

Behavior of Embankments Constructed on Soft Soil Deposits Reinforced with Rigid Inclusions

Mohamed M. S. El-Gendy, Ayman L. Fayed, Yasser M. El-Mossallamy



Abstract: Large settlement associated with the construction of embankments on soft soil deposits is a challenging geotechnical problem that needs a special treatment. Reinforcing the embankments utilizing geosynthetics is an effective technique used to reduce the differential settlement, while the total settlement is unchanged. A more efficient technique is utilizing a combination between soft soil reinforcement using piles or rigid inclusions, thus increasing the equivalent stiffness of the entire soft soil stratum, and a load transfer layer reinforced by one or more layers of geosynthetics on top of the inclusions' head, in order to improve the load distribution process between the rigid elements.

In this paper, the behavior of soft soil deposits reinforced with rigid inclusions is studied using three-dimensional finite element analysis, utilizing the "PLAXIS 3D 2020" software. Verification of the adopted modeling procedures is performed by the back analysis of a well-documented case study of a physical laboratory scaled model. Results of the numerical model showed a good agreement with the laboratory measurements in terms of both the settlement and load distribution aspects.

Furthermore, results of both the developed numerical model and selected performed numerical analyses, from the literature, for the same case study, were compared showing better efficiency of the developed model compared to others and more consistency with the real behavior of the laboratory model.

The verified model confirmed the efficiency of increasing the friction angle of the embankment on the load transfer mechanism between the rigid inclusions, and hence decreasing the resultant settlement.

Keywords: Soft Soil, Rigid inclusions, Piled embankment, Numerical model.

I. INTRODUCTION

Soft soil deposits are generally characterized by low bearing capacity and high compressibility; thus, improvement of such deposits is mandatory prior to construction. Different improvement techniques are usually adopted to improve soft soils such as stone columns, vertical drains accompanied by preloading, rigid inclusions such as controlled modulus columns (CMCs), and many other methods. Rigid inclusions are successfully used to control the

settlement and increase the bearing capacity of the foundations constructed in weak soil formations.

Physical laboratory models are commonly used to investigate the effectiveness of the ground improvement approach using rigid inclusions. Test results demonstrate that the composite foundation with rigid inclusions can reduce the settlement of the embankments significantly [1]. A full-scale field vertical load test was conducted on a controlled modulus column to investigate the short-term effects of installation on the surrounding soil [2]. Controlled Modulus Columns (CMCs) were studied to investigate their effect on the stability of slopes [3]. Elasto-Plastic finite element analysis was conducted to simulate the embankment soil foundation system, including different subsurface layers' properties and CMCs, where the developed model was verified using field data and showed reasonable agreement with the observed performance of the embankment in terms of the vertical displacements [4]. Furthermore, a series of laboratory tests of embankments resting on rigid inclusions was conducted, consisting of 12 trials [5]. The study was divided into two parts. The first part of the study aimed to clarify the load distribution on the piles, deformations in the geosynthetic reinforcement (GR) and subsoil, and the strains caused by the vertical load. The tests are similar to those reported by [6] and [7], which form the basis of the German standards [8]. Numerical models were performed based on the physical model reported by [5], using PLAXIS software to simulate the scaled model test, as illustrated by [9], and other models reported by [10] and [11]. In this paper, the finite element code, PLAXIS 3D 2020, is employed to simulate the laboratory model of [9]. Verification of the FEM is performed to confirm the validity of utilizing the finite element method in numerically simulating the behavior of embankments on soft soils deposits improved using rigid inclusions, and to study the main factors affecting the efficiency of this ground improvement technique.

II. THE LABORATORY SCALED TEST (K2)

[9] adopted a model similar to the model introduced by [6]. The model consists of a steel box, subsoil, embankment, piles, geosynthetics, and loads, as shown in Fig. 1.

Four piles are fixed on the box base, and then a foam cushion, simulating the soft soil, is placed between the piles. The box is then filled with water to simulate the groundwater table. A sand layer laid above the foam cushion and piles, then the steel frame with the attached GR layer on it is placed on the top of the sand layer. Settlement transducers and strain gauges (as possible) are fixed to the GR rib and making sure that the strain gauges are set to zero, then the embankment fill is applied with a water cushion on the top of the embankment. Finally, the steel box is closed with its cover.

