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SKIRT FOUNDATION AND PATTERN OF CONTACT PRESSURE

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الملخص العربي:
تواجه الأساسات المنفذه علي التربة التضاغطية مثل التربة اللينة العديد من المشاكل التي يجب أخذها في الإعتبار عند تصميم الأساس مثل مشاكل الهبوط وقدرة التحمل ويتم حل مشكلة الهبوط بإتباع الحدود المسموح بها في الكودات بينما يتم تحسين قدرة التحمل للتربة عن طريق إتباع إحدي طرق التحسين كإستخدام أساسات الحافة. وتبحث الدراسة الحالية سلوك أساسات اللبشة الجاسئة والمرنة في وجود الحواف في ظروف تربة لينة مع الأخذ في الإعتبار نمط توزيع الحواف مع اللبشة ونمط ضغط التلامس للتربة. وتم تمثيل المشكلة عدديا بإستخدام برنامج (Plaxis 3D) لكل من اللبشة بدون حواف وبحواف موزعة بنمط ضغط التلامس رأسيا وكذلك توزيعها أفقيا كمحور أحادي أو ثنائي التوزيع. وبينت النتائج أن نمط ضغط التلامس له تأثير في قيمة قدرة التحمل مع توافق جيد لكل من أساس اللبشة الجاسئ والمرن.

ABSTRACT
Foundations on compressible soils such as soft clay faces many problems which must be taken into consideration for foundation design such as settlement and bearing capacity. Settlement problem is governed by the allowable limits in the codes of practice, while the bearing capacity problem can be improved by using many improvement techniques or suggesting numerous foundations systems such as skirt foundation.

The present study investigates the behavior of skirted rigid and flexible raft foundations resting on soft clay taking into consideration the different skirt configurations. The mode of contact pressure distribution for soft soil under raft foundations was considered when the skirt configurations were adopted in the study. Non skirted and skirted foundations with different flexibility have been numerically modelled using 3D Plaxis program. Based on the pattern of contact pressure, shape of skirt has been configurated, analyzed and discussed for both flexible and rigid foundations. Distribution of skirt in plan is also considered as a one way and intersected two-way. The results showed that the convexity of skirts configuration is significant for flexible foundations while for rigid foundation, both convex and semi-convex skirts have the same effect. Moreover, the outcomes of stresses beneath foundations showed well agreement to the induced theoretical contact pressure for cohesive soil in flexible condition and to some extent for semi- flexible conditions.

Keywords: Contact Pressure, Raft, Skirt Foundation, Soft Clay, 3D Plaxis

1. BACKGROUND
The behavior of foundations with underlying supporting soil systems is considered complex due to the variation of properties for different system components. The stiffness and size of the foundations are important factors that must be taken into consideration for optimal skirt configuration and design. The optimal foundation thickness and the accompanying skirt configuration have to be investigated for a robust

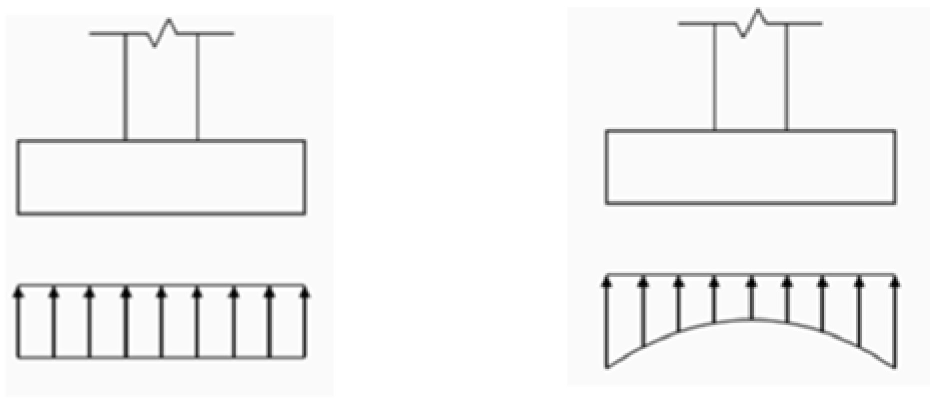
foundation system [Lemmen, (2016)]. The contact stress distribution beneath the footing is considered one of the most important aspects of interaction between the structure and the underlying soil [Conniff and Kiousis, (2007)]. The most common contact stress distribution is shown in figure 1. The flexibility of foundation leads to a more uniform contact stress distribution while rigid foundations show local concentrations for stress at edge which may cause local soil failure [Leshchinsky, (1990)]. The foundation stiffness can be classified as flexible or rigid according to the equation 1 [ECP 203, (2007)] for spacing between columns less than 1.75/β where β can be determined by equation (1).

$$\beta = \sqrt[4]{\frac{k.b}{4E_c\,I}} \qquad (1)$$

Where: β is coefficient, K is Winkler subgrade reaction, b is the strip breadth and E_cI is the bending rigidity for strip.

