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The Behavior of the Tunnel Reinforced with Geogrid in Soft Soil Under the Effect of Axial Load

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Abstract

The soft soil's poor tensile strength requires reinforcing to increase bearing capacity, improve stability, and reduce settlements. This study assessed the efficacy of using geogrid layers to enhance and secure the soil surrounding tunnels. enabling the tunnel to endure pressure, particularly during excavation. The utilization of geogrids in soil reinforcement has experienced a substantial rise as a result of their consistent dimensions and exceptional tensile strength. To quantify the exerted force transferred to the tunnel, during this study utilized various testing tools, including a soil container, a steel loading frame, data loggers, a 0.5-ton load cell, and a miniature pressure cell. The vertical loads are applied by utilizing a hydraulic jack. A series of eleven tests were conducted on the tunnel at two depths of 1.5D and 2.5D, where D is the tunnel's diameter. The different models of geogrid layers showed that using two layers of geogrid at the first dimension, 0.5B and 1B from the base, led to a significant increase in tunnel stability. Two layers of reinforcement were used in both directions, giving the soil a high bearing capacity for the loads applied to the tunnel. This resulted in an improvement, a 1.65 in 1.5D and a 1.82 in 2.5D. The pressure above the pipe decreased by approximately 7.1kPa at the first tunnel depth and about 3.5kpa at the second depth. In conclusion, the study found the geogrid improves the stability of the tunnel by equally distributing loads and minimizing stress concentrations, hence decreasing the chances of collapses or deformations.

Keywords: Soft Soil; Tunnel; Geogrid; Axial Load; Improvement of Soil.

1. Introduction

Clay soil is problematic for low bearing capacity and excessive settlement. Many studies deal with improving this type of soil, and there are many techniques to improve the soil and structure above and below this soil [1–2]. Al-Saoudi et al. [3] studied to increase the stiffness of soft clay soil by adding columns made of sand; they concluded that the sand columns, when stabilized with lime, can increase stiffness highly by increasing the stiffness of the soil near the columns and reducing its initial water content. Tunneling on soft soil encounters many stability and collapse difficulties. Soft soil has lower stability in comparison to rocky soil, hence augmenting the probability of collapses and cracks during and after excavation. The infiltration of groundwater into the tunnel can lead to erosion of the adjacent soil and heightened pressure on the structural integrity of the tunnel. Distortions The soft soil may undergo substantial deformations as a result of excavation and building forces, which might cause stability problems in the tunnel.

Reinforced earth is employed in the planning and building of foundations and structures that retain soil. Reinforced earth is a composite material of soil that has high compressive strength but low tensile strength. The concept of earth reinforcement is not recent. The Ziggurat of the ancient city of Agar-Quf represents the oldest known instance of soil reinforcement. The approach of reinforced earth was pioneered by Vidal [4]. Initially, the focus of the study was on the

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examination and creation of retaining walls. These principles were later employed to examine their application in enhancing the load-bearing capacity of shallow foundations and highways. A novel material known as a geosynthetic has been introduced for reinforcement purposes. This material is composed of parallel pairs of tensile ribs with openings large enough to allow the passage of surrounding soil, stone, or other geotechnical elements. Das and Shin [5]. conducted a study on the long-term settlement of a surface strip foundation that was supported by geogrid reinforcement and placed on saturated clay. The foundation was also subjected to a cyclic load with a low frequency. The findings indicate that the use of "full-depth reinforcement geogrid" can potentially decrease the long-term settlement of a foundation by around 20% to 30% in comparison to a situation lacking reinforcement.

The study conducted by Karim et al. [6] examines the impact of utilizing multiple enhancing strategies, including fly ash, geo-grid, and fly ash, on the behavior of soft clayey soil. The models that have been tested span a wide range of boundary conditions, including untreated, Geo-grid-reinforced, fly ash-treated, and fly ash-treated with Geo-grid. There are several variables in their study: velocity, number of Geogrids, and the foundation type. The results showed that the model, when treated with two layers of geogrid and the addition of fly ash, exhibited maximum improvement.

The improvement of clay in kaolinite soil was studied by Hashemi et al. [7] by adding cement and exposing it to heat. The heat used in this study is a range of 25–600 degrees Centigrade. Different percentages of cement were added to the soil when exposed to heat. The results showed that the head increased the amount of dihydroxylation, but the coefficient of consolidation decreased gradually.