Revised Manuscript Received on April 25, 2020.

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Table-I: Characteristics of the laboratory tests [9]

Test no.	Test code	GR description	GR material	GR stiffness J 2% (direct. 1/direct. 2) kN/m
1	N1	2 laid grids biaxial	PET	2090
2	N2	1 laid grid biaxial	PET	1045
3	T1	1 woven geotextile	PP	670
4	K1	1 woven grid biaxial	PVA	2399/2904
5	T2	1 woven geotextile	PP	970/1810
6	K2	2 woven grids	PVA	2269
7	T3	1 woven geotextile	PP	970/1810
8	S1	2 extruded grids	PP	757
9	T4	1 knitted grid biaxial	PET	1715/1742
10	K3	2 woven grids uniaxial	PVA	2269
11	S2	2 extruded grids	PP	757
12	N3	2 laid grids biaxial	PET	2090

The detailed construction stages are illustrated in Fig. 2. A series of twelve laboratory model tests were performed on piled embankments by [9], as illustrated in Table-I, to examine the validity of the existing EBGEO (2010) analytical model, in terms of the load distribution, deformations and strains, and hence improving the accuracy of the theoretical model. Each of the performed laboratory models was denoted by a certain identity code, in which the model (K2) is the case that is considered and studied in this paper. As a result of the laboratory model test outcomes, the total applied load is divided into three parts. Load part (A) is defined as the portion taken directly by the rigid inclusion (CMCs), while load part (B) is the load transferred to the CMCs via the developed tension in the geosynthetic reinforcement (GR). The remaining part of the total load that is denoted by the load part (C) is defined as the load division carried by the subsoil around the rigid inclusions (foam cushion). Each of the three parts was measured directly using transducers through the laboratory tests for the sake of comparison with the analytical model results.

For the laboratory test (K2), Fig. 3 presents the relation between the net applied load on the X-axis and the load parts A and B on the Y-axis [5]. During the top-loading stages, where the top loads are applied while drainage is prevented, the absolute value of the load parts A and B increases, while their percentage relative to the total net load decreases due to the built-up porewater pressure. In the drainage stage, the absolute value of the load parts A and B increases as a result of the improvement in the arching behavior of the fill soil layer due to the dissipation of the built-up porewater pressure. Moreover, it can be noticed from Fig. 3 that the percentage of the load part A, measured at the end of the drainage phases, decreases while the applied total net load increases. This demonstrates that the improvement in the arching effect is more significant in the lower loading values rather than the higher loading levels.

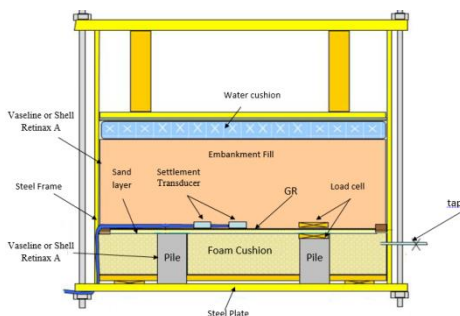


Fig. 1. Laboratory scaled-model components [5]

