The Egyptian Int. J. of Eng. Sci. and Technology
Vol. 15, No. 2 (May 2012)

EIJEST

STRUCTURAL BEHAVIOR OF FOLDED STRIP FOOTINGS*

Sayed S. Abdel Salam, Gouda Attia, Tarek N. Salem, Mahmoud S. El-kady**

Structural Eng., Zagazig University, Egypt.

ABSTRACT

Folded foundations have been used as an alternative to the conventional flat shallow foundations, in situations involving heavy loads or weak soils. They can be geometrically shaped in many forms especially for continuous footings such as strip footings. The purpose of this study is introducing an alternative foundation shape that reduces the cost of foundations by reducing the amount of reinforcing steel through choosing the most effective folded strip footing shape. The study is performed in two main phases. First, experimental study is performed using eighteen (18) half scale footings of which nine (9) footings are of rectangular shape and nine (9) footings are of folded shape by a folding angle of 20^o. The experimental setup is composed of steel tank with dimensions of 2.5m length * 2.5m width * 2.10m height. The tank is filled with medium dense sand. A numerical study using the finite element software ADINA is also performed in which the soil underneath the footing is modeled with a nonlinear Mohr-Coulomb soil model with model parameters obtained from the experimental phase of the study. Experimental results showed that maximum compression stresses in the footing body decreased within a range of 45%, and the tension stresses are also reduced by the same amount in folded strip footings when compared with conventional rectangular footings. Measured settlements also decreased within a range of 13% up to 25% in folded strip footings over the conventional rectangular ones. There is a good agreement between the numerical and experimental studies of which about 10% difference in settlements, and about 15% difference in compression and tension stresses.

KEYWORDS: Shallow Foundations, Folded Strip Footings, Finite Element, Settlement.

COMPORTEMENT STRUCTURAL DES SEMELLES BANDE PLIEE

RÉSUMÉ

Fondations pliés ont été utilisés comme une alternative aux classiques plats fondations superficielles, dans les situations impliquant des charges lourdes ou les sols faibles. Ils peuvent être de forme géométrique sous de nombreuses formes en particulier pour les semelles filantes comme semelles filantes. Le but de cette étude est l'introduction d'une forme autre fondement qui réduit le coût des fondations en réduisant la quantité d'acier d'armature en choisissant la plus efficace forme pliée semelle filante. L'étude est réalisée en deux phases principales. Tout d'abord, l'étude expérimentale est réalisée en utilisant dix-huit (18) semelles échelle dont la moitié neuf (9) sont les semelles de forme rectangulaire et neuf (9) les semelles sont de forme pliée par un angle de pliage de 20 °. Le dispositif expérimental est composé de cuve en acier avec des dimensions de longueur 2,5 m largeur 2,5 m * 2,10 m * hauteur. Le réservoir est rempli avec du sable dense à moyen terme. Une étude numérique utilisant le logiciel d'éléments finis ADINA est également effectuée dans lequel le sol sous le pied est modélisé avec un modèle de sol de Mohr-Coulomb non linéaire avec les paramètres du modèle obtenu à partir de la phase expérimentale de l'étude. Les résultats expérimentaux ont montré que les contraintes de compression maximales dans le corps pied a diminué dans une fourchette de 45%, et les contraintes de traction sont également réduits du même montant dans les semelles filantes pliées en comparaison avec les semelles classiques rectangulaires. Tassements mesurés ont également diminué dans une fourchette de 13% jusqu'à 25% en semelles filantes jointes sur les classiques rectangulaires. Il ya un bon accord entre les études expérimentales et numériques dont environ 10% de différence dans les colonies, et sur la différence de 15% en compression et des contraintes de traction.

MOTS-CLES: fondations superficielles, semelles filantes pliées, éléments finis, tassement.

* Received: 20/11/2011, accepted: 22/1/2012 (Original Paper)

** Contact author (m.s.h.kady@gmail.com, +2 0100 569 3006)

1. INTRODUCTION

In this paper, the structural and geotechnical behavior of folded strip footings are studied experimentally using footings of both folded shape and rectangular shape as reference samples. The influence of interaction between plain strip footing and soil beneath it, on the distribution of contact pressure and internal stresses subjected to static or dynamic loads, has been described by many researchers, e.g. the effect of footing dimensions on the contact pressure and internal stresses for a strip footing, (Abdel Salam, S. S. and Mashhour, M., (1985) [5]. Abdel Salam, S. S. (1989) [8], presented an analytical study of a reinforced folded strip footing and pointed that the most preferable value of the angle of inclination, is equal to 20^o. G. Attia (2000) [13] presented an experimental and numerical study of folded strip footing by using photo-elasticity and finite element methods to investigate the folded strip footing subjected to vertical load accounting for the soil-structure interaction effect. The author concluded that the normal stresses and displacements of soil under folded strip footing decrease with increasing the inclination angle and soil modulus of sub-grade reaction. More research in numerical and experimental analysis of the folded strip footings are available.

