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Bearing capacity and failure mechanism of skirted footings

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Abstract. The article presents the results of finite element analyses carried out on skirted footings. The bearing capacity increases with the provision of the flexible and rigid skirt, but the effectiveness varies with various other factors. The skirts are more efficient in the case of cohesionless soils than cohesive and c-ϕ soils. Efficiency reduces with an increase in the soil strength and footing depth. The rigid skirt is relatively more efficient compared to the flexible skirt. In contrast, to the flexible skirt, the efficiency of the rigid skirt increases continuously with skirt length. The difference in the effectiveness of both skirts becomes more noticeable with an increase in the strength parameters, skirt length, and footing depth. The failure mechanism also changes significantly with the inclusion of a rigid skirt. The rigid skirt behaves as a solid embedded footing, and the failure mechanism becomes confined with an increase in the skirt length. Few small-scale laboratory tests were carried out to study the flexible and rigid skirt and verify the numerical study results. The numerical analysis results are further used to develop nonlinear equations to predict the enhancement in bearing capacity with the provision of the rigid and flexible skirts.

Keywords: bearing capacity; failure; FEM; improvement factors; skirted foundation

1. Introduction

A large number of technologies and methods have emerged over the last three decades to improve the performance of foundations resting over soils with low bearing capacity. Provision of a skirt is one of the methods. Skirt constrains the soil mass embedded inside the cell formed between skirts and increases the effective depth of footing and bearing capacity (Tani and Craig 1995, Shukla 2022). The skirted footing can be an attractive alternative to piles foundation for jacketed structure (Acosta-Martinez *et al.* 2008). The structural skirt decreases the settlement and increases the bearing capacity (Al-Aghbari and Dutta 2008, Khatri *et al*. 2017, Sajjad and Masoud 2018, Al-Aghbari and Mohamedzein 2018). The bearing capacity can be increased to 1.5 to 8.1 times the capacity of conventional circular footings in cohesionless soils, depending on skirt length (Al-Aghbari and Mohamedzein 2006, Sajjad and Masoud 2018). Several studies described the application of structural skirts in marine and various other conditions where a shallow foundation cannot be preferred (Bransby and Randolph 1999, Hu *et al*. 1999, Al-Aghbari and Mohamedzein 2004, 2006). Unlike strip footing, the failure plane is confined in skirted footing, where failure planes extend to the ground level (Randolph and Watson 1999). Yun and Bransby (2007b) observed that the contribution of end bearing resistance is not significant to consider in the design of skirted footing. Saleh *et al.* (2008) assessed the optimum length of the skirt to be half of the footing width under inclined loading. Nazir and Azzam (2010) found that small-scale circular footing bearing capacity increased substantially when sand piles were used along with the skirt. The skirts are relatively more effective in loose soils (Wakil 2013, Eid 2013, Shukla 2019). Based on numerical modelling, Bienen *et al*. (2012) highlighted that skirted foundations with internal skirts may be an economical choice for large bucket foundations under combined loading. Mana *et al.* (2013) found that a higher number of internal skirts are required for the soil of considerable strength heterogeneity, and a smaller number of internal skirts are required in circular footings of large embedment depth. In another study, Mana *et al*. (2014) reported that the displacement of the skirt varies from 0.1 to 1 time the foundation diameter under the combined effect of seepage and swelling. Stergioub *et al*. (2015) observed critical spacing between skirts to be approximately four times the footing diameter under vertical loading. The skirt length and spatial variability of the shear strength significantly affect the bearing capacity and failure envelopes (Selmi *et al.* 2019). Yan *et al*. (2020) presented the results of large-scale model testing conducted on a newly designed caisson foundation consist of a skirted middle rectangle, and two sides skirted semicircles. It was observed that the foundation sinks due to self-weight and fails due to tilting.

There is an ambiguity over the magnitude of improvement in bearing capacity with the provision of the skirt. Some studies found that increasing the skirt length is relatively less effective than increasing the depth of conventional strip footings (Tani and Craig 1995, Yun and Bransby 2007a, Bransby and Yun 2009, Eid 2013, Vulpe 2015). However, other studies found that increasing the skirt length is more effective than increasing the depth of conventional strip footings (Al-Aghbari and Mohamedzein

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2004, Park *et al*. 2016, Zhang and Ding 2011).

Literature review shows that most of the studies are confined to circular and other isolated skirted footings without considering the skirt flexibility. The behaviour of footing may also depend on the flexible and rigid nature of the skirt. Strip footing is a frequently used foundation in rural areas in developing countries. Therefore, it is essential to assess the influence of skirts on bearing capacity improvement of strip footing. This study investigates the effects of various factors on the capacity of flexible and rigid skirted strip footings through elaborative finite element analysis. The failure mechanism of skirted footing is presented in detail to illustrate the differences in rigid and flexible skirted footing behavior. Nonlinear multiple regression analysis is also carried out to quantify the effects of rigid and flexible skirts. These equations may help engineers and researchers to predict the improvement in bearing capacity directly without extensive numerical or experimental study. Few experimental tests were also conducted to determine the bearing capacity of flexible and rigid skirted footing and to validate the numerical study results.

2. Modelling of problem

The problem was simulated as a plane strain model using a limit analysis program OptumG2. Limit analysis has nowadays very popular to determine the bearing capacity and depict the failure mechanism (Michalowski 2001, Soubra 1999, Wang *et al*. 2001). Both upper and lower bound limit analyses were performed, and the average value was considered. The sand was used as a foundation material and was modelled by the Mohr-Coulomb model (Lemaitre 2001).

The soil has been discretized using a three-node element in lower bound analysis, as it satisfies all three conditions required for the lower bound and provides rigorous lower bounds. The stress varies linearly between nodes. Two zero-thickness elements link lower bound elements. This induces statically admissible stress discontinuities between elements. The lower limit load is determined for the maximum lower bound by finding a load that satisfies a statically admissible stress field. Makrodimopoulos and Martin (2007) found that quadratic displacement elements (i.e., six nodes triangular element) are suitable for obtaining rigorous upper bound provided that sides are straight. Therefore, the soil has been discretized as six node triangular elements in the upper bound analysis, where the displacement variation is considered quadratic. The displacements are continuous between the elements. The minimum upper bound limit load satisfies a kinematic velocity field defined by the compatibility and associated flow rule equations at triangular elements and velocity discontinuities at soil-skirt interfaces and velocity boundary conditions. Associate flow rules do not consider the influence of dilation on the behaviour of dense sand. However, the dilation effect (dilatancy angle, ψ) on soil behavior can be incorporated by considering a modified internal friction angle. The modified angle of internal friction (ϕ_{mod}) can be obtained with the help of Eqn. 1 presented by Drescher and Detournay (1993). The present study uses the formulation developed by Makrodimopoulos and Martin (2006, 2007) and Krabbenhøft *et al.* (2007, 2008) for lower and upper bounds. Lower and upper bounds have been used in association with conic optimization. It is an effective second-order optimization technique, and several researchers have used it in limit analysis to get the optimized upper and lower bound (Krabbenhøft *et al.* 2007, Ukritchon and Keawsawasvong 2016).

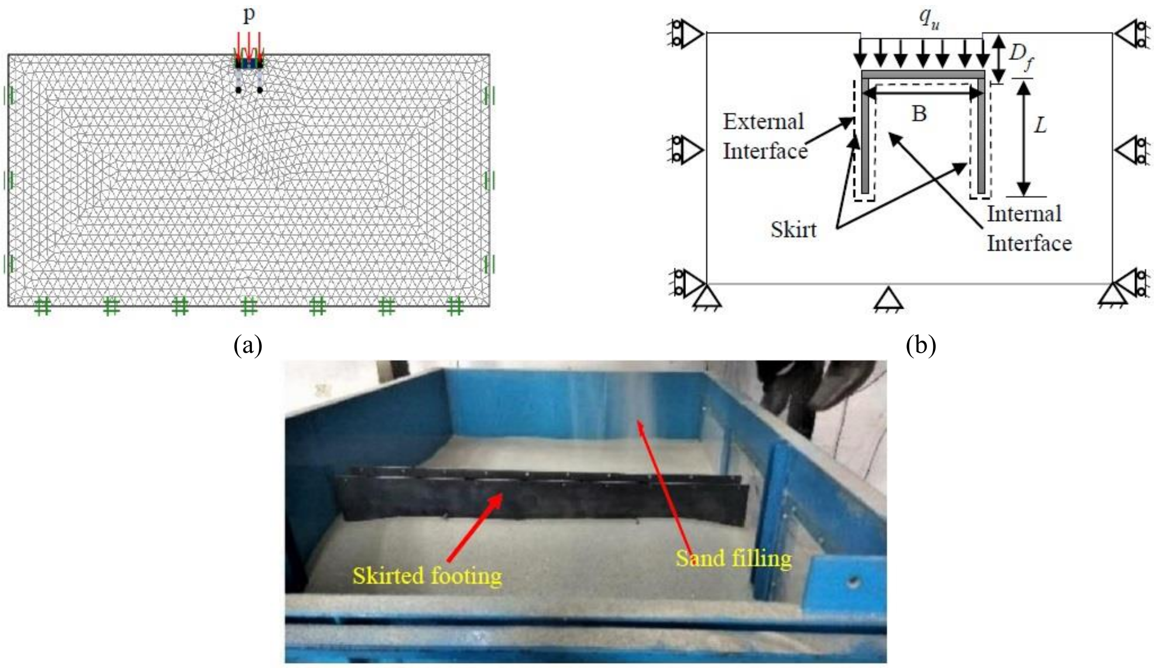
$$tan\phi_{mod} = tan\phi \frac{cos\psi \ cos\phi}{1 - sin\psi sin\phi} \tag{1}$$

The skirt was modelled as a plate element. The flexible skirt is assumed to be made of steel. A plate that possesses infinite stiffness was used to simulate the rigid skirt. Fig. 1 shows the model used to simulate the skirted footing. The rigid connections were used to connect the skirt with the foundation. This rigid connection enables the foundation to efficiently transfer the loads from the bottom foundation plate to the skirt efficiently, and finally, the load is transferred to the soil. Earlier studies found that the separation is negligible in the inner interface between soil and skirt (Chen and Randolph 2007, Mana *et al*. 2012). Therefore, the present analysis assumed that the internal interface and adhesion factor were approximately fully bonded. While in the outer interface, partial slip is allowed. However, to determine the effect of interface properties, the properties of interface elements were also changed significantly, and a wide range of skirt-soil interface factors (0.5-1) has also been considered to cover all possible roughness conditions.

