CHAPTER IV

SUMMARY OF FINDINGS

Post-Terzaghi developments in bearing capacity theories could be classified into three distinct approaches namely, scale effect, progressive rupture failure concept, compressibility of sand and mixed mode failure. Scale effect demands to reduce the bearing capacity factors with increase in size of the plate. A non-linear variation with width is observed by various workers. Progressive rupture failure necessitates the change in dilation of the granular mass along the failure surface. Progressive rupture at various stress levels is considered by various investigators. Cavity expansion concept of elasto-plastic solids is considered for getting and illustrating variation of compressibility with frictional parameters to obtain equation of bearing capacity factors.

Present work proposes a theoretical model for computing bearing capacity of plane and skirted footings accounting inherent additional points obscuring some of the deficient points and proposing analytical relation for bearing capacity factors exhibiting the frictional and dilatant behaviour of granular mass under axial, eccentric and oblique loads.
Modification in classical theory was made effective in present work by proposing a coefficient \( C_s \) due to scale effect in the equation of modified \( \phi_m \). Progressive rupture is incorporated by varying frictional parameter linearly along the rupture surface to account for the dilation of the sand.

Present work has proposed a mechanistic model of confined sand mass within the skirts of skirted footings and developed a relation which can describe the improved state of stress. The improved state of stress within the skirts is included by a factor \( C_t \) considering areas of inert triangular wedges under skirted strip footings and equivalent conventional footing accounting the possible confinement in the sand depending on void ratio. Further, the theoretical model is extended for eccentric, oblique and horizontal loads. The rupture surface in eccentric load is on the side of the load and full mobilisation of passive resistance on failure side. In oblique loads, the failure side is dependent on incident line of the load on the bottom plane of the surface of the skirted footing with respect to centre-line whereas in horizontal loads, the failure loads are computed considering the modified angle of friction within the skirts and a passive resistance of soil against outer surface of skirt. Fortran program is used to compute the theoretical relationships of bearing capacity factors for plane and skirted footings. The confirmation of proposed theory with classical can be obtained by inserting idealisation i.e. \( \phi_m = \phi \).

7.1 THEORETICAL EXPOSITIONS

(i) For a plane footing width of 140 mm the modified bearing capacity factors are the same as classical. Unlike Terzaghi's the bearing capacity factors are greater for smaller plates and smaller for larger plates.

(ii) The equation of radius of log-spiral of classical is replaced by incorporating \( \phi_t = (\phi_m + \phi)/2 \) to take into account the progressive rupture failure. The effect of progressive rupture phenomenon is to reduce the equivalent friction parameter, \( \phi_t \), along the rupture surface to some extent for smaller plates and to increase to some extent for larger plates tending to change the bearing capacity factors accordingly.
Axial loads

(iii) Bearing capacity factors for skirted footings under axial load increase with skirt angle $\alpha$ up to $30^\circ$ and then drops while the factors increase with aspect ratio $k$ for any skirt angle. This is because of beneficial mechanism of proposed theoretical model stating the same wedge angles.

(iv) Theoretical bearing capacity parameters ($N_{qs}$ and $N_\phi$) increase with increase of the angle of internal friction, $\phi$, under axial, eccentric and oblique loads for plane footings for all width of plates.

(v) For given angle of internal friction, theoretical bearing capacity factors reduce with increase of eccentricity and inclination, both, keeping the positive direction of inclination of loads.

(vi) For skirted footings, under eccentric and oblique loads, theoretical bearing capacity factors increase with the angle of skirt in the range of $\alpha=30^\circ$ to $45^\circ$ and thereafter drop. With increase of eccentricity and inclination, the peak value of bearing capacity factors shifts towards $\alpha=45^\circ$. This is because of variation in theoretical wedge angles $\alpha_1$ and $\alpha_2$. The bearing capacity factors increase with aspect ratio for all inclinations and eccentricities.

(vii) For the skirted footings under horizontal loads infers that modified angle of friction (at interface of the soil plug within skirts with foundation soil) increase with the angle of skirt up to $45^\circ$ to $50^\circ$, thereafter reduces.

(viii) Frictional resistance at the interface of plane footing subjected to horizontal loads is dependent on weight of the plate. In case of skirted footing, in addition to the self weight of footing model, the weight of soil plug within the skirts is additive for this effect.
(ix) The theoretical failure load depends on frictional resistance at the base and the passive resistance offered by foundation soil against the skirts, which is maximum for skirt angle of $90^\circ$. The frictional resistance increases up to skirt angle of $\alpha = 45^\circ$ to $50^\circ$ and then drops, provided that the skirted footing is subjected to initial seating load.

