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Statistical Analysis of the Influence of Soil Parameters on the Bearing Capacity Reduction Factor Using the Design of Experiments Method

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ABSTRACT

When a foundation rests at the edge of a slope, its stability becomes a major concern, particularly regarding the precise determination of its bearing capacity. Nevertheless, it is necessary to account for the influence of the slope on bearing capacity when designing structures to ensure their stability and overall safety. Consequently, authors have proposed introducing a bearing capacity reduction factor, following the example of Bakir and Gemperline. However, these authors (Bakir, Gemperline) have provided analytical expressions for estimating the reduction factor to be applied to the bearing capacity of the soil; these expressions do not depend on the physical and mechanical properties of the soil. This paper propose an statistical analysis of the influence of those parameters (cohesion, friction angle, and Young modulus) by using design experiment methods and the analysis of variance method. It shows an influence of 81.25% of cohesion, and 12 % of Young's modulus, while the friction angle has no influence.

Keywords : Shallow foundation, reduction factor, design of experiment, analysis of variance, bearing capacity

1. INTRODUCTION

The bearing capacity of shallow foundations is of great importance in geotechnical engineering ; it has been the subject of numerous studies. Most of these studies have been conducted under conditions where the foundation rests on horizontal soil. However, given the ever-increasing pace of urban development, foundations may be constructed on slopes or at the edge of a slope (embankments, excavations, abutments, etc.). Nevertheless, when a foundation rests at the edge of a slope, its stability becomes a major concern, particularly regarding the precise determination of its bearing capacity. Nevertheless, it is necessary to take account the influence of the slope on bearing capacity when designing structures to ensure their stability and overall safety. Consequently, authors have proposed introducing a bearing capacity reduction factor, following the example of Bakir and Gemperline. However, these authors (Bakir, Gemperline) have provided analytical expressions for estimating the reduction factor to be applied to the bearing capacity of the soil; these expressions do not depend on the physical and mechanical properties of the soil. However, given that the geological context and soil layers differ from one region to another, uncertainties arise regarding the values these expressions would yield for soil types different from those tested. The objective of this article is to evaluate the impact of soil parameters on the bearing capacity reduction factor using statistical methods. Samples were collected at Daral Pheul site, located in the Thiès region of Senegal. The influence or not of soil parameters such as cohesion, angle of friction, and Young's modulus was demonstrated through a graphical analysis of the design of experiments method and analysis of variance.

2. MATERIALS AND METHODS

Bearing capacity of a shallow foundation located near a slope

The specific configuration of a foundation located near a slope is a common scenario in practice [Figure 1]. Meyerhof [1] proposed the following equation (equation (1)) for calculating the bearing capacity of such a foundation :

$$q_u = 0{,}5\gamma B N_{\gamma q} + c N_{cq} \qquad (1)$$

Where γ is the specific weight, c the cohesion, B the sole width, and $N_{\gamma q}$, N_{cq} bearing capacity factor

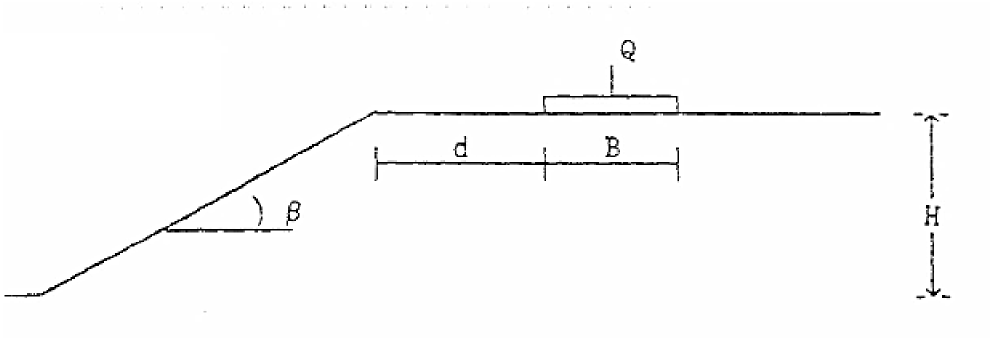

Figure Shallow foundation located next to a slope [1]
β: angle of slope, d : distance of foundation from edge of slope, B:sole width, H : slope height

