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Numerical modeling of the behavior of a surface foundation located in the proximity of a slope

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Article

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Abstract

Some foundations are placed on or near slopes or excavations, such as roads in mountainous areas, tower footings for power lines, and bridge abutments. The design of foundation under these conditions is complex and the studies available in this regard are limited and concerned mostly about the determination of the reduction of the bearing capacity coefficients associated with the presence of the slope except for Meyerhof who was a pioneer in developing a theory in 1957 to determine the ultimate bearing capacity of a foundation near a slope. However, the theory was independent of the slope inclination. In this study, we attempted to numerical modeling of the behavior of a shallow foundation using the finite element technique together with Plaxis 8.2 software to simulate the case of a foundation near a slope, in terms of examining the bearing capacity of the foundation for given slope features, soil characteristics and geometry conditions located near a slope subjected to a centered and / or eccentric load. The results obtained confirm that the position of the eccentricity of the load relative to the head of the slope has a significant effect on the bearing capacity. Indeed, it becomes larger when the eccentricity is located far from the crest of the slope. Thus, the bearing capacity of a footing subjected to a centered load ($e/B = 0$) is greater than that of the same footing subjected to an eccentric load ($e/B = 0.1$). It is noted that the results obtained from the present study are in good agreement with those of the literature.

1. Introduction

Shallow foundations are intended to ensure the stability of a structure on the ground and to transmit all the stresses to the deep permanently and uniformly. The need to study the mechanical behavior of shallow foundations and the desire to progress towards taking into account a performance criterion in their design, form a research subject of interest which is not only academic (Bencheikh, 2005).

The problem of determining the bearing capacity of a foundation, resting on a soil layer of given resistance, constitutes one of the oldest and fundamental questions of geotechnical engineering, this problem is currently well mastered, Terzaghi (1943) was the first to propose a general equation for evaluating the bearing capacity of a shallow foundation, resting on a mass of soil stressed by a centered vertical load in the form:

$$q_u = 0,5\gamma B N_\gamma + cN_c + qN_q \tag{1}$$

with: q_u = Bearing capacity (kN/m^2); B = foundation width (m); γ = soil density (kN/m^3); q = vertical load lateral to the foundation (kN); c = cohesion of the soil under the base of the foundation (kN/m^2); N_γ, N_c and N_q = bearing factors depending only on the angle of internal friction φ of the soil under the base of the foundation.

Since the appearance of the Terzaghi equation (Equation 1), there have been a large number of laboratory test campaigns and many methods have been developed with the aim of validating or improving its field of validity, these methods have an identical pace since they follow the superposition of the three terms introduced by Terzaghi (1943). There is the limit equilibrium method (Terzaghi, 1943), the method of characteristics or slip line (Sokolovskii, 1960), the limit analysis method (Michalowski, 1997; Boutahir Born Bencheikh, 2021) and numerical methods, which are generally based on the finite element method or the finite difference method (De Borst & Vermeer, 1984; Frydman & Burd, 1997).

Luxurious resorts built on foothills or located near shores are enjoyable and desirable by people, while it is

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problematic for engineers. Because in the case of building near or in slopes, the bearing capacity of the foundation is not only function in the soil condition but also in the geometry of the slope, in this case, the ultimate bearing capacity is governed by either the bearing capacity of the foundation or by the overall stability of the slope, the combination of these two factors complicate modeling of the problem (Dey et al., 2019; Boutahir Born Bencheikh, 2021). Despite the importance of the subject of building near slopes, there are limited studies available in this regard except for Meyerhof, who was prominent in developing a theory in 1957 (Meyerhof, 1957) to determine the ultimate bearing capacity for foundations built near slopes and predict the reduction in the bearing capacity coefficients associated with the presence of the slope (Boutahir Born Bencheikh, 2021; Belabed & Bencheikh, 2008; Bencheikh, 2010),

$$q_u = 0.5\gamma B N_{\gamma q} + cN_{cq} \tag{2}$$

$N_{\gamma q}$ and N_{cq} were presented by Meyerhof (Bencheikh, 2005) for different geometric configurations, these factors depend on the angle of internal soil friction. Hansen (1970) proposed correction coefficients for non-embedded strip foundations, established at the top of an embankment and subjected to a centered vertical load; Hansen (1970) gives the same correction coefficient for the surface term and the embedment term, Under the form:

$$i_{q\beta} = i_\beta = \left(1 - 0.5tan\beta\right)^5 \tag{3}$$

where = β is the angle of the slope with respect to the horizontal.

