Simplified Conceptual Equation for Soil-Structure Interaction for Simple Structures on Dry Soils Due to Vertical Loads for Practical Purposes*

معادلة مبسطة لحل تفاعل التربة مع الأساس لمنشأ بسيط على تربة جافة تحت القوى الرأسية للإستخدامات العملية

Fawzi Abu Al-Adas*[1], Abdul Razzaq Touqan[2] & Mahmud Dwaikat[2]

فوزي ابو العدس، عبد الرزاق طوقان، محمود دويكات

[1] M.Sc. graduate student, faculty of graduate studies, An-Najah National University, Nablus, Palestine. [2] Department of civil engineering, An-Najah National University, Nablus, Palestine

*Corresponding Author: f.abuadas@live.com

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Abstract

The non-uniform settlements represent a big challenge for the structural engineers because of the problems caused by this phenomenon, where many cracks in the walls, columns and slabs occurred due to the non uniform settlements, which ranges from small cracks to major cracks that threat the safety of the building and the residents. Along the years, the geotechnical engineers have developed many methods to find the settlements in soil. However, these methods need certain expertise in the properties and the conditions of soil and some other tests, which the structural engineers in Palestine lack of such expertise. Therefore, and because of the importance of the soil structure interaction, this paper focuses on a simplified method to estimate the settlements of soil, where by using simple equations the settlement of soil can be predicted with acceptable accuracy for the practical purposes, like design or field checks.

Key words: Soil-Structure interaction, Soil settlement, Displacement of structure, Modulus of elasticity of soil, Direct approach, Finite elements.

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ملخص

تمثل مشكلة الهبوط غير المتكافئ للتربة في المنشآت تحدياً كبيراً للمهندسين الإنشائيين بسبب المشاكل الكبيرة التي تسببها هذه الظاهرة على شكل تشققات في الأسقف والجدران والأعمدة، والتي تتدرج من تشققات بسيطة إلى تشققات شديدة قد تهدد سلامة المبنى والقاطنين. على مدار الأعوام، قام مهندسوا التربة بتطوير العديد من الطرق لقياس الهبوط الناتج في التربة، إلا أن هذه الطرق تحتاج إلى خبرات ومعلومات خاصة عن خصائص التربة وحالتها الواقعية وبعض الاختبارات و التي يفتقر لها الكثير من المهندسين الإنشائيين في فلسطين. لذلك ولأهمية معرفة التفاعل بين التربة والمنشأ، يأتي هذا البحث ليسلط الضوء على طريقة بسيطة لتوقّع الهبوط في التربة تحت المنشأ، حيث و باستخدام بعض المعادلات يمكن توقع الهبوط في التربة تحت المنشأ بدقة مقبولة للاستخدامات العملية كالتصميم أو التحليل الميداني.

الكلمات المفتاحيه: تفاعل التربة مع الأساس، هبوط التربة، الإزاحة في المنشأ، معامل المرونة للتربة، طريقة مباشرة، عناصر محدودة

1 Introduction

It is well known that structure and soil can be considered as one system that bears the external forces as one unit. Thus, understanding the interaction between soil and structure is a key element for the structural and geotechnical engineers. The debate is generally about the quantity of the interaction and the significance of each part. What is currently available for engineers are assumptions that have been used to simplify the analysis and the calculations.

Generally, two main assumptions are commonly used: the flexible soil-rigid structure assumption, which is adopted by the geotechnical engineers, and the rigid soil-flexible structure, which is used by the structural engineers to (Lai & Martinelli 2013). However, these assumptions do not reflect the real behavior of the soil structure interaction, where both the soil and structure are flexible, and realistic model of structure and soil interaction can lead to an optimal and economical structure (Breeveld, 2013).

Underestimating the soil structure interaction effects leads to structural problems that sometimes cause severe damage for the structural elements. For example, consider a structure built on two types of soil with a significance variation in stiffness. Ignoring the soil differential displacements will lead to non-uniform settlement that will cause unexpected stresses on the structural members, which sometimes may lead to failure.

Many methods were followed in order to deal with the soil-structure interaction problem. There are the direct and the indirect approaches. According to (Lai & Martinelli 2013), in the direct approach the soil volume and the structure are both part of the same model which is analyzed in a single step by using one of several numerical discretization techniques (e.g. Finite Element Method, Spectral Element Method, Finite Difference Method, etc.). That means the direct method depends on the actual modeling of the soil as three dimensional multi-nodded elements using a finite element tool with the actual properties of the soil, in addition to the modeling of the structure with its actual properties. This method is the most accurate method, but the disadvantages of this method are many, including the difficulty of the analysis, the long calculation time, the need of certain expertise in mathematics and finite elements theory and tools, and the need of detailed information about the soil.

On the other hand, the indirect method which is defined by (Kausel & Roesset, 1974) as a “technique by which a soil structure interaction problem is solved by decomposing the superstructure-foundation-soil system into two subsystems”. The response of the overall system is then obtained from the application of the theory of superposition. This method is considered easy to implement and not time consuming. However, because it is built upon simplified assumptions, it gives approximate results and has a lot of limitations.

(Das, 2009) states that in general, settlement of a foundation consists of two major components, elastic settlement and consolidation settlement. Also he sorts the settlement calculation methods into three main categories depending on the methodology, which are:

1. Methods based on observed settlement of structures and full scale prototypes. These methods are empirical, and depend on the results from empirical tests, like standard penetration test (SPT) and the

cone penetration test (CPT). Many methods are developed to find the settlement empirically: Terzaghi and Peck (1948, 1967), Meyerhof (1965), DeBeer and Martens (1957), Hough (1969), Peck and Bazaraa (1969), and Burland and Burbidge (1985).

2. Semi empirical methods. These methods are based on a combination of field observations and some theoretical studies. They include the procedures outlined by Schmertmann (1970), Briaud (2007), and Akbas and Kulhawy (2009).