(x) As the sand within the skirts is properly densified, the energy correction i.e. $\tan \delta/\tan (\phi)$ will tend to unity theoretically in the absence of normal load.

(xi) The FEM analysis employing ANSYS software suggests that the equivalent modulus of sand within the skirts increases up to an angle of skirt of $30^\circ$ which drops thereafter, reaches to more or less same value of plane footing at an angle of skirt of $90^\circ$.

7.2 EXPOSITIONS FROM MEASUREMENT FACTORS AND SET UPS

The degree of exposition of any engineering measurement depends on degree of exactitude of the experimental set up. Major factors that influence the measurement of load settlement, the vertical soil pressure measurement and contact pressure are density of sand bed, physical properties of models, experimental set up and accuracy of measurement system.

(i) The raining method having truncated prism shaped rainer having one way valve at the bottom employed for getting consistent density in sand mass is best suited compared to other conventional methods in achieving uniform and consistent density. Lift of rainer through rope, axle, and wheel arrangement is convenient device for accomplishing homogeneous moderate dense sand mass.

(ii) The rigidity or flexibility of footing can affect load settlement and contact pressure behaviour. The reduction of the stiffness of the foundation at the interface results into increased settlements with no significant and consistent deformation in slip surface. Generally the rigidity induces non-linear contact
pressure distribution while a little flexibility improves the contact pressure diagram significantly. The integrity of the skirts with plane part of footing helps reducing the stress concentration at the junction while the confined sand within the skirts induce a small flexibility to an overall foundation system.

(iii) For the same level of loading on plane footing model, the settlement of the rough footing is less than that of smaller footing under the same test conditions. In case of skirted footings, the roughness of the base (inside surface of footing) has negligible effect on the bearing capacity and load settlement behaviour. This is attributed to the confined sand mass alongwith skirted strip footing acting as a unit.

(iv) The ultimate bearing capacity decreases with width of the footing for both the plane and skirted footing under the same test conditions. To achieve the rigidity, the appropriate thickness of model is adopted. As the projected width at the surface of the skirted footing has a vital role on bearing capacity, both the ends of the skirted footing are made vertical.

(v) Width of the tank for testing strip footing models should be able to accommodate the rupture shear surface. Minimum length of the tank should be 5 to 8 times the footing width (strip footing). The depth of the tank should accommodate the stress contour of $0.1q$ where $q$ is the intensity of the surface load.

(vi) The design capacity of loading frame should be at least 2.5 times the expected maximum ultimate reaction load, so as to ensure against the endurance limit. The capacity of the set up is based on the available reaction load, which is derived from the weight of the tank filled with sand.

(vii) Chalk dust layers near the perspex sheet is suitable for studying the movement of sand for the observation of the failure patterns. The prototype
test set up is suited for applying the reaction loading on large size model of maximum 400 kN capacity for field simulation.

(viii) System of load application through calibrated screw jack by electronic load cell seems to be suited over conventional systems. For proper dispersion and transfer of strip load to the model in turn to the soil by I section or by steel strips is appropriate method. For eccentric and oblique loads application of special wooden wedge is convenient to transfer the point of load application through jack and load cell at required eccentricity and obliquity with respect to centre-line of model footing at the top.

(ix) To avoid electronic system deficiency, the settlement measurement through extensometer along with electronic system seems is essential to compliment the deficiency of each other. A system consisting of earth pressure cells, switching and balancing unit interfaced with indicators is suitable for measurement of vertical soil pressure distribution.

(x) A new technique of housing the contact pressure cells in dentoplast material is developed in the investigation found to be efficient in placement of the cell and converging all wires to one chord leading to the measuring system. Controlled jellification time and designed water powder (W:P) ratio helps further in tremmie pouring in the model.

(xi) Placement of the model in the tank is regulated in such a way to secure occupancy of the sand uniformly within the skirts by applying necessary seating load.

(xii) Exact measurement of the magnitude of the horizontal loads at the point of application is an essential factor of the loading arrangement to avoid frictional losses at the loading point.

(xiii) The arrangement of placement of sensitive spring balance in-between model and pulley load arrangement is convenient device compared to proving ring.
and hydraulic jack for the precise measurement of the horizontal load applied to the footing model.

