.* between buildings B2 - B3 (**Figure 6** and **Figure 7**). The anchoring elements that reinforce it are chosen according to the software proposal [26]. Plaxis provides the possibility to model interfaces between materials with specific geomechanical properties. These are used for simulations of the 3rd $^{\text{case}}$ (between retaining wall and soil).

The water table level is considered to be at great depth (20 m from the base of the area) since we did not encounter it during field surveys.

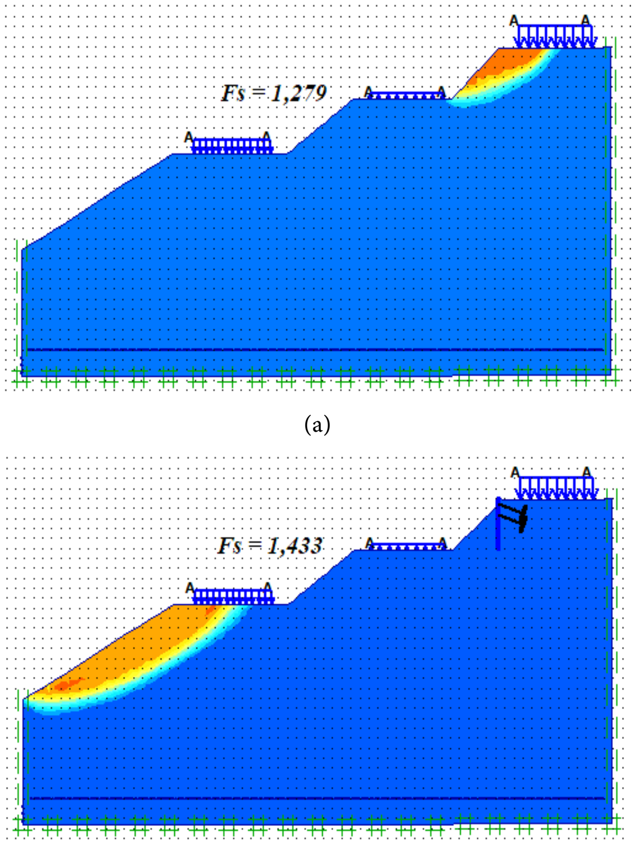


(a)



(b)

Figure 6. Factor of security F_s in a drained situation without support (a) and with support (b).



(a)

(b)

Figure 7. Factor of security F_s in an undrained situation without support (a) and with support (b).

3. Material Properties, Loads and Characteristics of Buildings

3.1. Soil Properties

A geotechnical testing program was developed in order to identify the type of soil in the area studied, determine its mechanical parameters and all other parameters necessary to introduce into the calculation code for modeling.

This geotechnical campaign mainly consisted of carrying out:

- Tests for the physical properties of the soil (volume weight, water content, etc.);
- Soil identification tests (particle size analysis and Atterberg limits);
- Oedometric tests;
- Straight shear tests.

The soil identified is a sandy loamy soil. The study of consolidation showed that the soil of the study area is a soil likely to develop large deformations for the depth reached by 3 m, since any overload can increase the effective stress to a level that the soil has never reached.

Table 1 below gives a summary of the results of the tests carried out which constitute input parameters in the calculation code for the modeling.

Table 1. Soil properties.

Parameters	Symbol	Value	Unit
Behavior model	Mohr-Coulomb (elasto-plastic model)		
Soil state	Drained/Undrained		
Wet density	γ_h	21.39	kN/m^3
Saturated density	γ_{sat}	21.48	kN/m^3
Vertical permeability	Ky	0.0072	m/jour
Horizontal permeability	Kx	0.0072	m/jour
Young's modulus	E_{ref}	11023.67	kN/m^2
Poisson Coefficient	γ	0.35	-
Cohesion	C	22.29	kN/m^2
Internal friction angle	Φ	29.63	°
Dilatancy angle	ψ	0.00	°

3.2. Reinforced Concrete Properties

For the reinforced concrete elements, properties in Table 2 below were considered.

Table 2. Reinforced concrete properties

Parameters	Symbol	Value	Unit
Density Weight	γ	25.00	kN/m^3
Young's modulus	E	31,000.00	MN/m^2
Poisson Coefficient	γ	0.25	-

3.3. Properties Considered for the Retaining Wall and Anchoring

Table 3 below gives the retaining wall and anchor properties considered.

Table 3. Retaining wall and anchor properties.

