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Failure mechanism and bearing capacity of inclined skirted footings

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Abstract. The use of a skirt, a vertical projection attached to the footing, is a recently developed method to increase the bearing capacity of soils and reduce foundation settlements. Most of the studies were focused on vertical skirted circular footings resting on clay while neglecting the rigidity and inclination of skirts. This study employs finite element limit analysis to investigate the bearing capacity enhancement of flexible and rigid inclined skirts in cohesionless soils. The results indicate that the bearing capacity initially improves with an increase in the skirt inclination but subsequently decreases for both flexible and rigid skirts. However, the rigid skirt exhibits more apparent optimum skirt inclination and bearing capacity enhancement than the flexible one, owing to differences in their failure mechanisms. Furthermore, the bearing capacity of the inclined skirted foundation increases with the skirt length, footing depth, and internal friction angle of the soil. In the case of rigid skirts, the bearing capacity increases linearly with skirt length, while for flexible skirts, it reaches a stable value at a certain skirt length. The efficiency of the flexible footing reduces as the footing depth and soil internal friction angle increase. Conversely, the efficiency of the rigid skirt decreases only with an increase in the depth of the footing. The paper also presents a detailed analysis of various failure patterns, highlighting the behaviour of inclined skirted footings. Additionally, nonlinear regression equations are provided to quantify and predict the bearing capacity enhancement with the inclined skirts.

Keywords: bearing capacity; enhancement factor; footing; inclined skirt; soil

1. Introduction

The rapid urbanisation has led to the unavailability of suitable land for construction, and this has forced engineers to use unsuitable land. Construction of foundations on these sites requires ground improvement to avoid problems of high settlements and low bearing capacities. A considerable number of soil improvement and reinforcing techniques have evolved within the last few decades. The provision of the skirt, which is a vertical projection attached to the footing, is one of the methods to increase the bearing capacity of the soils and reduce the foundation settlements (Bransby and Randolph 1997). A skirted foundation is a foundation having additional vertical projection around an isolated footing or on the sides of a strip footing. The skirt constrains the soil lateral movement below the foundation and between the skirt and transfers the load to a relatively greater depth, and the skirt increases the footing bearing capacity. Provisions of the skirt have many advantages over many other foundations. Construction of skirted footing may not be affected by the presence of a water table, and it does not need any excavation work for installation (Azzam and Farouk 2010). Skirted foundations are mostly used in the case of a bridge, wind turbines, jack-up structures, and subsea structures (Gerven 2011).

Literature is full of studies on skirted foundations resting on a variety of soils, subjected to various types of loads (Bransby and Randolph 1997, Hu *et al.* 1999, Byrne *et al.* 2002, Gerven 2011, Al-Aghbari and Mohamedzein 2004, 2006, Nazir and Azzam 2010, Wakil 2013, Bienen *et al.* 2012, Mana *et al.* 2012, Mana *et al.* 2013, Park *et al.* 2013, Mana *et al.* 2014, Vulpe *et al.* 2016, Khatri *et al.* 2017, Sajjad and Masoud 2018, Selmi *et al.* 2019, Alzabeebee 2020, Yan *et al.* 2020, Shukla and Jakka 2022, Bashir *et al.* 2023). These studies concluded that the foundation performance enhanced with skirt length, and the enhancement contributed to the increased effective depth of footing.

Many studies compared the behaviour of the skirted footing with strip/isolated footings. Some studies found that the increase in the effective depth due to the provision of a skirt is less efficient than the strip footing resting at the level of the skirt tip (Tani and Craig 1995, Bransby and Yun 2009, Eid 2013, Yun and Bransby, 2007, Vulpe *et al.* 2016).

It has also been found in a few studies that increasing the skirt length is comparatively more beneficial than increasing the embedment depth of solid footing (Al-Aghbari and Mohamedzein 2004, Zhang and Ding 2011, Golmoghani-Ebrahimi and Rowshanzamir 2013, Park *et al.* 2016). Shukla and Jakka (2022) presented the detailed failure mechanism of skirted footing and showed that the skirt effectiveness is a function of skirt length and rigidity.

Saleh *et al.* (2008) considered a footing with a one-sided inclined skirt under eccentric, inclined loading. It was observed that it helps to improve the lateral resistance of footing. It is possible that the inclined skirt on both sides of

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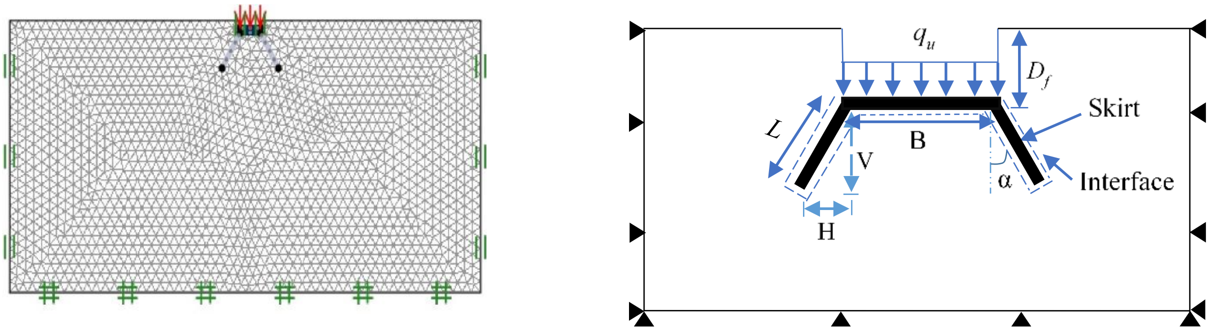


(a) (b)

Fig. 1 Details of Problem: (a) Finite element model used in the study and (b) Problem geometry

the footing may further enhance bearing capacity. However, the study on both sides inclined skirted footing is not available in the literature. It is also observed that most of the studies were constrained to vertical skirted circular footing only and mostly resting on clay. Strip footing is still popular in rural areas, and a detailed analysis is required for more clarity on the effect of skirt length on the bearing capacity of skirted strip footing, even for vertical skirted footing.

This study explores the response of vertical and inclined skirted footings resting over the cohesionless soil under purely vertical loading using finite element limit analysis (FELA). Based on the study, an optimum inclination and optimum skirt length are identified. The performance of the rigid skirt has also been explored in the study, which is missing in previous studies. The failure mechanism has also been presented in detail to highlight and explain the behaviour of inclined skirted footing.

2. Method of analysis

A two-dimensional numerical analysis was performed using a finite element limit analysis (FELA) program. The problem was simulated as a plane strain condition using a limit analysis program OptumG2. Both upper and lower bound limit analyses were carried out to determine the bearing capacity of inclined skirted footings with different skirt lengths and inclinations. The soil has been discretised using a three-node element in lower bound analysis, as it satisfies all three conditions required for the lower bound solution and provides rigorous lower bounds. The stress varies linearly between nodes. Two zero-thickness elements link lower-bound elements. This results in induced statically admissible stress discontinuities between elements (Hjiaj *et al.* 2005). The maximum lower bound is determined by evaluating a collapse load satisfying the stress equilibrium equations at triangular elements defined by the 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 all sides are straight. Therefore, the soil has been discretised as six noded triangular elements in the upper bound analysis, where the displacement variation is considered quadratic. The details of quadratic interpolation were already provided in a number of studies (Chen *et al.* 2004, Liew *et al.* 2006). In addition to ensuring displacement continuity between the elements, it is also important to consider the minimum upper bound limit load. 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 dense sand behaviour. However, the effect of the dilatancy angle on soil behaviour can be incorporated by considering a modified angle of internal friction. The modified angle of internal friction can be obtained with the help of expressions (Eq. (1)) developed by Drescher and Detournay (1993).

$$\phi_{\text{mod}} = \tan\phi \left(\frac{\cos\psi\cos\phi}{1-\sin\psi\sin\phi}\right) \qquad (1)$$

where, ϕ is internal friction, ϕ_m is the modified angle of internal friction to incorporate the soil dilation, ψ is the dilatancy angle

The present study uses the formulation introduced by Makrodimopoulos and Martin (2006, 2007) for lower-bound modelling as well as the formulation proposed by Krabbenhøft *et al.* (2007, 2008) for upper-bound modelling. Lower and upper bounds have been used in association with conic optimisation. It is an effective second-order optimisation technique, and several researchers have used it in limit analysis to get the optimised upper and lower bound bearing capacity (Krabbenhøft *et al.* 2007, Ukritchon and Keawsawasvong 2016, Shukla and Jakka 2022).

