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SKIRTED FOOTINGS FOR THE ENHANCED LOAD-CARRYING CAPACITY: MECHANISM OF LOAD TRANSFER AND CAPACITY IMPROVEMENT

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ABSTRACT

Skirted footings are emerging as a promising shallow foundation solution for modern construction, as they provide substantial improvements in bearing capacity and deformation control without resorting to deep foundations. This makes them a practical and potentially cost-effective option for sites characterized by weak or variable ground conditions. The study highlights how vertical and inclined skirts enhance bearing capacity, reduce settlement and improve stability by confining the underlying soil and modifying the load transfer mechanism. Key design parameters affecting the performance of skirted footing are embedment depth, skirt stiffness, and skirt inclination. The load-carrying capacity is found to be increasing with the increase in skirt length, embedment depth and skirt stiffness. A major focus of this review is the emerging concept of inclined skirted foundations, which demonstrate enhanced performance compared to conventional vertical skirted footings. Their improved mechanical efficiency positions inclined skirted footings as a viable alternative to both traditional skirted foundations and deep foundations. Recent studies demonstrated the high efficiency of inclined skirted footings in loose soil conditions, with reported bearing capacity improvements of up to 300% as compared to the traditional vertical skirted footings.

KEYWORDS: Skirted Footing, Shallow Foundation, Inclined Skirts

INTRODUCTION

Shallow foundations are fundamental to the construction of low- to medium-rise buildings and infrastructure, as they serve as the primary interface between structural loads and supporting soil. Their simplicity, cost-effectiveness, and ease of construction make them preferable in many civil engineering projects, particularly in regions with moderate loading and favorable soil conditions. Despite these advantages, shallow foundations are highly sensitive to subsoil variability, especially when placed near slopes, in weak soils, or under dynamic (e.g., seismic) loading conditions. Traditionally, shallow foundations such as strip, pad, isolated and raft footings have been extensively employed due to their economic and constructional feasibility. They are commonly adopted in urban and rural infrastructure for residential buildings, retaining walls, and small industrial structures. However, their performance is significantly influenced by soil type, moisture variation, and topographic features.

In challenging ground conditions — including soft clays, loose sands, or sloping terrains — shallow foundations often fail to meet design requirements for bearing capacity and settlement control (Shukla and Jakka 2017, 2019). Enhancing the load-carrying capacity of shallow foundations becomes critical in such scenarios to ensure structural safety, serviceability, and longevity. Skirted foundations have

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been widely studied because they can increase bearing capacity, reduce settlement, and improve lateral stability by mobilising side resistance and forming a confined soil plug, with research evolving from offshore bucket applications to onshore shallow foundations in sands and clays using analytical models, laboratory tests, centrifuge studies, and numerical limit analysis. Early work clarified the benefits of embedment and skirt–soil interaction in soft clays and highlighted plugging as a key mechanism for increased stiffness and reduced settlement (Tani and Craig, 1995; Bransby and Randolph, 1998; Hu et al., 1999), while later studies demonstrated strong gains in vertical and lateral performance and emphasised skirt length and interface roughness as dominant factors in sands (Watson and Randolph, 1998; Yun and Bransby, 2003, 2007; Al-Aghbari and Mohamedzein, 2004; Eid, 2009, 2013; Gourvenec, 2008; Bransby and Yun, 2009). Recent investigations expanded to dynamic loading, layered soils, and advanced geometries, including multi-compartment skirts, and reported capacity improvements commonly in the range of about 2 to 6 times over unskirted footings, depending on soil state and skirt geometry (Vulpe et al., 2013; Shukla 2018; Ghorai and Chatterjee, 2020; Santoshkumar and Ghosh, 2020; Shukla and Jakka 2019, 2020; Dutta et al., 2020, 2022; Rezazadeh and Eslami, 2020; Liu et al., 2021).

The need to enhance the load-carrying capacity of shallow foundations under such conditions is thus critical. Various methods have been developed to address this issue, including soil improvement through compaction, grouting, and chemical stabilization; the use of geosynthetics and reinforcements; modifications in footing geometry; and, in extreme cases, shifting to deep foundation systems like piles and piers. While each approach offers certain advantages, they also come with notable limitations. Ground improvement techniques may require extensive time, specialized equipment, and are often expensive or ineffective in the long term. Geosynthetics may degrade or require precise placement to be effective. Meanwhile, pile and deep foundation systems, although structurally robust, involve high costs, require heavy machinery, and are not always feasible in low-cost or remote projects.

