BEARING CAPACITY OF STRIP FOOTING USING KREY'S METHODS (FRICTION CIRCLE METHOD)

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ABSTRACT

In geotechnical investigation, determination of the bearing capacity of foundation soil constitutes is an important task. Most of the previous studies investigated the stability of such foundation system using classical bearing theory. The classical bearing theory was developed depending on the theory of plasticity with the assumption that the soil behaves as a rigid-plastic material. The bearing capacity theories require making a guess on the shape and geometry of the most critical failure surface (mechanism of failure) a priori. Most theories assumed the geometry of the failing soil mass is symmetrical with respect to the center of the footing, while, Krey suggested that the geometry of the failing mass is unsymmetrical. Numerical methods do not require an initial assumption the geometry of the failure mode. In the present work, a numerical study assisted by a computer program is carried out using (Krey's method) to investigate the center of the slip circle gives the minimum bearing capacity of the footing. Also, PLAXIS 2D used for analysis of some cases of studies by Krey's method. Krey it's of the present study is compared with the classical theories of the ultimate bearing capacity. The predicted values of ultimate bearing capacity of soil of this study are less than those of others theories of ultimate bearing capacity. In order to facilitate the calculation of bearing capacity the proposed equations are used. It is a function of (footing width, (B), ratio of footing depth to its width, (R_f) , angle of internal friction of soil, (φ), and soil cohesion ,(c),.

Keywords: Ultimate bearing capacity, strip footing, mechanism of failure, centre location of slip failure, shape of slip failure, Krey's method

1. Introduction

The function of a foundation is to transfer the load of the superstructure to the underlying soil formation without overstressing the soil. The soil must be capable of carrying the load of structure(s) placed upon it without shear failure and with the resulting settlement being tolerable for that structure. Many investigations on the subject of ultimate bearing capacity have been carried out during the past century. Subsequently, numerous proposals have been advanced regarding considerations, criteria, and procedures for evaluation of the ultimate bearing capacity of soils. Among the very early contributors was Prandtl [16] who developed a solution for a surface strip footing over perfectly plastic cohesive-frictional weightless half-space soil. Reissner [7] extended the solution of Prandtl to include the effect of a uniform surcharge load on the resistance of penetration of ultimate applied load. Since real soils possess weight, Terzaghi [8] was the first who introduce the concept of ultimate bearing capacity and presented a comprehensive theory for the evaluation of such capacity of shallow foundations. Subsequently, the bearing capacity theory went through many modifications to account for different features such as foundation shape, load inclination, ground slope, nonsymmetrical loads, and water table. The general bearing capacity theories proposed by Meyerhof [12], Hansen [9], Vesic [19] and others are now routinely used in foundation

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design. The bearing capacity theories mentioned above require making a guess on the shape and geometry of the most critical failure surface a priori. In most cases, the selection of the failure mechanism strongly influences the quality of the solution. Here, the importance of analytical approaches, like finite element method and finite element-based limit analysis, which do not require an initial (user-defined) assumption on the geometry of the failure mode. Most failure mechanisms have been traditionally used to study the bearing capacity problem of strip footings under plane-strain conditions assumed the geometry of the failing soil mass is symmetrical with respect to the center of the footing. Krey [10] suggested that the geometry of the soil mass is unsymmetrical.

Many experimental works has been done to determine the ultimate bearing capacity and mechanism of failure for soil under footing (Eastwood [3] leshchinsky and Morozzi [11], Meyerhof, G., G [13], Mohammed A.A. H. [15] and Milovic, D. M. [14]).With the latest advances in computer speed, linear and nonlinear analyses have found more applications in soil mechanics including the bearing capacity problem. However, finite element solutions are approximations to the exact solution. Many authors used finite element method to determine ultimate bearing capacity of soil (Griffiths [8], Frydman and Burd[7], Yin, et al [20], Zienkiewicz et al. [21], De Borst and Vermeer [2], and Femman and Bemmebarek[6]).

In the present work, a numerical study is carried out for the strip footing rests on the humongous soil (c, φ) to investigate the effect of the footing width and relative depth to width ratio on the ultimate bearing capacity using Krey's method (friction circle method)assisted by a computer, MATLAB programs.

2. Krey's Method (1936) after {5}

In fact, the surface failure of the soil due to footing load is continuous surface not broken lines. Krey (1936) suggested a graphical method to determine the soil bearing capacity of strip footing. He assumed the surface of sliding being to consist of a circular arc under the footing, terminating in a tangent at (45 - *φ/2)* degrees to the ground. Krey's method is the same friction circle method of the stability of slop. Krey stated that the centre of the most dangerous circle would lie on the same level as the underside of the footing and various trial centers are taken at this level Krey's models contain active zone ABDJK and passive zone DGJ. Failure occurs when passive zone sliding up on the plane DG by effect of rotating mass of the active zone about centre of arc BD as shown in Fig. (1).

