Effect of Neighboring Footings on Single Footing Settlement

Marawan Shahein
University of Tanta, Egypt

Ali Hefdhallah
Arab Academy for Science Technology & Maritime Transport, Egypt

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Marawan Shahein
University of Tanta
Tanta, Egypt

Ali Hefdhallah
Arab Academy for Science Technology & Maritime Transport
Cairo, Egypt

ABSTRACT

The most economic type of foundations is shallow isolated footings. It is common practice to estimate settlement of shallow isolated footings without consideration of the influence of neighboring footings or loaded areas. In fact there is few, if any, available method to estimate settlement of isolated footings taking into consideration such an effect of neighboring loaded areas. Such an effect might be vital in a lot of cases. This paper presents a case history that shows the importance of such an effect. The case history in hand consists of 28 auxiliary buildings of an Electrical Power plant near Cairo, Egypt. A total of 175 boreholes were drilled to characterize the ground conditions in the site. The maximum allowable settlement was one of the major criteria of the project. Settlement analysis had to be carried out for each of the project building. In each building, the settlement was calculated under the center of each footing due to the load imposed from the footing and that due to the stresses on the surrounding footings of the structure. In addition, Settlement was computed for the case of single footing without influence of surrounding loaded footings as the case of the common practice in the geotechnical engineering profession. Settlement analysis was carried out by computing a profile of elastic stress increase due to all loaded areas at the foundation level. Settlement at a point is then computed at the foundation level by integrating vertical strains of the layered ground under the footing. The results of the analysis suggested that the effect neighboring footings could be important to the extent that necessitates the change of the foundation system from isolated footings to raft foundation in the light of the maximum allowable settlement of each foundation system.

INTRODUCTION

In geotechnical engineering practice, the geotechnical engineer tends to adopt the most economic type of foundations which is the shallow isolated footings. The isolated footings are designed to satisfy one of two criteria that are no violation of any of either shear failure bearing capacity or maximum allowable settlement specified by the project based on the function of the building.

The footings that are founded on granular soils usually do not face the problem of exceeding the bearing capacity values. On the other hand, the allowable bearing pressure is determined based on pressures that do not cause settlement exceeding the maximum permissible settlement. The settlement of footings is mainly influenced by availability of shallow weak soil layer under the footing.

It is common practice to estimate settlement of shallow isolated footings without consideration of the influence of neighboring footings or loaded areas. In fact there is few, if any, available method to estimate settlement of isolated footings taking into consideration such an effect of neighboring loaded areas (Mesri, 1991 and Lee et al., 2010). It should be noted that shallow foundations for typical building structures consist of multiple footings, often in close neighborhood. The interaction between adjacent footings may result in settlements greater than those for isolated footings. Such an effect might be vital in a lot of cases. Thus neglecting such an effect between adjacent footings may result in un-conservative footing design.

This paper presents a case history that shows the importance of such an effect. The case history in hand consists of 28 auxiliary buildings of an Electrical Power plant near Cairo, Egypt. A total of 175 boreholes were drilled to characterize the ground conditions in the site. The maximum allowable settlement was one of the major criteria of the project. Settlement analysis had to be carried out for each of the project building. In each building, the settlement was calculated under the center of each footing due to the load imposed from the footing and that due to the stresses on the surrounding footings of the structure. In addition, Settlement was computed for the case of single footing without influence of surrounding loaded footings as the case of the common practice in the geotechnical engineering profession. The results of the analysis suggested that the effect of neighboring footings could be important to the extent that necessitates the change of the foundation system from isolated footings to raft foundation in the light of the maximum allowable settlement of each foundation system.

PROJECT DESCRIPTION

The case study in hand is a 1500 MW combined-cycle power plant project that is under construction at north western side of Great Cairo, Egypt. The surface area of the site is about 290,000 m2. Before the commencement of construction, the site is an agricultural farmland. The project consists of 48 buildings. Most of the units consist of reinforced concrete skeleton structural system. The buildings have different foundation systems, with or without basement. Most of the structures are founded on reinforced concrete shallow foundations

STRATIFICATION

A total of 175 boreholes were drilled to characterize the ground conditions in the site. There is high variation in the soil stratification through the site. The site stratification includes sand and clay layers. There are layers of silt and gravels appear in some borehole logs. The soil general stratigraphy in the project site is shown in Fig. 1. The soil profile consists of top agricultural fill layer with thickness less than 0.6 m from the ground surface. The top layer is underlain by upper sand layer that is 4.75m to 9.00m in thickness. The upper sand layer is inter-layered by up to 1.5 m thick clay layers in some localities. The upper sand layer is underlain by silty clay layer that is 1.00m to more than 15.00m in thickness. A lower sand layer appears under the silty clay layer and extends down to end of boring in most of borehole logs. A gravel layer may appear in some boreholes under the lower sand.

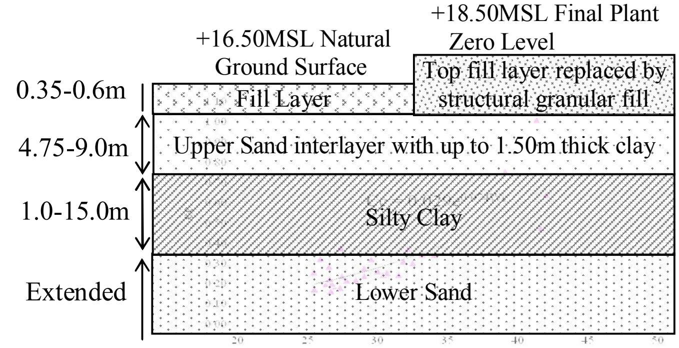

Fig. 1. General soil profile at the plant site.

The ground water level varies from 0.70m to 2.96m from natural ground surface.

For construction purposes, the surface fill is removed and about 2 m thick structural granular fill is placed.