However, the behavior of foundations located near a slope is less well understood, and there is considerable uncertainty regarding the design methods for determining the appropriate reductions in bearing capacity. Research has been conducted on this topic by various researchers, using both experimental approaches (centrifuge model tests, scale model testing, and full-scale tests for B > 0.3 m) and theoretical methods, with the aim of determining the bearing capacity reduction factors to be considered for foundations located at the edge of a slope. Numerous tests have been conducted by researchers on centrifugal models to determine the bearing capacity reduction factor due to a slope (Table 1) [2]

Table 1 : Experimental and theoretical approaches for determining bearing capacity reduction factor

		Authors
Experimental approach	Tests on centrifuged models	Grenier tests (1988)
		Gemperline tests (1988)
		Terashi and Kitasume tests (1986)
		Kimura tests (1985)
	Scale model testing	Giroud and Tran-Vo-Nhiem tests (1994)
		Labègue tests (1973)
		Dembicki and Zadroga tests (1974)
	Full-scale testing	Shields and Bauer tests (1977)
Theoretical Approach		Meyerhof (1957)
		Brinch et Hensen (1970)
		Bakir (1993)

Gemperline (1988) [3] conducted 215 tests on scale models in a centrifuge, simulating foot walls located near a slope upstream of its crest, and based on these tests proposed bearing capacity reduction factor that take into account a very large number of parameters. For non-embedded footings, he proposes the following formulas for a tapered footing (Equation (2)) and a rectangular footing (Equation (3)):
slip-on sole:

$$i_\beta = 1 - 0,8[1-(1-tg\beta)^2]\left[\frac{2}{2+\left(\frac{d}{B}\right)^2 tg\beta}\right] \qquad (2)$$

rectangular sole:

$$i_\beta = \left\{1 - 0,8[1-(1-tg\beta)^2]\left[\frac{2}{2+\left(\frac{d}{B}\right)^2 tg\beta}\right]\right\} * \left\{1 + 0,6 * \frac{B}{L} * [1-(1-tg\beta)^2]\left[\frac{2}{2+\left(\frac{d}{B}\right)^2 tg\beta}\right]\right\}$$

(3)

The centrifuge tests conducted at the Central Laboratory of Bridges and Roads (LCPC) in Nantes by Bakir (1993) led to the proposal of an alternative formula for determining the bearing capacity reduction factor i_β, based on the relative distance *d/B* and the angle of the slope β. it is presented in the following form, with α = 6 (equation (4)) [4], [5]:

$$\begin{cases} \frac{d}{B} \leq \alpha & i_\beta = 1 - 0,9tan\beta(2-tan\beta)\left[1-\frac{d}{\alpha B}\right]^2 \\ \frac{d}{B} > \alpha & i_\beta = 1 \end{cases} \qquad (4)$$

β: angle of slope, d : distance of foundation from edge of slope, B:sole width
None of the formulas presented here depend only on β, no on the geotechnical parameters. In the following of this paper, we will examine the influence of geotechnical parameters on the reduction factor.

Design of experiments methods
Design of Experiments (DOE) mathematical methodology used for planning and conducting experiments as well as analyzing and interpreting data obtained from the experiments. It is a branch of applied statistics that is used for conducting scientific studies of a system, process or product in which input variables (Xs) were manipulated to investigate its effects on measured output variable (Y). [6] (figure 2)

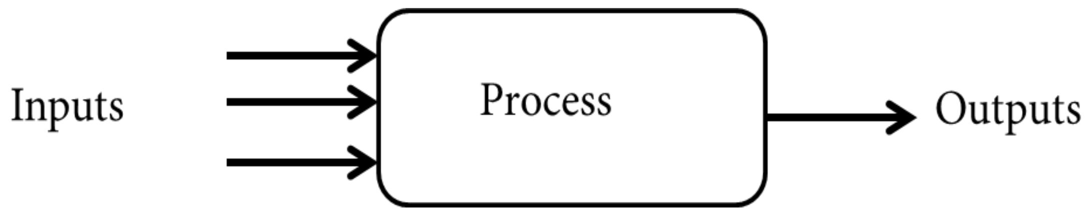

Figure 2 Design of experiment process black box [7]

In order to obtain good results from a DOE, the following 5 steps shown in figure 3 below are necessary [8].