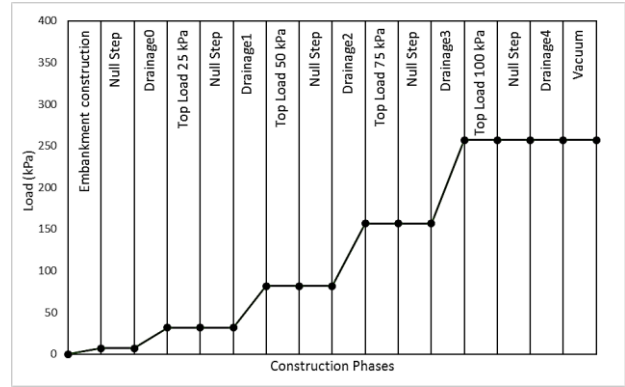


Fig. 2. Construction stages

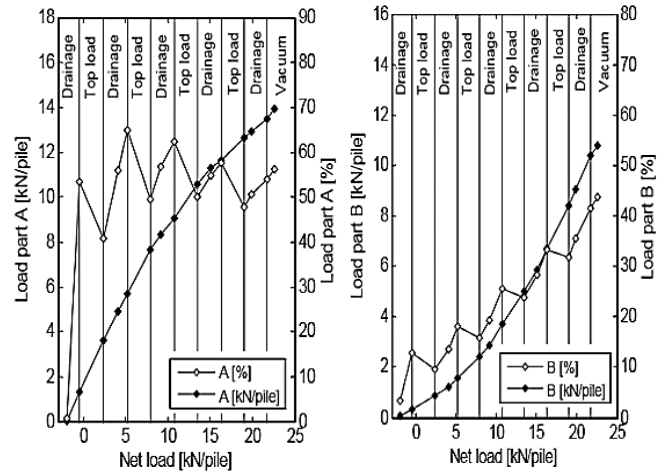


Fig. 3. Load parts A and B from the laboratory model [5]

A. Measured vertical displacements

The locations of the settlement transducers z1, z2 and z3 placed on the GR layer are shown in Fig. 4. The relation between the settlement values measured at these transducers, and the net loads applied to the embankment is shown in Fig. 5. As the net loads increase, the vertical displacement at each transducer increases.

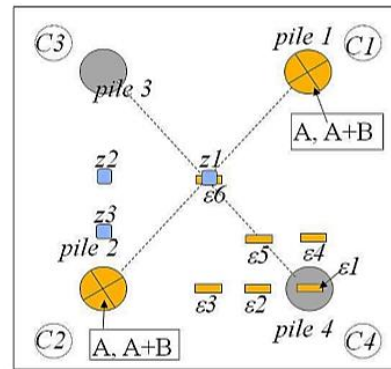


Fig. 4. Positions of the measuring equipment in the laboratory scaled-test [5]

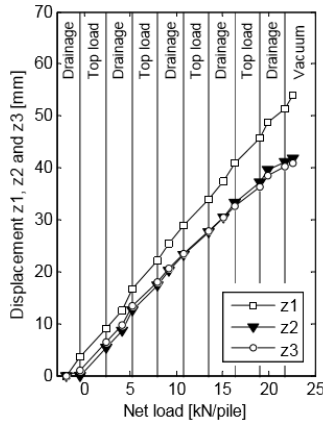


Fig. 5. Vertical displacements of the GR in the lab. test K2 [5]

III. PREVIOUS NUMERICAL SIMULATION OF THE PHYSICAL MODEL

The performed laboratory test and specifically the K2 scaled model test was subjected to extensive numerical modeling by different researchers as [10] and [11].

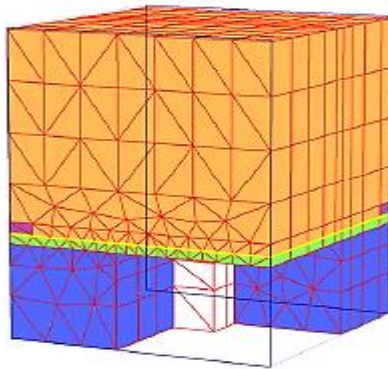


Fig. 6. Finite Element model of the lab. test K2 [10]

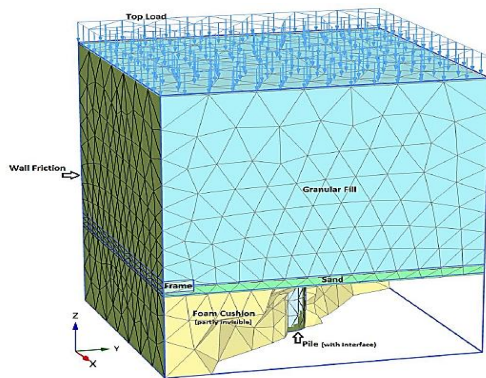


Fig. 7. Geometry of the developed 3D model [11]

[10] used PLAXIS 3D tunneling to simulate the physical laboratory model. Fig. 6 shows the mesh adopted in this simulation. Furthermore, [11] performed a numerical model by using the PLAXIS 3D software, where the used mesh is presented in Fig. 7.