ENGINEERING PROPERTIES OF SUBSURFACE LAYERS

The engineering properties of the granular soil layers are summarized in Table 1. The effective friction angle is estimated for the replaced granular layer based on experience in similar sites in Egypt. The friction angle is estimated for both upper and lower sand layers based on SPT N values. The deformation modulus of the replaced granular layer is estimated based on experience in similar sites in Egypt in general. The deformation modulus of both upper and lower sands are estimated based on the results of SPT using the following empirical relationship based on Burland and Burbidge (1985) and Terzaghi et al. (1996)

$$Es = 0.6\ N^{1.4} \quad (1)$$

Table 1. Compressibility Parameters of Granular Soils

Soil Layer	USCS	γ, kN/m^3	Drained Friction Angle, ^{o}	Deformation Modulus, MPa
Replacement Fill	-	19.0	36	50
Upper Sand	SP to SM	18.5	32	20 - 35
Lower Sand	SP to SM	18.5	35	60 - 75

The silty clay is stiff to very stiff with natural water content of the silty clay layer is in the range of 20% to 57% with an average of about 30%, while the clay content is in the range of 17% to 93%, with an average of 48%. The liquid limit of the clay is in the range of 26% to 110% with an average of 65%. The plasticity index of the clay is in the range of 10% to 78% with an average of 39%. The silty clay layer is classified according to USCS to be CL to CH. The average unit weight of the layer is about 19 kN/m^3.

Based on unconfined compressive strength tests on Shelby tube samples, the undrained shear strength is in the range 65 kPa and 210 kPa with an average of 133 kPa. There is no specific trend for undrained shear strength with depth.
The compressibility parameters of the silty clay layer based on results of Oedometer tests are summarized in Fig. 2. A site specific correlation between compression index and water content is developed. The correlation, together with water contents profile, results in compression index profile the summary of which is shown in Fig. 2. Shown also on Fig. 2

are the overconsolidation ratio and void ratio profiles. Based on results of Oedometer tests, the ratio between recompression index to compression index Cr/Cc to be in the range of 0.10 to 0.15.

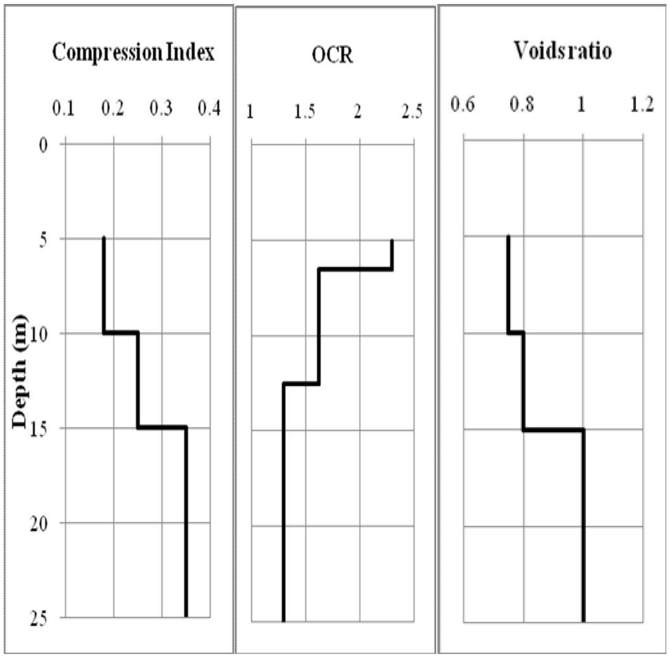

Fig. 2 Compressibility parameters for silty clay layers

SETTLEMENT ANALYSIS

Based on shear strength parameters listed above for the soil layers encountered in the site, considering foundation embedment depth of about 1.5 m, and utilizing Terzaghi equation, results in bearing capacity against shear failure for individual footings to be in excess of 32 kPa. It should be noted that the neighboring footings increases the bearing capacity of a footing as compared to that of single footing (Stuart, 1962, Das and Larbi-Cherif, 1983 and Das, 1999). However, allowable bearing pressure is not mainly controlled by shear failure under the footings; maximum allowable settlement is on the other side another controlling criteria.

Settlement analysis are carried out using settlement calculation software (SETMAX) that was developed by Prof. Maximovic (Maximovic, 2002). The program computes the value of the settlement of the point on the surface of the layered system by integrating strains at depth.

In case of granular soils, the following model is used for determining the compression in the sandy layers simply by:

$$\varepsilon_z = \frac{\Delta\sigma'_z}{M_v} \tag{2}$$

Where:

$\Delta\sigma$': increase of the stress due to the additional surface loading as calculated using elastic stress distribution.

M_v : coefficient of volume compressibility

In this paper, the deformation modulus is conservatively used instead of constrained modulus substituting the coefficient of volume compressibility.

In case of clay, the conventional Clay model is used. The model relies on parameters that are derived from the Oedometer tests. The following parameters are utilized in computing the settlement:

C_c: compression index valid for the stress level above pre-consolidation stress.
C_r: re-compression index applicable for the stress range lower than the pre-consolidation stress.
e_o : initial soil void ratio
p_o : initial vertical effective stress
p_c : Pre-consolidation effective stress.

The strain in the clay model is computed by one of the following expressions:

If $p_o + \Delta\sigma'_z < p_c \longrightarrow \varepsilon_z = \frac{C_r}{(1+e_o)}\log\left(\frac{p_o + \Delta\sigma'_z}{p_o}\right)$ (3a)

If $p_o + \Delta\sigma'_z > p_c \longrightarrow \varepsilon_z = \frac{C_r}{(1+e_o)}\log\left(\frac{p_c}{p_o}\right) + \frac{C_c}{(1+e_o)}\log\left(\frac{p_o + \Delta\sigma'_z}{p_c}\right)$ (3b)

Strains are computed in each slice and integrated numerically for the whole depth of the given layer or sequence of layers. Settlements under the different points of flexible foundations are calculated where as for rigid footings the settlement is calculated by using the equivalent Kany's points. Kany's points are four points centrally symmetrical to the footing center. If the single footing is considered, settlement for the four points will be the same; however, in the case of eccentricity or influence of the neighboring loads, the settlement at the different points may have been considered to estimate the rotation of the footing.

