concrete finite element mesh with Young's modulus (E_c) of 2.1E+4 MPa, unit weight of 24.0 kN/m^3, and poison's ratio of 0.15.

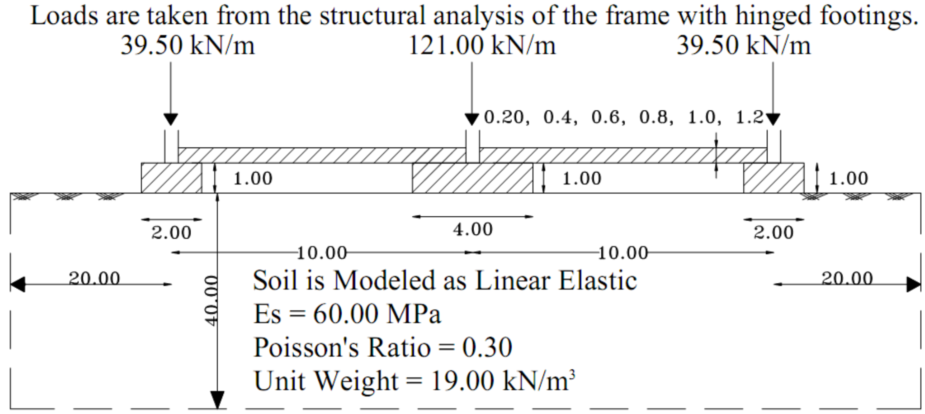


FIG. 3. Soil-Foundation system model

Figure (4) displays the resulted finite element mesh. Mesh generator based on the input of the geometry model automatically performs the generation of an appropriate finite element mesh and the generation of boundary conditions. The mesh was chosen to be very fine to neglect the effect of the size of meshes on results.

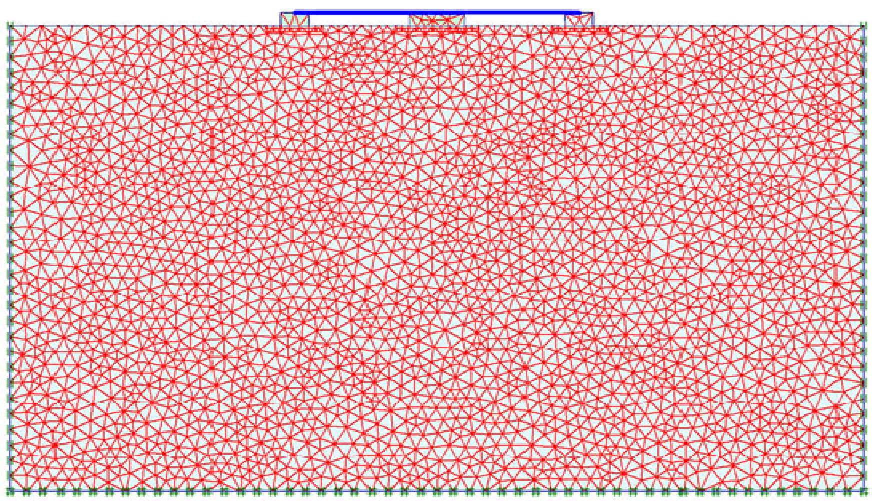


FIG. 4. Generated finite element mesh

RESULTS AND DEISCUSSION

Differential Settlement

To display the effect of the rigidity of the tie slab on the settlement and the differential settlement, settlement ratio (S/S_{max}) is depicted. It relates any point settlement by the maximum settlement under the footings. Figure (5) shows the settlement ratio under the footings. The horizontal axis of the figure represent the X-coordination of the foundation system model in PLAXIS, and settlement ratio represented in the vertical axis. It can be seen that, the increase of slab thickness leads to decrease in the corresponding differential settlement. It is the result of increasing of outer footing settlement and decreasing of the inner footing settlement. In addition, the tie-slab increases the tilting of the outer footing because the slab is connected with the half width of the footing only. Therefore, the use of tie beams that connect footings should be extended to the edge of the outer footings, or the tilting should be accurately calculated and checked according to the standards requirements; we do not have simple yet method to accurately calculate this resulted tilting.