Retaining wall			
Parameters	Symbol	Value	Unit
Behavior model	Elastic		
State of concrete	Non porous		
Axial rigidity	EA	3.10E+07	kN/m
Flexural rigidity	EI	2.58E+06	kNm^2/m
Equivalent thickness	D	1.00	m
Weight	W	25.00	kN/m/m
Anchoring			
Axial rigidity	EA	2.00E+06	kN
Spacing	Ls	5.00E+00	m

3.4. Loads and Characteristics of Buildings

The 3 designed buildings rest on general raft foundations. Their characteristics are given in Table 4

Table 4. Loads and characteristics of buildings.

Dimensions in plan	Length	15.00 m
	Width	15.00 m
Height between floors	3.50 m	
Foundation type	General foundation of A = 15.30 m ×15.30 m	
Loads transmitted to the ground (including foundation load)		
Building	Floor	Load **q** (kN/m^2)
B1	Ground floor +2	**62.65**
B2	Ground floor +0	**25.60**
B3	Ground floor +4	**98.08**

The calculation of loads is carried out according to the Eurocode standard.

4. Presentation, Discussion, and Implication of Results

The results presented in this point mainly concern the analysis of slope stability by numerical simulation. Those of the experimental study of soils have already been presented in point 3.a) above.

4.1. Presentation of Results

The simulation results obtained are summarized in Table 5 below while Figures 8-13 presented in point b show their effect on stability (variation and decrease/increase) depending on the simulation cases. These results give, depending on the simulation cases adopted, the variation in the safety coefficient (factor of security) of the site, the total deformations and the effective stresses induced in the ground.

Table 5. Summary simulation results.

	Case A: Initial situation		Case B: Loaded situation without support		Case C: Loaded situation with support	
	Drained	*Undrained*	*Drained*	*Undrained*	*Drained*	*Undrained*
F_s [-]	1.937	1.666	1.619	1.279	1.715	1.433
ε_{tot} (%)	5.35	7.49	10.15	15.64	11.86	14.8
σ_{eff} (kN/m^2)	1280	1340	1310	1340	1330	1340

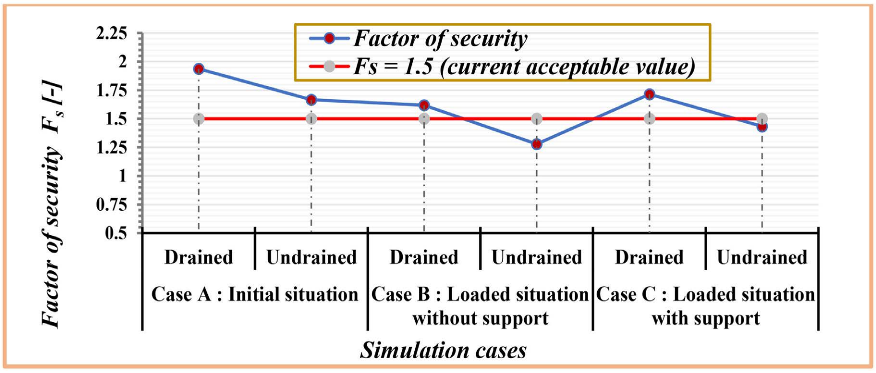


Figure 8. Variation of the factor of security at stability F_s depending on the simulation cases compared with $F_s = 1.5$.

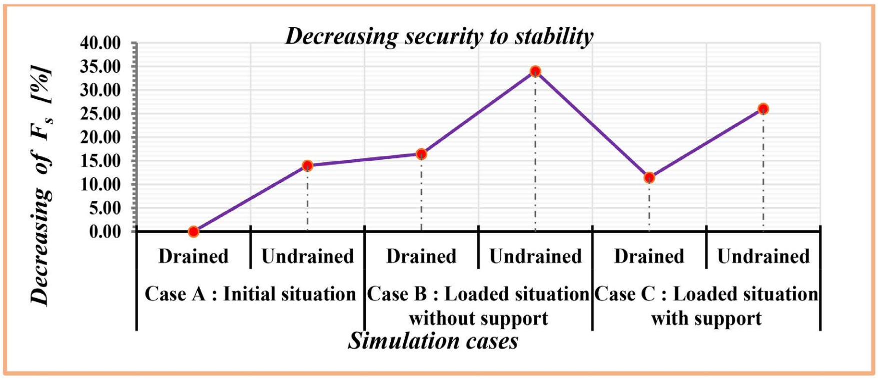


Figure 9. Reduction of the factor of security at stability in (%) depending on the simulation cases.

