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Finite Element Analysis of Skirted Strip Footing Resting on Cohesive Slopes

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Abstract

The bearing capacity of footing with and without a skirt has been investigated using a series of finite element analyses using the Geo-slope program. Several models were conducted with varying skirt depths and slope crest lactations. The impact of slope inclination β, height H, and soil undrained shear strength Cu were also covered. The paper findings demonstrated that several factors significantly change the estimate of bearing capacity with great effectiveness that is ranging between 16.7% and 52.7% for D/B = 0.5, 1 and 1.5, and L/B (distance from edge slope/width of footing) = 0, 1, 4 and 8 respectively, and 18.2%, 36.4, 57.6%; 11.6%, 17.6%; 27.9% kPa, for D/B (depth of skirt/width of footing) = 0.5, 1 and 1.5 and L/B = 0, 1, 4 and 8 respectively in case β=10° slope inclination with H/B =2 and C_u=60 kPa for D/B = 0.5, 1 and 1.5 and L/B = 0, 1, 4 and 8 with C_u=20 kPa respectively in case β=10° slope inclination with H/B =2, also the critical L/ B ratio is 4. Beyond this value, the increase in bearing capacity became constant.

Keywords: Bearing capacity; Cohesive soil; Finite elements; Skirted footing; Slope

1. Introduction

Footings located on or near slopes, such as bridge piers on approach embankments, transmission tower foundations, and buildings on hill slopes, can encounter challenges when the slope face acts as a finite boundary. This situation may lead to an insufficient and unsightly as the foundation approaches the limit state under applied loads, and the plastic failure region develops. The aforementioned phenomena may significantly reduce the foundation's carrying capacity depending on the footing location and how steep the slope is. Additionally, the slope's exposed face causes observable outward displacement, which can eventually result in alarming settlement failure of the foundation [1]-[3]. Skirted foundations are steel or concrete, with a relatively thin plate or wall beneath the perimeter. Hence, the name and a top raft serve as the foundation. The skirt creates an enclosure where the earth is securely contained after penetrating the ground beneath the foundation. To transfer weights to the soil at the skirt tip's level, the constrained soil and the skirt work together as a unit. These skirts enhance the foundation's performance, reducing settlement and increasing bearing capacity [4].

Skirted foundations have proven suitable substitutes for surface, pier, and piling foundations in wind turbines, jacket structures, offshore industries, and oil platforms. When compared to traditional deep foundations, the primary benefits are their quick and simple installation and cost-effectiveness. Several researchers have used physical modeling and numerical analysis to study how well these foundations work, and they have reported improved behavior [5]-[7].

According to an analysis of the performance of a skirt beneath the foundation, deep foundations can take the role of skirted foundations in weak soils [8].

Using the finite-element method, the shape of a skirted foundation affected how these foundations behaved. The outcomes demonstrate that, when compared to a strip foundation, the circular foundation performs better [9].

Physical model testing [10]-[12] reported notable improvements in the load-deflection characteristics of a foundation. The findings demonstrated that using skirts increased shallow foundations' bearing capacity by up to 312% and decreased their settlement by up to three times. Also, according to studies by Alansari et al. [13] and Eid [14], the bearing capacity of shallow foundations rises as skirt depth decreases and sand shear strength decreases. The results also showed settlement reductions of up to 70% when skirts beneath shallow foundations were situated on sand.

The number of combined foundations under the effect of horizontal and vertical moment loads shows that significant changes in the ground fault mechanism compared to a simple edge mat led to a significant increase, especially in the horizontal load-bearing capacity. Also, the identified effects are mainly due to increased moment resistance [15].

The outcomes of a laboratory test program designed to find the optimal skirt foundation length-to-diameter ratio in order to maximize bearing capacity on gypsum sand soils with different relative densities were presented by Mahmood et al. [16] Fattah et al. [17]. A 54% gypsum content of gypsum soil was chosen from the city of Tikrit, which is located north of Baghdad. Model tests were conducted on relatively dry soil densities of 55% and 70% to create load curves for circular skirt foundation designs. These designs' skirt ratios (L/D length/diameter ratio) were 0, 0.25, 0, 5, 0, 7, 1, 1. 5, 2, and 3. The bottom line is that on gypsum soil, by increasing the relative density and the depth/diameter ratio, a skirt improves the bearing capacity of the foundation surface.

Using Plaxis3D, 3D FEM analysis of an octagonal raft foundation with and without skirts was carried out. The work parameters considered how the loading circumstances, skirt length (L), and skirt spacing (D) affected the foundation conditions' bearing capacity and settling. The findings demonstrated that moment loading with longer skirts was the cause of the decrease in differential settling and rotation (L) [18].

The gypseous sand soil stage was considered when performing finite element studies with varied skirt depth to footing diameter ratios (d/D). The findings demonstrated that the soil stage and the skirt embedment ratio substantially impacted the final bearing capacity and the settling of weak soil, with an increase in the latter leading to better-skirted footing performance. Moreover, the loading stage exhibited the least settlement improvement, while the collapsing soil stage exhibited the most significant amount [19].

The load-displacement relationship (P-δ) of flat and various shell foundation types was the subject of earlier research. Numerous factors, such as the foundation's geometry and the soil's characteristics, have also been considered. The findings demonstrated that in various sand conditions, particularly in weak sand layers with low relative density and angle of internal friction, increasing the embedment depth ratio increases foundation capacity. Conical shells with varying D/B ratios have a larger bearing capacity than skirted ones, as shown by the findings of bearing load in loose sand, which is especially evident when $D/B \leq 0.5$ [20].