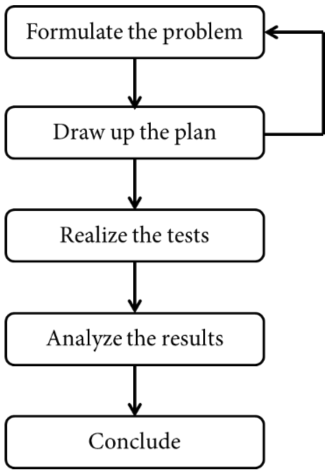

Figure 3: Steps for conducting design of experiment method

Formulating the experimental problem involves describing, on the one hand, the objectives and expected outcomes of the experimental design, and on the other hand, the inputs and outputs of the black box, which symbolizes the phenomenon under study. To fully construct a design of experiments, one must define the combinations of factors to be tested, the number of repetitions (if any) for all or part of the plan's combinations, the order in which the tests will be conducted, and, if necessary, the division of the tests into sequences. There are several methods for constructing the design of experiments matrix or test matrix, the most commonly used of which are the full factorial design, the fractional factorial design or orthogonal fractional design, and composite designs. [9]. The tests consist of measuring the responses for all combinations of factors indicated in the test matrix. Analyzing the test results involves quantifying the influence of the factors using an algebraic calculation that first involves calculating the effects of the factors or interactions of the factors on the response and then interpreting them graphically. It also involves determining, using a statistical calculation, whether the effect of these factors is truly significant.

To study the influence of each parameter individually, let denote M_y the overall mean of all the test results. Thus, to calculate the effect of a factor F at level k, we must calculate the mean of the responses, M_{oy} (F_k) when that factor is at level k, and then calculate the difference from the overall mean. This is given by equation (5) :

$$f_k = M_{oy}\,(F_k) - M_y \qquad (5)$$

To calculate the effect of two parameters, A and B, simultaneously, we use the equation (6)

$$(ab)_{ij} = M_{oy}(A_i, B_j) - M_y - a_i - b_j \qquad (6)$$

$M_{oy}(A_i, B_j)$ is the average of the responses when A is at level i and B is at level j; a_i is the effect of A at level i; b_j is the effect of B at level j

3. RESULTS AND DISCUSSIONS

3.1 Area Study Presentation

For the purposes of the study, samples were collected at the Daral Peulh site at points A and B, with respectively coordinates (14°47'11.09“N, 16°58'17.78”W) and (14°47'10.96“N, 16°58'17.35”W) (Figure 4). Tests conducted on these two samples concluded that the soil at the site consists primarily of plastic clayey gravel according to the LCP classification. Table 2 below presents the results of the shear tests for samples A and B

Table 2 : Results of the shear tests on the two samples

Soil samples	**Cohesion**	**Friction angle**	**Water content**
	C (kPa)	φ (°)	w(%)
A	20	26,56	15,39
B	25	21,67	15,32

Figure 4: Site sampling

3.2 Soil bearing capacity calculation

In this study, we consider an unanchored, rigid, and rough strip foundation with a width of $B = 1m$, on a soil mass and located at a distance d from the crest of a slope that forms an angle $\beta = 26{,}6°$ with the horizontal (Figure 5). A load of $10KN$ is applied to the foundation. The problem is modeled using a 2D geometric model with a width of 20B and a height of 10B in Plaxis 2D.