For the study of a foundation at the edge of an embankment, Giroud & Tran (1971), Graham et al. (1988) developed calculation methods based on the concept of slip lines. Furthermore Kusakabe et al. (1981), Saran et al. (1989), Narita & Yamaguchi (1990) and De Buhan & Garnier (1998) have studied this problem by the kinematic approach of the theory of calculation at failure. Magnan et al. (2004) obtained results for the case of a continuous shallow foundation, established near an embankment, and subjected to vertical, inclined and eccentric loading, using finite element calculations with the CESAR-LCPC code, based on elasto-plastic calculations (MCNL module), as well as regularized kinematic analysis (LIMI module). Bakir et al. (1994) presented a summary of experimental research carried out to study a slipping foundation near an embankment. Then Jiao et al. (2015) adopted a kinematic analysis based on discretization to study the bearing capacity of a saturated and non-homogeneous soil slope (Boutahir Born Bencheikh, 2021). Later, Qin & Chen Chian (2017) estimated the stability of a two-level slope in stratified soils using kinematic analysis. In the field of full-scale experiments, we find the work of Shields et al. (1977b) and Bauer et al. (1981). Gemperline (1988) carried out a large series of tests on centrifuged models, considering a powdery soil and varying the geometric and mechanical parameters. These tests made it possible to propose an analytical expression to evaluate the reduction coefficient of lift i_β as a function of the angle β of the slope, with respect to the horizontal and with respect to the relative distance *d/B* of the foundation from the edge of the Bank. The expression proposed by Gemperline (1988) for the reduction coefficient i_β has the following form:

$$i_\beta = 1 - 0.8\left[1 - \left(1 - tan\beta\right)^2\right]\frac{2}{2 + \left(\frac{d}{B}\right)^2 tan\beta} \tag{4}$$

It should be noted that this expression does not depend on the angle of internal friction φ of the soil.

Despite the research developments cited above, very little information is available on the bearing capacity of strip footings near slopes, which is the consideration of the present research. The purpose of which is the treatment, by the Plaxis 2D code, of the problem of frictional soil interaction and continuous superficial foundation, of width *B*, subjected to a centered and eccentric vertical load established at a distance *d* from the crest of a slope, characterized by an angle β less than the angle of internal friction φ of the ground. This study aims at the numerical estimation of the lift factors N_γ, as well as the lift reducing factors i_β.

2. Parametric study

A behavior study of a non-embedded, rigid and rough strip foundation with a width B = 2 m resting on the surface of a rubbing ground and located at a distance d from the crest of an embankment. The problem is modeled by a plane geometric model (2D) with a width equal to 20*B* and a height equal to 10*B*. The supposedly perfectly rigid (*Eb/Esol* = ∞) and rough foundation, which is placed on the surface of the slope. The studied massif does not present any geometric symmetry; it is therefore modeled in its entirety (Peters, 2011).

In addition, the boundary conditions are considered by blocking the horizontal displacements on the vertical ends and by blocking the horizontal and vertical displacements for the lower end (Peters, 2011).

For reasons of readability, we show a representation, the geometrical definition retained for this study is represented on Figure 1 and model modeling in Plaxis2D is represented on Figure 2, the calculations in this study carry several variations of several parameters:

a) A horizontal surface (β = 0);
b) The angle of internal friction φ = 25°, 30°, 38° et 40°;
c) The angle of inclination of the slop β = 15°, 30° et 45°;
d) The variation of *d/B*: distance between bare soles and the head of the slope;
e) The variation of *e/B* the eccentricity of the load.

The numerical analysis was carried out using the PLAXIS 8.2 software allowing modeling in plane deformation. The mesh used in this model consists of a 15-node triangular element.

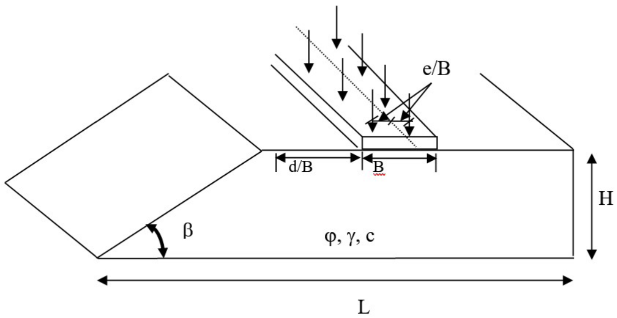

Figure 1. Definition of parameters.