Geotechnical engineers have a complicated problem when designing foundations on slopes. Location, loading pattern, slope angle, footing depth of embedment, edge distance from slope face, foundation soil's shear strength properties, and additional factors like rainfall, seismic activity, and foundation material saturation level all have an impact on a footing's stability when it is on or near a slope. Because of the limited zone of passive resistance that develops toward the slope face, footing placed close to a slope's face is expected to have less bearing capacity. Most of the work has been done to determine how much weight a strip footing can support when it is placed on a sandy soil slope that is less cohesive and dry, as well as to investigate the effects of the regulating factors (the footing's width, the setback distance, the slope's steepness, and the loading type on the footing). Very few published works discuss laboratory investigations for square and circular footings resting on a slope [21]-[26].

The objective of the present work is to explore the possibility of increasing the stability of foundations near slopes by exerting skirts on the footings and working on the effect of skirt dimension on bearing capacity and settlement of footing on clay soil slope. The analysis was conducted numerically via the finite element method. The importance of the work lies in investigating the effect of skirts on increasing foundation confinement near slopes and submitting a recommendation for using such types of foundations near slopes.

2. Description of the Problem

The skirt thickness was considered equal to the footing thickness = 0.3 m and the slope height ratio (H/B = 2 and 4, where H is the slope height), as illustrated in Fig. 1. Consequently, the following equation is a description of the bearing capacity of a rough strip footing with skirts under static conditions [27].

$$q_u = f(\frac{\boldsymbol{L}}{\boldsymbol{B}} \frac{\boldsymbol{D}}{\boldsymbol{B}} \frac{\boldsymbol{H}}{\boldsymbol{B}}\ \boldsymbol{Cu}\ \boldsymbol{\beta}) \tag{1}$$

3. Finite Element Description and Constitutive Models

The finite element mesh by Geo – -studio (SIGMA / W) program is illustrated in Fig. 2. The footing with the underneath soil was modeled using elements. The soil slope skeleton and the footing with skirts were modeled using eight nodded quadrilateral isoparametric elements. The bottom of the mesh is restricted in both horizontal and vertical directions, and the mobility of its right- and left-hand edges is also limited. For the top edge, both directions are available. Additionally, it is assumed that the top and bottom edges are permeable and the side boundaries are impermeable, meaning that no flow is permitted through them. In this work, two constitutive models are used to describe the stress-strain behavior of the soil. A linear elastic model describes the footing with skirts, and an elastic-plastic model with the Mohr-Coulomb failure criterion is used to simulate the slope with the soil underneath. Finding a more precise value for qu requires applying all effective parameters simultaneously to the numerical model. Table 1 lists the characteristics of the soil. Conventional soil parameters were used to select the qualities.

Table1. Soil properties used in the analysis

Property	Unit	Values
Undrained shear strength, Cu	kN/m^2	20 40 60
The angle of friction, Ø	Degree	10 20
Moisture content, w	%	15 10

Saturated unit weight, γ_{sat}	kN/m^3	20.0 20.2 20.5

4. Failure Definition

Numerous methods have been presented to determine the footing's ultimate bearing capacity and failure. One of these was the tangent proposal presented by Fellenius [27], where the intersection of the load-settlement curve's two tangents serves as the basis for the definition of failure. While the second tangent is tangent to the lower, flatter portion of the curve, the first tangent is to the curve's initial part. This work's definition of failure was based on this standard.

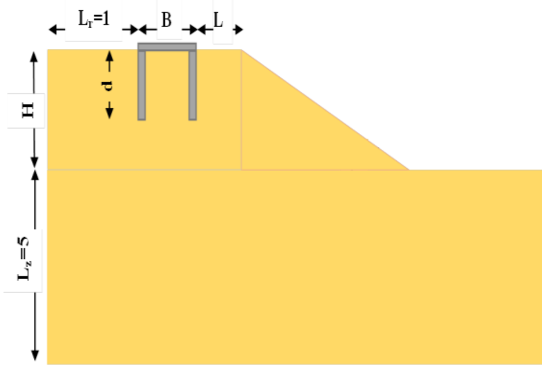


Figure 1. Geometry of the problem

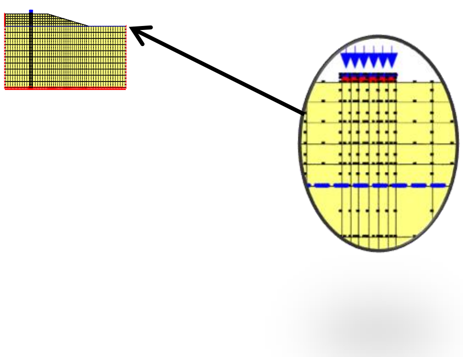


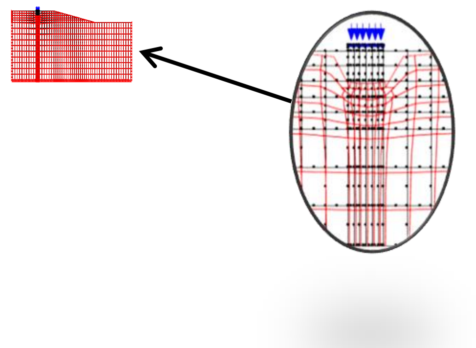
Figure 2. The finite element mesh of a foundation slope system without skirted cu = 20 kPa, d = 0 m, H = 4 m and Ø =10°