3. Methods based on theoretical relationships derived from the theory of elasticity. The relationships for settlement calculation available in this category contain the term modulus of elasticity of the soil. Equations 1 and 2 are based on the theory of elasticity for area loads (Das, 2008):

$$\Delta_{corner} = \frac{qB}{2E}(1-\upsilon^2) * I_9 \tag{1}$$

$$\Delta_{center} = \frac{qB}{E}(1-\upsilon^2) * I_9 \tag{2}$$

Where:

q: external pressure value.

Δ: elastic settlement of soil.

B: width of area load.

E: modulus of elasticity of soil.

υ: Poisson's ratio.

I_9: influence factor that depends on the dimensions of the area load (Das, 2008).

However, the previously mentioned methods are geotechnical engineers' specialty, which makes it difficult for structural engineers to apply because it requires certain expertise and knowledge in geotechnical engineering. Therefore, the aim of this paper is to fit a simple equation that can be used to calculate the soil settlement easily with acceptable accuracy, in order to facilitate the practical needs for the structural engineers.

To achieve this purpose, a detailed three dimensional structural model is created for the problem using SAP2000 (CSI, 2010), and the settlement of the soil and the displacement of structure are obtained for various set of parameters of the model. Then these results are normalized and fitted to a simple equation which can be used to predict the settlement of soil. In order to simplify the procedure, the normalized results will be presented as ratio to the total displacement. The ratios of soil settlement to total displacement $\frac{\Delta_{soil}}{\Delta_{total}}$ and the ratios of displacement of structure to total displacement $\frac{\Delta_{structure}}{\Delta_{total}}$ are obtained. The importance of this step is that the settlement of soil can be found by finding the displacement of structure and knowing the displacement ratios.

2 Finite elements model description

2.1 Geometric properties

The used model for the problem is chosen to be as simple as possible. A square column with vertical stress applied to the top of the column, and a square single shallow footing placed on a soil. The square shape is used to simplify the calculations and to reduce the number of variables. Both the structure and the soil are defined as three dimensional multi nodded elements using the finite element tool SAP2000.

According to (CSI, 2010), the solid element is an eight node element for modeling three dimensional structures and solids, which is based upon an isoperimetric formulation that includes nine optional incompatible bending modes. Each element has its own coordinate system for defining material properties, loads and for interpreting output.

The size of the mesh is selected from previous experiences based on achieving sufficient accuracy and to reduce time of analysis. Trial and error approach is followed by changing mesh size unit and it is conceded that stress and strain results do not vary significantly. The mesh sizes are selected to gradually decrease when moving towards the structure in order to satisfy acceptable accuracy of the results. Figure 1a shows plan sketch for a representative model, while Figure 1b shows a cross section sketch. Figure 1c shows a representative meshed plan and Figure 1d shows a representative meshed section.

2.2 Model parameters

The chosen parameters of the model as shown in Figure 1 are: the dimension of footing side *l*, the dimension of column side *c*, depth of footing *d*, height of column *h*, compression stress assigned to the top of the column σ, dimensions of soil, which are fixed as 25m*25m area with 15m depth, in addition to the stiffness of soil, which is considered as a main parameter.

Poisson's ratio that is used is 0.3, which represents the average of the ratios of the soil, and this ratio exists in all the soil types. Using Equation 1 and 2, it is concluded that the maximum error for the higher and lower ratio does not exceed 15%, which is acceptable.

2.3 Materials description

The materials of soil and structure are assumed fully elastic, homogeneous and isotropic in order to simplify the model (Kocak and Mengi, 2000). The soil is assumed to be dry with no water pores in order to find the immediate settlement only and ignore the consolidation settlement (Bowles, 1982). According to (Bowles, 1982) this method is "used for all fine-grained soils including silts and clays with a degree of saturation S $\leq$ 90 percent and for all coarse-grained soils with a large coefficient of permeability". The modulus of elasticity of soil can be used as a main property and parameter for the calculations, where it is considered one of the acceptable methods used to find the settlement of soil (Das, 2009), and as (Holtz and Kovaks ,1981) stated "the immediate, or distortion, settlement, although not actually elastic is usually estimated by using elastic theory". The structural material of the column and footing is concrete, and it is considered to behave elastically with modulus of elasticity of 24500 MPa. The soil is considered elastic and stiffness used for soil vary from a very soft soil of 5MPa modulus of elasticity, to a very stiff soil with 10000MPa modulus of elasticity (Geotechdata, 2016). The materials for both soil and structure are assumed weightless, in order to ignore the settlement due to the own weight.

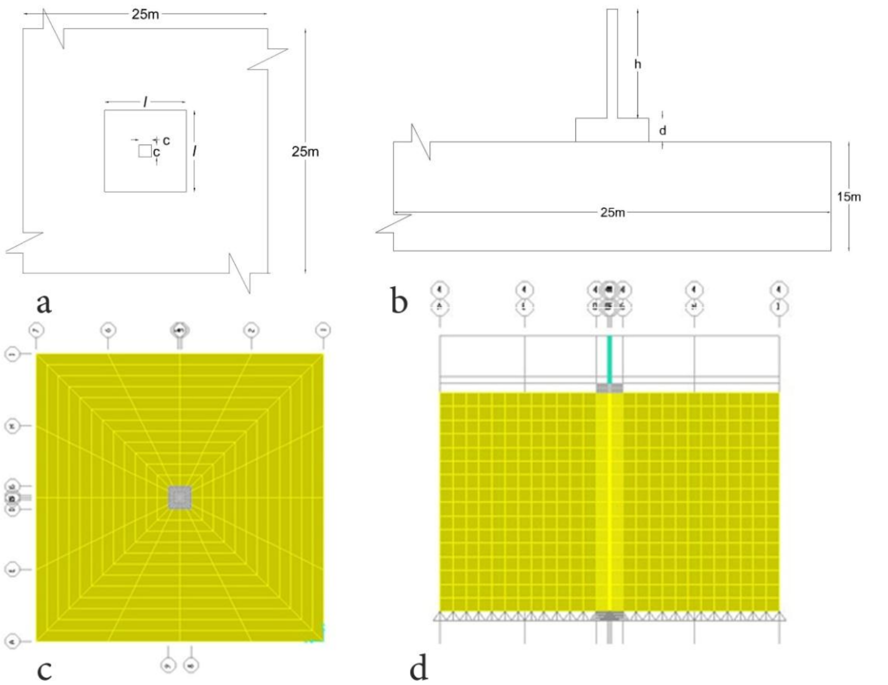

Figure (1): a) The plan of the model. b) The elevation of the model, c) Plan view of the meshed model. d) Side view of the meshed model as simulated in SAP2000