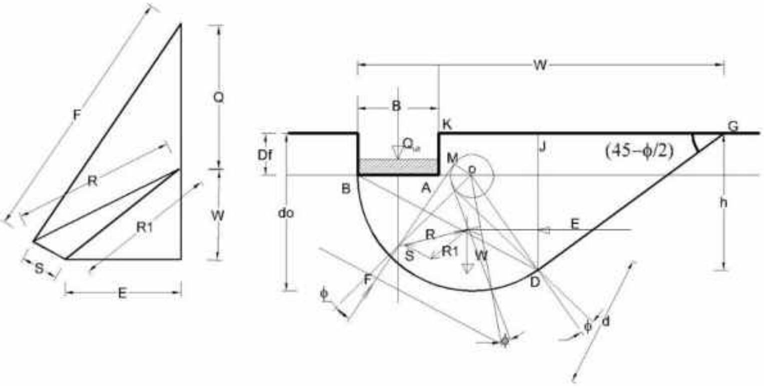

Fig. 1. Failure mechanism, according to Krey's method (after [5])

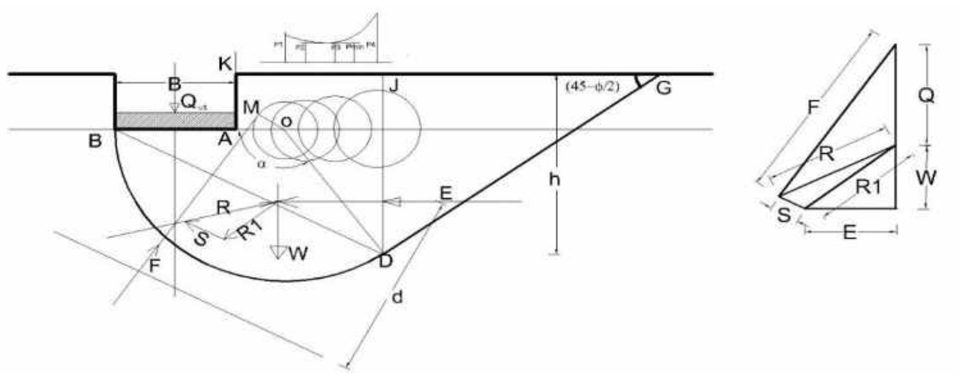

Fig. 2. Determination of ultimate bearing capacity force Q_{ult} using Krey's method (friction circle method)

2.1. The graphical procedure is as follows

1- Let the centre of the slip surface on the same level as the underside of the footing (Fig. (2).

2- Measure DJ and calculate E using the following equation.

$$E=0.5 * k_p \gamma (DJ)^2 + 2*c*DJ*\sqrt{K_p}$$

Where

$$k_p = \tan^2\left(45 + \frac{\varphi}{2}\right)$$

3- Measure the area ABDJK and calculate W, W= area(ABDJK)*γ

4- Determine the resultant of E and W to give R_1

5- Determine the cohesive force along the slip surface

$$S=c*L_{arc}(BD) = c*r*\alpha \quad \text{where } \alpha = (135 - \varphi/2) \text{ degree}$$

with distance from centre of slip surface $d = \frac{L_{arc}(BD)}{L_{chord}(BD)} = \frac{\alpha\, r}{2\sin(\alpha/2)}$ where r is the radius of slip surface

6- Find the resultant of W, E and S to give R
7- Now there are three forces at only one point R (resultant of (W, E and S), F (soil resultant reaction on slip surface, known direction and application point tangent of friction circle from left side but undetermined value) and Q_{ult} (ultimate load can carry by footing, know direction and application point.
8- Draw a tangent to the friction circle through M (intersected R, Q_{ult}) to obtain the direction of the F, the force triangle can be completed and Q_{ult} can be obtained.
9- This procedure is repeated for several trial circles and the minimum value of the Q_{ult} can be obtained.
In the present study all trials which were done and shown in Fig (2). Produced automatically by the program and Q_{ult} (ultimate bearing load) can be easily obtained.

3. Main aim of the present work

The main aim of the present work is to transfer the shown case of the ultimate bearing capacity of soil, using the Krey's method (friction circle method) into group of equations can be solved easily by computer with accuracy. Many trials are used to find the minimum soil bearing capacity which considered the centre of the slip arc locate on line pass on base of footing.

4. Parameters Studied In the Program

4.1. Footing characteristics

Footing width B= 1, 2, 3 and 4 m
Ratio of footing depth to footing width R_f = 0.0, 0.5, 1, 1.5 and 2

4.2. Soil properties

Soil cohesion, c = 0, 2, 4, and 10 t/m^2
Angle of internal friction of soil, φ = 5, 10, 15, 20, 25, 30, 35, 40 and 45 degree.

5. Procedure of Calculations

1- For a constant value of B=1 (width of footing) angle of internal friction, φ, is changed nine times φ = 5, 10, 15, 20, 25, 30, 35, 40 and 45 and corresponding Q_{ult} (ultimate load) was found. The ultimate bearing pressure can be determined by Q_{ult}/B, and maximum extent of failure surface, w.

$$\frac{w}{B}=\frac{r+(D_f+r\cos\beta)\cot\beta+r\sin\beta}{B} \qquad \text{where } \beta = 45-\varphi/2$$

and maximum depth of failure surface , $\frac{d_0}{B}=\frac{r+D_f}{B}$

where B is the footing width, w maximum extent of failure surface, d_o maximum depth of failure surface from ground surface shown Fig. (1).
2- The value B is changed four times and step No. 1 is repeated.
3- For R_f (Depth to width ratio) =0, 0.5, 1.0, 1.50 and 2 steps 1nad 2 are repeated.
4- For c= 0, 2, 4, 10 t/m^{2}steps 1, 2 and 3 are repeated.
5- Results for steps 1, 2, 3 and 4 are shown in figures (3 to10)