CASES OF CONFIGURATIONS OF NEIGHBORING SURFACE LOADED AREAS

In order to investigate the influence of neighboring footings on settlement of single footings, settlement computation is carried out for a footing in the footings layout of the building considering the influence of other footings in the configuration cases listed in Tables 2. In each configuration; corner, edge and center footings are considered as shown in Table 3.

ANALYZED BUILDINGS

Four buildings are analyzed. All the buildings are two story reinforced concrete skeleton buildings without basement. All the buildings are initially designed to be founded on isolated shallow footings. The following table summarizes the information about the buildings analyzed in this paper.

Table 2. Description of Configurations of Neighboring Footings

Configuration	Description
(1)	Loads from single footing
(2)	Loads from footing in addition to loads from two footings along a line
(3)	Loads from footing in addition to loads from four footings along two perpendicular directions
(4)	Loads from footing in addition to loads from eight footings along the perimeter
(5)	Loads from footing in addition to loads from all footings in the layout of the entire building.

Table 3. Illustration of footings arrangements configuration in the settlement analysis.

Loading Case No.	Footing Type		
	Corner Footing	Edge Footing	Center Footing
1			
2			
3			
4			
5			

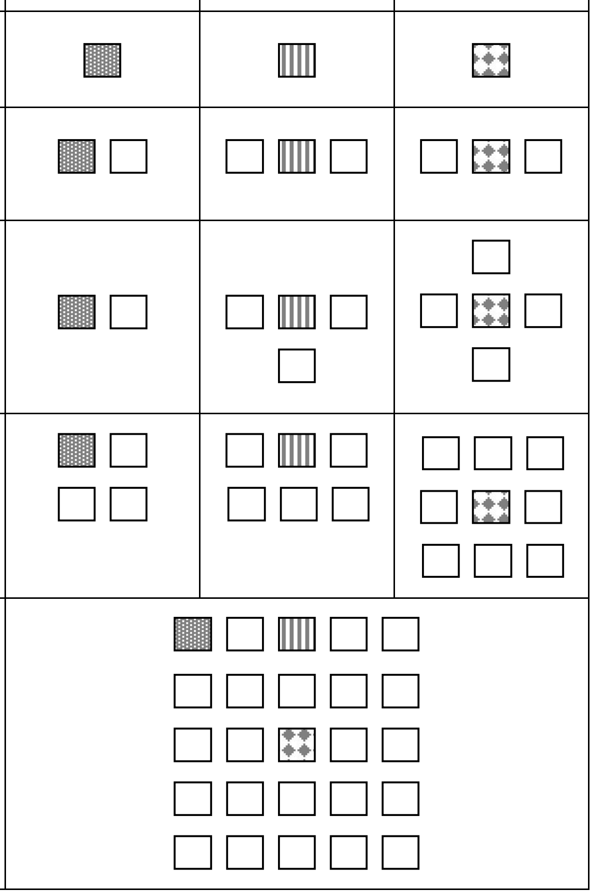

Table 4. Summary of information about the analyzed buildings

Building Name	Foot Print Area (mxm)	Number of Footings	Foundation Level (m)
Workshop	36x40	41	1.60
Fire Fighting	42x18	30	1.70
Guard Dormitory	21x27	26	1.20
Gasoline Station	25x15	17	1.65

The layout of footings for Workshop, Fire Fighting, Guard Dormitory and Gasoline Station buildings are shown in Figs. 3, 4, 5 and 6, respectively. Tables 5, 6, 7 and 8 show summary of footings dimensions and stresses on footings for each building considered in this paper.

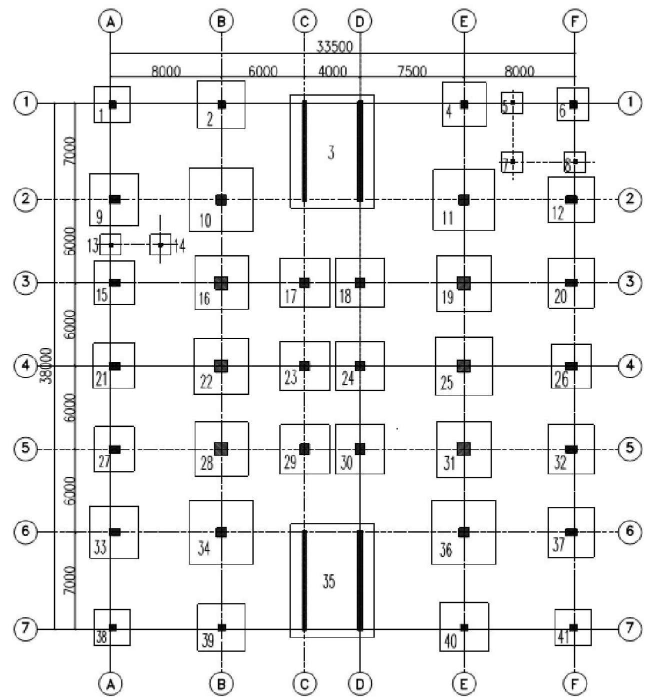

Fig. 3 Footings layout for the Workshop building.

Table 5. Summary of dimensions and stresses under the footings of Workshop building.