5. Results

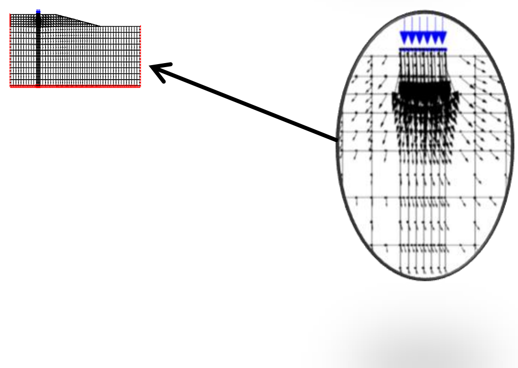
For the situations of (cu = 20 kPa, d = 0 m, H = 4 m, and = 10°), the results of the finite element analysis for the foundation without skirts adjacent to the clay slope are shown in Fig. 3. The figures show a typical displacement vector and a deformed mesh that was found through analysis for the problem, respectively. The bulk of soil particle deformation and flow occurs at the slope face, as indicated by the observed total displacement vectors at failure, which are concentrated beneath the foundation. Such skirts improve the inertial stability of a slope and the subgrade, as opposed to the case of a foundation without skirts. The finite element outputs for a slope and a skirt foundation-soil system are displayed in Fig. 4. To reduce the slope's proximity to a slope with minimal horizontal deformation is a wise move.

5.1. Effect of Skirt Depth and Height of Slope

Models were conducted on un-skirted footings with the same width on the same soil formation to examine the impact of skirt length on the bearing capacity (BC) of shallow footings. The pressure-settlement relationships were plotted for every test on identically sized footings. Typical pressure-settlement curves of footing-skirt soil system for skirt depth (0, 1, 2, and 3m), embankment height (4 and 8 m), distance from slope (0 and 8 m) and inclination slope 10° and shear strength (20, 40 and 60 kPa) are shown in Figs. 5, 6 and 7, respectively.

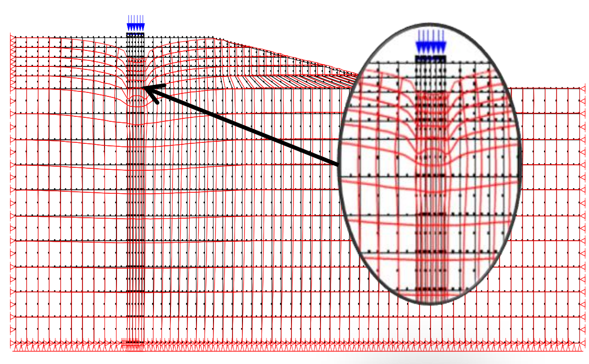


a. Deformed mesh.

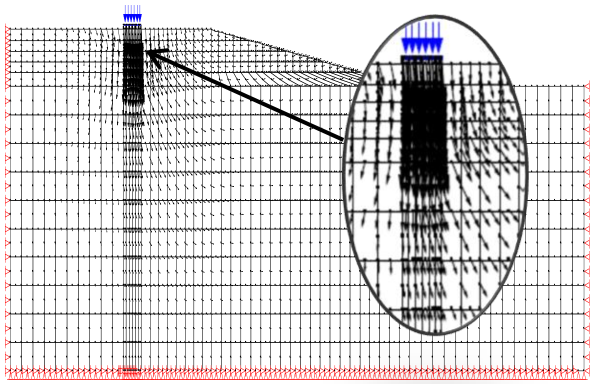


b. Displacement vectors

Figure 3. The finite element output of a foundation on a slope without skirted c_u=20 kPa, d=0m, H=4m, and Ø=10°



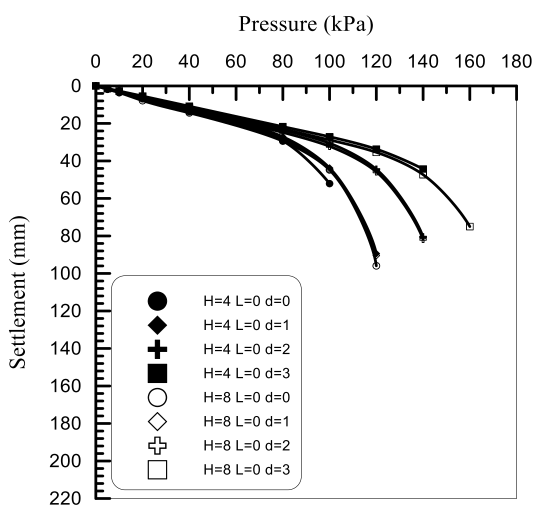
a. Deformed mesh.



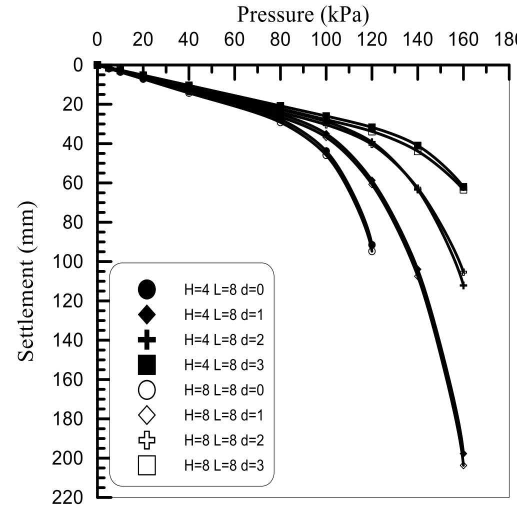
b. Displacement vectors

Figure 4. The finite element output of a foundation on a slope without skirted c_u=20 kPa, d=3m, H =4 m, and Ø =10°.