(xiv) The measurements of tilt of the model footing under eccentric/oblique load by extensometer on both the sides of the centre-line of the footing are a worth pursuit.

7.3 FINDINGS BASED ON EXPERIMENTS

Summary of inferences derived from the experimental investigations is:

(A) Axial load

Apart from same pattern of load-settlement, stress contour and contact pressure below conventional footing, the bearing capacity parameters and distribution of contact pressure improved very much at range of skirt angle 30° to 45° in skirted footing, and vertical stress ratio at any depth co-efficient is more compared to conventional one. Skirted footing derives more beneficial effect over plane footing.

(i) In case of plane footings, the ultimate pressure increases non-linearly with width and projected width of the skirted footings, which is attributed to average shear strength along the slip line under the foundation varies inversely with footing size.

(ii) For the same skirt angle with the increase of aspect ratio, the ultimate load linearly increases. Among all values of angle of skirt α, the ultimate pressure initially increase up to 30° and then drops for medium and large size models.

(iii) The bearing capacity ratio (BCR) and bearing capacity efficiency (BCE) of the small models increases with angle of skirt α, up to 45°, and then decreases, while for medium and large size models BCR and BCE increase up to 30° and then decreases exhibiting a value of 135% for α = 30°. The bearing capacity ratio increases with aspect ratio k for given value of top width (Bt) and angle of skirt α for all the sizes of models.
(iv) In small size model, the settlement ratio is found to be less than 1.0 for all values of $\alpha$. The settlement ratio at failure ($SR_f$) reduces initially from unit value of plane footing and thereafter increases slightly (remaining less than one) up to skirt angle of $45^\circ$ which shows decreasing trend tending constant thereafter for medium and large models. The variation of settlement ratio with angle of skirt $\alpha$ is uncommon with small size model. It increases up to $30^\circ$ to $45^\circ$, thereafter decreases. With increase of skirt angle, the higher variation is concurrent with reverse trend of bearing capacity ratio after skirt angle $45^\circ$.

(v) For any skirt angle $\alpha$, the secant modulus is less than experimental initial tangent modulus, $E_i$ but greater than experimental failure modulus $E_f$. For same $B_t$ and $k$, initial modulus $E_i$, secant modulus, $E_s$; and failure modulus, $E_f$ increase up to $30^\circ$ to $45^\circ$ skirt angle, then decreases for small, medium and large size models. For plane footings, these values initially increase up to 30 to 50 mm wide plate, then continuously decrease with the width of the plate.

(vi) For plane footing (for models up to width of 50 mm), the width dilatancy decreases with the width of the plate, while increases from plate width of 50 mm to 160 mm, thereafter tends to remain constant. For skirted footings for a given top width, the width dilatancy decreases with skirt angle in the range of $30^\circ$ to $45^\circ$, thereafter it shows increasing trend tending to constancy (with maximum value of 6%), while for medium and large size models, width dilatancy increases with angle of skirt $30^\circ$ to $45^\circ$ and thereafter it drops.

(vii) For plane footings, the value of $N_y$ decreases with width of the plate experimentally ($N_{y,exp}$) as well as theoretically ($N_{y,th}$). $N_{y,exp}$ is fitted with $N_{y,th}$ for all width of plates, with the variation of only 10 to 15 % except for the small width of plates. The higher variation in these values is observed for small models. For skirted footings the values of $N_{y,exp}$ and $N_{y,th}$ increase with angle of skirt up to $30^\circ$, thereafter decreases for small, medium and large size models. Large variation in experimental and theoretical values in small size models while 5 to 10% variation in medium and large size models are observed at any skirt angle.
(viii) The failure load ratio (FLR) reduces with the increase of width of plate up to 150 mm, tending to constancy thereafter. For given top width $B_t$ and angle of skirt $\alpha$, the failure load increases with width of the skirt.

(ix) The trend of load-settlement diagram of embedded footing is similar to that of the surface footings exhibiting proportionate increase in bearing capacity in plane and skirted footings. The failure pressure increases with the increase of surcharge ratio $D_f/B_t$. The bearing capacity ratio increases linearly with surcharge ratio for a given skirt angle and top width. The similar trend is observed with bearing capacity efficiency. Theoretical and experimental values of $N_q$ are almost concurrent for various models showing 2 to 5% deviations. Width dilatancy increases with increase of aspect ratio for given surcharge ratio. The skirt efficiency is in the range of 150% to 200%.