2.4 Basic assumptions

In order to reduce the number of parameters, the parameters are normalized as: width of footing side to depth of footing $\left(\frac{l}{d}\right)$, width of column side to length of footing side $\left(\frac{c}{l}\right)$ and the ratio of the soil modulus of elasticity to the concrete modulus of elasticity $\frac{E_{soil}}{E_{structure}}$, where $E_{structure}$ is considered to be represented as the modulus of elasticity of the material used, which is the concrete. The normalized ratios are considered the main variables, while the column's height is assumed constant with 3m, and the stress is assumed constant with the value of 6000kN/m^2, which represents the average service load capacity of the reinforced concrete column. Although, as the results are ratios of the total displacement in elastic conditions, the stress has no significant effect on the ratios due to the elasticity of the materials.

Because of the large dimensions that are assumed for the soil, end restrains have negligible effect because the amount of stresses at the edges is negligible. Beneath the depth of the soil, a layer of rigid bedrock is assumed. The base joints of soil are restrained with pin supports. The interface between the joints of the footing and the soil is assumed continuous, and separation between joints of footing and soil due to the shear deformation is ignored as the frictional forces on shear are very small and negligible for the case of vertical forces only, where the horizontal forces are neglected in this study.

3 Procedure of analysis

In order to find the displacement ratios $\left(\frac{\Delta_{soil}}{\Delta_{total}}, \frac{\Delta_{structure}}{\Delta_{total}}\right)$ in certain model, the raw displacement values are found by analyzing the model for each set of parameters. Once the total displacement and the soil displacement are found, the displacement of structure can be obtained by subtracting the two values. The same model is analyzed using different parameters. For a certain $\left(\frac{l}{d}\right)$ value many $\left(\frac{c}{l}\right)$ values are used, and for a certain $\left(\frac{c}{l}\right)$ value all the proposed soil materials are used. Random geometrical parameters are used. There are: $\left(\frac{l}{d}\right)$ values of 3, 6 and 8. And $\left(\frac{c}{l}\right)$ values of 0.15, 0.2, 0.25 and 0.3.

4 Results and Discussions

Table 1 represents a tabulated raw output data as a sample, for $\left(\frac{l}{d}\right)$ value of 6 and $\left(\frac{c}{l}\right)$ value of 0.15. The table shows the total displacement, soil displacement, structural displacement and the displacement ratios. Figure 2 is a representative diagram that shows $\frac{\Delta_{\text{structure}}}{\Delta_{\text{total}}}$ and $\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}}$ curves for the model with values $\left(\frac{l}{d}\right)$=6 and $\left(\frac{c}{l}\right)$=0.15.

Figure 2 clarifies the limits of the main two assumptions mentioned earlier. The rigid structure-flexible soil assumption can be applied for soft soils, and it is obvious from Figure 2 that for small value of $\frac{E_{soil}}{E_{structure}}$ the value of $\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}}$ is approximately 1. On the other hand, the rigid soil-flexible structure assumption is applied for structures built on hard soils, which gives high values of $\frac{E_{soil}}{E_{structure}}$, and from Figure 2 the value of $\frac{\Delta_{\text{structure}}}{\Delta_{\text{total}}}$ for high $\frac{E_{soil}}{E_{structure}}$ is approximately 1.

By reading all the resulting curves for all set of $\left(\frac{l}{d}\right)$ and $\left(\frac{c}{l}\right)$ ratios, it can be said that for $\frac{E_{soil}}{E_{structure}}$ of $4 * 10^{-4}$ or less the rigid structure flexible soil can be safely used, and for $\frac{E_{soil}}{E_{structure}}$ of 0.4 or higher, the flexible structure rigid soil can be used safely. This means that for the modulus of elasticity ratio ranging from $4 * 10^{-4}$ to 0.4, both the soil and structure cannot be considered rigid, and the relative flexibility of soil and structure must be considered in calculation of settlements. The physical meaning of the intersection in Figure 2 is that for a certain modulus of elasticity ratio, both the soil and structure has an identical displacement, and each one shares half of the total displacement.

Table (1): Representative sample showing the results from SAP2000 model, with $\left(\frac{l}{d}\right) = \mathbf{6}$ and $\left(\frac{c}{l}\right) = \mathbf{0.15}$

E Soil MPa	**Δ total mm**	**Δ Soil mm**	**Δ Structure mm**	**E Soil/ E Structure**	**Δ Soil/ Δ Total**	**Δ Structure/ Δ total**
5	33.35	32.40	0.93	2.0E-04	0.97	0.03
10	17.30	16.35	0.93	4.0E-04	0.95	0.05
50	4.44	3.51	0.93	2.0E-03	0.79	0.21
100	2.81	1.88	0.93	4.0E-03	0.67	0.33
500	1.45	0.50	0.93	2.0E-02	0.35	0.65
1000	1.23	0.30	0.93	4.0E-02	0.25	0.75
5000	1.02	0.09	0.93	2.0E-01	0.09	0.91
10000	0.99	0.06	0.93	4.0E-01	0.06	0.94