2. EXPERIMENTAL MODEL TESTS

The structural behavior of folded and rectangular strip footings is studied experimentally using eighteen (18) footings. Nine (9) footings are of rectangular shape which are used as reference footings and nine (9) footings are of folded shape. Previous studies indicated that folding the rectangular strip footing by 20^o resulted in much better behavior when compared with the rectangular ones[8]. Therefore, the folded strip footing angle is chosen to be 20^o to allow for ease in experimental study and also for the footing construction process in the field. The footing material is reinforced concrete with Modulus of Elasticity of concrete $E_c = 1.97*10^4$ MN/m^2, and Poisson's ratio $\mu = 0.16$. Soil boundaries are simulated by a soil model with dimensions (2.5m length * 2.5m width * 2.10m height). The side boundaries are restricted to allow for settlements to take place at model edges, without allowing for lateral movement. However, the movement of the lower boundary is restricted in both directions. Photo (1) shows general layout of the soil model showing restrictions. Medium dense sand is used in analysis to cover the most frequently encountered soils in many parts of Egypt, as shown in table (1). Photo (2) shows general layout of the soil model showing the footing dimensions, loading position, and strain gauges arrangements. Strip footings are precast bored with half scaled dimensions when compared with numerical model.

Photo (1): Configurations of the Soil Model.

Photo (2): Sample Loading and Strain Gauges Arrangement.

To account for the effect of increasing the number of floors in the building, six cases of loading are applied to model buildings of one up to six floors respectively. These loads are 50, 100, 150, 200, 250 and 300 kN/m'. Analysis of results will be due to previous parameters in addition to the effect of footing steel reinforcement ratio which will be equal to (0.15%, 0.25%, and 0.35% of the total concrete area), also depth to span ratio (t/L) will be equal to (0.20, 0.30, and 0.40) as shown in table (2).

Table (1): Soil Parameters for Model.

Unified Classification	Medium Dense Sand
E_s (MN/m^2)	50.0
□ (deg)	34.0
C (kN/m^2)	0.0
ν (Poisson's ratio)	0.30

Table (2): Model Parameters.

Angle of inclination(ɵ) (degree)	0	20	
t/L	0.20	0.30	0.40
Reinforcement %	0.15	0.25	0.35

2.1 Analysis of Results

The structural behavior of folded and rectangular strip footings is studied experimentally using both shapes which are used as reference footings and folded shape by folding the rectangular strip footing by 20°. This folding angle resulted in much better behavior when compared with the rectangular ones.Analysis included the effect of increasing the applied pressure over the footing on the underlying soil settlements. Stresses within the concrete footing are also presented showing the maximum compression stresses, and tensile stresses along the steel bars.

2.1.2 Effect of increasing the footing applied pressure on maximum compression stresses

The applied pressures are typical values for one up to six floors with one floor increment respectively. Figs. (1 through 5) show that increasing the applied pressure resulted in a noticeable increase in the underlying soil settlement for both folded and rectangular strip footing cases. Also, it is noticed that excessive soil settlement accompanied by local shear failure is carried out and average settlement is calculated for every footing by two LVDT (Linear Variable Versus Displacement Transducer) which are put at the ends of the strip footing as shown in photo (3). Figs. (1 through 5) show that soil settlement levels under folded strip footings are noticeably lower than those of the rectangular strip footings, especially at higher stress levels. The maximum soil settlement in the soil under the folded strip footings are about two thirds of those taking place under rectangular strip footings, at the same loading values. Moreover, the rate of increase in soil settlement due to increasing the stress levels is noticeably higher in rectangular strip footings than those in folded strip footings.

Photo (3): Measuring of Soil Settlement.

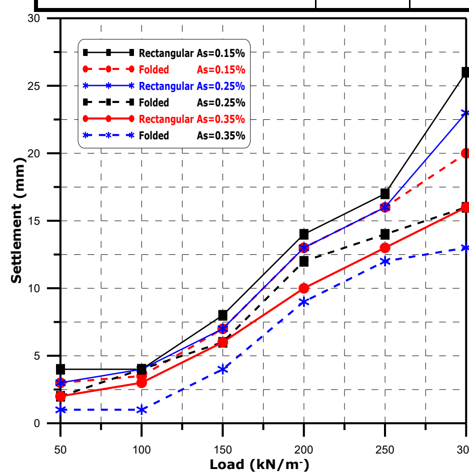


Fig. (1): Effect of Increasing the Applied Load on Settlements under Folded and Rectangular Strip Footings for (t/L=0.20).

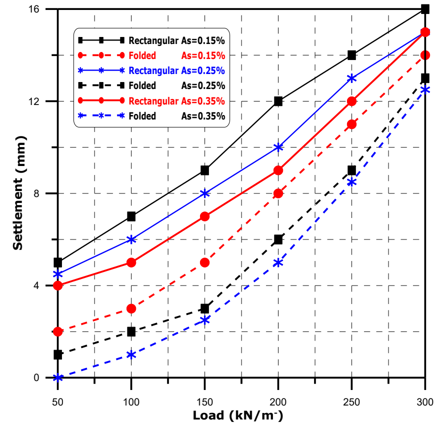


Fig. (2): Effect of Increasing the Applied Load on Settlements under Folded and Rectangular Strip Footings for (t/L=0.30).

