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Design and Analysis of Ribbed Raft Foundation Resting on Swell-Shrink Soils

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A B S T R A C T

Expansive soils shrink and swell with drying and wetting cycles. The shrink-swell capacity of expansive soils can result in differential movement beneath foundations which is a very common cause of foundation problems. Ribbed slab, often called waffle slab, is one of the efficient and inexpensive foundation solutions for use under light structures resting on shrink-swell soils. This paper presents a numerical analysis that is used to calculate displacement and internal forces in ribbed slab foundations resting on swell/shrink soil. The stiffness of the ribbed slab is modelled as an equivalent flat slab of constant thickness and the straining actions are calculated for the case of central heave. A parametric study of the effect of beam dimensions and rib spacing is performed to assess the optimum configuration. Dimensioning of the waffle slab system; slab thickness, depth and width of beams and spacing, is performed according to the Egyptian Code of Practice for the design of concrete structures. The results show that beam depths of 0.4 m and 0.45 m were safe and recommended under this condition of heave scenario. All beams with depths of 0.3 m cannot resist the resulting bending moments, While beams with 0.35 m depth are only safe when the beam width is not less than 0.2 m.

1. INTRODUCTION

Soil material that display volume change of up to 30% or more in soil moisture supply are alluded to as swelling soils [1, 2]. Swelling soils, sometimes called shrink-swell soils, owe their attributes to the presence of particular types of clay minerals. The response of swell-shrink takes form of a volume change; swelling after wetting (as the clay minerals retain water atoms and expand when exposed to moisture or incompletely soaked), and shrinkage after drying (leaving enormous voids in the soil while losing moisture contents). [3]. Their plasticity indices range high and their bearing capacities contrast from when wetted with when dried [4]. Swell-shrink soils, which are expanded because of high ground moisture, experience a deficiency of soil strength and the subsequent instability can bring about different forms of foundation problems [2]. These soils are generally found in dry and semiarid areas that in these regions the climatic conditions change throughout the year from wet to dry or the other way around [1]. During times of high moisture, soil can apply a tremendous uplift pressures which can cause lifting of structures and cause cracks. Then again, during times of falling soil moisture, soil will "shrink" and can bring about building settlement. In any case, deterioration can be extensive [2].

The moisture distribution which doesn't occur uniformly inside the soil (underlying the foundation) brings about differential soil movement and instability that lead to significant distresses in the foundations [5]. Differential instead of total movements of the foundation soils are liable for the major structural damage. Differential movements reallocate the structural loads which lead to the concentration of loads on parts of the foundation and enormous changes in moments and shear forces in the structure [6].

Deterioration to light weight structures constructed on reactive soils are a considerable geotechnical hazard which can be found on all the continents on the earth [7]. Several forms of structural damage associated with swelling of expansive soils in different countries are reported. In Egypt, expansive soils are found in several areas such as: Aswan, Edfu, Luxur, Esna, Assiut, Sohag, Fayuim, Suez, Esmaelia, Nasser City, new Cairo , New valley, Sinai, etc. [8]. The issues are significant in Australia as roughly 30% of the absolute land zone is covered by swelling soils, and these regions are frequently associated with a harsh semi-arid climate (for example long dry period followed by a short period of high rainfall) [9].

Light structures, for example, single or double storey structures which generally transmit smaller stresses to the

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soil than the swell pressure are subjected to damage. This is due to the disability of the structures to suppress the differential heave of the swelling foundation compared to the heavy, multi-storey structures. Soil differential movement places repetitive stress on structures which can cause differential slab movements in low rise buildings. If the foundations isn't of a stiffness enough to withstand the gaps brought about by the differential soil movements, and if the superstructure isn't of a suitable flexibility, the resulting distortions can be catastrophic. This will result in cracking, permanent deformation and/or extensive damage to walls, ceilings and plumbing due to slabs being unable to satisfy the differential deflection requirements. [6, 10].

2. THE PROPOSED MOUND SHAPE

The differential movements of soils due to uneven wetting/drying under the foundation slab will give rise to two distinct distortion modes (or mound shapes). Many authors have provided several methods for predicting the mound shapes or modes [11]. In most cases, it is very difficult to predict the distortion mode which a foundation may experience as a result of subgrade swelling and shrinkage. As a result, two distortion patterns which will produce the extreme values of internal forces and deflection were suggested for design of slabs on ground [12]. Figure (1) shows the two movement scenarios of heave which represent the worst cases of loading, namely central and edge heave cases [13].

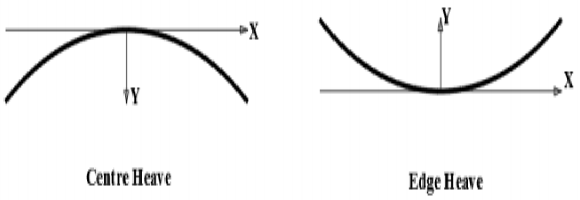

Figure (1): Soil mound shapes by Mitchell's method (Mitchell 1984).

