# FINITE ELEMENT METHOD FOR IMPROVING SOFT SOIL UNDERNEATH A BALLAST RAILWAY TRACK

**S. F. Ibrahim[1], A. H. Aziz[2], G. M. Aboud[3], and I. T. Jawad[4]**
[1] Al Minstansiria University; Tel: 009647901303569; Email: drsaadfarhan @yahoo.com
[2] Al Mustansiria University; Tel: 009647901256225
[3] Al Mustansiria University; Tel: 009647903446762; Email:ghufraan_eng@yahoo.com
[4] Ministry of youth & sport; Tel: 009647703992601; Email: alsaedstar11 @hotmail.com

## ABSTRACT

It is always recommended to improve the properties of the soft soil beneath the railway tracks to increase its ability in bearing different applied loads and to control the expected generated settlements. The most methods used to improve the soil are in using a ballast layers with or without reinforcement by a single geogrid layer or a geogrid layer at different depths. This study presents a three-dimensional finite element analysis for soft soil underneath a ballast railway track by using a finite element program (ANSYS v.11.0) which considered efficient used in many engineering applications and most completeness. Twenty four models were selected using a nonlinear three- dimensional finite element to study the effect of ballast thickness, mechanical properties of soft soil undrained shear strength and modulus of elasticity E, reinforced using geogrid layer to improve the soft soil. Using the element called Solid65 of 8- nodes brick element with three degree of freedom to represent the ballast. And using element called Solid 45 of 8- nodes brick element with three degree of freedom this element is in ANSYS to represent the soft soil and steel plate. Shell element 4- nodes with six degree of freedom (using three degree of freedom only) (Shell 181 in ANSYS) to represent the geogrid layer under and within ballast layer. The results show that increasing the undrained shear strength Cu and modulus of elasticity E will decreasing the settlement of soft soil and increasing the ultimate load. Increasing ballast thickness lead to decreasing the settlement of soft soil and increasing the ultimate load this mean that modulus of elasticity play main role to controlling settlement of soft soil (Ultimate displacement under plate loading) and ultimate load . The results show that the load capacity increase about 7.63% , 7.88 % , 13.80 % for Cu= 9KPa and 3.18 % , 3.27 % ,5.29 % for Cu=25 KPa comparing with reference model ,the settlement decreases about 0.86 % , 0.9% , 1.55 % for Cu =9 Kpa and 0.62% , 0.64% , 1.33% for Cu=25 KPa

*Keywords: ANSYS, railway, geogrid, ballast, reinforcement soft soil*

## INTRODUCTION

Soft clays are recent alluvial deposits probably formed within the last 10,000 years characterized by their flat and featureless ground surface. (Brand and Bernner, 1981) are identified by their low undrained shear strength ($C_u$ < 40 kPa (B.S-CP8004:1986)) and high compressibility ($C_c$ between 0.19 to 0.44). They are found at high natural moisture content, typically ranging from 40-60% with plasticity index ranging from 45-65% (Broms, 1987). Soils with such characteristics create serious problems to geotechnical engineering associated with stability and settlements problems. Many techniques are available to improve such soils based on reducing the water content by several mechanisms such as sand drains, wicks, electrical osmosis, geogrid and thermal treatments. On the other hand some other techniques are also developed towards improving the engineering properties of these clays by introducing sand compaction piles or stone columns, where holes with specific depth and diameter are made within the soil in a grid form and backfilled with granular material. The ANSYS computer program is a large-scale multipurpose finite element program which may be used for solving several classes of engineering analyses. The analysis capabilities of ANSYS include the ability to solve static and dynamic structural analyses. The program contains many special features which allow nonlinearities or secondary effects to be included in the solution, such as plasticity, large strain, hyperelasticity, creep, swelling, large deflections, contact, stress stiffening, temperature dependency ,material anisotropy and radiation.

## AIMS OF THE STUDY

The main aims of this study are to investigate theoretically the improvement of soft soil reinforced with geogrid layers with or without ballast. The effect of soft soil characteristics (angle of friction and cohesion), thickness of ballast layers

and presence or absent of geogrid on ultimate load capacity, vertical displacement (settlement) and mode of failure under monotonic loads (pressure) will be investigated. The work includes the following two main categories:
1-To implement a nonlinear finite element procedure to analyze all adopted models.
2-To assess finite element analysis results.

## MATERIAL PROPERTIES AND MODELING

### Soft Soil

Geotechnical design and execution of civil engineering structures on soft to very soft soil are usually associated with substantial difficulties since this type of soil is sensitive to deformation and possesses very small shear strength (Kempfert and Gebreselassi, 2006). In general, there is no clear definition of soft clay. There are several approaches which can be used in identifying and classifying of soft soil

### Shear Strength Parameters of soil ($C_u$ and ф)

Shear strength parameters of soil ($C_u$ and ф) can be determined experimentally by Triaxial testing in clay (consolidated undrained test-CU). The values of friction angle (ф) and Cohesion ($C_u$) are obtained by drawing a common tangent to effective-stress Mohr's circles (Mohr-Coulomb envelope) for various tests.