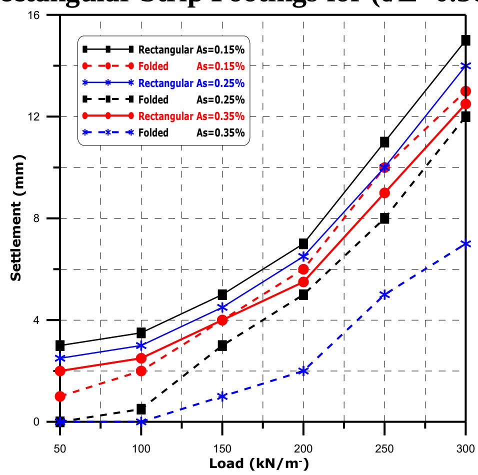


Fig. (3): Effect of Increasing the Applied Load on Settlements under Folded and Rectangular Strip Footings for (t/L=0.40).

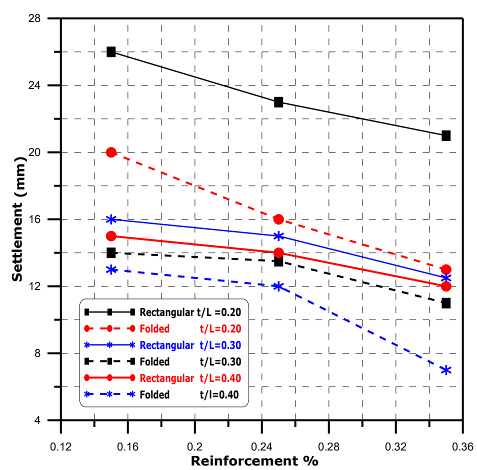


Fig. (4): Effect of Reinforcement Ratio on Settlements under Folded and Rectangular Strip Footings.

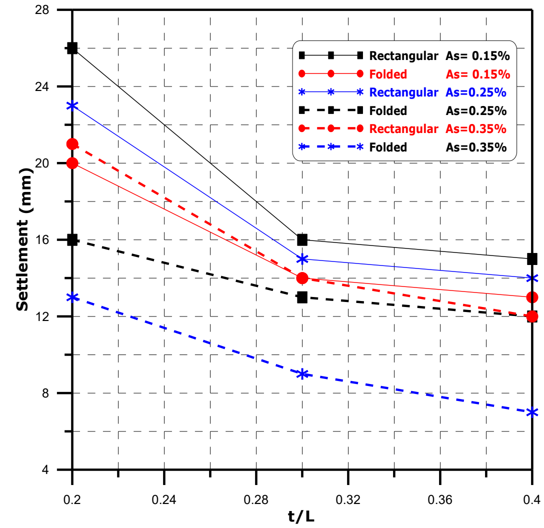


Fig. (5): Effect of Depth to Span Ratio on Settlements under Folded and Rectangular Strip Footings.

Initial cracks and total failure are noticeable in both rectangular and folded strip footings with (t/L=0.20, and As=0.15%Ac) as shown in photos (4 and 5). But the load capacity of folded strip footing at failure is larger by about $30kN/m^{-}$.

Photo (4): Failure Shape of Rectangular Strip Footing.

Photo (5): Failure Shape of Folded Strip Footing.

2.1.2 Effect of increasing the footing applied pressure on maximum compression stresses

The maximum concrete compression stresses occurs at the wall face where the position of maximum bending moment. It is noticed that concrete compression stresses in folded strip footings are about two thirds of those encountered in rectangular strip footings as shown in figs. (6 and 7). Thus, more economic concrete mix design can be performed to account for the reduction in the needed concrete compressive strength.

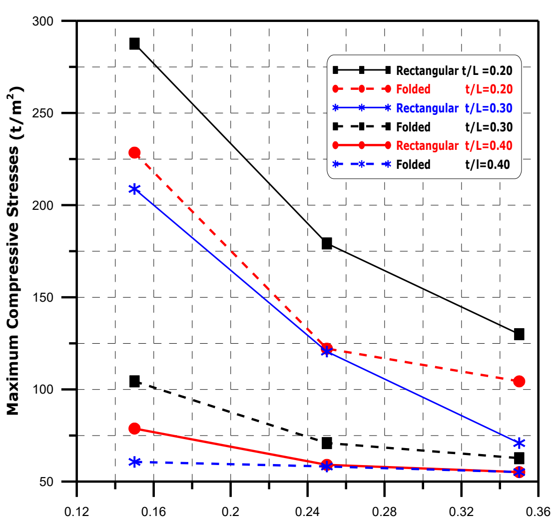


Fig. (6): Effect of Reinforcement Ratio on Maximum Compressive Stresses under Folded and Rectangular Strip Footings.

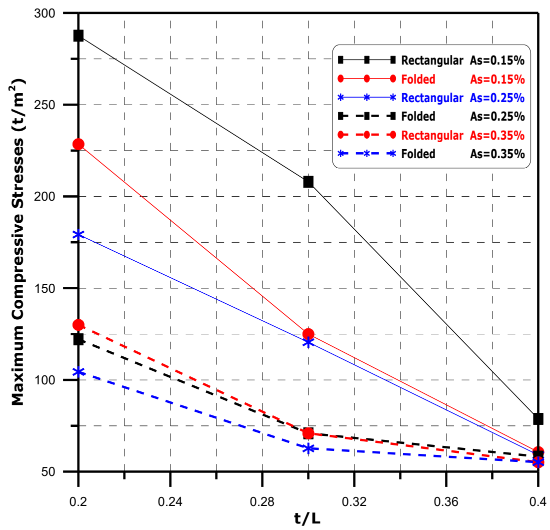


Fig. (7): Effect of Depth to Span Ratio on Maximum Compressive Stresses under Folded and Rectangular Strip Footings.