In this context, the development of modified shallow footing systems that are both effective and economical becomes a pressing need. Skirted footings offer a viable alternative, especially for foundations on problematic soils or sloped ground. These systems incorporate vertical or inclined structural members around the footing perimeter, which act as passive reinforcing elements. The skirts confine the soil beneath the footing, and forming soil plug which acts as a part of the footing. As documented in recent studies—including the work of Shukla (2018), Shukla and Jakka (2022, 2023) observed that both flexible and rigid skirts significantly improve load-bearing behavior under static and seismic conditions. Furthermore, inclined skirts have demonstrated even better performance by redirecting failure mechanisms more effectively than vertical skirts.

This manuscript presents the governing mechanisms and design sensitivities of skirted footings on level ground by critically examining how skirt length, embedment depth, soil strength, and skirt stiffness jointly influence confinement, plug formation, failure surface development, and the resulting capacity and settlement response.

OVERVIEW OF SKIRTED FOUNDATIONS

Skirted footings are a specialized form of shallow foundations designed to improve bearing capacity, limit settlement, and increase resistance to vertical and lateral forces, especially in problematic soils. They consist of a conventional footing base with extended vertical members called skirts attached around its perimeter as represented in Figure 1. The length of skirts is represented as (L_s) or (D_s) and the depth of footing is represented as (D_f). These skirts penetrate the soil beneath and around the footing, creating a confinement effect that enhances the mobilization of shear resistance and controls soil displacement. A key distinction must be made between onshore skirted footings and their offshore counterparts, commonly known as bucket foundations or suction caissons. While both systems use embedded skirts to improve foundation performance, they differ significantly in shape, construction method, and operational context. Offshore bucket foundations are large, cylindrical steel structures with an open base and closed top, often several meters in diameter and height. These foundations are placed on the seabed and installed using suction pressure, which pulls the caisson into the sediment. The suction creates a pressure differential that assists in driving the skirt deep into soft marine soils. The installation process is fast, noise-free, and avoids piling making it ideal for sensitive offshore environments.

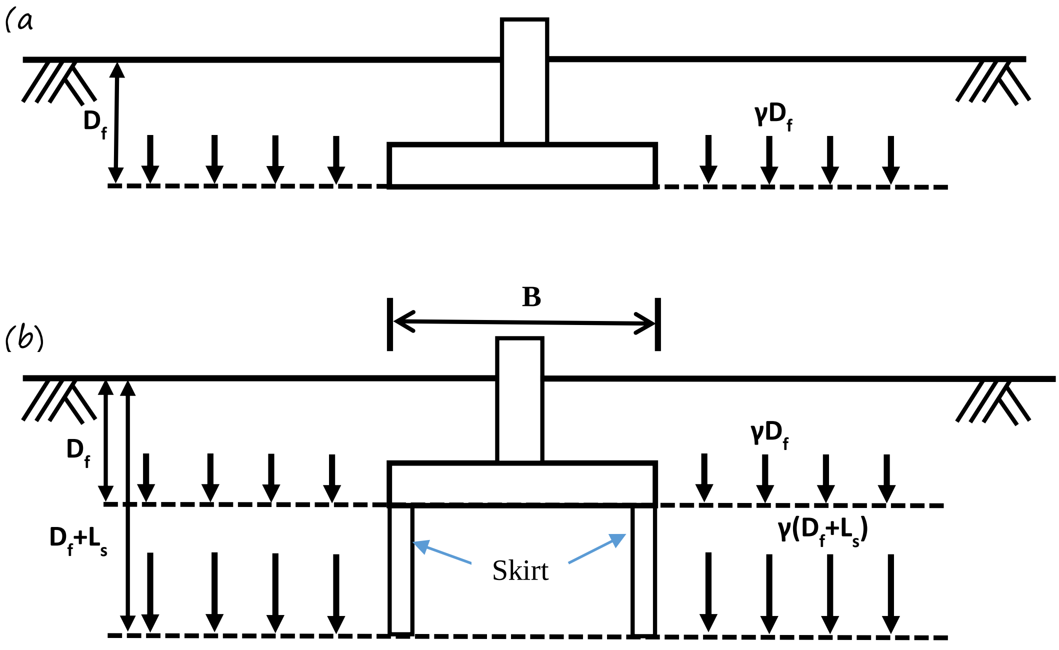

Fig. 1 Schematic diagrams illustrating the differences between shallow and skirted footings: (a) conventional shallow footing; (b) typical skirted footing, in which external skirt elements are attached to the edges of the conventional footing

