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SOIL-STRUCTURE INTERACTION MODELLING OF FOOTINGS CONNECTED BY GROUND TIE-BEAMS

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ABSTRACT

Ground tie-beams are widely used to connect shallow foundations (isolated footings, combined, strip..etc.). The primary purpose of ground tie-beams is to decrease the differential settlement between footings under applied load conditions. The scarcity of realistic design procedures for the ground tie-beams leads the foundation designers to rely on their experience and common local practices.

This paper studies the ground tie-beams connected with isolated footing in a coupled structural model using PLAXIS 3D and MIDAS GEN (Finite element software). In the present study, both PLAXIS 3D (simulate soil as a 15-node 3D continuum model) and MIDAS GEN (simulate soil as a Winkler model) have been used to precisely determine straining action and settlements. A 3D model contains nine footings with different dimensions including 12 ground tie-beams with a constant depth and different widths. Founded on hard clay soil has been developed and studies.

The investigation resulted in a difference between the settlement of the PLAXIS 3D model and the MIDAS GEN model. A correction value was developed to account for the effect of interference of stress of footings because of the rigidity of ground tie-beams and superstructure by adjusting elastic settlement values.

KEYWORDS: *PLAXIS, MIDAS GEN, Mohr-coulomb, Settlement, Ground Tie-Beams.*

1. INTRODUCTION

One of the most troublesome issues in geotechnical engineering is the 3D numerical model of soil structure because soil behaviour is non-linear. Winkler, in 1867, was the first one to suggest an approach for subgrade modulus. According to Winkler's theory, subgrade modulus for beam or mat foundation rested on soil can be represented by springs. Many researchers helped to understand and develop this approach. Some researchers dealt with this approach from a mathematical point of view and others evaluated the results of field tests conducted in many types of soil.

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The objective of this research is to study the influence of building rigidity on the differential settlement and the effect of ground tie-beams connecting Isolated footings on subgrade reaction modulus values. In general, subgrade reaction modulus depends on soil stiffness and footing configuration. The main purpose of ground tie-beams is to decrease differential settlements between footings. Many parameters affect the performance of ground tie-beams such as span, depth and width. Kamar, A.M. 2017 [1] presented that increasing the depth of tie-beam and footings decrease vertical and horizontal displacement. Abd El Samee 2018 [2] presented that increasing ground tie beam dimensions decreases the values of bending moment and shear forces for the tie beam. Also, he concluded that the stress distribution under footings decreases with increasing tie-beam dimensions(width and depth). EI-Kasaby, EI-Sayed A.A. 1993 [3] investigated the relationship between both settlements, differential settlement, contact pressure and subgrade reaction (ks) for strap foundation rest on stiff soil. Their research shows two main points. First, increasing subgrade reaction and strap beam depth decreases the contact pressure under strap foundations. Second, increasing of subgrade reaction decreases also both settlement and differential settlement for stiff clay soil. Elsamny, M. K.[4] developed two equations to calculate settlement under two isolated footings connected with ground tie-beams one for square footings and the other for rectangle footing. In this study, PLAXIS 3D V20 (a finite element software package) was used to simulate a numerical model for a concrete structural building consisting of 6 floors rest on soil. Several cases were proposed to study the effect of the supper structure rigidity on settlement.

Similarly, MIDAS GEN (a finite element software package) was used to simulate the building using Winkler model under footings (loaded with vertical loads equal to 6 floors weight). Hence, correction values ($\Delta H_{corrected}$) were developed to adjust ground tie-beams straining actions obtained by the Winkler model (MIDAS GEN) based on the results of PLAXIS 3D continuum modelling.

2. PROBLEM DESCRIPTION

In this research, The first objective is to study the influence of building rigidity on foundation performance. The effect of the number of floors and the ground tie-beams stiffness on differential settlement are investigated. PLAXIS 3D was used to simulate a concrete building resting on a half-space continuum soil. The building’s foundation system consists of square footings connected by ground tie-beams and resting on hard clay soil type with as shown in Figure (1). In Figure (1), Several run models were simulated with different number of stories and variable ground tie-beam widths to study the effect on differential settlement. The dimensions of footings are shown in Figure (2).

The second objective was to develop more representation subgrade reaction modulus values. Subgrade reaction modulus of soil is widely used for the foundation design purpose of the majority of structural analysis and design software packages. The straining action values (Bending moment and shear forces) depends on determining the value of the subgrade reaction modulus of soil. The subgrade reaction modulus value depends on two parameters: stress on soil and settlement of footings. Settlement usually consists of two-component: immediate and consolidation settlement. Immediate settlement values can be estimated by closed-form equations. However, there is no available calculation procedure for the settlement of footings connected with ground tie beams. This methodology depends on simulations of footings connected with ground tie-beams using finite element software as in a half-space model with two methods (PLAXIS 3D) and Winkler springs model (MIDAS GEN) to optimize the elastic settlement. Isolated footings connected with ground tie-beams and supper structure contains 6 floors had been simulated with PLAXIS 3D to calculate the actual settlement (for isolated footings connected with ground tie-beams). Then correct the value of the immediate settlement (calculated from the manual equation as per Joseph E. Bowles [5] for square footings) to produce a correction equation for immediate settlement to correct subgrade modulus used in MIDAS GEN.

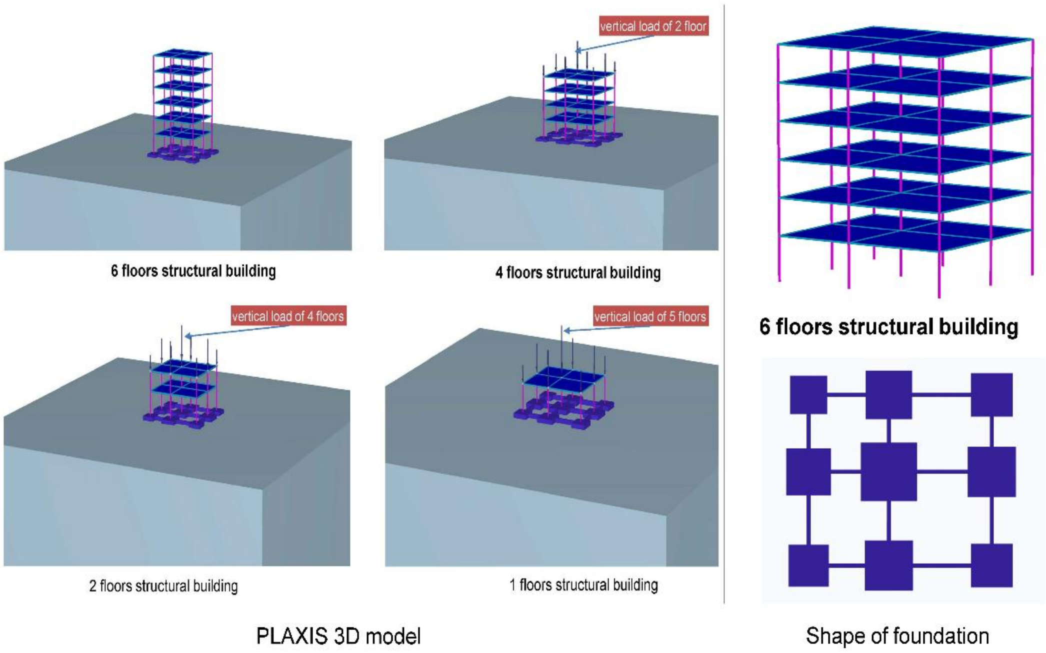


Figure (1): 3D superstructure with isolated footing having ground tie-beams supporting on soil.