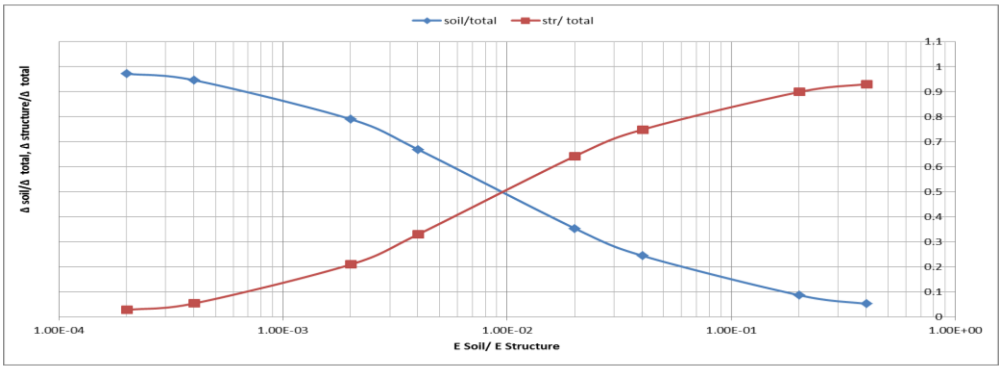

Figure (2): A representative diagram showing $\frac{\Delta_{structure}}{\Delta_{total}}$ and $\frac{\Delta_{soil}}{\Delta_{total}}$ curves for the model with values $\left(\frac{l}{d}\right) = \mathbf{6}$ and $\left(\frac{c}{l}\right) = \mathbf{0.15}$.

Figures 3 through Figure 5 show the soil displacement ratio diagrams, while Figures 6 through Figure 8 shows the ratio of structural displacement. The logarithmic value of $\frac{E_{soil}}{E_{structure}}$ is used to refine the drawings into more understandable drawings, and to facilitate the data fitting.

The diagrams confirm the limits of the main two assumptions mentioned earlier. From Figure 3 through Figure 5 for small value of $\frac{E_{soil}}{E_{structure}}$ the value of $\frac{\Delta_{soil}}{\Delta_{total}}$ is approximately 1. Moreover, from Figure 6 through Figure 8 for high value of $\frac{E_{soil}}{E_{structure}}$ the value of $\frac{\Delta_{structure}}{\Delta_{total}}$ is approximately 1.

It was noticed that for a certain modulus of elasticity ratio $\frac{E_{soil}}{E_{structure}}$, the soil displacement ratio increased with the increasing of $\left(\frac{l}{d}\right)$ and $\left(\frac{c}{l}\right)$ ratios. This can be explained using the mechanics of materials principles.

The increase of these two ratios will affect the stiffness difference between the column and the footing.

Increasing $\left(\frac{c}{l}\right)$ value will increase the dimensions of the column, which will increase the stiffness of the column, or reduce the dimension of the footing reducing the stiffness of the footing. On the other hand, increasing $\left(\frac{l}{d}\right)$ value will reduce the depth of the footing, which will reduce the moment of inertia. It is noticed from Figure 3 through Figure (8 that $\left(\frac{c}{l}\right)$ effect is significant, and any change will affect the results. However from Figure 9 it is noticed that $\left(\frac{l}{d}\right)$ effect is less significant than $\left(\frac{c}{l}\right)$.

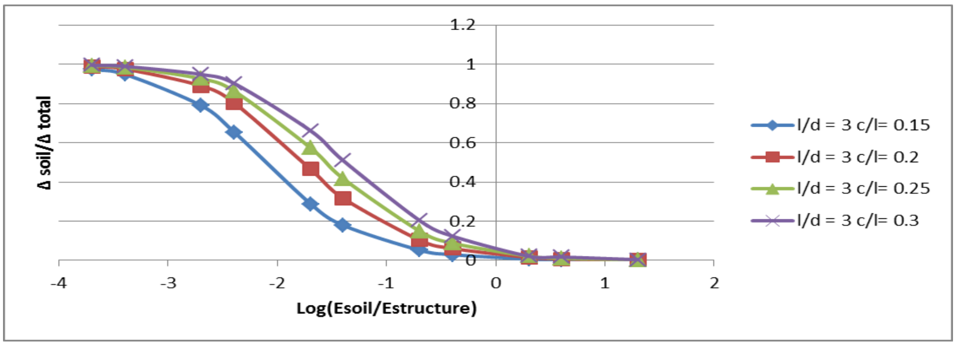

Figure (3): The change of $\frac{\Delta_{soil}}{\Delta_{total}}$ curves for $\left(\frac{l}{d}\right)$ value 3 and various $\left(\frac{c}{l}\right)$ values.

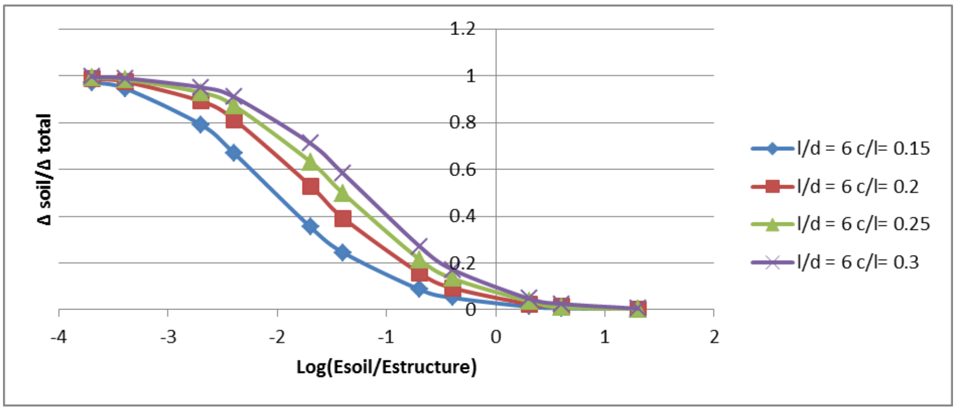

Figure (4): The change of $\frac{\Delta_{soil}}{\Delta_{total}}$ curves for $\left(\frac{l}{d}\right)$ value 6 and various $\left(\frac{c}{l}\right)$ values.