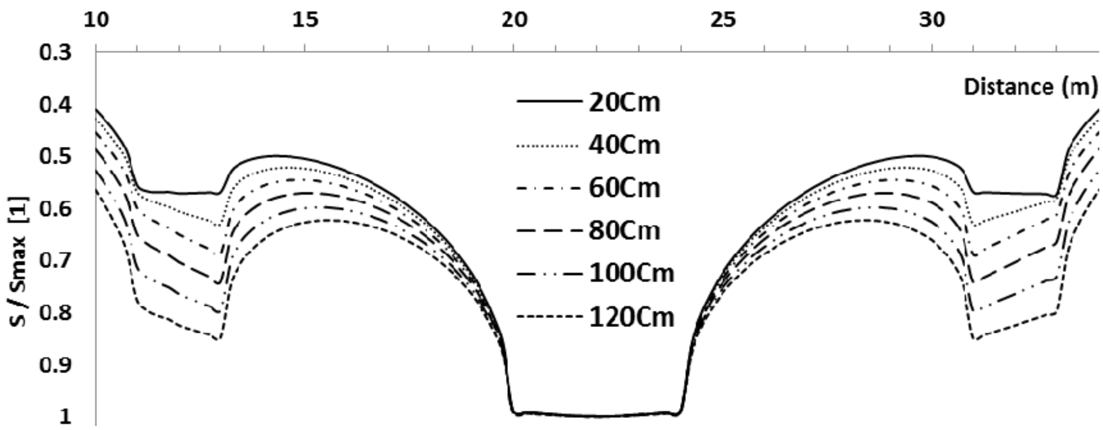


FIG. 5. Settlement ratio under foundations for different tie-slab thicknesses.

Dimensionless differential settlement (Δ) between the mid-width of the corner and inner footings at each thickness was depicted by using the following equation:

$$\Delta = \left(\frac{\Delta s}{L}\right) x \left(\frac{E_s}{P_s}\right) \quad \text{.............. (4)}$$

Where:

L is the distance between the middle point of corner footing to the middle point of inner footing = 10.00 m

E_s is the Young's modulus of the soil = 60.00 MPa

P_s is the distributed load acting on slabs = 10.00 kPa

The relation between the dimensionless differential settlement and the slab thicknesses was in Figure (6).

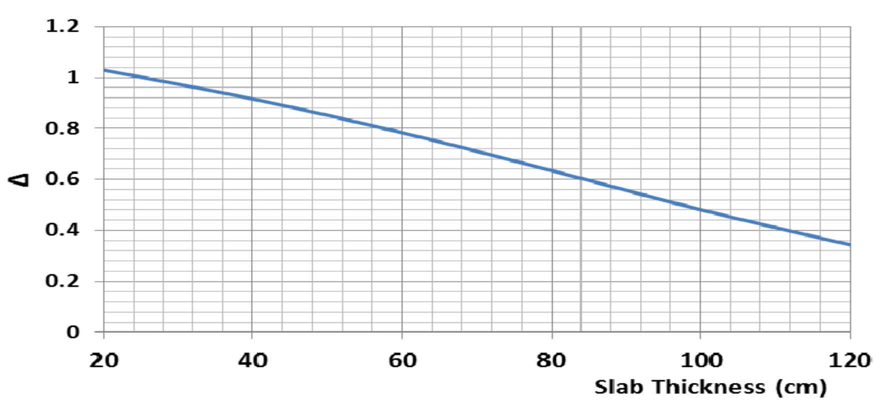
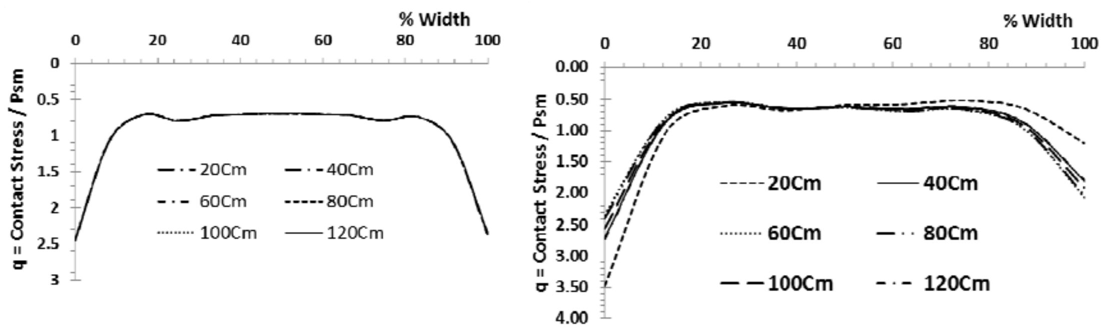