Depending on the length of the skirt, the domain area was changed to avoid the boundary effect. The minimum length and width of the domain are maintained to be 20B and 10B, respectively. However, in rigid skirted footing, the length of the domain was increased by 1.5 times of those kept in flexible skirted footing, as the shear zone area is significantly higher in rigid skirted footing.

Three adaptive iterations were used in the study. This allows mesh refinement in particular areas without mesh refining of the whole domain. The number of adaptive iterations is fixed to 3. The load is increased in a load multiplier until a state of incipient collapse is reached. The bearing capacity values were larger in the upper bound compared to the lower bound. However, the difference in bearing capacity ratio determined from both bounds is very marginal. An average of lower and upper bounds collapse load is used in the analysis, which may be close to the actual collapse load. A number of studies have used the Optum G2 to determine the bearing capacity (Keawsawasvong and Ukritchon 2016, Shukla and Jakka 2018). The other application and details of Optum G2 are provided in a detailed manner in the literature (Chwała and Puła 2020, Chwała 2021).

The experimental testing was carried out in a tank of 2.1 m ×1.2 m ×1.2 m (Length × width × Height). The footing is made of 20 mm thick and 100 mm wide steel plates, and skirts are made of 3 mm thick mild steel plates. The length of the skirt is varied from 0.5B to 1.5B. In experimental



(a) (b)

(c)

Fig. 1 Details of Modelling: (a) FEM Model, (b) details of skirted footing and (c) experimental setup

testing, dry cohesionless soil with an internal friction angle of 37^0 is used as the foundation soil. Internal friction angle is determined from the direct shear test. From grain size distribution, it is observed that almost 95% of the particle size is fine sand, and less than 2% is fine soil. The soil is uniformly distributed, and coefficients of curvature of sand are determined to be 1.85 and 1.17, respectively. The specific gravity of sand is found to be 2.66. The testing was carried out on a skirted footing with length varying from 0.5 times of footing. Similarly, C sections have simulated the rigid skirt, which behaves like a rigid skirted footing.

3. Parameters considered in analysis

Various factors affecting skirted strip footing performance, such as length of skirts, type of soil, strength parameters of soil, and depth ratio of footing, are considered in the analysis. The ranges of parameters used in the study are shown in Table 1.

The angle of shearing resistance varies from 25 to 45^0. Most commonly, the undrained compressive strength of clays (q_u) is varied from 40 to 320 kPa, so cohesion (c_u) is assumed to be varying from 20 to 160 kPa (Swiss Standard SN 670 010b; NAVFAC Design Manual 7.2). The unit weight of sand varies from 15 to 18 kN/m^3, while the unit weight of clay varies from 14 to 15 kN/m^3. The unit weight of c-ϕ is assumed to be 15kN/m^3.

4. Validation of model used in the study

For validation of the numerical model, results are compared with earlier studies results. The bearing capacity

Table 1 Details of considered parameters

Type of soil	Strength parameters	Skirt ratio (L/B)	Depth Ratio (D_f/B)
Cohesive soil	$c_u/(\gamma B)$ =0.7, 1.4,2.8, 5.3, 10.6	0, 0.5, 1, 1.5, 2	0, 0.5,1, 1.5
Cohesionless Soil	ϕ^0 =25, 30, 35, 40, 45	0, 0.5, 1, 1.5, 2	0, 0.5 1, 1.5
c - ϕ soil	ϕ^0=25, $c_u/(\gamma B)$ = 0, 0.35, 0.70, 1, 1.4,1.8 $c_u/(\gamma B)$ =0.36, 0.7,1.4 and, ϕ^0 =20, 25, 30, 35	0, 0.5, 1, 1.5, 2	0, 0.5 1, 1.5

factor (N_γ) of a conventional strip footing resting on a surface obtained from the numerical model for a different angle of internal frictions of soil ($25^0 \le \phi \le 45^0$) is compared with traditional theories values (Fig. 2(a)). The bearing capacity factor obtained from the numerical model is well below the values Terzaghi (1943) presented and greater than Hansen (1970). However, the values are found close to those suggested by Meyerhof (1965) and Vesic (1973). The results of flexible and rigid skirted footings are also compared with the numerical studies of Lyamin *et al.* (2007) and are shown in Figs. 2(b) and 2(c), respectively.

Lyamin *et al.* (2007) results are presented in dashed lines. The improvement factors (I_f) determined numerally are comparable up to a skirt length of 1.5B in a flexible skirt. For a skirt length greater than 1.5B, the difference becomes significant. The difference is attributed to the deflection of the flexible skirt beyond the skirt length of 1.0B. This fact can be realized in Fig. 2(c), where a comparison of the results of rigid skirts in the present study is made with Lyamin *et al.* (2007). Lyamin *et al.* (2007) have conducted experimental studies on a block foundation,

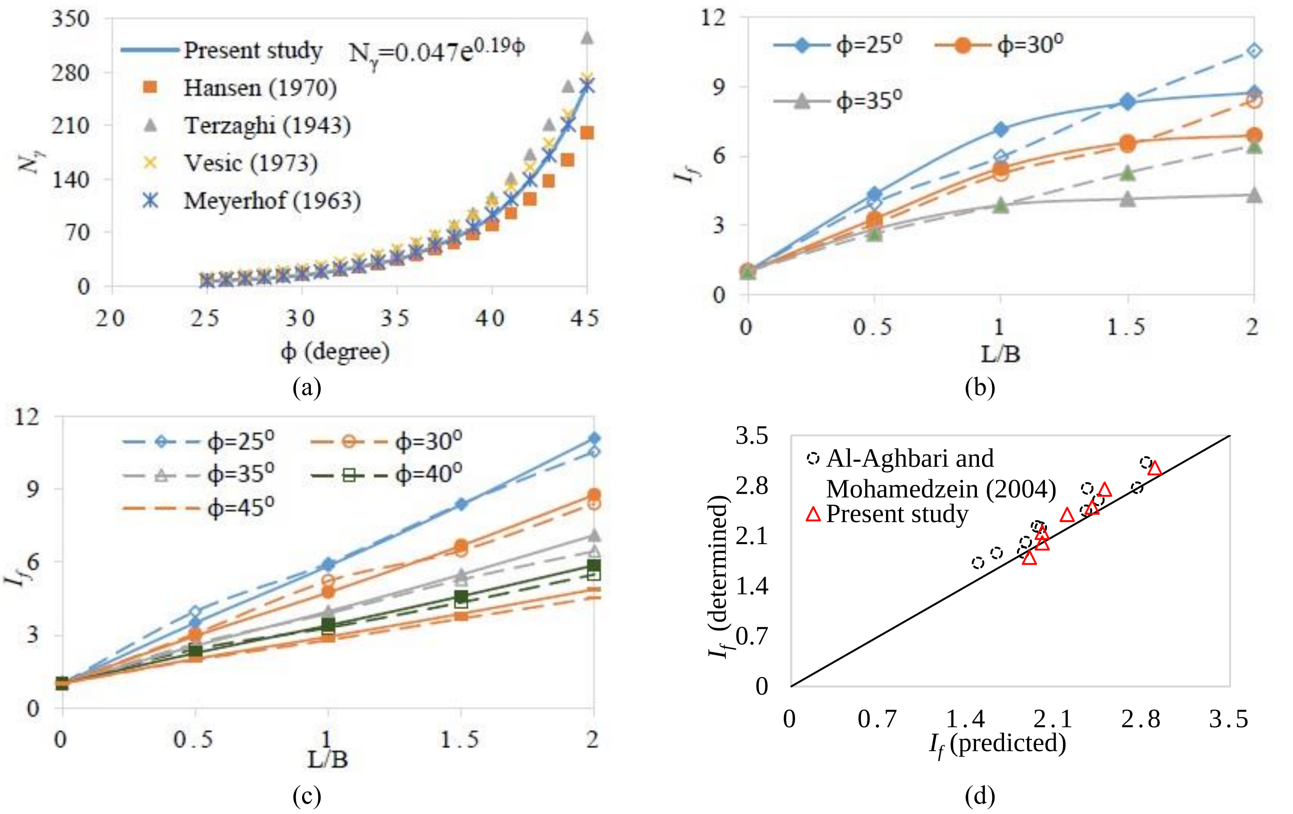


Fig. 2 Comparison of results with the previous study results: (a) traditional theories, (b) Flexible skirt with Lyamin *et al.* (2007), (c) Rigid skirt with Lyamin *et al.* (2007) and (d) Flexible skirted footing I_f with the experimental studies

which behaves as a rigid embedded footing. As seen from the plots, the variation of I_f of rigid skirts agrees with the compared study. This indicates that increasing the length of the rigid skirt leads to bearing capacity improvement very much equal to those achieved by increasing the depth of conventional strip footing with a depth equal to skirt length (Fig. 2(c)).

5. Results and discussions

The load-settlement curve of the rigid and flexible skirted footing of various lengths resting over a soil bed prepared at the relative density of 35% is presented in Fig. 3. It shows that a rigid skirt behaves like flexible skirted initially, and after a certain loading, improved load-settlement behaviour is observed in rigid skirted footing.

The secant modulus is almost the same for rigid and flexible skirted footing for any skirt length, but peak strength improved with the provision of the rigid skirt. The difference in behaviour becomes more noticeable with the increase in the skirt length and the relative density of soil. The rigid skirt sustains a higher load and fails at a relatively higher strain than a flexible skirt.