Philosophy of contact pressure in the area of soil-structure interaction sheds the intention of many researchers all over the last decades such as H.E. Lemmen (2016), k.S et al (2017) and Hrubesova Eva. Et al (2018). The distribution of contact pressure and stress under skirted strip footing have been investigated for different skirt angles [Ohri, (1988)]. Skirted footing with skirts at 45^0 and length of 0.5 footing width is capable to withstand 30 % more pressure than non-skirted one [Singh and Ohri, (1981)]. Rao and Sharma (1980) explored the beneficial effects of vertical skirts in increasing the bearing capacity and reducing settlement.

In the present study, the behavior of skirted foundation resting on soft clay has been investigated with different skirt length and configuration. The effect of convexity of skirts has been studied for one way and two-way intersected skirts. On the other hand, the effect of foundation thickness on settlement and stress has also been investigated for different skirt configurations, from which an optimal system has been recommended.



Uniform Distribution **Cohesive Soils**

Fig. 1 Stress distribution beneath footings (After, Mosley and Bungey, 1987)

2. SOIL AND STRUCTURE PROPERTIES

The physical and engineering properties of soft clay soil exists in some regions north east of Egypt have been collected and characterized. The soil is consisting of clay deposit extending down to about 60 m. The soft clay becomes medium stiff at depth 25 m and shows stiff characteristics at depth 50 m. The structural element that transfers the loads into the underlying soil is reinforced concrete raft foundation with thicknesses of 0.3, 0.5 and 1.00 m representing flexible, semi-flexible and rigid foundations respectively. The definition of flexibility and rigidity has been evaluated based on ECP 203 and ECP 202/3. The raft foundation has been stiffened with steel skirts having 50 mm thickness. Tables 1 and 2 show the different parameters for both soil model and structure components.

Table (1) Soil Properties

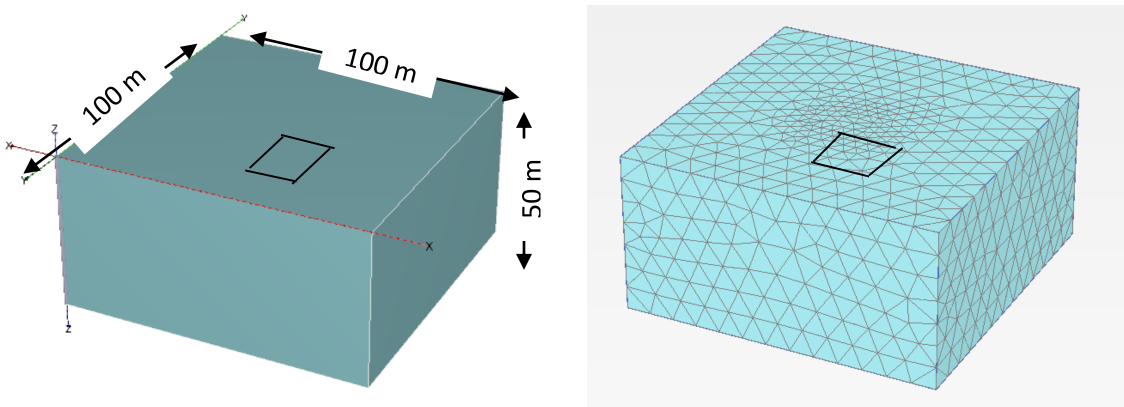
Parameter	Name	Soil
Material model	MC	Mohr-Coulomb
Drainage type	Type	drained
Unit weight above phreatic level, kN/m^3	γ_{unsat}	16
Unit weight below phreatic level, kN/m^3	γ_{sat}	18
Stiffness, kN/m^2	E	3000
Poisson's ratio	υ	0.4
Shear Strength, kN/m^2	S	25
Lateral earth pressure coefficient	k_o	0.99

Table (2) Raft and Skirts Properties

Parameter	Raft	Skirts
d (Thickness)	0.3, 0.5 and 1.00 m	0.05 m
γ (Density)	25 kN/m^3	78 kN/m^3
E (Modulus of Elasticity)	22E6 kN/m^2	210E6 kN/m^2
υ (Poisson's ratio)	0.3	0.3

3. PROPOSED 3D MODEL

Plaxis 3D has been used to evaluate the effect of convexity of the adopted skirt configuration. A 3D model 100 m x100 m x50 m has been used to simulate the considered conditions. Raft foundation having 10x10 m plan dimensions with different thickness has been simulated at the center of the soil body at depth 2.0 m below the surface. Figure 2 shows the model dimensions and the generated mesh in which the soil near the structure has been refined to get more precise output. Skirts with constant length 5 m has been modelled. Also, Convex and semi-convex configurations have been modelled.