FIG. 6. Relation between dimensionless differential settlement and slab thickness

It can be seen that, the differential settlement decreases approximately linearly with the increase of tie slab thickness.

Contact Stress

The contact stress under the foundation is obtained from the output of the perpendicular force to the interface element. The dimensionless contact stress with respect to the average contact stress is obtained, as shown in Figure (7). It was found that, the dimensionless contact stress under the inner footing, (7-a), is almost the same for different tie slab thicknesses. While for the outer footing, (7-b), the contact stress was found unsymmetrically, because the tie slab connects the half width of the outer footings. This explain the tilting of the footing, as contact stress under the tied side is much larger than other side. This concentration of the stress also may lead to soil failure.



(a) inner footing (b) outer footing

FIG. 7. Dimensionless contact stress under inner and outer footings for different tie-slab thicknesses

Figure (8) shows the relation between the average contact stresses (P_{sm}) with slab thicknesses under the inner and outer footings.

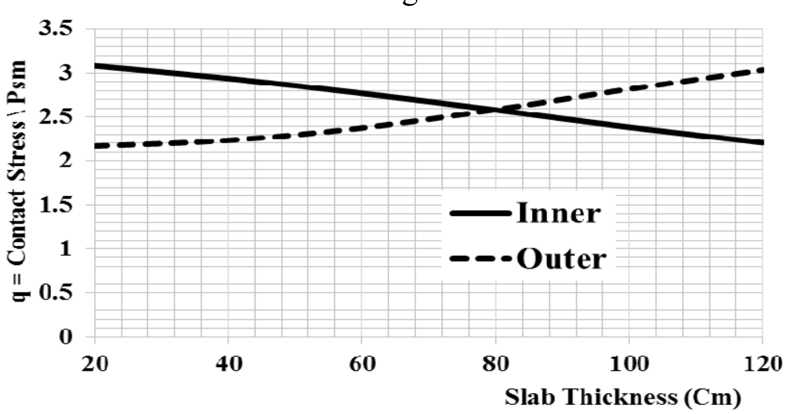


FIG. 8. Relation between average contact stresses with the slab thicknesses

It can be investigated that, the increase of the slab thickness leads to increase Psm under outer footing and decrease Psm under inner footing. This explain the damping of the differential settlement under the foundation system. This redistribution of contact stress is explained by the redistribution of the acting load on the footing due to the tie-slab rigidity. The increase of Psm under outer footing leads to increase the settlement more than that estimated without soil structure interaction. In addition, the resulted settlement under inner footing is less than that resulted without including soil structure interaction in the analysis. The redistribution of the loads was taking action on foundation level without change in the normal force in the walls that calculated from frame structural analysis with representing the foundations as hinged supports.

CONCLUSIONS

From the Figures and findings, the following can be summarized:

1. The increase of tie slab thickness leads to decrease in the resulted differential settlement.
2. The differential settlement decreases approximately linear with the increase of tie slab thickness.
3. When the tie slab not extended to the edge of the outer footings, the increase of tie slab thickness leads to increase of tilting of the outer footings. It should be accurately calculated and checked according to the standards requirements.
4. If the tilting of the outer footing is more than the allowable tilting, increase the tie slab rigidity and extend it to the outer footings edges. It may lead to decrease the tilting.
5. The depth of the tie slab does not affect the distribution of the contact stress under the inner footing.
6. Distribution of contact stress under outer footing is unsymmetrically, because the tie slab connects half width of the outer footings with the inner footing.
7. Concentration of the outer footing stresses in one-side possibly will leads to soil failure under the footing.
8. Increasing the depth of the tie slab is decreasing the average contact stress under inner footing, and increasing the average contact stress under outer footings. It relates with the distribution of the loads acting on the footings due to the rigidity of the tie slab.
9. The redistribution of the loads was taking action on the foundation level that leads to change in the acting loads on the footings and walls. It mean that tie slabs shall affect the straining actions of itself and superstructure members.

