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Impact of Shallow Foundations Rigidity on Low-rise Buildings Performance Resting on Varying Ground Conditions

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ABSTRACT: Background: Due to the extent of housing development in hilly terrains in many countries, ground preparation and re-leveling have come into effect. So, the construction of buildings on subsoil that comprises fill and cut becomes inevitable. Objective: Increasing the structure stiffness to minimize the differential settlement is one of the options that could be utilized for such cases. In the current study, a parametric study was performed to assess the influence of the stiffness of structures on reinforced concrete framed structures resting on variable ground conditions using finite element models. The investigated structure rests partially on dense sand and partially on loose, dense sandy soil. The structure stiffness varied with different tie beam depths. The distortion angle values were compared with the safe limit specified in standards to reduce cracks in brick walls. The results are presented in the form of curves, which allow engineers to evaluate the reasonable structure stiffness. Current research has shown that the tie beam rigidity can significantly reduce the distortion angle and allow the shallow foundation to be considered as a convenient option despite being located on a hill. Conclusion: The foundation rigidity improves the building's rigidity as a whole. Increasing tie beam rigidity decreases the differential settlement and the building distortion, reducing the straining actions on reinforced concrete elements and limiting the cracking of brick walls.

Keywords: Differential settlement, Angular distortion, Soil Foundation, Tilt, Low rise Buildings

INTRODUCTION

Variation in ground conditions below one structure could result in structural distress.Therefore,the effect of these conditions on the structure behavior should be investigated. The first step in the design process of structures is the site investigation which is carried out to measure the validity of the soil to support such structures. This validation lets us specify the number of parameters necessary to ensure the efficiency of buildings, such as a foundation type (shallow or deep), foundation rigidity, foundations system, and top floor rigidity. Mountains and Hilly terrains were found to be used as the foundation of buildings in some locations. These areas are not suitable for construction unless significant ground preparations include ground preparation, and include ground preparation, and cut earthworks. Hence, these earthworks lead to variations in ground conditions beneath one building. This would significantly impact the building performance, significantly impact the building performance, particularly for residential and low-rise buildings normally found on shallow foundations.

Many causes give rise to building damage, such as concrete shrinkage, thermal expansion or ground movements. Damages due to ground movements largely occur because of numerous soil conditions. Such damages may be categorized into three main types, which should initially be defined: 'aesthetic', 'serviceability' and 'stability'. The first comprises damage that affects the appearance of the building such as the façade paints hair cracks. The second includes fracturing of serviceability pipes and jamming in doors and windows. The third damage category includes preventative actions such as repairing or strengthening the structural elements. The ground settlement profile below the building can help in predicting the possible damage to buildings. (Charles and Skinner, 2004) defined settlement types into six categories according to uniformity, distortion and tilt of the building, as shown in Fig. 1. Type (i) is defined as a uniform settlement. Such settlements are not affecting the building elements. However, it may result from serviceability damage. Type (ii) is a uniform settlement with some rotation for the whole building that might occur because of the high rigidity of the building to act as a rigid body. If the ground settlement profile is not uniform, whether the soil properties are different or the loading conditions over the soil are varied, types (iii), (iv), (v), and (vi) will occur and the building may be distorted.

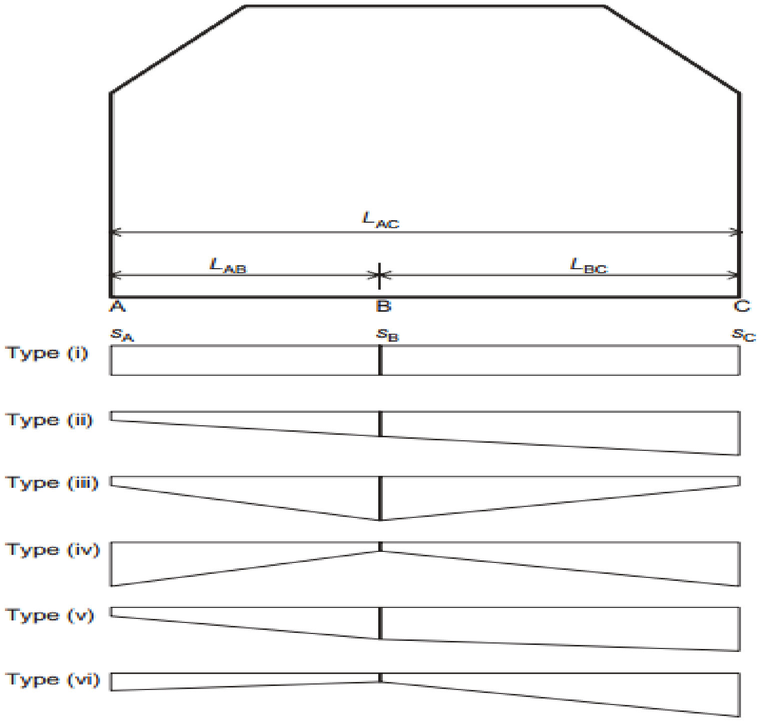

Fig. 1. Basic Types of Foundation Settlement (Charles and Skinner, 2004)

Differential settlement (δ) is a definition that describes the difference in vertical ground movement. It is the difference between the maximum and minimum settlement between two points. Tilt (ω) describes the rotation of the building with no distortion. A small foundation tilt may not distort buildings, but excessive tilt may cause structural damage. The differential settlement divided by the distance over which the differential settlement occurs is called Angular distortion (β) (CFEM, 2006). (Skempton and Macdonald, 1956) suggested this definition as their criterion for building damage. The deflection ratio (Δ/l) is defined by (Polshin, D. E., 1957) as equivalent to angular distortion. It is the ratio of relative deflection (Δ) divided by the length of the deflected part, where the deflection (Δ) is the maximum settlement below the building.