In contrast onshore skirted footings are often rectangular, square or strip-shaped in plan, and are constructed by casting skirts integrally with the footing slab or bolting them after placement. The conventional skirts are typically made of steel or reinforced concrete and extend vertically. The construction is simpler and requires no suction or specialized marine equipment. Instead, excavation and formwork techniques used in regular foundation construction are adapted for the construction of skirts. While concrete skirts can be constructed by excavation, steel skirts can be easily installed by driving. Additionally, the size and depth of skirts in onshore use are much smaller, usually up to two times the footing width (2B), and can be tailored based on local soil conditions and load requirements.

While offshore bucket foundations are effective in marine environments, their application in onshore construction is limited by several practical challenges: the suction technique is ineffective in dry or partially saturated soils; construction requires specialized marine-grade equipment; and cost becomes prohibitive in land-based projects.

These constraints prompted the adaptation and simplification of the skirt concept into skirted footings, optimized for onshore use. These footings retain the mechanical benefits of enhanced confinement and load resistance while being cost-effective, easier to construct, and flexible in geometry.

MECHANISM OF CAPACITY IMPROVEMENT

Skirted foundations enhance the performance of shallow footings through a combination of soil confinement, increased effective depth, and skirting action. The addition of skirts alters the failure surface beneath the footing, transitioning it from shallow punching or general shear to a deeper, more confined mechanism that improves load transfer to the deeper soil mass. The follow up section explains the distinct mechanisms of bearing capacity improvement enabled by vertical skirts, which have demonstrated unique advantages across various soil and loading conditions.

1. Improvement Due to Vertical Skirts

Vertical skirts are aligned perpendicularly to the footing base and are the most widely studied configuration in both offshore and onshore applications. Their improvement mechanism relies on soil entrapment between the skirts, mobilization of soil strength along the sidewalls and increased bearing resistance due to deeper failure surfaces. Skirts confine the soil mass beneath the footing, forming a deep-seated wedge that resists vertical loading and minimizes deformation. This confinement enhances shear resistance within the soil plug and helps distribute applied loads more efficiently to greater depths.

Figure 2 illustrates the load dispersion through the soil via an enhanced failure surface formed by vertical skirts. The skirts increase the effective depth of the footing system improving load transfer mechanism and shear resistance. The failure surface is deepened, and the load is distributed to deeper soil as well as along the skirts, enhancing load carrying capacity of skirted footing.

Bransby and Randolph (1998) and Yun and Bransby (2003) demonstrated through centrifuge modeling that vertical skirts for offshore conditions reduce settlement and increase stiffness by up to three times compared to surface footings. Further, it is found that vertical skirted footing capacity is not merely equivalent to embedded footing at the tips of the skirts (Shukla and Jakka 2022). Shukla (2018) and later Shukla & Jakka (2022) verified these effects through finite element simulations and model tests, on skirted footing resting on level and sloping ground. Their work confirmed that skirts not only deepen the stress bulb but also engage sidewall friction to counteract both vertical and lateral forces and thereby the capacity of vertical skirted footing is more than that embedded footing placed at the tips of the skirts.

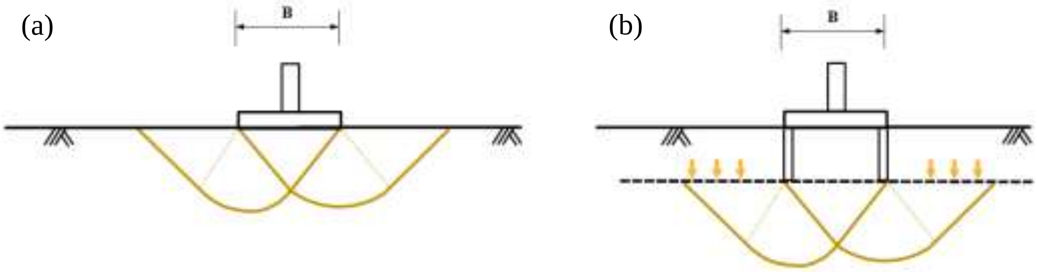

Fig. 2 Failure surfaces developed beneath different types of foundations: (a) conventional shallow footing; (b) vertical skirted footing, in which the failure surface is shifted downward to the skirt tips [adapted from Bashir and Jakka, 2024a]