(x) It is observed that the scale effects, which were pronounced in small size models and reduced with medium models, are further reduced with prototypes. Therefore the experimental bearing capacity factors fit well with the theoretical ones in plane and skirted prototype strip footings. The other expositions that were observed with medium models viz. BCR, BCE, settlement ratio, WD, etc. may hold true for prototypes.

(xi) It is observed that higher the applied pressure on plane footing, the greater is the depth and lateral extent of the stress contour of a given pressure intensity, though the variation is not significant. The significant depth and width (at $\alpha/q = 0.25$) reduce with increase of footing width which is 4 to 4.5 and 3 to 4 times the width of footing respectively which remain the same (2 to 3 times) after 200 mm width of plate. Vertical stress ratio reduces with the increase of depth coefficient.

(xii) The observed vertical stress distribution for the skirted footing is different than of a plane footing. The significant depth and significant width increase with the angle of skirt $\alpha$ up to $30^0$ and then reduces. The stress contours of a
given stress intensity shifts downward with increase of pressure in the footing. For all the skirted footings $\sigma_v / q$ decreases with the increase of the depth $z$ and also decreases on any horizontal plane with the increase in radial distance. The vertical stress $\sigma_v$ is maximum at given depth for $\alpha = 30^\circ$.

(xiii) The radius of the pressure bulb increases with the increase of skirt angle in the range of $30^\circ$ to $45^\circ$, beyond which it decreases. The radius of the pressure bulb for any fraction of the applied stress is more compared to the conventional footing. Also for the given vertical stress ratio the depth coefficient $z/B_1$ is more compared to the conventional footing which indicates that the significant depth for settlement computation or shear failure calculation is more in comparison to the conventional one for the given value of $\alpha$. However, if a plate deriving the same vertical load as the skirted footing is used, the actual extent of the pressure bulb for plane footing will be more than that of the skirted footings. Moreover, the concept of equivalent plane footing also justify the statement thereby skirted footing derives more advantage of low interference of pressure bulb with adjacent footing and significant depth.

(xiv) The contact pressure in longitudinal direction under plane footing at the centreline seems to remain fairly constant in the middle 60% to 70% of the length of the footing. This is attributed to uniform distribution of transmitted load with the help of a beam / load platen inserted between the footing and loading.

(xv) The contact pressure distribution under the plane footing is of parabolic shape having maximum value at the centre and zero at the edges at all applied loads.

(xvi) In case of skirted footing with the increase of applied pressure, the contact pressure increases at all points. For surface skirted footings, contact pressure at centre increases with $\alpha$ up to $30^\circ$, thereafter it can drop, and at
junction point and the edge point it increases with angle of skirt, \( \alpha \). From the trend of contact pressure diagrams, the contact pressure is fully developed at the ultimate pressure at edges of the skirts unlike plane footing. The contact stresses at edges seem to be more or almost remaining the same with the centre, while at the junction points of the footing the contact pressure exhibit less value than the centre and the edge at the ultimate load, unlike with conventional plane footing, exhibiting almost uniform contact pressure distribution.

(xvii) The contact pressure ratio (CPR) at centre increases linearly up to 2/3\textsuperscript{rd} failure load and it may tend to constant. Also at all percentages of failure loads, the CPR increases with the skirt angle up to \( \alpha = 30^\circ \), beyond which it decreases. At junction point contact pressure ratio increases with the loads. The contact pressure coefficient \( \sigma_{cp}/q \) at failure pressure varies with the angle of skirt.

(xviii) In case of embedded skirted footings, the contact pressure increases at the centre and at the edges (more at centre than at edge) with increase of surcharge. Contact pressure distribution for surface skirted footing always be above the diagram of footing with surcharge. However, at failure load, the contact pressure diagram tends to be uniform due to more increase at the edges simultaneously.

Variation in load settlement and bearing capacity parameters with respect to various sizes of models is attributed to the scale effect, reduced to minimum for large size models. More the confinement of sand in skirted footing, the higher is the magnitude of the vertical stress at the given depth is a reason of great stress value below the skirted footing (\( \alpha = 30^\circ \)) than that of plane footing. The skirted footing provides the effect of embedment by virtue of its slope at the edges which helps in making contact pressure uniform unlike plane surface footing which may allow lower factor of safety in determining allowable bearing pressure in the design.
(B) Eccentric vertical load

The pattern of load settlement diagrams remains unlike to that of skirted footings subjected to axial loads under the influence of eccentric load, the stress contour will be dragged on the load side compared to axially loaded footing. Though the general pattern of the contact pressure curve remains identical with axial load, the magnitude of contact pressure at junction point and at end point are different than axial load, exhibits higher magnitude on load side. Due to eccentricity dragging of contact pressure diagram exhibits non-uniformity compared to axial case.

