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Bearing capacity of skirted footing subjected to inclined loading

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Abstract. Skirted foundations are popular nowadays due to relatively higher bearing capacity and greater stability than strip footing. Foundations are generally subjected to inclined loading in the field. This study aimed to determine the effect of load inclination on bearing capacity, failure mechanism, and efficiency of skirted footing resting on cohesive soil using the finite element method. The footing has been assumed to be rigid, while the skirt has been assumed to be rigid as well flexible in nature. The bearing capacity of footing increases with the increase in skirt length, undrained strength, and footing depth. The provision of the skirt increases the bearing capacity by 1.4–5 times the capacity of strip footing. The bearing capacity decreases with an increase in load inclination, but the effectiveness of the skirt is found to increase. However, efficiency decreases significantly with an increase in the footing depth. The failure mechanism, as well as skirt effectiveness, is independent of soil strength. The failure zone always remains in the bulb shape, irrespective of any other factors. The skirt efficiency enhances by the provision of the rigid skirt in place of a flexible skirt.

1. Introduction

A large number of techniques and methods have been developed over the last three decades to improve the bearing capacity [1]. Provision of the skirt is one of the techniques to enhance the bearing capacity. Various experimental and numerical studies observed that the provision of the skirt enhances the bearing capacity significantly under different loading conditions [2]. The skirted footing constrains the soil mass between skirts, increasing footing depth and bearing capacity [3]. Numerous studies have been carried out to understand the application and advantages of skirted footing under different soil conditions, especially where shallow foundations are not recommended, such as soils with low bearing capacity, sites with scouring problems, and marine environment [4–7]. Randolph and Watson [8] suggested that the failure planes do not extend to the ground level in skirted footings, unlike the conventional strip footings. In another study, Al-Aghbari and Mohamedzein [7] concluded that the provision of skirts increases the bearing capacity of the foundation by 1.5 to 8.1 times the capacity of conventional circular footings in cohesive soils. However, Yun and Bransby [9] noted that the contribution of end bearing resistance of skirts is insignificant and can be ignored while designing the foundation.

The provision of structural skirts has decreased the overall settlement and increased strip footings bearing capacity [10–12]. It has also been reported that under inclined loading, the optimum length of the skirt is equal to half the width (B) of the footing. Nazir and Azzam [13] reported that small-scale circular footing bearing capacity increased substantially when sand piles were used along with the skirts. Some studies highlighted the effectiveness of skirted footings on loose soils [6, 14–16]. In another study on the behaviour of skirted circular footings on soils with significant strength heterogeneity, Mana et al. [17] observed that a higher number of internal skirts are required; however, the required number of internal skirts reduces with an increase in embedment depth. In a similar study, Mana et al. [18] reported that under the combined effect of seepage and swelling, the displacement of the skirt varies between 0.1 and 1 times

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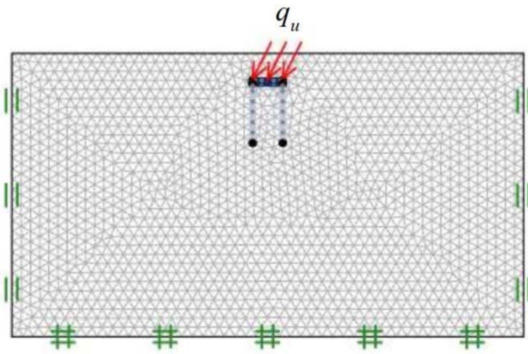
the foundation diameter. Stergiou et al. [19] noted that the critical spacing between skirts is approximately four times of footing diameter under vertical loading. Azzam [20] reported the increment in skirted footing displacement resting on slopes subjected to seismic action. Some studies found that increasing the skirt length is relatively less effective than increasing the depth of conventional strip footings [3,9, 17, 21–22]. However, some other studies concluded that the provision of the skirts is more effective compared to increasing the depth of conventional strip footings [23–25].

From the literature, it can be established that the provision of the skirt increases bearing capacity and reduces the settlement, owing to an increase in the foundation depth. Most of the studies on the skirted foundations are confined to circular and other isolated footings subjected to vertical loading. Strip footing is a frequently used foundation in rural areas, especially in developing countries. Also, footing may be subjected to inclined load as well. Only a very few studies considered the skirted strip footing subjected to inclined loading. However, earlier studies have not discussed the failure mechanism and skirt efficiency in a detailed manner. Therefore, it is essential to assess the influence of skirts on the improvement of the bearing capacity of strip footing subjected to inclined loading.

2. Methods

2.1. Numerical Modelling

A finite element plane strain model has been used to simulate the problem. The domain area has been assumed to be large enough to avoid any boundary effect. The footing width (B) has been assumed constant throughout the study. The minimum length and width of the domain have been maintained to 30B and 15B, respectively. All displacements have been restrained along the bottom horizontal boundary. Only vertical displacements have been allowed along the vertical boundaries. The numerical model used in the study is shown in Fig. 1.



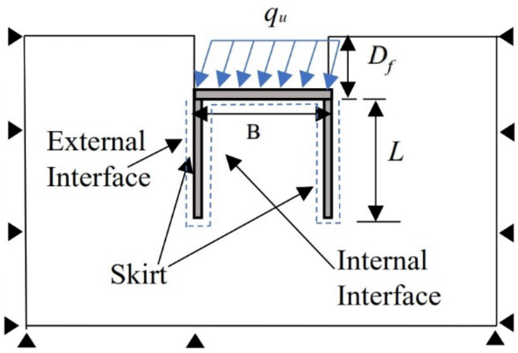


Figure 1. Details of Models: (a) the numerical model; (b) details of the modelling.