## MECHANICALPROPERTIES OF BALLAST

Compression Strength of Ballast The compressive test strength of Ballast should be performed on cubic samples measuring (70 mm) on each edge. For each test, four samples shall be taken from quarry face, in such way as to reflect parent rock characteristics. The average compression strength of four samples shall not be less than 600 Kg/cm$^2$ (60MPa). Tensile Strength of Ballast Experimental results, McDowell and Bolton (1998) show that the mean tensile strength ($\sigma_f$) of single particle can be considered as a function of average particle size (d) as shown in the following empirical equation:

$$\sigma_f = \frac{F}{d^2} \quad (1)$$

where ($\sigma_f$) is the characteristic tensile stress induced within particle at failure, (F) is the force applied and (d) is the particle size. It may be noted that the tensile strength of Ballast are ignored and not considered in the present study.

## FAILURE CRITERIA FOR SOFT SOIL

Yield criterion as shown in Fig. 1, the Drucker-Prager are widely used for finite element analysis of granular material problems (such as soil, gravel, sand, rocks….etc). In ANSYS program, the option uses the Drucker-Prager yield criterion is available with either an associated or non-associated flow rule. The yield surface does not change with progressive yielding, hence there is no hardening rule and the material is elastic- plastic

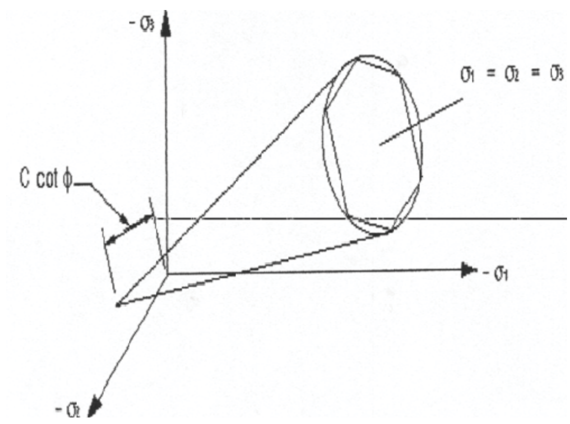


Fig. 1 Drucker- Prager and Mohr-Coulomb yield surfaces

## FAILURE CRITERIA FOR BALLAST

The actual behavior and strength of ballast materials are very complex because they depend on many factors such as the physical and mechanical properties of the particles such as ballast size, air voids, friction between particle and the nature of loading. No single mathematical model can describe the strength of real ballast materials completely under all conditions; so, simple models or criteria are used to represent the properties that are essential to the problem being considered. Willam and Warnke (1975) developed a mathematical model capable of predicting failure for the solid cracking in tension and crushing in compression. In concrete applications, for example, the solid capability of the element may be used to model the concrete. Other cases for which the model is also applicable would be reinforced composites (such as fiberglass), and geological materials (such as rocks) (ANSYS, 2007)

## FAILURE CRITERIA FOR GEOGRID AND STEEL PLATE

For most metals, Von-Mises yield criterion is used because is simpler to use in theoretical application (Chen, 1982). This criterion assumes that

failure (yielding) occurs when the octahedral shear stress ($\tau_{oct}$) reached its critical value.
Mathematically, this criterion can be expressed in the following form:

$$f(J_2)=J_2-k^2=0 \quad (2)$$

where k= Failure (yield) stress in pure shear
$\frac{1}{\sqrt{3}} f_y$ =

Figure 3 shows the Deviatoric and Meridian sections corresponding to Von-Mises failure surface.

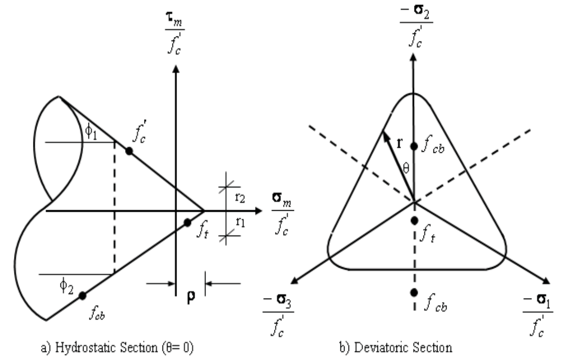


Fig. 2 Failure surface (Chen, 1982)

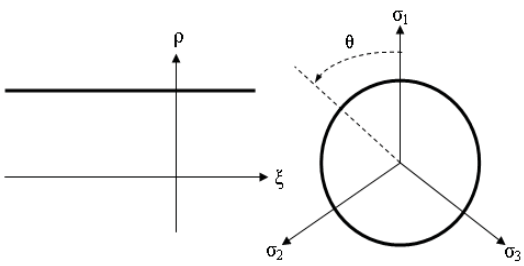

Fig. 3 Meridian and deviatoric sections for Von-Mises Criterion

## FINITE ELEMENT MODELING

As mentioned before, the ANSYS computer program was utilized for analyzing all models. Model components encountered throughout the current study, corresponding finite element representation and corresponding elements designation in ANSYS are presented in Table 1.