2.1.3 Effect of increasing the footing applied pressure on maximum tensile stresses

Maximum tension took place at the position of the main footing steel reinforcements. One more time, the steel tension stresses in case of folded strip footing is almost two thirds that of the rectangular strip footings, indicating the need for lower quantity of steel reinforcements in the short direction also. Also, it is noticed that the maximum tension took place at the position of the main footing steel reinforcements. As shown in figs. (8 and 9), the steel tension stresses in case of folded strip footing is almost two thirds that of the rectangular strip footings, indicating the need for lower quantity of steel reinforcements in the short direction also. Noticeable reductions in the tension forces took place in the inclined parts of the footing. Moreover, lower compression stresses are noticed at the compression zone of the folded strip footing than that took place in the rectangular ones. This assures the effectiveness of folded shape over the rectangular shape by requiring less concrete compressive strength.

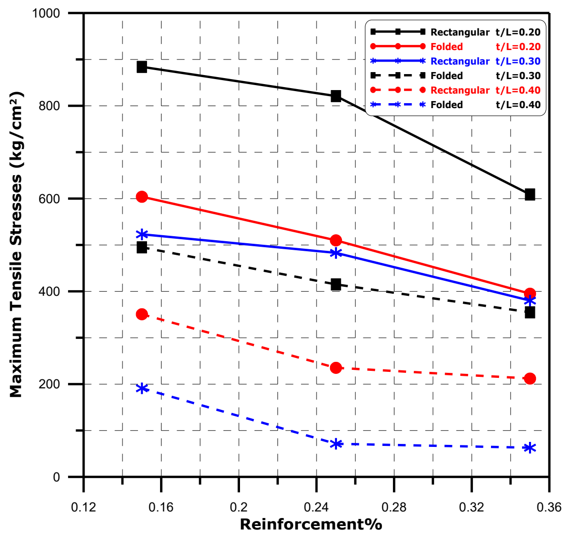


Fig. (8): Effect of Reinforcement Ratio on Maximum Tensile Stresses under Folded and Rectangular Strip Footings.

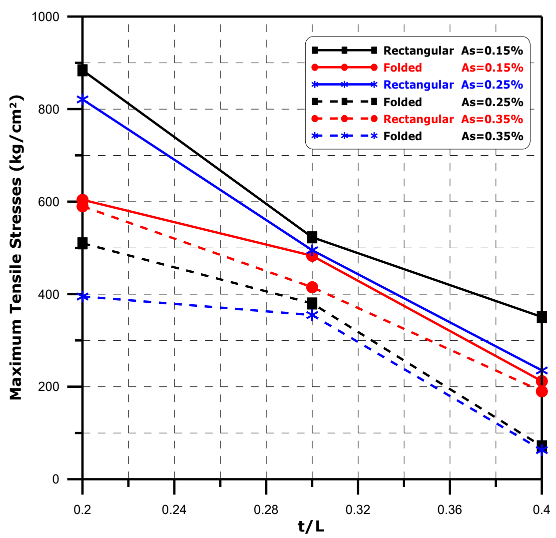


Fig. (9): Effect of Depth to Span Ratio on Maximum Tensile Stresses under Folded and Rectangular Strip Footings.

2.1.4 Distribution of stresses in the footing body by contour maps

It is necessary to simulate and present the compression and tension stresses along the rectangular and folded strip footings body. Fig. (10) shows sections of rectangular and folded strip footings respectively with positions of concrete strain gauges. There are four concrete strain gauges, two at the top and two at the bottom of strip footing arm. Concrete strain gauges are located at the wall face (at section 1-1), where the position of maximum bending moment.

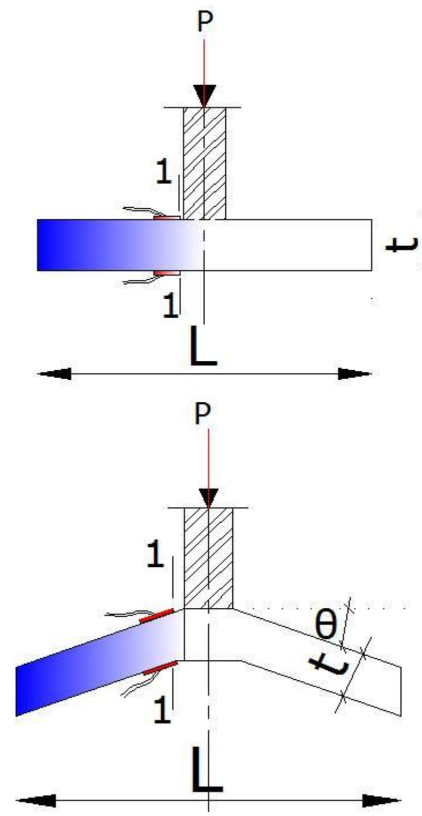


Fig. (10): Positions of Concrete Strain Gauges in Strip Footing Arm.