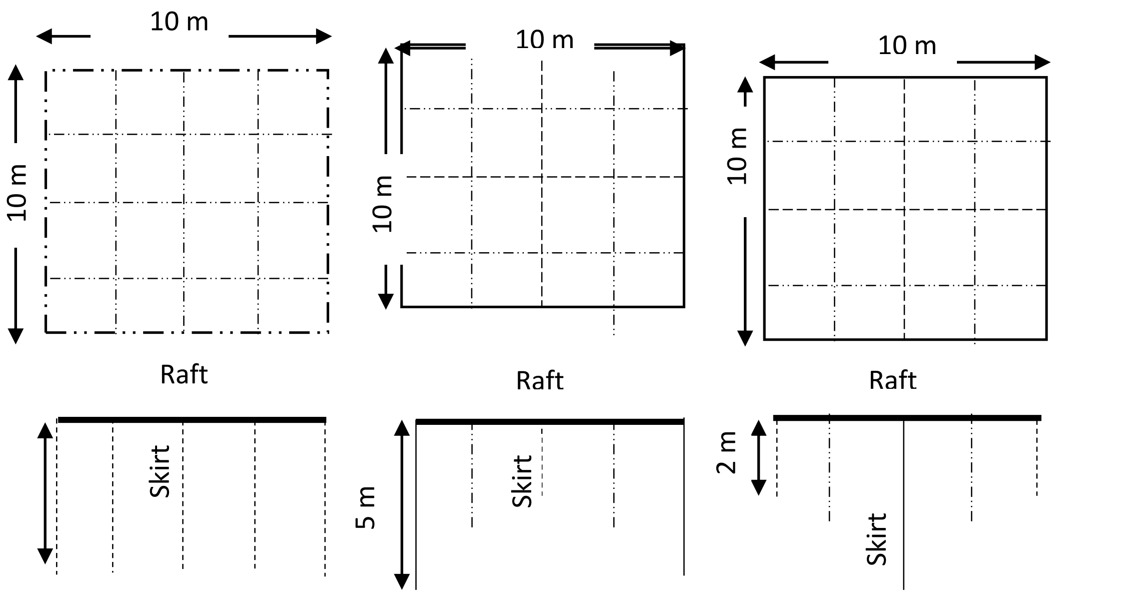


a) Soil Cluster **b) Generated Mesh**

Fig. 2 Soil 3D Plaxis Model

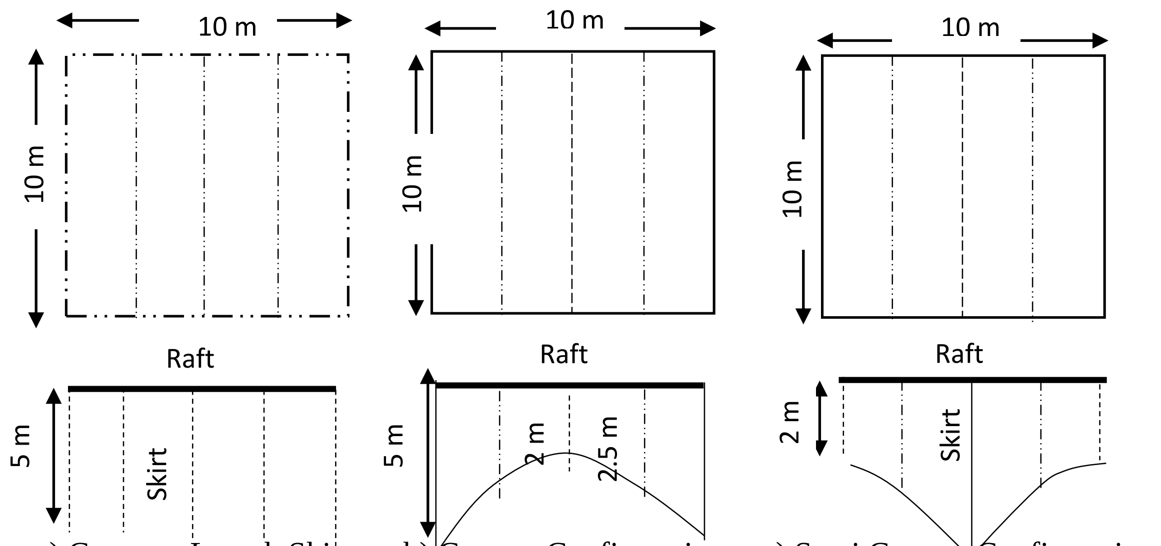
4. SKIRT CONFIGURATION

Different skirts configurations have been modeled and analyzed. Initially, outer and inner skirts have been used with constant length equal 5 m according to the configurations shown in Figure 3 and 4. Figure (3a) shows intersected skirts with which the raft has been stiffened with skirts in both directions while Figure (4a) shows one way skirts with which the raft has been stiffened in one direction. The same trend has been applied with different skirt length to create convex and semi-convex geometry shown in Figures 3b, 3c, (4b) and (4c). The convexity and concavity of skirts represent the common stress distribution under flexible and rigid foundations. All cases have been modeled and analyzed under different stress levels.



a) Constant Skirt Length b) Convex Configuration c) Semi Convex Configuration

Fig. 3 Intersected (Two-Way) Skirt Configuration



a) Constant Length Skirt b) Convex Configuration c) Semi Convex Configuration

Fig. 4 Single (One-Way) Skirt Configuration

5. RESULTS AND DISCUSSION

The load displacement curves for non-skirted and skirted foundations with different skirt configuration and length have been generated. The versatile scenario has been plotted in which the settlement increases as the load increases for different geometry conditions. The non- skirted foundation shows the highest settlement, while skirted foundations exhibited lower values. Both convex and semi-convex skirts show the lowest settlement values. That is attributed to the effect of skirts on the rigidity of foundations as well as the confinement of the underlying soil. The effect of different skirt configuration on improved stress is summarized in Table (3).