## THREE DIMENSIONAL SOLID ELEMENTS

Three dimensional solid elements (SOLID-45 in ANSYS) are used for three dimensional modeling of solid structures such as reinforced concrete and geological materials (such as rocks and soil). The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y and z directions (Fig. 4). The element has plasticity, creep, swelling, stress stiffing, large deflection and large strain capabilities. It may be noted that, in the present study, this element is used to model soft soil layers.

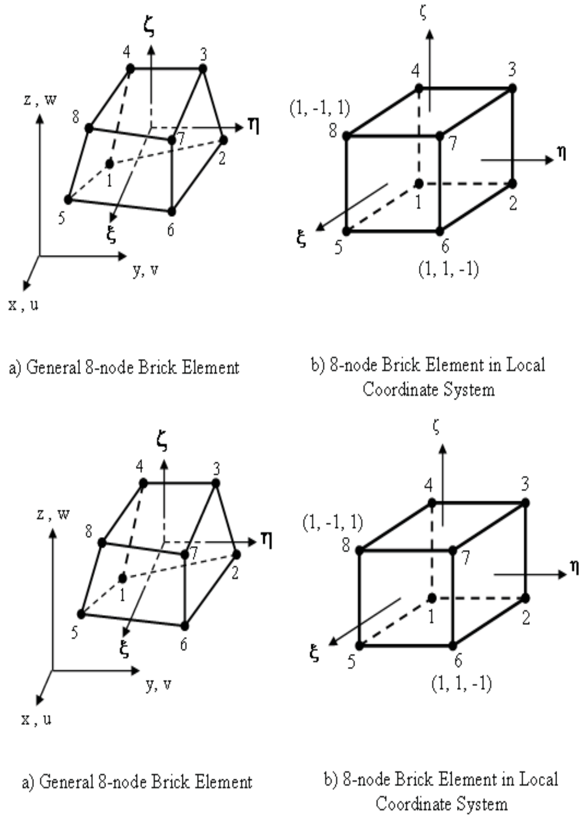


Fig. 4 Three dimensional solid elements (Solid-45)

Table 1 Finite element representation of model components

| Model component | Finite Element representation | Element designation in ANSYS |
|---|---|---|
| Ballast (Rocks) | 8-Nodes Brick Element (3-Translation DOF per node) | SOLID-65 |
| Soft Soil<br>Steel Plates | 8-Nodes Brick Element (3-Translation DOF per node) | SOLID-45 |
| Geogrid | 4-Nodes Shell Element (3-Translation & 3-Rotational DOF per node) | SHELL-181 |

## FOUR NODES SHELL ELEMENT

Four nodes shell element (SHELL-181 in ANSYS) is used for analyzing thin to moderatelythick shell structures. It is a 4-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. (If the membrane option is used, the element has translational degrees of freedom only). Thiselement is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. SHELL-181 may be used for layered applications for modeling laminated composite shells or sandwich construction. In the present study.

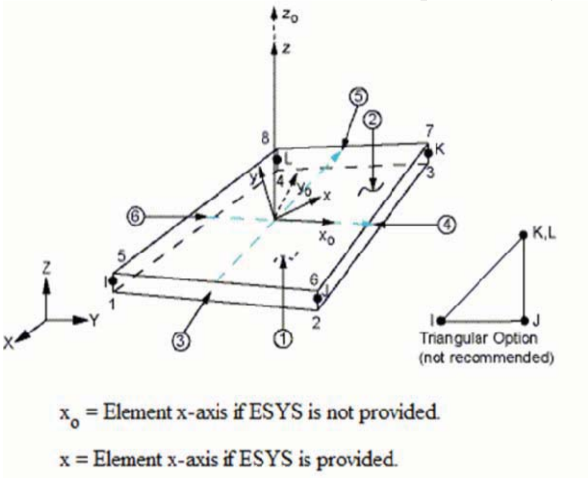


Fig. 5 Four nodes shell element (Shell-181 )

## THREE DIMENSIONAL REINFORCED CONCRETE SOLID

Three dimensional reinforced concrete solid (SOLID-65 in ANSYS), is used for the three dimensional modeling of solids with or without reinforcing bars (Fig.6). The solid is capable of cracking in tension and crushing in compression. In structural applications, for example, the solid capability of the element may be used to model the concrete. Other cases for which the element is also applicable would be reinforced composites (such as fiberglass), and geological materials (such as rock). The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. It may be noted that, in present study, this element were used to model all ballast layers

## NUMERICAL APPLICATIONS

### Geometry and Model Creation

In actual field condition, the soil is usually of infinite extent both in horizontal and vertical directions. In the finite element idealization the horizontal boundary of the soil blocks in the (x) and (y) directions. The dimensions of the soft soil considered in the analysis were (1000x400x500mm) for the length (in x-direction), width (in z-direction) and depth (in y-direction) respectively. All dimensions of soft soil layer have been kept constant for all analyses. While, the depth (thickness) of ballast layers were variable and depend on considered case (state). It may be noted that, the adopted dimensions were employed in the experimental work done by (Abbawi, 2010).