(i) The load and settlement at failure reduce with the increase of eccentricity for plane and skirted footings shifting the load settlement diagram towards vertical axis, indicating decrease of ultimate load from zero to maximum at applied eccentricity of 0.2B ranging 45% reduction in plane and 15% reduction in skirted footings. Similar behaviour is observed to the given settlements, say, 2.5%, 5%, 7.5%, etc. of projected width of skirted footing.

(ii) In case of skirted foundation, the state of confined stress within the skirt attribute to resist more failure load compared to the conventional footing for the same eccentricity. Also, the skirted footing having Bt = 300 mm, k = 0.33, angle of skirt of 30° resists 1.8 times the failure load compared to the conventional footing while the 45° skirt exhibits 1.5 times the failure load.

(iii) In case of skirted footing with same Bt, k, and a, the failure load, BCR_{sfs}, BCE_{sfs}, width dilatancy WD and settlement ratio SRf_{sfs} decrease with increase of e/Bt ratio.

(iv) For same e/Bt ratio the failure load, BCR_{sfs}, BCE_{sfs}, BCR_{ap}, and WD increase up to α = 30° to 45° and thereafter reduces. Also for the same e/Bt ratio, above parameters increase linearly with aspect ratio.

(v) For the same top width Bt, angle of skirt α and aspect ratio k, the SRf_{sfs} reduce with e/Bt ratio, while SRf_{ap} and SRf_{up} increase with α up to 30° and then reduce with lower eccentricity, while it reduces for all α at higher eccentricities.

(vi) Experimental moduli (Ei, E*) increase from e/Bt = 0 to 0.1, thereafter drops for any value of eccentricity. In general, for any value of α and k, failure modulus Ef remains almost constant for any e/Bt ratio. The patterns of experimental
modulus shown in analysis are due to the transition of elastic to elasto-plastic equilibrium.

(vii) The bearing capacity parameters $N_{th}$ and $N_{exp}$ decrease with the increase of eccentricity ratio for given value of $\alpha$ and $k$. For the same $e/B_t$ ratio, $N_{th}$ and $N_{exp}$ increase up to $\alpha = 30^\circ$ and thereafter drops. Similarly for same $e/B_t$ ratio, $N_{th}$ and $N_{exp}$ increase with $k$. The experimental values are little higher than theoretical values with a deviation of 20 to 25 per cent for the range of skirt angle of $30^\circ$ to $45^\circ$.

(viii) In general, higher the applied pressure on the footing, the greater is the depth and lateral extent of the stress contour of a given pressure intensity. The pattern of isobars indicates pulling of the contours on the load side, due to eccentric load, though the lateral extent of the pressure bulb remains less than that of the axial load for any eccentricity.

(ix) With the increase of $z/B_t$ the stress ratio $\sigma_f/q$ reduces for any value of $e/B_t$ ratio and at a given $z/B_t$, it reduces with increase of $e/B_t$ ratio. The significant depth is nearly 2.7 to 5.0 times the projected width of the footing as against 4.5 to 6 times the axial case. The significant depth coefficient $(SD/B_t)$ reduces with the increase of $e/B_t$ ratio and radius of pressure bulb reduces with increase of eccentricity for any increase of skirt angle $\alpha$. For a given $x/B_t$ ratio, the $\sigma_f/q$ reduces with increase of $e/B_t$ ratio, while for a given $e/B_t$ ratio, with the increase of $x/B_1$ ratio, $\sigma_f/q$ reduces.

(x) The contact pressure increases at all points with the increase of applied pressure. The contact pressure at centre is less while it is greater at load side and less at remote side compared to that of axial load. The contact pressure diagram is dragged towards the load side exhibiting maximum contact pressure at the (in the vicinity of) point of application of eccentric load.

(xi) In the contact pressure diagrams for eccentric loads, the curves are crossing with the curve of axial load exhibiting reverse magnitude thereafter tending to zero contact pressure at the edge i.e. the line of curve which was above the curve of $e=0$ on remote side, is found below that curve on load side. The above point of concurrency shifts towards the edge on load side with the increase of the load from $Q_f/3$ to $2Q_f/3$ and to $Q_f$.