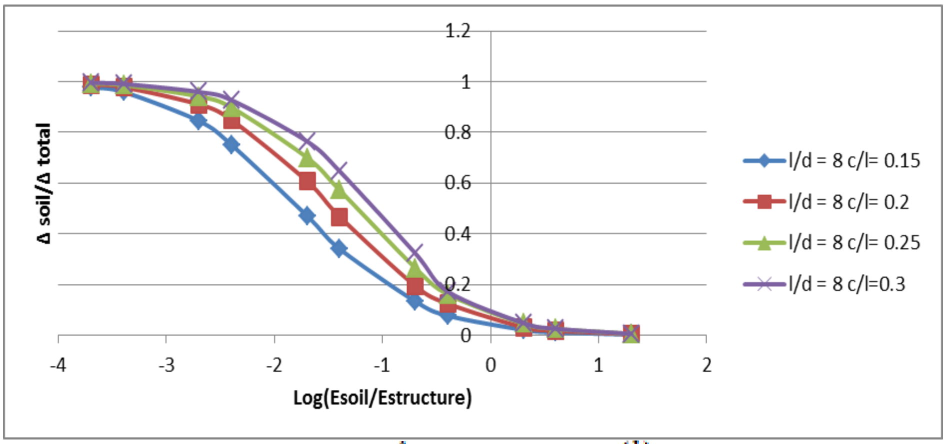

Figure (5): The change of $\frac{\Delta_{soil}}{\Delta_{total}}$ curves for $\left(\frac{l}{d}\right)$ value 8 and various $\left(\frac{c}{l}\right)$ values.

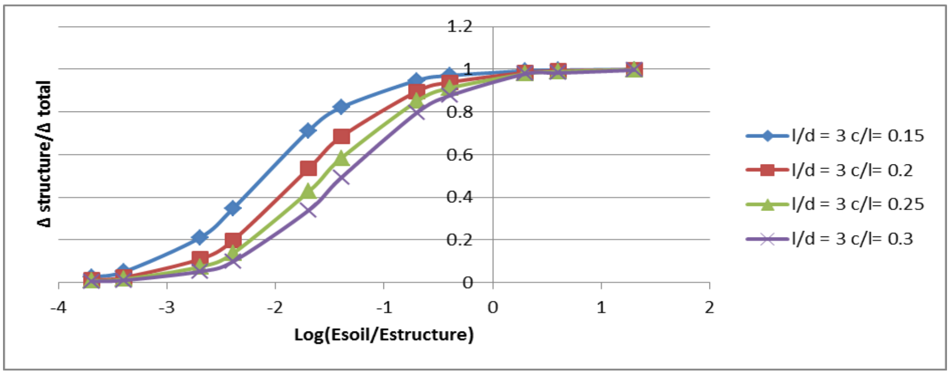

Figure (6): The change of $\frac{\Delta_{structurel}}{\Delta_{total}}$ curves for value $\left(\frac{l}{d}\right)$ =3 and various $\left(\frac{c}{l}\right)$ values.

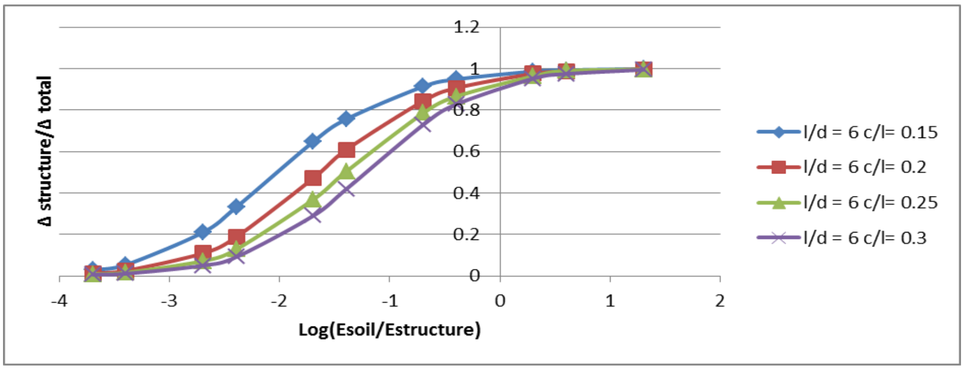

Figure (7): the change of $\frac{\Delta_{structurel}}{\Delta_{total}}$ curves for value $\left(\frac{l}{d}\right)$ =6 and various $\left(\frac{c}{l}\right)$ values.

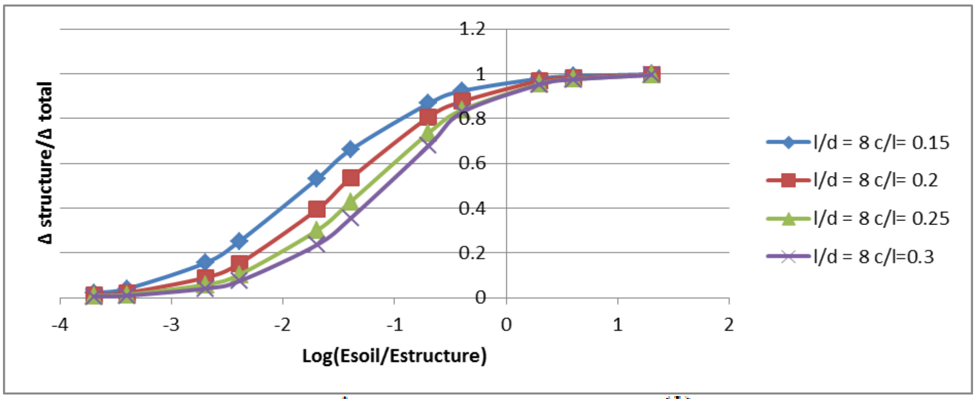

Figure (8): the change of $\frac{\Delta_{structurel}}{\Delta_{total}}$ curves for value $\left(\frac{l}{d}\right)$ =8 and various $\left(\frac{c}{l}\right)$ values.