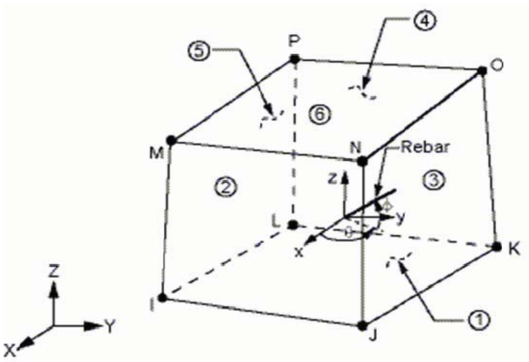


Fig. 6 Three dimensional reinforced concrete solid (Solid-65)

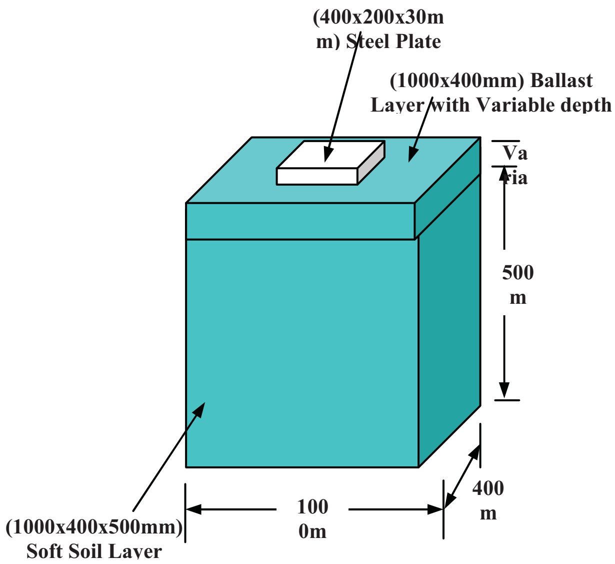


Fig. 7 Dimensions of adopted models

### Loading and Boundary Conditions

Displacement boundary conditions (which represent the conditions at the interface of model) are needed to constrain the model to get a unique solution. To ensure that the model acts the same way as a real case, boundary conditions need to be applied at all sides of the model, and where the loadings exist. The word load in ANSYS includes boundary condition and external or internal applied force (different types of load available in ANSYS such as structural, thermal, magnetic, electric,

fluid…). The type of loading were used in this study was concentrated loads with different value; Due to load concentration on ballast elements, crushing of the ballast started to develop in the elements located directly under the loads. Subsequently, adjacent ballast elements crushed within several load steps. As a result, the model showed a large displacement, solution diverged and finally, the finite element model fails prematurely. Therefore, to prevent this phenomenon, two techniques were used:-
1-Finer mesh was used under applied load.
2-Steel plates were used under load.
In the present study, the second technique was adopted, and the employed boundary conditions were as follows:-

1-Hinges,at side of model in X and Z directions and rollers in Y directions

2-Fixed at bottom face of the model (restrained the nodes in X, Y and Y directions)

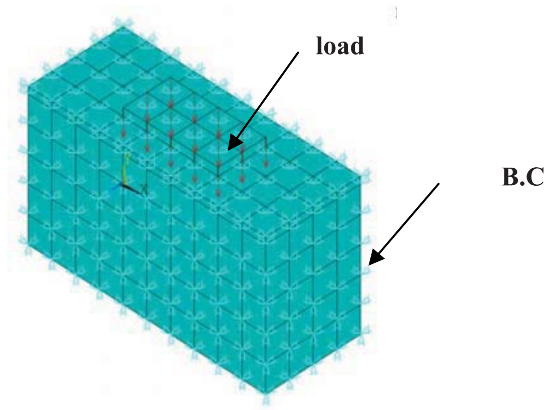


Fig. 8 Boundary conditions and loading of the model

## FINITE ELEMENT MODELING

A twenty four model, divided into four groups were created in the present study as shown in Table 1 It may be noted that each model was designated in a way to refer to Soft soil layer, first Ballast layer, Geogrid layer, second Ballast layer, undrained shear strength (Cu=9kPa and Cu=25kPa) and thickness of ballast layer (25, 50, 75 and 100mm). Therefore, the model (SBGB-1), for example, is a finite element model consists of soft soil layer, first ballast layer, geogrid layer located at (25 mm) from the top layer of ballast, second ballast layer, undrained shear strength of (Cu=9kPa) and thickness of ballast layer (50mm).