(xii) The variation of contact pressure is dependent on angle of skirt $\alpha$, the eccentricity ratio, effective width and magnitude of loading. The pattern of the curves for $\alpha = 30^\circ$ and $45^\circ$ illustrates that the curve is dragged towards the load-
side, and this drag increases with increase of $e/B_t$ ratio. The uniformity of contact pressure increases as the load approaches to its ultimate value.

(xiii) Compared to the plane footing, even at higher $e/B_t$, the skirts make the contact pressure distribution more uniform exhibiting the efficiency of the skirts. It seems that the skirted footing can be subjected to larger eccentricity than that of conventional footing without loosing its contact with sand. Contact pressure distribution values for skirted foundation indicate that the tendency towards negative pressure is reduced to a greater extent compared to the conventional footing. The ratio of contact pressure distribution on load side to that of the remote side reduces with angle of skirt up to 30° and then increases at all loads.

(xiv) For the same load, settlement and tilt of eccentrically loaded plane and skirted footings increase with increase of $e/B_t$ ratio. With increase of load from zero, tilt bears a linear relationship with load up to failure load and then continues to increase non-linearly up to residual load. Skirt resists more tilt compared to plane footings at a given eccentricity.

(xv) The contact pressure distribution diagram for skirted foundation reveals that the tendency towards negative contact pressure within the limits of eccentricity ($e<0.5B_t$) is reduced to a greater extent compared to the conventional strip footings. Similar is the observation with the eccentric and oblique loads. This is because of the interlocked stresses in the confined sand mass in the inert zone on the other side of the load application.

The shifting of load-settlement diagram under eccentric load unlike to axial case is due to the load required to induce the plastic failure and the mechanical strain needed is less compared to that of axial case reflecting the change of wedge angles on load side and on remote side. Skirted footing can take larger eccentricity of failure load is due to more resistance offered against horizontal component of eccentric load. Contact pressure at the base of eccentrically loaded skirted footing is higher on load side because of soil on this side passes into plastic stage first developing rupture surface fully and tends to fail by tilting.

(C) Oblique load

The load settlement diagrams subjected to oblique centrally located and eccentrically located load remains unlike to that of vertical axial and eccentric loads.
For oblique load acting at centre, pattern of isobars indicates dragging of the contours in the direction of the horizontal component of the oblique load. The contact pressure diagram below skirted footing is unlike to axial and eccentric vertical loads exhibiting non-uniformity. For oblique load acting at centre, pattern of isobars indicates dragging of the contours in the direction of the horizontal component of the oblique load.

(i) The general shape of the load-settlement curve remains the same, however, they shift towards the vertical axis with increase of eccentricity and obliquity.

(ii) The bearing capacity ratio (BCR), bearing capacity efficiency (BCE), settlement ratio (Sr), width dilatancy (WD) and various experimental modulii (E_i, E_s and E_f) are observed to reduce with eccentricity for given obliquity and also with obliquity for given eccentricity for plane footing of large size.

(iii) For the same top width B_t, angle of skirt \(\alpha\), and aspect ratio k, the BCR_{s/s} and BCR_{s/p}, BCE_{s/p} and BCE_{s/s} decrease with the increase of obliquity for given eccentricity and also with eccentricity for given obliquity. Also for the same obliquity, as the eccentricity increases, BCE_{s/p}, BCE_{s/s}, BCR_{s/s} and BCR_{s/p} increases up to \(\alpha = 30^\circ\) and then reduces. Failure load, BCR_{s/s}, BCR_{s/p}, BCE_{s/s} and BCE_{s/p} show decreasing trend up to about \(i = 5^\circ\) and thereafter decrease gradually.

(iv) Failure load increases with angle of skirt up to \(30^\circ\), thereafter it drops for any given obliquity. Similarly, for any given \(\alpha\), the failure load reduces gradually with obliquity. Failure load reduces gradually with degree of inclination. For any obliquity the failure load increases from \(\alpha = 0^\circ\) to \(30^\circ\) thereafter it drops. For the same settlement, the skirted footing having angle of skirt \(30^\circ\) resists about 1.8 times the failure load as compared to conventional footings while that with skirt angle of \(45^\circ\) exhibits about 1.65 times the failure load.