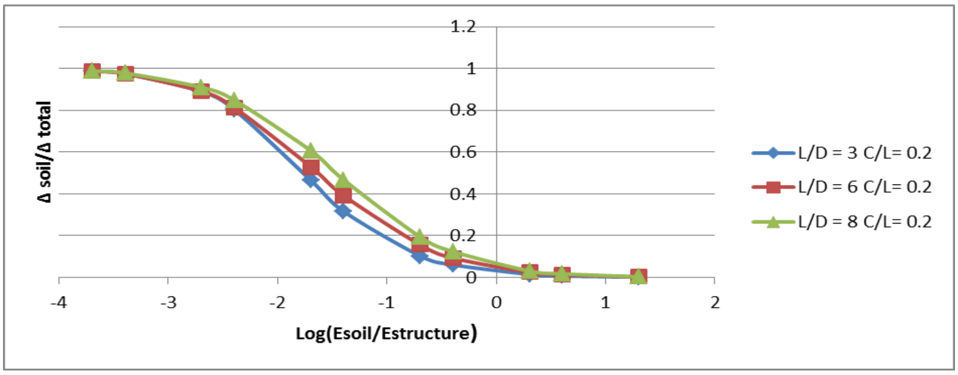

Figure (9): The change of $\frac{\Delta_{soil}}{\Delta_{total}}$ curves for $\left(\frac{c}{l}\right)$ value 0.2 and various $\left(\frac{l}{d}\right)$ values.

Changing the ratios will lead to flexible behavior in the footing due to the stiffness differences between the column and the footing, which will affect the stress distribution from the footing on the soil and increase the magnitude near the column which will cause higher soil settlements.

The slope of the curves can be related to the stresses in soil and structure. The slopes of most curves are almost identical as can be seen from Figure 3 through Figure 8, this behavior is expected because the materials are assumed elastic.

It can also be explained using the practice of the footing design. When the stress of the structure affecting the soil is higher than the bearing capacity of the soil, the designer must increase the footing area in order to increase the distribution area on the soil and decreasing the stress magnitude. This practice corresponds to changing $\left(\frac{c}{l}\right)$ ratio by decreasing it, which will give a lower $\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}}$ ratio. Although, decreasing $\left(\frac{c}{l}\right)$ values will increase $\left(\frac{l}{d}\right)$ thus increase $\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}}$ a little, but because the effect of changing $\left(\frac{c}{l}\right)$ value is much higher than changing $\left(\frac{l}{d}\right)$ value, the settlement of soil will decrease.

5 Data fitting

5.1 General equation

In order to use the data for practical reasons, it is important to have a general equation that can be used to predict these data for any similar structure with similar conditions.

The curves can be fitted using a type of the logistic function (Weisstein, 2016), which is governed by the following equation:

$$f(x) = \frac{x_1}{1+e^{-k*(x-x_0)}} \tag{3}$$

Where:

x_1: is the curve’s maximum value.

k: is slope of the curve.

x_0: is the x value of the Sigmoid's midpoint.

After fitting the data, Equation 4 and Equation 5 were concluded to find the displacement ratios. k gives a values of the range 1.85 to 2.1, thus the average is approximated to the value 2, and the calculations are adjusted for this value

$$\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}} = \frac{1}{1+e^{2*(\log(\text{Sr})+x_0)}} \quad (4)$$

$$\frac{\Delta_{\text{structure}}}{\Delta_{\text{total}}} = 1 - \frac{1}{1+e^{2*(\log(\text{Sr})+x_0)}} \quad (5)$$

Where

$$\text{Sr} = \frac{\text{E}_{\text{soil}}}{\text{E}_{\text{structure}}} \quad (6)$$

$$x_0 = \ln(\alpha) * \ln\left(\frac{c}{l}\right) \quad (7)$$

$$\alpha = 0.0043\left(\frac{l}{d}\right)^2 + 0.0443\left(\frac{l}{d}\right) - 3.1721 \quad (8)$$

5.2 Equation verification

To test that the equation converges to the results of the cases of upper and lower limits of the modulus of elasticity ratios, the following calculations have been conducted. For the flexible structure rigid soil assumption, the Sr value is ∞, and the structure must participate of 100% of the total displacement.

$$\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}} = \frac{1}{1 + e^{2*(\log\infty+x_0)}} = 0$$

$$\frac{\Delta_{\text{structure}}}{\Delta_{\text{total}}} = 1 - 0 = 1$$

On the other hand, for the rigid structure flexible soil assumption, the Sr equal zero which gives exponential value of $-\infty$.

$$\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}} = \frac{1}{1+e^{2*(\log(0)+x_0)}} = 1$$

$$\frac{\Delta_{\text{structure}}}{\Delta_{\text{total}}} = 1 - 1 = 0$$

The equation that resulted from the data fitting is further validated against other independent finite element results with new values for $\left(\frac{l}{d}\right)$ and $\left(\frac{c}{l}\right)$ ratios, where the displacement ratios were calculated for random ratios and compared with the finite element results in Figure 10 and Figure 11. The calculated values of the slopes of the curves are around between 0.98 and 1.02, which is considered an acceptable value.