Previous studies on skirted footing revealed that the separation is insignificant in the inner interface between soil and skirt [26–27]. Therefore, the adhesion factor was assumed to be 1, which indicates no slipping condition. While for the external interface, the value varied from 0.5 to 1.0, which demonstrates the partial mobilisation. Three to four adoptive iterations were used in the earlier studies to get stable results [28–29]. It allows the refinement of mesh in particular areas where shear is dissipating. More than 9000 elements do not improve the result significantly. Therefore, 9000 elements were used in the first adoptive iterations. The number of elements was increased to 12000 in the third adaptive iteration.

The soil has been modelled as a 15 node Gauss element, and the foundation has modelled as a rigid material (undeformable) plate element. The skirt has also been modelled as a plate element made of infinite stiffness. A standard rigid connection (zero degrees of freedom) was made between the skirts and the bottom foundation plate, allowing efficient transfer of loading from bottom foundation plates to skirts. Mohr-Coulomb model is used to model the soil. The load was applied in terms of load multiplier. The resultant pressure, q_u has two components, one horizontal component (H), and other vertical components (V). The loading inclination (θ) with the ground surface and resultant loading (q_u) can be expressed as:

$$\cos(\theta) = q_u / \mathrm{H},$$

$$\sin(\theta) = q_u / \mathrm{V},$$

$$(q_u)^2 = \mathrm{H}^2 + \mathrm{V}^2.$$

A number of factors affecting the performance of skirted strip footings, such as length of skirts, type of soil, strength parameters of soil, load inclination, and depth ratio of footing, are considered in the analysis. The skirt length (L) to footing width (B) ratio is varied from 0 to 2 with an interval of 0.5. Similarly, the footing depth (D_f) is varied from 0 to 1.5B, with an interval of 0.5B. A number of studies used undrained strength to characterise the consistency of cohesive soils [30]. In the present study, the broad range of undrained strength has varied from 20 kPa to 320 kPa. This range is sufficient to replicate the probable range of soil consistency. Based on the literature review, the unit weights of soil have varied from 14 kN/m^3 to 17 kN/m^3. The parameters considered in the study are presented in Table 1.

Table 1. Details of considered parameters.

c_u (kPa)	Consistency	$c_u/(\gamma B)$	L/B	(D_f/B)	Loading inclination (H/V)	No. of analysis
20	Soft	0.7	0, 0.5, 1, 1.5, 2.0	0, 0.5,1.0	0, 0.5, 1, 1.5, 2	150
20	Medium	1.4	0, 0.5, 1, 1.5, 2.0	0, 0.5,1.0	0, 0.5, 1, 1.5, 2	150
80	Stiff	2.8	0, 0.5, 1, 1.5, 2.0	0, 0.5,1.0	0, 0.5, 1, 1.5, 2	150
160	Very stiff	5.7	0, 0.5, 1, 1.5, 2.0	0, 0.5,1.0	0, 0.5, 1, 1.5, 2	150
320	Hard	10.6	0, 0.5, 1, 1.5, 2.0	0, 0.5,1.0	0, 0.5, 1, 1.5, 2	150

2.2. Verification of the Numerical Model

Before analysing the skirted footing under inclined loading, the model used in the present study has been verified using earlier studies [31–33]. The bearing capacity factor (N_q), which considers the effect of soil weight, has been compared with earlier studies in Table 1. The average values are close to those presented by Yin et al. [31] using FLAC. However, N_q is much higher than those determined by traditional limit equilibrium theories [32–33]. The difference in the bearing capacity factors indicates the limitation of earlier traditional theories. These theories replaced the surcharge loading to equivalent uniformly distributed loading. This assumption neglects the shearing resistance of soil above the base of the footing. Therefore, Terzaghi [32] and Meyerhof [33] provide more conservative N_q.

The normalized bearing capacity ($q_u/\gamma B$) is also compared with the results of Kusakabe et al. [34] for purely cohesive soil and shown in Fig. 2(a). Kusakabe et al. [34] presented both lower and upper-bound solutions. The present study results are lower than the upper bound solution and more than the lower bound bearing capacity. The results of skirted footings are also compared with the results of an experimental study carried out by Al-Aghbari and Mohamedzein [16] and the numerical study results of Laymin et al. [35], and shown in Figs. 2 (b) and 2(c), respectively. The improvement factor (I_f), which is defined as the ratio of bearing capacity of the skirted footing to the strip footing, has also been compared with earlier studies. The improvement factor (I_f), indicates the effectiveness of the skirt. Fig. 2 shows that the results are shows comparable to those determined by Al-Aghbari and Mohamedzein [16] and Laymin et al. [35]. The comparison shown in Tables 1, 2, and Fig. 2 depicts that the present model can be used to predict the behaviour of skirted footing in the clay.

Table 2. Comparison of numerical results (N_q) determined by the present study with earlier studies.

Studies	ϕ = 25^0	ϕ = 30^0	ϕ = 35^0	ϕ = 40^0	ϕ= 45^0
Present study	15.50	24.70	45.20	89.70	195.56
Yin et al. (2001)	12.00	22.00	44.00	70.00	180.00
Meyerhof (1965)	10.70	18.40	34.78	64.10	134.70
Terzaghi (1943)	12.65	22.50	41.40	81.30	173.30