For instance, having high soil moisture condition in the soil around the edges of a structure can produce an expanding pressure underneath the edges of the structure, while the water content of the soil underneath the middle remains constant. This outcomes in a mode known as end lift/heave. Otherwise a center lift/heave mode would happen when high soil moisture condition presence under the center of the slab, so swelling is concentrated underneath the middle of the structure or where shrinkage happens under the edges [14-16].
The two distortion modes were applied for designing the slabs, as the loads of the superstructure would be hold along a span generated by edge lift, or hold in a cantilevered fashion out to the edge of the foundation in the case of centre lift. The foundation slab interacts with these mounds pushing down on the high spots and bridging the low spots [10]. Either type of heave will damage the superstructure if the slab is not designed appropriately to withstand the uneven distribution of the volume changes underneath the foundation [15]. In this paper, modelling of the initial swelling profile obtains by the following mound shape equation (1) which is developed by Abdelmalak [17].

$$\rho(x) = f\gamma_h H \Delta U_{edge} \sum_{n=1}^{\infty} \left\{ \left[\frac{2\pi\left(n-\frac{1}{2}\right)(-1)^{n-1} \exp\left(-\sqrt{\frac{\omega H^2}{2\alpha_{field}}}\right) + 2\sqrt{\frac{\omega H^2}{2\alpha_{field}}}}{\frac{\omega H^2}{2\alpha_{field}} + \pi^2\left(n-\frac{1}{2}\right)^2} \right] \left[\frac{\cosh\left(\left(n-\frac{1}{2}\right)\pi \frac{x}{H}\right)}{\cosh\left(\left(n-\frac{1}{2}\right)\pi \frac{L}{2H}\right)} \frac{(-1)^{n-1}}{\pi\left(n-\frac{1}{2}\right)} \right] \right\} \quad (1)$$

Where:
$\rho(x)$= surface soil movement under the impervious cover (heave height corresponding to X-distance), m,

Coefficient (ƒ) = the ratio of vertical to volumetric strain,

γ_h= slope of the volumetric stain versus suction, pF units,

H= depth of active zone, m,

$\Delta U_{edge} = change\ in$ suction, pF units,

ω = frequency of surface suction change cycles,
$\omega = \frac{2\pi}{T}$, T=weather periodic time

α_{field}= field coefficient of diffusivity, m2/day,

X= horizontal distance under the impervious slab, m,
L= length of slab, m,

3. FOUNDATIONS ON EXPANSIVE SOIL

Generally, the type of foundations on expansive soil depends on many factors such as: degree of swelling potential, thickness of swelling soil, depth of swelling soil from possible water intrusions and also the type of construction projects adjacent to expansive soils.
Structures that are constructed on expansive soils exert a pressure which tends to lessen soil movement. Foundation loading pressure should surpass the swelling pressure to avoid heave of foundations, but at the same time less than the soil bearing capacity to guard against foundation displacement. But what actually happens is that the foundation loading pressure didn't exceed the swelling pressure.
Many researchers have proposed several methods to deal with the structural damages caused from high swelling potential of expansive soils. The main aim with any foundation type is to reduce the effects of movement, especially the differential movement. Many strategies were developed to mitigate the swelling potential of soils. The first strategy is to obviate the structure from soil movements

by controlling the direction of expansion. The technique is to let the soil expand into cavities built underneath the foundation which result in releasing the soil movements with decreasing effect on the structure. This technique is described by Bowles [4]. A common type is the construction of waffle slabs. This type of foundation, the reinforced concrete ribs hold the structural load and the voids allow the soil to expand inside it. Another strategy is to design a foundation that is stiff enough and to construct a structure with great rigidity to tolerate the detrimental effects of swelling soils from movement [4, 15].

4. WAFFLE SLAB FOUNDATION SYSTEM

4.1. Description of the Waffle Slab System

A waffle slab foundation, also termed as ribbed slab foundation, has a grid-like system (called the ribs) at the bottom. It consists of an edge beam and a series of narrow internal beams in each way that support the slab panels. The sides of the slab are constructed by edged formwork and blocks to create the formed voids between the beams. The waffle voids allow the expansion of the soil inside it. A post-tensioned or fibre reinforced or reinforced beams (ribs) cast integrally with the floor slab, to form a footing system of relatively high strength and stiffness. Waffle raft achieve their strength by increasing their heights above ground. The deeper the beams – the more stiffness the system has. The more stiffness the slab has, the more it can resist ground movement of active soils [18-20].

In waffle raft, the slab transmits the loading forces from the super-structure to the reinforced concrete ribs that hold the structural load and resist moments and shear due to differential heave of the expansive soil. The waffle slab foundation is designed to resist both positive and negative moments from the superstructure loads and from the pressure due to under slab soil swelling. Usually negative moment controls the design of the waffle slab system. [20, 21].