IV. THREE-DIMENSIONAL NUMERICAL SIMULATION OF THE LABORATORY PHYSICAL MODEL K2

A. Model description

Due to symmetry, only one-quarter of the problem is modelled, as a one pile surrounded by soft soil (foam

cushion), to minimize the analysis duration. The model extents are 0.55 m in both the X and Y directions. The horizontal movement is prevented at all the vertical boundaries. Furthermore, the drainage of the excess porewater pressure is not allowed at these boundaries through all stages. Both the horizontal and vertical movements of the lower horizontal boundary are not allowed, while the drainage of the excess porewater pressure is allowed only during the drainage phases.

B. Constitutive models and materials parameters

The numerical model adopted in the back analysis of the scaled model (K2) consists of several elements, including the pile, subsoil, sand, embankment fill, and the GR layer. The different parameters utilized in the model are based on the parameters stated by [10] and [11]. The developed mesh is shown in Fig. 8, furthermore, the parameters of the different elements adopted in the model are shown in Table-II and Table-III. The Linear Elastic (LE) constitutive model is used to simulate the behavior of the piles, foam cushion and the very dense sand layer above the piles’ heads. The Hardening Soil constitutive model (HS) is adopted to model the sand soil above the foam cushion and the embankment fill.

Table-II: Geotechnical parameters and constitutive models adopted in the 3D F.E. model

Model Property	Units	Foam Cushion	Pile	Sand Layer Above Foam cushion	Sand Layer Above Pile	Embankment Fill
Constitutive Model	—	LE	LE	HS	LE	HS
Drainage	—	undrained (A)	Non-porous	Drained	Drained	Drained
$\gamma_{unsaturated}$	kN/m ³	10.15	13.64	18.67	18.67	16.59
$\gamma_{saturated}$	kN/m ³	10.15	—	18.67	18.67	16.59
E_{s0}^{Ref}	kN/m ²	5.0	2.943×10^6	19.66×10^3	400.0×10^3	58.870×10^3
E_{Oed}^{Ref}	kN/m ²	—	—	19.66×10^3	—	58.870×10^3
E_{UR}^{Ref}	kN/m ²	—	—	58.98×10^3	—	176.60×10^3
m	—	—	—	0.5	—	0.74
C	kN/m ²	—	—	1.0	—	1.0
ϕ	°	—	—	30.0	—	43.0
ψ	°	—	—	0.0	—	0.0
v'_{ur}	—	0.33	0.0	0.2	0.0	0.2
P_{ref}	kN/m ²	—	—	100	—	100
K_o^{nc}	—	—	—	0.50	—	0.318
R_{inter}	—	1.0	1.0	0.60	1.0	0.8



Table-II: Geosynthetic Reinforcement properties

Geo-synthetic Reinforcement properties	Units	PVA woven Grids
Material Type		Elastic
Tensile Stiffness (EA1)	kN/m	2269.0
Tensile Stiffness (EA2)	kN/m	2269.0
Shear stiffness (GA)	kN/m	0.0

V. COMPARISON BETWEEN THE RESULTS OF THE DEVELOPED NUMERICAL MODEL, LABORATORY SCALED TEST (K2) AND PREVIOUS PUBLISHED NUMERICAL MODELS

A. Load Distribution

The load distribution results of the developed numerical model in this study are compared to the previous numerical models published by [10] and [11], as shown from Figures 9 to 12. The results yielding from the numerical model are divided into load parts (A, B and C) as well as the summation of both load parts A+B.