The typical enhancement in bearing capacity with skirt length is presented in Fig. 4. The right half (Figs. 4(a), 4(c) and 4(e)) and left half (Figs. 4(b), 4(d) and 4(f)) show the variation for rigid and flexible skirted footing. The I_f increases with an increase in the length of the skirt. The

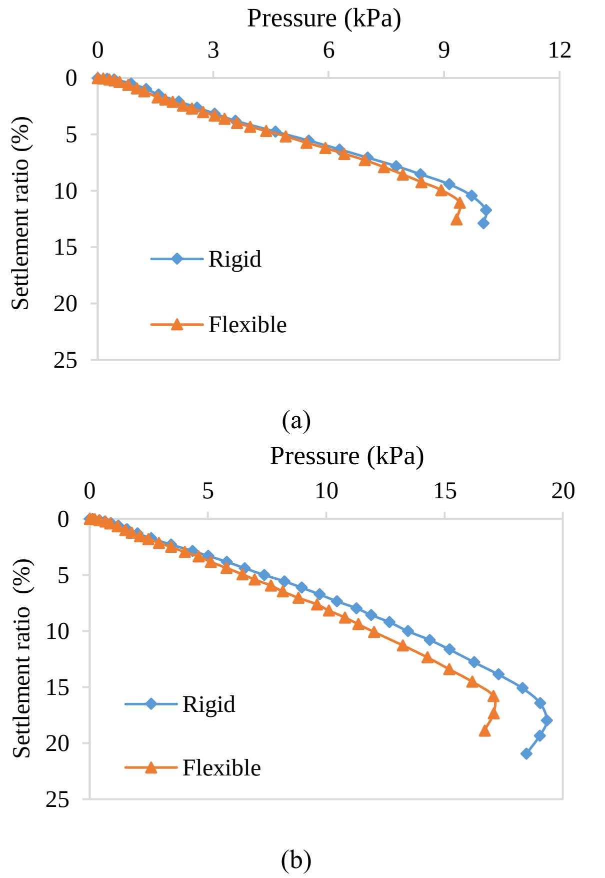


Fig. 3 Load settlement curve for rigid and deformable skirt: (a) L/B=0.5 and (b) L/B=1.0

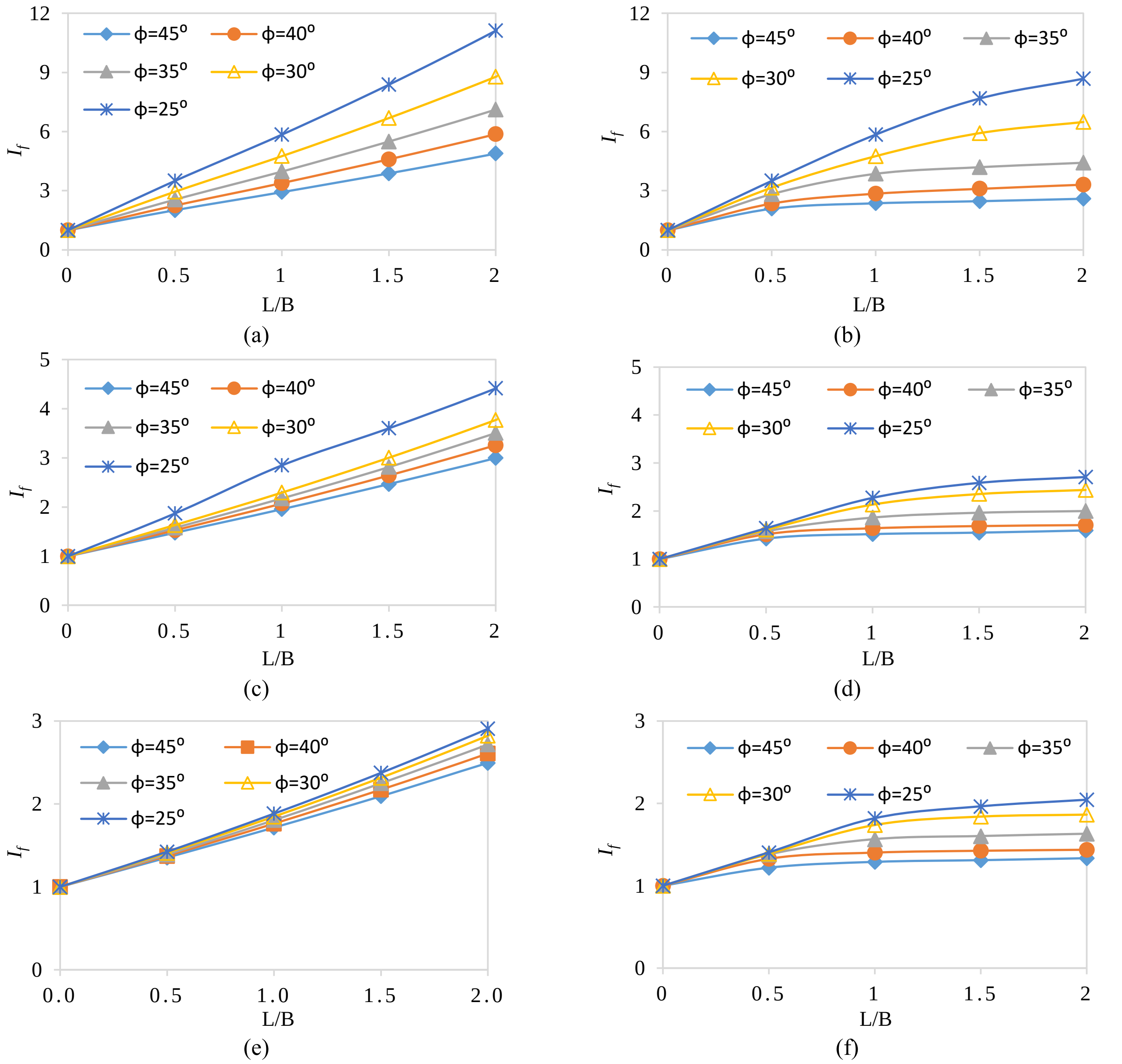


Fig. 4 Effect of skirt length on bearing capacity improvement: (a) D_f/B = 0.0, rigid skirt, (b) D_f/B= 0.0, flexible skirt, (c) D_f/B = 0.5, rigid skirt, (d) D_f/B = 0.5, rigid flexible, (e) D_f/B = 1.0, rigid skirt and (f) D_f/B =1.0, flexible skirt

constrained soil mass between skirts acts as a single mass and behaves like a part of footing. Consequently, it increases the depth of footing. The increase in footing depth increases the resistance against vertical and lateral movement of soil (Wakil, 2013). Additionally, the skirt performs like a vertical reinforcing element, contributing to increased bearing capacity. The relative increase in soil bearing capacity by providing skirt is relatively more in loose soils ($\phi \leq 30^0$) than dense soils ($\phi \geq 40^0$) as dense soil is already at optimum strength, and provision of the external reinforcing element increases strength nominally only.

Unlike flexible skirted footing, the I_f increases continuously with the length of the rigid skirt. It is contributed to a continuous increase in stiffness of the soil-foundation system in the case of a rigid skirt. However, the efficiency of a flexible skirt with a length equal to or greater than the optimum skirt length (1.0B-1.5B) becomes saturated due to skirt deflection. Deflection is due to large lateral earth pressure and lateral movement of soil under extensive loading. The critical length of flexible skirted footing depends upon the footing depth and strength of the soil.

Fig. 5 shows a typical variation in failure mechanism (shear dissipation) for a rigid and flexible skirted footing with a depth ratio of 1 resting over a cohesionless with an internal friction angle of 35^0. The left and right parts in each figure represent the failure mechanism of rigid and flexible skirted footings, respectively. The failure mechanism is symmetrical about the footing axis as the soil has been considered isotropic and homogeneous.

The soils, in reality, are anisotropic, and the failure mechanism can be asymmetrical (Fenton and Griffiths

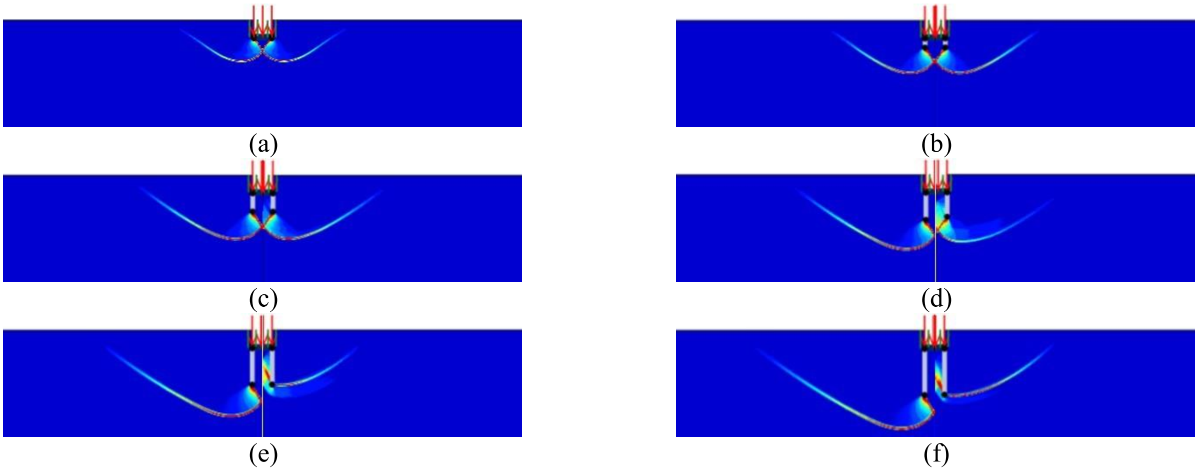


Fig. 5 Effect of skirt length on failure mechanism: (a) Un-skirted footing, (b) L/B=0.5, (c) L/B=1.0, (d) L/B=1.5, (e) L/B=2.0 and (f) L/B=2.5

2003, Valore *et al.* 2017, Puła and Chwała 2018, Ziccarelli *et al.* 2017). The bearing capacity is slightly higher in anisotropic soil (asymmetrical failure) compared to isotropic soil (symmetrical failure) (Puła and Chwała 2018). Neglecting the anisotropic nature leads to a safer side design. The area of the shear zone increases with the increase in skirt length. Up to a skirt length of 1.0B, the shear zone area is symmetrical and identical for both rigid and skirted footing, indicating equal efficiency as shown in Fig. 4. The increase in the shear zone area in the flexible skirt is considerable up to the skirt length of 0.5B-1.0B. In contrast, there is a steady increase in the shear zone with length in rigid skirts.

The elastic wedge is evidently forming up to skirt length equal to 1.0B in the flexible skirt, and the slip line originates from the tip of the skirt. However, in skirts with considerable length (L/B>1.5), the slip surface forms well within the soil confined between skirts. At very higher skirt lengths (L/B ≥2), the slip lines originate from the connection points between skirt and footing due to skirt deflection toward the direction of soil movement (Figs. 5(e) and 5(f)). It reduces the efficiency of the flexible skirt significantly. The length of slip lines is also relatively large in a rigid skirt. Therefore, rigid skirted footing behaves precisely like a conventional strip footing resting at skirt tips. It means that flexible skirt length may not always yield benefits compared to those that can be attained by increasing the depth of conventional strip footing, as considered in earlier studies (Al-Aghbari and Mohamedzein, 2004, Chetia and Das 2010, Park *et al.* 2016, Zhang and Ding 2011). In rigid skirts, the slip lines originate from the skirt tip.