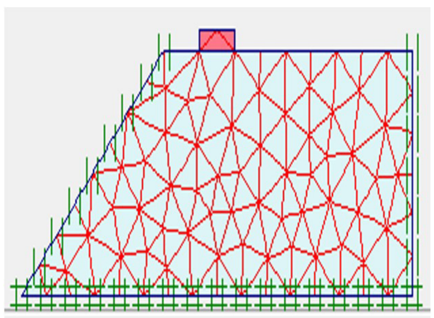

Figure 2. Presentation of the digital model.

3. Material characteristics

3.1 Characteristics of the soil mass

The soil used in this analysis given in Table 1 is dense sand without cohesion obeying the nonlinear criterion of Mohr-coulomb governed by an unassociated constitutive law. Attention is drawn to the fact that this criterion is recommended for its simplicity and the availability of parameters (Mazouz, 2020; Acharyya & Dey, 2017).

3.2 Foundation characteristics

The foundation is treated as an elastic beam element based on Mindlin's beam theory where the most important parameters are the bending stiffness *EI* and the axial stiffness *EA* and for the foundation to be rigid a thickness equal to 1 m has been chosen, due to the stiffness condition ($0.2B \leq e \leq 0.5B$), where e: thickness of the foundation and B is its width (Mazouz, 2020). The footing properties used in the calculations are listed in Table 2.

4. Results

4.1 Test validation test (foundation on horizontal surface $\beta = 0$)

Before starting the analysis of the effect of a footing placed on the surface of a sandy slope subjected to centered and eccentric loads, it was considered useful to study the usual cases of a footing resting on a homogeneous soil. This study allows us to have an idea on the behavior of the footing given in Figure 3 and will serve at the same time as a validation test for our simulation procedure; we show in addition, the degree of reliability of the PLAXIS 8.2 code for the calculation of the ultimate limit load (Boutahir Born Bencheikh, 2021).

For a threaded foundation resting on a rubbing soil, established on a horizontal surface, the formula of the bearing capacity is given by the following relation: (DTU, 1988; Paris, 1993; Eurocode, 2004; Bencheikh, 2010; Belabed & Bencheikh, 2008):

$$q_u = \frac{1}{2}\gamma B N_\gamma \tag{5}$$

where: N_γ = bearing factor of a foundation established on a horizontal surface soil. This gives the expression for the bearing factor N_γ as follows: (DTU, 1988; Paris, 1993; Eurocode, 2004):

$$N_\gamma = \frac{2q_u}{\gamma B} \tag{6}$$

with: $q_u = \sum \frac{Mstage * Ql}{S}$

Q_1 (kN/m^2) = ultimate tensile strength;
S (m^2) = Section of the sole = $B*1m$;

Table 3 and the Figure 4 resume the variation of the factor N_γ with the internal friction angle φ for the proposed model. We notice that the factor N_γ increases regularly when the internal friction angle φ increases moreover the numerical results obtained allowed us to determine the value of the lift factor N_γ and that we can compare with the results obtained by some authors.

In the Table 3 the values of N_γ are calculated with the following rough rule:

$$\psi = \varphi - 30° \; for \; \varphi > 30°.$$

$$\psi = 0° \; for \; \varphi < 30°.$$

The results presented in the Table 3 and in the Figure 4 give a comparison of the N_γ values for a spinning sole with a rough base placed on a sand with various angles of internal friction ($\varphi = 25°÷40°$), compared with those available in the literature. The results obtained show that the present study approximates and performs quite well with the results given by these authors.

4.2 Influence of soil non-associativity on bearing capacity

Conventional limit equilibrium and limit analysis methods consider an associated flow rule. However, real soils

Table 1. Properties of the soil surface.

Parameters	Name	Unit	Sand
Typical model	Model	-	Mohr-Coulomb
Behavior type	Type	-	Drained
Dry density	γ_{unsat}	kN/m^3	16.7
wet density	γ_{sat}	kN/m^3	19.3
Young's modulus	E_{ref}	kN/m^2	12000
Poisson coefficient	v	/	0.3
Cohesion	C	kN/m^2	1
Friction angle	φ	(°)	38
Interface effort reduction factor	R_{inter}	-	Rigid
Internal friction angle	φ	(°)	Variable (25, 35, 38 et 40)
Angle of dilatancy	Ψ	(°)	Variable $\psi = 8$ associativity $(\varphi = \psi)$ non associativity($\psi = 2/3\varphi$, $\psi = 1/2\varphi$)

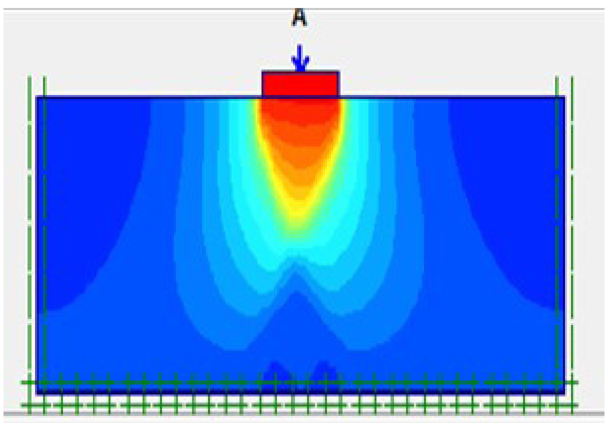

Figure 3. Modeling of a sole on a horizontal surface.