As per different soil conditions, the building performance may be significantly affected. Many case histories were investigated in research to estimate the potential damage of structures due to different site conditions such as adjacent deep excavation, open excavation and ground subsidence (Kog and Ph, 1978; Boone, 1996; Boone, Westland and Nusink, 1999; Lin *et al.*, 2000; Charles and Skinner, 2004; Anastasopoulos, 2013; Franke *et al.*, 2019). An analytical and large-scale experimental method was employed to quantify RC frame response to excavation-induced settlement (Laefer *et al.*, 2009). The superstructure and its foundation rigidity play a central role in resisting deformation due to different soil conditions. The building distortion would be converted to the rotation when the structure is rigid. To improve the building's rigidity, reasonable rigid foundations should be used. Moreover, the frame action may be developed to increase the overall building stiffness (Almasri and Taqieddin, 2009; Arapakou and Papadopoulos, 2012; Hany Farouk 1, A.M. ASCE, M.Sc. and Mohammed Farouk 2, 2014). Building damage caused by ground movement may be evaluated using several approaches. The first approach is the observational method which is an effective way that has been used to survey the damage of the building for many existing cases and develop guidelines for future assessment of similar cases (Meyerhof, 1956; Skempton and Macdonald, 1956; Bjerrum, 1963; BRE, 1995; Zhang and Ng, 2007). Skempton and MacDonald 1956 investigated data from 98 existing buildings, 40 of which showed signs of damage. The allowable settlement and angular distortion are suggested as a basis for the design. The angular distortion which causes cracking of the panels in frame buildings was found to be more than 1/300. (Meyerhof, 1956; Bjerrum, 1963) used the same criteria to investigate the limit of the distortion angle, which causes cracks in the brick walls.

(Boscardin and Cording, 1989) examined case studies of small frame structures and brick-bearing wall structure performance located near open open-cut excavations or tunnels and compared the results with analytic studies. The effect of horizontal strain, differential settlement, and building orientation relative to the excavation is considered to investigate their effects on the building response. In Fig. 2, a line was drawn to show how the amount of damage is related to angular distortion and horizontal strain.

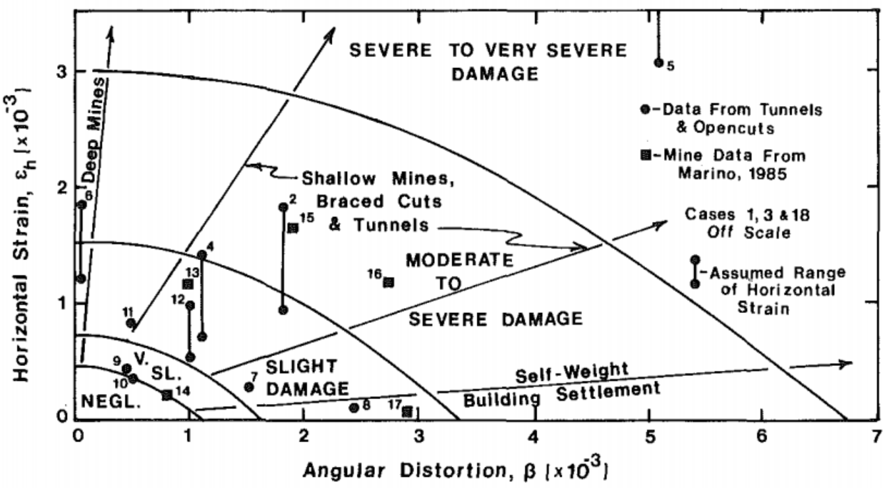

Fig. 2. Building Damage Corresponding to Angular Distortion and Horizontal Strain (Boscardin and Cording, 1989)

The second approach was concerned with the allowable settlement of buildings and used the concept that the onset of visible cracking is associated with a critical tensile strain (Polshin, D. E., 1957; Burland, J. B., and Wroth, 1975; Finno *et al.*, 2005). Recent works on the racking of filled frames with brick walls describe some full-scale tests on frames filled with brick walls; it was observed that visible cracking first occurs at the diagonal tensile strain of 0.115 percent. An elastic, weightless, and uniform beam of length L and height H with unit thickness is used to apply the concept of critical tensile strain, which helps illustrate several vital features. First, a bending or shear mode of deformation could occur. The bending mode causes direct tensile strain.

Nevertheless, the shear mode of deformation causes diagonal tensile strain. The physical model test is the third approach used to evaluate ground movement's effect on building behavior. This approach represents the building and soil with relatively large model scales, as shown in Fig. 3 (Son and Cording, 2005; Laefer *et al.*, 2009). The fourth approach is the finite element analysis to simulate the whole building with the subsoil to investigate the soil structure interaction (Son and Cording, 2005, 2007, 2011; Cording *et al.*, 2010).

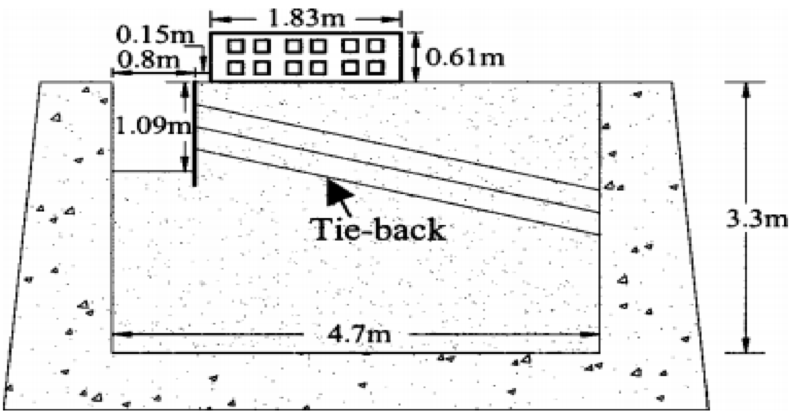

Fig. 3. Representing Building and Soil using Large Model Scale Tests (Son and Cording, 2007)

The previous studies were concerned with the effect of soil conditions on building performance and set definitions and techniques to expect the damage that might occur to buildings at different site conditions. The other abnormal foundation conditions usually cause excessive total and differential settlement, lateral movement, tilting and distortion of buildings. Therefore, improving the rigidity of the foundation is essential during the design stage to confirm their capacities to resist straining actions resulting from the differential settlement. Due to the wide variability generally encountered under buildings, even within one site, such assessment might be time-consuming and impractical. Standard guidelines would assist engineers in such cases to carry out their assessment reliably with ease, fast and in a standardized approach. The impact of the foundation rigidity and building floor stiffness on the whole building's performance was not studied sufficiently in the research. In this research, numerical models were employed to assess the effect of the variation of ground and rigidity of the structure on the performance of the structure. This study will validate the used approachesapproaches used in the literature and provide standard guidelines for typical design.