## MODELS PARAMETERS

The finite element models adopted in this study have a number of parameters, which can be classified into four categories:
i- Soft soil property parameters, Table 2
ii- Ballast property Parameters, Tables 3
iii- Geogrid property parameters, Table 4
iv- Steel plates property, Table 5

Table 2 Soft soil property parameters

| Parameter | Definition | value | Note |
|---|---|---|---|
| Cu | Unrained shear strength (kPa) | 9.0<br>25 | Assumed |
| E | Elastic Modulus of Elasticity (MPa) | 4.5<br>12.5 | $E=250C_u$-<br>$500C_u$* |
| ν | Poisson's ratio | 0.15 | * |
| ϕ | Angle of Friction | 0 | |

* Das, (2006)

Table 3 Ballast property parameters

| Parameter | Definition | value | Note |
|---|---|---|---|
| $f_c'$ | Ultimate Compressive Strength (MPa) | 48 | * |
| E | Elastic Modulus of Elasticity (MPa) | 130 | * |
| ν | Poisson's ratio | 0.45 | * |
| βc | Shear transfer Coefficient | 0.22 | ANSYS 2007 |
| βo | Shear transfer Coefficient | 0.2 | |

* IRAQ RAILWAY COMPANY

Table 4 Geogrid property parameters*

| Parameter | Definition | value | Note |
|---|---|---|---|
| $f_t$ | Peak tensile strength (N/mm) | 13.5 | * |
| E | Elastic Modulus of Elasticity (MPa) | 25 | * |
| ν | Poisson's ratio | 0.3 | * |
| t | Thickness (mm) | 3 | Assumed |

*Saudi Arabian stander organization (SASO) test method ISO10319

Table 5 Steel plate property parameters

| Parameter | Definition | value | Note |
|---|---|---|---|
| $f_y$ | Ultimate tensile strength (MPa) | 420 | * |
| E | Elastic Modulus of Elasticity (MPa) | 200x10$^3$ | * |
| ν | Poisson's ratio | 0.3 | * |
| t | Thickness (mm) | 30 | * |

*(ACI-318-08)

## RESULTS OF THE ANALYSIS

After creating the model and entering all associated model parameters, the analysis is performed. The ANSYS divides the load into a number of sub-steps and performs the iteration for each sub-step until reaching the convergence Fig. 9 and Fig. 10 show the deformed shape of model for two undrained shear strength when the undrained shear strengths of untreated soil changed from (9kPa) to (25kPa), the modulus of elasticity increased and the load capacity increased for about (160%), while, the settlement decreased for about (47%). This means the undrained shear strengths represent important parameters to improve soil and as a result, the load capacity increased. Table 6 shows the result and Fig. 11 shows the effect of undrained shear strength and modulus of elasticity on the load-settlement relationship.

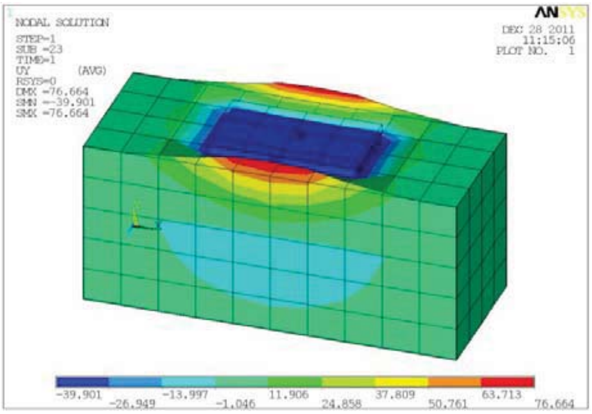


Fig. 9 Failure mode of untreated soil model S-1

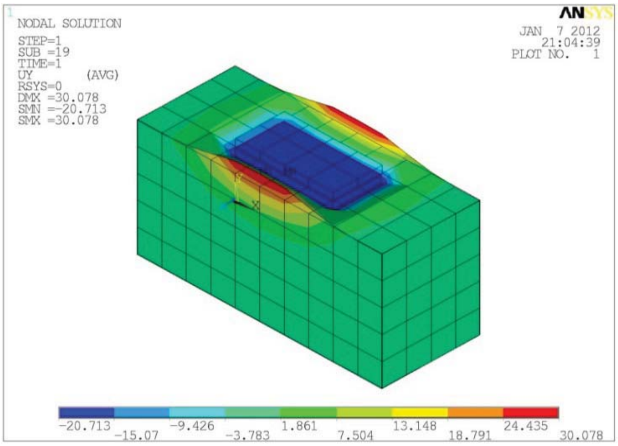


Fig. 10 Failure mode of untreated soil model S-2

Table 6 Ultimate load and maximum settlement for Group-1

| Group | Model | E (kPa) * | $P_u$ (kN) | $(P_u)_i/(P_u)_R$ | S(mm) | $(S)_i/(S)_R$ |
|---|---|---|---|---|---|---|
| G-1 | S-1 | 2150 | 8.0 | - | 40 | - |
| | S-2 | 45000 | 20.8 | 2.6 | 21 | 0.53 |