The effect of footing depths on improvement factors for footing resting over the soils of different internal friction angles (ϕ=25^0, 35^0, and 45^0) is presented in Fig. 6. Bearing capacity enhances with footing depth due to enhanced surcharge and confinement, but the efficiency of the skirt (I_f) reduces with the increase in footing depth (D_f/B). A similar observation is made in a rigid skirt as well. However, the decrease in efficiency of the skirt with footing depth is relatively more in the rigid skirt than in the flexible skirt.

The difference in the efficiency of the flexible and rigid skirt is becoming more noticeable with the increase of the angle of internal friction of soil. In the soils with a low internal friction angle (ϕ ≤ 30^0), the I_f in rigid skirted footing is approximately 130% to 150% of those observed in the flexible skirt. This difference increases to approximately 200% in soils with a higher angle of internal friction (ϕ ≥ 40^0).

The effect of footing depth on the failure mechanism for rigid and flexible skirted footings of length 1.0B is shown in Fig. 7. The shear zone, contributing to bearing capacity, increases with an increase in the footing depth. It enhances the bearing capacity of the footing. The increase in the shear area with an increase in footing depth is substantial in rigid skirted footing compared to the flexible skirted footing. Fig. 6 depicts that the relative improvement in bearing capacity (I_f) reduces with the increase in footing depth even though the area within the failure surface is not decreasing. This contrary behaviour is observed because the increase in the bearing capacity (or shear zone area) with footing depth is fairly large in conventional strip footing compared to the skirted footing. The deflection of the flexible skirt increases with an increase in footing depth, which reduces the efficiency of the skirt.

The improvement factor for various embedment depths (D_f/B =0, 0.5, and 1.0) is shown in Fig. 8. The absolute bearing capacity increases and I_f decreases with the increase in the angle of internal friction of soil. The reduction in skirt efficiency enhances with an increase in the skirt length. The effect of the angle of internal friction is significant in surface skirted footing but diminishes with the footing depth increase. However, the adverse effect of the friction angle on the efficiency is relatively less noticeable in a rigid skirt than in a flexible skirt. The relative stiffness of a flexible skirt compared to soil decreases with the increase in the angle of internal friction, which reduces the efficiency of the skirt. However, the relative stiffness of the rigid skirt does not get much affected by soil density due to its large stiffness. The flexible skirt with a higher length deflects at large loading. Therefore, the reduction in efficiency with friction angle is relatively low in a rigid skirt and higher in a

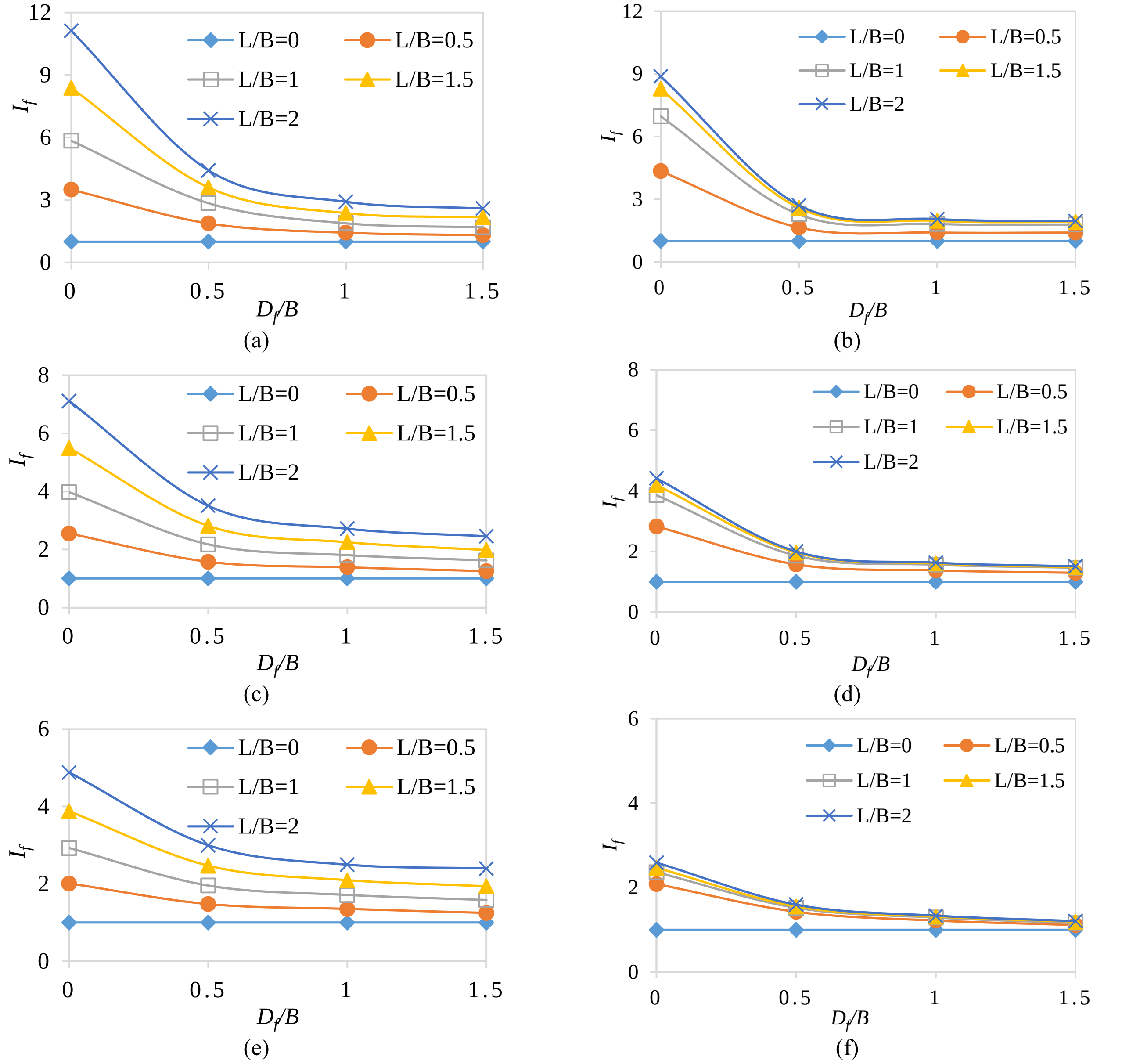


Fig. 6 Variation of I_f with depth ratios: (a) Rigid skirt, ϕ=25^0, (b) Flexible skirt, ϕ=25^0, (c) Rigid skirt, ϕ=35^0, (d) Flexible skirt, ϕ=35^0, (e) Rigid skirt, ϕ=45^0 and (f) Flexible skirt, ϕ=45^0

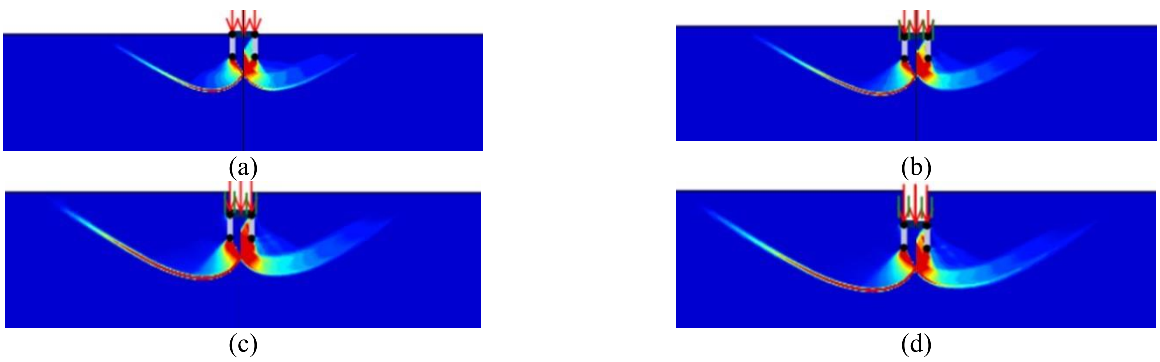


Fig. 7 Effect of embedment depth on failure mechanism: (a) D_f/B =0, (b) D_f/B =0.5, (c) D_f/B =1.0 and (d) D_f/B =1.5

flexible skirt. The strength of weak soil increases significantly with the incorporation of skirts

The bearing capacity improvement with the angle of internal friction is relatively more in strip footing than skirted footing. The reinforcing effect also decreases with an increase in the internal friction angle of sand (Gray *et al.*