Fig. 1 shows the details of the model used to simulate the inclined skirted footing. The different types of connections are possible to connect the footing and skirt, which may affect the footing behaviour. However, rigid connections were used in the present study 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, and finally, the load is transferred to the soil. Earlier studies found that the separation is negligible in the inner interface between the skirt and soil (Chen and Randolph 2007, Mana *et al.* 2012). Therefore, the internal interface was assumed to be 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.

A large domain area was chosen in the analysis so that the study results remain independent of domain boundaries. The domain width was kept equal to 30 times the footing width (B) and depth equal to 15B in cases of flexible skirted footing. This domain size is enough to avoid or minimise the influence of numerical model boundaries on analysis results. However, in rigid skirted footing, the domain length is increased to 60B, as convergence is achieved only after a domain size of 55B in some cases. The sand was used as a foundation material and was modelled by the modified Mohr-Coulomb model. The footing was considered to be made of rigid plate. The skirt was modelled as a flexible and rigid plate element. A plate that possesses infinite stiffness has been used to simulate the rigid skirt. The flexible skirt is assumed to be made of steel. All analyses were also repeated on the rigid skirt.

One of the most important aspects of the analysis is the use of adaptive iterations, which automatically refine the mesh and save a lot of time in the limit analysis. Second, the most important aspect of the analysis is the second-order conic programming. The analysis details and various assumptions made in the formulation are provided in Krabbenhoft *et al.* (2015). Similar to previous studies, mesh adaptivity was used to refine the mesh to attain precise results (Lyamin *et al.* 2005, Keawsawasvong and Ukritchon 2016, Shukla and Jakka 2018, Shukla 2022). The mesh was refined in every iteration in the portion critical for failure mechanisms. Shear dissipation and strain dissipation criteria were used to refine the mesh in lower bound and upper bound limits, respectively. The number of adaptive iterations is fixed to 5. The load is increased in the form of a load multiplier and is increased until a state of incipient collapse is reached. After the analysis, the collapse load for different skirt lengths and different inclinations was determined. The bearing capacity values were found to be higher in the upper bound as compared to the lower bound. However, the difference in bearing capacity enhancement determined from both bounds is very marginal. An average lower and upper collapse value is used in the analysis, which may be close to the actual collapse load.

3. Details of considered parameters

Various parameters influencing the behaviour of inclined skirted strip footing, such as the inclination of the skirt, strength parameters of soil, embedment depth of footing, and length of the skirt, are considered in the analysis. The skirt inclination is normalised (Horizontal: Vertical) to make it a non-dimensional term. The embedment depth of the footing (D_f) and skirt length (L) is normalised to the footing width (B). Table 1 shows the range of various considered parameters. From Fig. 1, the skirt inclination (α) with vertical and skirt length can be determines by Eqs. (2) and (3), respectively.

Table 1 Details of the considered parameter

ϕ (^{0})	Skirt length ratio (L/B)	Skirt inclination (H:V)	D_f/B
25	0, 0.5, 1, 1.5, 2	0, 0.2:1, 0.4:1, 0.6:1, 0.8:1,1:1, 1.5:1, 2:1	0, 0.5, 1.0, 1.5
30	0, 0.5, 1, 1.5, 2	0, 0.2:1, 0.4:1, 0.6:1, 0.8:1,1:1, 1.5:1, 2:1	0, 0.5, 1, 1.5
35	0, 0.5, 1, 1.5, 2	0, 0.2:1, 0.4:1, 0.6:1, 0.8:1,1:1, 1.5:1, 2:1	0, 0.5, 1, 1.5
40	0, 0.5, 1, 1.5, 2	0, 0.2:1, 0.4:1, 0.6:1, 0.8:1,1:1, 1.5:1, 2:1	0, 0.5, 1, 1.5

$$\tan\alpha = \text{H/V} \tag{2}$$

$$\text{Skirt length (L)} = \sqrt{H^2 + V^2} \tag{3}$$

where, α is the skirt inclination with vertical, V is the vertical projection and, H is the horizontal projection of the skirt, L is the length of the skirt

For uniformity purposes, the interval of friction angle (ϕ) was maintained constant, and it was varied between 25^0 and 40^0 with an interval of 5^0. The soil with angles of internal friction 45^0 possesses significant bearing capacity, and strip footing might perform satisfactorily. Therefore, it has not been considered in the present study. Most of the earlier studies have found that the optimum length of the vertical skirt varies from 0.5 to 1.0 times the footing width (Al-Aghbari and Mohamedzein 2004, Yun and Bransby 2007, Eid 2013, Shukla 2019). In the case of the inclined skirt, the optimum length of the skirt is not known. Therefore, a more comprehensive range of skirt lengths needs to be considered, and here, it is varied from 0.5 to 2 times the footing width.

4. Validation of the numerical modelling

Before analysing the influence of skirt inclination, the developed finite element limit analysis model was validated using the results of earlier published studies (Ukritchon *et al.* 2003, Chakraborty and Kumar 2013, Cascone and Casablanca 2016, Lyamin *et al.* 2007, Michalowski 1997, Martin 2005, Kumar and Khatri 2008). The bearing capacity factor, N_γ determined through the numerical model, is compared with the values suggested by earlier studies for a rough base rigid strip footing resting on cohesionless soils and is shown in Table 2. The bearing capacity has been compared for different angle values of internal friction of soil ($20^0 \leq \phi \geq 45^0$). The comparison shows that the model used in this study gives reasonable bearing capacity factors.