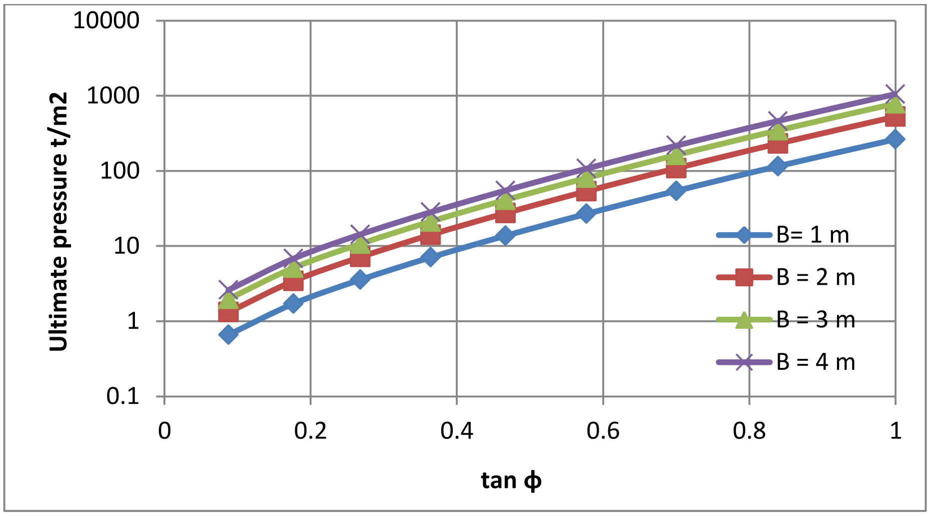

Fig. 3. Ultimate bearing capacity versustan ∅ at $R_f = 0.0$ for different values of B

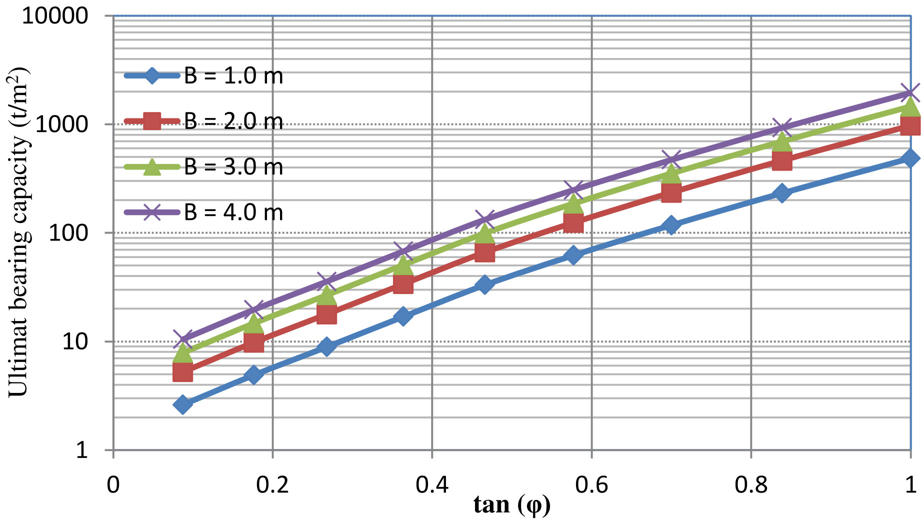

Fig. 4 . Ultimate bearing capacity versustan ∅ at $R_f = 1.5$ for different values of B

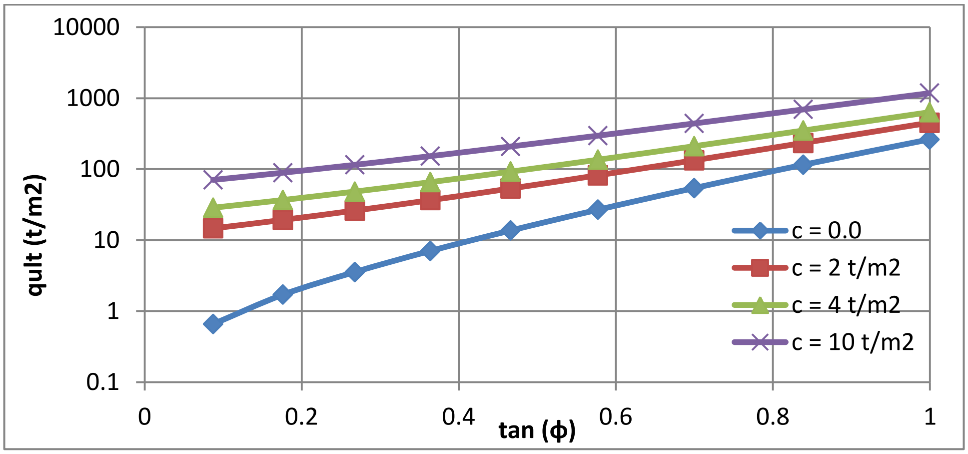

Fig. 5. Ultimate bearing pressure versustan ∅ at $R_f = 0.0$ for different values of c