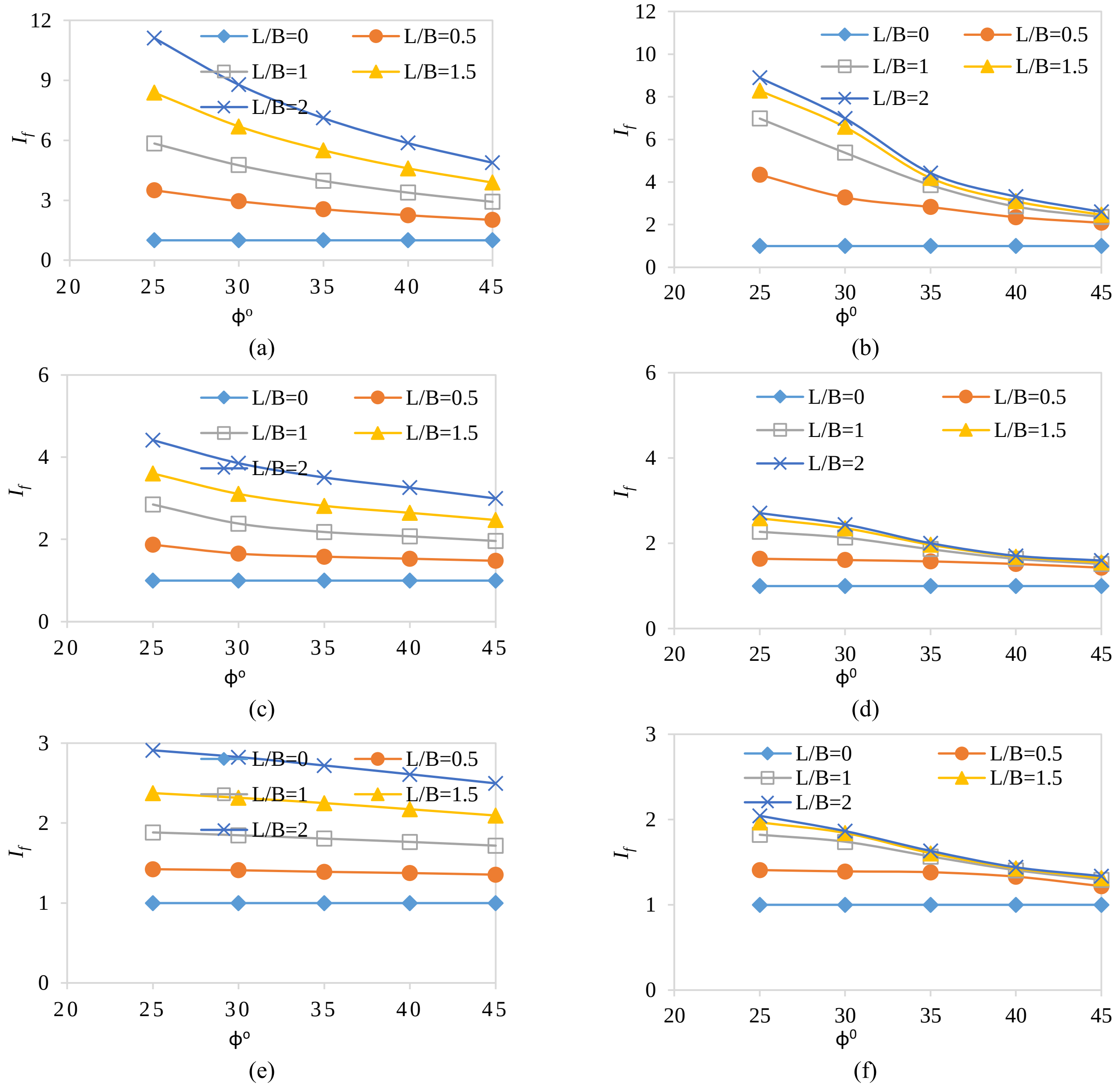


Fig. 8 Variation of I_f with angle of internal friction: (a) Rigid skirt, D_f/B = 0, (b) Flexible skirt, D_f/B =0, (c) Rigid skirt, D_f/B = 0.5, (d) Flexible, D_f/B =0.5, (e) Rigid skirt, D_f/B = 1.0 and (f) Flexible skirt, D_f/B =1.0

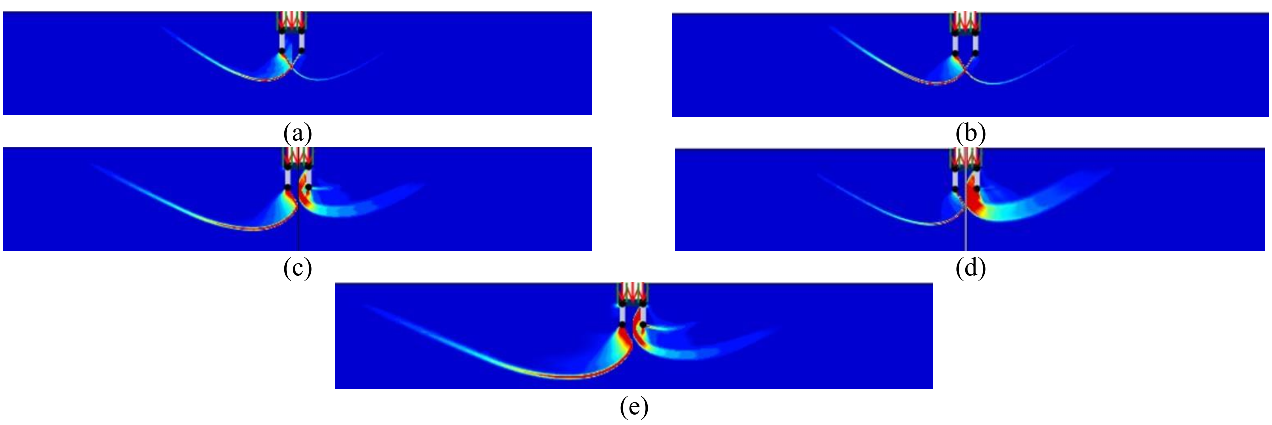


Fig. 9 Effect of internal friction angle on failure mechanism (a) $\phi=25^0$, (b) $\phi=30^0$, (c) $\phi=35^0$, (d) $\phi=40^0$ and (e) $\phi=45^0$

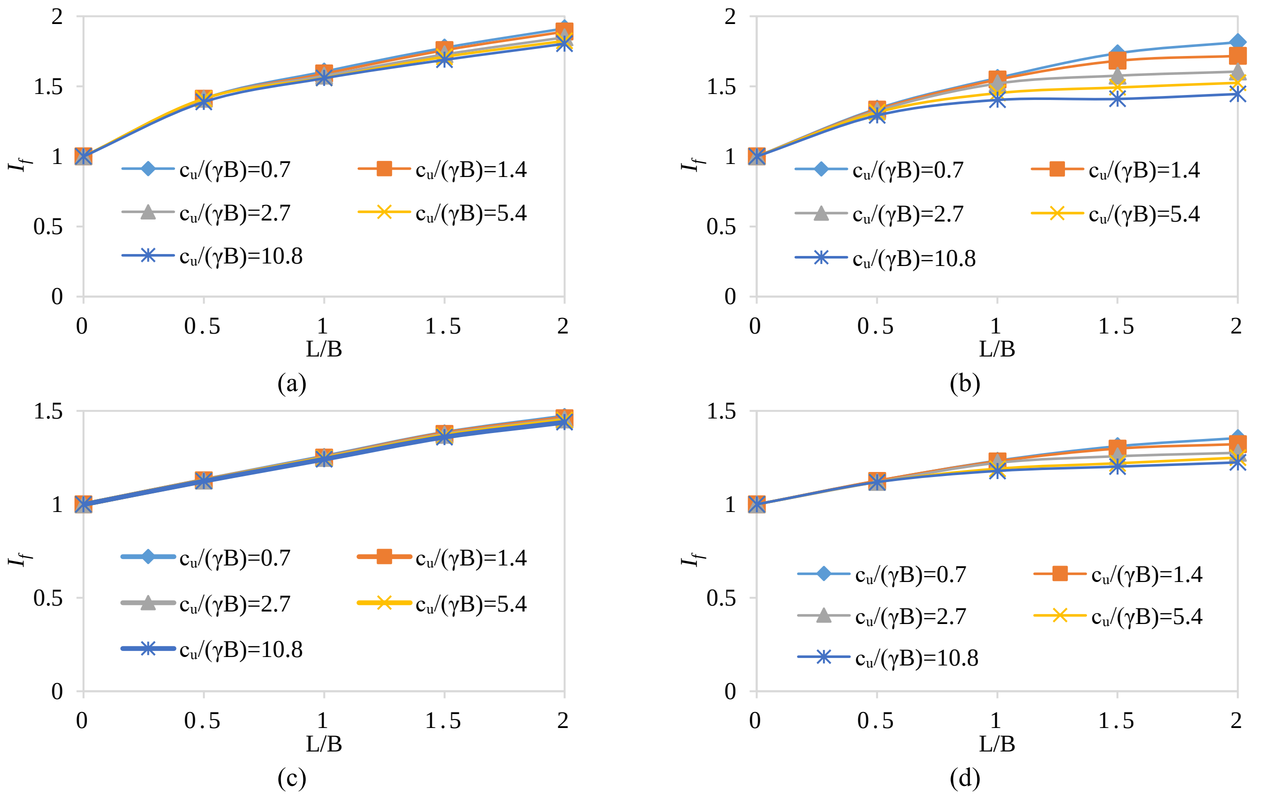


Fig. 10 Effect of skirt length on I_f in cohesive soil: (a) Rigid skirt, D_f/B = 0.0, (b) Flexible skirt, D_f/B =0.0, (c) Rigid skirt, D_f/B =1.0 and (d) Flexible skirt, D_f/B =1

Table 2 Improvement factor (I_f) and optimum length

ϕ (^{0})	D_f/B	Optimum skirt length (L_0/B)	Improvement factor (I_f)	
			Flexible	Rigid
25-30	0	1.5	8.2-6.0	8.3-6.5
	0.5	1.0-1.5	2.5-2.2	3.5-3.0
	1	1	1.8	1.9
30-35	0	1.5	6.0-4.0	6.5-5.3
	0.5	1	2.2-1.8	3.0-2.8
	1	1	1.8-1.5	1.9-1.5
35-40	0	1	4.0-2.2	7.0-5.0
	0.5	1	1.7-1.5	2.8-2.5
	1	0.5	1.5-1.3	1.5-1.4
40-45	0-1	0.5	2.2-1.2	2.5-1.4

1983, Huang and Tatsuoka 1994). All these factors contribute to a significant reduction in the skirt efficiency with the increase in the angle of internal friction. Eid (2013) and Wakil (2013) also found that the efficiency of the skirt reduces with the increase in soil density.

The skirt deflection further increases with the increase in the internal friction angle of soil. Subsequently, the efficiency of the flexible skirt is significantly less than the rigid skirt. This drawback can be improved through a rigid skirt that does not deflect even in soils with a large internal friction angle (Figs. 9(a)-9(e)).

Based on numerical analyses performed, the most efficient/optimum length of the flexible skirt and corresponding improvement factor for different depths of footing and internal friction angles of soil are shown in Table 2. The optimum length of the skirt is found to be nearly equal to the width of footing in soils with the angle of internal friction of 35^0, and a further increase in skirt length has only a nominal effect on bearing capacity enhancement. The optimum length of the flexible skirt and corresponding I_f values reduce with the increase in footing depth ratio and internal friction angle of soil. The optimum skirt length decreases from 1.5B to 0.5B with an increase in internal friction angle from 25^0 to 45^0. However, I_f increases continuously in rigid skirts; therefore, it is difficult to suggest the value of optimum length for a rigid skirt. A further detailed investigation is required to reach any conclusion in this regard.