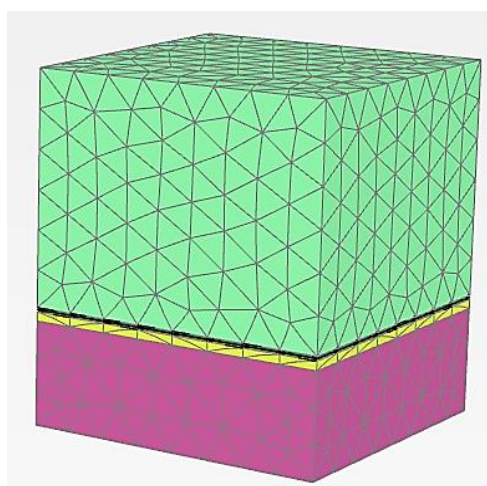


Fig. 8. Developed F.E. mesh for the K2 model

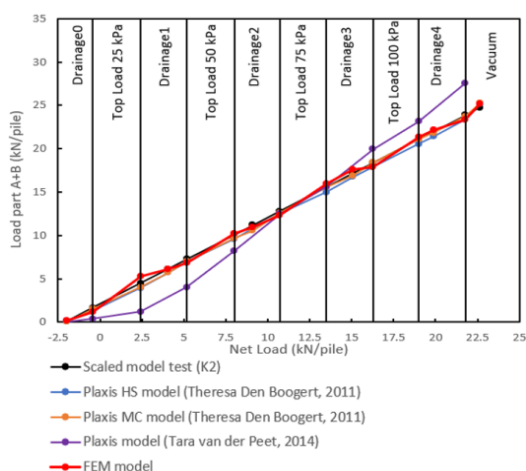


Fig. 9. Propagation of Load parts (A+B) of the developed and investigated published numerical models

Fig. 9 shows the results of the summation of the load parts A and B, that is transferred to the pile via both the arching effect and tension in the GR. The figure shows a good agreement between the values estimated by the developed numerical model, the scaled model (K2), and the numerical model presented by [10], while the values estimated by the numerical model introduced by [11] are inconsistent with other models.

Furthermore, all numerical models show similar behavior

to the actual behavior recorded in the laboratory model when considering the load part C, as shown in Fig. 10.

Fig. 11 shows that both the developed and the previously published numerical models are able to reasonably predict the value of the load part A, in comparison with the measured results of the scaled model (K2), only at the early stages of the test, till the application of the 50 kPa top load. After that, the numerical models tend to slightly overestimate the value of the load. This applies to all the investigated models except the one presented by [11] that shows a large difference between the measured and predicted values during all stages.

Similarly, the load part B yielding from [10] shows a good agreement with the scaled model measurements and the back-analysis values till the application of the 50 kPa top load, after which divergence occurs between the curves. Moreover, the values from [11] numerical model are generally less than both the back analysis and the laboratory measurements, as shown in Fig. 12.

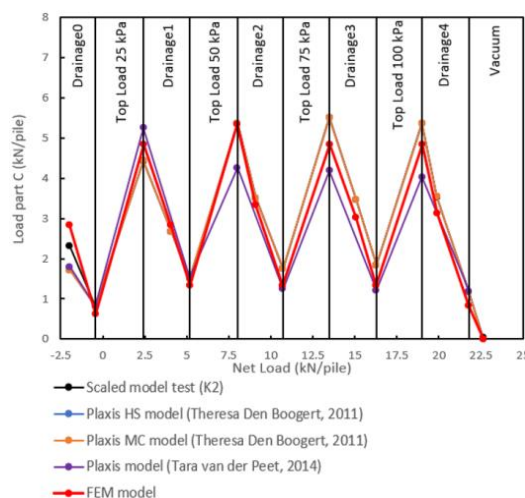


Fig. 10. Propagation of Load part C of the developed and investigated published numerical models

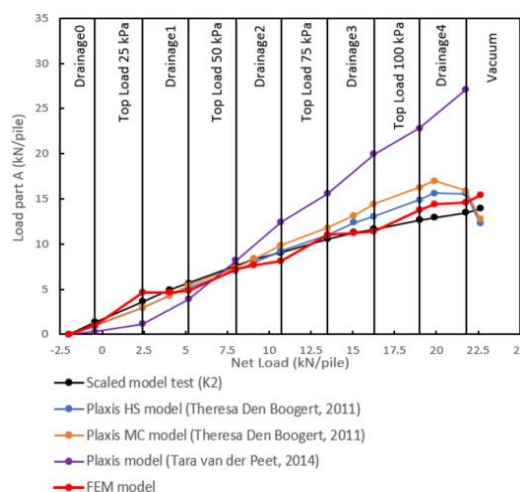


Fig. 11. Propagation of Load part A of the developed and investigated published numerical models