Table (3) Effect of Skirt Raft

Raft Thick (m)	Without Skirt kN/m^2	One Way Stress (kN/m^2)				Two Way Stress (kN/m^2)			
		Conv	Change (%)	Semi-Con.	Change (%)	Conv	Change (%)	Semi-Conv	Change (%)
0.3	80	150	87.5 %	120	50 %	120	50 %	80	0.00 %
0.5	80	125	56.3 %	110	31.5 %	100	25 %	80	0.00 %
1.00	80	80	0.00 %	80	0.00 %	80	0.00 %	80	0.00 %

Table 3 illustrates the improvement rates in terms of percentages. The carrying capacity of semi-convex geometry increased by 50% more than non-skirted foundations, while for convex geometry, the increase was more than 75%. The convex geometry recorded stress level higher than the semi-convex one by more than 20 % when the raft thickness is 500 mm while this increase became about 37.5% when the raft thickness is 300 mm. The convex skirts geometry has proved to be efficient system to upgrade the applied stresses within the acceptable settlement limits. The unconfined compressive strength of soft clay is 0.25-0.5 kg/cm2 according to the Egyptian code for soil mechanics and foundations. By comparing this stress to the maximum improved carrying capacity, it can be observed that the stress level has been reached more than twice this value for semi-convex skirt configuration, and about three times for convex skirt configuration.

Figure 5 through 7 show the load displacement curve for one-way skirted foundations with different skirts geometry and raft thicknesses, compared with non-skirted raft. The obtained stresses have been correlated to the non-skirted raft obtained stress q_{all} = 80 kN/m^2 at the allowable settlement. Also, the measured settlement has been correlated to the foundation breadth. The maximum allowable settlement for foundations has been taken as 150 mm as recommended by the Egyptian Code (ECP 202/3) for rafts on clay deposit. Non- skirted foundations can carry 80 kN/m^2 as a maximum applied stress corresponding to the maximum allowable settlement for all raft thicknesses. The same stress level has been reached for convex and semi-convex skirts when the raft thickness is 100 cm. Therefore, the effect of convexity and semi-convexity has negligible effect for rigid foundations. The rate of stress level started to increase for semi-convex skirts to 110 kN/m^2 when the raft thickness is 500 mm while it became 120 kN/m^2 for raft with thickness 300 mm. The convex skirts showed the highest capability of stress 125 kN/m^2 and 150 kN/m^2 for raft with 500 mm and 300 mm thickness respectively. The stress level increases as the raft flexibility increases at the same allowable settlement.

Figure 8 through 10 illustrate the load displacement curve for skirted foundations having different thicknesses with intersected skirts. The maximum attained stress is 120 kN/m^2 at convex condition for raft of 300 mm thickness. This stress is slightly lower than that previously attained at convex one-way skirts for 300 mm raft by about 20 %. This decrease might be attributed to the soil disturbance caused by the multi-directional skirt penetration as well as the single behavior of each soil cluster enclosed by the skirts. On the other hand, for one-way skirts, less disturbance is made, and the soil behaves as one unit enclosed by the outer skirts and one-directional skirts. The convex configuration proved also that it is better than the semi-convex one and it is much closer to the traditional contact pressure distribution beneath foundations on clay.

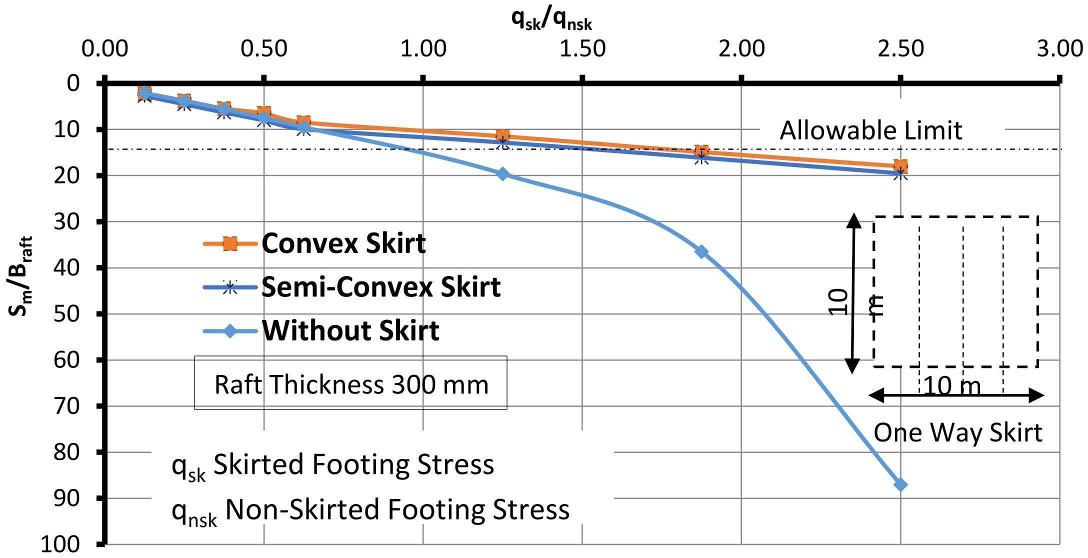


Fig. 5 Effect of Raft Flexibility on the Load-Displacement Relationships for one-way Skirt Configuration (Raft 300 mm)