4.2. Section Parameters of the Waffle Slab System

Figure (2) shows the individual waffle mat form which is 475x475 mm, with heights ranging between 200 mm and 300 mm. The forms are designed to be used in arrays of up to four forms per void unit, typically with 150 mm to 200 mm wide beams spaced 1100 mm or 1800 mm center-to-center. A post tensioned or rebar reinforced concrete slab, usually 100–150 mm thick, is monolithically poured directly over the waffle boxes. A varying beam depth from 300 mm to 450 mm (the depth of the beams is the slab thickness plus the depth of the waffle mat form). The number of beams in each direction should be the slab dimension divided by rib spacing, plus one. The width of the edge beams was set to 300 mm, the typical minimum width for edge beams in the waffle mat system (Figure 2) [22, 23]

Figure (2): Parameters of the waffle mat boxes [23].

5. NUMERICAL MODEL

Plaxis finite elements software is adapted to analyze the stiffened slabs-on-grade foundation documented by Abdelmalak on swell/shrink soils and compare the results to verify the model. The mound shape which is obtained from equation (1) is used in this analysis to represent an edge drop case (the case where the soil is shrinking around the edges of the slab) [17]. The foundation is located at the center of the modeling soil as in figure (3). The linear-elastic model is adopted for soil and foundation slab. A linear elastic model is used, since there is no need to consider plasticity in such analysis when the focus is on the mound formation. The analysis carried out through three programs, namely, input, output and plotting programs. Firstly, the foundation stiffness is calculated to represent the equivalent of a flat section to be used in the numerical simulation of the stiffened slabs on a predefined mound shape that is simulated in the first stage. The load is applied in increments in the final stage, accompanied by an iterative analysis. The Output program is adopted for the calculation process and producing the results. Furthermore, curves are presented for graphical features of the behavior mechanism.

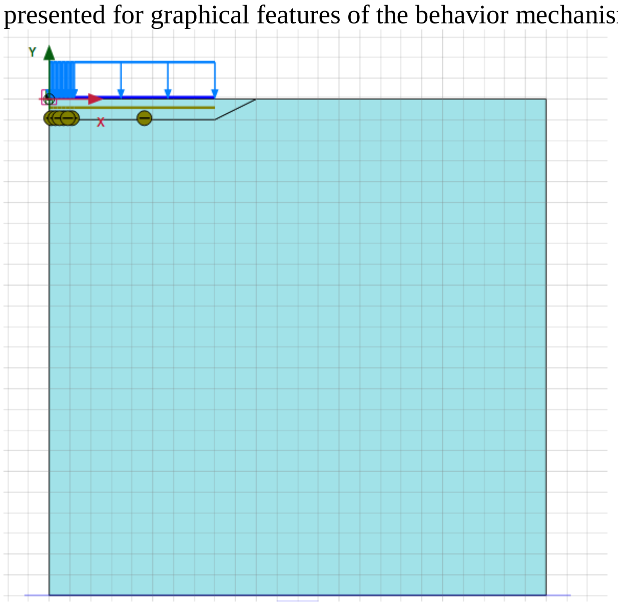

Figure (3): Model Verification using plaxis software.

5.1. Plane Strain Analysis

A 2-D plane strain condition was simulated and analyzed using the finite element software package, PLAXIS.

5.1.1. Model geometry

The foundation slab has a breadth of L=16 m, and an equivalent thickness (depth) of 0.38 m. If L is the breadth of the slab, the soil was 3L=48 m wide and 1.5 L=24 m deep.

5.1.2. Materials

Table (1): Properties of the foundation slab and the soil.

	E (MPa)	υ	EA (KN)	EI (KN.m^2)
Foundation slab	20000	0.2	7600000	91453.33333
Soil	60	0.3	-	-

E: modulus of elasticity

υ: Poisson's ratio

EA: axial stiffness

EI: flexural rigidity

5.1.3. Meshing

L is the breadth of the slab so the mesh was 3L wide and 1.5 L deep. Because of symmetry, half the model was simulated. In the 2D analysis, the medium-mesh was created with a local element size factor of 0.1 under the slab while a factor of 1 away from the slab as shown in Figure (4). Rollers are set on left and right side boundaries of the soil domain to allow vertical movement. Hinged ones are at lower base of model to prevent any movement in both directions. Figure (5) shows the deformation of the finite elements mesh. For the 2D analysis, 15-node elements were chosen for the soil and raft. Only 5 kN/m uniform loading condition that imposed on the slab is considered in this analysis.