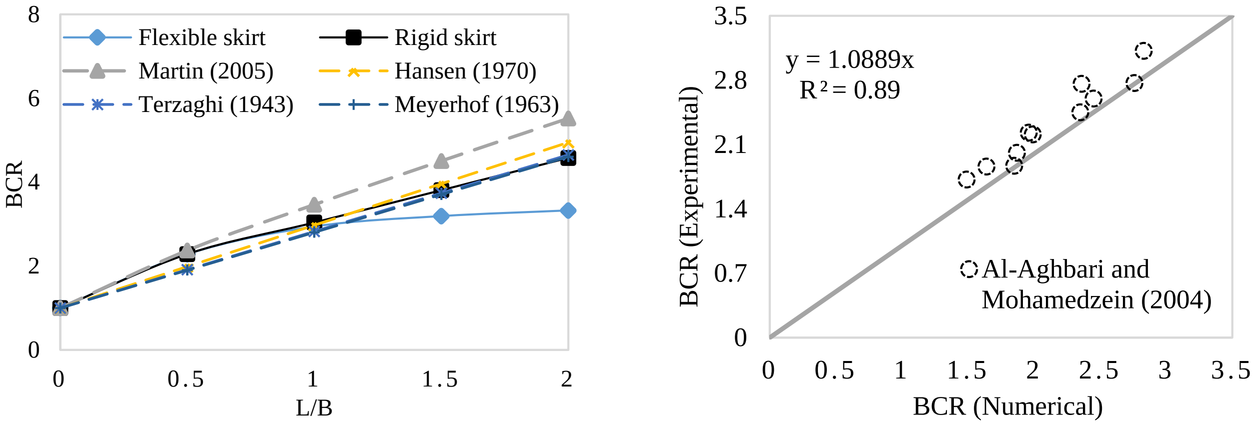
The values are found close to those presented by Cascone and Casablanca (2016). Further, the values are found to be marginally lower than the upper bound solution of Lyamin *et al.* (2005) and Michalowski (1997) and the method of stress characteristics solution presented by Martin (2005). In contrast, the values are greater than the earlier lower bound analysis of Ukritchon *et al.* (2003),

Table 2 Comparison of determined bearing capacity factor (N_γ) with previous studies

Studies		**ϕ=25⁰**	**ϕ=30⁰**	**ϕ=35⁰**	**ϕ=40⁰**	**ϕ=45⁰**
Present study		6.78	14.77	35.88	88.71	233.08
Bolton and Lau (1993)		11.6	23.60	51.00	121.00	324.00
Kumar (2003)		6.46	14.68	34.31	85.10	232.64
Ukritchon *et al.* (2003)		5.95	13.20	29.30	69.90	165.00
Martin (2005)		7.36	16.73	39.18	97.01	260.20
Lyamin *et al.* (2007)	UB	7.09	15.90	36.98	91.86	255.44
	LB	6.44	14.57	33.81	82.29	234.21
Kumar and Khatri (2008)		6.02	13.65	31.90	77.88	204.53
Chakraborty and Kumar (2013)		6.43	14.53	33.54	81.80	210.00
Zhu (2000)		7.86	17.57	40.20	97.92	263.74
Michalowski (1997)		9.76	21.39	48.68	118.82	322.83
Cascone and Casablanca (2016)	UB	6.75	15.23	35.97	87.03	239.98
	LB	6.49	14.75	34.48	85.58	234.32

Table 3 Comparison of determined bearing capacity factor (N_q) with previous studies

Studies details	**ϕ=25⁰**	**ϕ=30⁰**	**ϕ=35⁰**	**ϕ=40⁰**	**ϕ=45⁰**
Terzaghi (1943)	12.65	22.50	41.40	81.30	173.30
Meyerhof (1965)	10.70	18.40	34.78	64.10	134.70
Yin *et al*. (2001)	12.00	22.00	44.00	70.00	180.00
Ebid *et al*. (2021)	12.40	18.40	41.30	64.20	-
Present study	15.36	24.34	44.69	90.96	197.92



(a) (b)

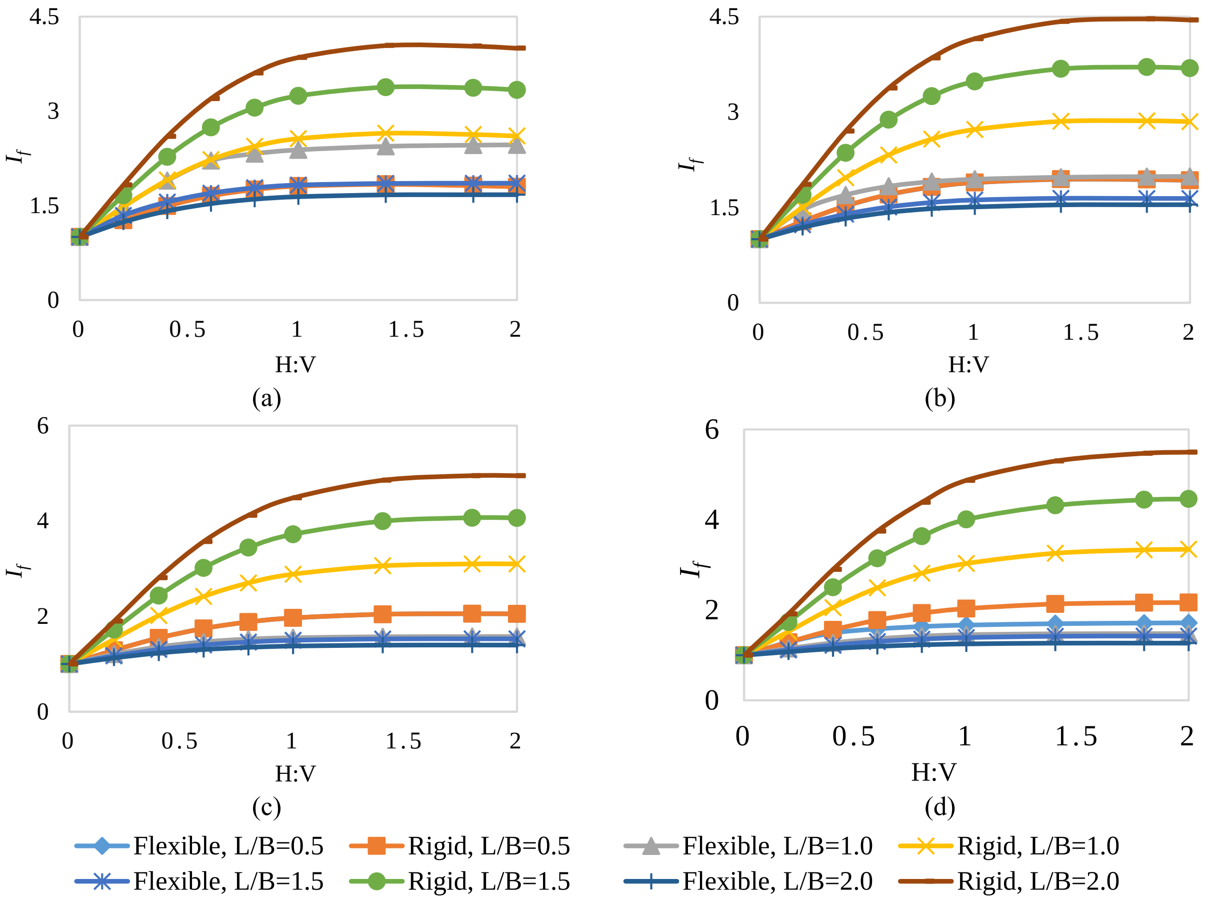
Fig. 2 Validation of the numerical model: (a) Skirted footing with traditional methods and exact solution of Martin (2005) and (b) Flexible skirted footing BCR with the experimental studies

Lyamin *et al.* (2007), Kumar and Khatri (2008) and Chakraborty and Kumar (2013). However, the bearing capacity is significantly lower than the solution presented by Bolton and Lau (1993).

Table 3 compares the values of N_q derived from the numerical modelling with previously proposed values. The average values of N_γ for different ϕ are similar to those proposed by Yin *et al*. (2001). The average values, however, are significantly higher than those predicted by conventional bearing capacity theories (Terzaghi 1943, Meyerhof 1965) and Ebid *et al.* (2021). Both studies replaced the surcharge loading with an equivalent uniformly distributed load, ignoring the soil shear resistance above the footing. Consequently, most of the earlier studies, including Terzaghi (1943), offer conservative bearing capacity factors, N_q.

