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Effect of grid foundation shape on soil-foundation interaction

تأثير شكل الأساسات الشبكيه علي السلوك بين التربه والأساسات

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الملخص: تهتم هذه الدراسه بالأساسات الشبكيةِ الضحلةِ التي تَستندُ إلى التربةِ المُتَجانسةِ والتفاعل بين هذا النوع من الأساسات الشبكيةِ والتربه، حيث أنه قد لوحظَ إختراق الأساسات للتربه كما كان متوقعا حدوثهُ. لذا تمت دراسه وتحليل هذا النوع من الأساسات باستخدام نماذج التحليل اللاخطي المختلفه. وقد قورنت النّتائِجِ التي تم الحصولُ عليها لمستويات التحميل المُخْتَلِفةِ وتم تعريف السلوك اللاخطّي لمادّةِ التربةِ بنموذج hardening plasticity cap model بينما تم تعريف الأساسات الشبكيه بنموذج elasticity model. متغيّرات التحليلَ التي تم دراستها للأساسات الشبكيةِ تم إعاده دراستها مره أخري علي أساسات ضحله مستطيله . وأجريت الدراسه علي توزيعات الإجهادِ النسبيةِ داخل التربةِ الناتجه من الأساسات الشبكيةِ والمستطيلة باستخدام برنامجُ العناصرِ المحدودهِ Abaqus cae V 7.1 .

Abstract: This work is concerned with the shallow grid foundation resting on homogenous soil. The interaction between grid foundation and soil, where the expected penetration may occur was observed. So, small and high deformation analysis types were performed. A comparison between results for various loading cases has been obtained. The nonlinear behavior of soil material was defined by hardening plasticity cap model while elasticity model was chosen for the foundation. The analysis variables for grid foundation were performed again for a regular rectangular raft foundation. The relative stress distributions inside the soil for the two foundation geometries 'grid and rectangular' have been observed. The finite element Program Abaqus cae V.7.1 is the used in the analysis.

1. Introduction:

The grid foundation is a special type of shallow foundation, in which, the grid shapes have the great effect in transferring the concentrated column loads applied on its interactions and load paths. Thus, the effect of shape is the first aim of this study. The loading techniques and the geometry of any foundation and the interference between its parts have a great effect on assigning the results of the analysis. The theory of interfering foundations was first suggested by Das and Larbicherif [1983] [5] where; the effect of interference of soil shear zones on the bearing capacity of footings investigated and limited to parallel strip or rectangular foundations. Then, many investigations on non regular shallow foundations were done using laboratory and numerical "FLAC 3D & ABAQUS 3D software" investigations, and there is a general agreement between numerical and experimental results. But numerical results seem to show slightly more bearing capacity than experimental values [9]. For sandy soil, the effect of interaction becomes highly significant for granular soil with friction angle greater than 30^o [11].

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The behavior of multi-edge foundation 'Cross-shape, H-shape and T-shape' was investigated through experimental laboratory tests [8]. The bearing capacity of multi-edge foundation is generally greater and has a better performance than that of square shaped foundation with the same width [8], and that is because of the interference of shear zones under the collected parts increases the shear resistance for the soil. Also, the behavior of interference between parallel strip footings and its effect on the bearing capacity of foundations is investigated [15]. In this case of geometry, if the distance between foundations is small, the efficiency of interference is decreased. So, the maximum bearing capacity is related to the medium distance between the footings [10, 14].

The accuracy of the finite element analysis is still a point of concern although it starts several decades ago. This accuracy 'or factors of nonlinear analysis' was classified by Bathe into four classes which will be examined in this case study [3]. The second aim of this work is to discuss the effect of simulating a real soil foundation problem by different analysis types whether in linear or nonlinear classifications to reach the real and more accurate stress-strain soil behavior.