It can be noticed from the figures that the BC increased by about (18%, 40%, and 45%), (30%, 34% and 40%), (16%, 40% and 57%) and (28%, 32% and 38%) as increasing the depth of skirt (d) from (0 – 3 m) and height of slope 4 m and 8 m for footing on slope edge (L= 0 and L = 8 m), respectively for inclination angle (β = 10°). The effect becomes constant when the footing is located away from the face of the slope (L = 8 m). Also, the curve behavior changes and becomes a straight line with increasing depth of the skirt. This increase may be due to the change due to the entire or partial confinement of the soil's formed plastic zone; therefore, additional displacement is needed to mobilize the soil's shear failure plane. This may help explain why the footings can withstand a more significant failure load as the skirt length increases. It may also help explain why strain hardening occurs during the pressure process and clay compressibility changes. Additionally, the results indicate that the slope height had little effect on the bearing capacity value as the skirt depth increased. Still, a significant increase was observed as the shear strength increased [28].

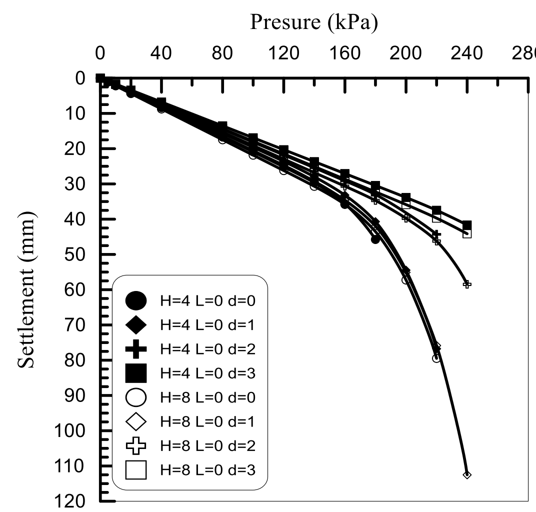


a. L = 0

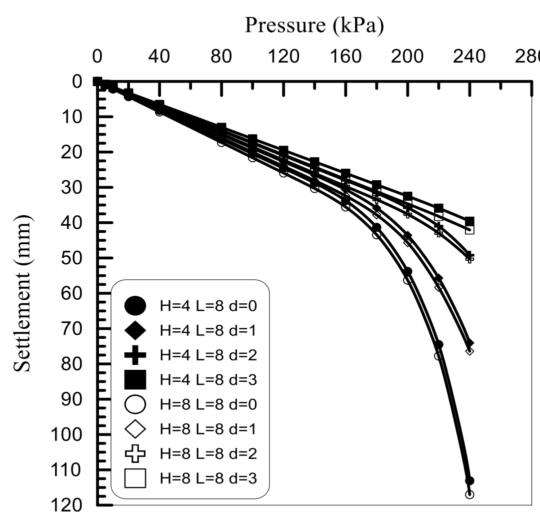


b. L = 8 m.

Figure 5. Pressure – settlement relation for skirted footing near a slope when C_u = 20 kPa and Ø = 1

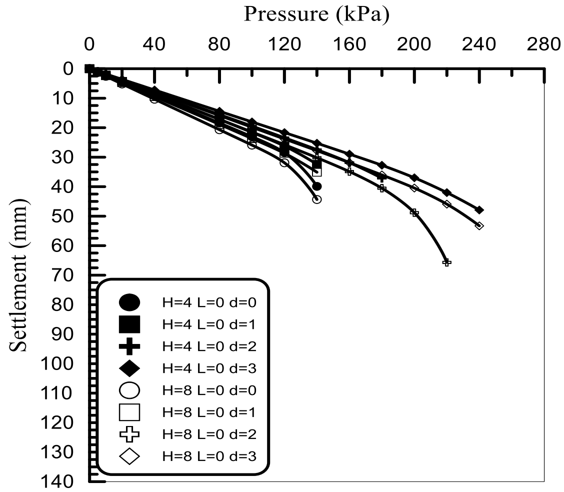


a. L =0

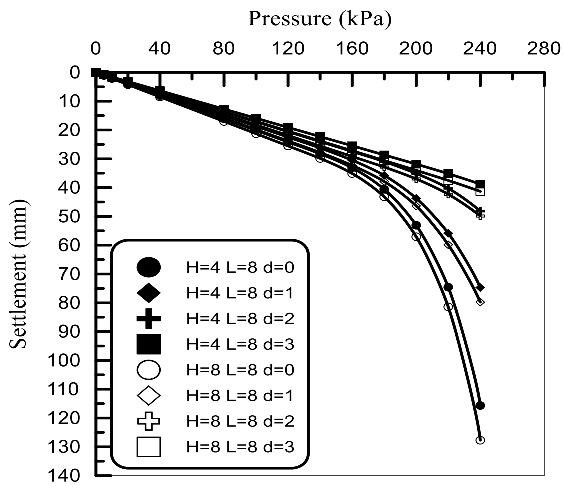


b. L = 8 m.

Figure 6. Pressure – settlement relation for skirted footing near a slope when C_u = 60 kPa



a. L = 0



b. L =8 m

Figure7. Pressure – settlement relation for skirted footing near a slope when C_u = 60 kPa and β = 10°.