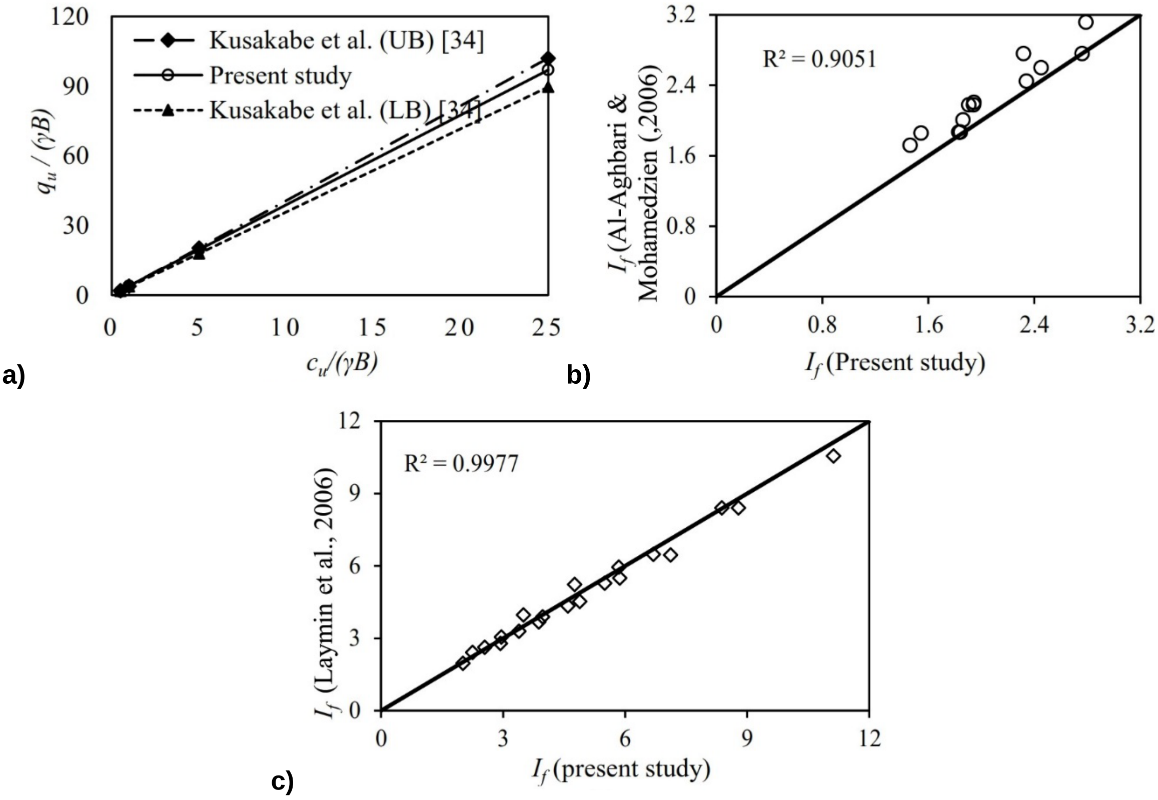
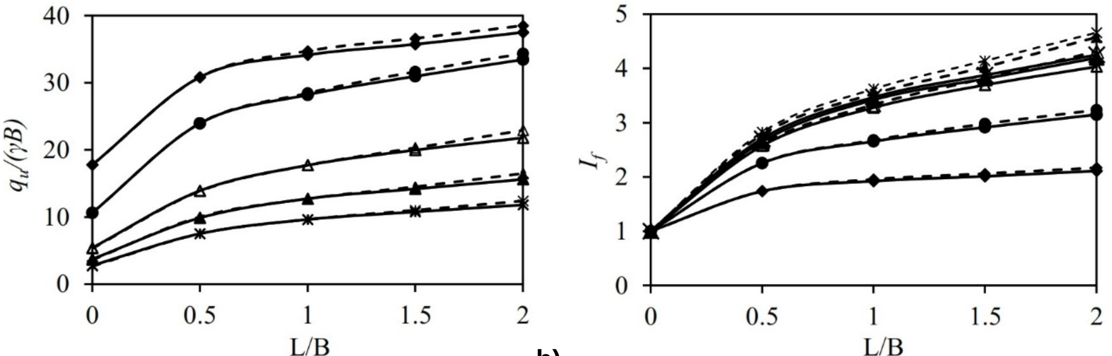


Figure 2. Verification of the model through comparison with published studies:
(a) with Kusakabe et al. [34], (b) with Al-Aghbari and Mohamedzein [16], (c) with Laymin et al. [35]

3. Results and Discussions

The results of rigid and flexible skirted footings are presented together for comparing the behaviour. The flexible skirted footing results are shown in the solid lines and rigid skirted footing results by the dashed line in each plot. The bearing capacity decreases with the adhesion factor decreasing due to reduced adhesion between the skirt and soil. However, the improvement factor shows the only marginal change.

The effect of the length of the skirt on bearing capacity ($c_u/\gamma B$) and improvement factor (I_f) is shown in Fig. 3. The bearing capacity improves continuously with an increase in the length of flexible and rigid skirts, but the increment rate becomes less observable at higher skirt lengths (L/B > 1.5). The increase in bearing capacity is due to increased footing depth [3]. The increase in bearing capacity is maximum for purely vertical loading, and the footing is resting on the ground surface. The influence of skirt length on bearing capacity reduces with footing depth. Similar to the bearing capacity factor, the bearing capacity improvement (I_f) increases with skirt length. The bearing capacity improvement augments with an increase in load inclination (Fig. 3 b, d, e), and the maximum is observed at maximum load inclination. The strip footing does not support large lateral loads, and footing may even slide at a small horizontal load, especially when embedment depth is small. However, the bearing capacity increases significantly with footing depth for inclined and horizontal loading.



b)