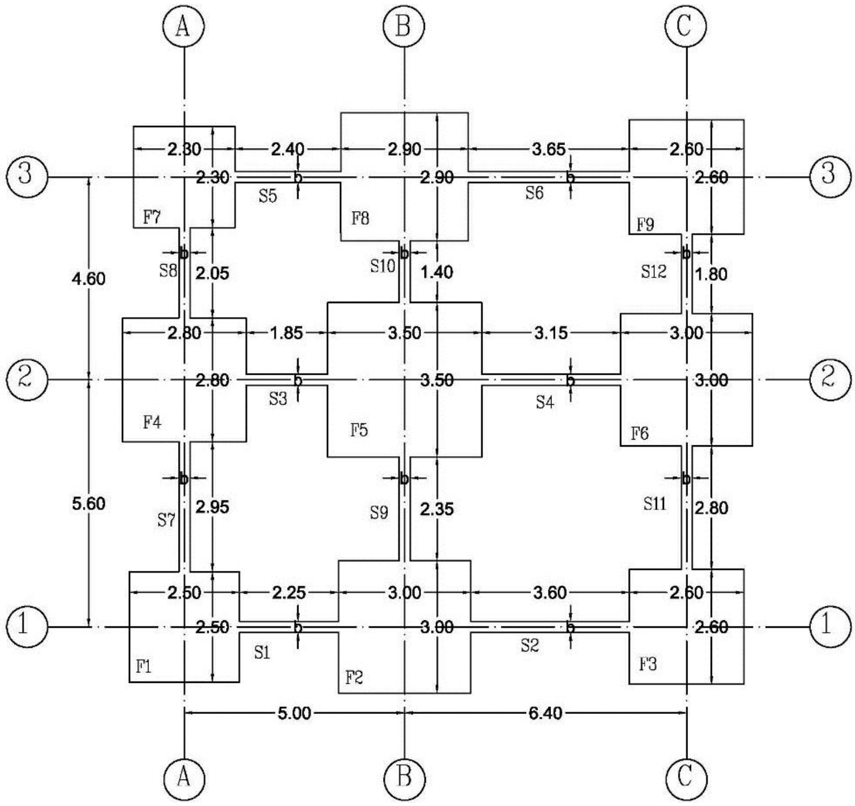


Figure (2): Plan of footings and ground tie-beams dimensions with fixed depth 60 cm.

3. NUMERICAL MODEL

PLAXIS 3D V20 has been used to simulate the chosen model shown in Figure (1). There are many reasons to choose PLAXIS 3D. First, PLAXIS 3D has numerous soil constitutive models that simulate soil behavior. The other reason, in PLAXIS can compute the soil-foundation interaction model by considering deformations and plastic properties of soil. PLAXIS 3D can also model both soil and structural elements of the building to calculate stresses and straining actions. The superstructure of the concrete building consists of 6 floors each floor consists of twelve beams with section dimensions 25*60 cm, four solid slabs with a thickness of 16 cm and carried by nine columns with section dimensions 40*40 cm. The shallow foundation system consists of isolated footings connected with ground tie-beams of variable clear distance between footings. The arrangement of footings and ground tie-beams are shown in Figure (2). The following settings and some assumptions were adopted in the 3D model:

1. The soil and concrete material is simulated by isotropic homogeneous material using the Mohr-Coulomb model and elastic material properties, respectively.
2. The superstructure concrete building is presented with only statically vertical loads dead load (representing the own weight of building) in addition to cover load (2.00 kN/m^2), wall load (5.20 kN/m $^)$and live load (2.00 kN/m^2) according to Egyptian Code for Loads [6].
3. Boundary condition of soil: vertical and horizontal movements are prevented at the bottom and sides of the soil block as shown in Figure (3).
4. Twenty (20) models have been simulated by PLAXIS 3D to investigate the influence of superstructure rigidity on the performance of the footings connected with ground tie-beams. several cases were investigated by reducing the number of stories to four, two and one floors. However, reduction of the number of stories is associated with decresse in vertical load which also impact the performance of ground tie-beams. To compensate such effect, additional external vertical points load (applied on top columns of the superstructure) have been applied with equivalent load to the reduced floors as shown in Figure (4). Figure (4) illustrates four cases with variable number of floors (six, four, two and one floors). Tabel (1) shows different study cases. Selected cases have chosen with variable width for ground tie-beams (b =25,30,50&70 cm, depth equal 60 cm) as shown in Tabel(1).

On the other hand, MIDAS GEN software simulates a Winkler model for soil as point spring or area spring. The MIDAS GEN 3D model simulates the footings and ground tie-beams as shell elements as shown in Figure (5). The following settings and assumptions were adopted in the 3D model using MIDAS GEN:

1. The soil was modelled as springs with coefficients equal to subgrade reaction modulus. The behavior of defined spring reflects Hooke's law. Bowles[5] explain subgrade reaction modulus as the relationship between soil pressure and deflection.
2. All footings have been dimensioned to distribute the column loads of the buildings to the soil with contact pressure not exceeding the allowable soil capacity of the hard clay soil was calculated with B.C equation and assume soil cohesion (400,000 Kpa) and found to be (185 Kpa).
3. The same 16 models of cases similar PLAXIS 3D (cases of footings connected with ground tie beams) runs have been studied using MIDAS GEN as shown in Tabel (1).