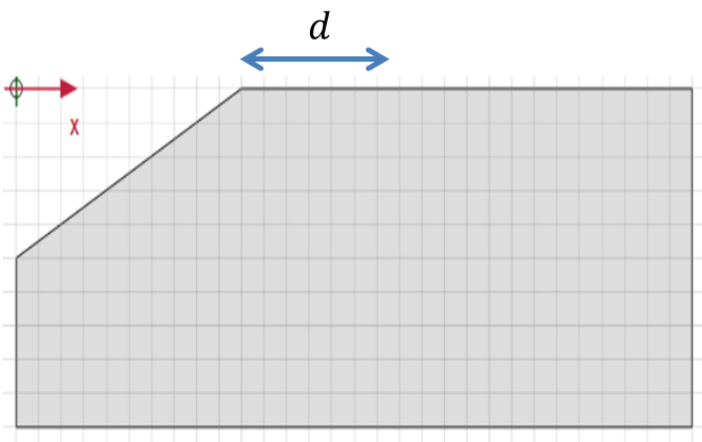

Figure 5 : Geometrical model

By applying a load of $10KN$ and initially fixing the footing at a distance of $d = 7m$, the bearing capacity $(q_{u,d=1})$ is calculated by varying the parameters (cohesion, angle of friction, and Young's modulus); then the footing is placed at a distance of $d = 1m$, and the new bearing capacity of the soil ($q_{u,d=7}$)is calculated. Thus, the reduction factor i_β is calculated using the relationship given by Equation (7).

$$i_\beta = \frac{q_{u,d=1}}{q_{u,d=7}} \quad (7)$$

3.3 Design of experiments and test Results

The different parameter levels are defined in Table 2.

Table 2: Parameters levels

	Levels			
Parameters	**1**	**2**	**3**	**Units**
A : Cohesion	3,3	11,4	31,3	KPa
B : Friction angle	14,7	32,7	39,5	Degrés □□□
C : Young modulus	15000	20000	30000	KPa

Table 3 presents the experimental design matrix containing the results obtained from the numerical simulation. This design is a full factorial design, which allows experiments to be conducted using all possible combinations of the different levels of the selected parameters. There are 27 possible combinations.

Table3: Experiment matrix and results of the new tests

N°	A	B	C	iβ	N°	A	B	C	iβ
1	3,3	14,7	15000	0.59809	15	31,3	32,7	20000	0.84275
2	11,4	14,7	15000	0.84646	16	3,3	39,5	20000	0.59806
3	31,3	14,7	15000	0.92275	17	11,4	39,5	20000	0.72516
4	3,3	32,7	15000	0.69804	18	31,3	39,5	20000	0.84275
5	11,4	32,7	15000	0.88646	19	3,3	14,7	30000	0.59809
6	31,3	32,7	15000	0.94275	20	11,4	14,7	30000	0.84646
7	3,3	39,5	15000	0.70213	21	31,3	14,7	30000	0.94228
8	11,4	39,5	15000	0.89646	22	3,3	32,7	30000	0.69809
9	31,3	39,5	15000	0.96275	23	11,4	32,7	30000	0.84646
10	3,3	14,7	20000	0.59802	24	31,3	32,7	30000	0.94275
11	11,4	14,7	20000	0.72516	25	3,3	39,5	30000	0.70209
12	31,3	14,7	20000	0.91275	26	11,4	39,5	30000	0.84646
13	3,3	32,7	20000	0.59802	27	31,3	39,5	30000	0.91754
14	11,4	32,7	20000	0.72516					

The effects of A (cohesion), B (angle of friction), and C (Young's modulus) are denoted by a_j, b_j, and c_j, respectively, where $j = 1,2,3$ denotes the parameter levels

Tables 4 (a), (b), and (c) show the results of the average effects of parameters A, B, and C, respectively, obtained using Equation (5). Negative values indicate that the parameter has a negative effect on the response, while positive values indicate the opposite. When the value is close to zero that's mean the influence of the parameter is weak.

Table 4 : Average effect of parameters A, B, and C

a_1	-0.14786	b_1	-0.01458	c_1	0.03718
a_2	0.02477	b_2	0.00657	c_2	-0.06150
a_3	0.12309	b_3	0.00801	c_3	0.02432
Average effect of A		Average effect of B		Average effect of C	

The results of these interactions are presented in Tables 5(a), (b), and (c). They show the mean values of the interactions between parameters A and B, then A and C, and finally B and C. If the observed value is lower or higher than the overall mean, this indicates that the interaction between the parameters has a negative or positive effect on the response, respectively.