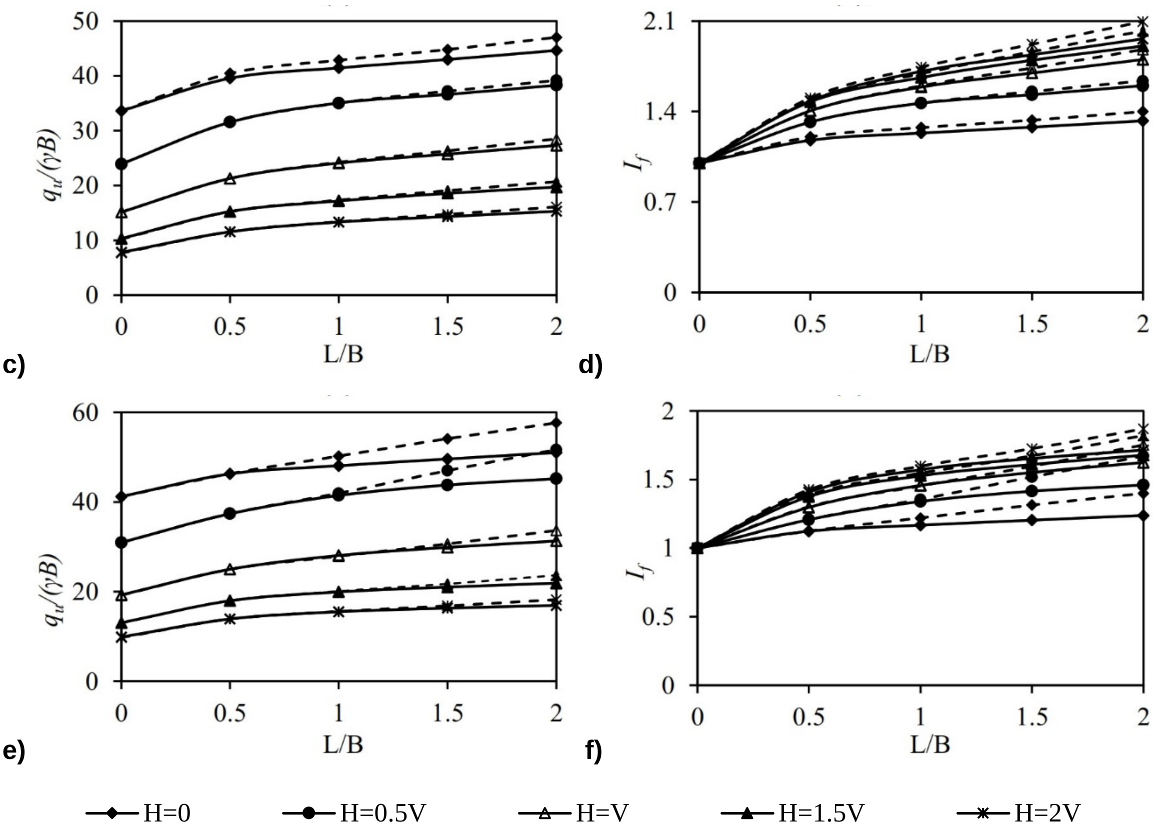


Figure 3. Variation of bearing capacity and I_f with skirt length (a) $q_u/\gamma B$, D_f/B = 0; (b) I_f, D_f/B = 0; (c) $q_u/\gamma B$, D_f/B = 0.5; (d) I_f, D_f/B = 0.5; (e) $q_u/\gamma B$, D_f/B = 1.0; (f) I_f, D_f/B = 1.

The effect of skirt length on the failure mechanism is shown in Fig. 4. It shows that the failure mechanism changes with skirt length. The failure surface is not developing clearly in strip footing, but it becomes more evident with an increase in the skirt length. The failure zone area also increases with an increase in the skirt length, which increases the bearing capacity. The change in the failure mechanism is more noticeable with the provision of the small skirt (from L/B = 0 to L/B = 0.5). The failure mechanism and shape of the shear zone do not change with skirt length. The failure zone always remains in bub shape irrespective of skirt length. However, the strip footing subjected to purely vertical loading resting on clayey soils generally shows the circular shear zone [28, 36]. The area of the failure zone progressively increases with an increase in the skirt length. It can also be seen that the failure zone moves gradually toward the right side of the skirt axis, which is also the opposite of the direction of horizontal force. It is due to the rotation of the skirt tip.

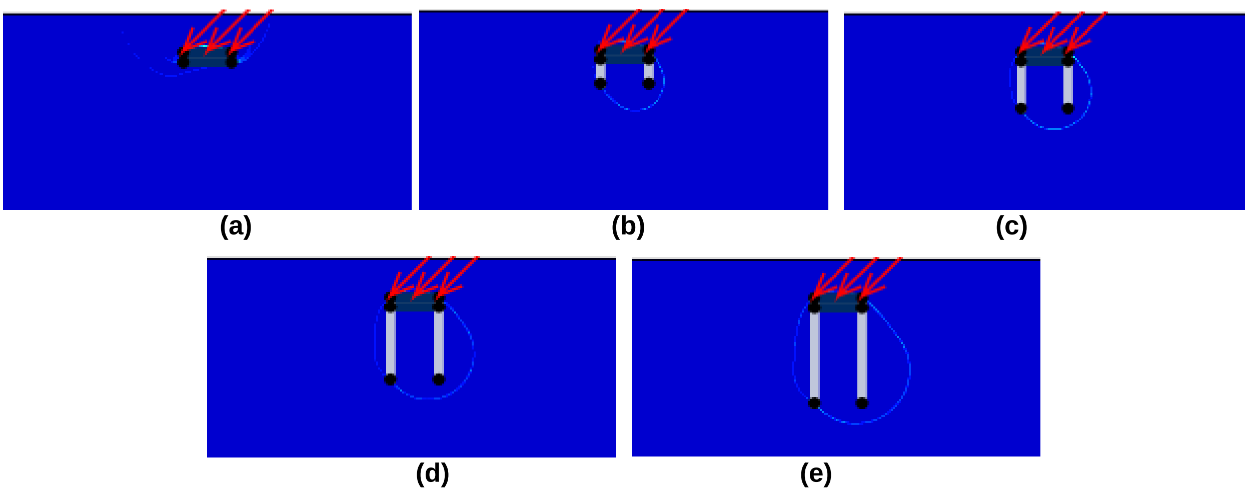


Figure 4. Effect of skirt length on failure mechanism: (a) L/B = 0, (b) L/B = 0.5, (c) L/B = 1.0, (d) L/B = 1.5, (e) L/B = 2.0.

The effect of footing depth (D_f/B) on bearing capacity and improvement for skirted footing is shown in Fig. 5. Interestingly, the bearing capacity increases and skirt efficiency reduces linearly with footing depth.