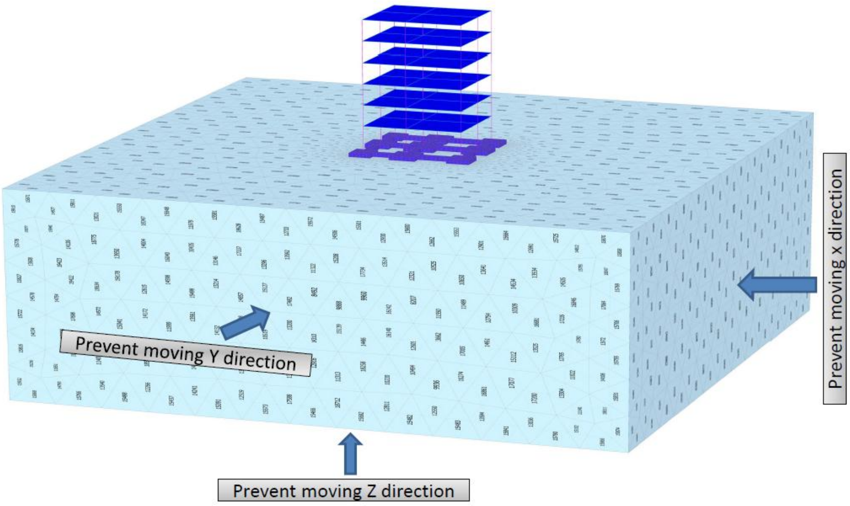


Figure (3): meshing and boundary for 3D half-space model

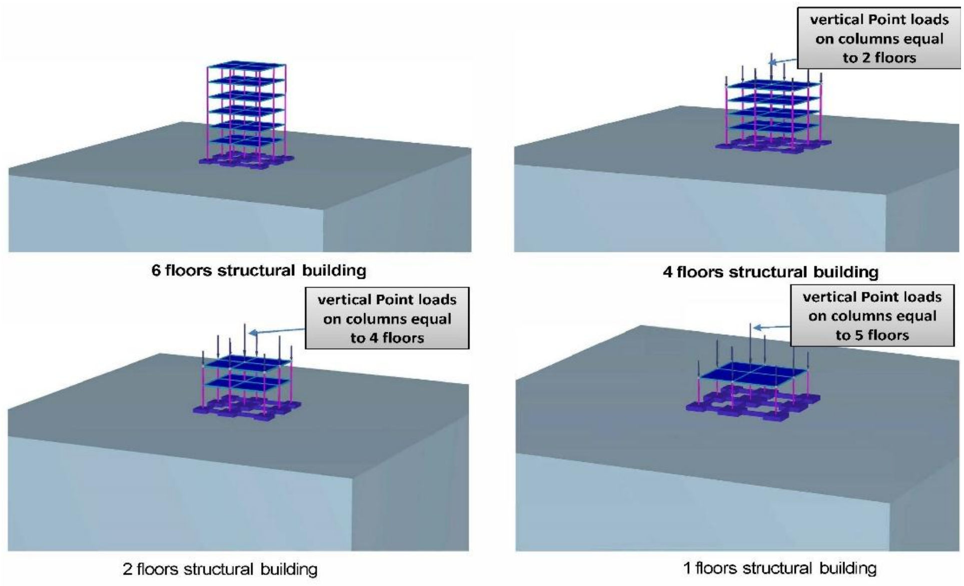


Figure (4): Changes in floors number with exchanging the reduction of floor's number with additional external vertical point loads

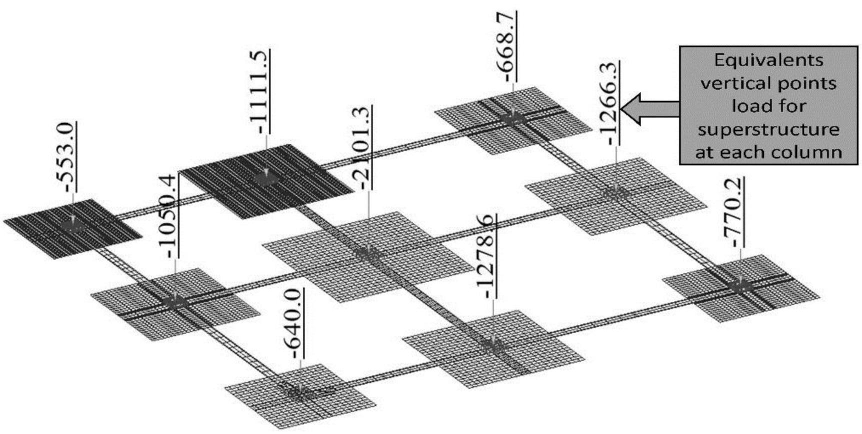


Figure (5): 3D Winkler model of footings by MIDAS GEN.

Table (1) : Study cases.

Number of floors	Width of ground beams (m)	Number of floors	Width of ground beams (m)	Number of floors	Width of ground beams (m)
6 floors	b=0.25 (m)	6 floors	b=0.50 (m)	6 floors	Without **ground tie-beams**
4 floors		4 floors			
2 floors		2 floors		4 floors	
1 floor		1 floor			
6 floors	b=0.30 (m)	6 floors	b=0.70 (m)	2 floors	
4 floors		4 floors			
2 floors		2 floors		1 floor	
1 floor		1 floor			

4. Material Properties

The mechanical properties for the chosen hard clay soil was estimated as per the typical values provided in the ECP [202/3] [7]. Tabel (2) presents material parameters for concrete and hard clay soil.

Table (2) : Materials properties for concrete building and soil.

Material Type	Material model	Unit Weight KN/m^3	Modulus of elasticity KN/m^2	Passion ratio	Cohesion KN/m^2	Fraction angle (degree)
Concrete	Elastic	24.52	22000000	0.2	0	0
Hard clay	Mohr-coulomb	21	40000	0.3	150	0

5. COMPUTATION PROCEDURE

Figure (6) shows a sample of settlement distribution diagrams along the axis (1 –1) using PLAXIS 3D for two different cases. Figure (6-a) shows settlement distribution diagrams along footings (axis (1 –1)) subject to variable superstructure rigidity (six, four, two and one stories) with the same applied vertical loads (as explained in Figure (4)) for the isolated footings connected with ground tie-beams (width b= 25 cm). Figure (6-a) shows that the settlement values increase at the centre of the middle Similarly, Figure (6-b) shows settlement distribution diagrams same axis for footings without ground tie-beams. footing. Figure shows the decrease in settlement distribution diagrams values between footings because the groud tie beams are not existing. Results of the settlement were obtained from PLAXIS 3D models for all study cases for each isolated footings. From the results, the differential settlement has been calculated for each two adjacent isolated footings at the centre for all the study cases.

For Winkler model, subgrade modulus was adopted by equation (1):

$$K_s = \frac{q}{\Delta} \qquad \textbf{Eq. (1)}$$

where q = the contact pressure under the footing,Δ = actual settlement under the footings.

PLAXIS 3D model results (using PLAXIS 3D) of the settlement at the middle of each footing connected with ground tie-beams were compared with the calculated settlement:

- Values of L_s and B_s for each footing (corner, middle and edge footing) was determined as shown in Figure (7). Figure (7) illustrate that L_s and B_s values equal the half-length of spans for each footing in the x and y direction respectively. Tabel(3) include values of L_s, B_s and the results of settlement values from the PLAXIS 3D runs versus the settlement values calculated using elastic equation (2) (Timoshenko and Goodier (1951))[5] for each footing for all cases.

$$\Delta H = q_0 B' * \frac{1-\mu^2}{E_s}\left(I_i + \frac{1-2\mu}{1-\mu} I_2\right) I_F$$

Eq. (2)

where Δ H = the elastic settlement under the middle of footings,q_0 = Intensity of contact pressure in units of Es, B' = Least lateral dimension of contributing base area in units of Δ H, I_i = Influence factors, which depend on L'/B' thickness of stratum H, Poisson's ratio /i, and base embedment depth D, E_S = Modulus of elasticity of soil, μ = Poisson's ratio of soil

- The normalized ratio for footing dimension to corresponding ground tie-beams length in each direction $(B/B_s) * (L/L_s)$ was calculated for each footing.
- Tabel (3) summarizes settlement values ΔH_{FEM} (for cases ground tie-beams width b= 25,30,50,70 cm) using PLAXIS 3D model and settlement values ΔH calculated by elastic equation (2) for all footings center. Figure (8) presents normalized footing to ground tie-beams dimensions versus the ratio between elastic equation (2) settlement. The optimized $\Delta H_{corrected}$ is a Relationship between settlement ΔH_{FEM} / ΔH and normalized footing to ground tie-beams dimension $(B/B_s) * (L/L_s)$. $\Delta H_{corrected}$ can be used as a settlement correction value to account for ground tie-beams rigidity effect and stress interface.