Table 5 : Effets of interactions

	B1	B2	B3
A1	0.59806	0.66471	0.66743
A2	0.80603	0.81936	0.82270
A3	0.92593	0.90942	0.90768

(a) interaction of A and B

	C1	C2	C3
A1	0.66609	0.59803	0.66609
A2	0.87646	0.72516	0.84646
A3	0.94275	0.86609	0.93419

(b) interaction of A and C

	C1	C2	C3
B1	0.78910	0.74531	0.79561
B2	0.84242	0.72198	0.82910
B3	0.85378	0.72199	0.82203

(c) interaction of B and C

3.3.1 Individual effect of parameters

Figures 6(a), (b), and (c) show the effects of the parameters individually. These figures illustrate more clearly the influence each parameter can have on the response. Figure 6 (a) shows that parameter A at level 1 has a negative influence on the response; however, at level 2, the influence is weakly positive, and at level 3, it is strongly positive. As for parameter B (Figure 6(b)), its influence remains weak, both positively and negatively. Parameter C has a positive influence at levels 1 and 3 and a negative influence at level 2, which is relatively weak in all cases.

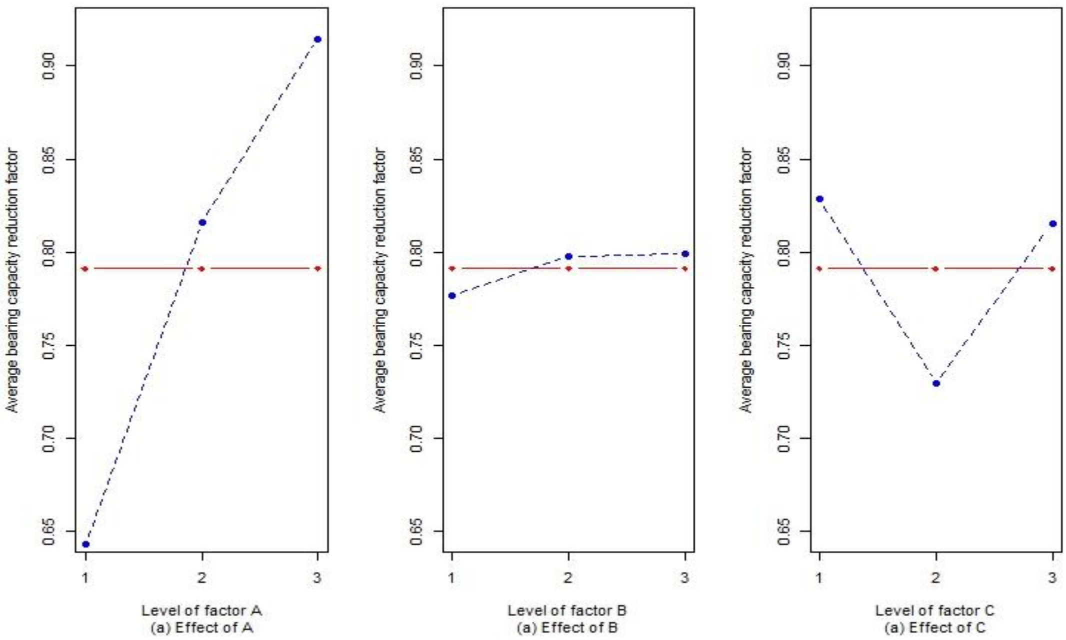

Figure 6 Effect of parameters A, B et C

3.3.2 Influence des paramètres simultanément

This section discusses the effects of parameters when they act simultaneously.

Figures 7, 8, and 9 below illustrate the effects of interactions between parameters.

Figure 7(a) shows that when parameter A is at level 1, the effect of B is negative. However, when A is at levels 2 and 3, the effect of B is positive.

Figure 7(b) shows the influence of parameter A as B varies. We observe that in all cases, the influence is identical: at level 1, the influence of A is negative, and it is positive at levels 2 and 3.