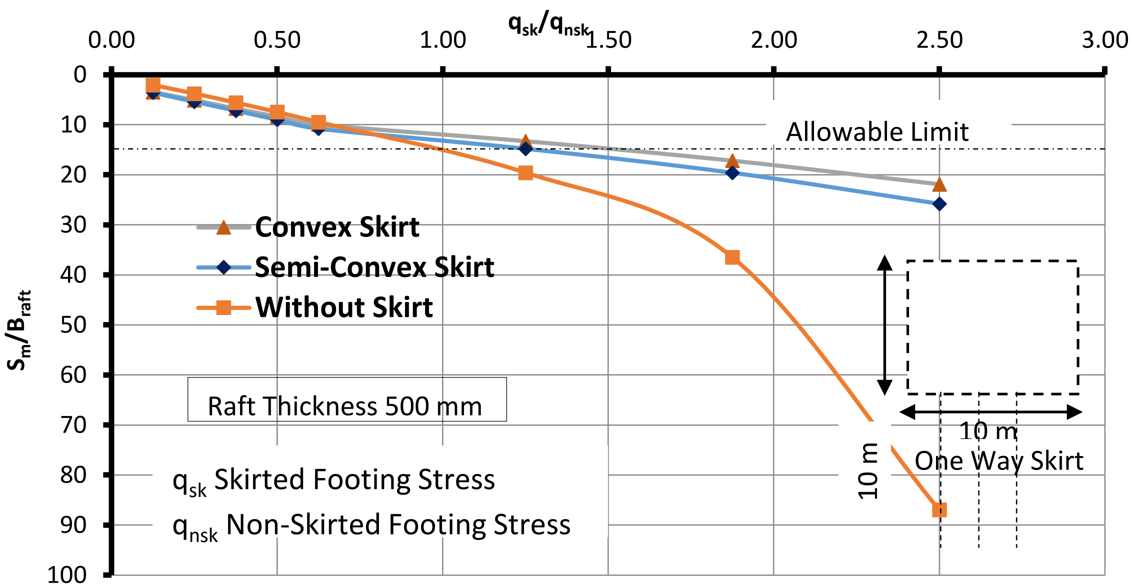


Fig. 6 Effect of Raft Flexibility on the Load-Displacement Relationships for one-way Skirt Configuration (Raft 500 mm)

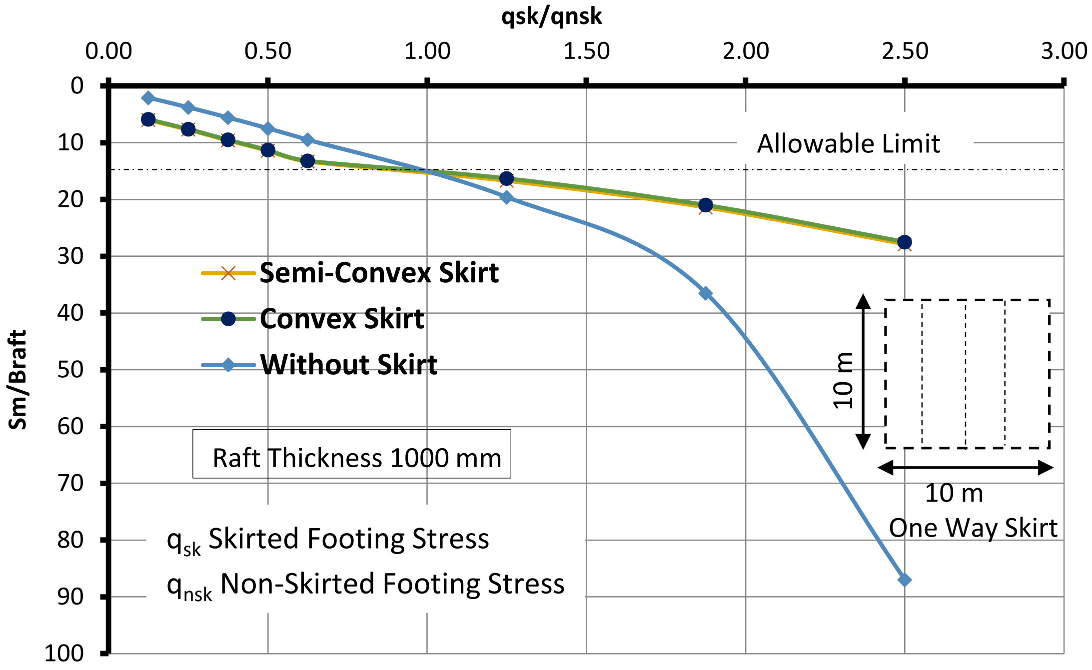


Fig. 7 Effect of Raft Flexibility on the Load-Displacement Relationships for one-way Skirt Configuration (Raft 1000 mm)