2. METHODOLOGY

In the current research, several modes or shapes of common ground variations typically observed during the construction of traditional buildings will be studied. A typical structural system commonly used with a typical foundations system will be considered for building. The current study focuses on low-rise buildings and residential villas with three stories and four spans. Numerical models are employed using PLAXIS 3D for building with the supporting soil. The parameters in models are as follows: Depths of tie beams, young’s modulus and friction angle of loose soil. Soil elements in PLAXIS are used to model the structure and the supporting soil with reasonable friction between different materials. The maximum settlement, distortion angle, and bending moments in beams are investigated for each studied case. The results were studied for different tie beam depths. The calculation of the distortion angle is determined using the maximum difference of vertical displacement divided by the horizontal distance between two points as per the Canadian Manual of foundations (CFEM, 2006), as shown in Fig. 4.

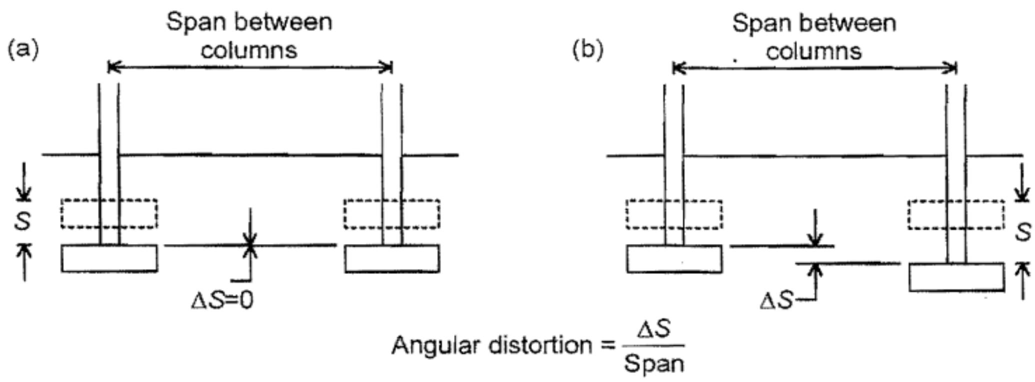

Fig. 4. Illustration of angular distortion calculation method of Angular Distortion for shallow foundations (CFEM, 2006)

2.1. Modelling Assumptions and Definitions

The suggested structure to study is a reinforced concrete building with three floors with isolated footings. The building was designed according to the Egyptian Code of Practice (ECP Committee-203) and performed using SAP2000 to simulate a 3D model for the structure, as shown in Fig. 5. Using the estimated geometry of the structure, PLAXIS 3D finite element models were developed in phases to assess the effect of the different ground conditions on the structure performance as shown in Fig. 6.