The reduction in efficiency is noticeably up to the depth of 0.5B and remains almost constant with a further increase in the depth (Fig. 5, b, d, f). The bearing capacity factor increases due to an increase in surcharge and confinement, but the effectiveness of the skirt (I_f) is reduced. The influence of embedment depth on bearing capacity and efficiency of the skirt decreases with an increase in the skirt length. The bearing capacity improvement with footing depth is substantial under purely vertical loading but diminishes with horizontal loading. The efficiency reduction is due to a decrease in the confining effect and due to the rotation of the skirt.

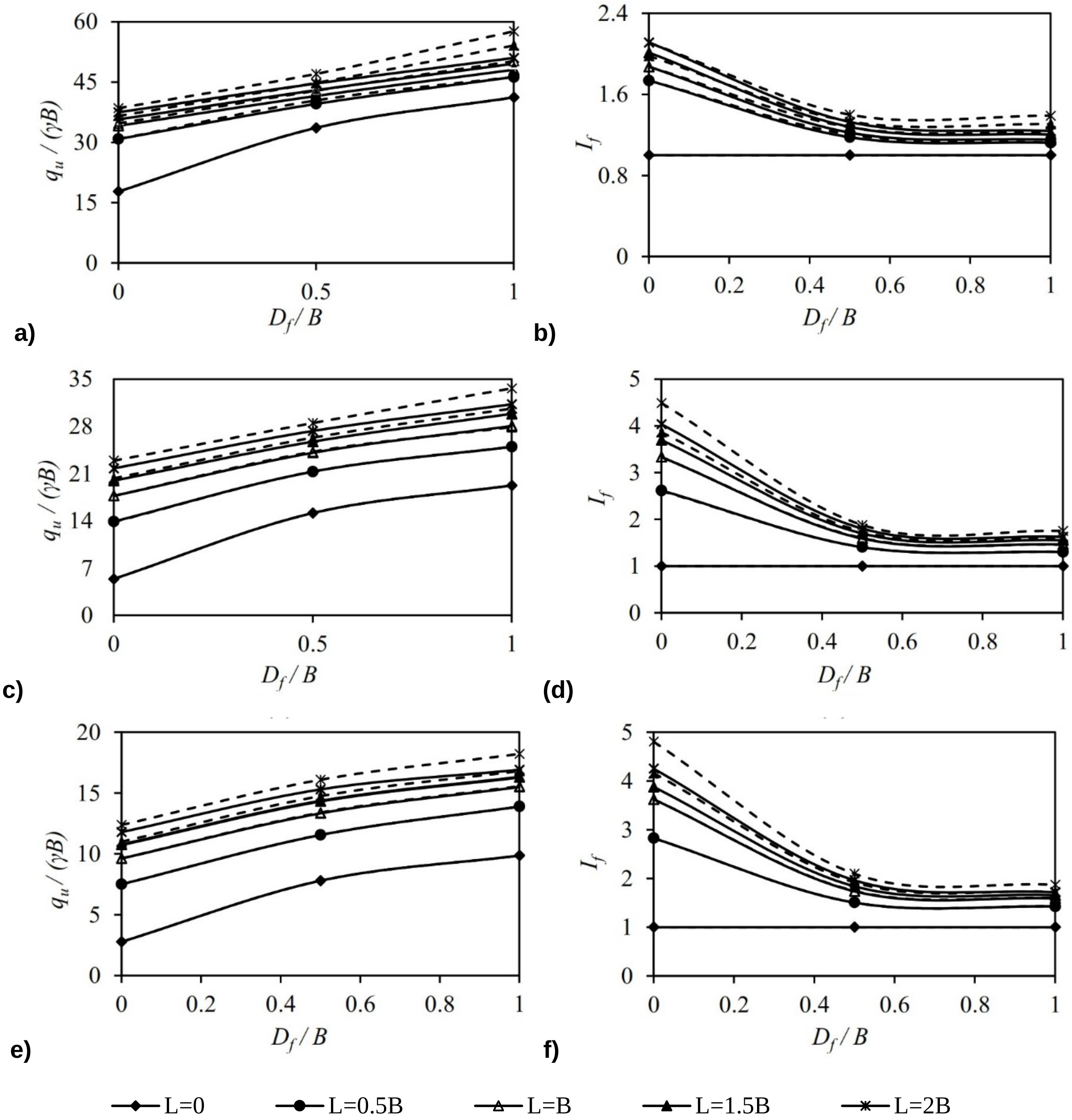
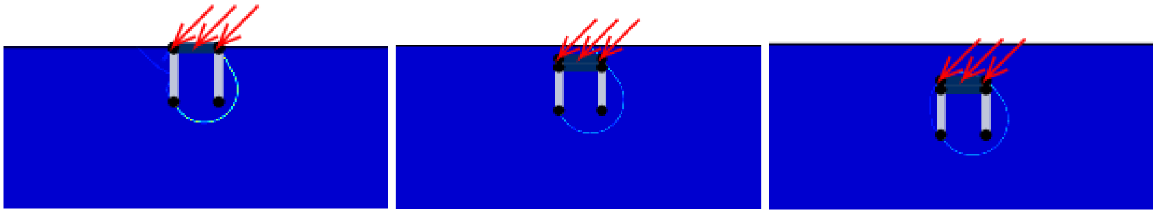


Figure 5. Variation of bearing and I_f with depth ratio: (a) $q_u/\gamma B$, H/V = 0; (b) I_f, H/V = 0; (c) $q_u/\gamma B$, H/V = 1; (d) I_f, H/V = 1; (e) $q_u/\gamma B$, H/V = 2; (f) I_f, H/V = 2.

The effect of change in footing depth on the failure surface is shown in Fig. 6. The failure mechanism remains almost unchanged with a change in the footing depth. The area of the failure zone remains almost constant, with an increase in the skirt length. With an increase in the footing depth, the surcharge on footing increases, which increases the bearing capacity (Fig. 5 a, c, e). However, the change in the failure zone area is relatively significant in strip footing, which causes a sharp increase in the bearing capacity factor compared to the skirted footing. As I_f represent the efficiency of skirt relative to strip footing, the I_f reduces with footing depth. A similar reduction in skirted footing efficiency has been observed in the skirted footing under purely vertical loading. As bearing capacity increases with increases in the footing depth, the moment acting on the skirt tips also increases, which increases the rotation of the failure surface toward the right side of the footing axis. It causes a decrease in the efficiency of the skirt.