All these classifications were widely studied by different techniques; one of them was through study the structural finite "Solid-Shell" elements where, the large deformation contact analysis defined by augmented Lagrangian method, and a comparison of using the different contact algorithms especially used for problems in sheet metal forming [10]. Also high deformation was defined by the Arbitrary Lagrangian-Eulerain (ALE) method through studying the failure mechanism of a horizontally layered cohesive soil under the vertically loaded rigid strip and circular footings [17]. The recent technique is a numerical method for large deformation problems of soil referred to as Remeshing and Interpolation Technique with Small Strain model (RITSS). This method was used in pipeline and foundation penetration analyses. The RITSS method is based on a standard small strain algorithm, but with frequent remeshing. Also, error estimation and H-adaptive mesh generation techniques was incorporated into the RITSS approach to reach the accuracy of large deformation analyses of foundations but with optimum meshes to minimize computational times [12, 13].the RITSS method defect are that it needs a big memory capacity during the analysis.

The concept of these experiments could be used to investigate any grid foundation to obtain the soil stresses beneath these foundations. It is also recommended to explain the bearing capacity of a foundation which affected by its geometry and depends on the distance between the foundation parts.

2. Linear and nonlinear analysis.

2.1. Linear static analysis:

Boussinesq's equation for a concentrated point load is the used equation in the approximate solution for hand calculated linear static analysis, in which, the soil properties were not concerned.

2.2. Nonlinear static analysis:

To establish an appropriate finite element model for nonlinear analysis of an actual engineering problem, three solution variables must be verified; material models, the nonlinear kinematic formulations, and the incremental solution strategies [3].

a- Simulation material models:

In order to constitute stress–strain model of soil behavior, the following requirements must be achieved: a) an adequate description of main characteristics of elastic-plastic soil behavior, b) a stable and unique mathematical formulation, c) along with an efficient performance for numerical implementation and to ensure the soil description to be with practical characteristics. The soil model should be defined with only a few parameters, whose values are available from standard tests [7].

These all requirements are available by Drucker-Prager hardening cap model. Drucker et al. (1957) proposed that the soil behavior could be modeled as an elasto-plastic strain hardening material and extended Drucker–Prager frictional model with a spherical end-cap, combined with the Drucker–Prager cone. The cap was used to control the plastic volumetric change of soil and location of cap was dependent upon soil density [6, 4]. Then very important improvements of the cap model performance were obtained by formulating consistent algorithmic loading–unloading conditions and modifying hardening law to associated one [12].

But the singularity of the tangent operator in the corner regions remains as an additional problem, which causes difficulties in numerical calculation. This problem was solved by introducing circular surfaces on both tension and compression sides, which are used to smoothly intersect the failure envelope, to result a new modified smooth elliptic cap model for soil mechanics [6], see Fig. [1].

This new modified smooth elliptic cap model was studied in several numerical examples and provided a very good performance in modeling of both, standard tests and practical problems [6]. The main advantage of this modified model is avoidance of corner regions in yield criterion without changing the original material parameters. Therefore this model shows very similar behavior as non-smooth elliptic cap model, and has a quadratic convergence rate [6].

Abaqus program also contains a similar modified smooth elliptic cap model which has been chosen for this theoretical study [2], see Fig.[1] yield surfaces in the p–t plane.

The soil material cap parameters used in the research was defined as the verification cap parameter concluded the linear elasticity parameters and the cap hardening parameters. The position of the yield surface defined in pure hydrostatic compression related to volumetric compressive plastic strain [2].

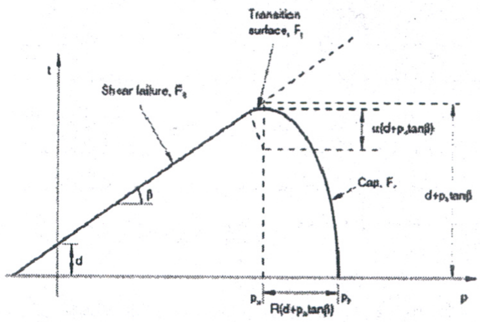


Figure 1: modified Drucker-Prager/Cap model.

b- Nonlinear kinematic algorithms in contact analysis:

The contact algorithms are classified into small and high deformation analysis.

i. Small deformation analysis (S.D.A):

Small deformation analysis will be defined in this study by the non-frictional contact type with a penalty formulation.

ii. High deformation analysis (H.D.A):

According to the geometry of grid foundation and during high loading levels, the grid may penetrate the soil, so large deformation analysis will be studied for grid and raft foundation in order to reach the effective simulation to this penetration contact formulation.