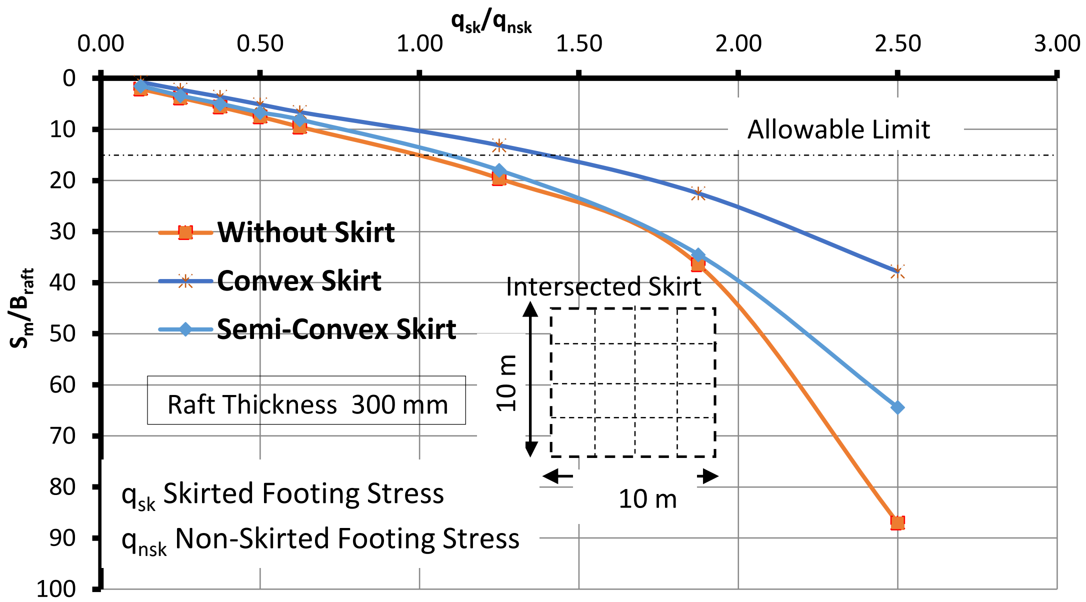


Fig. 8 Effect of Raft Flexibility on the Load-Displacement Relationships for Intersected Skirt Configuration (Raft 300 mm)

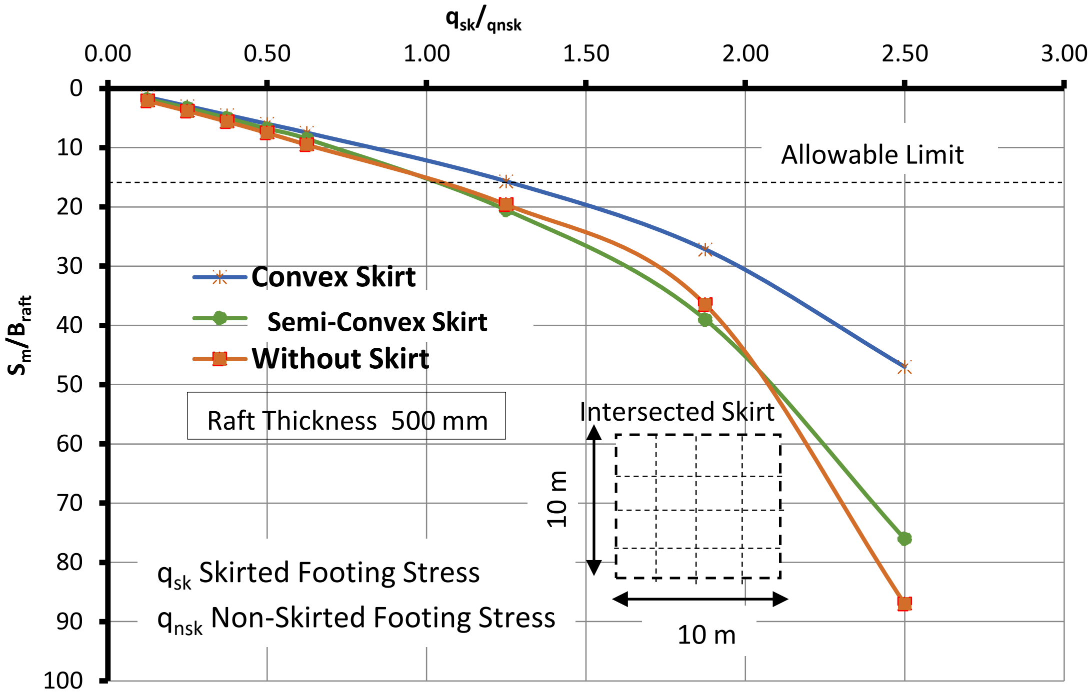


Fig. 9 Effect of Raft Flexibility on the Load-Displacement Relationships for Intersected Skirt Configuration (Raft 500 mm)