Hence, the corrected values of elastic settlement and new subgrade modulus using in MIDAS GEN was determined using the two following equations:

$$\boldsymbol{\Delta H_{corrected}} = [1.1185 * ((B/Bs) * (L/Ls)) + 1.1258] * \Delta H \quad \textbf{Eq. (3)}$$

where $\Delta H_{corrected}$ = the corrected value for elastic settlement refer to the chart in Figure (8), Δ H = the elastic settlement under middle of footings, $(B/B_s) * (L/L_s)$= normalized footing to ground tie-beams dimension refer to Figure (6).

$$\mathbf{K_s} = \frac{q}{\Delta H\ corrected} \quad \textbf{Eq. (4)}$$

where K_s = the corrected subgrade modulus used in MIDAS GEN, q = the contact pressure under the footing, $\Delta H_{corrected}$ = the corrected value for elastic settlement refers to the chart in Figure (8).

Foundations were modelled using MIDAS GEN using corrected subgrade modulus determined by equation (4).

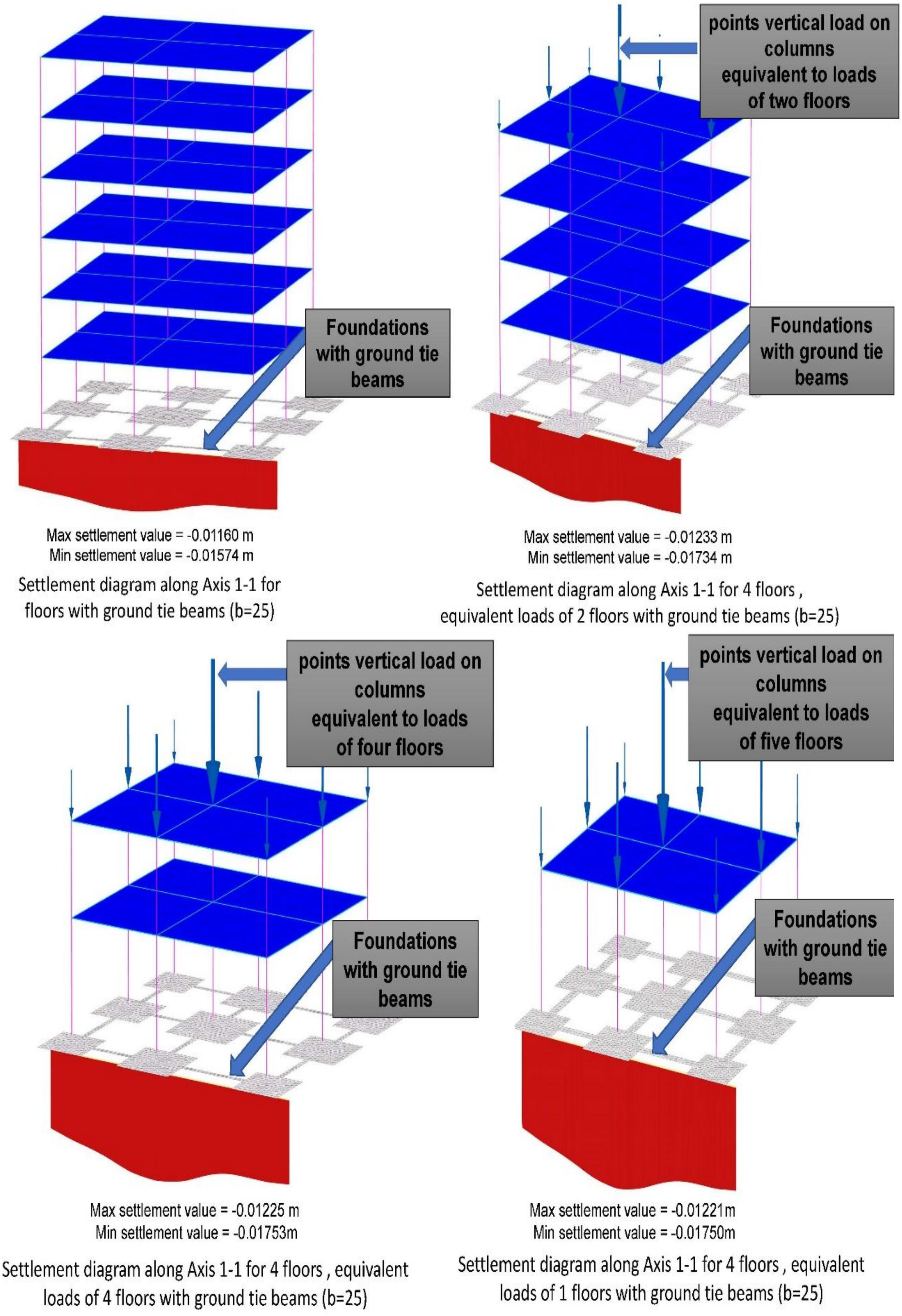


Figure (6-a): sample of PLAXIS 3D settlement distribution diagrams along axis (1 –1) for footings connected with ground tie-beams variable superstructure rigidity.