The results from vertical rigid and flexible skirted footing in terms of *BCR* are compared to those from traditional methods and Martin (2005), as seen in Fig. 2. The bearing capacity ratio (*BCR*) is defined as the ratio of the bearing capacity of a vertical skirted footing to that of a conventional strip/isolated footing without a skirt (Al-Aghbari and Mohamedzein 2004, Shukla 2022).

The *BCR* in rigid skirted footing is marginally less than those obtained by Martin (2005). However, the values are



(a) (b)

(c) (d)

Fig. 3 Effect of skirt inclination on bearing capacity enhancement for a rigid and flexible skirt length of 1B: (a) $\phi=25^0$, (b) $\phi=30^0$, (c) $\phi=35^0$ and (c) $\phi=40^0$

close to those obtained using traditional theories (Terzaghi 1943, Meyerhof 1965). It also shows that *BCR* in the flexible and rigid skirt is almost the same for skirt lengths less than 1B. However, in footings with a skirt length greater than 1B, the *BCR* increases marginally in the flexible skirt and is found to be minimal. The *BCR* in the rigid skirt is almost equal to the conventional footing placed at the tip of the skirt. It shows that rigid skirted footing behaves like a counterpart strip footing placed at the tip of the skirt. Therefore, a skirted footing cannot always be treated as strip footing if the skirt is not rigid. It needs to be made sure that the skirt is rigid relative to the soil to get the optimum benefit of skirted footing.

The BCR values determined from the present FELA study are reasonably comparable to that of Al-Aghbari and Mohamedzein (2004) and an experimental study carried out presently (Fig. 2(b)). However, the experimental values are always a little higher than numerical results. R^2 values are found to be 0.890 when compared with the results of Al-Aghbari and Mohamedzein (2004). Scaling effects have contributed to the difference in the numerical and experimental study.

5. Results of numerical study and discussions

The bearing capacity enhancement with the skirt inclination is measured in terms of the "Enhancement factor (I_f). It is the ratio of the bearing capacity of an inclined skirted footing to a vertical skirted footing. Therefore, the term I_f represents the relative enhancement in the bearing capacity of the inclined skirt over the vertical skirt. The increase in enhancement factor 'I_f' indicates the increase in the efficiency of the inclined skirt and vice versa. The effect of skirt inclination, embedment depth of footing, angle of internal friction of soil, skirt rigidity, and skirt length are discussed separately in the subsections. The value of skirt length and skirt inclination at which maximum enhancement is observed has been stated as optimum skirt length and optimum skirt inclination. The soil, in reality, is anisotropic, and the failure mechanism can be asymmetrical (Ziccarelli *et al.* 2017, Puła and Chwała 2018, Valore *et al.* 2017). The bearing capacity is slightly higher in anisotropic soil (asymmetrical failure) compared to isotropic soil (symmetrical failure) (Puła and Chwała 2018). Therefore, neglecting the anisotropic nature leads to a safer design.

5.1 Effect of skirt inclination

The typical variations in the enhancement factor (I_f) with the inclination of rigid and flexible skirts are shown in Fig. 3. The bearing capacity of flexible and rigid skirted footing enhances significantly with skirt inclination.

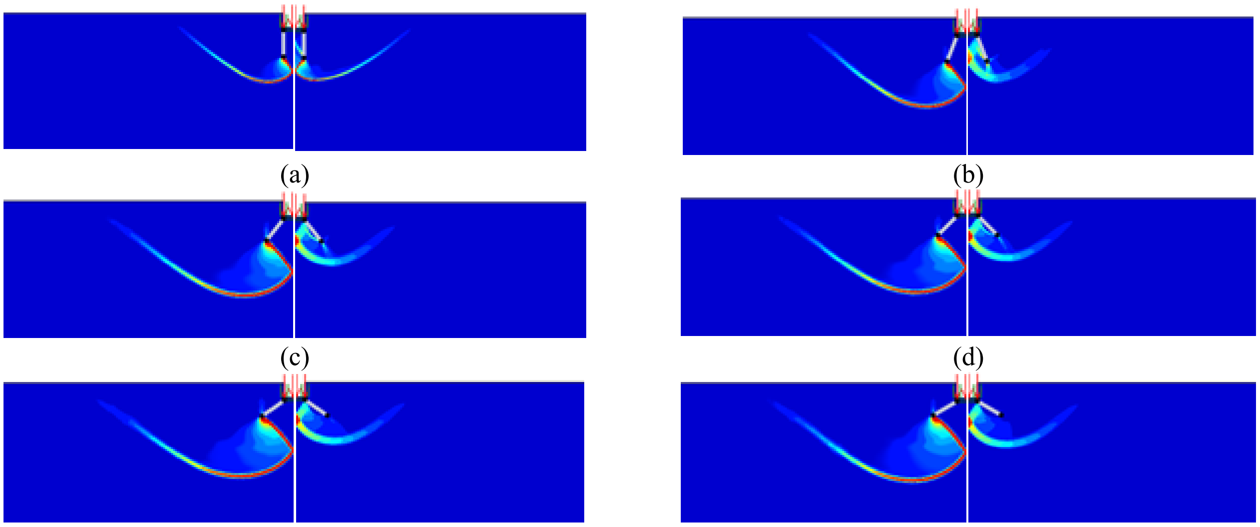

(a) (b) (c) (d) (e) (f)

Fig. 4 Variation in failure mechanism with skirt inclination: (a) Vertical, (b) 0.4H: 1V, (c) 0.8H: 1V, (d) 1H:1V, (e) 1.4H: V and (f) 1.8H: V

However, a rigid skirt is found to be more effective than a flexible skirt, and the difference in the enhancement factor becomes more apparent at a higher internal friction angle.

The variation in bearing capacity with skirt inclination depends on other factors, such as skirt length, soil angle of shearing resistance, and the embedment depth of footing.

The maximum improvement is achieved at a relatively higher skirt inclination in rigid skirts compared to flexible skirts. It means the optimum skirt inclination is higher in a rigid skirt. The optimum inclination and bearing capacity enhancement in flexible skirts becomes less perceptible with an increase in the soil internal friction angle. Nevertheless, in rigid skirts, optimum inclination and bearing capacity enhancement increase with the angle of internal soil friction. The provision of the skirt not only confines the soil but also acts as a reinforcing element and increases the bearing capacity.

The enahncement factor increases almost linearly with an increase in the skirt inclination up to a certain extent. Furthermore, an increase in the skirt inclination does not influence the enhancement factor significantly. The magnitude of the optimum skirt inclination reduces with the footing depth, internal friction angle of soil, and the skirt length. The skirt length effect on optimum skirt inclination is noticeable on footings resting over the ground level in loose soils.

The inclined skirt provides additional resistance by means of increased lateral and vertical resistance. The passive pressure acting on the surface in contact with inclined skirts is relatively high compared to the vertical skirt, which increases the passive resistance. The increase in passive resistance ultimately increases the bearing capacity. This behaviour is very similar to battered piles, where the negative batter angle significantly increases pile capacity (Zhang *et al.* 1999, Juvekar and Pise 2008, Seo *et al*. 2021).

For the soil with a low angle of shearing resistance ($\phi \leq 30^0$), the optimum skirt inclination is found to be 1.2H: 1V. However, soils with a higher angle of internal friction ($\phi \geq 40^0$) reduce to 0.6H: 1V. Figs. 3 (a)-3(c) also demonstrates that for the depth ratio of 0, the maximum enhancement is observed for skirt length 1B. The maximum enhancement for the depth ratio of 0.5 is approximately identical for skirt lengths of 0.5B and 1B. Similarly, in footing with a depth ratio of 1, the maximum enhancement is attained in the skirt length ratio of 0.5. The optimum skirt inclination in flexible and rigid skirted footings depends relatively more on skirt length and soil internal friction angle than the footing depth.