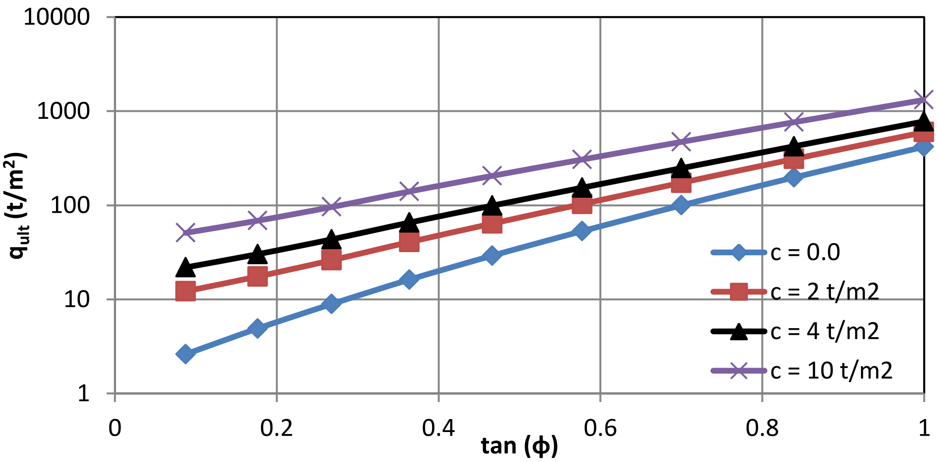

Fig. 6 . Ultimate bearing capacity versustan ∅ at $R_f = 1$ for different values of c

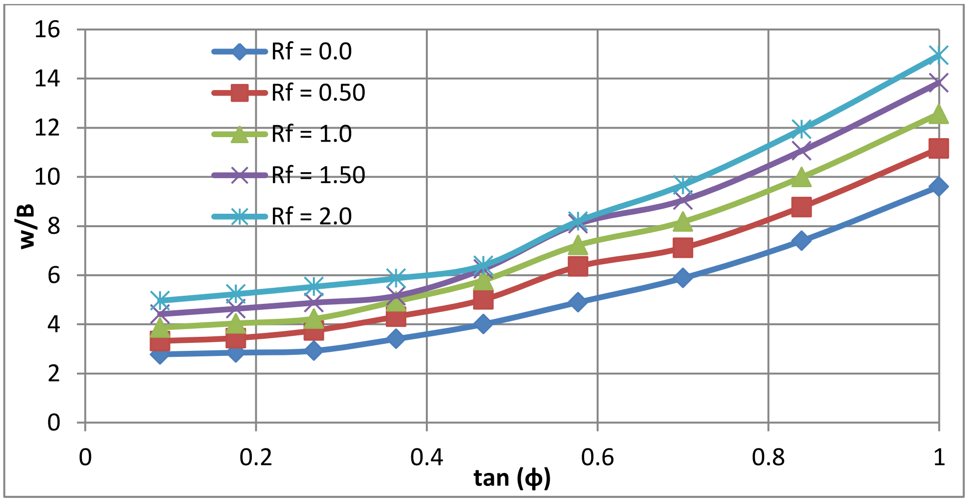

Fig. 7. Maximum extent of failure surface (w/B) versus tan(φ) at c = 0.0 for different values of R_f

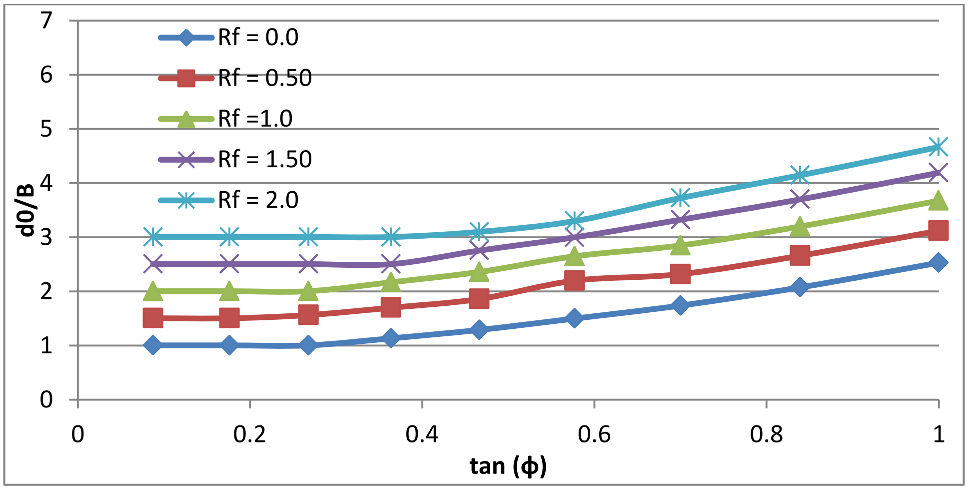

Fig. 8. Maximum depth of failure surface (d_o/B) versus tan (φ) at c = 0.0 for different values of R_f