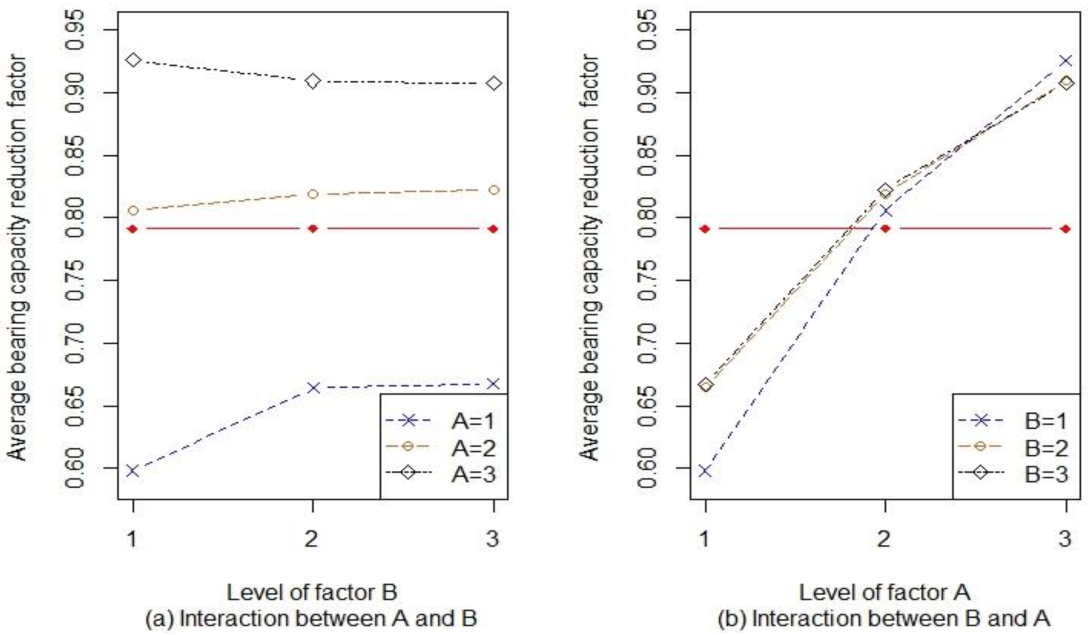

Figure 7 : Effect of interaction between the parameters B and C

Figure 8(a) shows that the effect of C follows the same pattern regardless of the level of A, but the magnitude of the effect varies. For A at level 1 and level 3, respectively, C has a completely negative effect and a completely positive effect. However, for A at level 2, the effect of C is positive at levels 1 and 3 and negative at level 2.

Figure 8 shows that regardless of the level of C, parameter A has a negative influence at level 1 and a positive influence at levels 2 and 3.