Traditionally, large deformation problems in solid mechanics have been solved numerically by the FE method using a Lagrangian method if geometrically nonlinear behavior is expected. During high deformation analysis an excessive mesh distortion may occur [17]. To avoid the defects of the previous method, another one is considered as a compound of the penalty method and the Lagrangian multipliers method 'augmented Lagrangian method'. It must also be mentioned that only linear convergence may be achieved for the Augmented Lagrangian parameters inside the Augmented Lagrangian iteration algorithm. Therefore many additional iteration steps may be required [10].

c- Incremental solution strategy:

Abaqus Standard uses a Newton's method to solve the nonlinear equilibrium equations. The solution is usually obtained as a series of increments, with iterations to obtain equilibrium within each increment. Increments must sometimes be kept small to ensure accurate modeling of history-dependent effects. The choice of the increment analysis size is a matter of computational efficiency as if the increments are too large, more iteration will be required. Furthermore, Newton's method has a finite radius of convergence [1]. Thus, there is an algorithmic restriction on the increment size. The used increment strategy started with a very small increment size and the whole number of increments are very large.

d- Finite element meshing:

The model meshing needs computational efficiency to achieve the suitable accuracy with the sufficient time and storage capacity of analysis. During this study, the finite element soil meshing was concentrated as finer under the grid foundation location, Fig. [2].

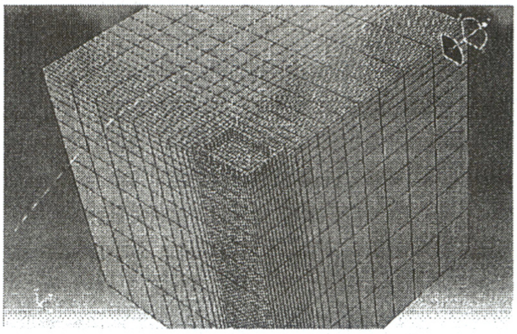


Figure 2: The mesh of soil finer under the grid foundation and tends to be coarse.

3. Model description:

The proposed model for grid foundation resting on C and φ soil was a 3D model. The soil depth was taken as (6.5B) and both length and width were (13B), where: (B) is the half length of the short grid beam of the footing, Fig. [3]. A relatively fine mesh was used in the analysis, Fig. [2].

The contact properties illustrated below:

Tangential behavior: is a penalty friction with a friction isotropic coefficient.

The normal contact behavior is a penalty constraint by allowing the foundation and soil to separate after contact. This was used for small deformation analysis, and augmented Lagrangian standard method with non linear contact analysis was used for high deformation analysis, where nonlinear effects of large displacements and affects subsequent steps was included in Abaqus cae [1]. Node-to-surface contact element approach is considered.

4. Study methodology:

As mentioned above, the required degree of nonlinearity depends on the case of study. Three types of study were chosen to discuss the nonlinearity degrees.

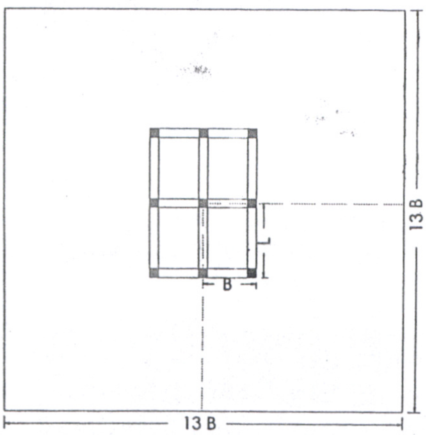


Figure 3: The axysymetric plane of the grid foundation and soil model.