Footing Type	Dimensions Range(m)		Stress Range (kN/m^2)
	a	b	
Corner	2.3-2.6	2.3-2.6	168-172
Edge	1.5-6.0	1.5-8.2	115-170
Interior	1.5-4.6	1.5-4.6	55-174

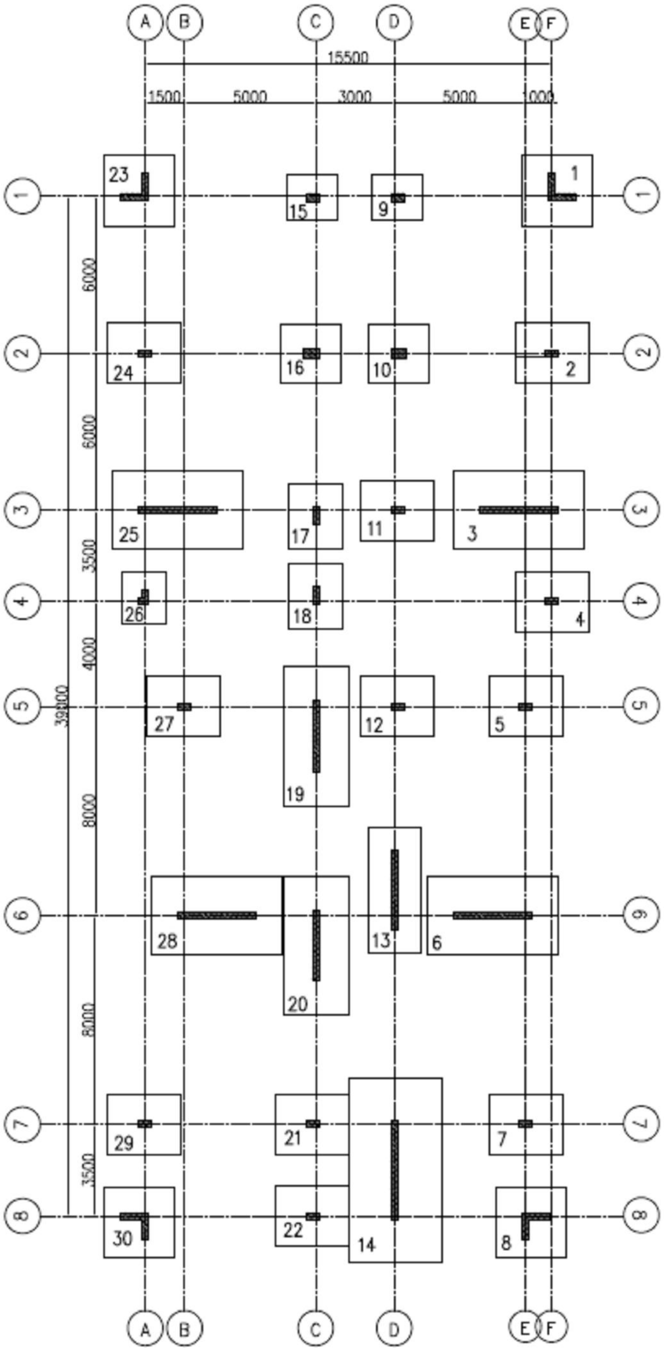

Fig. 4 Footings layout for the Fire Fighting building.

Table 6. Summary of dimensions and stresses under the footings of Fire Fighting building.

Footing No.	Dimensions Range (m)		Stress Range (kN/m^2)
	a	b	
Corner	2.70	2.70	60
Edge	1.75-7.0	1.75-5.0	63-173
Interior	2.2-5.3	2.0-2.8	91-174

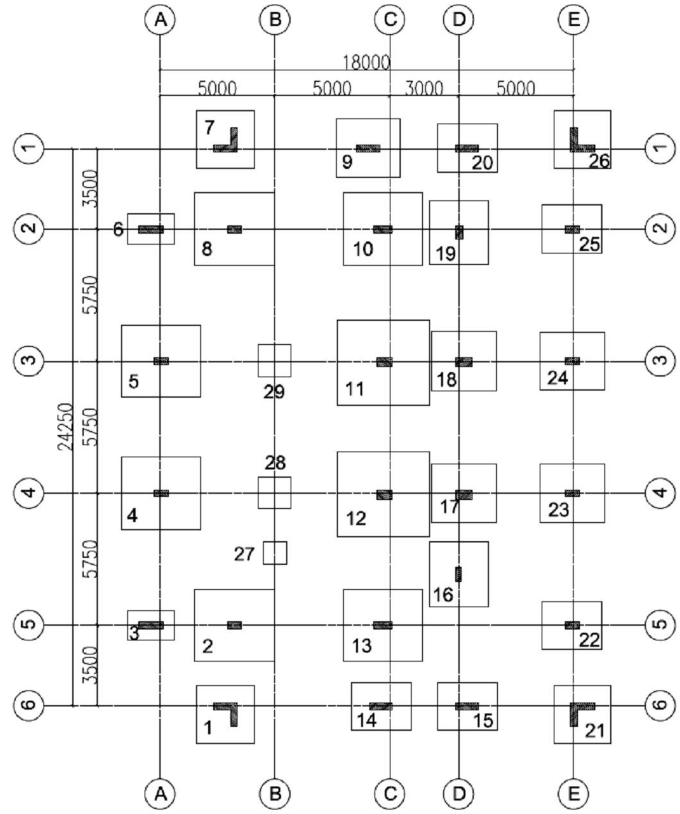

Fig. 5 Footings layout for the Guard Dormitory building.

Table 7. Summary of dimensions and stresses under the footings of Guard Dormitory building.