According to Fig. (10), there are concrete strain gauges at the positions of maximum compression and tension stresses occur. From the first principals, tension stress occurs just under loading position at the bottom of folded strip footing body. On the contrary, compression stress occurs under loading position at the top of the folded strip footing body. Along the rectangular and folded strip footing arms, both tension and compression stresses resulted from experimental tests presented by contour maps at the maximum load (300kN/m^{-}) are shown in figs. (11 through 16).

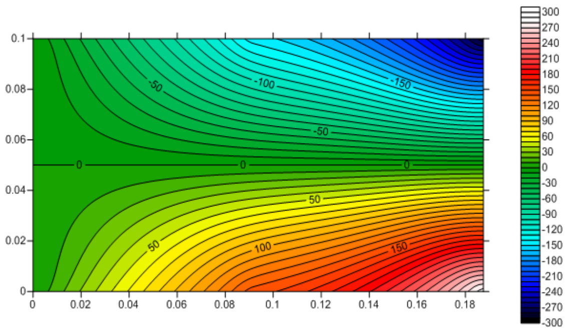


Fig. (11): Stress distribution in Rectangular Strip Footing Arm by Contour Map at (As=0.15%Ac, t/L=0.20).

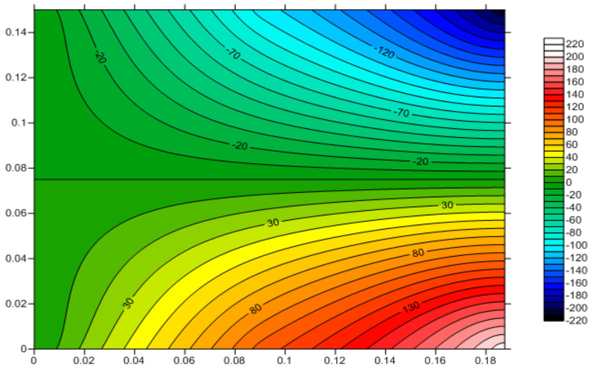


Fig. (12): Stress distribution in Rectangular Strip Footing Arm by Contour Map at (As=0.15%Ac, t/L=0.30).

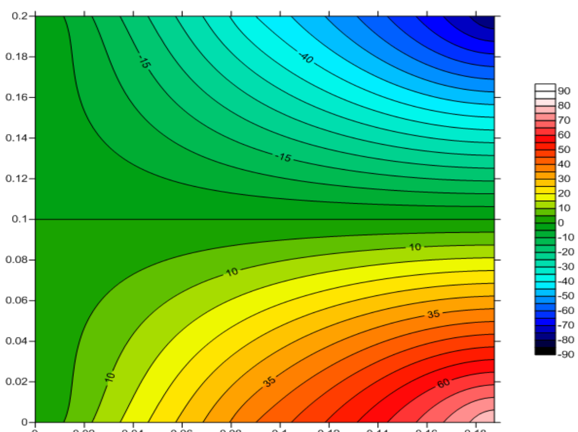


Fig. (13): Stress distribution in Rectangular Strip Footing Arm by Contour Map at (As=0.15%Ac, t/L=0.40)

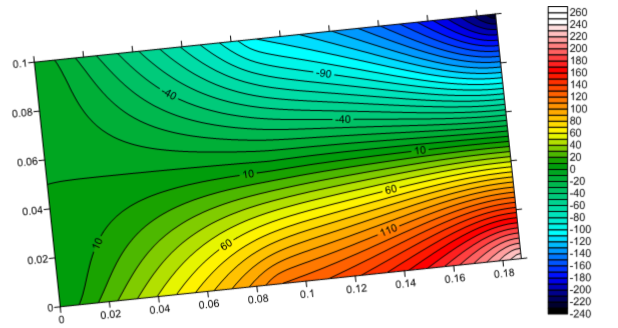


Fig. (14): Stress distribution in Folded Strip Footing Arm by Contour Map at (As=0.15%Ac, t/L=0.20).

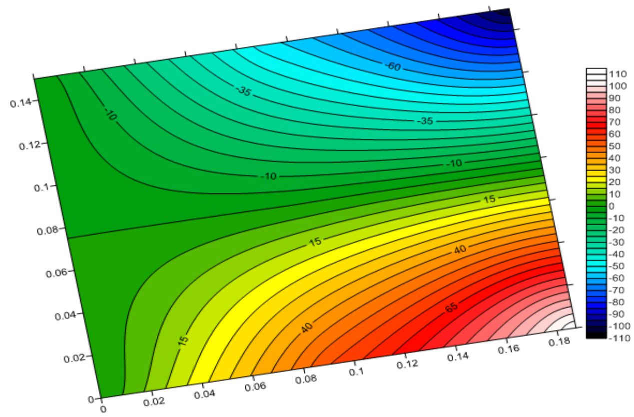


Fig. (15): Stress distribution in Folded Strip Footing Arm by Contour Map at (As=0.15%Ac, t/L=0.30).