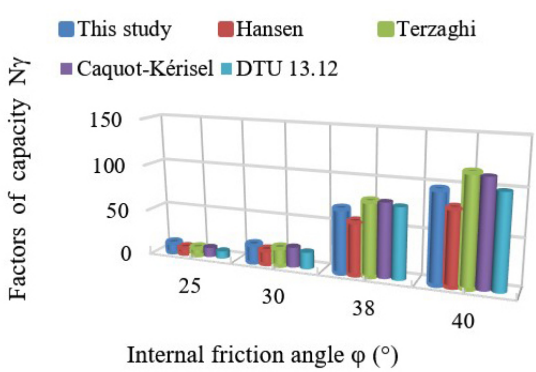

Figure 4. Comparison of N_γ values with those available in the literature.

have a non-associated flow rule, i.e., an angle of expansion smaller than the soil internal friction angle φ.

However, it can be easily evaluated by the following (rough) rule (Costet & Sanglerat, 1969):

Table 2. Characteristics of the foundation.

Parameters	Name	Unit	Value
Type of behavior	-	-	Elastic
Normal stiffness	EA	kN/m	2100
Flexural rigidity	EI	kNm^2	17500
Poisson coefficient	v	-	0.3

$$\psi = \varphi - 30° \text{ for } \varphi > 30°.$$

$$\psi = 0° \text{ for } \varphi < 30°.$$

The case where $\psi < 0°$ corresponds to very loose sands (state often-called metastable, or static liquefaction).

The value $\psi = 0°$ corresponds to a perfectly plastic elastic material, or there is no expansion when the material reaches plasticity. This is often the case for clays or sands of low or medium density under fairly strong constraints.

To show the influence of the non-associativity ($\psi < \varphi$) a variation of the angle of dilatation as follows: (Chatzigogos, 2007): $\psi = \varphi$, $\psi = (2/3)\varphi$ and $\psi = (1/2)\varphi$, the calculation results are summarized in the Table 4.

From this study it can be concluded that the use of the associated flow rule overestimates the bearing capacity components through the coefficient N_γ. Figure 5 shows that the bearing capacity depends on the dilatancy angle ψ, this dependence is significant for large values of the soil internal friction angle φ; where it is clear that when the dilatancy angle ψ decreases the bearing factor values N_γ decrease.

4.3 Foundation on the edge of a slope

Three study cases were conducted to investigate the effect of slope on the behavior of the bearing capacity of the spinning footing under eccentric loads (Shields et al, 1990). The Figure 6 illustrates these three load cases:

Table 3. Comparison of N_γ values for a rough-base spinning footing with those available in the literature (Terzaghi, 1943; Costet & Sanglerat, 1969; DTU, 1988; Hansen, 1970).

φ (°)	25	30	38	40
This study	10.750	19.470	68.200	96.210
Terzaghi	8.340	19.130	78.610	115.310
Caquot-Kérisel	10.400	21.800	79.500	113.000
DTU 13.12	8.100	18.100	76.230	100.000
Hansen	6.800	15.100	56.200	79.500

Table 4. Bearing capacity values as a function of ψ.

φ (°)	25	30	38	40
		$\psi = \varphi$		
N_γ	46.76	75.86	269.98	300.80
		$\psi = (2/3)\varphi$		
N_γ	25.20	50.13	170.36	200.80
		$\psi = (1/2)\varphi$		
N_γ	12.63	26.49	88.87	100.50

1. Centered load;
2. Positive eccentric load when the eccentricity of the load is near the slope;
3. Negative eccentric load when the eccentricity of the load is far from the slope.

During all calculations, each study was performed to investigate the effect of a single parameter while holding the other parameters constant. The variation of the parameters includes the eccentricity value (e) and the relative distance (d/B) (Shields et al., 1990) presented in the Figure 7.