Footing No.	Dimensions Range (m)		Stress Range (kN/m^2)
	a	b	
Corner	2.00-2.50	1.30-2.50	57-118
Edge	2.60-2.80	2.10-2.55	98-127
Interior	2.80-3.40	2.55-3.05	94-132

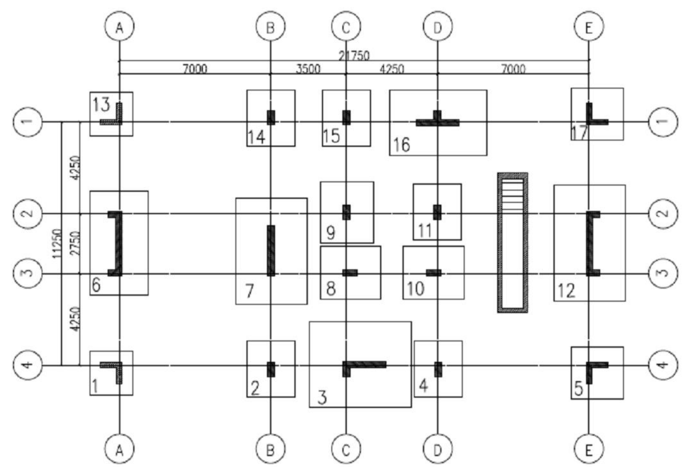

Fig. 6 Footings layout for the Gasoline Station building.

Table 8. Summary of dimensions and stresses under the footings of Gasoline Station building.

Footing No.	Dimensions Range (m)		Stress Range (kN/m^2)
	a	b	
Corner	2.00-2.40	2.00-2.40	97-108
Edge	2.25-4.50	2.60-5.40	35-140
Interior	2.55-3.60	2.45-4.9	92-121

COMPARISONS OF STRESS DISTRIBUTIONS UNDER FOOTINGS

Comparisons of stress distribution under samples of corner, edge and center footings and that under single footing with the same size and stress for each of the buildings are shown in Figs. 7, 8, 9 and 10.

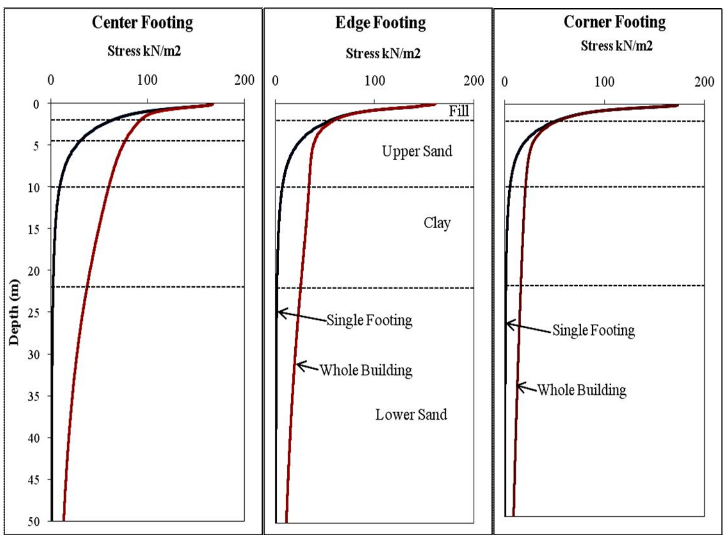

Fig. 7. Comparisons of stress distributions under the footings (Workshop building)

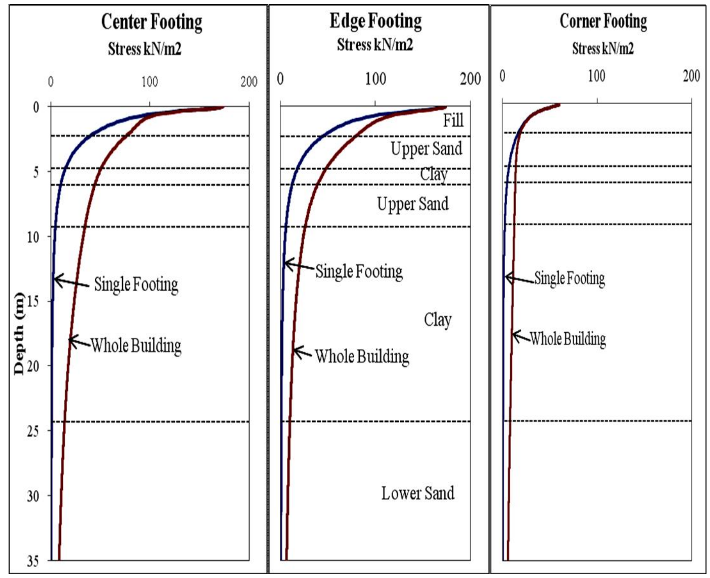

Fig. 8. Comparisons of stress distributions under the footings (Fire Fighting building)

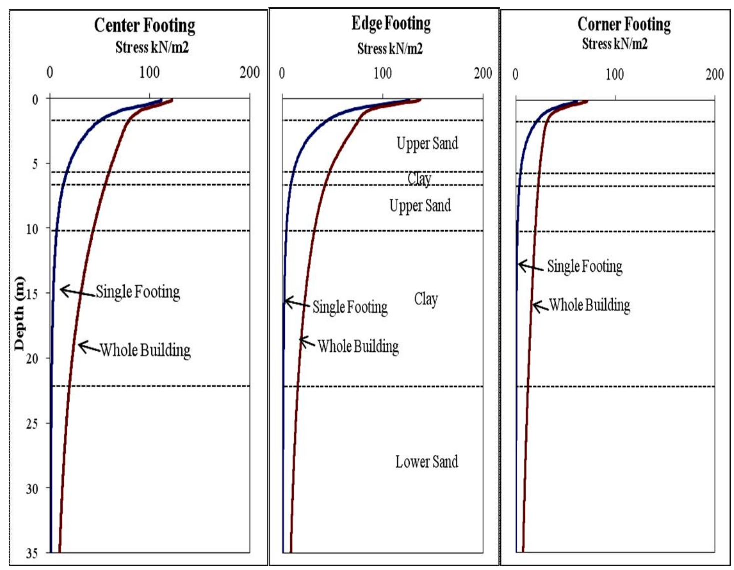

Fig. 9 Comparisons of stress distributions under the footings (Guard Dormitory building)

The comparisons in Figs. 7, 8, 9 and 10 show that the neighboring footings decrease rate of stress dissipation with depth under the footing and thus thicken the depth or zone that is influenced by the surface stress. The major influence happens under interior or center footing with the least influence is in the case of corner footing. The number of neighboring footings increases from the lowest in case of corner footing to center footing with the greatest number of influencing footings.