First: Grid foundation and rectangular raft foundation were tested for several degrees of linearity and nonlinearity cases

A) Conduct the manually linear analysis by Boussinesq's equation.
B) Conduct linear F.E analysis by assuming the soil and foundation as a one block with no contact in between.
C) Conduct the nonlinearity in soil material by F.E analysis with the assumption that the soil and foundation as a one block with no contact in between.
D) Conduct the nonlinearity in soil material by F.E analysis with small deformation (S.D.A) contact nonlinear analysis.
E) Conduct the nonlinearity in soil material by F.E analysis with high deformation (H.D.A) contact nonlinear analysis.

Second: Another type of analysis was performed, which consists of comparison between vertical stresses distributed in soil under loaded points. Stresses under grid beams resulted from high deformation analysis compared with that resulted from small deformation analysis.

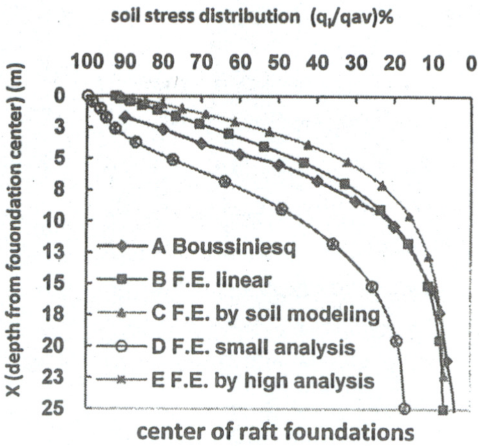
Third: To insure the effect of using high deformation analysis according to different loading levels, the first was allowable, the third was ultimate loading level, and the second was in between them. These cases of study were performed using small and high deformation analysis.

5. Results and discussion:

By study the relative inside soil stress distribution, the influence of analysis type was clear in grid and raft foundation. Each case of study resulted in a different relative vertical stress distribution in the soil. But using the material nonlinear parameters only is useless if there is no nonlinearity contact analysis between foundation and soil, Fig. [4, 5 and 6].

Also, the difference value may be neglected in studying rectangular raft and grid foundation if it is performed by high or small deformation analysis. This is for relative vertical stress distribution in the soil under the center of foundation.

This was expected because no high deformation allowed located under the center points if the loading limited by the allowable level. During apply the ultimate loading level as in Fig. [7] The grid beams penetrate the soil with relative settlements.



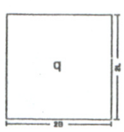
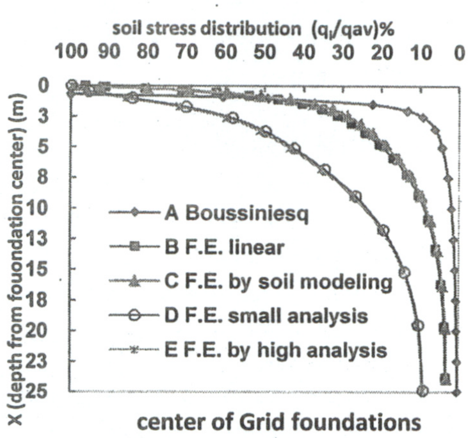


Figure 4: The percentage vertical soil stress versus with rectangular foundation depth.



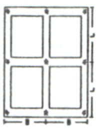
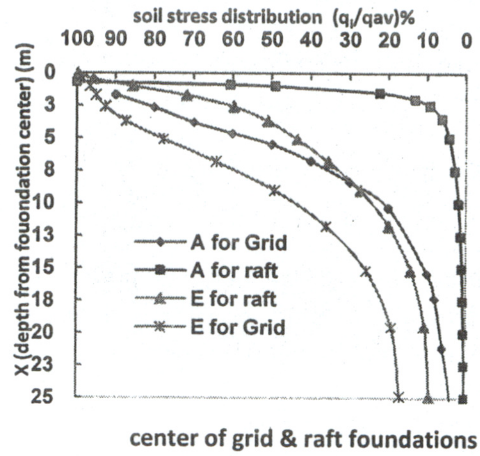


Figure 5: The percentage vertical soil stress versus with grid beam foundation depth.