4.2 Skirted footing on cohesive soils

Similar to cohesionless soil, an analysis was also carried out for cohesive soils. Variation of I_f with the change in skirt length is shown in Fig. 10. The improvement factor increases with the increase in the skirt length. The magnitude of the improvement factor in the rigid skirt is slightly higher than in the flexible skirt. The increase in I_f is higher in the soils with low strength. Unlike cohesionless soil, the I_f increases continuously even up to skirt length of 2B in cohesive soil. However, the magnitude of bearing capacity enhancement (I_f) is relatively small in cohesive soils (Figs. 4 and 10). It may have been attributed to the relatively more efficacious reinforcing effect in cohesionless soil than in cohesive soils (Shukla 2017). The

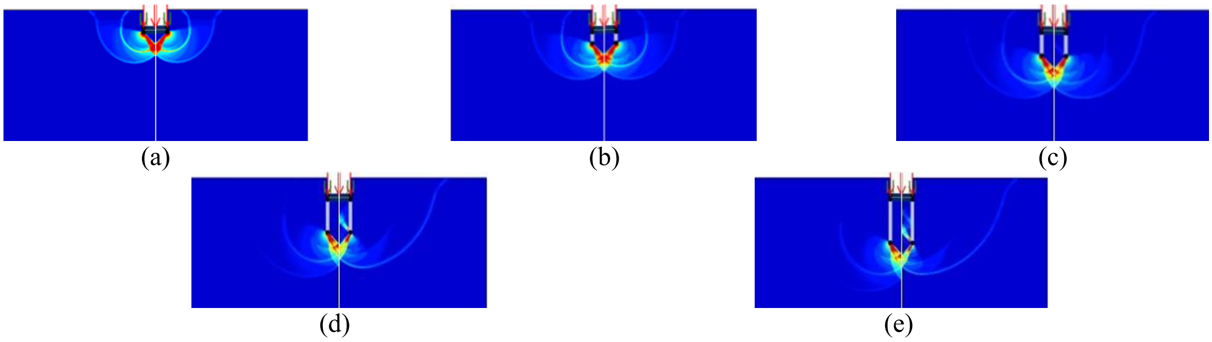


Fig. 11 Effect of skirt length on failure mechanism of skirted footing on cohesive soil (a) L/B=0, (b) L/B=0.5, (c) L/B=1.0, (d) L/B=1.5 and (e) L/B=2.0

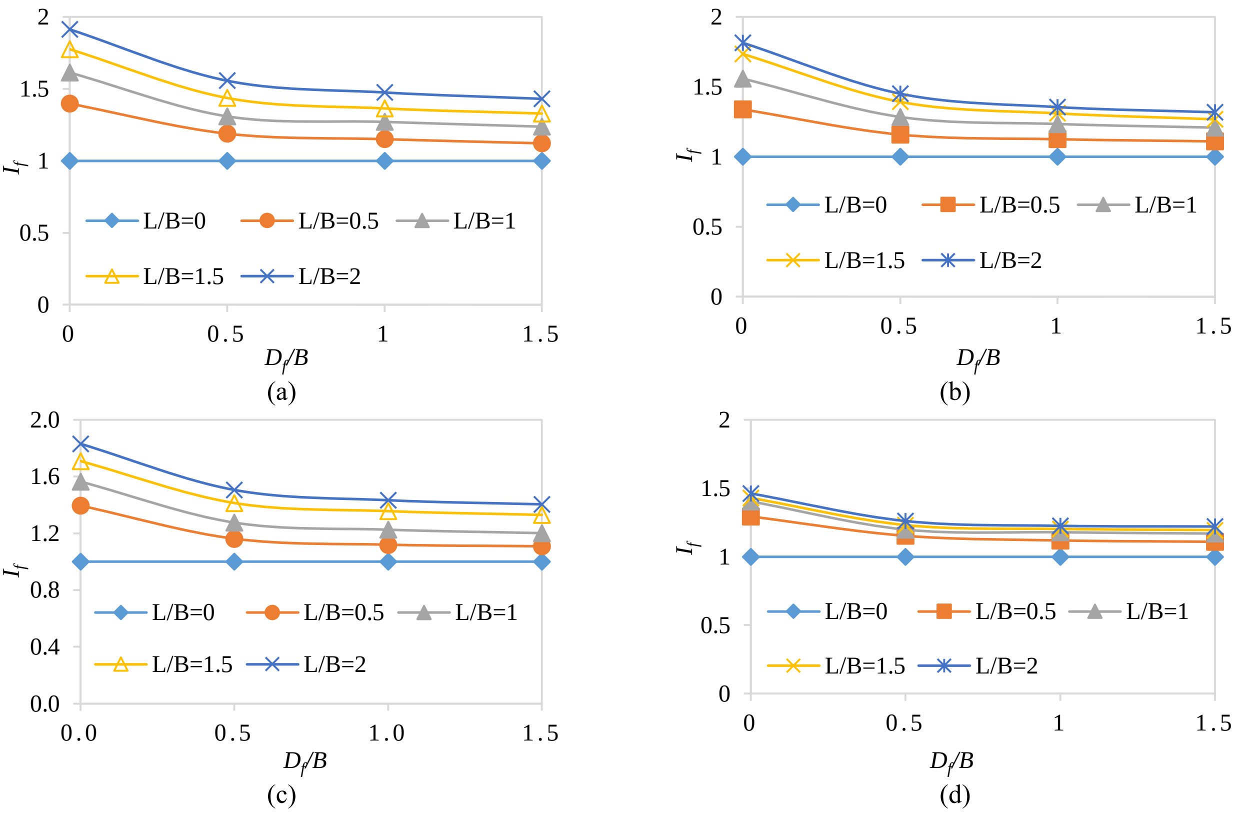


Fig. 12 Effect of footing depth on I_f in cohesive soil: (a) Rigid skirt, $c_u/(\gamma B)$= 0.7, (b) Flexible skirt, $c_u/(\gamma B)$= 0.7, (c) Rigid skirt, $c_u/(\gamma B)$= 10.6 and (d) Flexible skirt, $c_u/(\gamma B)$= 10.6

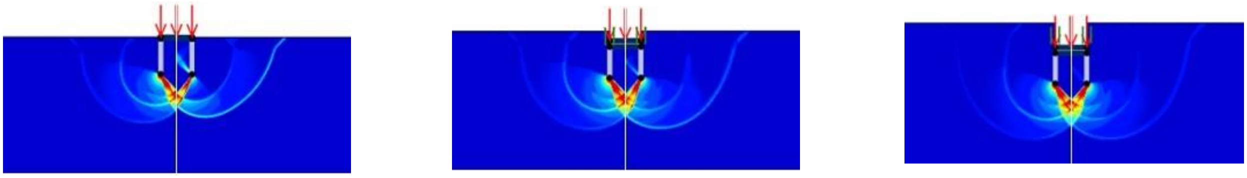
effect of skirt stiffness is minimal in cohesive soil compared to cohesionless soils. The optimum length of the skirt remains between 1.0B to 1.5B.

The typical effect of skirt length on the failure mechanism of a footing on cohesive soil is shown in Fig. 11. The failure mechanism changes with the change in skirt length. Up to skirt length of 1.0B, both rigid and flexible skirts behave identically. With a further increase in the length (L/B>1.0) of the rigid skirts, the load transfer mechanism changes from general shear failure to confined and similar to the deep foundations (Figs. 11(d) and 11(e)). In contrast to rigid skirt footing, the load transfer mechanism does not change with the length of the flexible skirt. The soil inside the flexible skirt deforms, and the failure surface initiates from the soil retained within skirts and reaches the ground surface.

Fig. 12 shows the typical variation in I_f with the increase in footing depth in cohesive soils. The I_f decreases with the increase in the footing depth. Effect of footing depth (D_f/B) is almost identical for the rigid and flexible skirt. The rate of decrease in the I_f is significant when footing depth increases from 0 to 0.5B, and a further increase in the footing depth (from 0.5 to 1.0) has only a negligible effect.

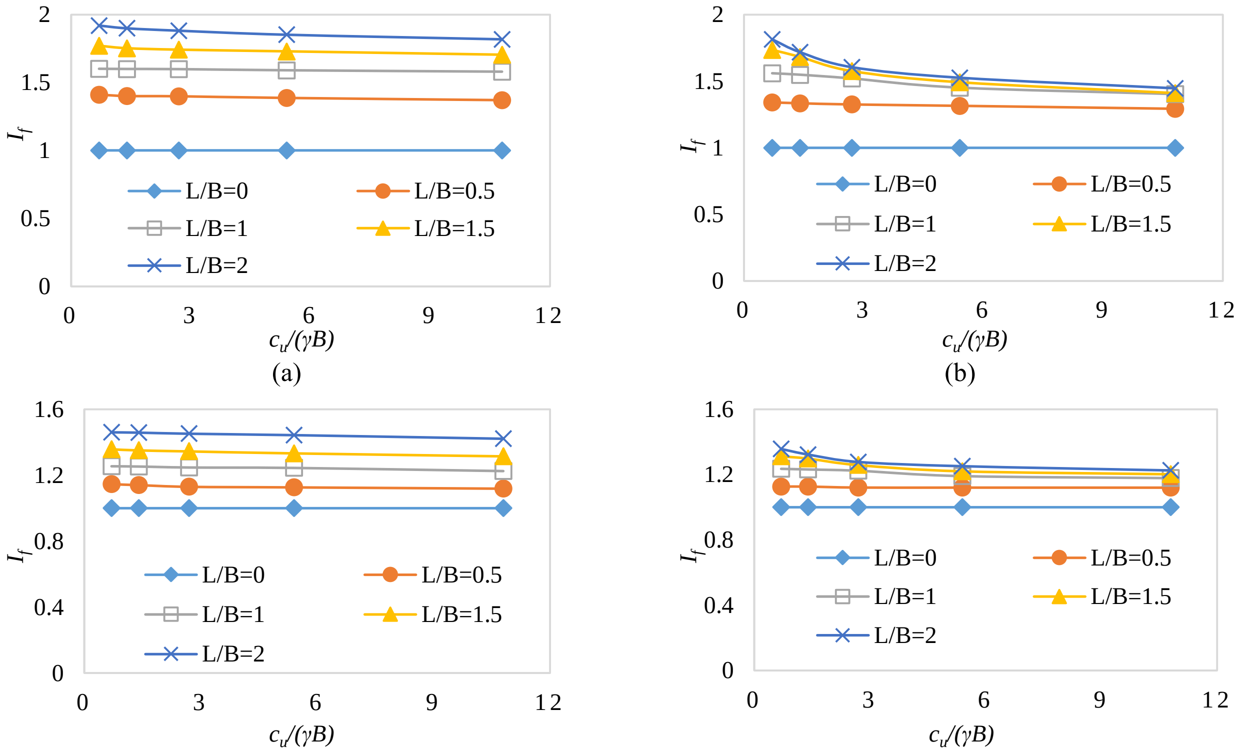
The influence of footing depth is relatively reduced with an increase in the soil strength. Comparing Figs. 7 and 12, it is observed that the effect of footing depth is more prominent in cohesionless soil than in cohesive soils. This observation is similar to conventional strip footings, where the depth factor increases significantly in cohesionless soil compared to cohesive soils (Terzaghi 1943).