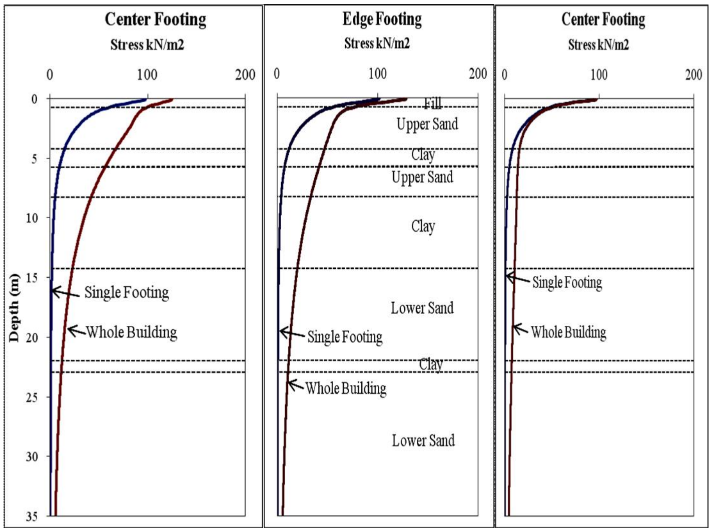

Fig. 10 Comparisons of stress distributions under the footings (Gasoline Station building)

COMPARISONS OF COMPUTED SETTLEMENTS

Settlements of Different Footings Configurations

Comparisons are carried out between settlement computed for single footings and settlement of the same footings with different footings configurations described in Tables 2 and 3. The comparisons are carried out in cases of corner, edge and center footings. Figures 11, 12, 13 and 14 show the results of the comparisons that are carried out for the four buildings considered in this paper.

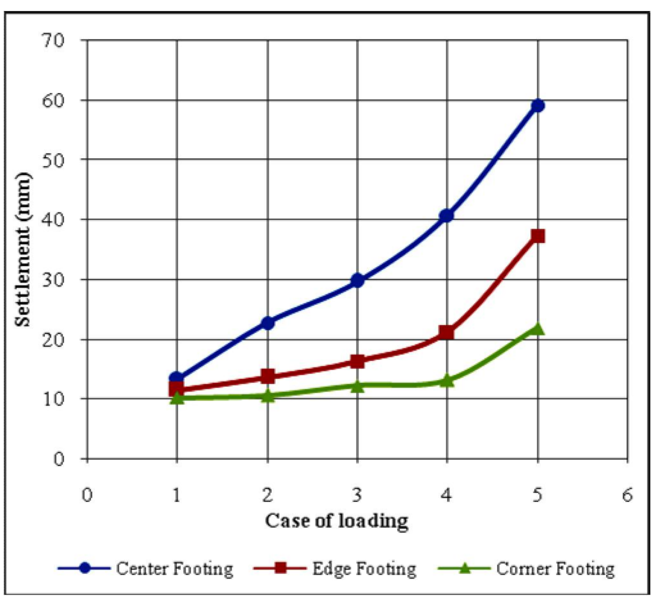

Fig. 11. Comparisons of settlements for different cases of loading for the Workshop building.

The change in case of loading or location of footing in the layout result in changes in number of influencing footings around a footing as described and shown in Tables 2 and 3. In general, the increase in number of influencing footings around a footing in consideration increases the settlement of the footing. This is due to thickening of the zone of soil influenced by the surface load. Such thickening may involve more compressible layers (Figs. 7, 8, 9 and 10). The increase in settlement due to change in case of loading or location of footing in a layout due to increase in influencing footings surrounding the footing is shown in Figs. 11, 12, 13 and 14. The increase in settlement may reach up to 4 to 5 times the settlement of single footing considering the soil profile and the spacing between footings.

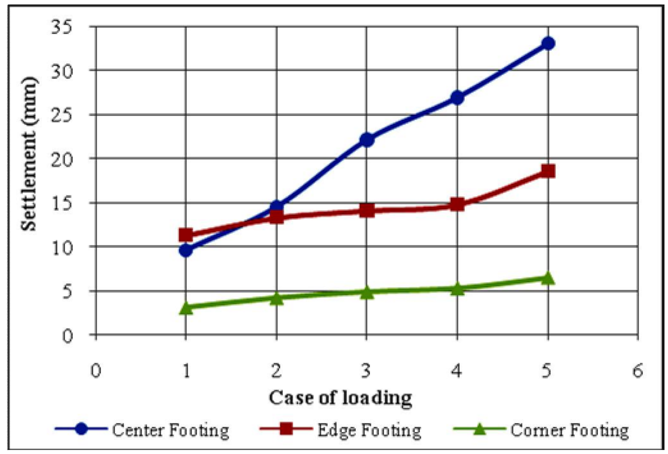

Fig.12. Comparisons of settlements for different cases of loading for the Fire Fighting building.