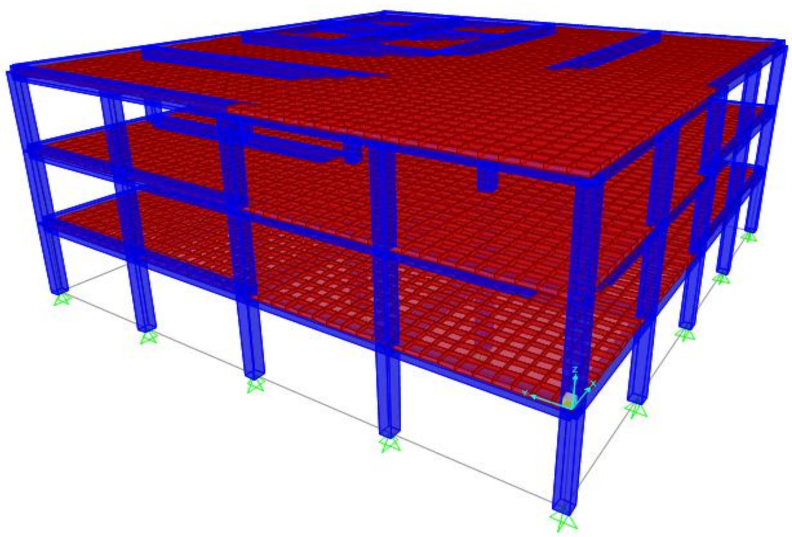

Fig. 5. SAP2000 3D model of the Investigated Building

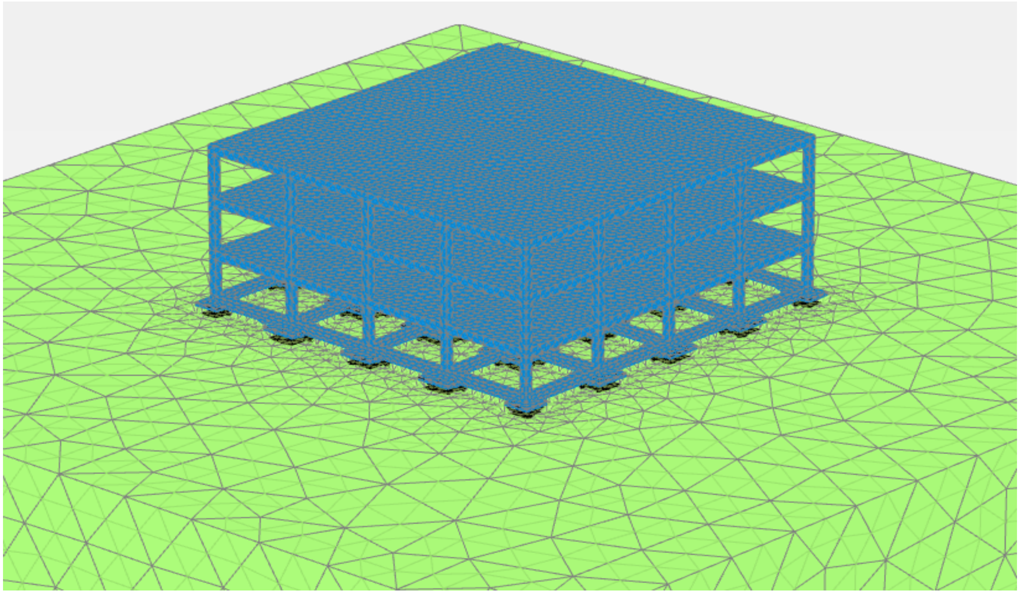

Fig. 6. Plaxis 3D Model of the investigated building with soil

The following phases were run: The superstructure with the estimated geometry resting on two different properties of sandy soils. The first type was assumed to be natural ground sand with a high young's modulus of 1000kPa and a friction angle of 46^0. Nevertheless, the second type of supporting soil properties is used as shown in Table 1. A further case was investigated, assuming the building rested on the same soil to be compared with the other cases.

Table 1. Soil Parameters

Phase	Parameters of Soil			
	Loose Soil		Dense Soil	
	Friction Angle (^{0})	Young's Modulus (MPa)	Friction Angle (^{0})	Young's Modulus (MPa)
1	28	10		
2	30	30		
3	36	50	45	100
4	40	70		
5	45	100		

The investigated structure layout shown in Fig. 5 is a three-story building with 4 bays in both directions, which may be described as follows: The statical system of the building was assumed to be solid slabs. Columns supported on isolated footing. Spacing between columns equals 5 m. Floor heights equal 3 m and isolated footing dimensions are estimated as per soil bearing capacity equals 1.5 kg/cm2. The structure geometry shown in Figs. 4, 5 and 6 was designed, sized and loaded according to the Egyptian Code of Practice (ECP Committee-203). Load cases and could be summarized as follows: Own weight of reinforced concrete equals 25 kN/m3, uniform floor load of 2.0 kPa, the uniform live load of 2.0 kPa, and uniform brick walls load of 3.5 kPa.

The compressive strength of the used reinforced concrete is 25 MPa with young's modulus 22000 MPa and Poisson's ratio 0.2. According to the finite element analysis of the structure, Table 2 shows the dimensions of the proposed dimensions of the structural parts.

Table 2. Building Geometry and Dimensions

Case	Building Parameters							
	Tie Beams (cm)		Columns (cm)		Floor Beams (cm)		Floor Slabs (cm)	Isolated Footing (cm)
	Width	Thickness	Width	Breadth	Width	Depth	Thickness	Dimensions
1		40						140 x 140 (Corner Footing)
2		60						
3		80						
4	25	100	40	40	25	50	16	190 x 190 (Edge Footings)
5		120						
6		140						
7		160						270 x 270 (Interior Footings)
8		200						

2.2. Finite Element Modelling

Superstructure geometry followed the design of the structure discussed before. The building model uses soil volume with a linear elastic material model. The strength of the interface between the superstructure and the soil was assumed to be 0.7 to simulate the interaction between the two types of materials.

3. RESULTS AND DISCUSSIONS

3.1. Settlement Profile

The studied structure is assumed to be supported partially on the cut (very dense sand) and fill (vert loose sand) shown in Fig. 7. To study the effect of the tie beam rigidity on the performance of the building, tie beam depth ranges from 40 cm to 200 cm with a width 25 cm. Angular distortion and the maximum settlement were recorded for each studied case and compared with each other.

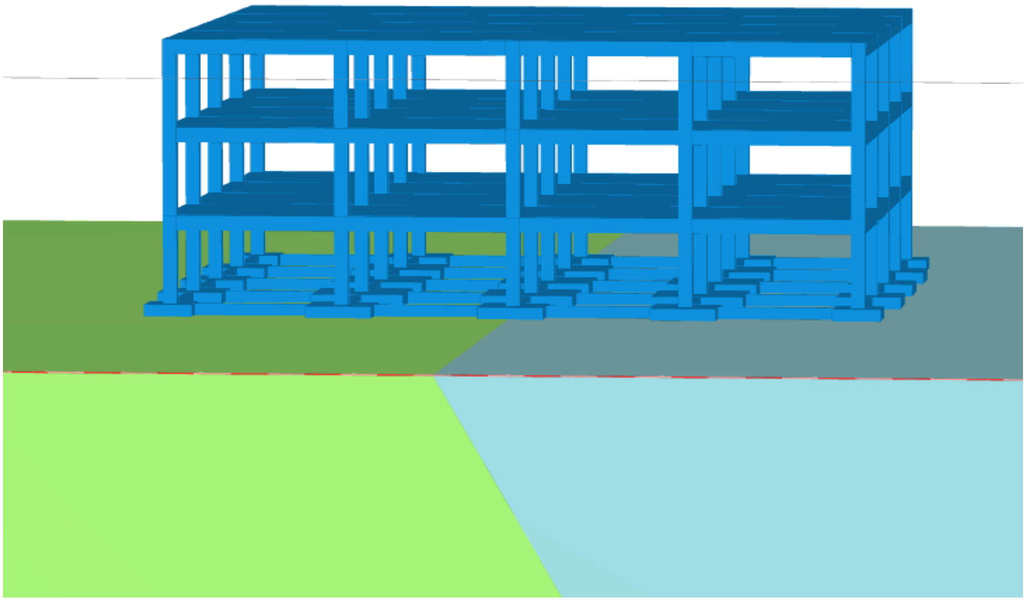

Fig. 7. Plaxis 3D model of a building showing subsoil condition

Figs. 8, 9, 10, 11 and 12 show the impact of the tie beam rigidity on the ground settlement along the building in the case of Emin/Emax = 10%, 30%, 50%, 70% and 100%. It is found that, for tie beam thickness less than 1.0 m, the settlement profile is almost the same. Moreover, the angular distortion of the middle bay between the loose sand and dense sand is great with small tilting, which means that the foundation of the building cannot withstand the soil's stiffness. When the tie beam depth increases to 1.0m, the foundation rigidity rises gradually, and the building rigidity improves adequately to prevent distortion induced by soil issues. After that, however, the tilting of the building increases. Tilting the building with a small distortion angle means that the buildings act as rigid bodies and rotate as one element. The resulting tilting should be considered in the case of construction on such soil conditions since such tilting would eventually lead to serviceability damages. The foundation helps convert the building distortion to tilting, preventing cracks and decreasing the straining actions exerted on the structural elements.