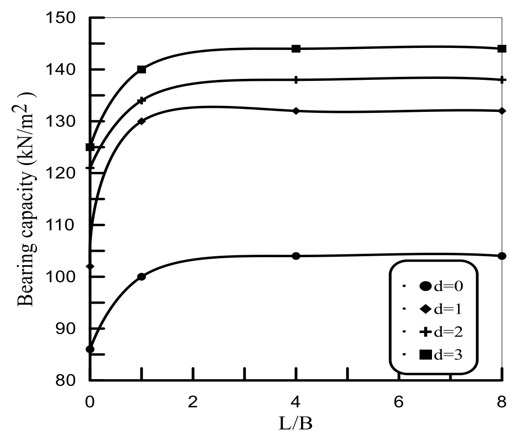
5.2. Effect of Foundation Position from Slope Edge and Slope Inclination

Figs. 8 to 10 demonstrate the effect of footing location from the slope of the top edge with different inclinations (10, 30, and 60 degrees) and heights of slope (4 and 8 m) with C_u= 20, 40, and 60 kPa. It can be noticed from these figures that the bearing capacity increased by about (20%) as the distance-to-width footing ratio increased until it reached L/B = 4, then the rate became constant for models without skirt (d = 0, L/B = 0, C_u = 20 kPa and β = 10°). Because skirts can significantly reduce slope deformation and increase slope stability when the skirted foundation is located far from the slope, the footing's likelihood of failing under distressing conditions due to the deformation of the slope face was reduced. The same behavior is acting for skirt models with a higher increasing rate in bearing capacity by roughly 53%.

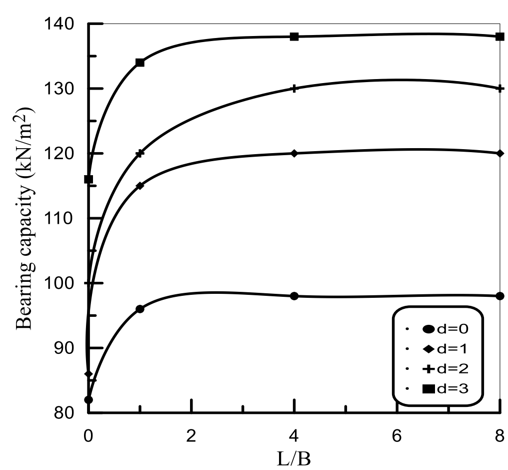
Additionally, work was done on how the slope angle affected a slope loaded with a skirted foundation's bearing capacity. Figures show that when the footing rests on or close to a slope with a lower inclination, it has a greater bearing capacity. It is evident that as the slope's angle of inclination increases, the bearing capacity decreases. This is explained by the fact that a steeper slope will have a smaller zone of passive resistance, which means that the soil near the slope face will provide less resistance to failure. The results also conclude the effects of soil strength. These numbers show that for d = 3 m, H = 4 m, and 8 m, respectively, at the same inclination, an increase in Cu from (20 to 60 kPa) increased bearing capacity from (125 to 312 kPa) and from (132 to 308 kPa). The results of 480 models are summarized in Tables 2, 3, 4, 5, and 6.

These findings are consistent with those of [29], who discovered that the bearing capacity of skirted footing increases between 1.92 and 2.27, depending on the skirt's surface, geometrical parameters, and the soil's attributes. Generally speaking, a higher L/D ratio will cause lines of failure beneath the footing to cross with the presence of skirts, preventing its influence from reaching the soil's surface. This confines the soil inside the skirt, increasing the bearing capacity.

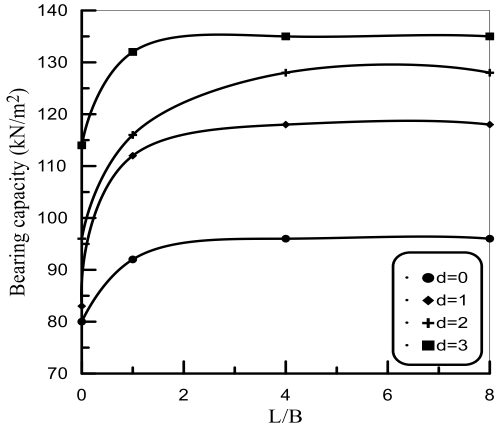
a. Cu = 20 kPa, H = 4 m, β = 10º.



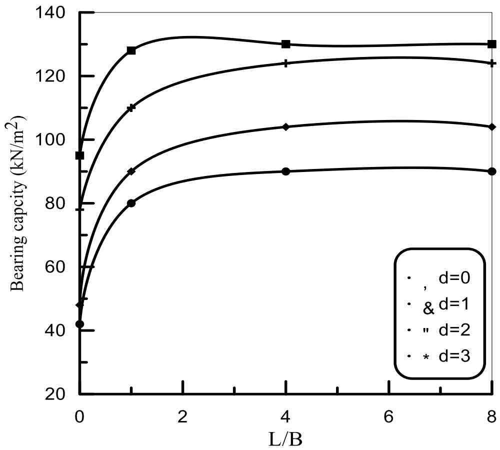
b. Cu = 20 kPa, H = 4 m, β = 10º.



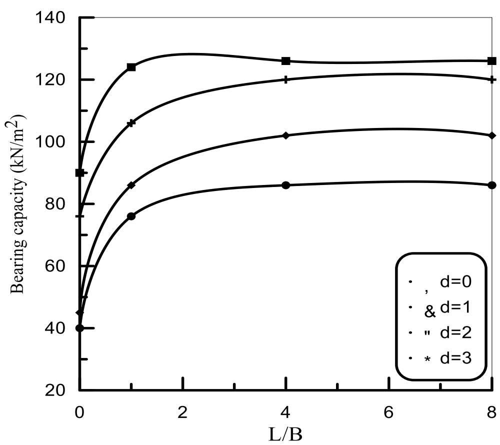
c. Cu = 20 kPa, H = 4 m, β= 30º.



d. Cu = 20 kPa, H = 8 m, β = 30º.