RECOMMENDATONS

1- Extend the tie beams that connect footings to the edge of the outer footings. We need many researches to evaluate the tilting exactly considering the effect of soil structure interaction, and then checked with the allowable tilting.

2- Increase the dimensions of the outer footings. The resulted average contact stress under outer footing is more than that calculated using conventional analysis. It the result of tie beams and superstructure effects.

3- Use appropriate rigidity for the tie beams to resist the differential settlement. We cannot specify exactly the degree of the rigidity of the foundations according to the soil structure interaction.

4- Increase the reinforcement if you increased the tie beams thicknesses, because the damped differential settlement causes large straining actions. These straining actions cannot be estimated using the conventional analysis that represents uniform contact stresses under footings.
5- Use a geotechnical finite element technique during the structural analysis of the superstructure with representing the soil by a suitable constitutive law.

ACKNOWLEDGMENTS

Praise and glory are due to ALLAH whom we attribute all our knowledge and success in our life. We would like to express sincere appreciation and deep gratitude to Prof. Dr. El-Kadi, Farouk for great effort for solving all problems during the research stages. Furthermore, the researchers are grateful to the Soil Structure Interaction Group in Egypt (SSIE). Finally, special thanks to Prof. PE. Dar Hao Chen and all Geo-Hubei team for they encouragement that made this research possible.

REFERENCES

Boussinesq, M.J. (1885), Application Des Potentiels, a l'Etude de l'Equilibre et du mouvement Des Solides Elastiques.

El-Kadi, F. (1967), Die Statische Berechnung Von Grundungsbalken und Grundungsplatten. Mitt. Inst. Verkehrswasserbau, Grundbau und Bodenmechanick der TH. Achen, VGB 42.

ElKadi, F. (1978a), Contact Pressure under Beam with Variable Moment of Inertia. The Bulletin of the Faculty of Engineering, Ain Shams University. No.8, PP.166-172.

El-Kadi, F. (1978b), Damped Differential Settlement for two Spans Structure. The Bulletin of the Faculty of Engineering, Ain Shams University. No.8, PP.130-142.

El-Kadi, F. and El-Nahhas, F. (1985a), Contact Pressure Distribution under Continuous Foundations of Multistory Structures. The Bulletin of the Faculty of Engineering, Ain Shams University. 17, PP.327-342.

El-Kadi, F. and El-Nahhas, F. (1985b), Some Analytical Aspects of Soil-Structure Interaction of Shallow Foundations. Proceedings of Tenth International Congress for Statistics, Computer Since, Social and Demographic Research, vol.4, PP.65-82.

El-Nahhas, F. (1975) Contact Pressure under Rectangular Plates Loaded at the Edges. M. Sc. Thesis, Faculty of Engineering, Ain Shams University.

Kany (1954), Beitrag Zur Berechung von Grundungskorpern auf nachgiegar Unterlage, Dissertation TH Darmstadt.

Kany (1959), Berechnung von Flachengrundungen, Berlin, W.Ernst U. Shon.

Ohde (1942), Die Berechung der Sohldruckverteilung unter Grundungskorpern. Bauingenieur 23, S.99 und 122.

"Effect of Floor Rigidity on Contact Stress and Differential Settlement"