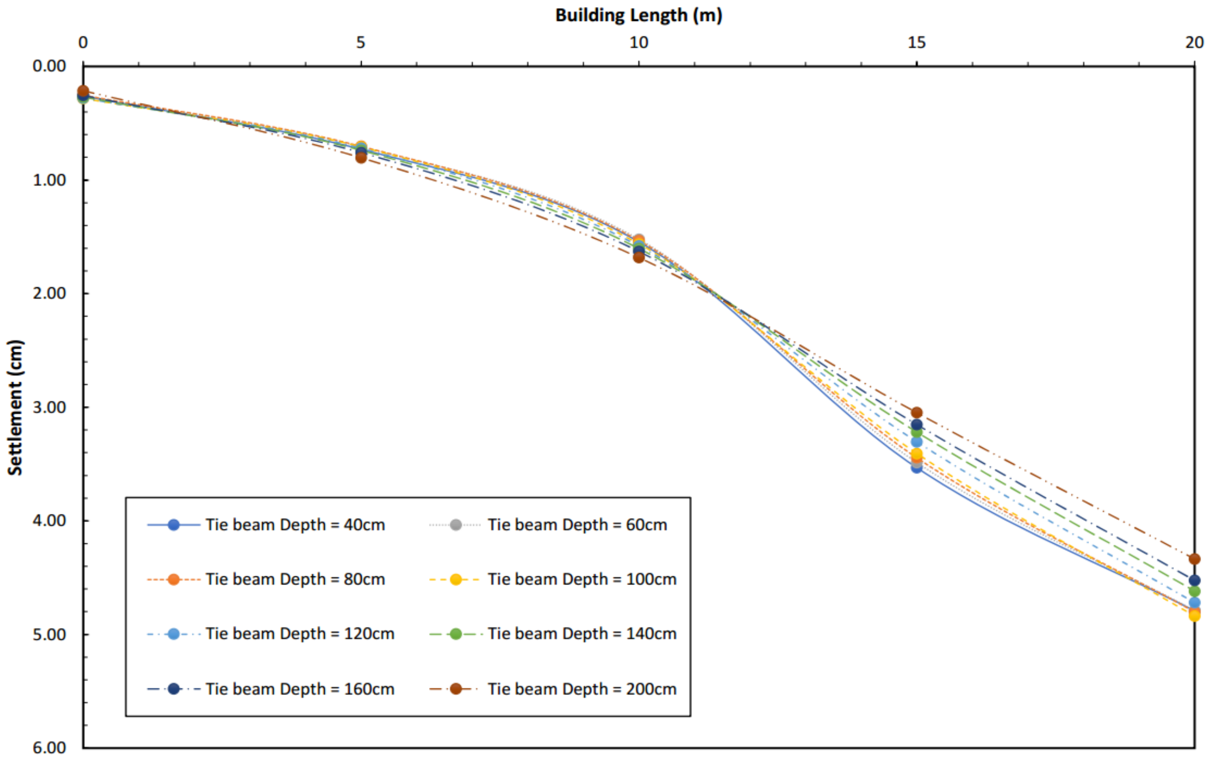

Fig. 8. Soil Settlement Profile Below Building using Different Tie beam Thicknessesat ratio of young's modulus of two types of soils equals 10%