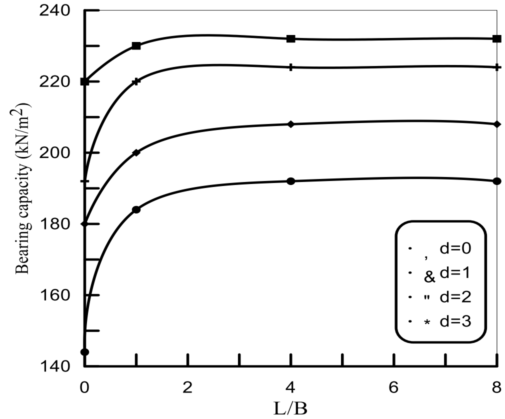


e. Cu = 20 kPa, H = 4 m, β = 60º.

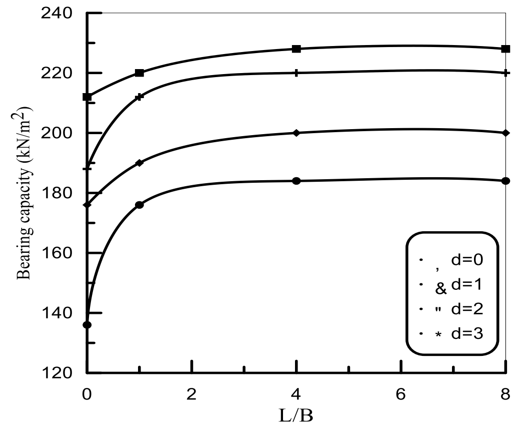


f. Cu = 20 kPa, H = 8 m, β = 60º.

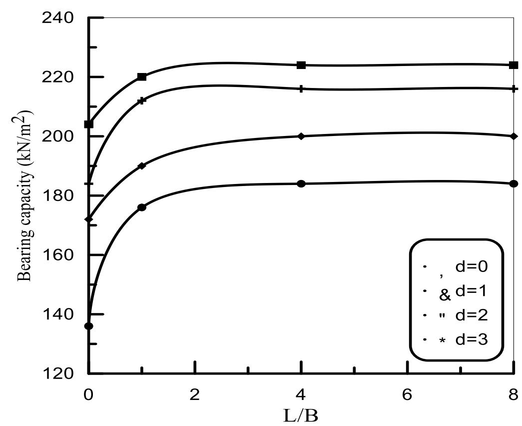
Figure 8. Effect of L/B on the bearing capacity of skirted footing near a slope with Cu = 20 kPa.



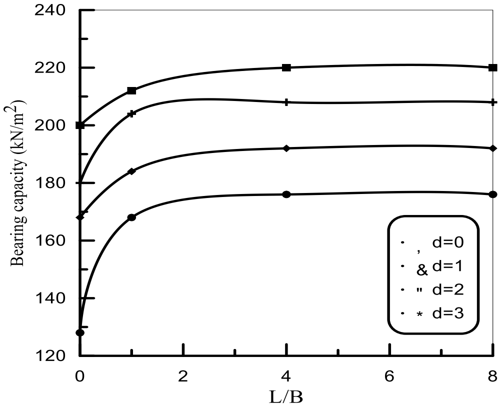
a. Cu = 40 kPa, H = 4 m, β = 10º.



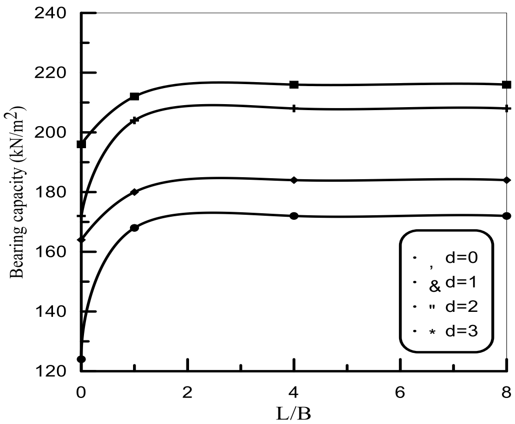
b. Cu = 40 kPa, H = 8 m, β = 10º.



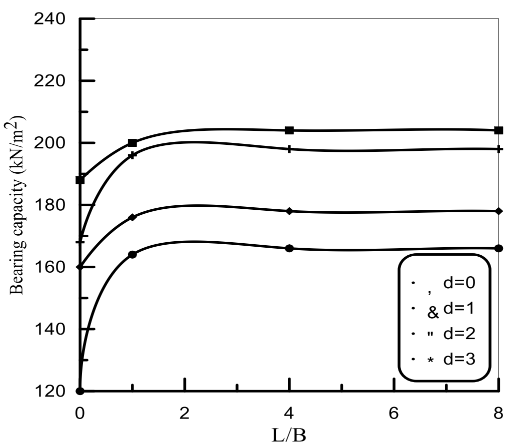
c. Cu = 40 kPa, H = 4 m, β = 30º.



d. Cu = 40 kPa, H = 8 m, β = 30º.