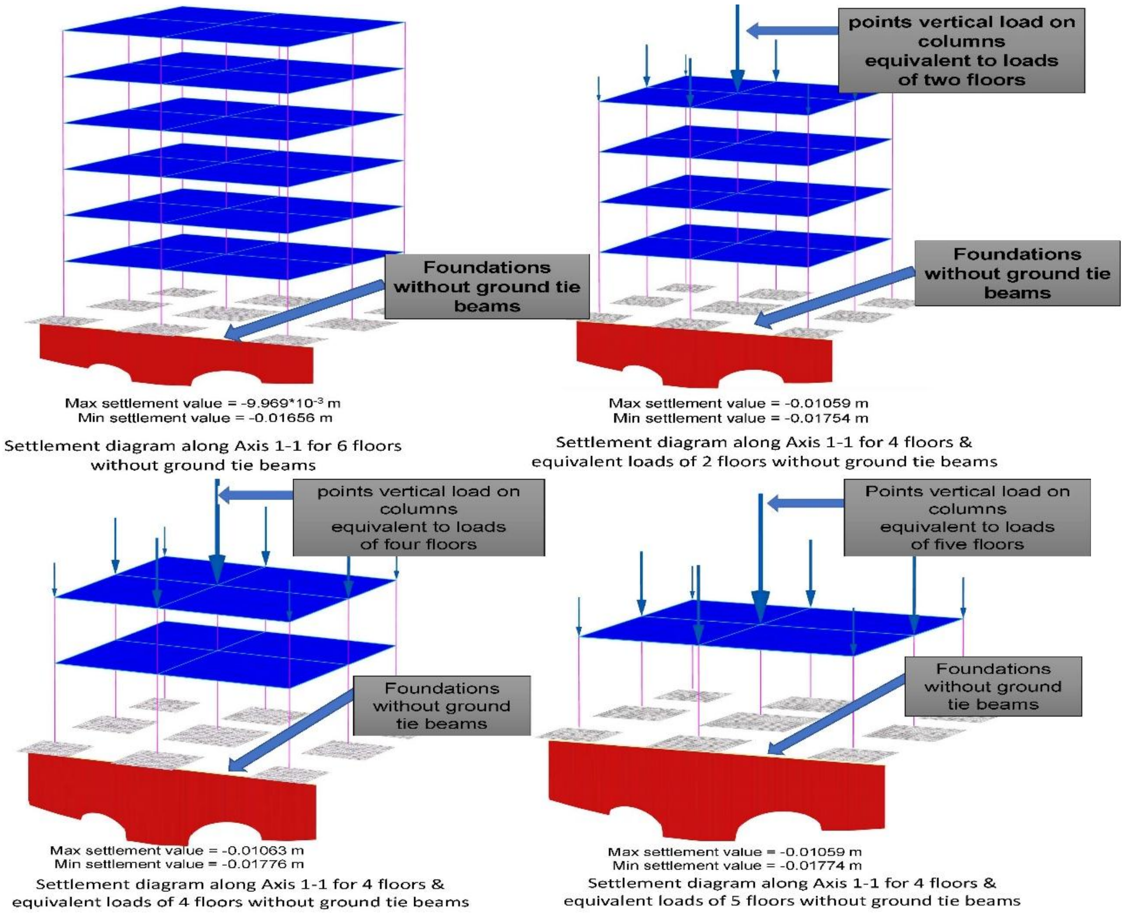


Figure (6-b): sample of PLAXIS 3D settlement distribution diagrams along axis (1 –1) for footings without ground tie-beams variable superstructure rigidity.

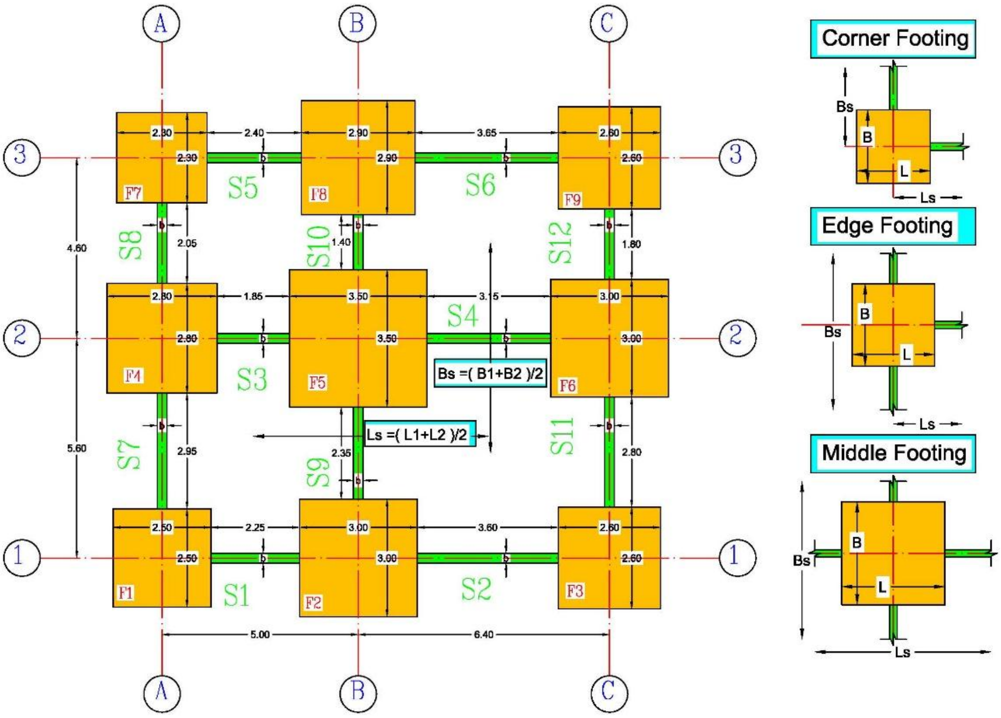


Figure (7): B_s & L_s calculation for each footing.

Table (3) : Values of Ls, Bs & settlements values at footings centre from PLAXIS 3D model and equation (2).

Footing number	B_s (mm)	L_s (mm)	$\Delta H_{FEM(25)}$ (1) (mm)	$\Delta H_{FEM(30)}$ (1) (mm)	$\Delta H_{FEM(50)}$ (1) (mm)	$\Delta H_{FEM(70)}$ (1) (mm)	ΔH (2) (mm)
F_1	2.375	2.725	-12.14	-12.43	-12.78	-12.74	5.66
F_2	5.925	2.675	-15.38	-15.47	-15.77	-15.66	9.02
F_3	3.1	2.7	-12.02	-12.34	-12.67	-12.55	6.46
F_4	2.325	5.3	-15.12	-15.35	-15.60	-15.52	8.01
F_5	6	5.375	-19.31	-19.34	-19.49	-19.34	12.39
F_6	3.075	5.3	-15.02	-15.14	-15.42	-15.36	8.94
F_7	2.35	2.175	-12.50	-12.74	-13.04	-13.02	5.32
F_8	5.925	2.15	-15.52	-15.69	-15.92	-15.84	8.18
F_9	3.125	2.2	-12.13	-12.36	-12.72	-12.67	5.70

(1) $\Delta H_{FEM(25,30,50,70)}$ is the true settlement values(using PLAXIS 3D) at footing center for cases with ground tie-beams width 25,30,50 and 70 respectively.
(2) ΔH calculated settlement values at the footing centre using elastic Eq. (2).