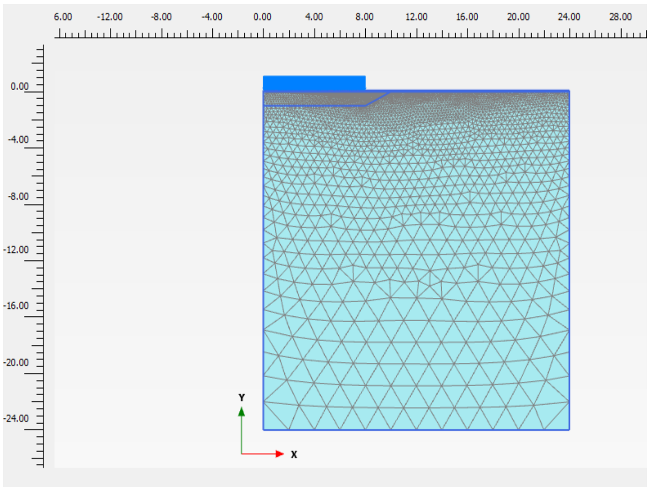

Figure (4): Finite-element mesh using plaxis software.

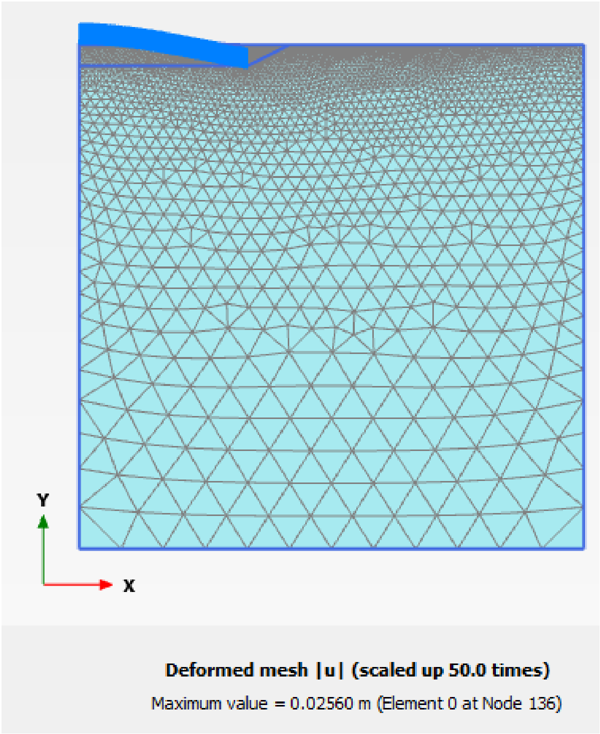

Figure (5): Deformed mesh.

5.2. Model Verification

For verifying the model, the results are compared with a documented numerical study by Abdelmalak [17] using two-dimensional finite element analysis software ABAQUS. The study represents a one storey light weight structure founded on a Stiffened slabs-on-grade foundation in Texas, USA [17].

Figure (6) shows the centre heave scenario of the referenced case study of Abdelmalak. The initial mound shape profile obtained using equation (1). The foundation slab which simulates as a plate element has a breadth of L=16 m, and an equivalent thickness (depth) of 0.38 m. If L is the breadth of the slab, the soil was 3L=48 m wide and 1.5 L=24 m deep and half the model was simulated.

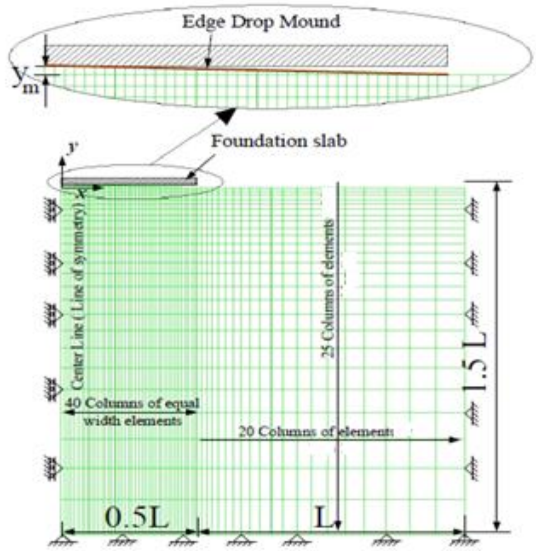

Figure (6): Numerical model of the case study for an edge drop case (Abdelmalak, 2007) [17].

Figure (7) presents the elevation of the soil mound and the foundation slab from footing center line. The initial soil mound, which is obtained from equation (1), starts at 0.085 m and after the analysis it settled to the final mound elevation of 0.083 m in both Plaxis and Abaqus software as the two elevations coincide. While the final foundation elevation is the same along the first 3 m and ends with 3.6% difference in elevation. Figure (8) shows the final settlements of soil mounds. The graph shows good agreement in both models with a difference of 18% in settlement at the center of the footing. Figure (9) shows the final settlements of the foundation slab. The graph demonstrates good agreement in the first 3 meters with a settlement difference of 21% at towards the center. Figures (10) and (11) present the shear forces and bending moments on the foundation slab. The main differences in the current results are attributed to the use of 15-noded element in Plaxis simulation; Abdelmalak used a 4-noded element in the Abaqus simulation.