The typical variation in shear dissipation with skirt inclination for soil with internal friction of 30^0 for a skirt length of 1.5B is shown in Fig. 4. These plots also show the failure surface. The left and right parts of each Figure show the failure surface for rigid and flexible skirts. The shear zone area (area within the failure surface) contributing to bearing capacity increases significantly in rigid skirts compared to flexible skirts. In the flexible skirted footing, the failure surfaces originate from inside the soil plug confined between the skirt for a skirt length greater than the optimum value, and the influence of the skirt becomes very minimal. Further, in a few cases, when the skirt inclination is more than 45^0, the slip lines originate from the points of connection between the skirt and footing (Figs. 4(c)-4(f)). Contrary to the flexible skirt, the failure always originates from the tip of the rigid skirt irrespective of skirt inclination (Figs. 4(a)-4(f)). This makes rigid skirts more efficient than flexible skirts.

5.2 Effect of skirt length

The variation in enhancement factor (I_f) with skirt length for various angles of internal friction of soil is shown in Fig. 5. The typical curves are plotted for the footing placed over the ground surface (D_f/B=0). Nevertheless, the bearing capacity increases with the flexible skirt length, the enhancement (I_f) in inclined skirts initially increases with the skirt length and reaches its maximum value, and an additional increase in skirt length reduces the skirt

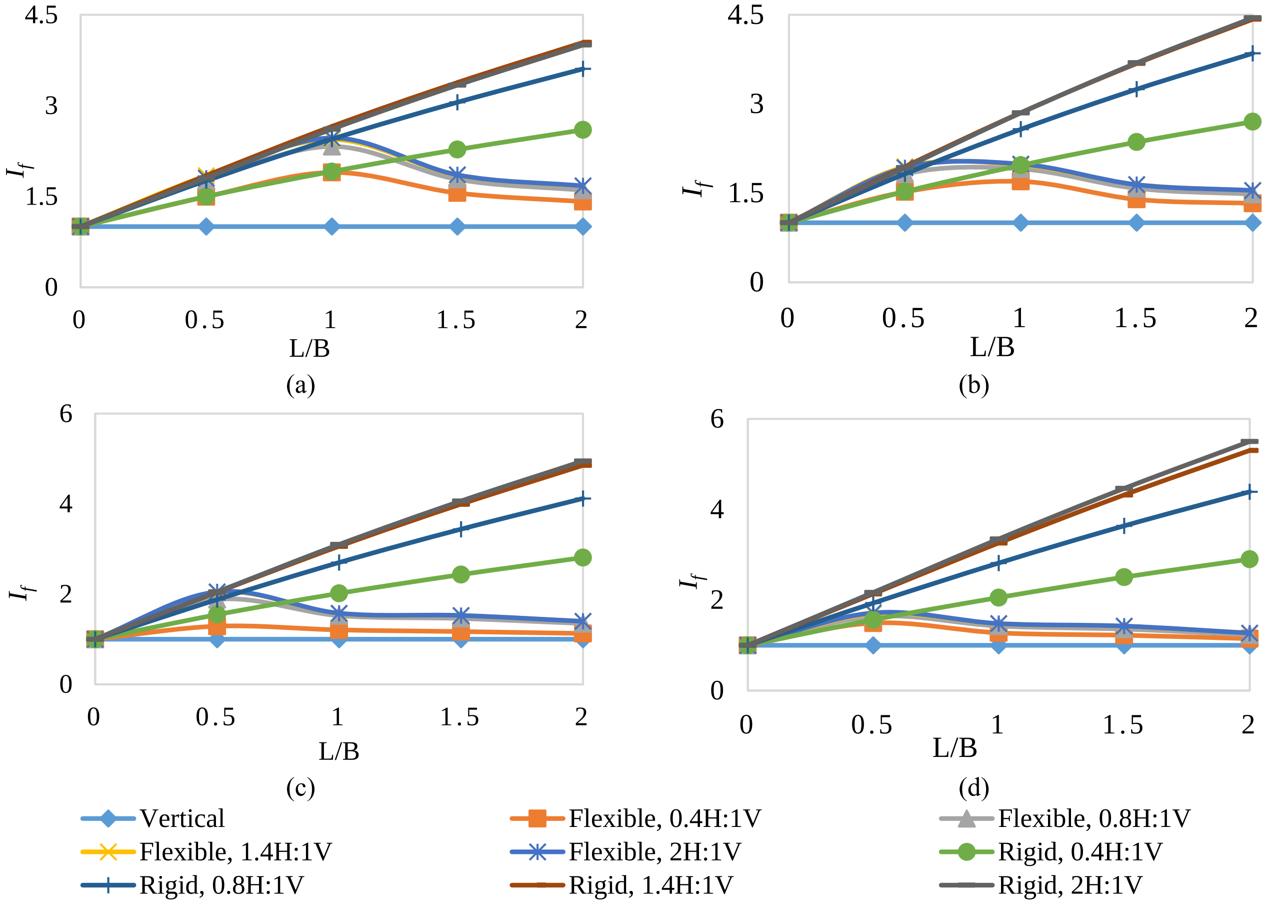


Fig. 5 Variation in bearing capacity enhancement with skirt length: (a) $\phi=25^0$, (b) $\phi=30^0$, (c) $\phi=35^0$ and (c) $\phi=40^0$