For a threaded foundation resting on a rubbing soil, established at the edge of a slope, the following relation: (DTU, 1988; Paris, 1993; Eurocode, 2004): gives the formula of the bearing capacity:

$$q_u = \frac{1}{2}\gamma B N_\gamma i_\beta \tag{7}$$

The Reducing coefficient of bearing capacity i_β (the ratio of the bearing capacity of a foundation established at the edge of a slope to the bearing capacity of the same foundation, established on the same ground with a horizontal surface); it thus corresponds to the following expression (DTU, 1988; Paris, 1993; Eurocode, 2004):

$$i_\beta = \frac{\left[q_u\right]_{d/\beta,\beta}}{\left[q_u\right]_0} \tag{8}$$

4.4 Influence of slope angle β

The ultimate bearing capacity values are summarized in Table 5 and Figure 8 for the different cases of slope inclination β = 15°, 30° and 45°.

The increase of the slope has an influence on the bearing capacity, the increase of the slope decreases the bearing capacity of the footing.

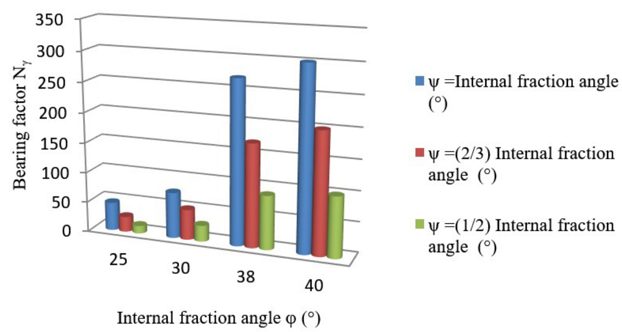

Figure 5. Lift factors as a function of ψ for a horizontal surface.

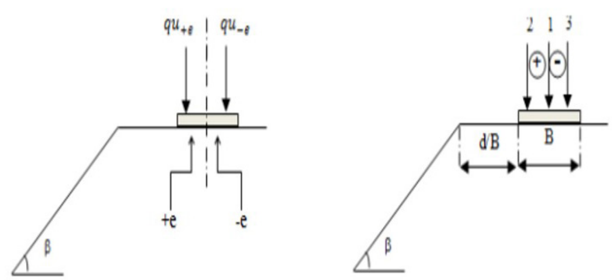

Figure 6. Sign convention (1) centered charge, (2) positive eccentric charge and (3) negative eccentric charge.

4.5 Influence of the distance d between the foundation and the crest of the slope

To study the effect of the eccentricity of the load and its position relative to the crest of the slope, as well as the effect of the distance between the edge of the footing and the crest of the slope (d/B), a series of finite element analyses were performed for d/B ratios varying between 0 and 3.5 in steps of 0.5 for different eccentricity ratios e/B = (0.0; ±0.1 and ±0.2).

The (+*e/B*) shows the eccentricity of the load towards the slope face while (-*e/B*) shows the eccentricity of the load towards the opposite slope face. To reach the limit load, an incremental load was applied to the foundation until the soil below the foundation failed for each value of the eccentricity ratio (*e/B*).

4.6 Foundation on horizontal surface $\beta = 0$ and load vertical

For the case of foundation on horizontal surface $\beta = 0$, and the eccentric load, the calculation results are summarized in the Table 6 and Figure 9:

4.7 Foundation on a sloping surface $\beta = 45°$ and subjected to a vertical load

Table 7 and Figure 10 shows the influence of the relative distance *d/B* on the bearing capacity for different values of *d/B*. This study shows that the location of the eccentricity of the load, in relation to the slope associated with the distance between the footing and the crest of the slope, significantly influences the bearing capacity. It can be observed that the ultimate bearing capacity generally decreases with increasing eccentricity ratio (±*e/B*) and increases with increasing relative distance *d/B*.

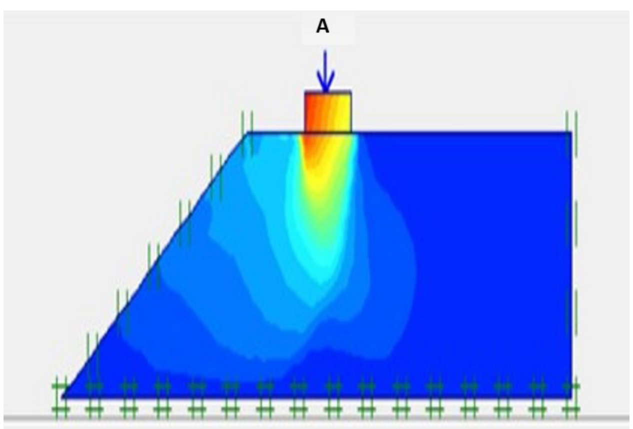

Figure 7. Footing on slope.