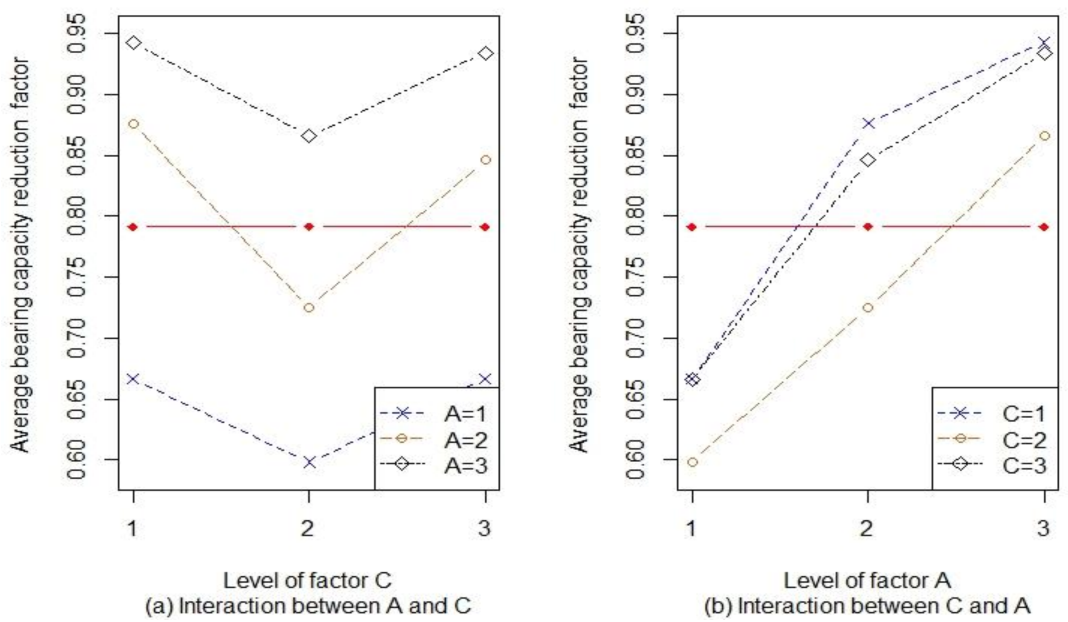

Figure 8: Effect of interaction between the parameters A and C

The figures 9 the effect of interaction between the young modulus (C) and the friction angle (B). Figure 9 (a) shows when the B parameter is a level 1, the C parameter has no effect in level 1 and 3, and its effect is negatively small in level 2. However when the B parameter is in the levels 2 and 3 the effect of C parameter in is similar. It is positively small in its level 1 and 3 and negatively small in its level 2. Regarding the figure 9 (b), it show the effect of B parameter when the C parameter is fixed. When C parameter is in level 1 the B parameter effect is negatively small in all levels, but when C parameter is in level 2 and 3 the effect of B parameter is positively small in all level.

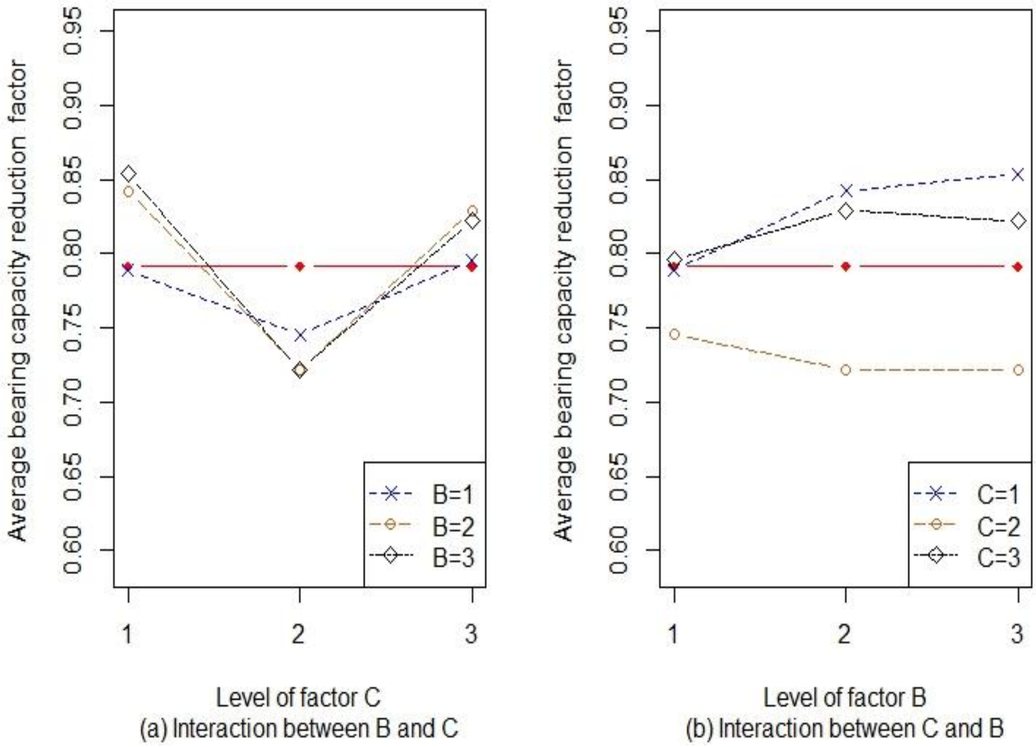

Figure 9 : Effect of interaction between the parameters B and C

Analysis of variance

Analysis of variance (ANOVA) provides a statistical test to determine whether a factor has a significant influence on the response. In this section, we perform a statistical analysis of the results from the experimental design presented in Table 3.