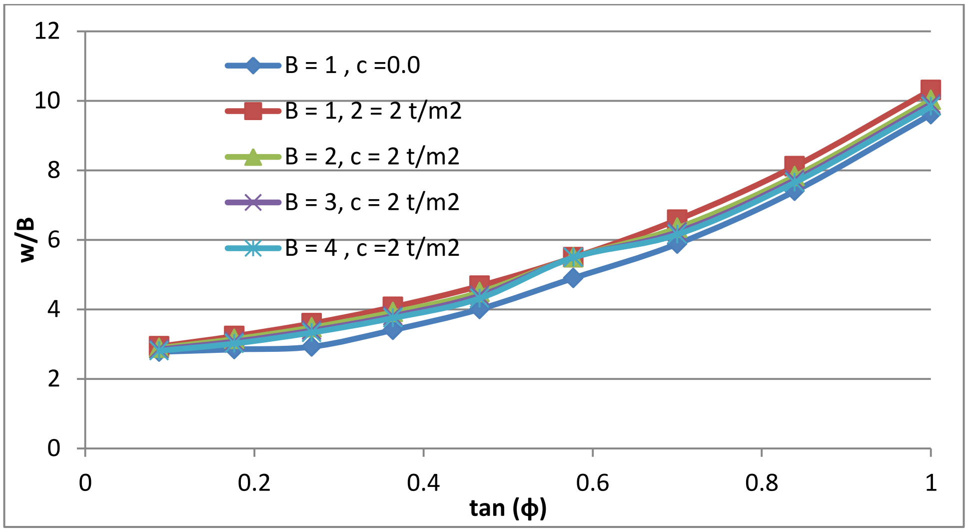

Fig. 9. Maximum extent of failure surface (w/B) versus tan (φ) at R_f = 0.0 for different values of c and B

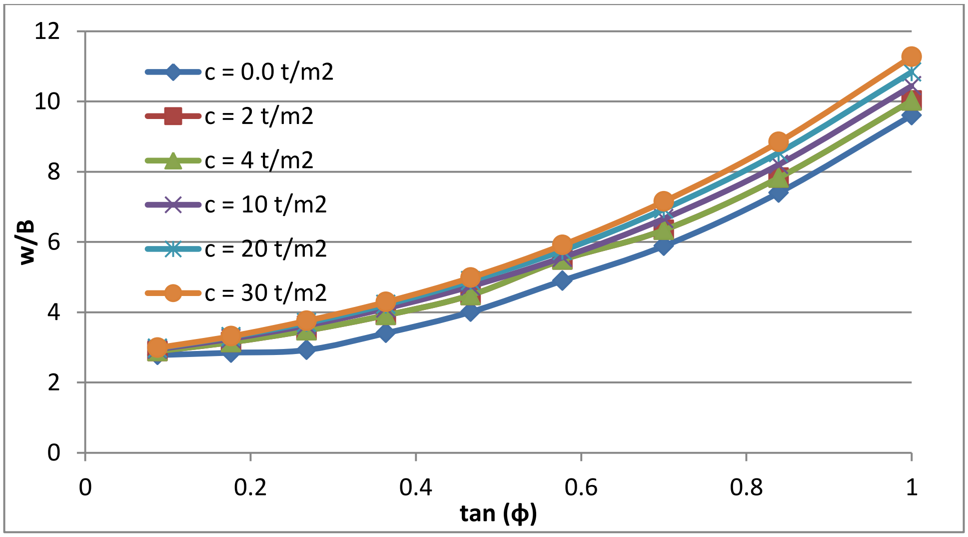

Fig. 10. Maximum extent of failure surface (w/B) versus tan(φ) at R_f = 0.0 and B = 2 m for different values of c

6. Analysis and Discussion

The discussion illustrates the effect of the foundation width, depth it width ratio and soil properties (c, φ) on the following items:

Ultimate bearing capacity of soil q_{ult},

Maximum extent of failure surface (w/B),

Maximum depth of failure surface (d_o/B) and

The deduced formula for determining q_{ult}, Nγq, N_c, w/Band d_o/B

6.1. Ultimate bearing capacity of soil (q_{ult})

The relation between ultimate bearing capacity of soil, q_{ult}, versus *tan*φ (φ is the angle of internal friction of soil) are plotted and shown Figs. (3 and 4). It is clear that with increasing φ and B the q_{ult} increasers for a constant value of R_f. The same trend is observed for the given values of R_f = 0.0, 0.5, 1.0). Figs (5and 6) show the relation between q_{ult} and *tan* φ for different values of c. It is clear that with increasing φ and c the q_{ult} increasers for a constant value of R_f. Similar trends are observed for the rest of given values of R_f.

6.2. Maximum extent of failure surface (w/B)

The relation between **(w/B)** versus *tan* φ are plotted and shown in Figs. (7, 9 and 10).It is clear that, with increasing φ and R_f the w/B increases. Figs (9 and 10) show the relation between w/Band *tan* φ for different values of c, B. It is clear that with increasing c and B the w/B slightly effect for a constant value of φ. Therefore the effect of the width of the footing and cohesion of soil may be neglected on the (w/B) and take the effect of friction only.

6.3. Maximum depth of failure surface (do/B)

The relation between (d_o/B) versus *tan* φ are plotted and shown Fig. (8). It is clear that with increasing φ and R_f the (d_o/B) increases.