4.8 Reducing coefficient of lift

4.8.1 Case: $\beta = 45°$

According to Meyerhof's theory in (Li et al., 2020; Wing, 2005), to express the effect of load eccentricity on the bearing capacity in the case of an eccentricity-slope combination, we use the reduction coefficient i_β, the ratio of the bearing capacity of a foundation established at the edge of a slope to the bearing capacity of the same foundation established on the same soil with a horizontal surface, and compared with the Meyerhof coefficient.

Table 8 and Figure 11 gives the values of the minority coefficient i_β for different cases of eccentricity for $\beta = 45°$, it can be seen that the reduction factor of the bearing capacity i_β increases in most cases with the increase of the relative distance *d/B*.

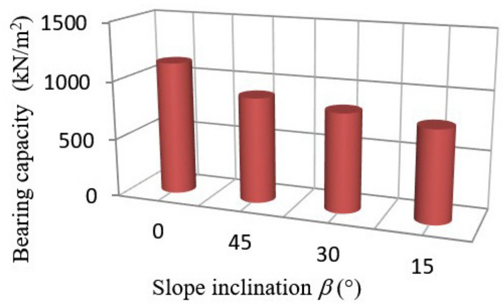

Figure 8. Bearing capacity values of the footing as a function of β.

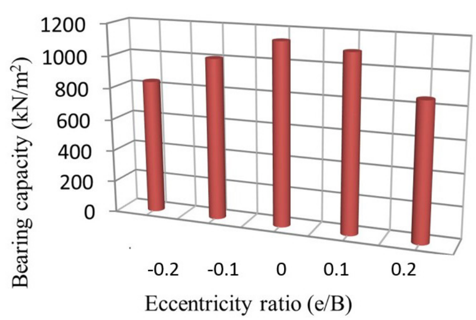

Figure 9. Influence of the load eccentricity on the bearing capacity for $\beta = 0°$.

Table 5. Bearing capacity values of the footing as a function of β.

β (°)	0	45	30	15
q_u = kN/m²	1138.73	899.87	839.5	780.16

Table 6. The bearing capacity of the sole for $\beta = 0°$.

	e/B				
	-0.2	-0.1	0	0.1	0.2
d/B = 4.5			q_u(kN/m²)		
	838.81	1008.55	1138.73	1100.50	856.43

Table 7. The bearing capacity of the sole for $\beta = 45°$.

Centered load		Eccentric load *e/B*			
d/B	*e/B*=0	*e/B* = -0.1	*e/B* = -0.2	*e/B* = 0.1	*e/B* = 0.2
		q_u(kN/m^2)			
0	691.265	604.095	573.965	609.730	668.150
0.5	426.075	452.065	422.625	404.455	364.895
1	483.805	464.715	437.690	428.950	386.170
1.5	503.355	508.340	491.395	479.665	457.815
2	568.330	551.310	521.755	587.650	550.050
2.5	626.060	601.335	573.850	623.415	595.700
3	659.755	649.060	613.755	642.390	606.050
3.5	781.195	750.605	687.335	754.770	685.900

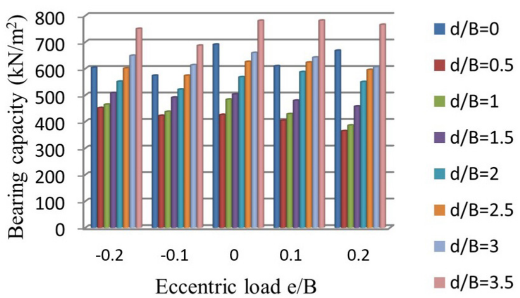

Figure 10. Variation of bearing capacity as a function of the ratio of eccentricity *e/B*.

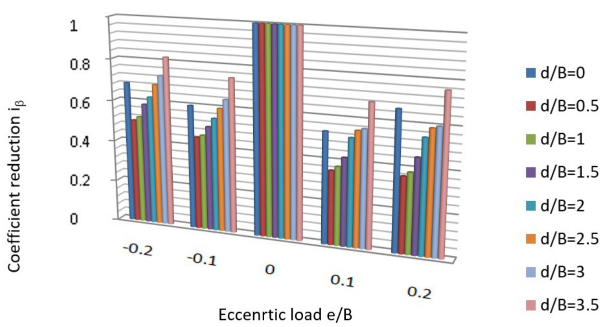

Figure 11. Variation of Reduction factor i_β as a function of the ratio of eccentricity *e/B*.

4.8.2 Case: $\beta = 30°$

Tables 9, 10 and Figure 12.