The finite element analysis types have great effects on the settlement, contact pressure, and stress distribution inside the soil and under the grid element.

This is especially when loading level are very high, which in turn change the foundation contact behavior from rigid to flexible foundation behavior , as in Fig. [8, 9, and 12] where P in (KN), where: S.D.A; and, H.D.A; small and high deformation analysis.



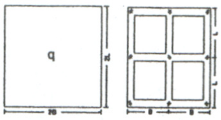


Figure 6: The percentage vertical soil stress versus with grid and rectangular foundation depth.

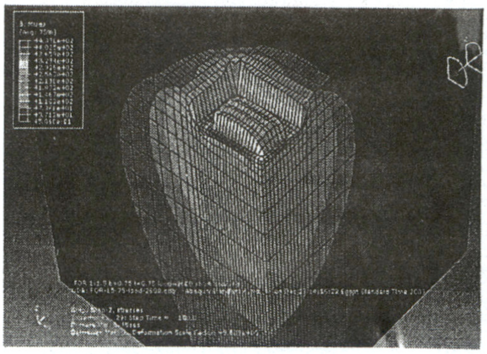


Figure 7: The grid beams penetrated the soı'.

It's worth to mention here that, fo· the contact pressure under the grid beams especially the middle beams, the deference of the contact results between high and small deformation analysis are greet especially when the foundation behaves as a flexible grid foundation , as shown in Fig. [8, 9], This point was agreed with the concluded in [10], that in general there are a differences in the contact stresses, "stress jumps", between neighbored contact points between 'penalty' small deformation analysis and high deformation analysis.

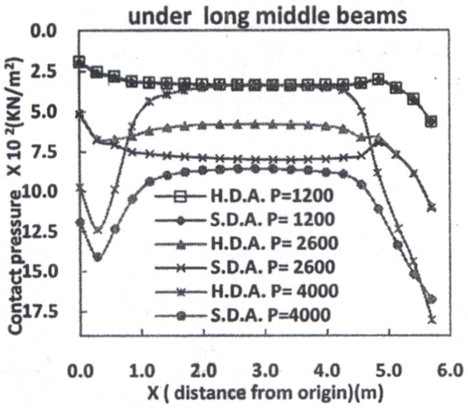
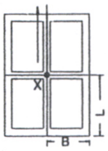


Figure 8: The contact stress under long middle Grid beam.



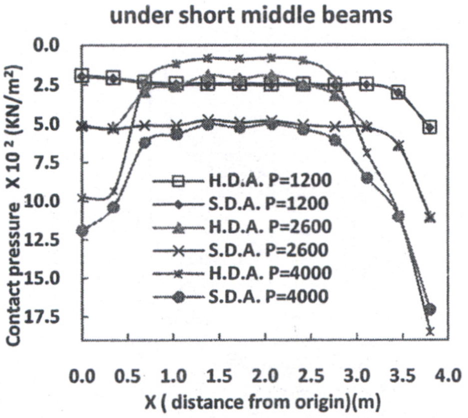
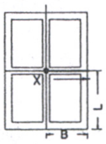


Figure 9: The contact stress under short middle Grid beam.



The contact pressure under the middle beams decreases in the middle of beam by a great value by using high deformation analysis, while all edge beams, either short or long, have a small changes by using the two types of analysis, especially when the loading values are relatively small. This means that, the interaction between grid beams effect was great for all the middle beams. This result in itself forces theory of interaction for grid foundation.