6.4. The deduced formula for determining q_{ult}, Nγq and Nc

6.4.1. For coshionless soil c=0.0

Based on the obtained data from run of program, the relation between $\mathbf{q_{ult}}$ and *tan* φ is drawn for different values of B= 1, 2, 3 and 4 and R_f = 0.0, 0.5, 1.0, 1.5 and 2.0. As shown in Figs. (3 and 4) for R_f =0.0 and 1.5. At all cases the ultimate bearing capacity increases exponentially with increasing $\tan\emptyset$and linearly with increasing B at a certain R_f. The relationship between $\mathbf{q_{ult}}$ and B for the different values of φ and R_f, may be represented by the following expression

$$q_{ult} = aB\gamma e^{b\tan\emptyset}$$

where a, b are coefficients obtained by regression formula depend on R_f and are listed in Table NO.1

Table 1.
a and b coefficients

R_f	0.00	0.50	1.00	1.500	2.000
Coefficient a	0.352	0.881	1.09	1.182	1.200
Coefficient b	6.400	5.632	5.672	5.752	5.846

The relationship between a and R_f , b and R_f may be represented by the following expression

$a = -.191R_f^2 + 0.687R_f + .587$ R^2 =0 .995 for $R_f \geq 0.50$

$b = 0.054R_f^2 - 0.009R_f + 5.612$ R^2 =0.998 for $R_f \geq 0.50$

6.4.2. Bearing capacity factor $N_{q\gamma}$

The ultimate bearing capacity of soil for cohesionless soil can be expressed by the following equation

$$q_{ult} = 0.5\, B\, \gamma\, N_{q\gamma}$$

Where $\boldsymbol{N_{q\gamma}}$ is the bearing capacity factor depend on angle of internal friction of soil and R_f , may be represented by the following equation

$N_{q\gamma} = ce^{d\tan\emptyset}$

Where c, d are coefficient obtained by regression formula depend on R_f and are listed in Table No. 2

Table 2.
c and d coefficients

R_f	0.000	0.50 0	1.000	1.500	2.000
Coefficient c	0.632	1.586	1.955	2.127	2.200
Coefficient d	6.400	5.632	5.672	5.752	5.846

The relationship between a and R_f , b and R_f may be represented by the following expression

$c = -0.32R_f^2 + 1.188R_f + 1.075$ $R^2 = 0.985$ for $R_f \geq 0.50$

$d = 0.054R_f^2 - 0.009R_f + 5.6120$ R^2 =0.998 for Rf≥ 0.50

6.4.3. For (c-φ) soil

Based on the get data from run of program, the relation between q_{ult} and $\tan\emptyset$ is drawn for different values of c =0, 2, 4, and 10 t/m^2 and R_f = 0.0, 0.55, 1, 1.5 and 2 as shown in Figs. (5 and 6). At all cases the ultimate bearing capacity increases exponentially with $\tan\emptyset$ increasing and linearly with increasing c at a certain R_f. The ultimate bearing capacity of soil can be divided into two parts. First part for cohesion while second part for friction. The relationship between $\mathbf{q_{ult}}$ and B for the different values of c, φ and R_f, may be represented by the following expression

$$q_{ult} = cN_c + a\,B\,\gamma\,e^{b\tan\emptyset}$$

$$\text{or } q_{ult} = cN_c + 0.5\,B\,\gamma\,N_{q\gamma}$$

$$N_c = \frac{q_{ult-aBe^{b\tan\emptyset}}}{c}$$

The value of N_c versus $\tan\emptyset$is plotted for different values R_f as shown in Fig. (11). It is clear that with increasing $\tan\emptyset$ the value of N_c increases, and slightly decreases with increasing $R_{f.}$ the relationship between N_c and $\tan\emptyset$ may be represented by the following expression:-

$$N_c = 5.5815\,e^{2.90\tan\emptyset} \qquad \varphi \geq 5$$

All the deduced formula can be easily calculated by ordinary calculator.

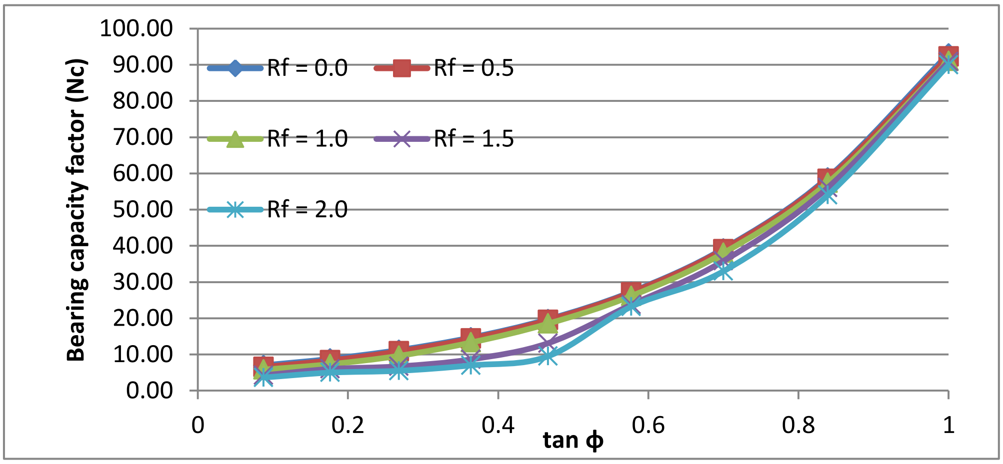

Fig. 11. Bearing capacity factor (N_c) versus tan φ for different Rf

6.4.4. Maximum extent of failure surface (w/B)

Based on the get data from run of program, the relation between **(w/B)** and *tan* φ is drawn for different values of R_f = 0.0, 0.5, 1, 1.5 and 2. as shown in Figs.(7). The relationship between **(w/B)** and tan (φ) for the different values of $R_{f,}$ may be represented by the following expression

$$\frac{w}{B} = e e^{f\tan\emptyset}$$

where e, f are coefficients obtained by regression formula depend on R_f and are listed in Table NO.3