Fig. 13 shows the typical effect of footing depth on the failure mechanism for a skirt length of 1.0B. The elastic



(a) (b) (c)

Fig. 13 Effect of skirt length on failure mechanism in cohesive soil (a) D_f/B =0, (b) D_f/B =0.5 and (c) D_f/B =1



(c) (d)

Fig. 14 Effect of undrained shear strength on I_f in cohesive soil: (a) Rigid skirt, D_f/B = 0.0, (b) Flexible skirt, D_f/B =0.0, (c) Rigid skirt, D_f/B =1.0 and (d) Flexible skirt, D_f/B =1.0

wedge is forming in rigid as well flexible skirted footings.

The shear zone area contributing to bearing capacity increases with footing depth, but the failure mechanism remains almost unvaried in skirted footing. Therefore, the improvement factor variation is nearly identical for rigid and flexible skirted footing (Fig. 12). The only difference between rigid and flexible is the origin of the failure surface. The failure starts either from the skirt tips or within the soil confined between the skirt in the flexible skirts. Whereas, in rigid skirted footing, the failure surface always starts from the tip of the skirt irrespective of footing depth.

Fig. 14 shows the reduction in improvement factor with the increase in soil strength. The I_f decreases trivially or remains almost constant in rigid skirted footing. The reduction is more noticeable in the flexible skirts when the strength ratio increases from 0.7 to 2.8. The further increase in strength ratio does not influence skirt efficiency significantly. The reduction in I_f with soil strength is significant in footing with skirt length greater than optimum length.

The stiffness of the flexible skirt relative to soil decreases with soil strength, and therefore, the improvement factor reduces with soil strength. However, the stiffness of rigid skirts always remains very high compared to soil, even in soil with very high strength. As a result, the relative stiffness of the skirt remains unaffected with an increase in the soil strength. Similar behavior is observed in the case of cohesionless soils (Fig. 8). Comparing Figs. 8 and 14, it can be observed that the efficiency of the skirt decreases significantly with an increase in the strength in cohesionless soil (increasing ϕ) than in cohesive soils (increasing c_u).

The typical variation in the failure mechanism, with an increase in soil strength for skirted footings with L/B=1.5, is shown in Fig. 15. Particularly at low strength ($c_u/(\gamma B)$ = 0.7 to 1.4), the failure mechanism is almost identical for rigid and flexible skirted footing (Figs. 15(a) and 15(b)). However, the increase in the soil strength leads to a difference in failure mechanism, and the difference becomes more visible with an increase in soil strength (Fig. 15(d) and 15(e)). Skirted footing behaves like a deep foundation at low strength, and deep confining failure is predominant, which changes to general or local shear

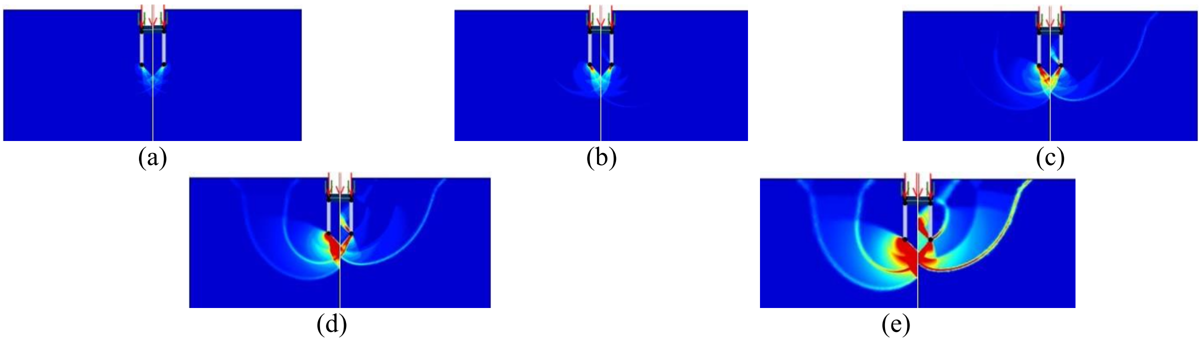


Fig. 15 Effect of soil undrained strength on failure mechanism for cohesive soil: (a) $c_u/(\gamma B)$ = 0.7, (b) $c_u/(\gamma B)$ = 1.4, (c) $c_u/(\gamma B)$ = 2.8, (d) $c_u/(\gamma B)$ = 5.3 and (e) $c_u/(\gamma B)$ = 10.6

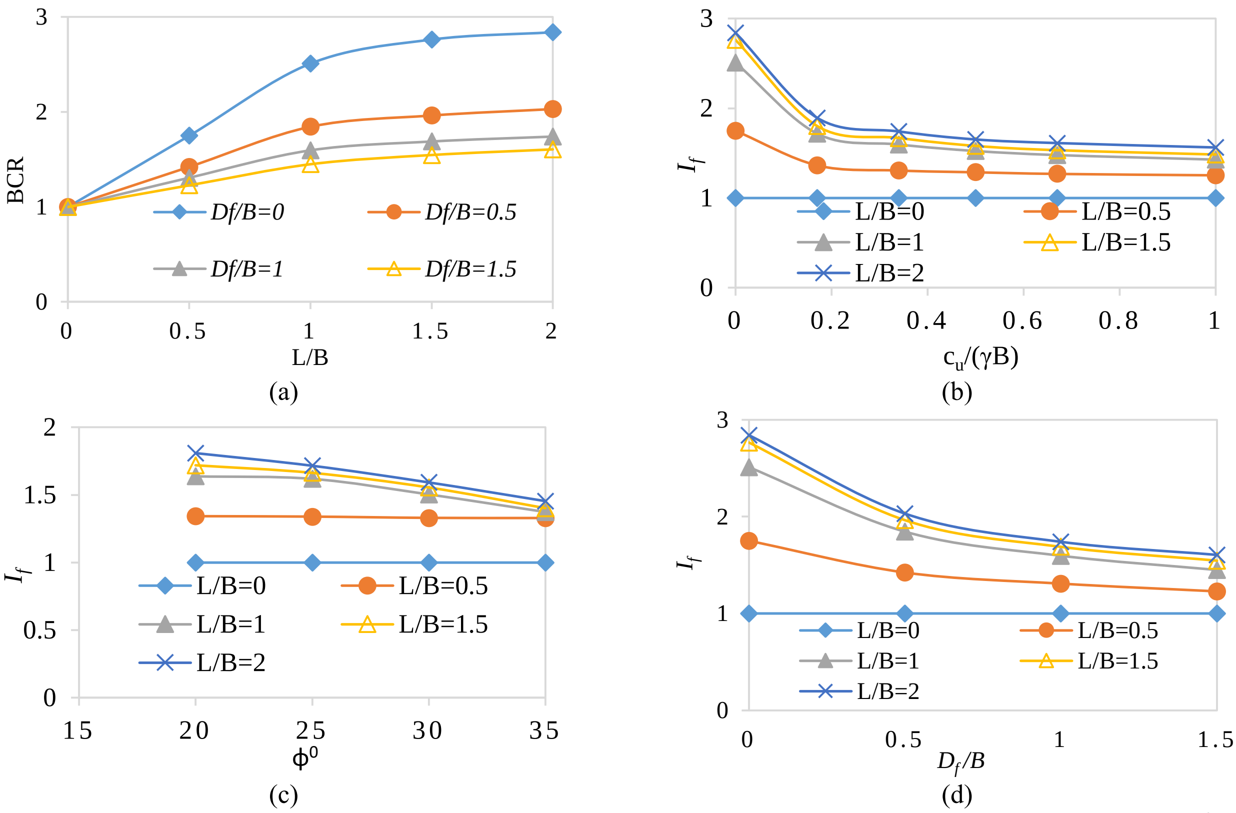


Fig. 16 Effect of various factors on improvement factor in c-ϕ soils: (a) Effect of skirt length ($c_u/(\gamma B)$ =0.36, ϕ =25^0), (b) Effect of cohesion (D_f/B =1, ϕ =25^0), (c) Effect of internal friction angle of soil ($c_u/(\gamma B)$ =0.36, D_f/B =1) and (d) Effect of footing depth ($c_u/(\gamma B)$ =0.36, ϕ =25^0)

failure with an increase in soil strength. Therefore, efficiency reduces with soil strength (Figs. 8 and 14). The change in the failure mechanism of skirted footing is attributed to the change in skirt stiffness relative to soil stiffness. At a low soil strength, the stiffness of the skirt (relative to soil) is very high, the load is transferred to a deeper depth, and the confined failure mechanism becomes predominant (Figs. 15(a) and 15(b)). This makes skirted footing behave like a deep foundation. However, the relative stiffness of the skirt reduces with an increase in the soil strength, which changes the load transfer mechanism.

The relative stiffness of the rigid skirt remains unaffected by an increase in soil strength. Therefore, the efficiency of rigid skirted footing either decreases very marginally or remains unaffected by the increase in the soil strength (Figs. 14(a), 14(c) and 14(e)).