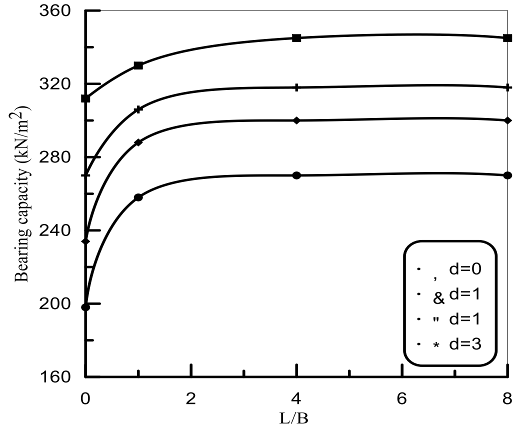


e. Cu = 40 kPa, H = 4 m, β = 60º.

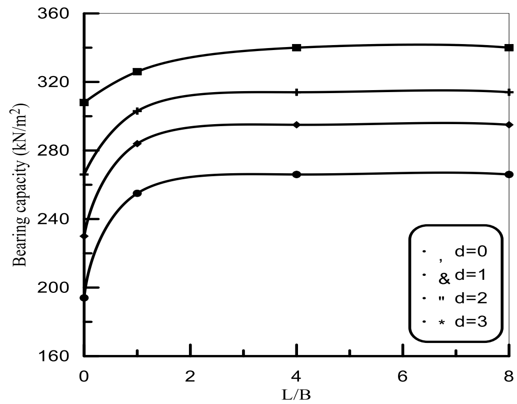


f. Cu = 40 kPa, H = 8 m, β = 60º.

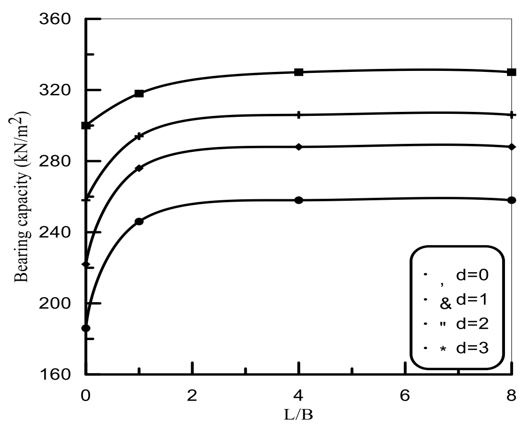
Figure 9. Effect of L/B on the bearing capacity of skirted footing near a slope with Cu = 40 kPa.



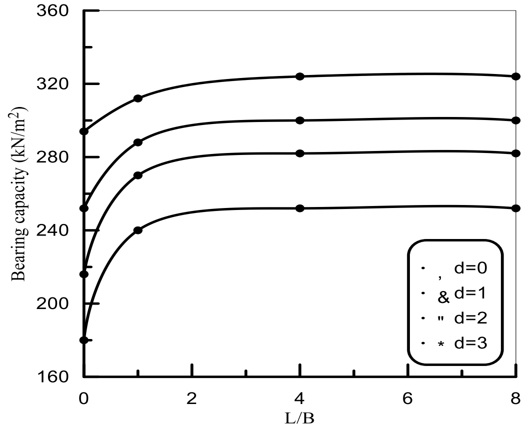
a. Cu = 60 kPa, H = 4 m, β = 10º.



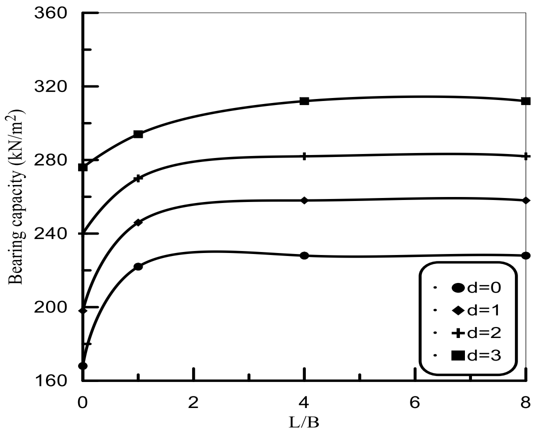
b. Cu = 60 kPa, H = 8 m, β = 10º.



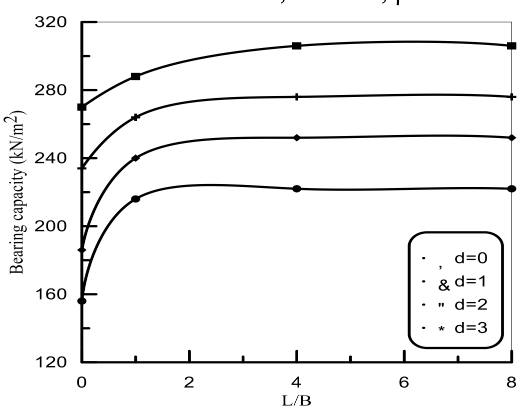
c. Cu = 60 kPa, H = 4 m, β = 30º.



d. Cu = 60 kPa, H = 8 m, β = 30º.



e. Cu = 60 kPa, H = 4 m, β = 60º.



f. Cu = 60 kPa, H = 8 m, β = 60º.

Figure 10 Effect of L/B on the bearing capacity of skirted footing near a slope with Cu = 60 kPa.

Table 2. Bearing capacity of a strip footing with vertical skirts placed on a slope, β =10°.