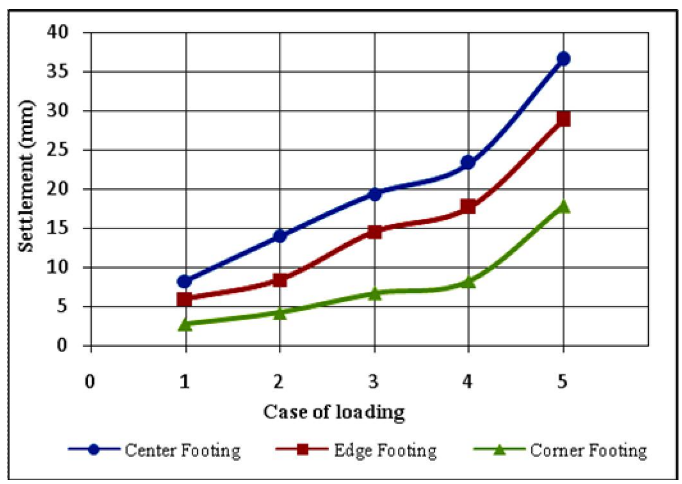

Fig. 13. Comparisons of settlements for different cases of loading for the Guard Dormitory building.

Settlements of Footings Along Axis of Each Building

Comparisons are carried out between settlement computed for single footings and those computed for footings along an axis of a building considering the influence of all the footings in the layout of the building. In case of Fire Fighting buildings, two perpendicular axes are considered. Figures 15, 16, 17, 18 and 19 show the results of the comparisons that are carried out for the four buildings considered in this paper. The numbers indicated on the single footing settlement lines are the stresses on each footing.

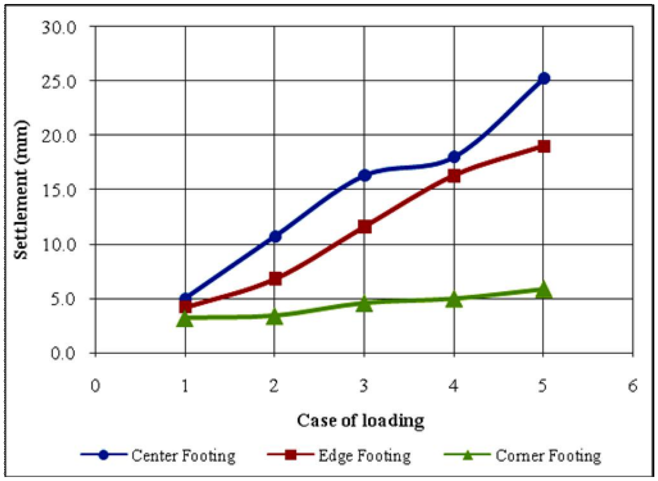

Fig. 14. Comparisons of settlements for different cases of loading for the Gasoline Station building

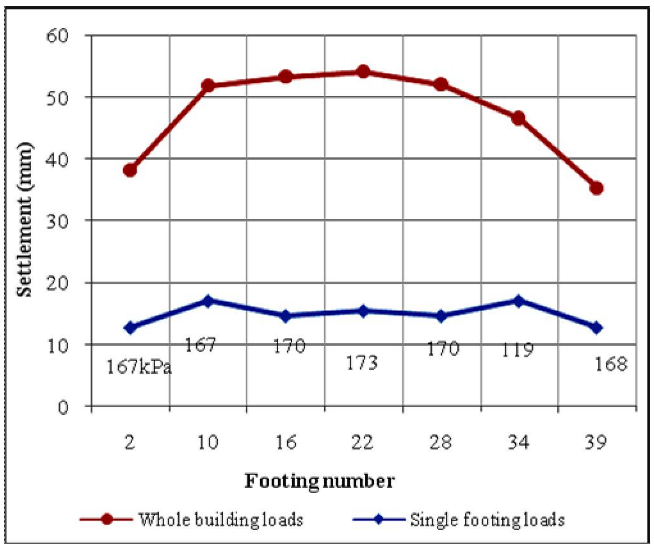

Figure 15. Settlement values along axis B-B for the Workshop building (see Fig. 3 to locate axis and identify footing numbers).

Figures 15, 16, 17, 18 and 19 show that the settlement of a footing taking into consideration the influence of all footings in the layout of the building can reach up to 4 to 5 times the settlement computed considering single footing. The increase in settlement can lead to change of foundation system due to exceeding the maximum allowable settlement such as the case of Workshop building (Fig. 15). According to specification of the project, the maximum allowable settlement for isolated footings is 25 mm which is satisfied considering individual footing calculation. The average settlement computed for the footings considering the influence of neighboring footings about 50 mm which violates the maximum allowable settlement. Such violation resulted in change of foundation system from isolated footings to raft foundations.

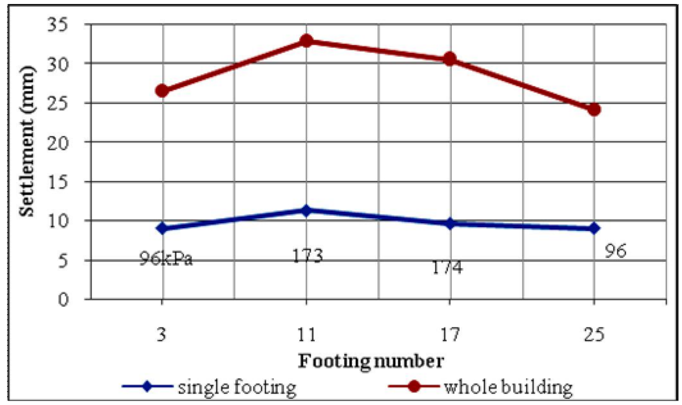

Fig. 16. Settlement values along axis 3-3 for the Fire Fighting building (see Fig. 4 to locate the axis and to identify footing numbers)

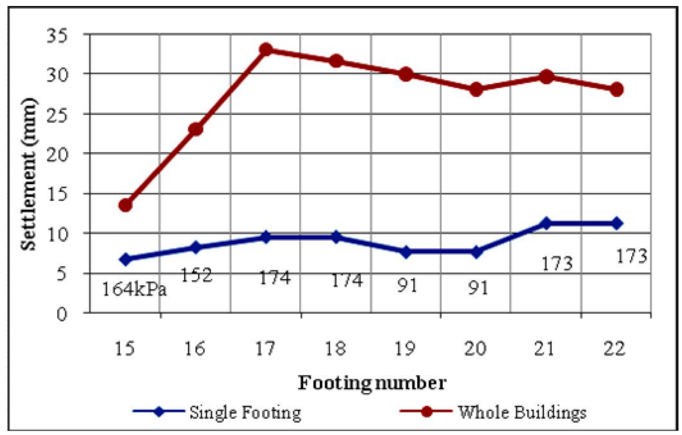

Fig. 17. Settlement values along axis C-C for the Fire Fighting building ***(see*** *Fig. 4 to locate the axis and to identify footing numbers)*