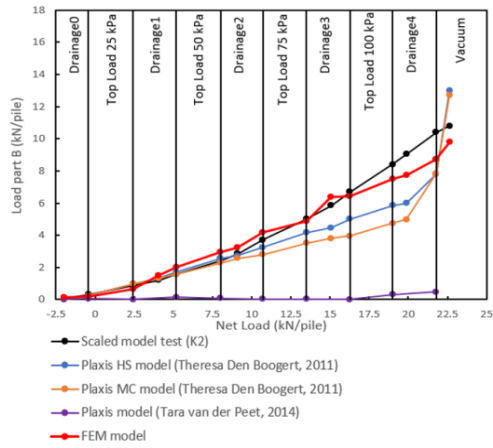


Fig. 12. Propagation of Load part B for various numerical models

B. Vertical Displacement

The vertical displacement was monitored during the laboratory tests using transducers at three different locations denoted as z1, z2 and z3, as shown in Fig. 4. Results of the numerical models, either the one developed through this study or the others published in the literature and investigated within the scope of this paper, are compared to the physical model's monitored displacements.

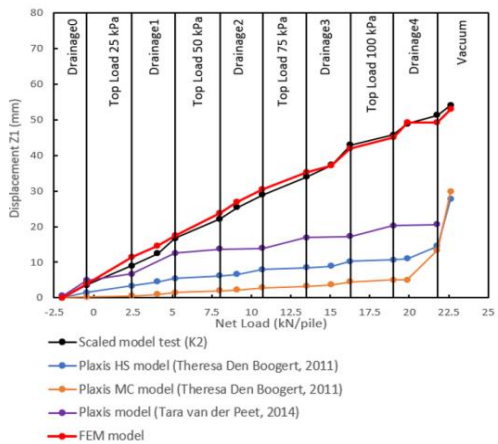


Fig. 13. Values of the vertical displacement at z1 for the developed and investigated published numerical models

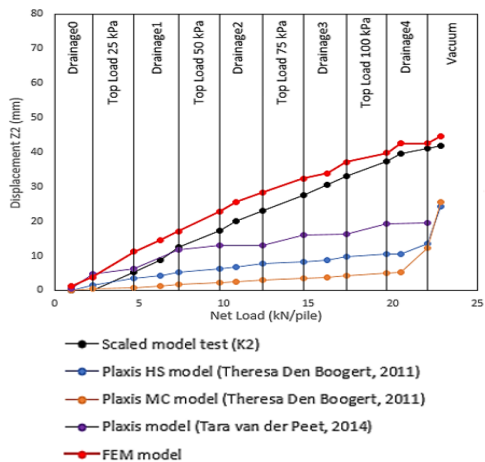


Fig. 14. Values of the vertical displacement at z2 for the developed and investigated published numerical models

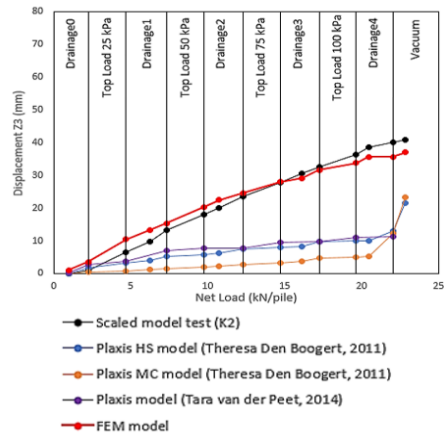


Fig. 15. Values of the vertical displacement at z3 for the developed and investigated published numerical models

Figures 13 to 15 demonstrate the comparison between the calculated and measured displacements. From these figures, it can be clearly noticed the good agreement between the results of the developed numerical model and the monitored values in the lab. The developed model can predict the vertical displacements at different locations with higher accuracy than the other investigated previously conducted and published numerical analyses.