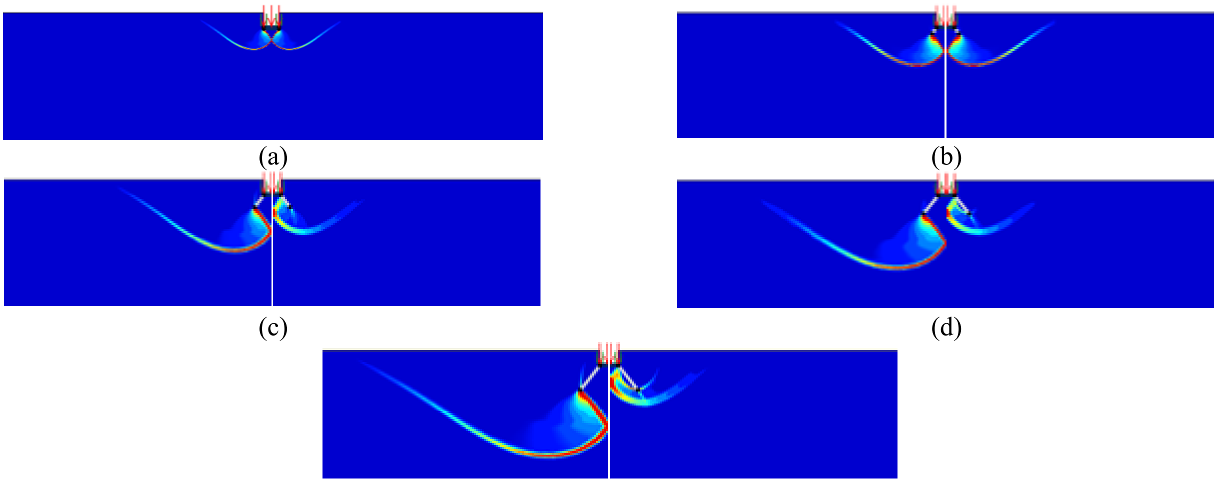
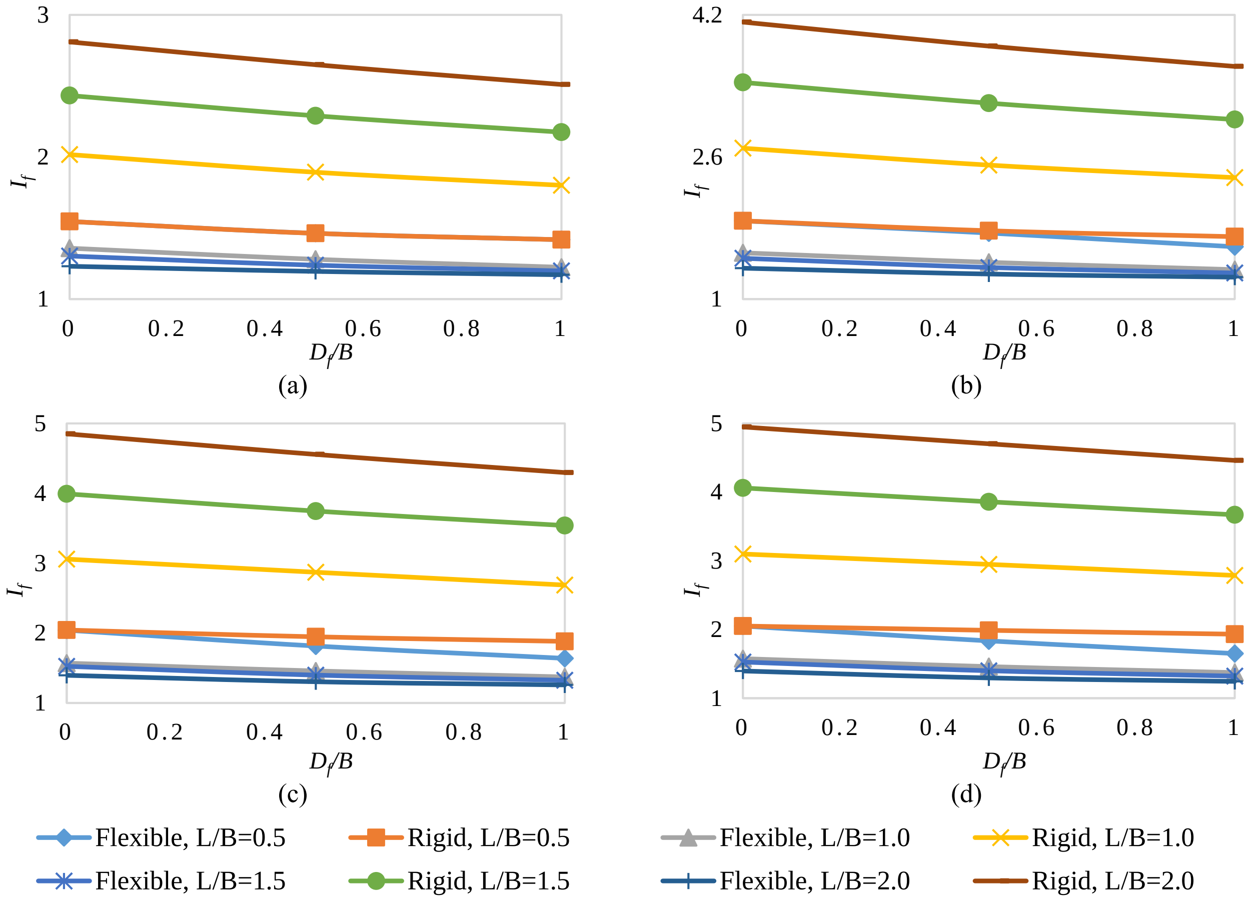


Fig. 6 Variation in failure mechanism with inclined skirt length: (a) L/B=0, (b) L/B=0.5, (c) L/B=1.0, (d) L/B=1.5 and (e) L/B=2.0

efficiency. The soil inside the skirts starts deforming in flexible skirts at longer lengths (Kellezi *et al*. 2008, Shukla and Jakka 2022). Hence, the efficiency of the flexible skirt does not increase continuously. However, bearing capacity and enhancement factor increase linearly in rigid skirts as the soil plug confined between skirts also acts as an integral part of skirted footing. The optimum length in an inclined skirt varies from 1B to 0.5B, which is less than those observed in the earlier studies on vertical skirts (Tani and Craig 1995, Al-Aghbari and Mohamedzein 2004, Eid 2013, Shukla and Jakka 2022).

The effect of skirt length also varies significantly with the angle of internal friction of soils. The optimum skirt length (at which efficiency is maximum) decreases with the



(a) (b) (c) (d)

Fig. 7 Effect of depth of embedment on bearing capacity enhancement: (a) 0.4 H:1V, (b) 0.8 H:1V, (c) 1.4 H:1V and (d) 2H:1V

increase in the shearing resistance angle of soil in a flexible skirt. The optimum skirt length is 1.0B for soils with an angle of shearing resistance of 25°, and it decreases to 0.5B for soil with an angle of shearing resistance of 40°. In vertical skirts, the optimum skirt length varies from 1.5B to 0.5B for the angle of shearing resistance of 25° to 40°, respectively. The optimum skirt length further reduces with footing embedment depth.

At the large inclination (H:V>1:1), the soil between skirts starts deforming at a smaller length than the vertical skirt due to a relatively less confining pressure inside the inclined skirts. Therefore, the optimum length of the skirt reduces with an increased skirt inclination. It is also observed that increasing the skirt length is more effective in foundations resting on the ground surface than resting at some greater depth. The optimum length cannot be suggested for a rigid skirted footing as efficiency (I_f) increases linearly with skirt length.

Fig. 6 shows the typical variation in failure surface with the increase in skirt length for rigid and flexible skirted footings of depth ratio 1 and skirt inclination of 0.8H: 1V. The length of the slip surface increases with the rigid skirt length. The bearing capacity enhancement is significant in a flexible skirted footing when the skirt length increases from 0 to 0.5B. However, an additional increase in the skirt length does not change the length of slip lines. The area that offers resistance to loading (the area within the fracture surface) is relatively higher in the rigid skirt. These observations demonstrate that the inclined rigid skirt acts as an integral part of a footing-skirt system for any length. Therefore, the effective depth and width increase more efficiently in the case of rigid skirted footing. Thus, the rigid skirted footing became equivalent to a strip footing with a width equal to the distance between skirt tips and placed at the level of skirt tips. Consequently, the enhancement in the bearing capacity is phenomenal in rigid skirted footing. However, in a flexible skirt, at a large skirt length (L/B > optimum length), slip lines originate from the footing edges rather than skirt tips, making the skirt and footing behave like a separate unit. It makes footing behaviour almost similar to conventional strip footing without any skirt. Therefore, a slight enhancement in bearing capacity is observed in a flexible skirt beyond the optimum length.