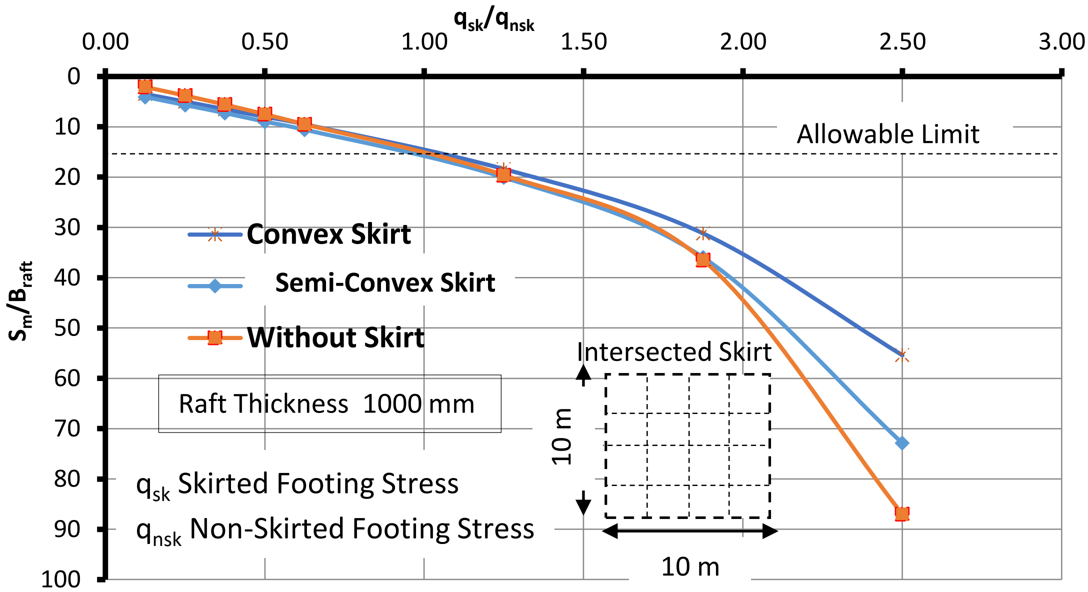


Fig. 10 Effect of Raft Flexibility on the Load-Displacement Relationships for Intersected Skirt Configuration (Raft 1000 mm)

Figure 11 shows the effect of foundation rigidity on the contact stress. It can be observed that one-way skirts showed considerable improved stress than intersected skirts. Also, the attained stress decreases as the foundation rigidity increases. For raft foundation having 1000 mm thickness, all configurations of skirts showed the same rate of stress. The higher rigidity of foundations inhibits the interaction between skirts and soil. On the other hand, this interaction increases as the foundation rigidity decreases due to the skin friction/adhesion interaction between foundation, soil and skirts. Figure 12 illustrates the distribution of displacement in the soil mass for skirted foundations with different skirt configuration. Convex one-way skirts showed well distribution for deformations than that for intersected convex skirts. On the other hand, one-way semi-convex skirts showed more concentrations for deformation than intersected semi-convex skirts. Deformations vector showed large stress concentrations around skirts tip due to the transference of stress to greater depth.