(a) (b) (c)

Fig. 6. Effect of footing embedment depth on bearing capacity:
(a) D_f/B = 0, (b) D_f/B = 0.5, (c) D_f/B = 1.0.

Fig. 7 shows that bearing capacity reduces, and the improvement factor increases with an increase in load inclination (H: V). The adverse effect of load inclination on bearing capacity is maximum for strip footing but diminishes with an increase in skirt length. The improvement factor increases linearly up to load inclination of 1; further, the increase in load inclination has only marginal influence. The bearing capacity and skirt efficiency are relatively higher for a rigid skirt than for a flexible skirt. The difference between rigid and flexible skirts becomes more noticeable with the increase in skirt length.

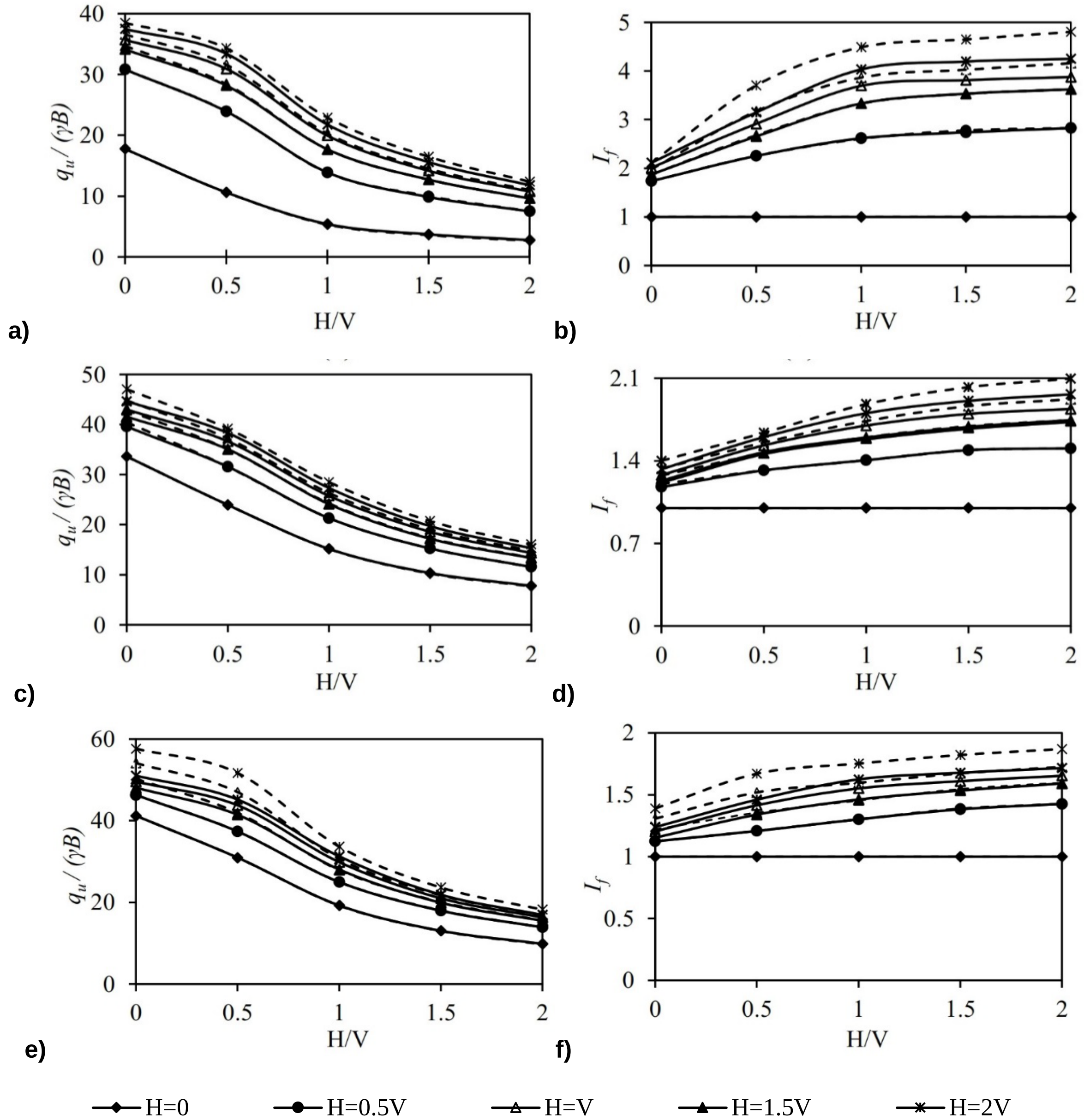


Figure 7. Variation of bearing capacity and I_f with load inclination: (a) $q_u/\gamma B$, D_f/B = 0;
(b) I_f, D_f/B = 0; (c) $q_u/\gamma B$, D_f/B = 0.5; (d) I_f, D_f/B = 0.5; (e) $q_u/\gamma B$, D_f/B = 1; (f) $q_u/\gamma B$, D_f/B = 1.

The effect of load inclination on the failure mechanism is shown in Fig. 8. It shows that the failure mechanism changes abruptly from confined failure to general shear failure with a change in load inclination. The failure zone remains bulb shape, irrespective of load inclination. Increasing the load inclination reduces the failure zone gradually only. As shown in Fig. 7 (a, c, e), it leads to an almost linear decrease in the bearing capacity. However, in strip footing, the effect of load inclination on bearing capacity is more severe, and bearing capacity decreases significantly as compared to the skirted footing. As I_f represent the efficiency or normalized bearing capacity relative to strip footing, skirted footing efficiency increased with an increase in the load inclination.