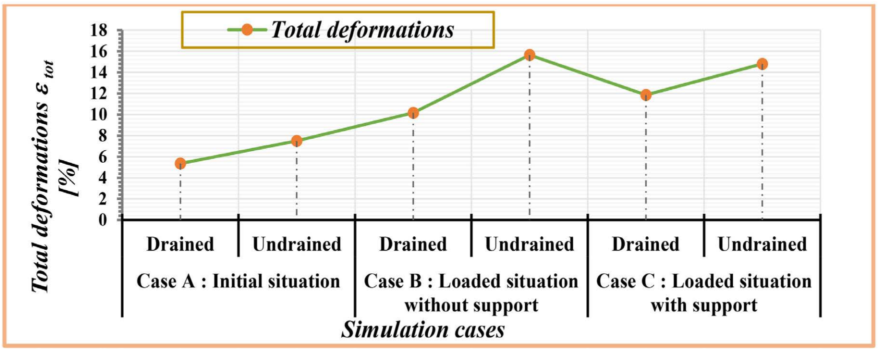


Figure 10. Variation of totatal deformations depending on simulation cases.

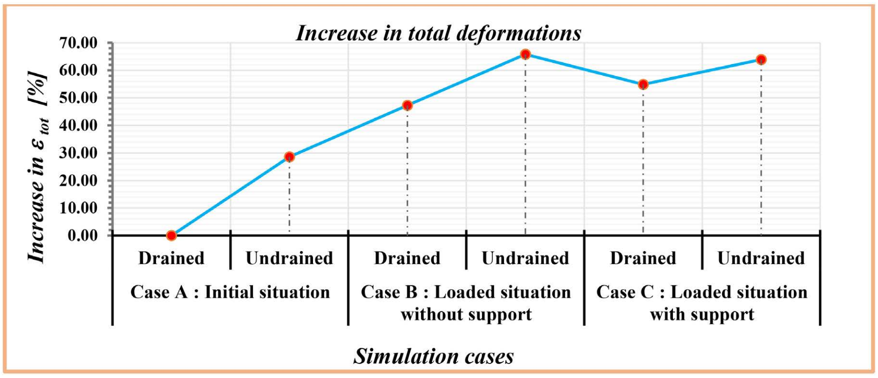


Figure 11. Increase in total deformations in (%) depending on the simulation cases.

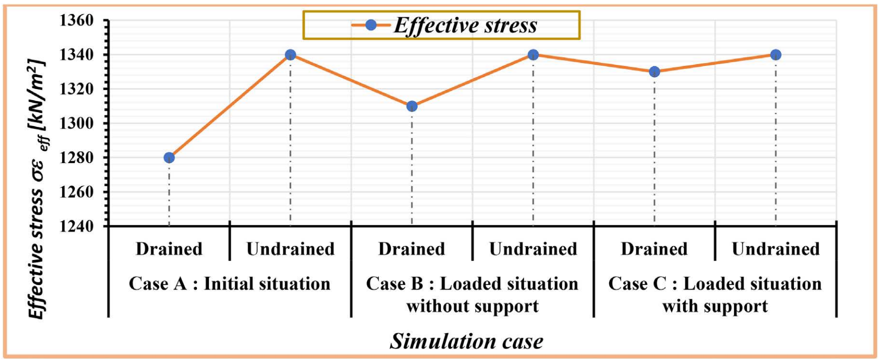


Figure 12. Effective stresses depending on the simulation cases.

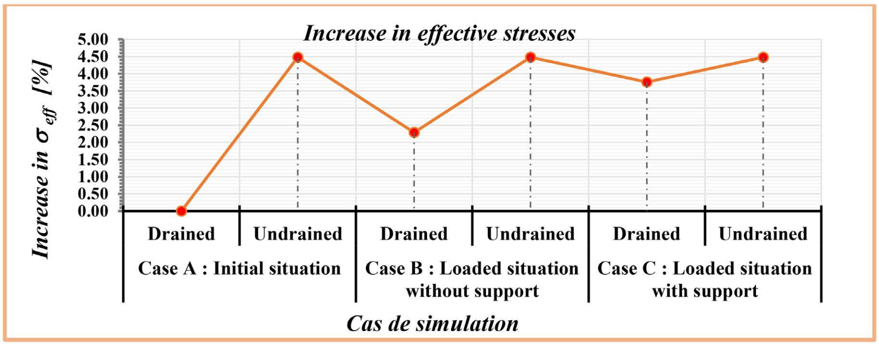


Figure 13. Increase in effective stresses in (%) depending on the simulation cases.