4.8.3 Case: $\beta = 15°$

Tables 11, 12 and Figure 13.

The variations of the reduction coefficient i_β as a function of the eccentric load ($\pm e/B$) with the relative distance are shown in Figures 11, 12 and 13. In general, for a relative distance, ($d/B < 3$), the behavior of a foundation subjected to two states of different eccentricities of the load (positive and negative) is completely different.

On the other hand, for the case of eccentric load located far from the face of the slope ($e/B < 0$), the values of the reduction coefficients i_β are greater than those generated by a loading near the opposite side of the slope ($e/B > 0$). Such a difference can be attributed to the inclination of the footing towards the slope, which results in a dispersion of the soil towards the slope for ($e/B > 0$).

However, the bearing capacity increases when the eccentricity of the load decreases regardless of either the position of the latter with respect to the slope, this up to $d/B \geq 3$, case where the lift of the foundation is almost the same for both cases of eccentricities (positive or negative).

5. Conclusion

The problem of the rigid shallow foundation resting near a slope is commonly experienced design problem encountered within engineering practice. Due to this, there have been a number of different numerical modelling studies conducted for the foundation problem, some in which have resulted in the preparation of ultimate bearing capacity design charts. The major focus of this study was to conduct modelling of the foundation model, whilst taking in real life foundation characteristic, to develop a qualitative set of results that could be used within the validation of previous simplified numerical models.

Numerical model was developed using finite element technique to examine the parameters governing the bearing capacity of shallow foundation near slope. Parametric study was conducted to examine the effect the angle of internal friction, the angle of inclination of the slope β, The variation of *d/B*: distance between bare soles and the head of the slope and the variation of *e/B* the eccentricity of the load. The results of the numerical modeling allow the following conclusions to be made:

Table 8. Coefficient reduction of bearing capacity for $\beta = 45°$.

e/B	Meyerhof	d/B							
		0	0.5	1	1.5	2	2.5	3	3.5
-0.2	0.6	0.684	0.503	0.521	0.585	0.622	0.684	0.730	0.819
-0.1	0.8	0.598	0.448	0.460	0.504	0.546	0.596	0.640	0.744
0	1	1	1	1	1	1	1	1	1
0.1	0.8	0.534	0.354	0.375	0.420	0.514	0.550	0.560	0.684
0.2	0.6	0.663	0.362	0.383	0.454	0.546	0.590	0.600	0.760

Table 9. The bearing capacity of the sole for $\beta = 30°$.

Centered load		Eccentric load e/B			
d/B	e/B = 0	e/B = -0.1	e/B = -0.2	e/B = 0.1	e/B = 0.2
		q_u(kN/m^2)			
0	492.085	515.890	367.310	470.235	417.795
0.5	424.695	370.645	338.330	381.685	342.125
1	449.765	437.115	420.210	458.620	411.170
1.5	571.320	556.600	521.410	534.980	497.835
2	603.750	590.180	553.725	570.630	495.353
2.5	676.085	651.475	609.040	675.740	600.070
3	744.855	733.930	681.375	701.730	644.690
3.5	746.120	706.675	664.585	760.610	741.060

Table 10. Coefficient reduction of bearing capacity for $\beta = 30°$.

e/B	Meyerhof	d/B							
		0	0.5	1	1.5	2	2.5	3	3.5
-0.2	0.6	0.437	0.456	0.500	0.621	0.660	0.726	0.821	0.792
-0.1	0.8	0.511	0.367	0.433	0.551	0.585	0.646	0.727	0.700
0	1	1	1	1	1	1	1	1	1
0.1	0.8	0.412	0.334	0.401	0.468	0.500	0.576	0.614	0.666
0.2	0.6	0.414	0.339	0.408	0.494	0.492	0.595	0.640	0.735

Table 11. The bearing capacity of the sole for $\beta = 15°$.

d/B	e/B				
	-0.2	-0.1	0	0.1	0.2
	q_u (kN/m^2)				
0	562.925	728.985	743.590	628.820	528.080
0.5	503.470	589.950	121.670	550.850	477.020
1	732.320	835.820	724.960	597.540	511.635
1.5	686.320	792.810	607.775	648.830	596.735
2	686.090	816.500	920.575	784.875	741.865
2.5	741.635	876.645	1003.950	963.930	782.000
3	762.450	803.275	1089.280	969.450	789.130
3.5	723.925	841.110	1012.460	906.545	722.660

Table 12. Coefficient reduction of bearing capacity for $\beta = 15°$.