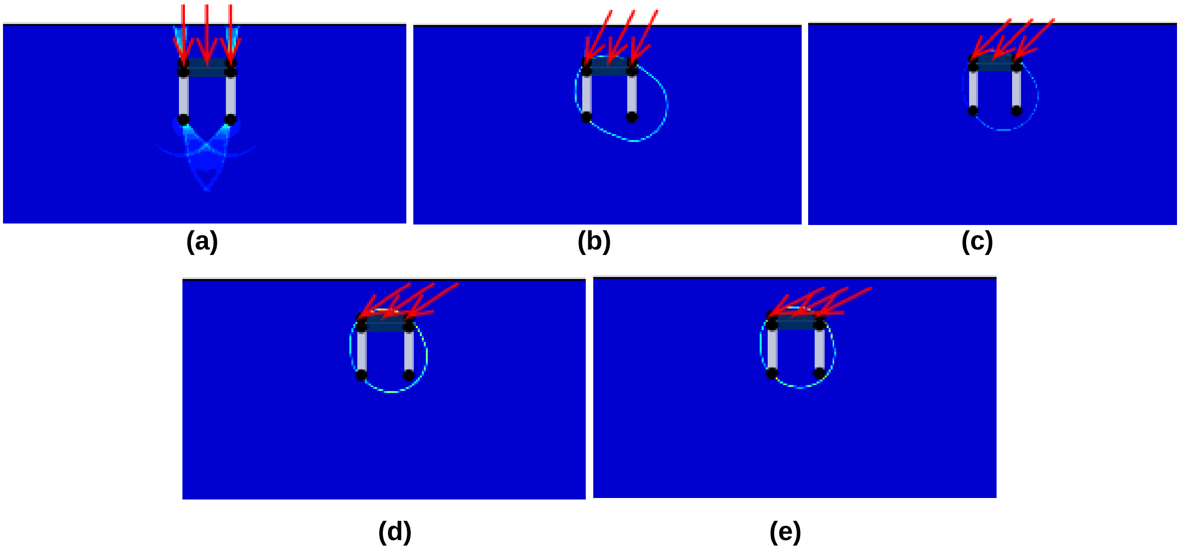
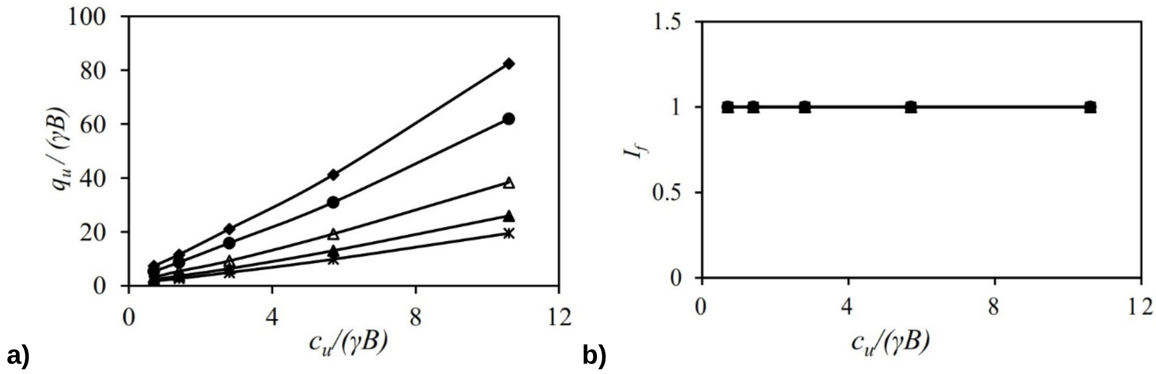


Fig. 8. Effect of load inclination on failure mechanism:
(a) H/V = 0; (b) H/V = 0.5; (c) H/V = 1.0; (d) H/V = 1.5; (e) H/V = 2.

The effect of undrained strength ($c_u/\gamma B$) for a skirted footing with D/B of 1 is shown in Fig. 9. The bearing capacity increases linearly with an increase in the undrained strength of the soil. Interestingly, the improvement factor is independent of soil strength (Fig. 9, c, d, f). The rate of increase in the bearing capacity is almost linear in strip and skirted footings. Therefore, the depth factor remains independent. Earlier studies highlighted that the efficiency of the skirt is a function of soil confinement or soil density in cohesionless soils [10–14]. However, the confinement does not increase with the soil strength in cohesive soil. Therefore, the failure mechanism of skirted footing does not change with the change in soil undrained strength. The area of the failure zone also remains almost the same irrespective of soil shear strength. Consequently, skirted footing efficiency is also almost constant, increasing the undrained strength considering the other parameters constant.