4.2. Discussion of Results

When we submit the soil, like any other material in general, to stress, deformations occur. These deformations will act on the structures and can cause disorders jeopardizing the proper use, or even the safety, of the structures. As we will see in the following discussion, these deformations will also impact stability in the case of sloping sites.

4.2.1. Factor of Security (F_S)

Figure 8 and Figure 9 respectively show the variation of Factor of security F_s to the stability compared with $F_s = 1.5$: acceptable current value [6] and its reduction in (%) depending on the simulation cases carried out.

From these two figures (**Figure 8** to **Figure 9**), we draw the following observations:

→ The maximum security value found is 1.937. It is found at the initial situation in the drained state. For such a situation, the value found is also smaller. This is certainly due on the one hand to a relatively high slope (30.8%) of the study area classified as steep [27]; on the other hand to the quality of the nature of the soil with low resistance characteristics (c = 22.29 kN/m^2 and φ = 29.63˚).

→ As can be noted, non-drainage and construction loads have a great influence on the variation from safety to stability. Compared to the security of the initial situation in the drained state (Case A drained), the variation in security at stability is decreasing depending on the simulation cases carried out. It decreases by 13.99% for the initial undrained situation (Case A undrained), by 16.42% for the loaded drained and unsupported situation (Case B drained), by 33.97% for the loaded undrained situation and unsupported (Case B undrained), 11.46% for the loaded, drained and supported situation (Case C drained) and 26.02% for the loaded undrained and supported situation (Case C undrained). We also see the influence of the retaining wall. In fact, the reduction in safety is minimal when there is a retaining wall.

→ The most unfavorable situation, which even gives security below the acceptable security, is the loaded, undrained and unsupported situation (Case B undrained) for which F_s = 1.279.

4.2.2. Total Deformations (ε_{tot})

Figure 10 to **Figure 11** respectively show the variation in total deformations and their increase in (%) depending on the simulation cases carried out.

These two figures (**Figure 10** to **Figure 11**) also allow us to draw the following observations:

→ Unlike the safety coefficient, the variation in total deformations depending on the simulation cases is increasing. Compared to the total deformations of the initial drained situation (Case A drained), the increase in total deformations depending on the simulation cases carried out is 28.57% for the initial non-drained situation (Case A undrained), 47.29% for the loaded, drained and unsupported situation (Case B drained), 65.79% for the loaded, undrained and unsupported situation (Case B undrained), 54.89% for the loaded, drained and unsupported situation sustained (Case C drained) and 63.85% for the loaded, undrained and sustained situation (Case C undrained). As can be seen, the retaining wall contributes to the increase in deformations by comparing the unsupported and supported drained loaded situations (Case B drained and Case C drained).

→ As for the safety coefficient, the most unfavorable situation, which gives large deformations, is always the loaded, undrained and unsupported situation (Case B undrained) with ε_{tot} max = 15.65%.

4.2.3. Effective Stresses (σ_{eff})

Figure 12 to **Figure 13** respectively show the appearance of the effective stresses, their increase in (%) depending on the simulation cases carried out.

We can also make the following observations from these two figures (**Figure 12** to **Figure 13**):

→ As for the total deformations, the variation of the effective stresses depending on the simulation cases is also increasing. Compared to the effective stresses of the initial drained situation (Case A drained), the increase in effective stresses depending on the simulation cases carried out is 4.48% for the initial undrained situation (Case A undrained), 2.29% for the loaded, drained and unsupported situation (Case B drained), 4.48% for the loaded, undrained and unsupported situation (Case B undrained), 3.76% for the loaded, drained and unsupported situation sustained (Case C drained) and 4.48% for the loaded, undrained and sustained situation (Case C undrained).

→ It should also be noted that the most unfavorable situation with large stresses coupled with large total deformations is always the loaded, undrained and unsupported situation (Case B undrained) with σ_{eff} max = 1340 kN/m^2 and ε_{tot} max = 15.65%. It can also be noted that for undrained situations, the effective stresses remain constant with increasing variable deformations. Indeed, the law used in this study, linking stresses to deformations, being an elastoplastic law (Mohr-Coulomb Model), in the plastic part, deformations increase for constant stresses.