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ABSTRACT: This paper presents the effect of soil, foundation, and superstructure interaction on the contact stress and differential settlement. In the recent ways of design, designers tried to resist the differential settlement by tie beams that connect the foundations. It is a complicated problem to calculate the differential settlement under the foundations taking the effect of the soil structure interaction. In addition, design of the tie beams that can resist the differential settlement by its rigidity only, results a huge beam section with a huge reinforcement. Usually the tie beams are constructed as flexible rigidity due to the thickness-length ratio. Therefore, the tie beams cannot resist the differential settlement alone and the superstructure members also shall work together with the tie beams. This paper presents the effect of the superstructure floor only without tie-beams on the contact stress and differential settlement. Floor rigidity has a significant effect on the contact stress that increases the outer footing contact stress and decreases the contact stress under inner footing. This interaction leads to damp the differential settlement under foundations. The floor rigidity affect the differential settlement and the differential settlement affect the straining actions acting on the floor. In addition, the straining actions affect the design of the floor sections that affect the floor rigidity. This closed form solution still in need to more researches to simplify the solution. Nowadays, it can be solved using a geotechnical finite element programs that can simulate the superstructure members. Therefore, calculation of the secondary stresses on the floors concerning differential settlement calculated without soil structure interaction is wrong.

INTRODUCTION

The prediction of contact stress and settlement under foundations depend on model superstructure, foundations, soil, and their simultaneous interaction. This represents a complex problem. The exact distribution of contact stress is highly indeterminate problem so the study for such case is still in need for more sophisticated yet simple way for calculation, for both geotechnical academic researchers and the practical structural engineers. There are three available methods to calculate contact stress under foundations, as following:

1- Conventional analysis.
2- Subgrade reaction theory.
3- Numerical analysis applying different constitutive laws.

Conventional Analysis

In this analysis, the contact stress is determined from pure equilibrium equation and the dimensions of foundation neglecting the deformation of both foundation and subsoil. Foundation is assumed initially rigid so the contact plane under foundation remains plain after load application. Only rigid body motion as translation or rotation is considered. The soil reaction of the foundation is assumed to follow the planer distribution, while the centroid of the soil pressure coincides with the line of action of the resultant force of all loads acting on this foundation. This method is preferable and the least exact method for most cases. The contact stress under a case of symmetrical footing is calculated using Navier equation.

A.C.I. Committee 436 (1966) suggested using linear distribution of contact stress under combined footing or rafting foundation if one of the following two conditions is satisfied

1) Column spacing is less than 1.75 / μ

$$\mu = \sqrt[4]{\frac{f * Ks * b}{4 * E * I}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where:

f = Size or shape factor for foundation on a particular type of soil.

K_s = Basic value of coefficient of vertical subgrade reaction for square area with width = 1ft (0.3054m).

b = Width of foundation.

E = Modulus of elasticity of foundation material.

I = Moment of inertia of the foundation perpendicular to the direction of the spacing between columns.

2) Raft foundation supporting a rigid superstructure.

Subgrade Reaction Theory

The model assumes that the soil acts as a bed of evenly spaced, independent, linear springs. It also assumes that each spring deforms in response to the vertical stress applied directly to that spring, and does not transmit any shear stress to the adjacent springs. However, in real soils the displacement distribution is continuous. The deflection under a load can occur beyond the edge of the slab and the deflection diminished at some finite distance. It considered not realistic model because it cannot take into account the effect of shear transmission of stresses to adjacent support elements. Consequently, the distributions of displacements are continuous. The deflection of a point in the soil occurs not just because of the stress acting at that particular point, but it is also influenced by a progressively decreasing extent by stresses at points further away.

Numerical Analysis Applying Different Constitutive Laws

Due to the limitations of the above methods, a method that can take effect of the shear transmission and good distribution of the contact stress is required. Models that are more realistic are recommended to use, but its complexity make it less attractive than the above methods. Therefore, the numerical analysis using different constitutive laws is recommended. By numerical analysis, the effect of the foundation rigidity on the contact stress can be taken into consideration. Figure (1) shows the numerical solution for contact stress under foundations on elastic media with different rigidities, after El-Kadi (1967), where (k) represents the coefficient of rigidity of the footing. Numerical analysis become complex when the superstructure modeled with the footings. Therefore, finite element method based on the numerical analysis is highly recommended for study the soil structure interaction. Using finite element, the soil with foundation and superstructure can be simulated. Soil can be modeled as mesh elements using different constitutive laws such as elastic or plastic models. Foundation and superstructure can be molded as beam "line" elements. The main concept of the calculation in finite element analysis is the compatibility equation.