5.3 Effect of embedment depth

The variation in bearing capacity enhancement (I_f) with the depth of inclined skirted footing resting on soil with an internal friction angle of 35^0 is shown in Fig. 7. Though the bearing capacity of inclined skirted footing increases with the increase in the footing depth, the efficiency is found to

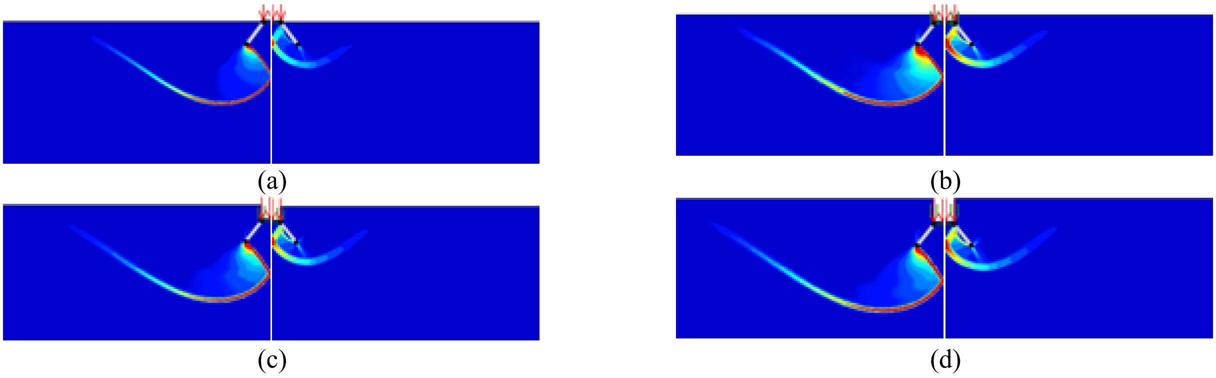

(a) (b) (c) (d)

Fig. 8 Variation in failure mechanism with with depth: (a) D_f/B =0, (b) D_f/B =0.5, (c) D_f/B =1.0 and (d) D_f/B =1.5

be reduced. This observation is similar to vertical skirts, where skirt efficiency reduces with the footing depth (Tani and Craig 1995, Shukla and Jakka 2022).

Tani and Craig (1995) also found that the soil overhead at the skirt tips level has a negligible effect on strip footing capacity. So, the bearing capacity enhancement of a footing with a higher depth is less than those observed in the case of surface footing and vertical skirted footing. This adverse effect of footing embedment on the effectiveness of the inclined skirt diminishes with the increase in the skirt inclination and soil internal friction angle. The maximum reduction in the effectiveness of the inclined skirt is found to be in cases of skirts with maximum inclination.

The typical variation in failure surface with embedment depth is shown in Fig. 8 for a footing with a skirt of inclination of 1H: 1V resting over the soil of internal friction of 30^0. The shear dissipation and length of the slip surface are also higher in the case of rigid skirts compared to flexible skirts. The area within the slip line increases with an increase in the footing depth. Though the area within the slip surface increases with the embedment depth, the enhancement factor decreases marginally (shown in Fig. 7). This contrary behaviour is observed because the bearing capacity enhancement with footing embedment is relatively higher in a vertical skirt compared to an inclined skirt.

5.4 Influence of internal friction angle

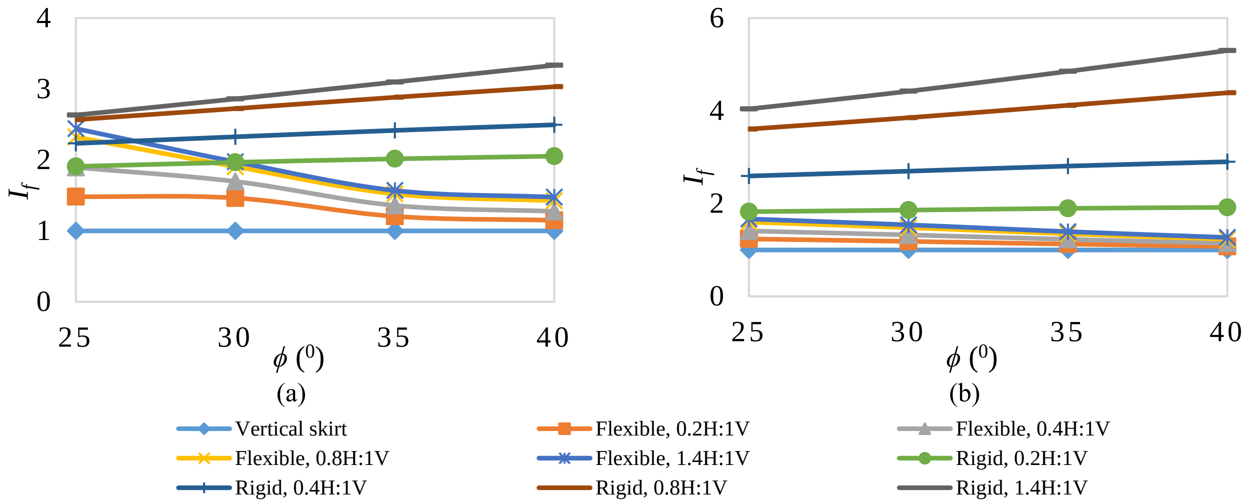
The effect of the soil internal friction angle on bearing capacity enhancement (I_f) depends significantly on the nature of the skirt (Fig. 9). The skirt effectiveness is enhanced with an increased angle of shearing resistance of soil in rigid skirts, whereas skirt effectiveness reduces in flexible skirts. The efficiency reduces due to a decreased relative stiffness of flexible skirts with the increase in the internal friction of soil. The adverse effect of soil internal friction on the efficiency of the flexible skirt enhanced with skirt inclination and an increase in skirt length due to a decrease in the relative stiffness of the skirt. However, in rigid skirts, the relative stiffness of the skirt remains unaffected for soil with significant shearing resistance as the rigid skirts possess infinite stiffness. Also, in rigid skirted footing, soil-foundation system stiffness is enhanced with the skirt length. This enhances not only the bearing capacity but the efficiency of rigid skirted footing also. The difference in the efficiency of the inclined flexible and rigid skirt becomes more perceptible with increased length. It is because a rigid and flexible skirt with a length less than or equal to half of the footing width behaves identically (behaves like a rigid element compared to soil). Contrary to flexible skirts, the variation in the efficiency of rigid skirts with skirt length and inclination widened with the internal friction angle.

6. Statistical analysis

Statistical analysis was performed to determine and quantify the effect of various factors on the bearing capacity enhancement of the flexible and rigid inclined skirts. It is observed from the numerical analysis that a total of four independent parameters (i.e., skirt length, skirt inclination, depth ratio of footing, and strength of soil) are influencing the bearing capacity enhancement. The numerical study results also demonstrate that the independent parameters and enhancement factor is non-linearly associated, especially in the flexible skirt; the nonlinearity is very high. Therefore, nonlinearity needs to be considered in the statistical modelling of inclined skirts.

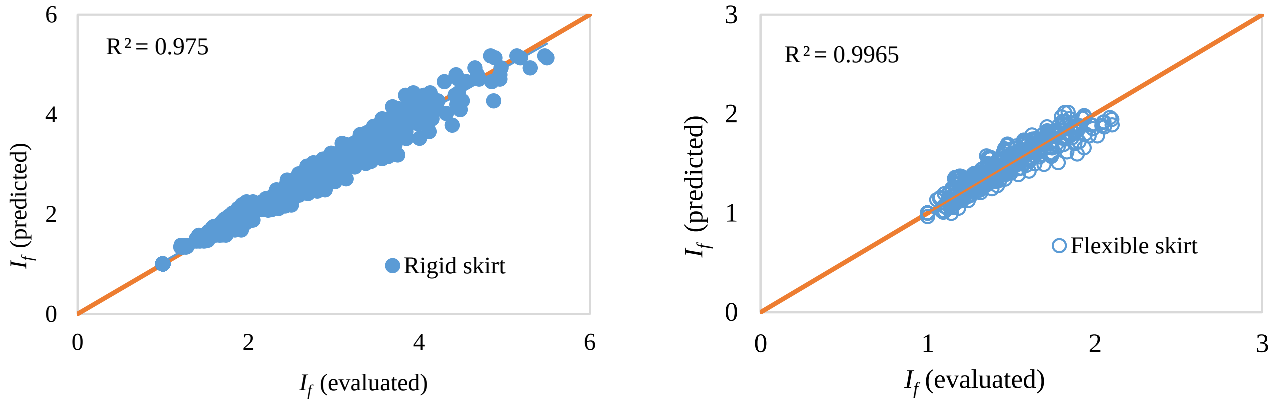
Based on regression analysis and comparative analysis, two separate equations have been proposed to estimate the enhancement factor for the flexible and rigid skirts. Various functions, such as linear, exponential, logrithmic and polynomial logarithmic, and the best relationship was used to develop the equations. It is observed that neither linear, logarithmic, nor exponential predict the behaviour accurately. The polynomial equation is found to be a relatively better approximation for modelling the inclined skirted footing.