2. Improvement Due to Inclined Skirts

Inclined skirts offer a geometrical advantage by directing the resisting soil pressure diagonally outward and downward, effectively modifying the failure mechanism beneath the footing. Figure 3 compares the

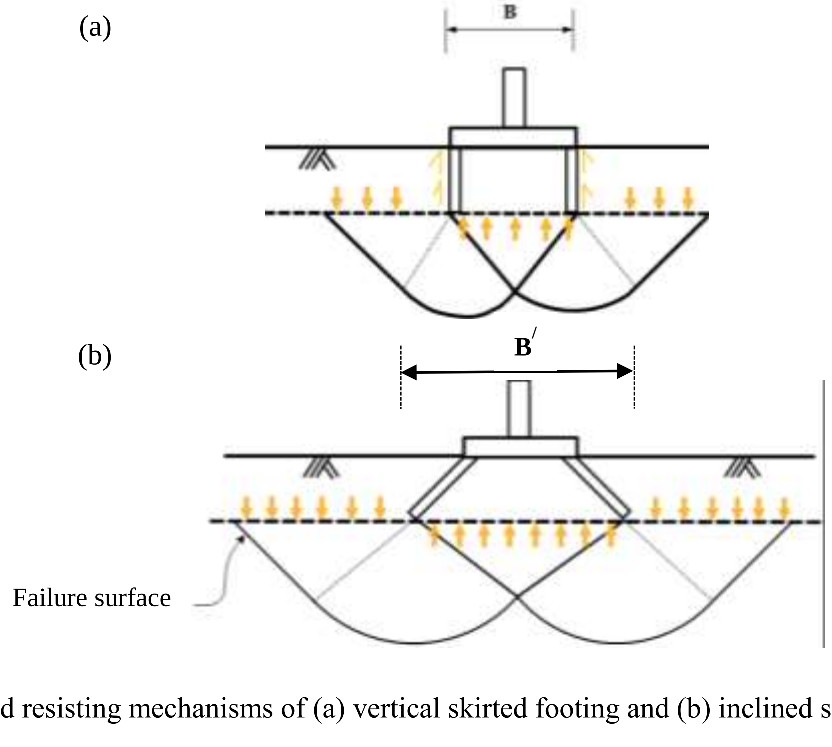

Fig. 3 Load resisting mechanisms of (a) vertical skirted footing and (b) inclined skirted footing

load resisting mechanisms and failure surfaces for a vertical skirted footing and an inclined skirted footing. These skirts are installed at an angle (typically between 5° and 30°) from the vertical, depending on design requirements and soil conditions. The load carrying capacity increases due to the inclination of skirts, as the inclination increases the combined effective width and depth of the footing. In the case of vertical skirts only effective depth is increased. Shukla (2018) doctoral study confirm that inclined skirts outperform vertical skirts in conditions by as much as 40–60% in terms of ultimate bearing capacity.

Together, vertical and inclined skirts provide powerful tools for geotechnical engineers to tailor footing performance to site-specific challenges. While vertical skirts are simpler to implement and effective on level terrain, inclined skirts introduce additional enhancement in load carrying capacity. The optimal inclination angle depends on skirt length, soil density, and seismic demand. Shukla and Jakka (2023) research suggests that an inclination of 0.8H:1V to 1.5H:1V offers the best compromise between load-bearing performance and constructability.

DESIGN PARAMETERS

The performance of skirted footings is highly sensitive to several design parameters, including skirt length, embedment depth, soil strength, and skirt stiffness. Each of these parameters interacts with the load transfer mechanism, confinement potential, and failure surface geometry. A nuanced understanding of their individual and combined effects is essential for optimal design, especially in scenarios involving weak soils. This section presents a critical review of these parameters and their roles in the behavior of skirted foundations.