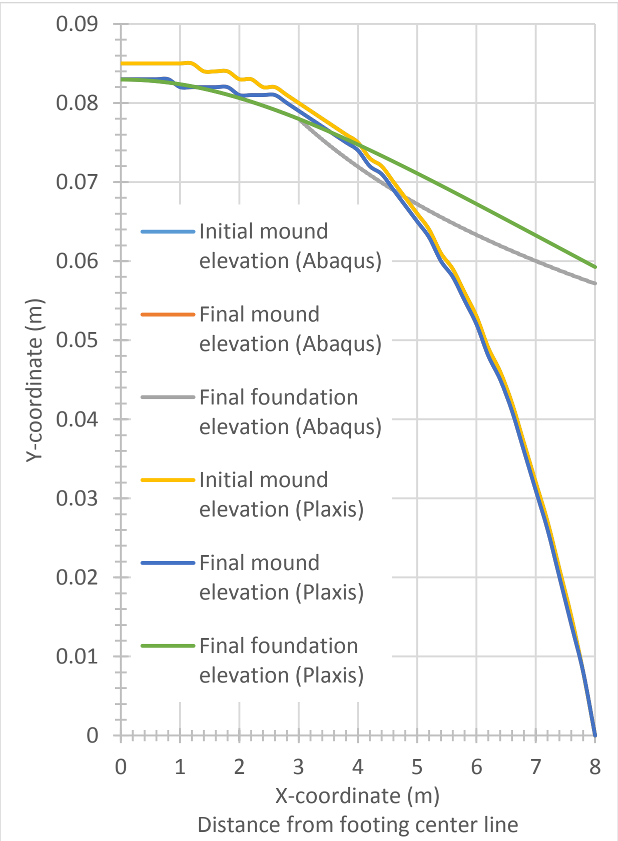

Figure (7): Soil mound and foundation slab profiles.

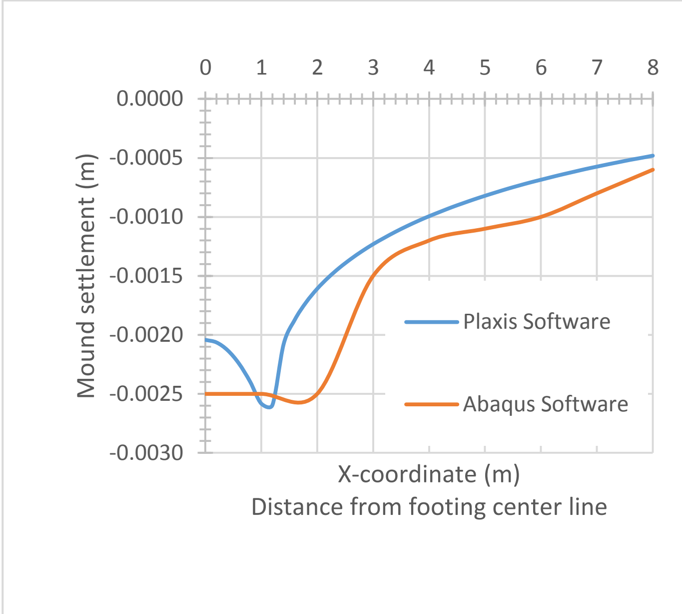

Figure (8): Final settlements of soil mounds.

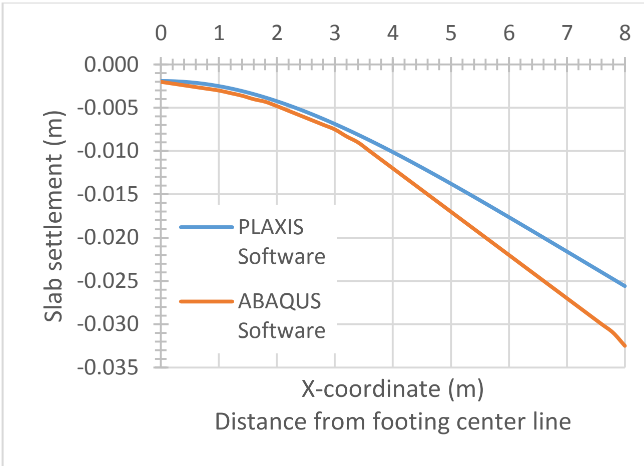

Figure (9): Final settlements of the foundation slab.