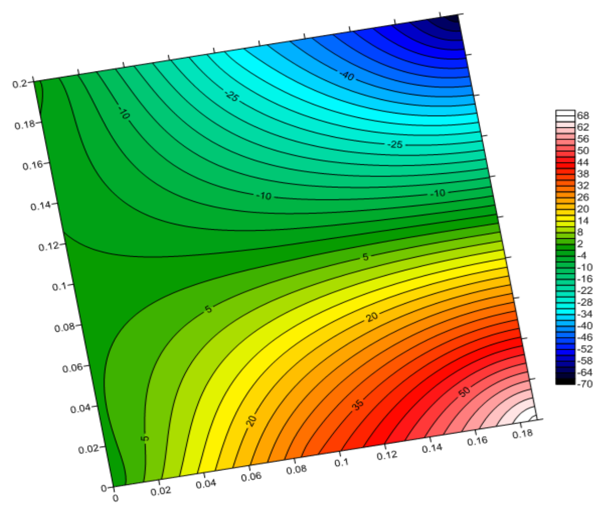


Fig. (16): Stress distribution in Folded Strip Footing Arm by Contour Map at (As=0.15%Ac, t/L=0.40).

3. VERIFICATION STUDY

A verification study is conducted to confirm the proposed model is fundamentally correct by checking model predications against available solutions. Numerical results with finite element (F.E) modeling are used to validate the experimental study. The behavior of folded and rectangular strip footings is studied numerically using the finite element technique ADINA (Automatic Dynamic Incremental Nonlinear Analysis). The soil underneath the footing is modeled with a nonlinear Mohr-Coulomb soil model, with the same model parameters presented previously. The footing material is reinforced concrete modeled using elastic isotropic material model. The side boundaries are presented using rollers to allow for settlements to take place at these edges, without allowing for lateral movement. However, the movement of the lower boundary is restricted in both directions. Fig. (17) shows general layout of the folded strip footing showing the footing dimensions, loading position. Fig. (18) shows the finite element mesh used in the analysis, along with the boundary conditions.

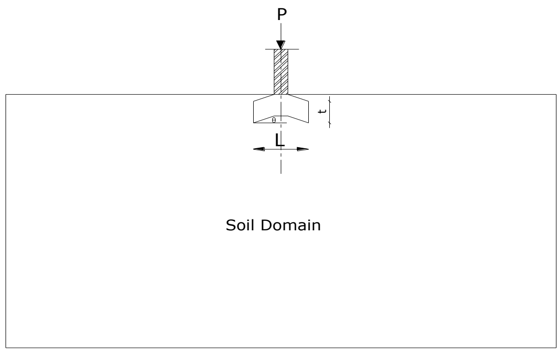


Fig. (17): Configurations of the Folded Strip Footing.

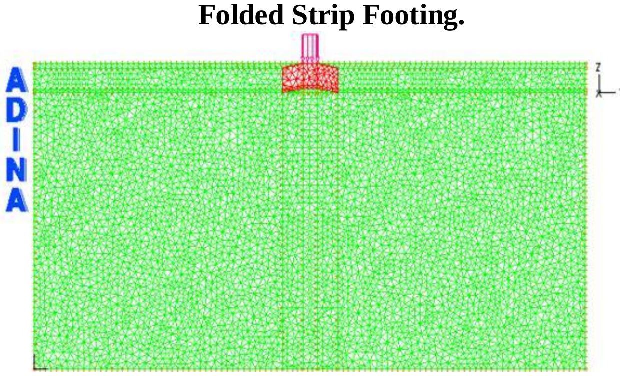
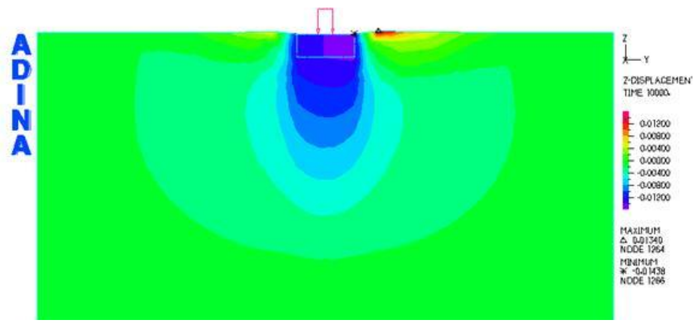


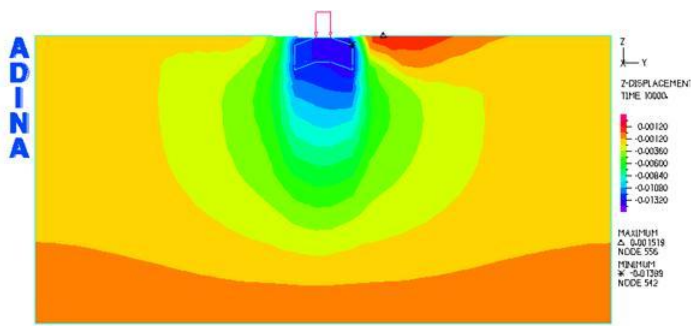
Fig. (18): The Finite Element Mesh of the Footing Model.

3.1 Distribution of Settlements within the Soil Domain

Figs. (19-a) and (19-b) show the distribution of settlement shading within the soil domain under the rectangular and folded strip footings respectively. The settlement values and distribution are almost the same in both cases, with slightly lower settlement values occurring under the folded strip footings.