*From Equation E=250 C-500C (Das, 2006)

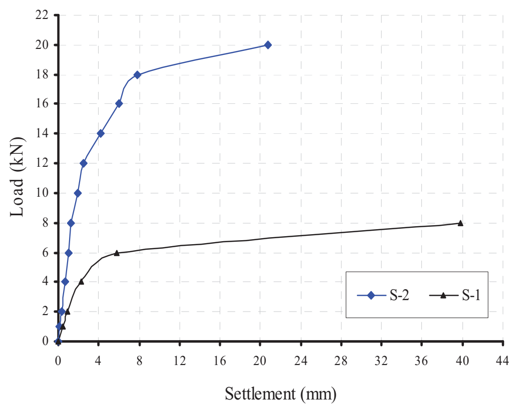


Fig. 11 Load-settlement curve for Group-1

### Models of Ballast Layer Overlaying the Soil (Group-2)

The second group consist of eight models (SB-1, SB-2, SB-3, SB-4, SB-5, SB-6, SB-7, and SB-8) performed with ballast layer overlaying the soft soil. The eight modes were performed using different ballast thickness (H) of (25, 50,75and 100mm). Four models were performed on each of the two undrained shear strengths (9kPa) and (25kPa).Table 7 shows comparison between the ultimate loads from the finite element analysis. Figures 12 and 13 shows The relationship between the applied load (P) and the corresponding settlement (S) for the models of the second group (SB-1, SB-2, SB-3, and SB-4) and (SB-5, SB-6, SB-7, and SB-8) were constructed and compared with reference models (S-1 and S-2).

Table 7 Ultimate load and maximum settlement for Group-2

| Group | Model | $(P_u)_R$ (kN) | $P_u$ (kN) | $(P_u)_i/(P_u)_R$ | $(S)_R$ (mm) | S (mm) | $(S)_i/(S)_R$ |
|---|---|---|---|---|---|---|---|
| G-2 | SB-1 | 8.0 | 23 | 2.88 | 40 | 16.33 | 0.41 |
| | SB-2 | | 30 | 3.75 | | 17.19 | 0.43 |
| | SB-3 | | 43 | 5.38 | | 24.47 | 0.61 |
| | SB-4 | | 61 | 7.63 | | 34.43 | 0.86 |
| | SB-5 | 20.8 | 35 | 1.70 | 21 | 8.87 | 0.42 |
| | SB-6 | | 41 | 1.97 | | 8.53 | 0.41 |
| | SB-7 | | 52 | 2.50 | | 10.41 | 0.50 |
| | SB-8 | | 66 | 3.18 | | 12.94 | 0.62 |

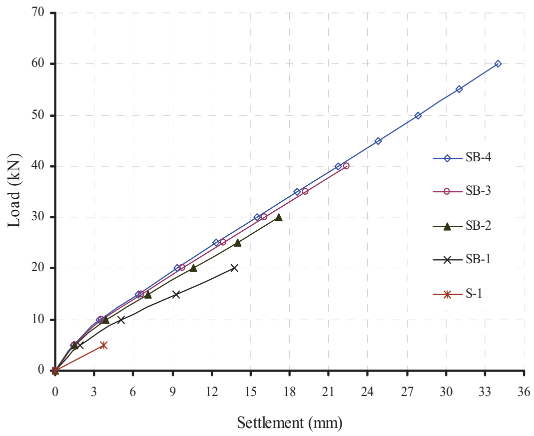


Fig. 12 Load-settlement curves for Group-2 and untreated model (S-1)

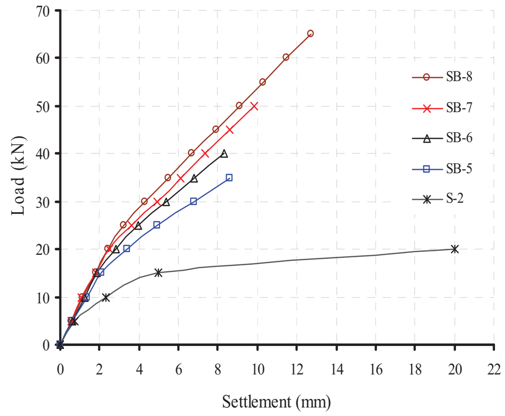


Fig. 13 Load-settlement curves for Group-2 for S-2

**Models of Reinforced Ballast by Geogrid Overlaying the Soil (Group-3)**

The third group consist of eight models were performed with ballast layer reinforced with geogrid overlying the soft soil. These models were performed using different ballast thickness (H) of (25, 50, 75 and 100 mm). Four models were performed on each of the two undrained shear strengths (9kPa) and (25kPa).