Eqs. (4) and (5) show bearing capacity enhancement changes with flexible and rigid inclined skirts, respectively. Initially, in regression analysis of flexible skirt, it is assumed that the I_f is a function of a total of 54 dependent variables, which are actually a function of 4 independent variables (L/B, D_f/B, ϕ, α). The multicollinearity analysis was also performed to eliminate irrelevant variables that do not affect the I_f significantly. It can be noted that R^2 reduces from 0.96 to 0.89 in flexible skirts when the number of assumed variables is reduced from 54 to 17. It shows that all variables assumed in the preliminary phase of statistical



(a) (b)

Fig. 9 Variation in bearing capacity enhancement of flexible and rigid inclined with angle of internal friction: (a) L/B=1.0 and (b) L/B=2.0



(a) (b)

Fig. 10 Comparison of predicted values with determined value: (a) rigid skirted footing and (b) flexible skirted footing

analyses affect the bearing capacity but not significantly. Reducing the number of variables significantly reduces the length of the predictive regression equation. Similarly, in rigid skirted footing resting on cohesionless soil, the number of assumed variables is reduced from 54 to 8, which reduces the R^2 value from 0.998 to 0.947. This is because the relationship between variables and enhancement factor were relatively less nonlinear than the flexible skirted footing.

This also shows that the factors supposed during the preliminary phase of analysis are not significantly affecting the bearing capacity of the footing. Therefore, R^2 changes marginally when many of the earlier variables are removed. The bearing capacity of inclined skirted footing can be

$$\begin{aligned} I_{f\,(flexible)} &= -0.65+2.0\tan\alpha(1-0.05L/B)+3.1L/B(1-0.28L/B-2.1\tan\phi-0.05D/B) \\ &+3.8\tan\phi(1-0.45\tan\alpha-0.1D/B)+0.67(\tan\alpha)^2(\tan\phi-1)+0.35(L/B)\tan\phi(D/B+3.6L/B) \\ &-0.8\tan^2\phi(1-3.1L/B+1.05\tan\phi-0.09D/B) \end{aligned} \tag{4}$$

$$I_{f\,(rigid)} = 2-4.2\tan\phi(1-1.7\tan\phi+0.9\tan{}^3\phi)+1.65(\tan\alpha)L/B(1-0.4(\tan\alpha)+0.55\tan\phi)-0.3(L/B)\tan\phi \tag{5}$$

$$\text{Bearing capacity of inclined skirted footing} = \text{Bearing capacity of vertical skirted footing} \times I_f \tag{6}$$

$$\begin{aligned} BCR_{(flexible)} &= 1-1.8D/B+2.6L/B(1.42L/B-1)+\tfrac{1}{4\tan\phi}(1+14.5D/B-3.2L/B)-0.03(D/B)(L/B)(1-27D/B) \\ &-\tfrac{D}{1.8B\tan\phi}(4L/B+D/B) \end{aligned} \tag{7}$$

$$\begin{aligned} BCR_{(rigid\ skirt)} &= 1+0.1D/B(1+45\tan\phi D/B)+L/B(6.4+0.1L/B)-0.6\tan\phi(8.75L/B+7.7D/B-1) \\ &-(D/B)(L/B)(6.2-5.5\tan\phi+0.1L/B) \end{aligned} \tag{8}$$

$$\text{Bearing capacity of vertical skirted footing} = \text{Bearing capacity of strip footing} \times BCR \tag{9}$$

where, I_f is efficiency factor, B=width of footing in meter, L is the length of the skirt, D_f= depth of footing, ϕ=angle of shearing resistance of soil (in degree), and α is an inclination of the skirt with vertical determined by using Eq. (6) if the bearing capacity of vertical skirted footing is known. The bearing capacity enhancement in flexible and rigid vertical skirted footing can be determined by using Eqs. (7) and (8), respectively.

The bearing capacity of vertical skirted footing can be evaluated by equation (9). A comparison of the predicted enhancement factor with the evaluated enhancement factor is shown in Fig. 10. It shows a good agreement between predicted values and evaluated values. It should be noted that the minimum value of the enhancement factor is 1, even though the predicted values are less than 1 in very few cases.

7. Conclusions

The bearing capacity of inclined skirted footing enhances significantly with skirt inclination. The enhancement in an inclined skirt varies from 110% to 400% to that of a vertical skirt, depending on various factors, such as the angle of internal friction of soil, embedment depth of footing, skirt rigidity, and the skirt length. The provision of the skirt increases the stiffness of the soil foundation system. The relative stiffness of the skirt is an important factor influencing the performance of the vertical and inclined skirt. However, the influence is relatively more in inclined skirted footing. The relative stiffness of the skirt decreases with an increase in the soil density or internal friction angle. The effectiveness of the inclined skirt reduces with a reduction in the relative stiffness of the skirt.

Rigid and flexible skirted footings behave differently for a skirt length greater than the optimum value due to differences in failure mechanisms. The rigid skirt does not deflect even at a higher inclination and under higher loading. This contributes to additional confinement and reinforcing effects compared to the flexible skirt. The provision of rigid skirts increases the depth and width of the footing effectively. At the same time, this increase is relatively less visible in the flexible skirted footing. The skirt effectiveness reduces with footing depth in both types of skirts.

The optimum length and inclination of the skirt reduce with increased soil internal angle friction. The optimum skirt inclination varies from 45^0 to 60^0 in the case of rigid skirted footing and 30^0 to 45^0 in flexible skirted footings. The optimum length of the flexible skirt varies from 1B to 0.5B for soils with an angle of internal friction from 25^0 to 40^0, respectively. Contrary to flexible skirts, the optimum skirt length, inclination, and efficiency of the rigid skirt increase with the increase in the angle of internal friction of soil. In rigid skirted footing, efficiency increases linearly with skirt length. The developed nonlinear regression equations reasonably predict the bearing capacity enhancement with varying skirt inclination and length.

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Symbols and Notations

B = width of footing;
D_f = depth of footing;
Ψ= dilatancy angle
L = skirt length;
D_f/B= footing depth to footing width ratio;
$H{:}V$ = skirt inclination;
I_f=enhancement factor;
BCR = bearing capacity ratio;
LB=lower bound
N_γ=bearing capacity factor considering soil weight only;
q=loading (kN/m)
$N_{\gamma q}$ = bearing capacity factor considering soil weight and surcharge together;
R^2 = regression coefficient
UB=upper bound
α = inclination of the skirt with vertical
ϕ= angle of internal friction of soil
ϕ_{mod} = modified angle of internal friction of soil