(a) Rectangular Strip Footing.



(b) Folded Strip Footing.

Fig. (19): Settlement Shading Distribution in Soil Domain for Rectangular and Folded Strip Footings for (As=0.15%Ac, t/L=0.40)

Fig. (20) shows a good agreement between both numerical and experimental study at the same conditions (As=0.15% of the concrete area, and depth to span ratio (t/L) =0.40). Also, different loads are applied to simulate number of floors from one up to six floors as follows (50, 100, 150, 200, 250 and 300 kN/m' respectively). There is a slight difference in settlement values with lower values under the folded strip footings for the same conditions. Fig. (20) shows also a linear increase in settlement values for the theoretical study. On the contrary, experimental study indicated that the maximum soil settlement in the soil under the folded strip footings are about two thirds of those taking place under rectangular strip footings, at the same loading values. Moreover, the rate of increase in soil settlement due to increasing the stress levels is noticeably higher in rectangular strip footings than those in folded strip footings.

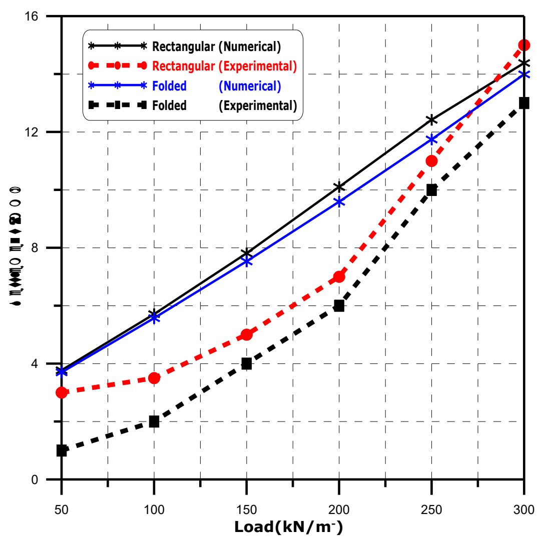


Fig. (20): Comparison Between Numerical and Experimental Study for Load- Settlement Curve at (As=0.15%Ac, t/L=0.40).

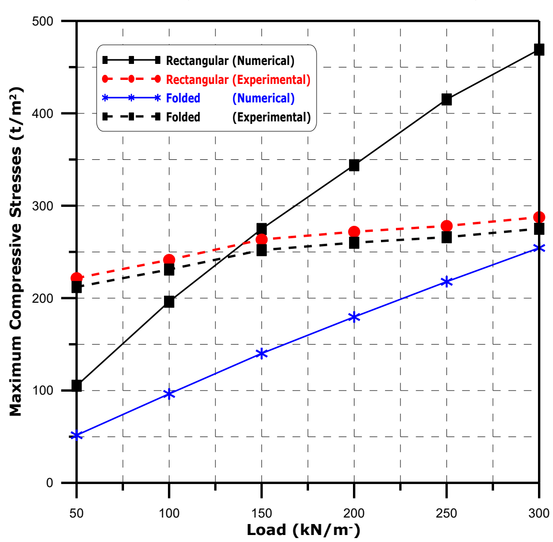


Fig. (21): Effect of Load on Maximum Compressive Stresses for Numerical and Experimental Study at (As=0.15%Ac, t/L=0.40).

Fig. (21) shows a linear increase in compression stress values for both rectangular and folded strip footings in the theoretical study. The maximum concrete compression stresses occurs at the wall face where the position of maximum bending moment. It is noticed that concrete compression stresses in folded strip footings are about half of those encountered in rectangular strip footings. Thus, more economic concrete mix design can be performed to account for the reduction in the needed concrete compressive strength.

4. CONCLUSIONS

This paper presents numerical modeling and experimental tests of the folded and rectangular strip footings resting over soils of different types. The aim of the current paper is to highlight the effectiveness of the folded strip footings over the rectangular ones. The paper also presented the internal forces and stresses as well as contact pressure distribution for a reinforced folded strip footing resting on elastic foundation. The influence of folding inclination angle (θ), and footing dimensions (t/L) on the results were studied. Based on the results of the paper, the following conclusions can be drawn:

1- In general, the folded form of strip footing satisfies a decrease in soil settlement, and stresses in both strip footing body and soil domain which achieves economic design.

2-The effectiveness of the folded strip footings over the rectangular ones is not just in the main short direction of the footing, but rather in the secondary long direction as well, in which the reinforcements are mostly needed in the lower straight portion of the folded strip footing only, with large reductions in the steel tension stresses in the folded portions of the footing.

3-The most preferable value of the angle of inclination (θ), is equal to 20^o. On the other hand and because the preferable angle is small, the soil at the foundation level can be made level and the folded form profile is achieved by a plain concrete layer beneath the R.C. footing.

4-Experimental results showed that maximum compression stresses in footing body decreased by about 70% for folded strip footing compared with conventional rectangular footing for different reinforcement ratios and by about 45% when increasing depth to span ratio (t/L) from 0.20 to 0.40.