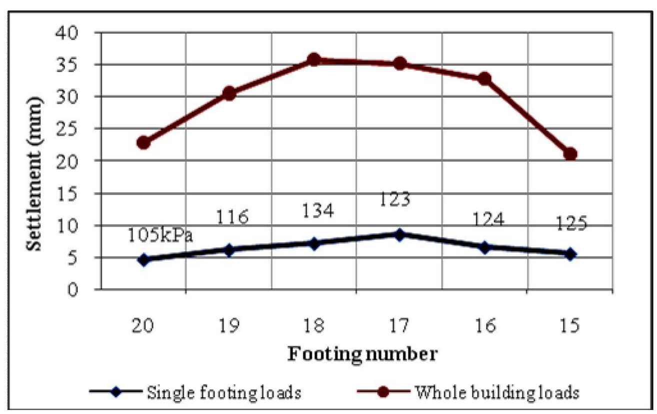

Fig. 18. Settlement values along axis D-D for the Guard Dormitory building (see Fig. 5 to locate the axis and to identify footing numbers).

The spacing between neighboring footings may significantly influence the increase in settlement computed taking into consideration surrounding footings in the layout as compared to that computed for single footing. In case of Fire Fighting building (Fig. 4 and 17), the decrease in spacing from relatively large spacing between footings 15 to 16 and 16 to 17 as compared to the spacing among the rest of footings along the axix C-C causes the increase in settlement from twice to about 3.3 times the settlement of individual footing.

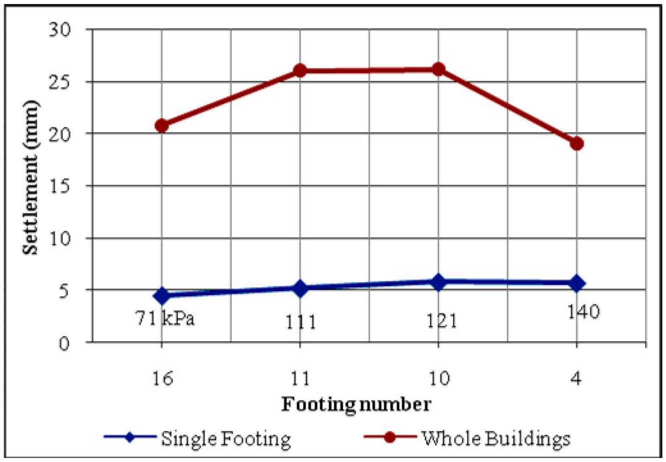

Fig. 19. Settlement values along axis D-D for the Gasoline Station building (see Fig. 6 to locate the axis and to identify footing numbers).

Considering the change in settlement or differential settlement between adjacent footings along axis of a building, it is interesting to note that the maximum differential settlement is up to about 1.5 times the settlement computed for individual footings.

The numbers presented in this section cannot be generalized until further investigation considering variety of soil profiles and wide spectrum of footings spacing.

CONCLUSIONS

The following could be concluded based on the data and analysis presented in this paper:

1) The neighboring footings decrease rate of stress dissipation with depth under the footing and thus thicken the depth or zone that is influenced by the surface stress. The thickening may involve soft compressible layer. The major influence happens under interior or center footing with the least influence is in the case of corner footing.
2) The increase in number of neighboring footings, due to case of loading or change in the location of the footing in the layout, causes increase of settlement as compared to individual footing. The increase in settlement may reach up to 4 to 5 times the settlement of single footing considering the soil profile and the spacing between footings.
3) The increase in settlement due to influence of neighboring footings can lead to violation of maximum allowable settlement specified by the project. Such violation can lead to change of foundation system from isolated footings to raft foundation to satisfy the settlement criteria.
4) The increase in settlement due to influence of neighboring footings increases with the decrease in spacing between footings.
5) The maximum differential settlement between adjacent footings considering influence of neighboring footings can reach up to about 1.5 times the settlement computed for individual footings.
6) The numbers presented in this paper cannot be generalized until further investigation considering variety of soil profiles and wide spectrum of footings spacing.

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REFERENCES

Burland, J. B., and Burbidge, M. C. [1985]. "Settlement of foundations on sand and gravel", Proceedings of Institution of Civil. Engrs, Part 1, Vol. 78, Dec., pp. 1325-1381.

Das, B. M. [1999]. "*Shallow Foundations: Bearing Capacity and Settlement*", CRC Press LLC.

Das, B. M., and Larbi-Cherif, S. [1983]. "Bearing capacity of two closely spaced shallow foundations on sand," Soils and Foundations, 23(1), 1.

Lee, J., Eun, J., Prezzi, M. and Salgado, R. (2010). "Settlement Estimation of Multiple Footings in Sands," Proceedings of 2nd International Symposium on Cone Penetration Testing, CPT'10, Huntington Beach, CA, USA

Maximovic, 2002 "Settlement of shallow footings: Software package for PC", SETMAX Software Manual..

Mesri, G. (1991). *Personal Communications.*

Stuart, J. G. [1962]. "Interference between foundations with special reference to surface footing on sand," Geotechnique, 12(1), 15.

Terzaghi, K., Peck, R. B. and Mesri, G [1996]. "*Soil Mechanics in Engineering Practice*", Third Edition, JohnWiley & Sons Inc, 549 p.