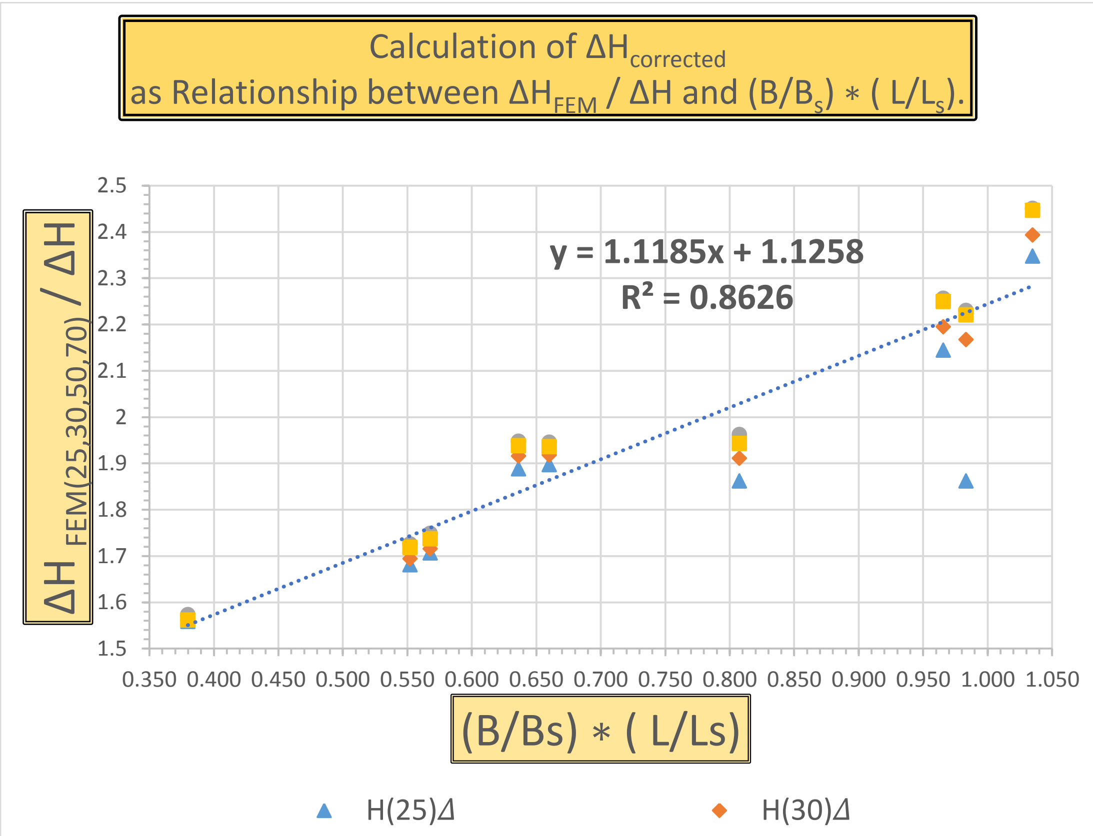
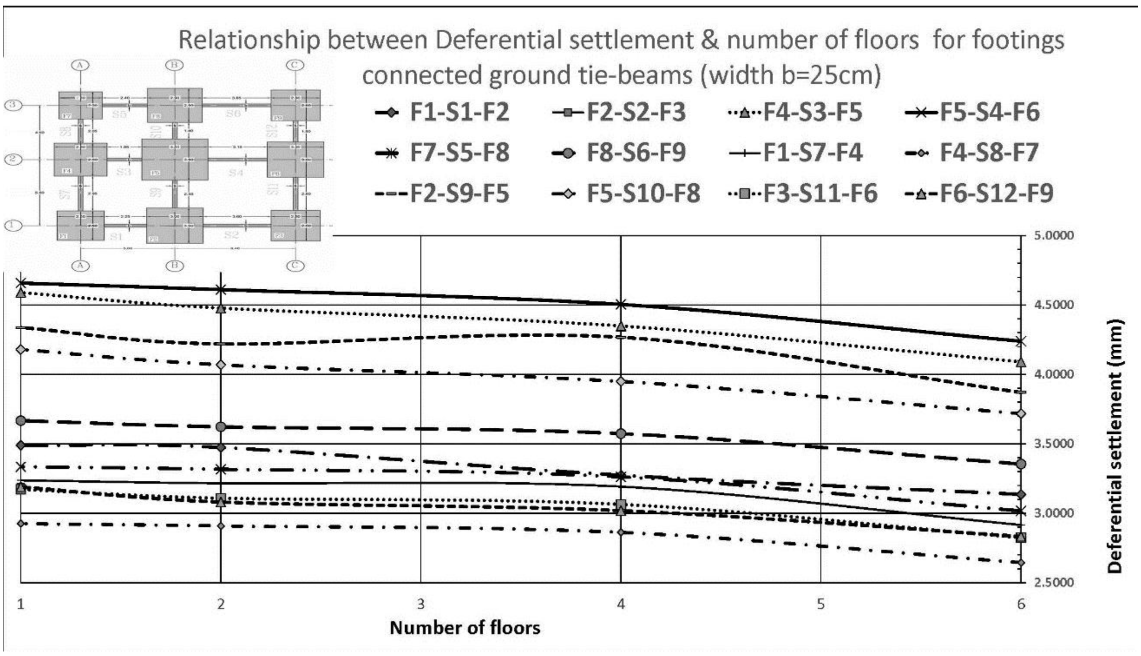


Figure (8): optimized $\Delta H_{corrected}$ as Relationship between settlement ΔH_{FEM} / ΔH and normalized footing to ground tie-beams dimension $(B/B_s) * (L/L_s)$.

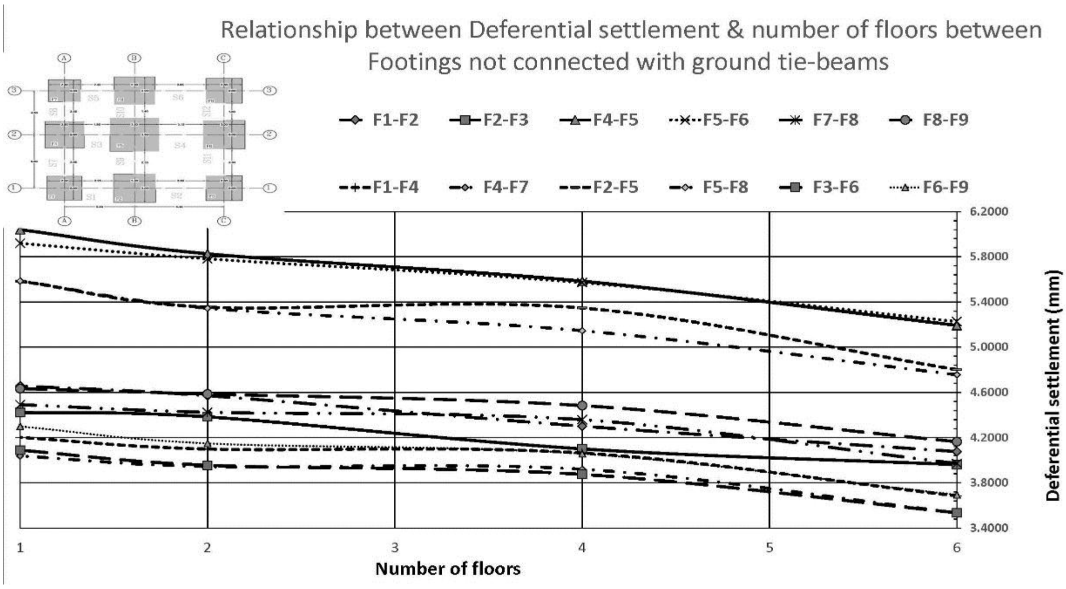
6. Results

Study cases were used to show the influence of ground tie-beams in reducing the differential settlement with variable superstructure rigidity. Figure (9-a) illustrates PLAXIS 3D results about the relationship between differential Settlement for every two adjacent footings and variables in superstructure rigidity (six, four, two and one floors) with the same applied vertical loads (as explained in Figure (4)) according to width(b=25) of ground tie-beams. Figure (9-b) illustrate also the relationship between differential Settlement and variable superstructure rigidity such as (such as Figure (9-a)) with a difference that footings are not connected with ground tie beams. Table (4-a) shows a sample of results of differential settlement for every two adjacent footings connected with ground tie-beams and present the calculation method of reduction percentage of differential settlement between footings using ground tie-beams with different widths (b=25,30,50and70) at study case 6 floors. After account reduction percentage of differential settlement in Table 4, Chart and table in Figure (10) shows the summary of all results for all cases referred to Table (1). Figure 10 shows that building rigidity and increasing ground tie-beams stiffness reduces the differential Settlement for footings.