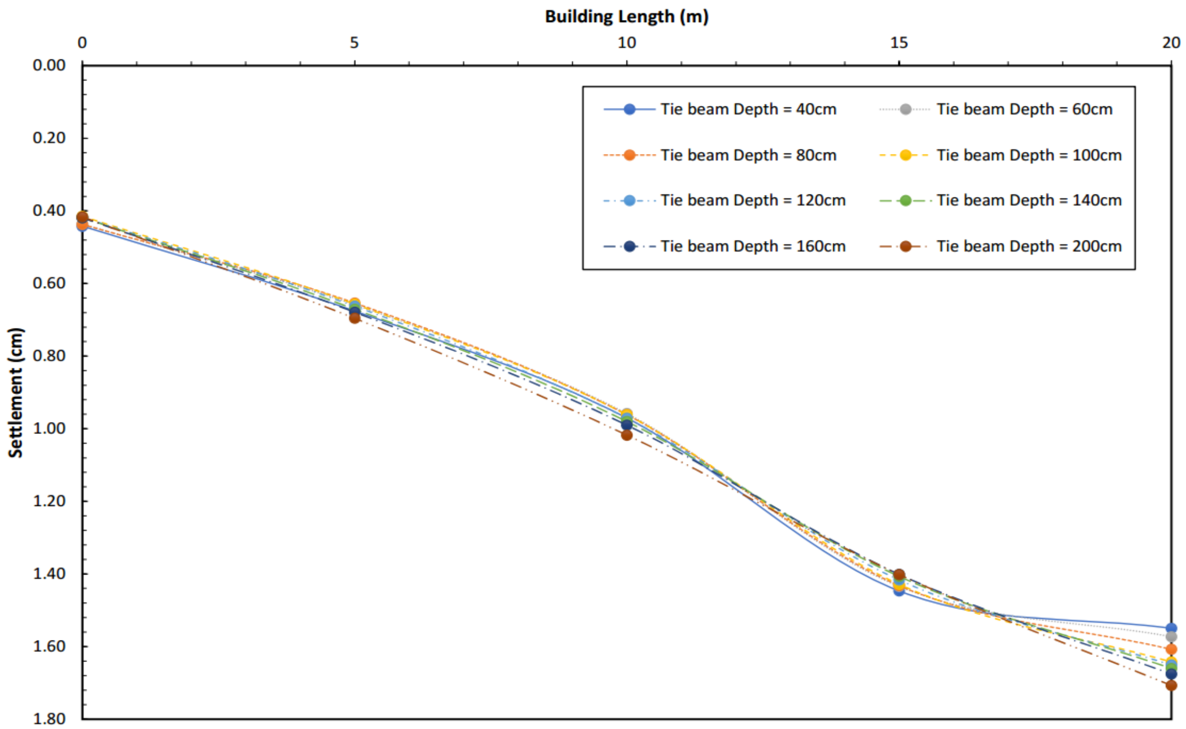

Fig. 9. Soil Settlement Profile Below Building using Different Tie beam Thicknesses at a ratio of young's modulus of two types of soils equals 30%

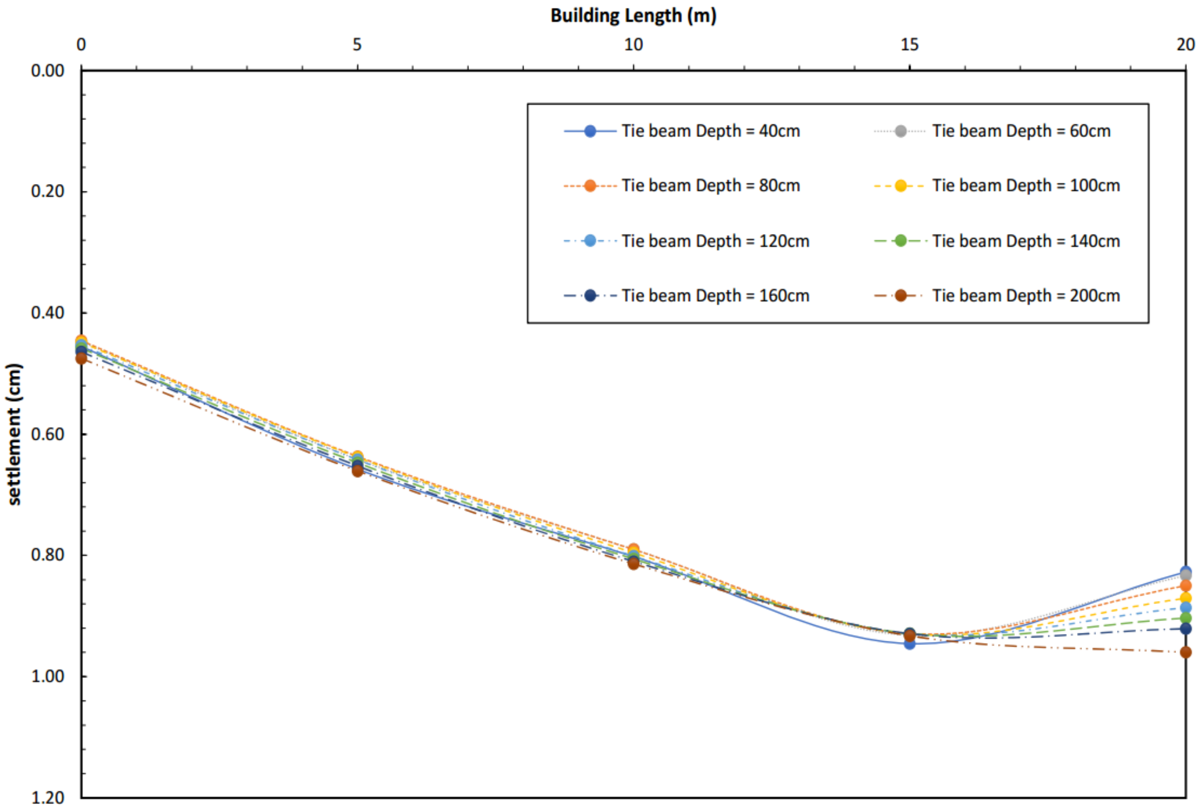

Fig. 10. Soil Settlement Profile Below Building using Different Tie beam Thicknesses at a ratio of young's modulus of two types of soils equals 50%