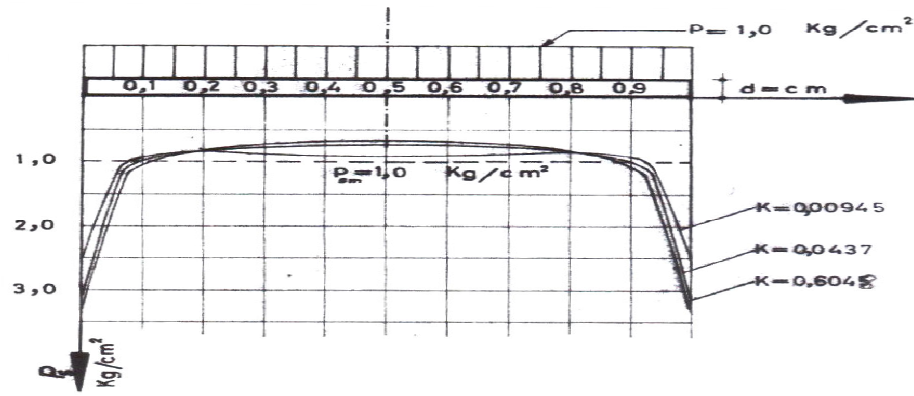

FIG. 1. Numerical solution for contact stress under foundations on elastic media with different rigidities, after El-Kadi (1967)

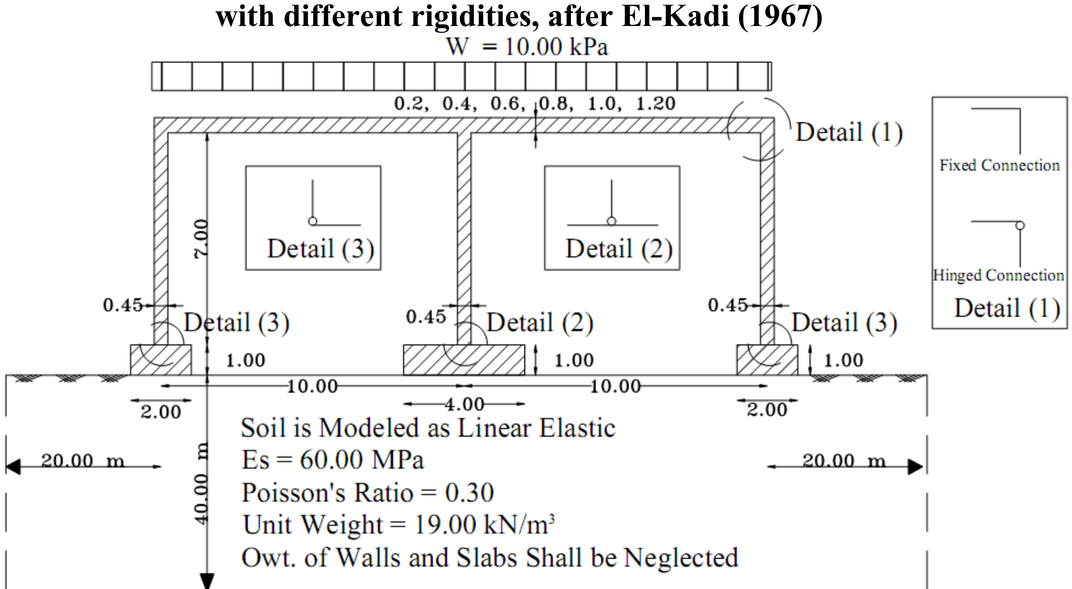

FIG. 2. Two bay frame model

MODELING

Two bay concrete frame was modeled using PLAXIS 2D V2012. It has bay span of 10.00-meter and 7.00-meter height, as shown in Figure (2). The inner footing of this frame was 4.00-meter breadth and 1.00-meter thickness, where the corner footings were 2.00-meter breadth and 1.00-meter thickness. The corner and inner walls were 0.45-meter thickness. Rotation of the walls was permitted at footings. Different slabs with different thicknesses of 0.20, 0.40, 0.60, 0.80, 1.00, and 1.20 meters were modeled. The applied load is distributed load of 10.0 kPa for different thicknesses. Own weights of walls and slabs were neglected. Walls connection were simulated by two models; hinge and fixed connections. For hinged connection, the translation in x-direction for the slab was not permitted to satisfy the stability requirements. A sandy soil was modeled using linear elastic constitutive law with the parameters that shown in Figure (2).