VI. EFFECT OF THE EMBANKMENT'S ANGLE OF INTERNAL FRICTION ON THE ARCHING EFFECT AND LOADS ON THE RIGID INCLUSIONS

The efficiency of utilizing rigid inclusions in improving the behavior of soft soil deposits depends on several parameters. The shear parameters of the embankment are considered the main factors that affect the mechanism of distributing the applied loads between both the rigid inclusions and the soft soil deposit, thus influencing the final achieved settlement.

The verified numerical model was used to investigate the effect of the internal friction angle value of the embankment soil on both the final settlement and the load distribution between the inclusions and the soft soil.

The results for settlement are shown in figures 16 to 18.

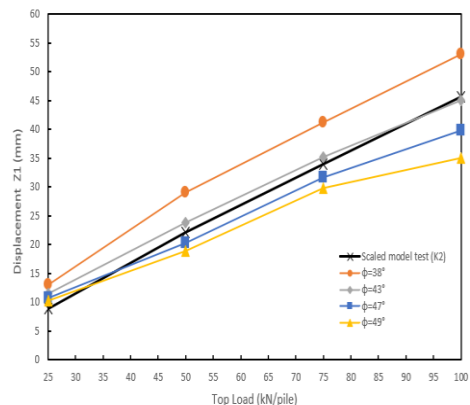


Fig. 16. Values of the vertical displacement at z1 for various embankment's angle of internal friction

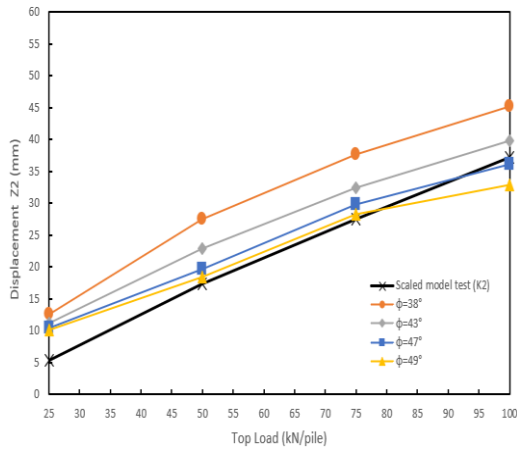


Fig. 17. Values of the vertical displacement at z2 for various embankment's angle of internal friction

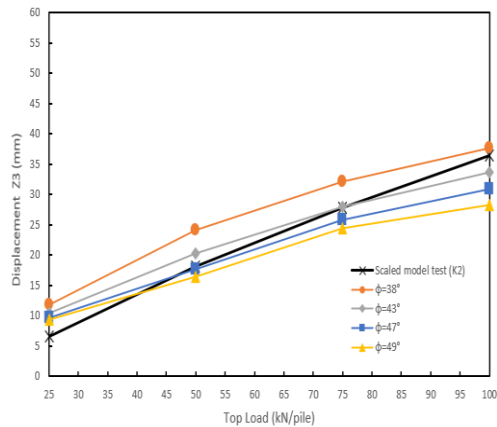


Fig. 18. Values of the vertical displacement at z3 for various embankment's angle of internal friction

A common behavior is recognized from these figures showing that the resulting estimated settlement at the different locations; z1, z2 and z3 respectively, is generally decreasing with the increasing of the internal friction angle of the embankment soil. This phenomenon can be attributed to the improvement in the arching action, and hence less loads are transferred to the soft soil, while a larger part is taken by the rigid piles.

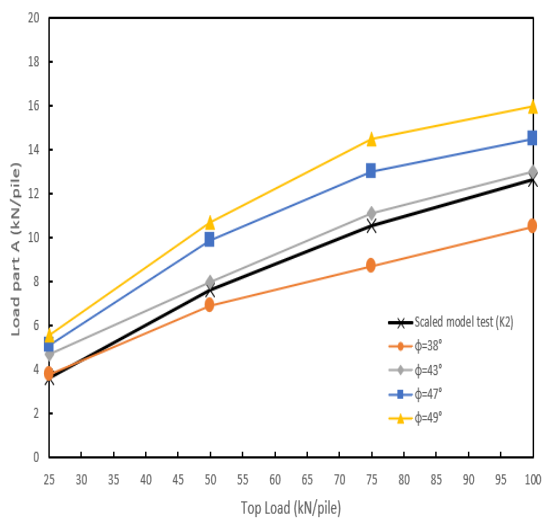


Fig. 19. Values of the load part A for various embankment's angle of internal friction