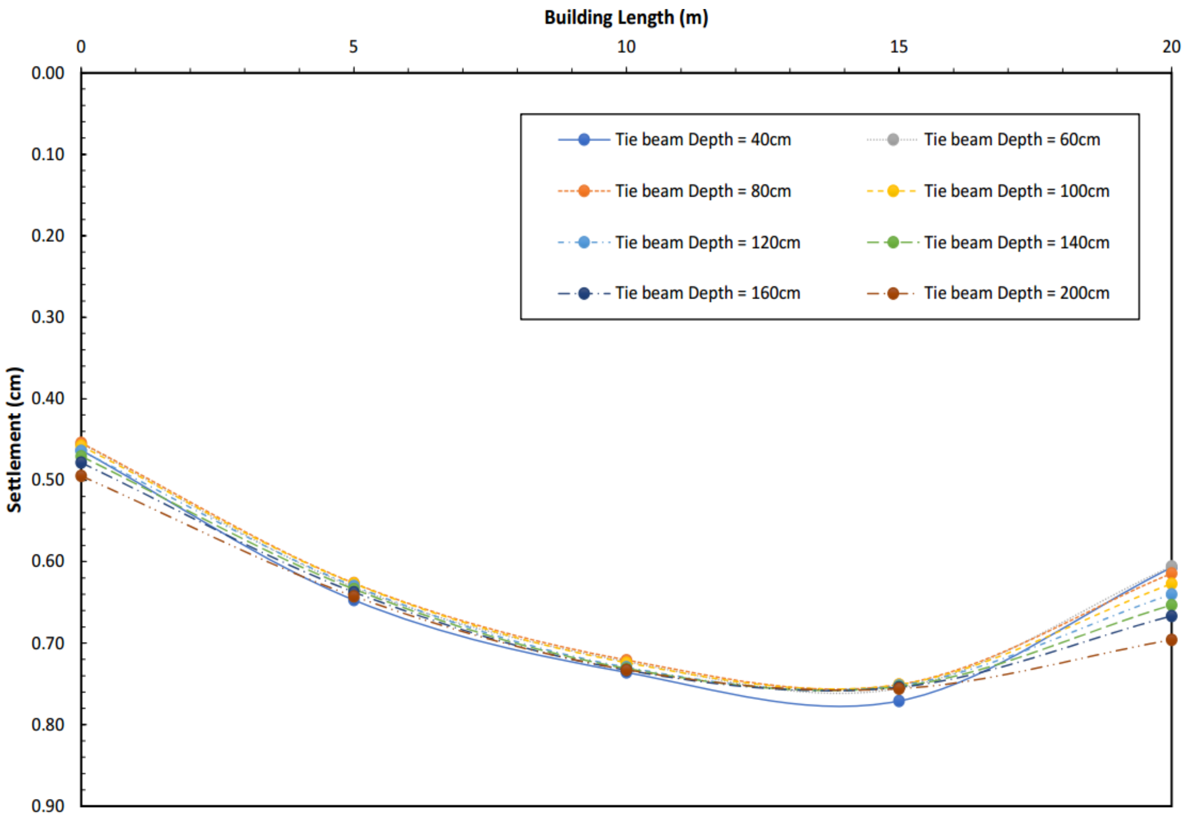

Fig. 11. Soil Settlement Profile Below Building using Different Tie beam Thicknesses at a ratio of young's modulus of two types of soils equals 70%

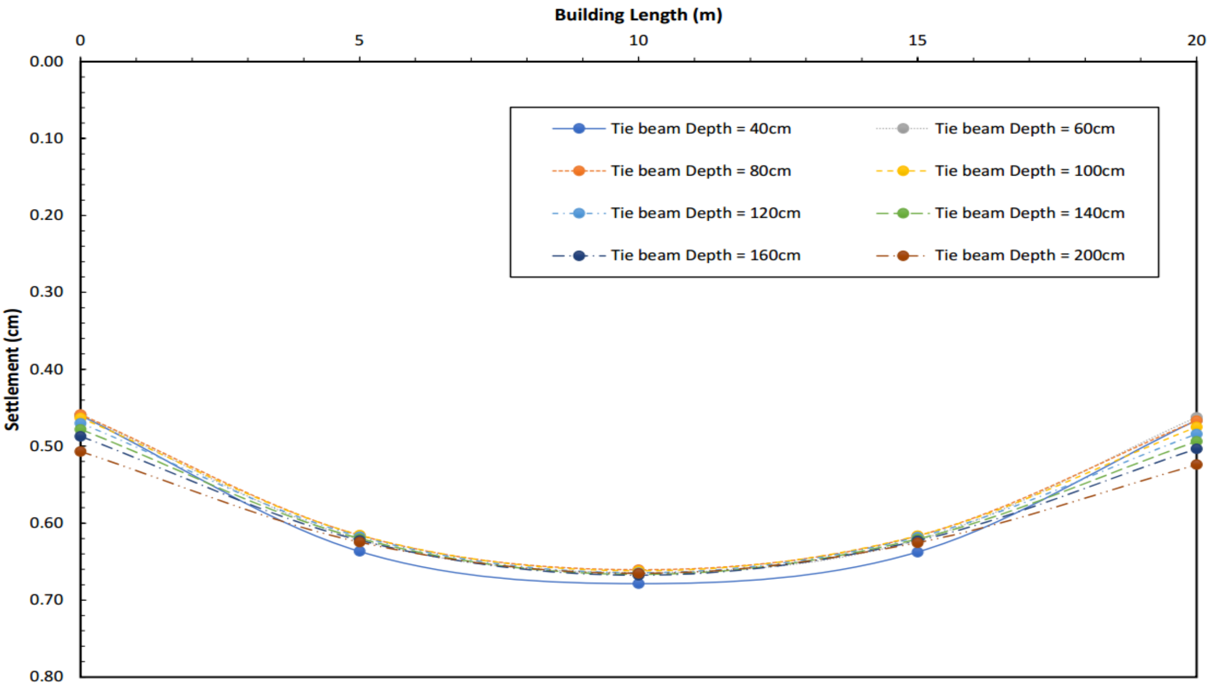

Fig. 8. Soil Settlement Profile Below Building using Different Tie beam Thicknesses at a ratio of young's modulus of two types of soils equals 100%

3.2. Angular Distortion

Fig. 13 shows the relationship between different ratios of young's modulus between the loose and dense soil and the angular distortion using different tie beam rigidities. It may be concluded that for Emin/Emax, more than 17% of the angular distortion reaches values less than 1/500. There is no need for tie beam depths of more than 40cm to resist building distortion. Furthermore, after Emin/Emax exceeds 33%, the angular distortion was increased between interior columns due to increasing settlement and decreased between the edge columns. The soil stresses below the foundations and the settlement profile were adjusted to be close to a parabolic curve with the maximum settlement at mid-span.