ANALYSIS AND DEISCUSSION

Differential Settlement

To display the effect of the floor rigidity on the settlement and differential settlement, settlement ratio is depicted. It relates any point settlement by the maximum settlement under the foundations. Figure (3) shows the settlement ratio under the foundations for the frame with fixed walls, and Figure (4) presents the settlement ratio for the frame with hinged walls.

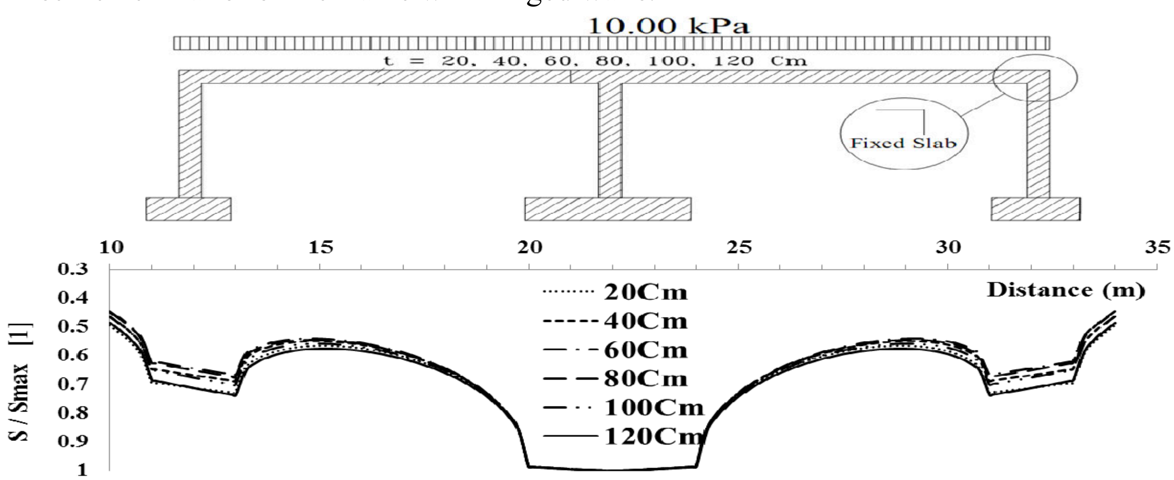

FIG. 3. Settlement ratio under foundations for frame with fixed wall

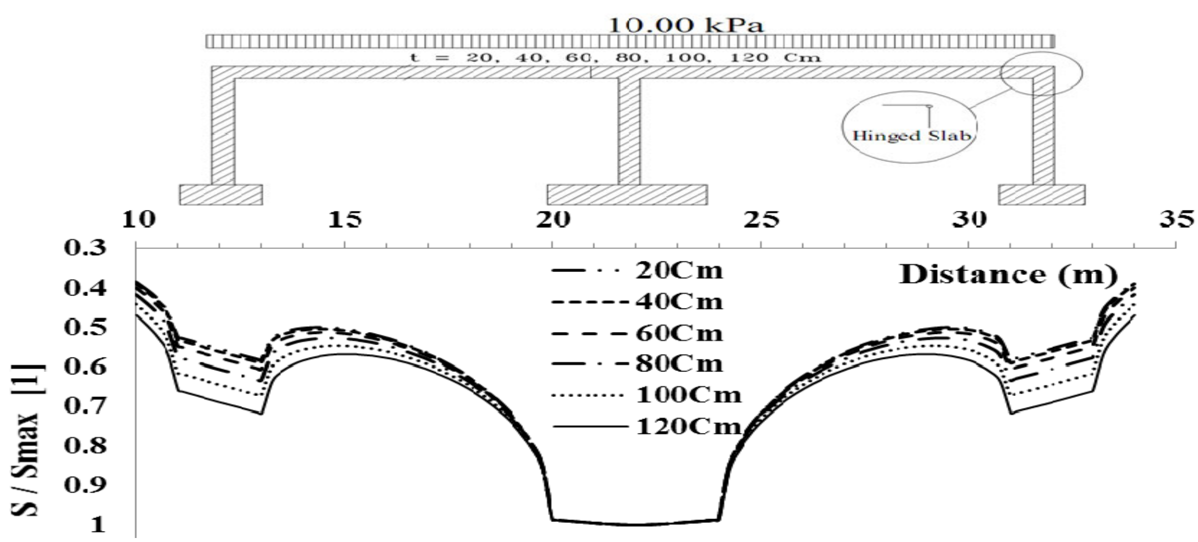

FIG. 4. Settlement ratio under foundations for different slab thicknesses

It can be seen that, the differential settlement of the hinged wall model decreases with the increase of slab thickness. This interaction is related to the redistribution of the loads by the floor rigidity. Floor rigidity of the hinged wall model works on increase the outer reaction and decrease the inner reaction. In the fixed wall model, it cab seen that the interaction is not clear. To clarify this interaction, relation between the differential settlement and the floor rigidity is required. Figure (5) shows the relation between the dimensionless differential settlements with the coefficient of the rigidity (K_f). The dimensionless differential settlement between the