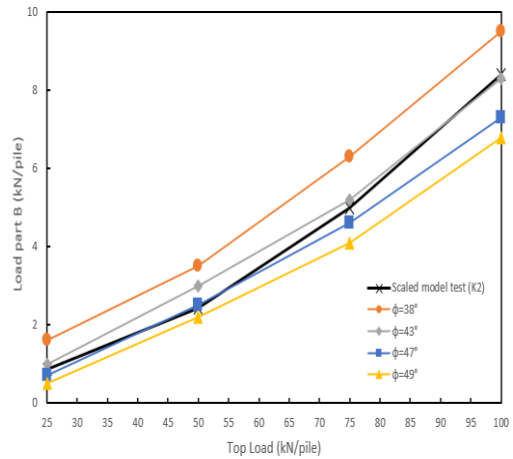


Fig. 20. Values of the load part B for various embankment's angle of internal friction

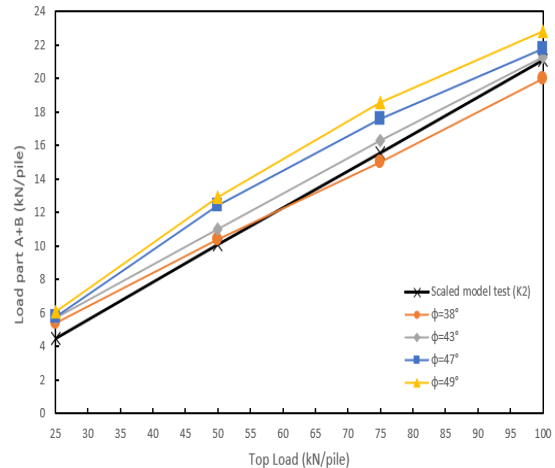


Fig. 21. Values of the load part (A+B) for various embankment's angle of internal friction

The variation of the load parts A, B and A+B with the variation of the internal friction angle of the embankment is shown in figures 19 to 21. It can be clearly noticed that the amount of load transferred to the inclusions increases with the increase in the internal friction angle of the embankment's soil. This confirms the improvement in the arching effect as the reduction in the obtained settlement is mainly due to the reduction in the load transferred to the soft soil deposits.

VII. CONCLUSION

Finite element analysis is performed to simulate a physical, well-instrumented laboratory model of soft soil formation reinforced using rigid inclusions. A thorough investigation of the reasonable geotechnical parameters to be adopted in the model was performed.

Hardening soil constitutive model was adopted to simulate the soft deposit behavior. A comparison between the results of the developed numerical model, laboratory model, and selected numerical analyses published in the literature was performed to investigate the accuracy and validity of the developed model.

The main points of comparison and interest are the load distribution between the rigid inclusions and the associated vertical displacements. The performed analyses clearly showed the capability of the developed sophisticated numerical model to reasonably simulate the actual behavior of the laboratory test. The obtained results and comparison with the previously published numerical models, for the same case study, revealed the ability of the developed model to simulate the arching effect and hence estimate the way of load distribution between the rigid inclusions and the soft soil deposit. The obtained results also showed the significant preference of the developed finite element model, over other investigated published numerical studies, for accurately predicting the settlement values at different locations. Although, the previous numerical models presented by [10] display similar behavior to that recorded in the laboratory, at the early stages, in terms of the load distribution, but the estimated vertical displacement values were considerably lower than that recorded in the laboratory. Moreover, the model introduced by [11] shows an inconsistent behavior in terms of both the load distribution and vertical displacement.

The performed parametric study using the verified numerical model, showed clearly the improvement in the arching effect of the embankment as a result of the increase in its internal angle of friction, which led to decreasing the obtained vertical displacements accordingly.

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