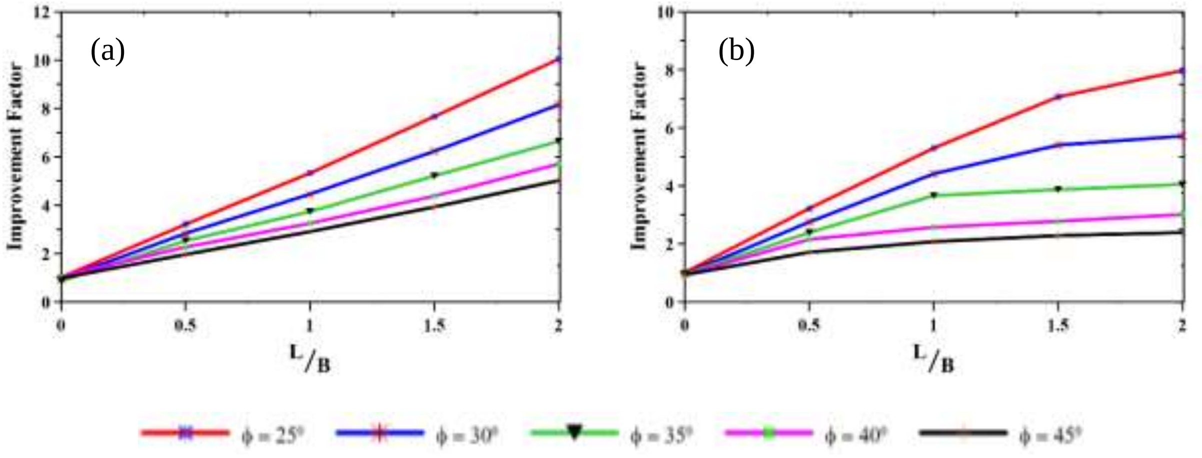

Fig. 4 Effect of skirt length on bearing capacity improvement for the embedment depth D/B=0 (a) rigid skirt; (b) flexible skirt. Adapted from Shukla (2018)

Skirt length ratio (L/B) is a primary driver of improvement. Increasing L/B typically enhances confinement of the soil beneath the footing, restricts lateral soil movement, and shifts the failure surface to greater depths, resulting in higher bearing capacity and reduced settlement. The improvement is generally nonlinear, with diminishing returns at larger L/B; for level ground conditions, many studies indicate that vertical skirts with L/B around 1.0 to 1.5 often provide an efficient balance, with bearing capacity increases commonly reported in the range of about 2 to 5 times compared with unskirted footings in sands and soft clays due to the plug effect and modified load transfer (Shukla 2018; Eid et al., 2013; Yun and Bransby, 2007; Watson and Randolph, 1998; Al-Aghbari and Mohamedzein, 2004). The plots show in Figure 4 the bearing capacity improvement factor, I_f, defined as the ratio of the ultimate capacity of a skirted footing to that of an unskirted footing, plotted against the normalized skirt length L/B (skirt length divided by footing width). Figure 4 (a) presents the variation of improvement factor for rigid skirts, while Figure 4 (b) presents for flexible skirts. In both cases, I_f increases with L/B, showing that longer skirts improve performance by deepening the failure mechanism, confining the soil plug, and mobilizing side resistance along the skirts. The improvement is strongest in loose sands (lower friction angle, for example $\phi = 25°$) and becomes smaller in denser sands (higher ϕ, for example $\phi = 45°$) because the unskirted footing already has higher capacity in denser sands. Rigid skirts show a more consistent, near-linear increase up to L/B = 2, whereas flexible skirts tend to show diminishing returns beyond about L/B ≈ 1 for medium to high ϕ due to skirt deformation and reduced confinement.