e/B	Meyerhof	*d/B*							
		0	0.5	1	1.5	2	2.5	3	3.5
-0.2	0.6	0.670	0.600	0.873	0.818	0.817	0.884	0.908	0.863
-0.1	0.8	0.722	0.584	0.828	0.786	0.809	0.869	0.796	0.834
0	1	1	1	1	1	1	1	1	1
0.1	0.8	0.550	0.482	0.523	0.568	0.687	0.840	0.849	0.794
0.2	0.6	0.524	0.473	0.508	0.592	0.736	0.776	0.783	0.717

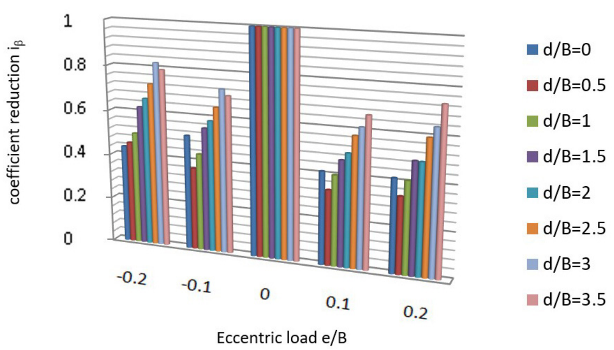

Figure 12. Variation of Reduction factor i_β as a function of the ratio of eccentricity *e/B*.

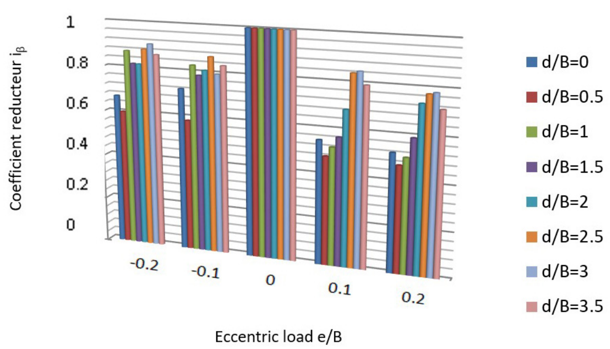

Figure 13. Variation of Reduction factor i_β as a function of the ratio of eccentricity *e/B*.

The bearing capacity of an eccentrically loaded footing is higher when the eccentricity of the load is placed away from the slope; The bearing capacity of a footing subjected to a centered load is greater than that subjected to an eccentric load (negative or positive);

The ultimate load-bearing capacity increases as the eccentricity of the load decreases;

The bearing capacity of the foundation placed near slope deceases with the increase of the slope angle and height while increases with the increase of the distance to the slope and/or the angle of internal friction of the soil;

The ultimate bearing capacity is higher in most cases under a negative eccentric load than under a positive eccentric load and this difference disappears when the footing is located at a relative distance *d/B* = 3;

The location of the load eccentricity with respect to the slope (load eccentricity near or far from the slope) combined with the relative distance *d/B* significantly influence the size and shape of the failure mechanism (see figures);

Is inversely proportional to the eccentricity ratio (±*e/B*) and increases with the increase of the relative distance *d/B*. The analysis of these tables emphasizes the case of the footing established at cases of relative distances *d/B* < 3, for which the ultimate bearing capacity for the positive eccentric load is lower than for the same negative eccentric load, However for a distance *d/B* = 3 and in both cases of eccentricity (negative or positive), the ultimate bearing capacity is approximately identical, Indeed, the influence of the location of the load eccentricity on the load-bearing capacity can be neglected. Therefore, the maximum edge distance was limited to 3*B*;

The results show that the bearing capacity and the reduction factor of the bearing capacity bearing capacity i_β increase with increasing relative distance *d/B*.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Bencheikh Messaouda: conceptualization, data curation, visualization, writing – original draft. Aidoud Assia: conceptualization, data curation, methodology, supervision, validation, writing – original draft. Boukour Salima: data curation, formal analysis, funding acquisition, investigation, methodology. Khaldi Nacira: supervision, writing – review & editing. Belabed Lazhar: visualization, writing, formal analysis.

Data availability

All data produced or examined in the course of the current study are included in this article.

List of symbols

c	Cohesion
d/B	distance between bare soles and the head of the slope.
e/B	eccentricity of the load.
i_β	Reducing coefficient of bearing capacity
E_{ref}	Young's modulus
R_{inter}	Interface effort reduction factor
EA	Normal stiffness
EI	Flexural rigidity
N_γ	Bearing factor of a foundation
Q_l	Ultimate tensile strength
φ	Angle of internal friction
β	Angle of inclination of the slop
γ_{unsat}	Dry density
γ_{sat}	wet density
v	Poisson coefficient
ψ	Angle of dilatancy

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