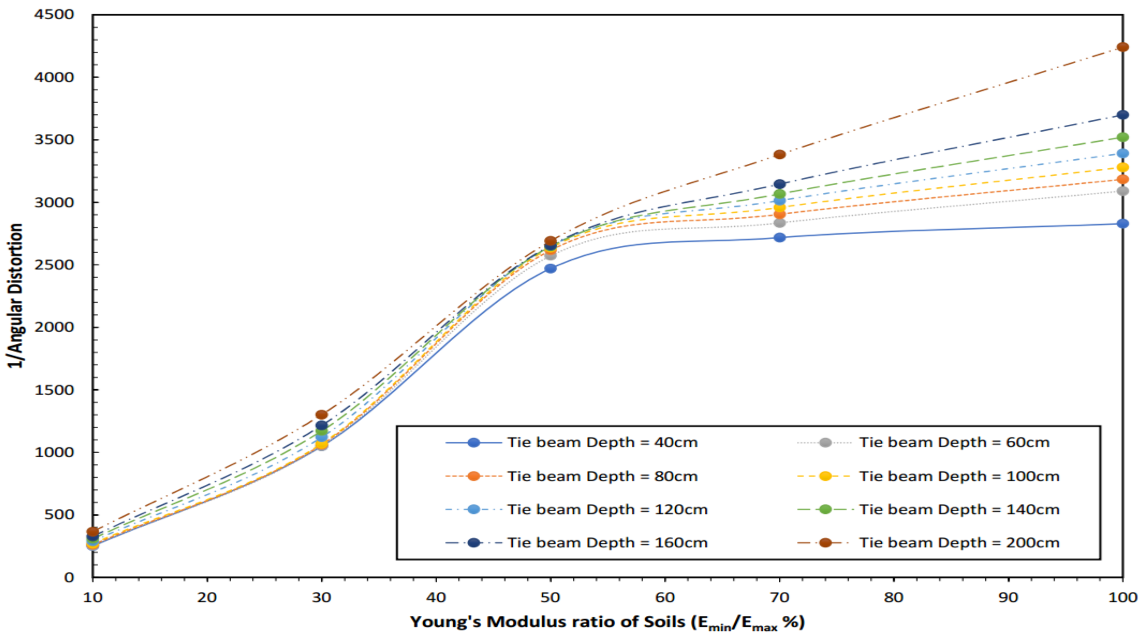

Fig. 9. Impact of Tie beam rigidity on the Angular Distortion values

3.3. Maximum Settlement below the building

Maximum settlement values shown in Fig. 14 are plotted for varied values of Emin/Emax. It is concluded that for tie beam depths less than 1.0 m, the settlement was found to be equal. However, the maximum deflection decreased significantly by increasing the ratio of Emin/Emax. Moreover, when the value of Emin/Emax had exceeded 30%, the full settlement decreased slightly.

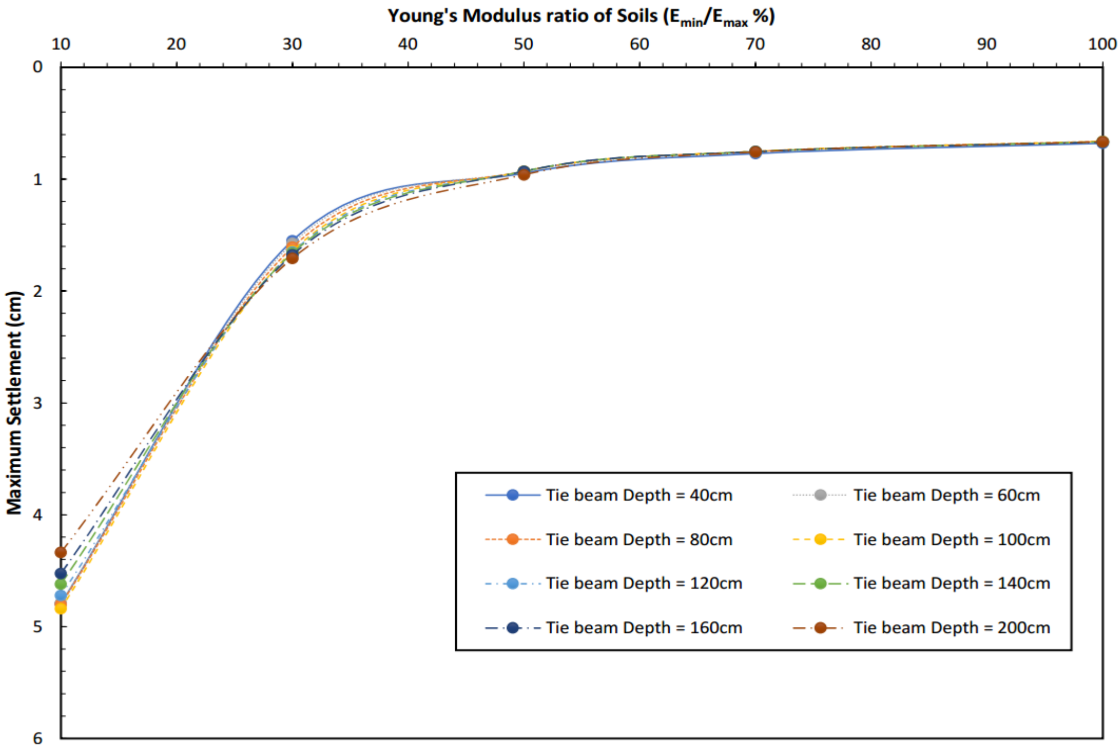

Fig. 10. Relation between the tie beam rigidity and the maximum settlement

5. CONCLUSION

The current study concluded that:

- The foundation rigidity improves the building's rigidity as a whole. By increasing tie beam rigidity, the differential settlement and the building distortion increase and expand the tilting, reducing the straining actions on reinforced concrete elements.
- Tie beams with a depth 60 cm, mostly used in -rise buildings, limit the distortion of structures at the ratio of young's modulus of weak soil to hard soil (Emin/Emax) by more than 17%.
- For tie beams depth of 2.0 m, the minimum ratio of Emin/Emax equals 13% cm to limit the building distortion to a safe limit.
- The maximum settlement value does not depend on the rigidity of the building; however, it depends on the soil parameters and foundation loads.
- The ratio of moment of tie beam to the first-floor, second-floor, and third-floor beams bending moments increased by 65%,95% and 140% in the case of Emin/Emax less than 30% compared with Emin/Emax equals to 100%.

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Conflict Of Interest:

The authors declare no conflict of interest.

Author's Contribution

Dr Ahmed Hosny conceived the presented idea. Dr Hossam Abdallah and Dr Sayed Elaraby developed the theory and performed the computations. Eng. Moaz Amer designed the model and the computational framework and analyzed the data. All authors discussed the results and contributed to the final manuscript.

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