Embedment depth further enhances performance by increasing overburden stress and mobilising additional soil resistance around and beneath the skirts, which delays the development of shallow mechanisms and increases stiffness and ultimate capacity (Bransby and Randolph, 1999). However, when results are presented using an improvement factor, increasing embedment can appear to reduce the improvement factor because the reference capacity of an unskirted footing also increases with embedment, consistent with the trend noted in Figure 5. The Figure 5 shows how the improvement factor I_f varies with embedment depth ratio D_f/B for sand with ϕ = 25, for different skirt lengths L/B. For both rigid and flexible skirts, I_f decreases sharply as D_f/B increases from 0 to about 0.5, and then reduces more gradually, indicating diminishing benefit of increasing embedment depth beyond moderate values. At any given D_f/B, longer skirts give higher I_f, so skirt length is the main contributor to capacity gain. Rigid skirts generally provide slightly higher I_f than flexible skirts at the same L/B and D_f/B, especially at shallow embedment, because better stiffness of skirts maintains soil plug formation and mobilizes interface resistance more effectively.

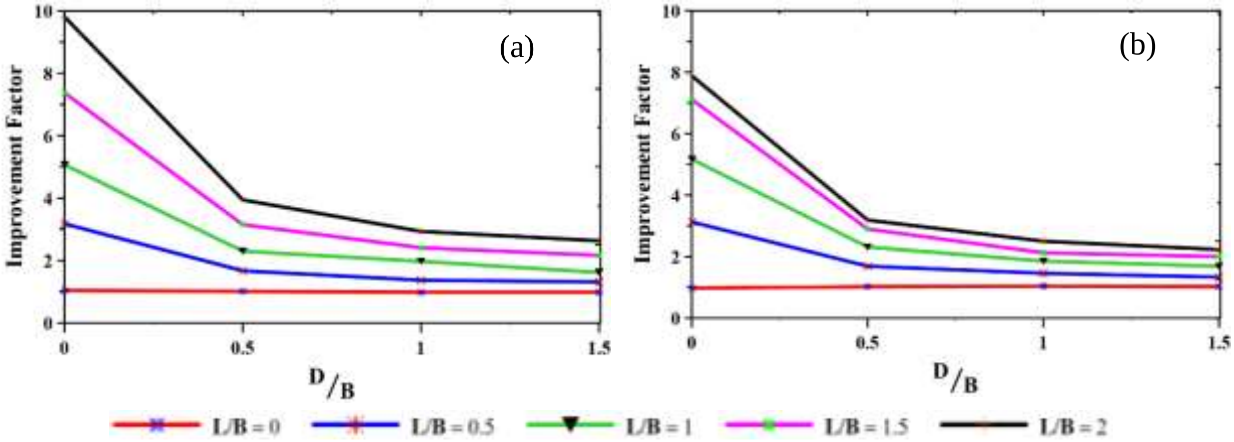

Fig. 5 Variation of improvement factor with depth ratios: (a) Rigid skirt, ϕ=25; (b) Flexible skirt, ϕ=25. Adapted from Shukla (2018)

Soil strength and profile determine the magnitude and mechanism of skirt effectiveness. In sands, higher friction angle and density increase absolute resistance and produce deeper, more confined failure zones. However, the relative degree of improvement due to skirts can decline as ϕ increases, aligning with the reduction in improvement factor in Figure 6 In soft clays, skirts increase side adhesion, suppress shallow rotational or punching behaviour, and promote a deeper plug-controlled response (Gourvenec, 2008; Bransby and Randolph, 1998; Yun and Bransby, 2003). In layered soils, skirts can be beneficial when they penetrate weak near-surface layers and engage stronger strata, but the response becomes sensitive to the layer interface depth, often requiring finite element analysis for reliable design (Ghorai and Chatterjee, 2020). Figure 6 shows that the improvement factor I_f generally decreases as the soil friction angle φ increases, for both rigid and flexible skirts. This means skirts provide the largest relative benefit in weaker soils (low ϕ), while in stronger soils (high ϕ) the unskirted footing already has higher capacity, so the additional gain from skirts becomes smaller. In all panels, increasing skirt length L/B consistently increases I_f, confirming that longer skirts mobilize greater confinement of the soil plug and more interface resistance. For D/B = 0 (plots a and b), the drop in I_f with ϕ is steep, especially for larger L/B, and rigid skirts tend to give slightly higher I_f than flexible skirts because their stiffness maintains confinement more effectively. For D/B = 1.0 (plots c and d), the overall I_f values are much lower (closer to 1 to 3), and the sensitivity to φ is reduced, indicating that at larger embedment depths the incremental benefit of skirts is limited and the response becomes less dependent on skirt rigidity.