The higher loading level, the higher contact under points of concentrated loads, and it decreases along the grid beam between these points. But by comparing the contact values along the short and long middle beams for flexible foundation, these differences indicate that the role of any grid beam in contact distribution depends on its length. Generally, the contact is relatively concentrated under the loading point for flexible foundation. It worth mentioning that, all the contact values depends on the relative rigidity between grid and soil. And if the foundation is very rigid according to the soil and the loading level, the high deformation analysis gives a relatively lower contact result throw the same shape and slopes compared with small deformation analysis as in figure [10].

Vertical stresses and settlement under the concentrated loaded points don't have any changes, except for flexible foundation for small and high deformation analysis Fig. [11, 12].

All the beams are sensitive to the high deformation analysis except edge beams and the settlement under all middle beams are decreased if using high compared with small deformation analysis results, while the great effects were under short middle beams Fig. [13].

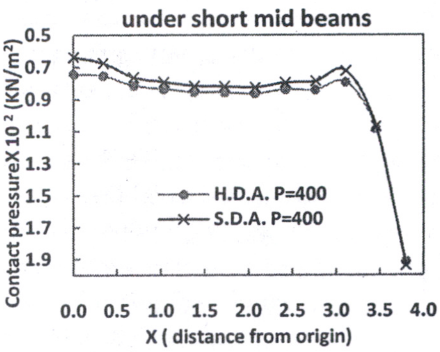
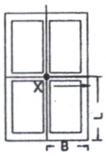
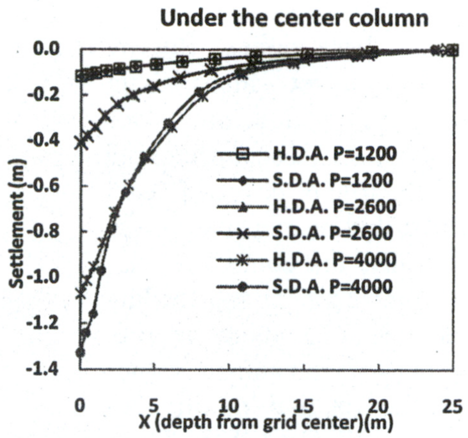


Figure 10: The contact stress for rigid grid foundation under its short middle beam.





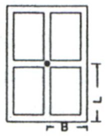
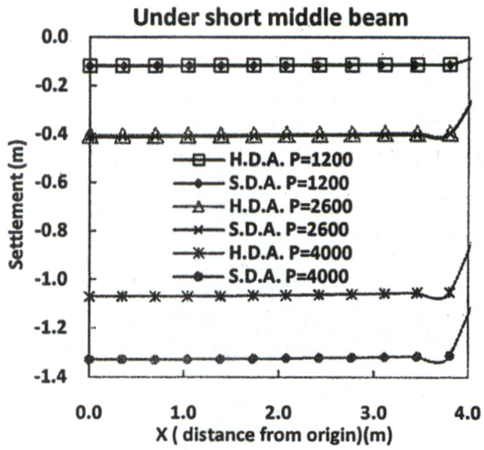


Figure 11: The effect of the deformation analysis type on the settlement under the center column.



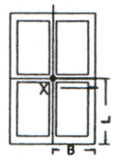
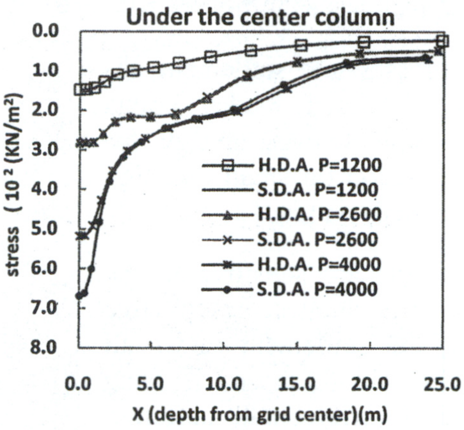


Figure 13: The settlement under short middle Grid beam.