mid-width of the corner and inner footings at different thicknesses of the slab was calculated by equation (2). Settlement has positive relationship with the acting load, so the dimensionless settlement should be divided by the load. While, Young's modulus is in inverse relationship with the settlement, so the dimensionless differential settlement should be multiplied by the Young's modulus of the soil.

$$\Delta = \left(\frac{\Delta s}{L}\right) x \left(\frac{Es}{Ps}\right) \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Where:

L is the distance between the middle point of corner footing and the middle point of inner footing = 10.00 m
E_s is the Young's modulus of the soil = 60.00 MPa
P_s is the distributed load acting on slabs = 10.00 kPa

Coefficient of the rigidity of the foundation soil system is calculated by DIN Standards (2005), equation (3).

$$K_f = \left(\frac{ds}{L}\right)^3 x \left(\frac{Ec}{12Es}\right) \quad \ldots\ldots\ldots\ldots (3)$$

Where:

K_f is the dimensionless coefficient of rigidity of foundation soil system
d_s is the slab thickness
L is the total slab length = 20.00 m
E_c is the Young's modulus of the concrete = 2.10E+04 MPa
E_s is the Young's modulus of the soil = 60.00 MPa

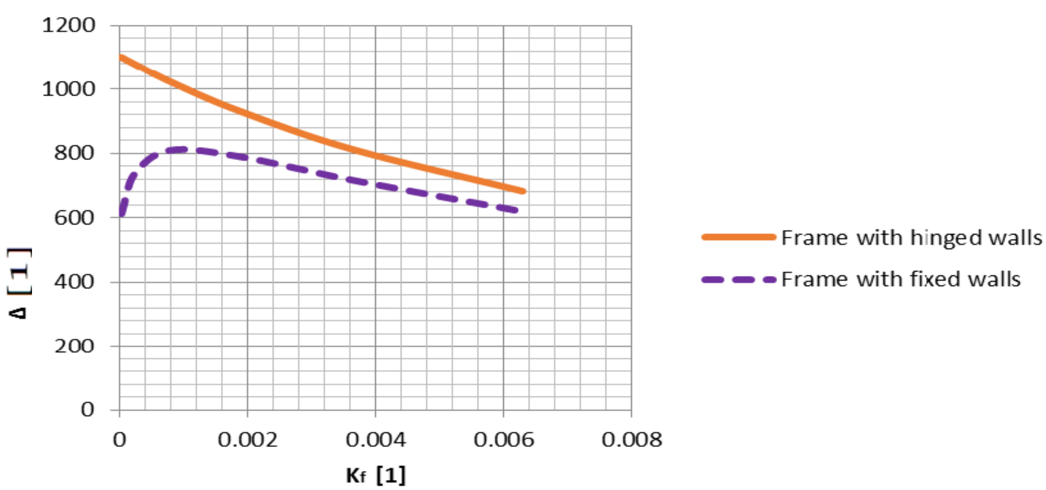

FIG. 5. Effect of floor rigidity on the differential settlement