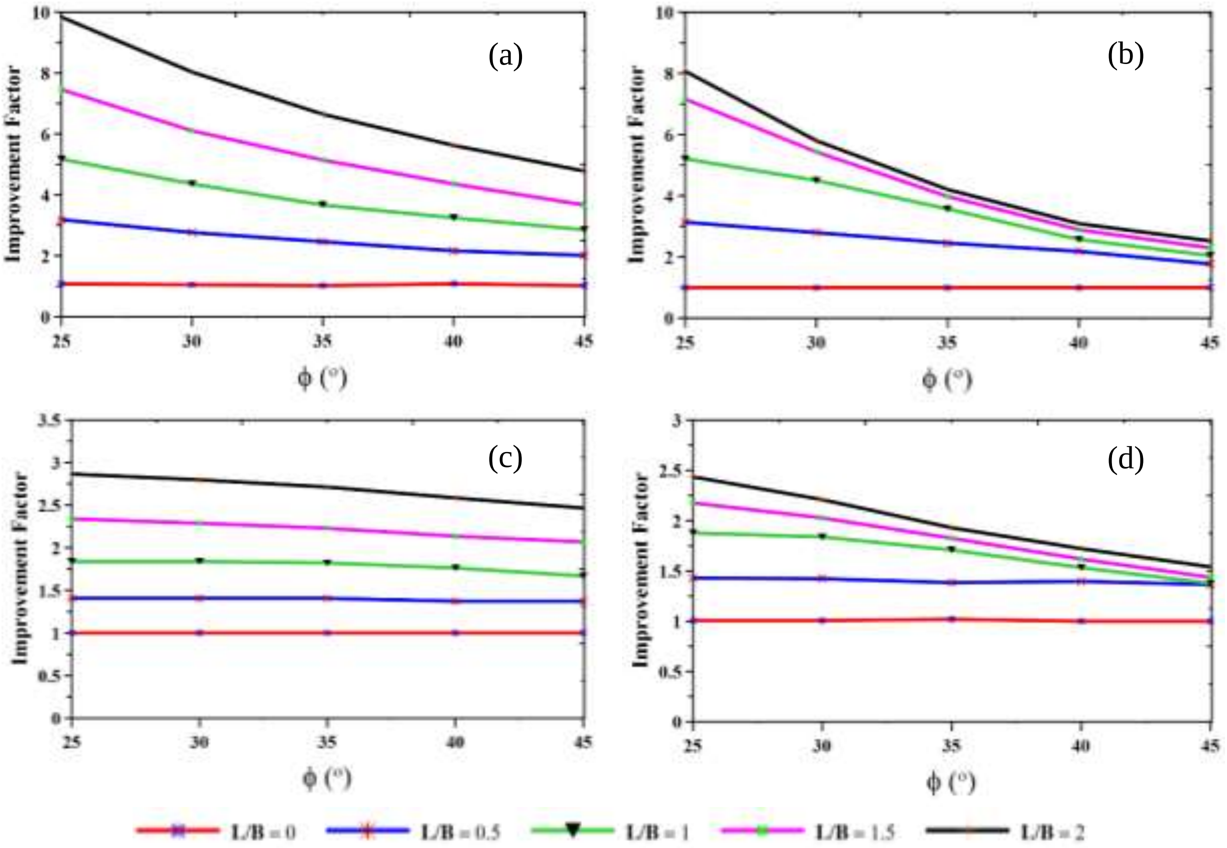

Fig. 6 Variation of improvement factor with angle of shearing resistance: (a) Rigid skirt, D/B= 0; (b) Flexible skirt, D/B=0; (c) Rigid skirt, D/B= 1.0; (d) Flexible skirt, D/B=1.0. Adapted from Shukla (2018)

Figure 7 illustrates the influence of the soil internal friction angle, ϕ, on the failure mechanism of rigid (left half) and flexible (right half) skirted footings. As ϕ increases from 25° to 45°, the overall shear zone expands in both cases, with the increase in its lateral spread being more pronounced than the increase in depth. The rigid skirt continues to develop a clear, well confined mechanism with rupture surfaces emerging from the skirt tips, indicating effective mobilization of soil strength and stable confinement of the soil plug. In contrast, the flexible skirt shows increasing deflection with increasing ϕ, which reduces confinement and limits the mobilization of soil resistance around the skirt. Consequently, the efficiency of the flexible skirt decreases in denser or higher ϕ soils, whereas the rigid skirt avoids this drawback by maintaining its geometry and consistently mobilizing a deeper, more effective failure mechanism. Similar trends are