4.3. Implication of Results

In view of the results of this study, the following implications can be made:

→ The study of consolidation resulting from the results of the experimental study presented in point 3.a above has shown that for the depth reached of 3 m, the soil of the study area is a soil likely to develop large deformations for any applied overload, it would be essential to prohibit the construction of major works there which could induce large deformations.

→ In view of the simulations carried out for the loaded case (Case B) which showed the influence of the load on safety and stability, the body responsible for granting building permits within its remit should limit the load (number of floors) not to be exceeded for the buildings which can be built there (single-family houses).

→ The simulation results have shown the contribution of the support in improving safety and stability, the spaces on which to build should be protected by a retaining wall in order to contribute to the stability of the area.

→ The effective solution is to play on the water aspects (drainage of the site) as demonstrated by the results of the simulations, effective drainage of the area should be carried out.

5. Conclusions and Perspectives

5.1. Conclusions

In this study, we analyzed the stabilization of sloping sites subjected to building construction loads. This was done by performing an experimental soil study in the laboratory and considering 3 main simulation cases: We first evaluated the stability of the study area for an initial situation (without loading and without support), then for a loaded situation without support and finally for a loaded situation with support. In order to evaluate the effect of the presence of water in the soil mass, the simulations were carried out in the state where the soil is drained and in the state where the soil is undrained for each of these 3 main simulation cases. Three buildings were designed in accordance with the existing buildings and their loads were calculated for the simulations of the last two cases.

Following this study, we can make the following conclusions:

➢ ***Experimental study***

The results in point 3.a. identify the soil of the study area as sandy loam soil. Furthermore, the consolidation study carried out in the laboratory showed that this soil is normally consolidated soil up to the depth reached of 3 m, that is to say soil likely to develop large deformations, since any overload can increase the effective stress to a level that the soil has never reached.

➢ ***Stability analysis by numerical simulation***

The simulation results show the influence of the initial state of the site (slope and soil quality with its resistance characteristics), building load, support and the effect of non-drainage on the stability of the study area as described below:

→ The high slope (30.8%) of the study area is classified as steep and the soil quality with low resistance characteristics ($c = 22.29\ \text{kN/m}^2$ and $\varphi = 29.63^{\circ}$) gives a maximum safety value of 1.937 in an initial, unloaded and drained situation. For such a situation, this value is obviously low.

→ In a loaded situation (Case B), unsupported, the safety went from 1.937 (initial drained situation) to 1.619 when the soil is drained, a decrease of 16.42% compared to the initial situation while it deteriorates further when the soil is undrained. Indeed, it went for the same case (Case B) from 1.937 to 1.279 when the soil is undrained, a decrease of 33.97% compared to the initial situation. This shows the effect of the loads and especially the more harmful presence of water in the soil on the stability of the slopes.

→ The influence of the retaining wall can also be seen. Indeed, although it contributes to the increase in deformations, by making a comparison for the same drained state (Cases B and C), it should be noted that for the simulation cases carried out, the reduction in safety is minimal when there is a retaining wall, *i.e.* a reduction of 11.46% (the lowest of the others: Case C drained) compared to the case where there is no support, *i.e.* a reduction of 16.42% (Case B drained).

→ The most unfavourable situation, which could lead to a failure (because it gives a safety below the acceptable safety), is the loaded, undrained and unsupported situation (Case B undrained) for which $F_s = 1.279$. Certainly, this is influenced by the loading and the non-drainage but much more by the non-drainage. Indeed, for the case of the study area and as can be seen, the loaded, unsupported and drained situation (Case B drained) for its part, gave a value $F_s = 1.619$ (acceptable). This situation only confirms the conclusion drawn above by indicating more clearly the dangerous effect of the loads and especially of the presence of water in the soil on the stability of the slopes.

→ The intensive increase of loads (multi-storey buildings) also contributes to the instability of the study area. In fact, by analyzing the safety for the loaded situation, the area of a probable failure (stress concentration zone) was noticed close to the most loaded building (R + 4) due to the latter (**Figure 6(a)**).

5.2. Perspectives

The simulations conducted in this study focus on the effects of loads, support and drainage/non-drainage on slope stability safety based on a 2D model.

As sloping soils can be complex, it would be interesting for future research, in addition to what we presented in this article, to consider the 3D nature of slope behavior and building interactions and maximize consideration of real soil conditions.

Similarly, other aspects require additional research. It would also be interesting to evaluate the effects of other means of reinforcing sloping sites such as substitution (purging all materials likely to slide, and replacing them with a better quality material), earthworks, or even afforestation and make a comparison in order to determine the most effective possible.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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