To determine whether a factor is significant or not, the Fisher-Snedecor test was performed. The test consists of comparing, for a given confidence level (1 – α), the values F_{sexp} and F_{stheo}, where F_{sexp} corresponds to the ratio (Equation (8)) between the variance associated with the main effect, denoted V_A (factor or interaction between factors), and that associated with the residuals, V_{Res}. F_{stheo} (equation (9)) corresponds to the value read from the Fisher-Snedecor table, which depends on the degrees of freedom of the main effect n_a and those of the residual n_r.

$$F_{sexp} = V_A/V_{Res} \quad (8)$$

$$F_{stheo} = F(n_a/n_r) \quad (9)$$

This test, known as the Fisher-Snedecor test, is conducted under the null hypothesis H_0, in which the true effects of the treatments on the response are assumed to be zero. In this case, the F_{sexp} follows a Fisher-Snedecor distribution.

Under the null hypothesis, H_0, the ratio F_{sexp} therefore has a probability :

- of $1-\alpha$ of falling between 0 and F_{stheo}
- of α of falling between F_{stheo} and infinity

that is to say

if $F_{sexp} < F_{stheo}$, Therefore, the value observed by Fexp is consistent with the null hypothesis H0, so the corresponding test is not significant

Else if $F_{sexp} > F_{stheo}$, then the value observed by F_{sexp} is not consistent with the hypothesis H_0, so the corresponding action is significant.

The standard presentation of the results of an analysis of variance is done using a summary table called an "analysis of variance table" (Table 6) [10]

Table 6 : Analysis of variance table

Sources of variation	**Sum of square (SCE)**	**%**	**Degree of freedom (ddl)**	**Variances**	**Fsexp**	**Fstheo**
A	SCE (A)	SCE(A)/SCE (T)	$n_a - 1$	VA	V_A/V_{Res}	
B	SCE (B)	SCE(B)/SCE (T)	$n_b - 1$	VB	V_B/V_{Res}	
…	…	…	…	…	…	…
AB	SCE (AB)	SCE(AB)/SCE (T)	$(n_a - 1)(n_b - 1)$	VAB	V_{AB}/V_{Res}	
…	…	…	…	…	…	…
Résidus	SCE (Res)	SCE(Res)/SCE (T)	n_r	Vres		
Total	SCE (T)		n – 1			

Table 7 presents the results of the analysis of variance. All the parameters studied influence the response, but in different ways. Parameter A (cohesion) has a significant influence of 81.25%, followed by Young's modulus, which has an influence of 12.43%. The angle of friction has a very weak influence with 0.67 %. Similarly, the interactions between the different parameters have only a weak influence less than 2 %.

Table 7 : Table of the analysis of variance results.

Source	**Sum of square (SCE**	**%**	**ddl**	**Variances**	**Fsexp**	**Fstheo**
A	0.33863	81.25347	2	0.16931	615.11650	3.11312
B	0.00288	0.69126	2	0.00144	5.23305	3.11312
C	0.05180	12.42910	2	0.02590	94.09250	3.11312
AB	0.00746	1.78885	4	0.00186	6.77108	2.80643
AC	0.00656	1.57339	4	0.00164	5.95554	2.80643
BC	0.00723	1.73556	4	0.00181	6.56941	2.80643
Res	0.00220	0.52838	8	0.00028		
Total	0.41675	100	26			

CONCLUSION

The work presented in this article used statistical methods to analyze the influence of soil mechanical parameters (Young's modulus, cohesion, angle of friction) on the lift reduction coefficient. The individual and combined effects of these parameters were analyzed using the design of experiments method and analysis of variance. It can be observed that despite the absence of these parameters in the formulas for the bearing capacity reduction factor proposed by certain authors, cohesion has an influence of 81.25%, Young's modulus an influence of 12%, while the influence of the angle of friction remains low, as well for the influence of interactions between the parameters remain low. It is important to continue the investigations and conduct a more analysis with other parameters and to vary the slope angle in order to determine whether these geotechnical parameters should be disregarded.

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