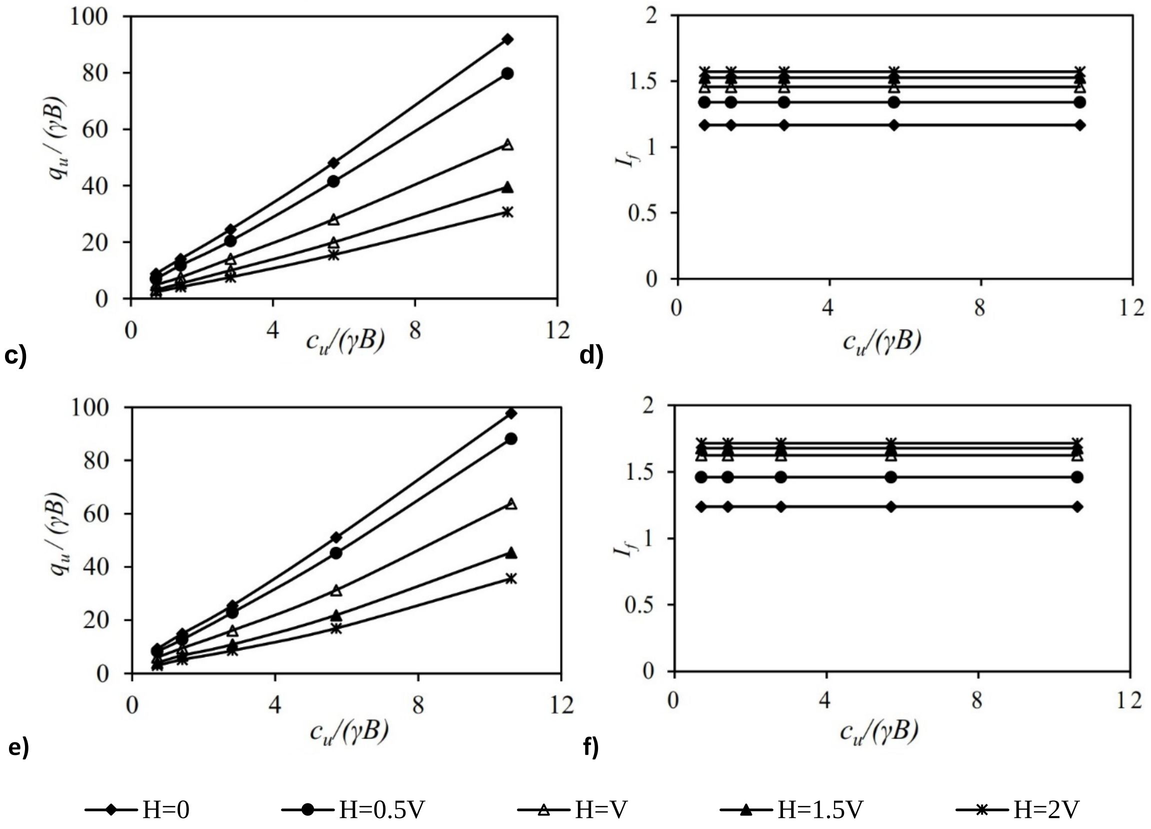


Figure 9. Variation of bearing capacity and I_f with undrained strenth: (a) $q_u/\gamma B$, L/B = 0; (b) I_f, L/B = 0; (c) $q_u/\gamma B$, L/B = 1; (d) I_f, L/B = 1; (e) $q_u/\gamma B$, L/B = 2; (f) I_f, L/B = 2.

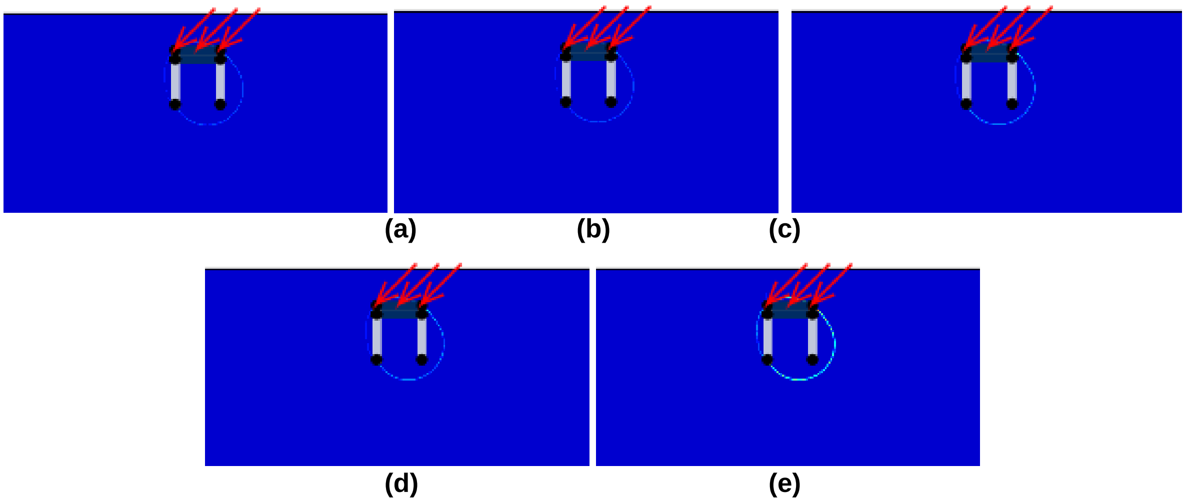


Figure 10. The effect of soil undrained strength on failure mechanism: (a) $c_u/(\gamma B)$ = 0.7, (b) $c_u/(\gamma B)$ = 0.1.4, (c) $c_u/(\gamma B)$ = 2.8, (d) $c_u/(\gamma B)$ = 5.7, (e) $c_u/(\gamma B)$ = 10.6.

4. Conclusions

The bearing capacity increases with the provision of the skirt. However, the efficiency of the skirt under inclined load is the function of many factors. The bearing capacity enhancement and the skirt's effectiveness are more visible in a rigid skirt than in a flexible skirt.

The bearing capacity and skirt effectiveness increase with skirt length. The provision of a small length skirt (L/B > 1) changes in failure mechanism and failure zone area significantly, but a further increase in the skirt length changes the failure zone progressively. The failure zone area reduces and moves opposite to the load direction with an increase in the load inclination.

The bearing capacity of skirted footing capacity reduces with increasing the load inclination. However, the effectiveness of the skirt (i.e., I_f) initially increases with an increase in the load inclination but becomes saturated for $\mathrm{H/V}$ of greater than 1.0.

The failure mechanism changes from confined failure to shear failure with increased load inclination. The bulb shape shear zone is the most prominent under inclined loading in cohesive soil.

The bearing capacity increases, and the effectiveness of the skirt reduce with footing depth. The adverse effect of footing depth on skirt efficiency intensified with skirt length. But the failure mechanism remains almost unchanged.

The bearing capacity of skirted footing increases with soil strength. However, the failure mechanism and efficacy of the skirt remain unaffected with an increase in the soil undrained strength.

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