Table 3.
e and f coefficients

R_f	0.000	0.500	1.000	1.50	2.000
Coefficient e	2.150	2.715	3.155	3.566	4.000
Coefficient f	1.455	1.393	1.366	1.330	1.261

The relationship between e and R_f, f and R_f may be represented by the following expression

$$e = 0.91R_f + 2.207 \qquad R^2 = 0.996$$

$$f = -0.09R_f + 1.451 \qquad R^2 = 0.975$$

6.4.5. Maximum depth of failure surface (d_o/b) from the ground surface

Based on the obtained data from run of program, the relation between $(\boldsymbol{d_o}/\mathbf{B})$ and *tan* φ is drawn for different values of R_f = 0.0, 0.5, 1.0, 1.5 and 2.0as shown in Figs. (8).The relationship between $(\boldsymbol{d_o}/\mathbf{B})$ and tan (φ) for the different values of R_f, may be represented by the following expression

$$(\boldsymbol{d_o}/\mathbf{B}) = ge^{h \tan \emptyset}$$

where g, h are coefficients obtained by regression formula depend on R_f and are listed in Table NO.4

Table 4.
g and h coefficients

R_f	0.000	0.500	1.000	1.500	2.00
Coefficient g	0.817	1.298	1.747	2.188	2.46
Coefficient h	1.100	0.851	0.715	0.613	0.51

The relationship between e and R_f , f and R_f may be represented by the following expression

$$g = 0.835R_f + 0.866 \qquad R^2 = 0.991$$

$$f = 1.062e^{-0.37R_f} \qquad R^2 = 0.991$$

7. Application of the Program and Deduced Formula and Comparison with Others

Some examples were solved using the suggested program and the formulas given by author. Comparison with the references given in Figs (12 and 13) and Table No. 5 and 6. Fig. 12 shows the q_{ult} versus tan φ at B =1 m ,R_f = 1, c = 2t/m^2 and γ = 1.8t/m3 using different methods. It is clear that the q_{ult} values determined by current method (Krey's method) are less than those of others methods. The results obtained from the current method are more nearest to those of ECP. Fig.13 shows the $N_{q\gamma}$ versus tan φ at ground surface form experimental work by Mohammed [15] and current method. As deduced from this figure the values of Nqγ good agree with current method and experimental work.

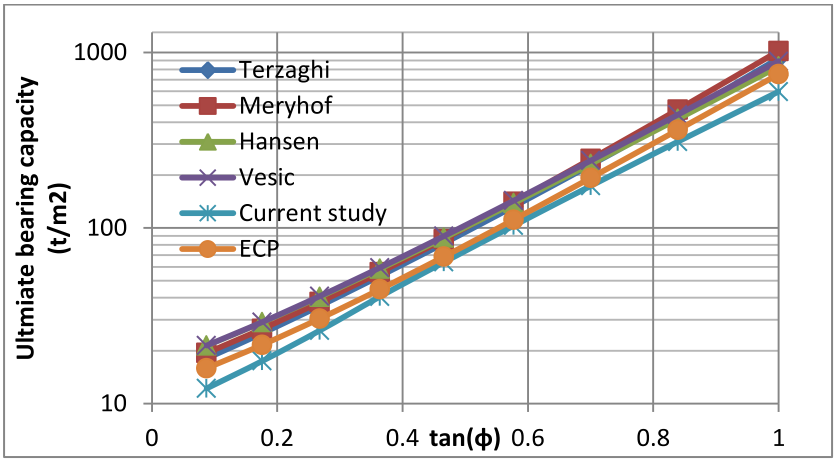

Fig. 12. Ultimate bearing capacity versus tan Ø at B = 1.0 m, Rf = 1, c = 2 t/m^2 using different methods

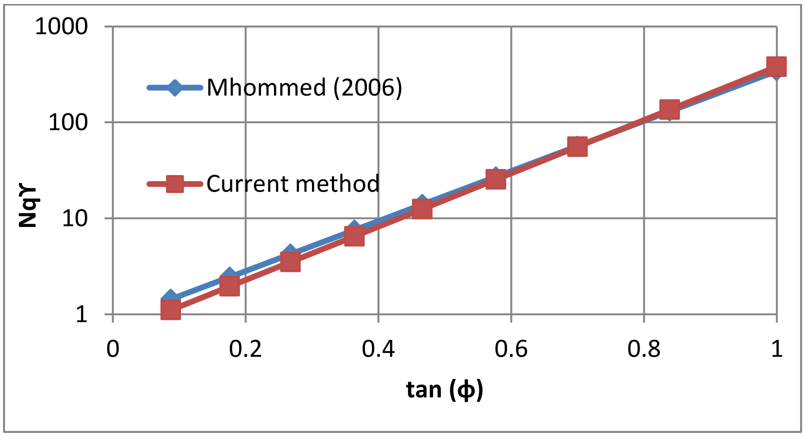

Fig. 13. Bearing capacity factor ($N_{q\gamma}$) versus tan φ at $R_f = 0.0$ for Mohammed [15] and current method s

Table 5.