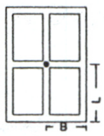
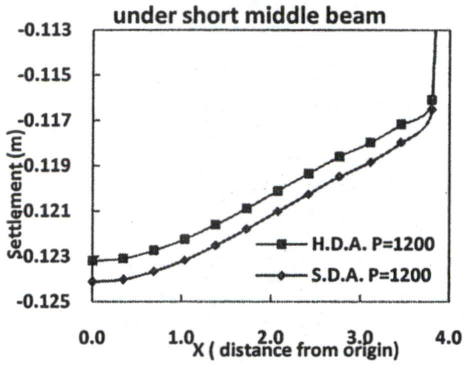


Figure 12: The internal soil stresses under the center column.



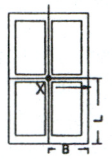
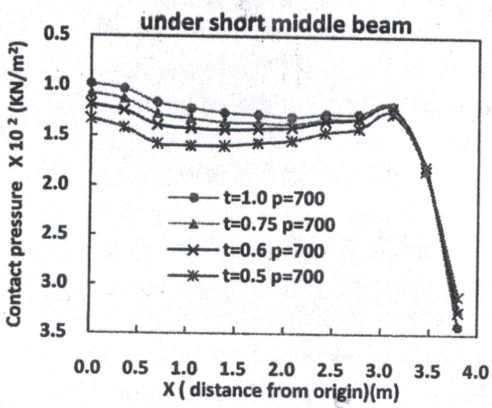


Figure 14: The settlement under short middle Grid beam for the allowable loading level.

The settlement decreases under all beams (long or short) approximately in the same ratio, when using high and small deformation analysis for all loading levels even when the loading level were allowable level; Fig. [14]. along all the different tested four beams; long, short, middle, and edge beams, there is a relative settlement between these beams and for high stiffness grid foundation, this type will be very sufficient for low cost and off shore building.

As mentioned above the length of grid beams have a great effect on the shape of contact distribution for all middle beams. So, the relative lengths of grid beams are studied throw two grid foundation models have a deference ratio of beam length. The first beam ratio are B:L= 1:1.5 and the other beam ratio are B:L= 1:2. This study are discussing a various foundation rigidities for a considered loading level where p=700 KN.

Although the foundation are rigid and the contact area are constant for all deferent grid rigidities, the contact stress decreases with the increase of foundation rigidity along all beams, as in figure [15], Which gives us another way to decrease the contact stress and in turn the settlement will decreases also under the beams without increasing the contact area, as in figure [16, 17].



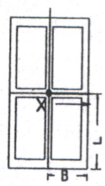
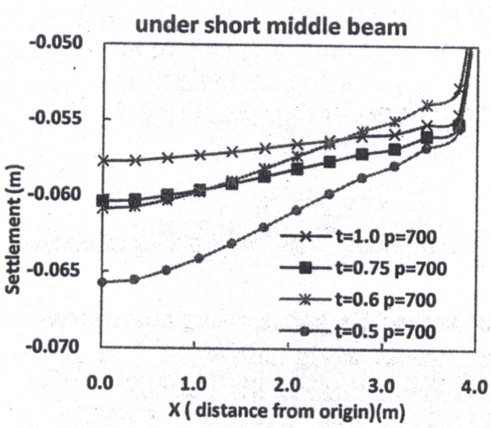


Figure 15: The contact stress under short middle beam for grid beam ratio **B:L =1:1.5**.



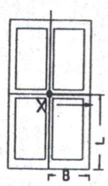


Figure 16: The settlement of short middle beam for grid beam ratio **B:L =1:1.5**.