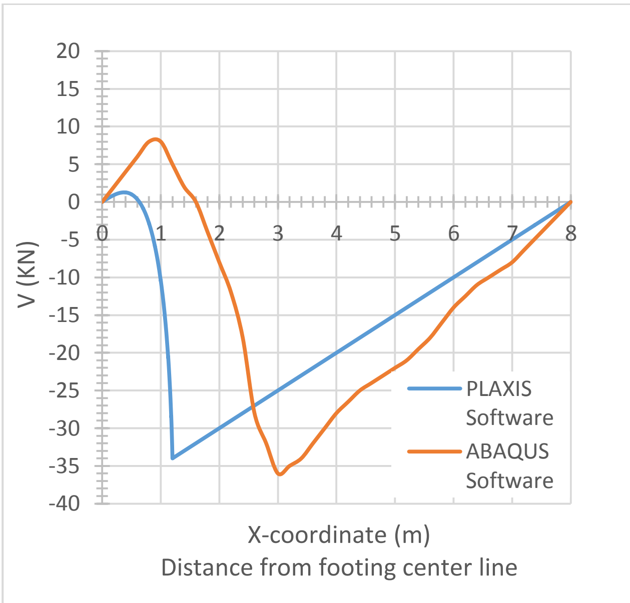

Figure (10): Shearing forces along the slab.

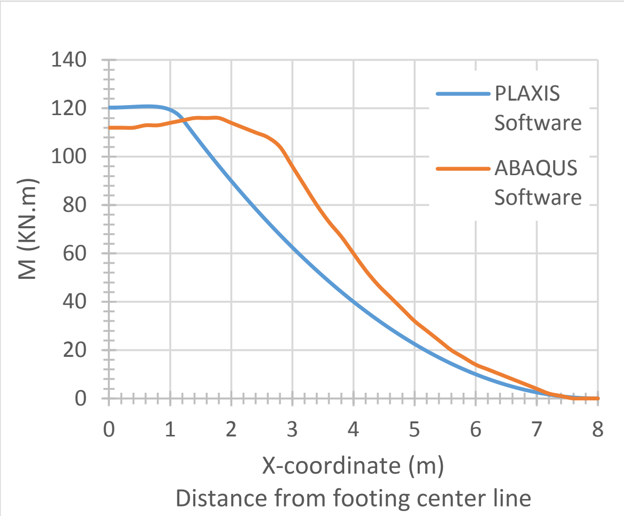

Figure (11): Bending moments along the slab.

5.3. Parametric Study

A parametric study was done on ribbed slab system to investigate the effect of the main factors controlling the behavior of foundations resting on expansive soils under central heave mode. The study is performed for studying the effect of dimensions and spacing of the ribbed slab system. The waffle slab parameters are the slab thickness, beam depths, beam width and beam spacing. These parameters are used to calculate the thickness of an equivalent stiffness flat slab. Table (2) shows the parameters of the ribbed foundations for 24 different cases that have been examined and the equivalent thickness for each case.

The total depth is varied from 0.3 m to 0.45 m. The beam width is varied from 0.15 m to 0.2 m. Spacing ranged between 0.65 m when the forms are used in arrays of two forms per void unit and 1.2 m in arrays of up to four forms per void unit. The soil parameters are the modulus of the soil which taken as E_{soil} = 60 MPa, and the Poisson's ratio Ʋs=0.3. The properties for the slab which is simulated as a plate element were the modulus of elasticity E_{conc}= 20000 MPa, Poisson's ratio Ʋc=0.2. The Concrete strength is 25 MPa and the steel grade is 360.

The resulting bending moment on each case is used in designing the section of the ribbed foundation slab according to the Egyptian Code of Practice and present the most appropriate ribbed foundation parameters under central heave scenario.

6. RESULTS AND DISCUSSION

Figures (12-15) present the applied bending moment on the foundation slab on the different cases that were examined using Plaxis software. Table (3) presents the results from the design of the 24 cases to present the most appropriate waffle slab dimensions under central heave scenario. According to the results, the parameters, which contribute the most in minimizing the expansive soil impact on foundations, are the total depth of the foundation and the beam width. All the cases which have total depth of 0.4 m and 0.45 m are safe in withstanding the resulting moment and shear from the swelling soil. In contrast, all the cases which have total depth of 0.3 m, were unsafe as this foundation system cannot withstand the resulting moments and shear from the swelling soil. The cases which have total depth of 0.35 m were safe only when the beam width is greater than 0.2 m. Figure (16) shows the ribbed slab dimensioning and typical reinforcement.

Table (2): Cases of the waffle slab parameters.