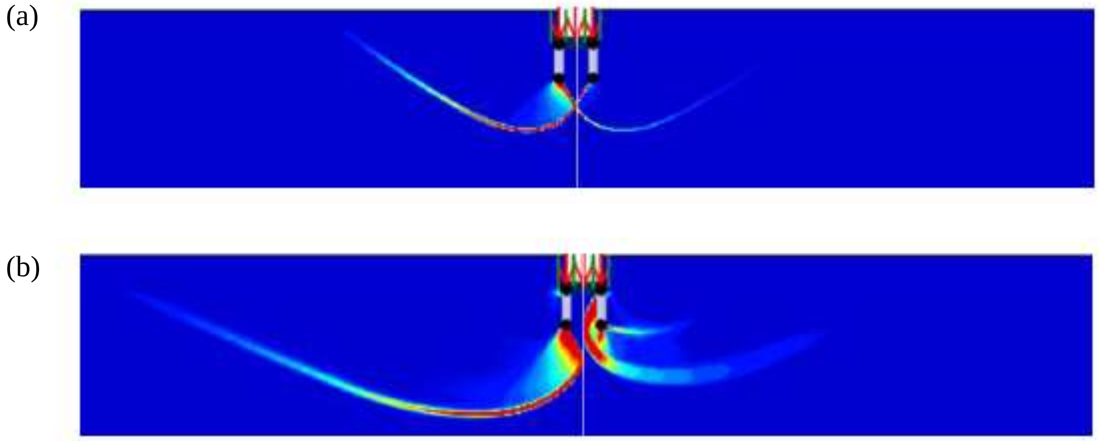

Fig. 7 Effect of angle of internal friction of on failure mechanism: (a) ϕ=25°; (b) ϕ=45°

generally observed in cohesive soils with increasing undrained shear strength, although the change in shear zone extent with strength is typically less pronounced than in cohesionless soils.

CONCLUDING REMARKS

Skirted footings offer a practical and efficient approach to enhance shallow foundation performance by improving confinement of the soil plug and promoting a deeper, plug controlled load transfer mechanism. The resulting improvements in bearing capacity, stiffness, and deformation control are governed primarily by skirt geometry (length, embedment, and inclination) and moderated by skirt stiffness, while the magnitude of benefit remains soil dependent due to variations in strength, density, and stratigraphy.

- The improvement factor increases mainly with skirt length ratio (L/B) and depth of embedment, as these parameters deepen the failure surface, extend the rupture path, and enlarge the mobilised soil zone, leading to predictable gains in capacity and reduced settlement and lateral deformation compared with unskirted footings.
- Vertical skirts improve capacity through the combined effects of increased effective embedment and mobilisation of sidewall resistance, and they are not just equivalent to a solid embedded footing at the skirt tip level because confinement and interface mechanisms provide additional resistance.
- The failure mechanism is strongly controlled by skirt inclination and stiffness. Inclined skirts further modify the mechanism by mobilising outward and downward resisting pressures, effectively increasing the combined effective width and depth of the system. Within the studied ranges, inclined skirts can outperform vertical skirts in ultimate capacity, but the benefit depends on skirt length, soil density or friction angle, and loading conditions.
- Skirt stiffness determines how effectively confinement is maintained under load. Rigid skirts preserve soil plug integrity and deliver more consistent performance across soil strengths, whereas flexible skirts may be economical but can deform outward and lose confinement if geometry is not optimised, particularly in the case of larger skirt lengths and soils with higher angle of internal friction ($\phi=40^o$).

Beyond the technical benefits, skirted footings have strong future potential for the construction industry as a cost effective shallow foundation alternative that can reduce excavation depth and minimise material use. Skirted foundations are particularly more effective in loose and medium dense soils where the angle of internal friction (ϕ) is less than 40°. However, there will be challenges in constructing inclined skirts particularly in cohesionless soils and stiff clays. With growing demand for resilient and sustainable infrastructure, continued development of practical design guidelines, construction methods, and field validation can support wider adoption of skirted footings in onshore foundations under different loading conditions.

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