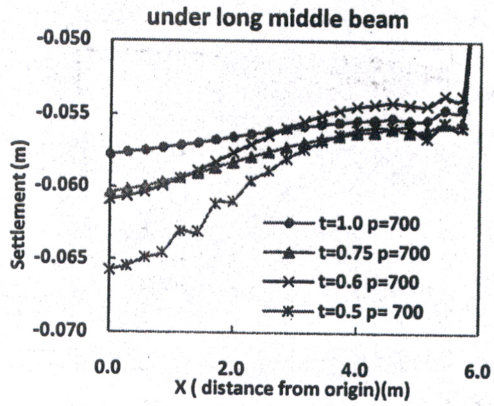
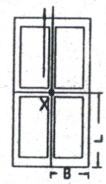


Figure 17: The settlement of long middle beam for grid beam ratio **B:L =1:1.5**.



By comparing the foundation rigidities for deferent ratios of beam lengths "B: L = 1:1.5 and 1:2" the contact stress changes its distribution slopes along the faced compared beams. Even in the same ratio of beam lengths say 1:2 the contact stress under long beam have an opposite stress distribution slope compared with that of under short beam, as in figure [18, 19].

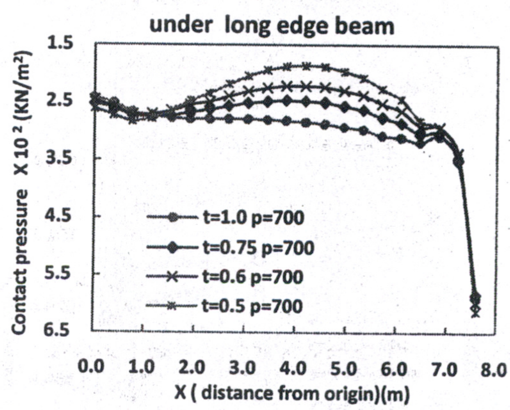
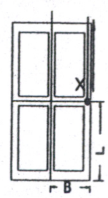
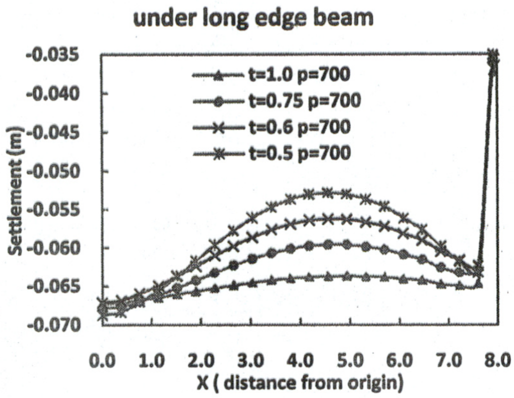


Figure 18: The contact stress under long middle beam for grid beam ratio**B:L =1:2**.





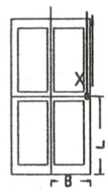


Figure 19: The settlement of long middle beam for grid beam ratio **B:L** =1:2.

For long edge beams the higher increase of the ratio beam lengths 1:1.5 and more, the lower contact stress under the middle of beams specially the long edges beams.

6. Conclusions:

There is a great difference in the relative stress flow "load path" distributed under the center of rectangular foundation compared with the other under the same point in grid foundation when the overall loads are the same. The influence of analysis types "degrees of nonlinearity" on the behavior of grid foundation interacted with soil was great, and no doubt that the analysis by high deformation analysis type and high degree of nonlinearity gives more real results than small deformation analysis type for any loading level and specially for the ultimate loading levels.

Although high deformation analysis effect was significant in flexible foundation case, it has an important role in the contact values in the middle of beams, especially the middle beams with deferent lengths, and the grid beams role in transferring loads are clear during the maximum allowable loading level.

It's recommended that whether the foundations are rigid or flexible, it's better to analyze it by long deformation analysis.

The higher foundation rigidity the lower contact pressure under all beams especially under the middle beams. And for long edge beams the higher increase of the ratio beam lengths 1:1.5 and more, the lower contact stress under the middle of beams.

The contact distribution under grid beams depends on the beam length and rigidity, and these points need more researches to evaluate the optimum ratio between grid beam lengths, which give, the best interaction effect between beams, and the best behavior of the whole grid type of foundation.

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