Figure 11 illustrates some of the results of bending moment diagrams along two axis (1-1) obtained from PLAXIS 3D and MIDAS GEN. Figure 11 presents the relative agreement between the results because of the optimization of the subgrade reaction modulus. After the optimization of subgrade reaction modulus. And so the Using of chart in Figure (8) improved the results of MIDAS GEN (using optimization of subgrade reaction modulus) and leads to the relative agreement in results with PLAXIS 3D model Winkler model (using subgrade reaction modulus)



a- ground tie-beams b = 25



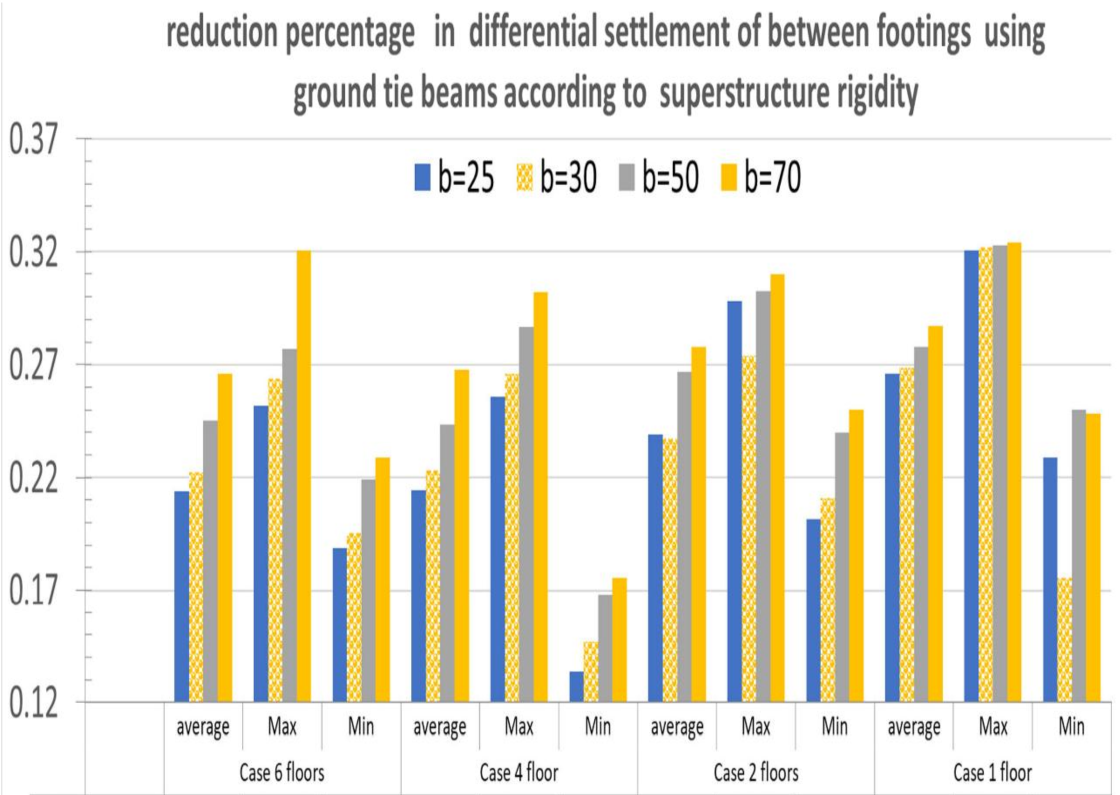
b – Footings not connected with ground tie-beams

Figure (9): Relationship between differential Settlement for every two adjacent footings and variable in superstructure rigidity for footings connected and not connected with ground tie-beams (width b=25 cm).

Table (4): Percentage reduction of differential settlement between footings after using ground tie-beams with variable width at study case 6 floor.

Calculation method of percentage reduction of differential settlement between footings after using ground tie-beams at study case 6 floor									
Element	$DF^{(1)}$ (mm)	$DF_{25}^{(2)}$ (mm)	1-(DF_{25}/DF)	$DF_{30}^{(2)}$ (mm)	1-(DF_{30}/DF)	$DF_{50}^{(2)}$ (mm)	1-(DF_{50}/DF)	$DF_{70}^{(2)}$ (mm)	1-(DF_{50}/DF)
F1-S1-F2	4.08	3.14	23.07%	3.09	24.08%	2.99	26.68%	2.93	28.12%
F2-S2-F3	3.96	3.19	19.38%	3.19	19.53%	3.09	21.91%	3.05	22.89%
F4-S3-F5	5.19	4.09	21.23%	4.03	22.32%	3.88	25.20%	3.79	27.03%
F5-S4-F6	5.23	4.24	18.89%	4.20	19.65%	4.06	22.28%	3.98	23.88%
F7-S5-F8	3.97	3.02	24.03%	2.96	25.46%	2.87	27.68%	2.80	29.41%
F8-S6-F9	4.16	3.35	19.44%	3.31	20.51%	3.20	23.23%	3.15	24.40%
F1-S7-F4	3.68	2.92	20.86%	2.90	21.29%	2.83	23.30%	2.50	32.06%
F4-S8-F7	3.53	2.64	25.19%	2.60	26.35%	2.56	27.63%	2.50	29.19%
F2-S9-F5	4.80	3.87	19.38%	3.84	20.03%	3.72	22.49%	3.64	24.14%
F5-S10-F8	4.76	3.72	21.84%	3.68	22.69%	3.57	24.94%	3.49	26.65%
F3-S11-F6	3.53	2.82	20.11%	2.83	20.04%	2.75	22.15%	2.72	23.12%
F6-S12-F9	3.69	2.83	23.30%	2.79	24.54%	2.70	26.77%	2.66	28.03%
Average			21.39%		22.21%		24.52%		26.58%
Max			25.19%		26.35%		27.68%		32.06%
Min			18.89%		19.53%		21.91%		22.89%

(1) DF is differential settlement values(using PLAXIS 3D) between every two adjacent footings centre for cases without ground tie-beams.
(2) $DF_{(25,30,50,70)}$ is differential settlement values(using PLAXIS 3D) between every two adjacent footings centre using ground tie-beams width 25,30,50 and 70 respectively.