Case No.	Slab length (m)	Number of beams	Slab thickness (m)	Waffle height (m)	Waffle box	Inner beam width (m)	Outer beam width (m)	Inertia (m^4)	Equivalent thickness (m)
1	L=16	14	0.1	0.2	1 m * 1m	0.18	0.42	0.014	0.22
2	L=16	14	0.1	0.25	1 m * 1m	0.18	0.42	0.022	0.25
3	L=16	14	0.1	0.3	1 m * 1m	0.18	0.42	0.032	0.29
4	L=16	14	0.1	0.2	1 m * 1m	0.2	0.3	0.014	0.22
5	L=16	14	0.1	0.25	1 m * 1m	0.2	0.3	0.022	0.25
6	L=16	14	0.1	0.3	1 m * 1m	0.2	0.3	0.033	0.29
7	L=16	14	0.15	0.2	1 m * 1m	0.19	0.36	0.022	0.25
8	L=16	14	0.15	0.25	1 m * 1m	0.19	0.36	0.033	0.29
9	L=16	14	0.15	0.3	1 m * 1m	0.19	0.36	0.046	0.33
10	L=16	14	0.15	0.2	1 m * 1m	0.2	0.3	0.022	0.25
11	L=16	14	0.15	0.25	1 m * 1m	0.2	0.3	0.033	0.29
12	L=16	14	0.15	0.3	1 m * 1m	0.2	0.3	0.046	0.33
13	L=16	24	0.1	0.2	1 m * 0.5 m	0.17	0.38	0.018	0.24
14	L=16	24	0.1	0.25	1 m * 0.5 m	0.17	0.38	0.029	0.28
15	L=16	24	0.1	0.3	1 m * 0.5 m	0.17	0.38	0.045	0.32
16	L=16	23	0.1	0.2	1 m * 0.5 m	0.2	0.4	0.019	0.24

17	L=16	23	0.1	0.25	1 m * 0.5 m	0.2	0.4	0.029	0.28
18	L=16	23	0.1	0.3	1 m * 0.5 m	0.2	0.4	0.045	0.32
19	L=16	24	0.15	0.2	1 m * 0.5 m	0.17	0.38	0.029	0.28
20	L=16	24	0.15	0.25	1 m * 0.5 m	0.17	0.38	0.045	0.32
21	L=16	24	0.15	0.3	1 m * 0.5 m	0.17	0.38	0.065	0.36
22	L=16	23	0.15	0.2	1 m * 0.5 m	0.2	0.4	0.029	0.28
23	L=16	23	0.15	0.25	1 m * 0.5 m	0.2	0.4	0.045	0.32
24	L=16	23	0.15	0.3	1 m * 0.5 m	0.2	0.4	0.065	0.36

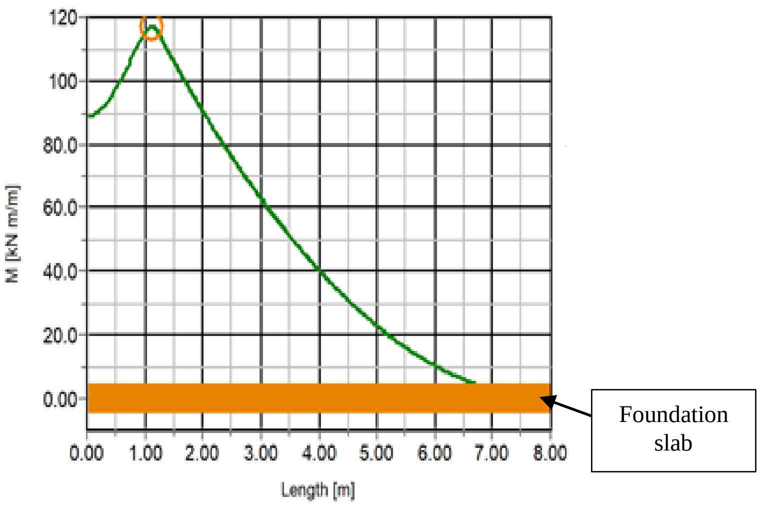

Figure (12): Bending moment for cases 1 and 4.

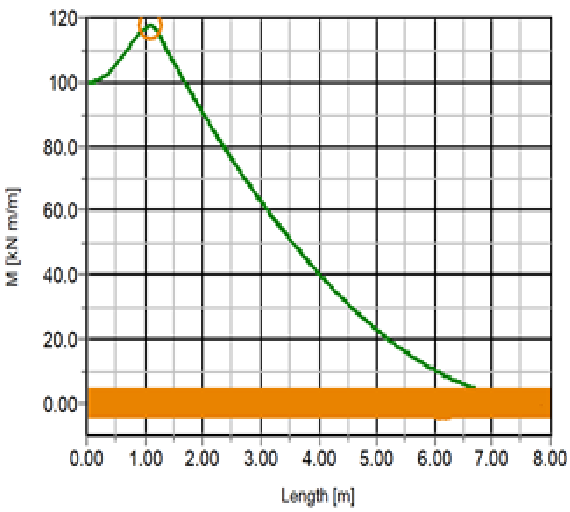

Figure (13): Bending moment for cases 2, 5, 7 and 10.