(v) It is found that the skirted footing can resist large eccentric oblique loads than the conventional footings without loosing its contact with sand. Also for a given load, this footing can resist more obliquity and simultaneously more eccentricity.
(vi) Settlement ratio $SR_{(s/s)}$ remains less than unity for all eccentricity and obliquity for a given skirt angle. More reduction is observed for inclination of 0 to 5. Thereafter the rate of reduction is slower. The effect of inclination and eccentricity reduces settlement at failure along with the reduction in failure load in plane as well as skirted footings, but in skirted footings, skirts provide more resistance against obliquity and eccentricity reflecting higher failure load compared to plane footing. For given eccentricity, skirted footing bears more contact with soil than plane footing (excluding $e = 0$ and $e = 0.5 B_t$). This is one of the reasons of more load carrying capacity of skirted footing under eccentric and oblique load.

(vii) For given eccentricity, with increase of obliquity, experimental modulli ($E_l$ and $E_s$) tend to decrease with combined eccentricity and obliquity. For given obliquity, with increase of eccentricity, experimental modulli $E_l$ and $E_s$ decrease and value of $E_t$ remains constant for all eccentricity and obliquity.

(viii) Width dilatancy (WD) for same $B_t$, $k$ and $\alpha$ sharply reduce with increase of obliquity up to $i=5^\circ$ thereafter the reduction is gradual for given $e/B_t$ ratio. The width dilatancy increases for skirt angles from $30^\circ$ to $45^\circ$, which can reduce afterwards for same $e/B_t$ ratio, obliquity, and $k$.

(ix) The bearing capacity parameters $N_{r,th}$ and $N_{r,exp}$ decrease with increase of obliquity and eccentricity for given $\alpha$ and $k$. For the same obliquity, and with given $e/B_t$ ratio, $N_{r,th}$ and $N_{r,exp}$ increase for $\alpha = 30^\circ$ and thereafter drops. The experimental values are higher than theoretical values with variation of 20 to 30 per cent for the range of skirt angle $\alpha = 30^\circ$ to $45^\circ$.

(x) When the same load is applied at an eccentricity in vertical direction, the dragging of the stress contour is on the load side. This unsymmetrical characteristic is dependent on the position of point of incidence of oblique load at plane of interface between confined sand mass within skirts and foundation sand mass. Further, if the same load is applied with an eccentricity and obliquity, the stress contour may tend to drag towards the horizontal component
of the oblique load. The combined effect in present investigation increase the dragging effect of the vertical eccentric load further in lateral direction. The region of distribution of vertical stress for a given pressure intensity, eccentricity ratio and given obliquity at any \( z/B_t \) increases on load side and decreases on remote side of the load, depending upon the magnitude of given eccentricity and obliquity.

(xi) The significant depth is nearly 1.9 to 3 times the projected width of the skirted footing for a given obliquity compared to 4.5 to 6 times for axial load and 2.7 to 5 times in eccentric load. Significant depth coefficient reduces with increase of obliquity at a given eccentricity ratio. For a given \( e/B_t \) ratio, \( \sigma_v/q \) (vertical stress ratio) increase with reduction in depth coefficient and vice-versa. Also for the same depth coefficient, increase of vertical stress ratio increases with eccentricity and obliquity. Among various inclinations of loads the size of respective pressure bulb at any depth coefficient is increased with the increase of angle of inclination of load in the direction of its horizontal component.

(xii) The magnitude of contact pressure at centre point, junction point and edge point of load side and remote side are different than the axial and eccentric vertical loads. Further, under higher obliquity of load, it may lead to negative pressure at remote edge side. This characteristic effect is pronounced in plane footing than a skirted footing.

(xiii) In skirted footings, for a given angle of skirt \( \alpha \), as the obliquity increases, the magnitude of the contact pressure decreases at centre point. The magnitude of contact pressure decrease on load side than that of the centre point A. The
behaviour of contact pressure at junction point on remote side, D₁, is indifferent to D, the junction point on load side because of the influence of oblique load exhibiting drag of the curve towards obliquity side. Compared to junction point, the contact pressure at the edges is more. At edge point at any level of loading contact pressure increases from $\alpha = 0^\circ$ to $30^\circ$ and then drops.

(xiv) With increase of skirt angle $\alpha$, for any obliquity and at any level of loading contact pressure increases up to $30^\circ$ tends to drop afterwards. For given angle of $\alpha$ and for a level of loading contact pressure ratio decreases for $i=0^\circ$ to $5^\circ$ and thereafter tends to increase and may remain towards constant. This is reflected with respect to drastic change in value of $Q_f$ for vertical axial load to initial obliquity of $5^\circ$, which gradually decrease with further increase of obliquity.