Initially a single layer of geogrid was placed along the interface plane between the ballast and soft soil. Figures 14 and 15 show the models reinforced with (25mm) ballast and a geogrid layer located between the soft soil and ballast layer and the effect of geogrid in settlement and ultimate load capacity for two undrained shear strength. Table 8 shows comparison between the ultimate loads from the finite element analysis

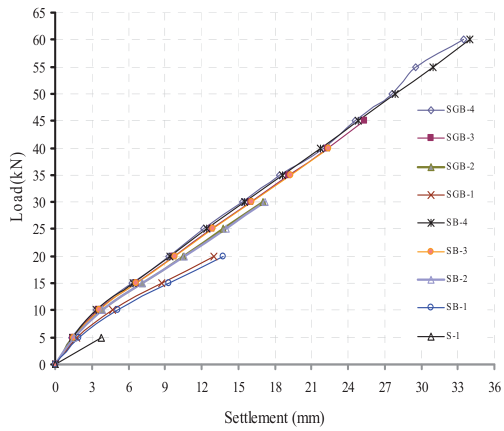


Fig. 14 Load-settlement curves for groups-2 and 3 and untreated model (S-1)

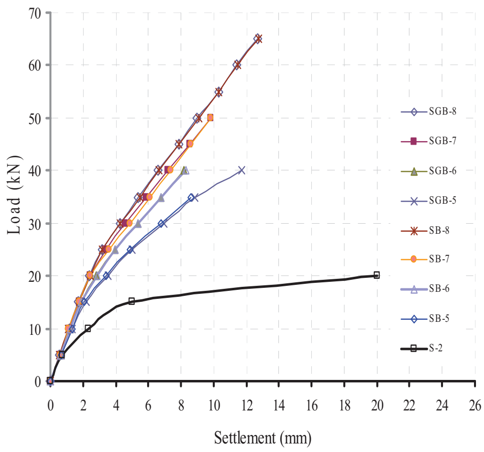


Fig. 15 Load-settlement curves for Groups- 2, 3and untreated model (S-2)

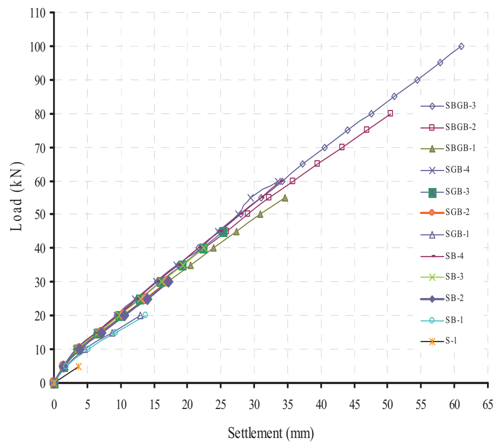


Fig. 16 Load-settlement curves for Groups-2, 3,4, and S-1

Table 8 Ultimate load and maximum settlement for Group-3

| Group | Model | $(P_u)_R$ (kN) | $P_u$ (kN) | $(P_u)_i/(P_u)_R$ | $(S)_R$ (mm) | S (mm) | $(S)_i/(S)_R$ |
|---|---|---|---|---|---|---|---|
| G-3 | SGB-1 | 8.0 | 25 | 3.13 | 40 | 16.5 | 0.41 |
| | SGB-2 | | 32 | 4.00 | | 18.6 | 0.47 |
| | SGB-3 | | 45 | 5.64 | | 25.7 | 0.64 |
| | SGB-4 | | 63 | 7.88 | | 36 | 0.9 |
| | SGB-5 | 20.8 | 43 | 2.07 | 21 | 13.2 | 0.63 |
| | SGB-6 | | 43 | 2.07 | | 9.5 | 0.45 |
| | SGB-7 | | 55 | 2.64 | | 11 | 0.44 |
| | SGB-8 | | 68 | 3.27 | | 13.5 | 0.64 |

**Models of Ballast Reinforced by Geogrid layer (The Geogrid Embedded in Ballast Layers for Group-4)**

The fourth group consist of six models were performed with ballast layer reinforced with geogrid layer in top these models were performed using ballast thickness (H) of (50, 75 and 100mm). The models performed by placing the geogrid layer at a distance (25mm) below the level of ballast thickness. Figures 16 and 17 shows the results demonstrate a substantial increase the ultimate load with increasing thickness of ballast due to the distribution of the applied load. Table 9 shows comparison between the ultimate loads from the finite element analysis. For the first three models of this group