4.3 Skirted Footing on c-ϕ Soils

Few cases of *c*-ϕ soils were also analyzed to determine the efficiency of skirted footing. In the *c*-ϕ soils, skirt efficiency is assessed by considering one parameter constant and changing the other strength parameter. Two cases have been used in the analysis to consider the practical range of soil consistencies. In the first case, the internal friction angle was kept constant, and the strength of the soil was varied ($0 \leq c_u/\gamma B \geq 1$). Whereas in the second case, the undrained strength is kept constant ($c_u/\gamma B$=0.36, 0.7, 1.4, 2.8), and the internal friction angle is varied from

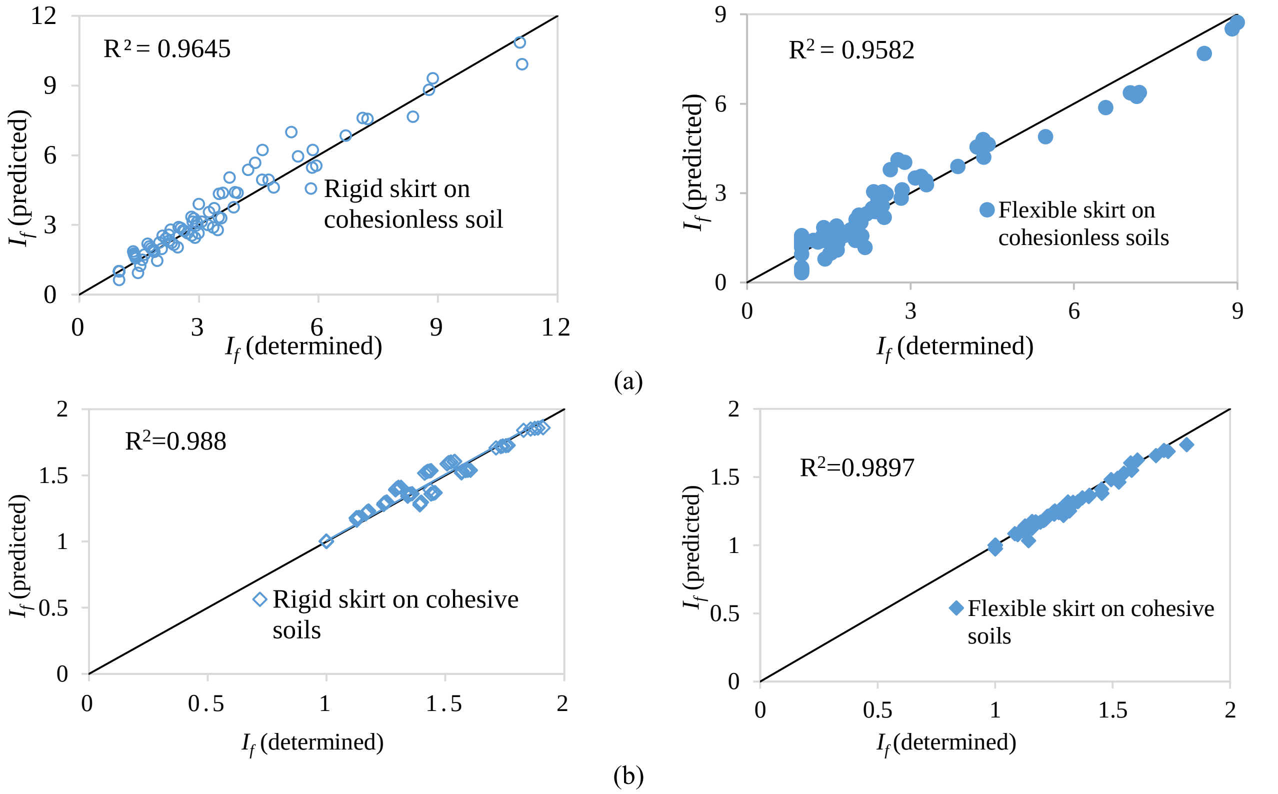


Fig. 17 Comparison of predicted values with determined value: (a) skirted footing on cohesionless soil and (b) flexible skirted footing on cohesive soil

25^0 to 35^0 with an interval of 5^0. In the first case, plots are similar to cohesive soils, and in the second case, plots are similar to those observed in cohesionless soils. In both cases, the I_f is relatively lower than the values observed in pure cohesionless soils. Therefore, all the plots are not presented here. The typical effect of various parameters on the improvement factor is shown in Fig. 16. The improvement factor increases with an increase in the skirt length. Similar to purely cohesionless and cohesive soils, the efficiency reduces with increased soil strength and footing depth (Figs. 16(b) and 16(d)). The reduction in I_f with footing depth and soil friction angle is more visible in cohesionless soil, and it diminishes with an increase in undrained strength for soil with a particular angle of internal friction. In cohesive soils or *c*-ϕ soils, the effectiveness of the skirt is less affected by the depth ratio of footing.

5. Statistical analysis

Statistical analysis was carried out to develop regression equations; those can predict the influence of various factors affecting rigid and flexible skirted footing efficiency. The numerical study results illustrate that the relationship between independent parameters and improvement factor is not linear, and hence, nonlinearity needs to be considered in statistical analysis. It is assumed that the improvement factor is a function of a number of variables. These are functions of 3 independent variables (L/B, D_f/B, c_u, or ϕ).

The equations are developed after a comparative study is performed to develop an equation that can effectively predict the effect of all these parameters within tolerable error. Various functions, such as linear, logarithmic, exponential, and polynomial, were assumed in the initial stage. The best relationship has been finally used to develop the equations.

$$I_{f\ (\phi\ soil,\ flexible\ skirt)} = 1 - 1.8D_f/B + 2.6\,L/B(1.42L/B - 1) + 0.25\,tan\phi\ (1 + 14.5\,D_f/B - 3.2\,L/B) - 0.03\ (D_f/B)(L/B)(1 - 27\,D_f/B) - (D_f/1.8B)\,tan\phi(4L/B + D_f/B) \quad (2)$$

$$I_{f\ (c\ soil, flexible\ skirt)} = 1 + 0.75L/B[1 - 0.04\,(c_u/\gamma B)] - 0.1\,D_f/B(1 + 7L/B - D_f/B) - 0.81(L/B)^2\ (1 - 0.7\,D_f/B) + 0.2(D_f/B)\ (L/B)[(D_f/B) + 0.125\,(c_u/\gamma B)] \quad (3)$$

$$I_{f\ (c\ soil, flexible\ skirt)} = 1 + 0.75L/B[1 - 0.04\,(c_u/\gamma B)] - 0.1\,D_f/B(1 + 7L/B - D_f/B) - 0.81(L/B)^2\ (1 - 0.7\,D_f/B) + 0.2(D_f/B)\ (L/B)[(D_f/B) + 0.125\,(c_u/\gamma B)] \quad (4)$$

$$I_{f\ (c\ soil, rigid\ skirt)} = 1 + 0.002\,(c_u/\gamma B) - 0.025D_f/B + 0.65L/B + 0.035(D_f/B)^2 - 0.1(L/B)^2 - 0.25\,(D_f/B)(L/B) \quad (5)$$

$$N_{\gamma q\ (skirted\ footing)} = N_{\gamma q\ (strip\ footing)} \quad (6)$$

Bearing capacity of skirted footing
= Bearing capacity of skirted footing x I_f (7)

$$I_{f\ (c\ soil, rigid\ \ skirt)} = 1 + c\frac{L}{B} \quad (8)$$

where, I_f =Bearing capacity improvement factor, B=width of footing, L=length of skirt, D_f = depth of footing, ϕ= internal friction angle of soil, c_u=undrained cohesion of soil, γ=unit weight of soil, $N_{\gamma q}$= bearing capacity factor considering the combined effect of soil weight and surcharge above the footing base the equations.

For developing the regression equation for rigid skirted footing resting on cohesionless soil, the variables are reduced from 27 to 10; thus, the R^2 value reduces from 0.994 to 0.964. The R^2 reduces from 0.994 to 0.988 in a cohesive soil when the number of variables is reduced from 27 to 10. Similarly, in the flexible skirted footing on cohesionless soil, reducing variables from 27 to 8 decreases the R^2 value from 0.990 to 0.958. It shows that all variables assumed in the initial phase of regression analyses do not affect it as expected initially. It has also reduced the length of the regression equation without much affecting the regression coefficient.

Eqs. (2) and (3) were developed to predict bearing capacity improvement with a flexible and rigid skirt on cohesionless soil. Similarly, Eqs. (4) and (5) were developed to predict bearing capacity improvement in cohesive soil with a flexible and rigid skirt. Eqs. (6) and (7), respectively, can predict the bearing capacity factor and ultimate bearing capacity of the skirted footing if the bearing capacity factor or bearing capacity of conventional strip footing is known.

A comparison of predicted with determined I_f is shown in Fig. 17 and shows a good agreement between predicted and evaluated values. It should also be noted that the value of I_f cannot be less than 1, and any value less than one should be assumed to be 1. It is also observed in statistical analysis that the efficiency of the skirt depends prominently on skirt length. The effect of strength parameters (c_u and ϕ) on the efficiency of the skirt is relatively more than the footing depth and relatively less than the skirt length. Byrne and Houlsby (1999) and Larsen (2008) presented a similar equation (Eq. (8)) to predict the bearing capacity improvement with the provision of the skirt. However, the presented equation does not incorporate the effect of soil properties, footing depth, and skirt properties. Byrneand Houlsby (1999) and Larsen (2008) proposed the value of 'c' to be 0.89 and 2.9, respectively.

7. Conclusions

The bearing capacity increases with the skirt irrespective of soil types, strength parameters, skirt rigidity, and footing depth.

The flexible skirted footing behaviour is identical to rigid skirted footing for skirt length less than or equal to optimum skirt length. The skirt efficiency remains identical for both skirts up to optimum skirt length. However, the rigid skirt is relatively more efficient for greater skirt length.

The optimum length of the flexible skirt is found to be in the range of 1.0B to 1.5B in soils with internal friction angle less than 35^0, whereas it varies between 0.5B to 1.0B in soils with an internal friction angle greater than 40^0. However, it is challenging to suggest any optimum length for rigid skirts as bearing capacity increases linearly with an increase in skirt length.

The effectiveness of the skirt (i.e., I_f) reduces with the increase in the strength parameters of soil (c_u and ϕ) and footing depth, and the reduction is significant in higher skirt length. The effect of these parameters on skirt effectiveness is more visible in cohesionless soils than in cohesive soils.

The bearing capacity enhancement is relatively small in cohesive soil compared to cohesionless soil, but the optimum skirt length is relatively higher than those observed in cohesionless soils. Efficiency is independent of undrained strength at short skirt lengths, but it reduces with strength at higher skirt lengths.

The increase in stiffness of the soil foundation system is relatively large in a rigid skirted footing compared to the flexible skirt. Footings with longer rigid skirts observe a deep confined failure mechanism. However, the flexible skirt of identical length fails in general shear failure. The difference in the failure mechanism of a rigid and flexible skirted footing contributes to the difference in the efficiency of the flexible and rigid skirt. The bearing capacity increases steadily with the increase in rigid skirt length. Unlike the flexible skirts, deflection of the rigid skirt is negligible even at larger skirt lengths, which increases the soil strength mobilization over a larger area. The rigid skirted footing is equivalent to a conventional strip footing placed at the skirt tip level. A flexible skirted footing behaves like a strip footing for a skirt length more than or equal to an optimum value. The developed nonlinear equations reasonably predict the bearing capacity improvement with a flexible and rigid skirt.

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