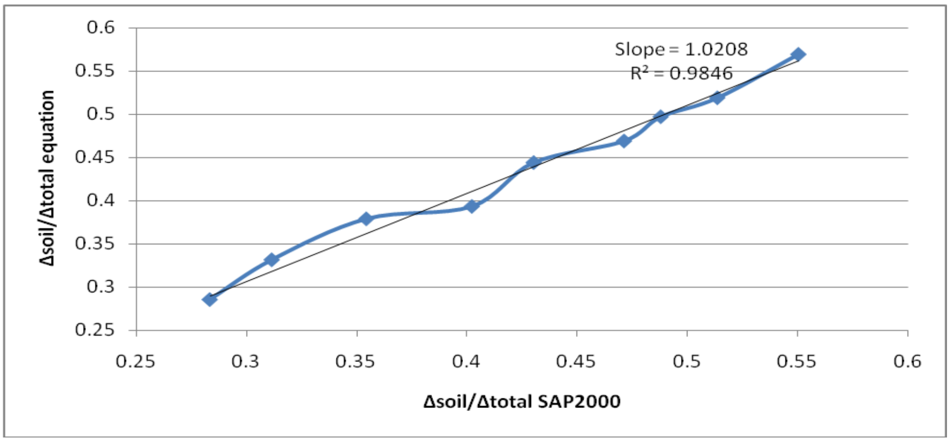

Figure (10): $\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}}$ from SAP2000 versus $\frac{\Delta_{\text{soil}}}{\Delta_{\text{total}}}$ from Equation 4.

As a comparison, Figure 12 shows an example for the structure displacement ratios results from the finite element tool SAP2000, and from Equation 5 with the variables values $\left(\frac{l}{d}\right) = 4$ and $\left(\frac{c}{l}\right) = 0.2$ for various modulus of elasticity of soil. From Figure 12, it is obvious that the two results are approximately equal.

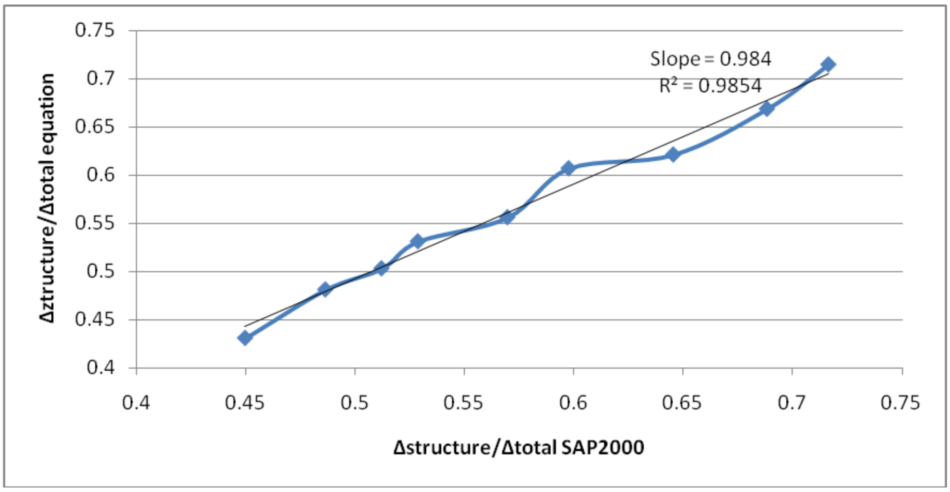

Figure (11): $\frac{\Delta structure}{\Delta total}$ from SAP2000 versus $\frac{\Delta structure}{\Delta total}$ from Equation 5.

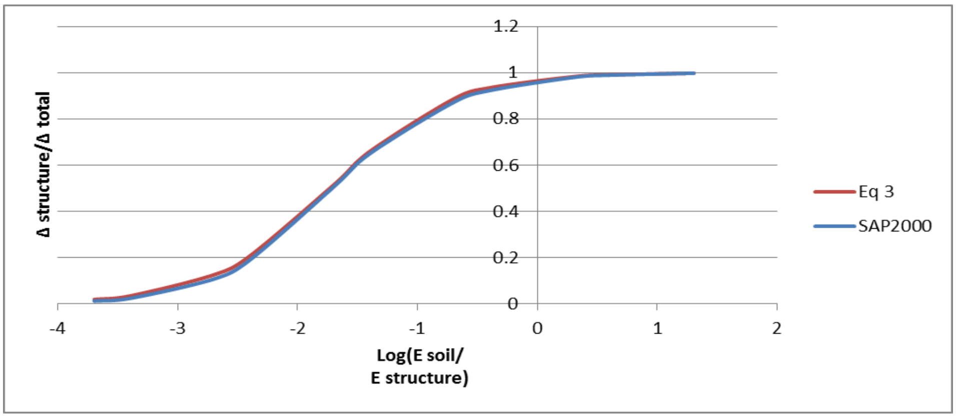

Figure (12): results from the finite element tool SAP2000, and from Equation 5. The variables values are $\left(\frac{l}{d}\right) = \mathbf{4}$ and $\left(\frac{c}{l}\right) = \mathbf{0.2}$.

6 Conclusions

Using a square footing of width *l* and depth *d* with a square column of width *c* and height of 3 meters, several points were concluded.

- The settlement of the soil increases by increasing the parameters $\left(\frac{l}{d}\right)$ and $\left(\frac{c}{l}\right)$.
- Equations were developed that can predict the displacement of the soil with acceptable accuracy by knowing the displacement of the structure, using any structural analysis program, and by knowing the modulus of elasticity of the structure and the soil.
- It is concluded that the effect of $\left(\frac{c}{l}\right)$ ratio is more significant than the $\left(\frac{l}{d}\right)$ ratio, where any small change of $\left(\frac{c}{l}\right)$ ratio changes the displacement ratios significantly, while changing $\left(\frac{l}{d}\right)$ ratio gives a small change in displacement ratios.
- The main assumptions used in structural and geotechnical engineering were discussed, and from the data resulted from the models, the limitation for each assumption is found from the main displacement ratios curves. Therefore, for soil modulus of elasticity ratio $\frac{E_{soil}}{E_{structure}}$ of $4 * 10^{-4}$ or less, the fixable soil-rigid structure can be used safely. While, for modulus of elasticity ratio of 0.4 or higher, the rigid soil-flexible structure can be safely used. However, for the modulus of elasticity ratio of $4 * 10^{-4}$ to 0.4, both the soil and structural displacements must be calculated.