	Case 6 floors			Case 4 floor			Case 2 floors			Case 1 floor		
	average	Max	Min	average	Max	Min	average	Max	Min	average	Max	Min
b=25	21.40%	25.19%	18.89%	21.45%	25.59%	13.36%	23.89%	29.79%	20.16%	26.60%	32.06%	22.89%
b=30	22.21%	26.35%	19.53%	22.32%	26.60%	14.67%	23.72%	27.40%	21.07%	26.85%	32.20%	17.55%
b=50	24.52%	27.68%	21.91%	24.35%	28.65%	16.82%	26.70%	30.23%	24.01%	27.80%	32.30%	25.02%
b=70	26.58%	32.06%	22.89%	26.77%	30.20%	17.55%	27.79%	31.01%	25.02%	28.70%	32.40%	24.83%

Figure (10) : Results of percentage reduction in differential settlement of footings according to use ground tie-beams for all cases of study.

7. CONCLUSIONS

For the influence of that building rigidity, this study proved differential settlement is influenced with ground tie-beams existence and building rigidity represented in floors number and ground tie-beams width. Table (4) summarize the results.

For the subgrade reaction modulus values optimizations, the research shows differences between settlement values (under the middle of each footing) calculated from the PLAXIS model and elastic settlement equation (2) (Bowels equation) due to the effect of ground tie-beams rigidity. The results of the analyses performed by PLAXIS 3D software have been used to correct the values of elastic settlement via the developed correction value ($\Delta H_{corrected}$) for isolated footings and lead to equation (3) for hard clay soil. The equation may provide a practical and useful solution for foundation designers who use the Winkler model to simulate soil by structural software such as MIDAS GEN.

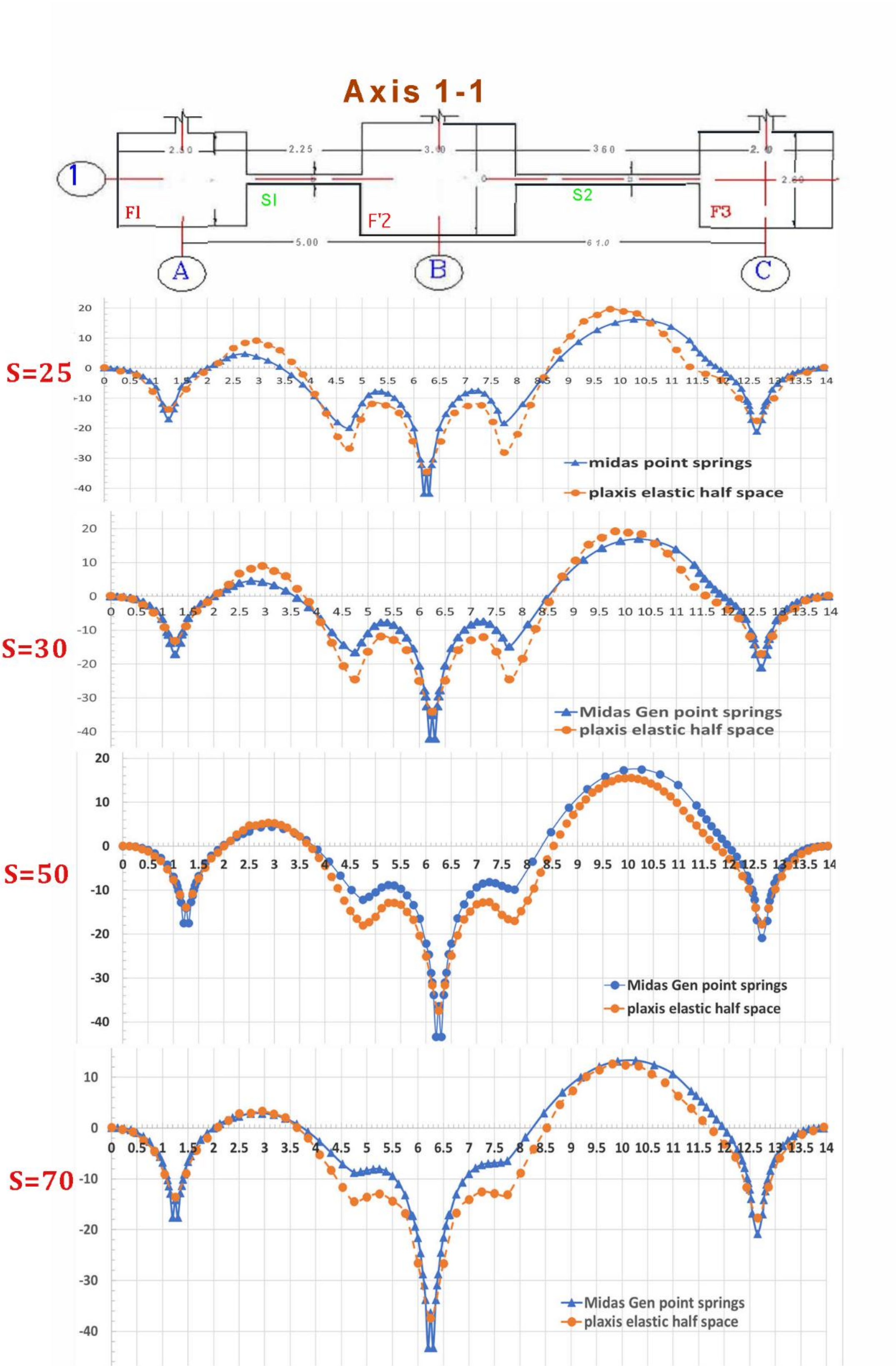


Figure (11): Bending moment diagram along axis (1 –1). shows the relative agreement between the results of PLAXIS & MIDAS GEN for 6 floors study case.

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تمثيل رد فعل التربة على الكمرات الرابطة بين القواعد

تُستخدم الكمرات الرابطة بين القواعد على نطاق واسع لربط الأساسات السطحية (القواعد المنفصلة ، القواعد المشتركة ، الشريطية .. إلخ). الغرض الأساسي من الكمرات الرابطة بين القواعد هو تقليل الفروق فى الهبوط بين القواعد تحت تاثير احمال المنشأ. إن ندرة إجراءات التصميم الواقعية للكمرات الرابطة بين القواعد تدفع مصممي الأساسات إلى الاعتماد على خبرتهم والممارسات المحلية الشائعة.

يقوم هذا البحث بدراسة الكمرات الرابطة بين القواعد المنفصلة المرتبطة بمبنى متعدد الطوابق باستخدام البرنامجين PLAXIS 3D و MIDAS GEN (Finite Element Software). في هذه الدراسة ، تم استخدام كل منPLAXIS 3D (محاكاة التربة كنموذج ثلاثي الأبعاد) و MIDAS GEN محاكاة التربة كنموذج (Winkler)لتحديد القوى الداخلية و مقدار الهبوط بدقة. يحتوي النموذج ثلاثي الأبعاد على تسعة قواعد بأبعاد مختلفة بما في ذلك ١٢ من الكمرات الرابطة بين القواعد المنفصلة ذات عمق ثابت وعروض مختلف. و تم عمل الدراسة على طبقة من التربة طينية صلبة.

تبين من الدراسة الاختلاف فى الهبوط بين PLAXIS 3D و MIDAS GEN.و لذلك لزم وضع عامل تصحيح لحساب تأثير تداخل الاجهادات بين القواعد و تأثير الكمرات الرابطة بين القواعد المنفصلة وايضا تاثير المنشأ و ذلك العامل لتصحيح قيم الهبوط .