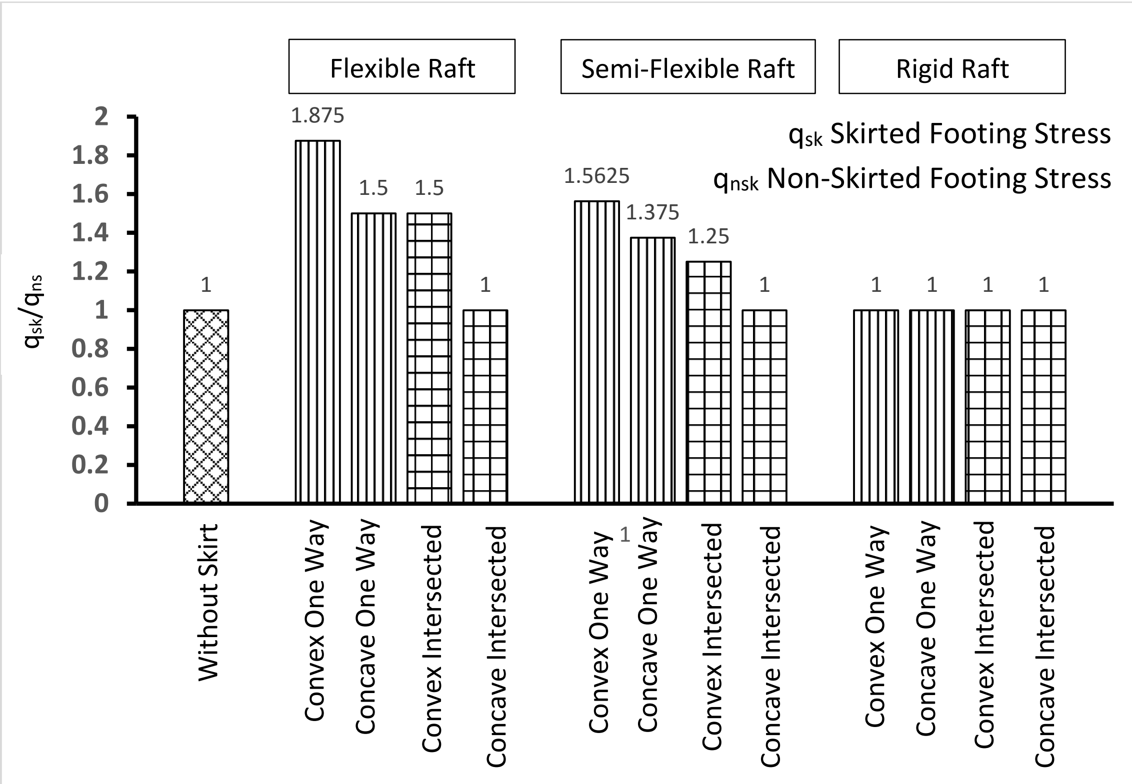
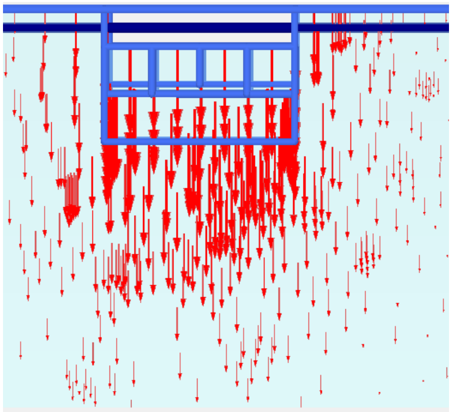
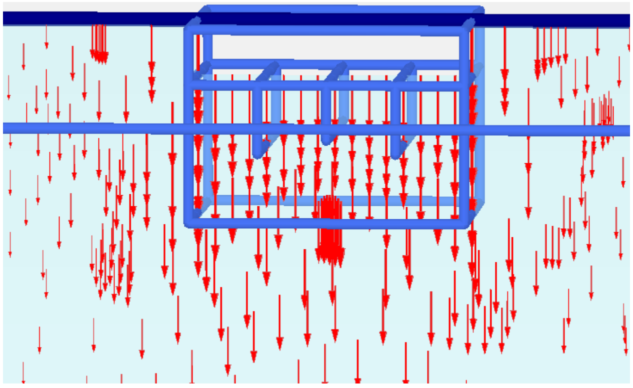


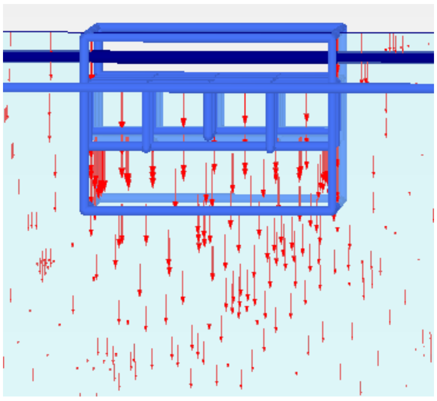
Fig.11 Effect of Raft Flexibility on the Stresses at Allowable Settlement for Different Skirt Configuration



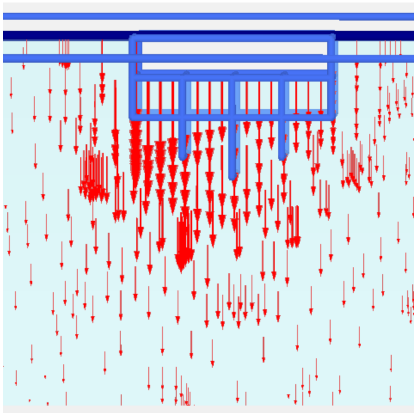
(Intersected Convex Skirts)



(One Way Convex Skirts)



(Intersected Semi-Convex Skirts)



(One Way Semi-Convex Skirts)

Fig. 12 Deformation Vectors for Different Skirt Configurations

6. Conclusions

From the study of skirt foundation, the following conclusions can be drawn

1. Skirt foundations proved to be efficient and economic system to enhance the capacity of weak compressible soils.
2. One-way convex skirt foundations increases the carrying capacity of the soft clay by more than 80%, while it is 50 % for intersected convex skirts.
3. The flexibility of foundation has significant effect on the performance of skirt foundation. As the skirt foundation gets more flexible, it shows high carrying capacity.
4. Convex skirt geometry shows an increase in the carrying capacity by about 25% for raft of 300 mm thickness. For raft of 500 mm and 1000 mm, the increase in carrying capacity is 10 % and 0 %, respectively
5. The maximum attained stress is about twice the unconfined compressive strength for semi-convex skirts, and it is triple for convex skirt configuration.
6. One-way convex skirts are better than intersected convex skirts due to the soil disturbance in the intersected condition as well as the single behavior of each soil cluster enclosed by skirts.

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