– This method can be used as footing design method. The designer can choose a suitable displacement ratio and assume suitable $\left(\frac{l}{d}\right)$. Then, the needed $\left(\frac{c}{l}\right)$ ratio can be found from the curves or the equation, and by knowing the width of the column, the width and the depth of the footing can be found. However, it must be noted that the footing dimension must be checked for the shear and punching shear forces, and the bearing capacity of the soil must be taken into consideration.

– It was noticed that the equations have limitations for certain $\left(\frac{c}{l}\right)$ and $\left(\frac{l}{d}\right)$ ratios, where for $\left(\frac{c}{l}\right)$ value of less than 0.15 or $\left(\frac{l}{d}\right)$ value more than 8 the equations failed to predict accurate settlements. Decreasing $\left(\frac{c}{l}\right)$ ratio would not be practical and most of the footing area would not be as effective. While increasing $\left(\frac{l}{d}\right)$ ratio will cause a sever reduction in the rigidity of the footing, which gives it flexible behavior comparing with the column rigidity, which will affect the stress distribution.

– Noticing that all the previous models were simple models of very simple structure, it is predicted to have certain errors if applied on frames. Small errors are expected if the soil beneath the frame was considered uniform of the same soil property. On the other hand, considerable errors are predicted in the actual displacements for frames with different types of soil. The unequal properties of soil will cause a less displacement than the calculated for the weak soil, and higher displacement for the stronger soil.

7 References

– Akbas, S.O. & Kulhawy, F.H. (2009). Axial compression of footings in cohesionless soils. 1: Load settlement behavior. *Journal of*

Geotechnical and Geoenvironmental Engineering, ASCE, 123(11). 1562-1574.

- Bowles, J. E. (1982). *Foundation design and analysis*. McGraw-Hill, New York, 285pp.
- Briaud, J.L. (2007). Spread footing on sand: load settlement curve approach. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 133(8): 905-920.
- Breeveld, B. J. S. (2013). Modelling the Interaction between Structure and Soil for Shallow Foundations-A Computational Modelling Approach (Doctoral dissertation, TU Delft, Delft University of Technology).
- Burland, J.B. & Burbidge, M.C. (1985). Settlement of foundations on sand and gravel. *Proceedings, Institutionof Civil Engineers*, 78(1): 1325-1381.
- CSI Analysis Reference Manual for SAP2000®, ETABS®, SAFE® and CSiBridge™ (2010), ISO# GEN062708M1 Rev.4 Berkeley, California.
- Das, B. M. (2008). *Advanced Soil mechanics*: Tylor & Frances, 88-149 pp.
- Das, B. M. (2009). *Elastic settlement of shallow foundations on granular soil: a critical review*. Geological Engineering, University of Wisconsin-Madison College of Engineering. Retrieved from http://gle.wisc.edu/wp-content/uploads/2013/07/Elastic-Settlement-Shallow-Foundations_A-Critical-Review-2.pdf
- DeBeer, E. & Martens, A. (1957). *Method of computation of an upper limit for the influence of heterogeneity of sand layers in the settlement of bridges*. Proceedings, 4th International Conference on Soil Mechanics and Foundation Engineering, London, 1: 275-281.

- Geotechdata, Soil elastic Young's modulus, Geotechdata.info (2016, April 3) Retrieved from http://www.geotechdata.info/parameter/soil-young's-modulus.html
- Holtz, R.D. & W.D. Kovacs (1981). *An Introduction to Geotechnical Engineering*, Prentice.Hall Inc., 733 pp.
- Hough, B.K. (1969). *Basic Soils Engineering*, Ronald Press, New York.
- Kausel, E., Roesset, J. (1974). *Soil structure interaction problems for nuclear containment structures*. American Society of Civil Engineers, New York.
- Kocak, S.; Mengi, Y. (2000). *A simple soil-structure interaction model, Applied Mathematical Modelling*. Volume 24, Page (607-635). Elsevier Science Inc.
- Maplsoft, a division of Waterloo Maple Inc. (2013). *Maple User Manual*. ISBN 978-1-926902-35-7
- Meyerhof, G.G. (1965). Shallow foundations. *Journal of the Soil Mechanics and Foundations Division*, ASCE, 91(2): 21-31
- Lai, C. G.; & Martinelli, M. (2013). *Soil-Structure Interaction Under Earthquake Loading: Theoretical Framework*. ALERT Doctoral School 2013 Soil-Structure Interaction, Page (3-43), The Alliance of Laboratories in Europe for Research and Technology.
- Peck, R.B. & Bazaraa, A.R.S.S. (1969). Discussion of paper by D'Appolonia et al, *Journal of the Soil Mechanics and Foundations Division, ASCE*, 95(3): 305-309.
- Schmertmann, J.H. (1970). Static cone to compute static settlement over sand. *Journal of the Soil Mechanics and Foundations Division, ASCE*, 96(3): 1011-1043.
- Terzaghi, K. & Peck, R.B. (1948). *Soil Mechanics in Engineering Practice*, 1st Edition, John Wiley and Sons, New York.

- Terzaghi, K. & Peck, R.B. (1967). *Soil Mechanics in Engineering Practice*, 2nd Edition, John Wiley and Sons, New York.
- Weisstein, Eric W. "Logistic Equation." From MathWorld--A Wolfram (2016, June 13) Web Resource. http://mathworld.wolfram.com/LogisticEquation.html.