5-Also, maximum tensile stresses in steel bars decreased by about 45% for folded strip footing compared with conventional rectangular footing at the same reinforcement and depth to span ratio (t/L) ratios.
6-The soil settlement is decreased by about 20% for folded strip footing compared with conventional rectangular footing in medium dense sand soil when increasing vertical static load from 50 to 300 (kN/m').
7-Settlement for experimental study decreased from 25% to 13% for minimum reinforcement ratio and different depth to span ratio (t/L).

8-There is a good agreement between both numerical and experimental studies for about 10% difference in settlement at minimum reinforcement ratio and depth to span ratio (t/L) equals 0.40. Also, Compression and tension stresses have 15% difference at minimum reinforcement ratio and depth to span ratio (t/L) equals 0.20.

REFRENCES

[1] Zeinkiwiez, O.C., "*The Finite Element Methods*", 3rd Edition, McGraw-Hill, London,(1977).

[2] Duncan, J. M., Byrne, P., Wong, K. S. and Mobry, P., "*Strength, Stress-Strain and Bulk Modulus Parameters for Finite Element Analysis of Stresses and Movement in Soil Masses*", Report N°. UCB/GT/78-02, Department of Civil Engineering, University of California, Berkeley, Co. (1978).

[3] Abdel Salam S.S., "*Stress Analysis in a Slice of Strip Footings*". M.Sc. Thesis Structural Eng. Dept. Cairo University (1979).

[4] Duncan, J.M., "*Hyperbolic Stress-Strain Relationships. Proc. of Workshop on Limit Equilibrium, Plasticity and Generalized Stress-Strain In Geotech Eng*". McGill Univ. May 28-30,(1980).

[5] Abdel Salam S.S. and Mashhour, M., "*Effect of Footing Dimensions on the Contact Pressure and Internal Stresses for a Strip Footing*" J. Egyptian Soc. of Engineers No. 1 Vol. 24, (1985).

[6] Mashhour, M. and Abd El Salam S.S., *"Finite Element Analysis of Strip Footing*". 9th Regional Conference, for Africa on soil mechanics and foundation engineering/ Lagos/ sept. (1987).

[7] Smith, I.M. and Griffiths, D.V., "*Programming the Finite Element Method*", John Wiley and Sons Inc., New York, (1988).

[8] Abdel Salam, S.S., "*Analysis of Reinforced Folded Strip Footing*" Third Arab Structural Eng. Conference, Emirates, Vol. 3, 5-8 March (1989).

[9] Angelou, T. A., "*Infinite Element-Theory and Applications*", J. Computers and Structures, Vol. 41, No. 5, PP. 959-962, (1991).

[10] Hashem M., Abdel Salam, S.S., and Deif, J.H., "*Experimental and Numerical Analyses of Continuous Strip Footing*" Civil Eng. Conference, Military Technical College, Cairo (1994).

[11] G. Attia, "*Analysis of Strip Footing Containing Cracks*" Conference of Civil engineering, Military Technical College, Cairo, Vol.1 pp. 111-122, (1994).

[12] G.T. Houlsby and A.M. Puzrin, "*The Bearing Capacity of a Strip Footing on Clay Under Combined Loading*", The Royal Society,(1998).

[13] G. Attia, "Experimental and Numerical Analysis of Folded Strip Footing" 8th Arab Structural Engineering Conference, Cairo, Egypt, V. 3, pp. 1063-1074, (2000).

[14] El-Shamy, E. A., and Abdel Salam, S.S."*Non Linear Analysis of Arched Strip Footing*", Military Technical College. International Conf. on Civil Eng and Arch. Eng. 4th ICCAE Conf. 16-16 May (2002).

[15] Ming Zhu, "*Bearing Capacity of Strip Footing on Two-Layer Clay Soil by Finite Element Method*", ABACOUS Users' conference, (2004).

[16] H.E. ABd-El-Mottaleb, "*Earthquake Nonlinear Modeling of R.C. Buildings Including Foundation-Soil Interaction*", Ph.D. Thesis, Structural Eng. Dept. Zagazig University,(2005).

[17] R. Roy, K. Bhattacharya and S.C. Dutta, "*Behaviour of Grid Foundation under*

static Gravity Loading" IE (I) Journal.Cr. Vol. 85,February(2005).

[18] C.X. Wang and J.P. Carter, "*Deep Penetration of Strip and Circular Footings Layered Clays*", Dept. of Civil Eng, The University of Sydney, Research Report R807. NSW, Australia, (2006).

[19] Idris Abubakar, "*Reliability Analysis of Structural Design Parameters of Strip Footings*". Journal of applied science and research 2(7): 397-401, (2006).

[20] Egyptian Code of practice and design for R.C. structures, The Housing and Building National Research Center of Egypt, ECP 203,Cairo-Egypt, (2007).

[21] Abdel Salam, S.S., El-Shamy, E. A.and H.E. ABd-El-Mottaleb, "*Analysis of Plain Concrete Strip Footings as a Foundation of Bearing Walls Structures*". Ain Shams Journal of Civil Engineering A S J C E, Sept. (2008).

[22] Abdel Salam, S.S.,El-Shamy,E.A.and H.E. ABd-El-Mottaleb," *Numerical Analysis of Arched Strip Footings as A Foundation system of Bearing Walls Structures*". Ain Shams Journal of Civil Engineering A S J C E, Vol. 2, pp. 109-118, Sept. (2009).