C_u (kPa)	H/B	L/B	q_u (kPa)			
			No skirt	$\frac{D}{B}=0.5$	1	1.5
20	2	0	86	102	121	125
		1	100	130	134	140
		4	104	132	138	144
		8	104	132	138	144
	4	0	84	98	118	132
		1	98	128	132	138
		4	101	130	134	140
		8	101	130	134	140
40	2	0	144	180	192	220
		1	184	200	220	230
		4	192	208	224	232
		8	192	208	224	232
	4	0	136	176	188	212
		1	176	190	212	220
		4	184	200	220	228
		8	184	200	220	228
60	2	0	198	234	270	312
		1	258	288	306	330
		4	270	300	318	345
		8	270	300	318	345
	4	0	194	230	266	308
		1	255	284	303	326
		4	266	295	314	340
		8	266	295	314	340

Table 3. Bearing capacity of a strip footing with vertical skirts placed on a slope, β =20°.

C_u (kPa)	H/B	L/B	q_u (kPa)			
			No skirt	$\frac{D}{B}=0.5$	1	1.5
20	2	0	84	100	106	120
		1	98	120	126	136
		4	100	128	134	141
		8	108	128	134	141
	4	0	82	88	103	118
		1	95	116	124	134
		4	98	125	132	139
		8	98	125	132	139
40	2	0	140	176	188	210
		1	180	196	216	224
		4	188	204	220	228
		8	188	204	220	228
	4	0	132	172	184	204
		1	172	188	208	216
		4	180	196	212	224
		8	180	196	212	224
60	2	0	192	228	264	306
		1	252	282	300	324
		4	264	294	312	336
		8	264	294	312	336
	4	0	188	225	260	303
		1	248	277	297	320
		4	260	290	308	334
		8	260	290	308	334

Table 4. Bearing capacity of a strip footing with vertical skirts placed on a slope, β =30°.

C_u (kPa)	H/B	L/B	q_u (kPa)			
			No skirt	$\frac{D}{B}=0.5$	1	1.5
20	2	0	82	86	100	116
		1	96	115	120	134
		4	98	120	130	138
		8	98	120	130	138
	4	0	80	83	96	114
		1	92	112	116	132

		4	96	118	128	135
		8	96	118	128	135
40	2	0	136	172	184	204
		1	176	190	212	220
		4	184	200	216	224
		8	184	200	216	224
	4	0	128	168	180	200
		1	168	184	204	212
		4	176	192	208	220
		8	176	192	208	220
60	2	0	186	222	258	300
		1	246	276	294	318
		4	258	288	306	330
		8	258	288	306	330
	4	0	180	216	252	294
		1	240	270	288	312
		4	252	282	300	324
		8	252	282	300	324

Table 5. Bearing capacity of a strip footing with vertical skirts placed on a slope, β =50°.

C_u (kPa)	H/B	L/B	q_u (kPa) No skirt	$\frac{D}{B}=0.5$	1	1.5
20	2	0	54	75	80	100
		1	82	95	115	130
		4	94	110	128	134
		8	94	110	128	134
	4	0	50	54	76	96
		1	79	90	112	128
		4	92	108	124	130
		8	92	108	124	130
40	2	0	132	168	180	200
		1	172	184	208	216
		4	176	188	212	220
		8	176	188	212	220
	4	0	124	164	172	196
		1	168	180	200	208
		4	168	180	200	208
		8	168	180	200	208
60	2	0	180	210	252	288
		1	234	264	276	306
		4	246	276	294	318
		8	246	276	294	318
	4	0	174	204	246	282
		1	288	258	270	300
		4	240	264	288	312
		8	240	264	288	312

Table 6. Bearing capacity of a strip footing with vertical skirts placed on a slope, β =60°.

C_u (kPa)	H/B	L/B	q_u (kPa) No skirt	$\frac{D}{B}=0.5$	1	1.5
20	2	0	42	48	78	95
		1	80	90	110	128
		4	90	104	124	130
		8	90	104	124	130
	4	0	40	45	76	90
		1	76	86	106	124
		4	86	102	120	126
		8	86	102	120	126
40	2	0	124	164	172	196
		1	168	180	204	212
		4	172	184	208	216
		8	172	184	208	216
	4	0	120	160	168	188
		1	164	176	196	200
		4	166	178	198	204
		8	166	178	198	204
60	2	0	168	198	240	276
		1	222	246	270	294
		4	228	258	282	312
		8	228	258	282	312
	4	0	156	186	234	270
		1	216	240	264	288
		4	222	252	276	306
		8	222	252	276	306

6. Conclusions

Using a skirt foundation enhances the footing's bearing capacity, lowers settlement, and changes how loads settle there. Skirted foundation bearing capacity was increased when compared to un-skirted foundation. Also, the increasing rate in bearing capacity for case β=10° slope inclination with H/B =2 and C_u=40 kPa. Because confinement limits the soil's ability to migrate toward the slope face, increasing skirt depth raises the footing's bearing capability. As the distance from the slope edge increases, the bearing capacity increases. The increase in bearing capacity became constant once L/B = 4 was reached. The carrying capacity decreases with increasing slope inclination, which is linked to increased soil movement towards the slope. Changes in the soil's undrained shear strength significantly impact the bearing capacity. Finally, skirt footing on a slope of a small depth and the edge of a steep slope gives an approximate bearing capacity for a slope with a significant slope inclination and a skirt with a considerable depth. Further investigations are required to validate other parameters.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution Statement

Hanan Adnan Hassan Afaj and Hadeel Ammar Mohammed: Proposed the work problem.

Najwa Wasif Jassim and Noor S. Al-Hassnawi: Developed the theory and performed the computations.

Mohammed Yousif Fattah: Verified the analytical methods and investigated and supervised the findings of this work.

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