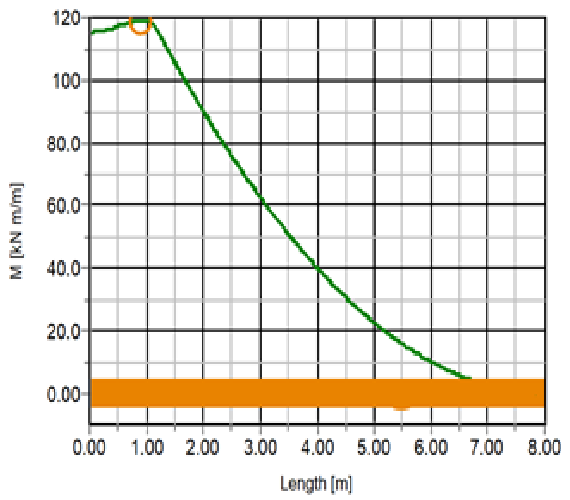

Figure (14): Bending moment for cases 3, 6, 8 and 11.

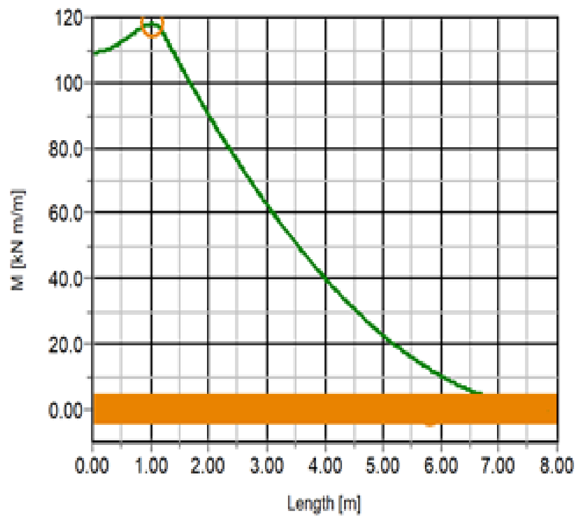

Figure (15): Bending moment for cases 9 and 12.

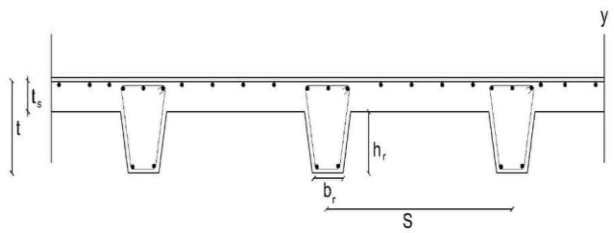

Figure (16): Ribbed slab dimensioning and typical reinforcement.

Table (3): Design results for the ribbed raft foundations.

Cases	Equivalent thickness	$M_{ult.}$ (KN.m)	Area of steel (cm^2)(maximum compression reinforcement) 0.4x$A_{S\ main}$	Area of steel (cm^2)(compression reinforcement) A_s^-	Total steel area (cm^2) $A_{S\ main}$	
1	0.22	114.6	6.2014	9.316	15.5035	Unsafe *
4			6.23	8.7	15.575	
2	0.25	115.1	5.304	5.95	13.26	Unsafe
5			5.342	5.23	13.355	Safe
7			5.32	5.58	13.3	Unsafe
10			5.342	5.23	13.355	Safe
3	0.29	115.6	4.528	2.88	11.32	Safe
6			4.734	2.46	11.835	
8			4.572	2.52	11.43	
11			4.734	2.46	11.835	
9	0.33	116.6	4.2928	0.632	10.732	Safe
12			4.318	0.17	10.795	
13	0.24	114.5	6.176	9.6	15.44	Unsafe
16			6.218	8.67	15.545	
14	0.28	115.4	5.304	6.35	13.26	Unsafe
17			5.354	5.26	13.385	Safe
19			5.304	6.35	13.26	Unsafe
22			5.354	5.26	13.385	Safe
15	0.32	116.3	4.708	3.77	11.77	Safe
18			4.76	2.525	11.9	
20			4.708	3.77	11.77	
23			4.76	2.525	11.9	
21	0.36	117.7	4.272	1.65	10.68	Safe
24			4.352	0.255	10.88	

M_{ult} : The actual moment on the foundation.
$A_{s\ main}$: Total steel area in tension and compression.
A_s^- : Area of compression reinforcement.

* The actual compression reinforcement is higher than the maximum compression reinforcement.

7. CONCLUSIONS

The main aim of the current research is to investigate the structural behavior of a waffle slab foundation with uniform thickness under the action of uplift pressure from the ground. The specific conclusions are as follows:

1. The parameters which contribute the most in the safety of the foundation system were the total depth of the foundation and the beam width.
2. The spacing between the ribs not contribute in the safety of the foundation system.
3. Total depths of 0.4 m and 0.45 m were safe and recommended under this condition of central heave scenario. In contrast, total depth of 0.3 m were unsafe and not recommended.
4. The cases with total depth of 0.35 m recommended only when the beam width is not less than 0.2 m.

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