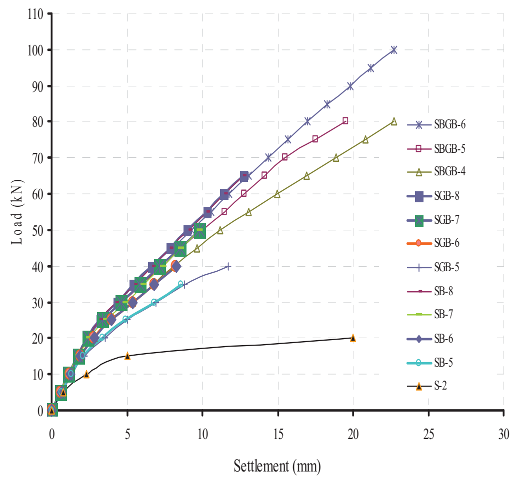


Fig. 17 Load-settlement curves for Groups-2,3,4, and S-2

Table 9 Ultimate load and maximum settlement for Group-4

| Group | Model | $(P_u)_R$ (kN) | $P_u$ (kN) | $(P_u)_i/(P_u)_R$ | $(S)_R$ (mm) | S (mm) | $(S)_i/(S)_R$ |
|---|---|---|---|---|---|---|---|
| G-4 | SBGB-1 | 8.0 | 56 | 7.00 | 40 | 35 | 0.88 |
| | SBGB-2 | | 82 | 10.30 | | 52 | 1.30 |
| | SBGB-3 | | 110 | 13.80 | | 62 | 1.55 |
| | SBGB-4 | 20.8 | 83 | 3.99 | 21 | 26 | 1.24 |
| | SBGB-5 | | 84 | 4.04 | | 21 | 1.00 |
| | SBGB-6 | | 110 | 5.29 | | 28 | 1.33 |

## CONCLUSIONS

Based on the results obtained from the finite element analysis for improvement of soft soil reinforced with or without geogrid, the following conclusions are presented

1.The vertical displacement (settlement) under the applied load decreases with the increase of shear strengths ($C_u$). Increasing of soil shear strength improve the load carrying capacity significantly. This enhancement starts even from the lower load and increases with increase in load.

2.The vertical displacement (settlement) under the applied load decreases with the increase of Modulus of Elasticity ($E$) of the soil. Increasing of soil modulus improve the load carrying capacity significantly.

3.The maximum vertical displacement under the applied load decreases with the increasing of the ballast thickness.

4.Presence of geogrid layers leads to reduce the vertical displacement (settlement), while the corresponding load carrying capacity increased significantly. The uniformly oriented geogrid and its ability to improve soft soils cause an increase in the load carrying capacity. This was combined with the ability of ballast layer to sustain larger compressive force at advanced stages of loading.

## RECOMMENDATIONS

A lot of research can be suggested for better understanding of adopted study, therefore, the following recommendations are suggested for the future work:-

1.Same adopted models can be used for other types of soils.

2.The concept of multi-layer of geogrid (embedded in soft soil layers) can be used for further investigations problems (related with soil improvement).

3.This work can be further extended by using multi-layer soil system with different parameters.

4.This work can be further extended by using other improvement systems of soft soil such as sand columns system.

## REFERENCES

Abbawi, Z.W.S., (2010), Evaluation of Improvement. Techniques for Ballasted Railway Track Model Resting on Soft Clay, Ph.D. Thesis, University of Technology, Iraq ANSYS, ANSYS Help, Release11, Copyright 2007.

Brand, E.W. and Brenner, R.P., (1981), Soft Clay Engineering Elsevier Scientific Publishing Company, Amsterdam, 778.

Broms, B.B., (1987), Stabilization of soft clay in Southeast Asia, Proc. 5th Intl. Geotechnical Seminar.

Chen, W., Plasticity in Reinforced Concrete, McGraw-Hill Book Company, :592, U.S.A, 1982

Das, B. M., (2006), Principles of Geotechnical Engineering 5th Edition Nelson, a division of Thomson Canada.

Drucker, D.C., and Prager, W., (1953), Soil mechanics and plastic analysis of limit design, Quasterly Appl. Math., 10:157.

Iraq Railway Company Ballast Specifications

Kempfert, H.G. and Gebreselassie,B.,(2006), Excavatons and Foundations in Soft Soil Spring-Verlag Berlin Heidelberg, Germany.

McDowell, G.R. and Bolton, M.D., On the micromechanics of crushable aggregates. (1998), Geotechnique 48(5); 667-679.

Willam, K., and Warnke, E., Constitutive model for the triaxial behavior of concrete, Proc. Intl. Association for Bridge and Structural Engineering, 19:174.

Yacoub, T.N, (2008), Comparison between Linear and Nonlinear 3-D Finite Element Analysis of Raft Foundation, M. Sc. Thesis, University of Technology, Iraq.