The load-settlement diagram shifts towards the vertical axis further is due to the less load required to induce the plastic failure and the mechanical strain needed compared to that of the axial and eccentric vertical load. The total resistance of soil is reduced because of the horizontal component of load tending to apply shear force in horizontal direction. The skirted footing derives more resistance compared to plane footing because of modified frictional strength of the sand ($\phi_m$) and due to the confinement of sand as well as passive earth pressure of soil adjacent to the skirts.

For oblique loads applied at centre, it is observed that vertical component of the ultimate load increases with the influence of skirt angle compared to the plane footing. This increase of vertical component will give more value of $\mu R$ for resisting lateral load and will give more failure load ratio. Above findings state that skirts derive pronounced advantage of getting higher vertical load in turns $\mu R$ value against horizontal load, in addition to the passive resistance offered by soil plug as well as the soil against skirt (i.e. passive pressure) though the skirts derive more vertical load for producing $\mu R$ compared to the passive resistance.
(C) Horizontal load

At all percentage of failure loads, the horizontal resistance offered in skirted foundation is found to be pronounced than the calculated theoretical load based on resistance against sliding. This resistance is contributed by modified value of the frictional angle as suggested in the theoretical development and passive resistance developed adjacent to the skirt. The percentage contribution of passive pressure in offering total resistance increases with the angle of skirt up to 90°.

(i) The horizontal displacement at failure increases gradually with the angle of skirt, however the prominent increase is observed in failure load with the angle of skirt of 90°. At working loads (Qf/3) the horizontal displacement remains more or less constant with appreciable increase in working load and for various skirt angles. For given aspect ratio, the failure load increases with \( \alpha \). Also for given \( \alpha \), the failure load increases with aspect ratio \( k \).

(ii) Horizontal load ratio (HLR) increases parabolically with skirt angle \( \alpha \) and is maximum at \( \alpha = 90° \). Maximum HLR for a given self-weight of model at \( \alpha = 90° \) increases with aspect ratio up to \( k = 0.5 \) and then decreases.

(iii) Horizontal displacement ratio (HDR) for skirted footings for given \( k \) increases non-linearly, reaches maximum value at \( \alpha = 90° \). Horizontal displacement ratio (HDR) for all skirt angles decreases with increase of aspect ratio, \( k \).

(iv) Horizontal failure modulus (HFM) remains more or less constant with angle of skirt, \( \alpha \).

(v) For given \( \alpha \), earth pressures increase with aspect ratio \( k \). Also for given \( k \), the earth pressure increases with \( \alpha \), reaching maximum at \( \alpha = 90° \).

(vi) The nature of graph of \( Q_f \) v/s angle of skirt \( \alpha \) is same experimentally and theoretically. The experimental values are higher than the theoretical values with a deviation of 15-20% for the range of skirt angles of 0° to 90°.
The prominent increase in failure load with increase in skirt angle \( \alpha \) with a miger increase of \( \delta \) is due to the availability of increase of passive resistance with increase of skirt angle \( \alpha \). For the same confinement of the sand, the coefficient of passive pressure, \( k_p \), though remains the same, the projected height \( h \) available against the skirt increases in the proportion of \( \sin \alpha \) (i.e. from 0 to 1). Further, the resistance of soil against horizontal displacement increases in proportion of the square of the height, i.e. proportional to \((kBt \sin \alpha)^2\). Thus to obtain more passive pressure, width of skirt \((kB_t)\) and angle of skirt \( \alpha \) should be increased to compensate the expected horizontal thrust.

The clue to the field problem of foundations of different structures viz., low rise buildings, multi-storeyed buildings, transmission line tower, offshore structures, etc., subjected to small and large vertical axial, eccentric, oblique and horizontal loads lies in adopting skirted foundations where angle of skirt varies directly with increase of inclination of load in these structures (30° to 60°, 60° to 90° and 75° to 90° respectively) so as to make best possible use of skirted foundations in respect of deriving maximum bearing capacity and uniform contact pressure distribution.

The computer programme of present work is an important theoretical feature, which can be used simply by substituting the properties of sand and selecting skirt angle as per eccentricity and obliquity of load on any of the above listed structures to determine the bearing capacity parameters for the use in design.