Values of q_{ult} for current method with respect to other methods for various footing dimensions and soil properties

Bearing capacity method		Test No.				
		Footing and soil properties	1	2	3	4
		D(m)	0.0	0.5	0.5	0.5
		B(m)	0.5	0.5	0.5	1.0
		L(m)	2.0	2.0	2.0	1.0
		γ(t/m3)	1.569	1.638	1.706	1.706
		φ(degree)	38.5	36.25	40.75	38.5
		C(t/m2)	0.637	0.392	0.78	0.78
Muhs(tests)	q_{ult} (t/m^2)	After (Bowles)	108	122	242	330
Terzaghi			94	92	229	197
Meuerhof			82	103	264	284
Hansen			72	98	237	234
Vesic			81	10.4	251	247
Balla			140	153	358	330
Plaxis 2D			80	78	182	171.1
Krey (current method		program	74	69.6	151.4	162.13
		deduced formula	75.6	68.9	161.6	162.2
Bearing capacity method		Test No.				
		Footing and soil properties	5	6	7	8
		D(m)	0.4	0.5	0.0	0.3
		B(m)	0.71	0.71	0.71	0.71
		L(m)	0.71	0.71	0.71	0.71
		γ(t/m3)	1.765	1.765	1.706	1.706
		φ(degree)	22	25	20	20
		C(t/m2)	1.275	1.47	0.98	0.98
Muhs(tests)	q_{ult} (t/m^2)	After (Das2001)	41	55	22	26
Terzaghi			43	65	25	29
Meuerhof			48	76	23	30
Hansen			50	80	22	31
Vesic			51	82	23	32
Balla			60	92	26	38
Plaxis 2D0			36.9	53	21.7	25
Krey (current method)		program	32	45	19.4	22.1
		deduced formula	32.9	41	20.7	21.8

Table 6.
Values of q_{ult}, (w/B) and (d_o/B) for current method with respect to other methods for various footing dimensions and soil properties

			Test No.		
			1	2	3
Footing characteristics	B(mm)		50	38	50
	R_f		0.0	0.0	0.2
Soil properties	φ(degree)		44		
Using methods	*Leshchinsky and Marcozzi,*	$q_{ult}(t/m^2)$	6.76	6.34	9.56
	Terzaghi		4.5	3.47	7.06
	Meryhof		9.1	6.92	9.54
	Hansen		7.04	5.36	9.07
	Vesic		9.54	7.27	11.57
	Current method		10.5	8.04	11.85
	Leshchinsky and Marcozzi	w/B	3.3	3.8	5.8
	Terzaghi and Meryhof		8.66	8.66	
	Hansen andVesic		10.8	10.8	
	Current method		6.43	6.43	6.96
	Leshchinsky and Marcozzi	d_o/B	1.2	1.33	1.76
	Hansen and Meryhof		2.83	2.83	
	Terzaghi		1.91	1.91	
	Current method		1.87	1.87	2.172

8. Conclusions

The problem of the ultimate bearing capacity determination of strip footing using Krey's method (friction circle method) on (c-φ) soil can be easily analyses and solved to find the ultimate bearing capacity, q_{ult}, bearing capacity factors (N_c and $N_{q\gamma}$), maximum extent and maximum depth of failure surface ((w/B) and (d_o/B) by a simple program by author instead of a graphical methods used before in this method. The recommend program based on footing characteristic and soil properties described in details of the case study. Simple formulas were deduced base on results obtained from run of computer program for the case study to calculate easily by a calculator (q_{ult}, N_c, $N_{q\gamma}$, w/B and d_o/B). A comparison was made between results of present work and other researches (experiential and theoretical) to evaluate to mention items. The obtained results approximately well agreed with some pervious works.

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قوة تحمل التربة لاساس شريطى باستخدام طريقة كيرى
(طريقة دائرة الاحتكاك)

الملخص العربى

فى الابحاث الجيوتقنية تحديد قوة تحمل التربة تعتبر من اهم المهام ومعظم الابحاث السابقة تدرس اتزان الاساس باستخدام نظريات التحميل الكلاسيكية حيث ان نظرية التحميل الكلاسيكية تم استنتجتها على نظرية المرونة و فرض سلوك التربة على انها مادة جامدة-لدنة وكذلك تتضمن تخمين شكل ومستوى الانهيار الحرج التى تعطى اقل قوة تحمل و جميع هذه النظريات تفترض مستوى الانهيار متماثل حول مركز الاساس بينما كيرى اقترح ان مستوى الانهيار غير متماثل حول مركز الاساس وعلى الرغم من ان الطرق العددية لا تطلب شكل مسبق لمستوى الانهيار مثل طريقة العناصر المحددة . فى هذا البحث استخدمت دراسة نظرية بمساعدة برنامج كمبيوتر (MATLAB) تم اعداده بواسطة الباحث مستخدما طريقة كيرى لبحث مكان مركز دائرة الانزلاق التى تعطى اقل قوة تحمل لاساس شريطى و ايضا استخدم برنامج (*Plaxis 2D*) لحل بعض الحالات التى درست بواسطة طريقة كيرى و قورنت نتائج البحث مع النتائج النظرية الاخرى والكود المصرى لميكانيكا التربة والاساسات (202). اوضحت المقارنة ان قيمة تحمل التربة من هذه الطريقة اقل عن المحسوب بالطرق الاخرى و مقاربه جدا لكود المصرى و لسهول حساب قوة تحمل التربة الحدية استنتجت معادلات بناءا على النتائج الناتجة من البرنامج يمكن منها حساب قوة التحمل للتربة باستخدام اله حاسبة عادية و هذه المعادلات معتمدة على عرض الاساس و نسبة عمق التأسيس الى العرض و خواص تربة التأسيس زواية الاحتكاك الداخلى (φ) و معامل تماسك التربة (c).