According to research by Al-Gharbawi et al. [8], the problematic soil is reinforced by micropiles that differ in depth and arrangement. This study utilized two types of soil: soft clay and loose sand. The primary objective was to explore the load-bearing capacity of a shallow foundation reinforced with micropiles. The micropiles employed in the study varied in terms of depth, configuration, and design.

In the work of Abdullah Ahmed [9], the crucial site of the tunnel at each depth was determined by analyzing eight positions of the tunnel center (diameter = 4 m) that were fixed beneath the building strip footing (width = 2 m) at various depths. According to the findings, the footing center line is the most crucial place for the tunnel to be located. This area is likely to experience the greatest amount of settlement, and the tunnel's presence will cause differential settlement whenever it is not located beneath the structure's center line.

To reduce the amount of cement used, Orumchi & Mojallal [10] investigated the treatment of a tunnel settlement using the grout mix based on its shear rather than compressive strength. The excavator soil was treated with a technique by injecting the grout material to treat the shear strength and record the shear strength parameters. This procedure enhanced the compressive strength and shear strength characteristics of the soil located above the tunnel. The cement content required for grouting is smaller than the usual cement-soil mixture. Increasing the cement content in grouting can enhance waterproofing and reduce issues such as shrinkage, swelling, and tension fractures.

Al-Farhan et al. [11] conducted a study on the correlation between soil and tunnel construction beneath a building. The examination was conducted using the Plaxis 2D application to analyze the impact of lateral stress on the tunnel. Multiple factors were modified to examine their influence on the tunnel. The findings indicated that an increase in the horizontal displacement was directly caused by the depth of the tunnel. As the tunnel approached the structure, there was a notable rise in differential settlement. Additionally, as the tunnel went deeper, the settlement reduced.

The study of Meng & Xu [12] investigates the impact of freeze-thaw cycles on the soil and the shear behavior of the geogrid-soil interface, specifically focusing on the interface temperature and freeze-thaw cycles. A total of eight direct shear tests and four tensile tests were performed on the interface between the geogrid and soil, as well as on the geogrids themselves under different conditions. After undergoing freeze-thaw cycles within the soil, the geogrids maintained a peak tensile strength that was comparable to that of the non-freeze-thaw samples. The tensile properties of geogrids remained unaffected by the number of freeze-thaw cycles. Under conditions of constant water content (w=6%), the peak shear stress at the interface between the geogrid and soil fell by 24% after undergoing 7 freeze-thaw cycles, as compared to the group that did not undergo freeze-thaw cycles. The cohesiveness and friction angle of the interface between the geogrid and soil declined as the number of freeze-thaw cycles increased, but eventually reached a stable state after 4 cycles. The geogrid reinforcement was strengthened due to the drop in the interface temperature. At temperatures below 0 °C, the shear stress was greater at the interface. However, when not frozen, the interface showed a lower shear stress with a consistently constant value.

The study of Foda et al. [13] conducted laboratory experiments on soft clay soil with a cohesiveness of 7 kPa. The studies involved unit cell stone columns with diameters of 50 and 75 mm and a stone column length to soft clay depth ratio (L/H) of 1 and 0.75. The stone columns were tested using crushed asphalt, crushed concrete, crushed ceramic, dolomite, and treated concrete as infill materials. Furthermore, experiments were carried out on both stone columns without reinforcement and stone columns encased in geogrid. The primary goal is to identify the most efficient filler material that enhances the load-bearing capacity and reduces settlement. The behavior of stone columns was evaluated by manipulating the stress concentration ratio (n) and the load improvement factor (LIF). The findings suggest that both the variables n and LIF exhibit an upward trend when the settlement-to-plate diameter ratio increases, eventually stabilizing at a value of 10% or above. Therefore, it can be deduced that the utilization of floating stone columns is more cost-effective compared to the utilization of end-bearing stone columns. Exploring novel methods for stabilizing soft clay: Incorporating eco-friendly materials into the stone column technique.

In the study of Al-Gharbawi et al. [14], it is not suitable to adhere to the seismic notion of aboveground structures in this investigation. A dynamic time-history analysis is a robust and efficient approach for investigating the seismic behavior of tunnels. This document discusses conventional subways. The analytical results show that the tunnel's overall alignment will have little effect on the tunnel itself. The seismic response of the tunnel is mostly determined by the relative movement of the surrounding earth. The analytical findings show a significant linear link between the tunnel's internal force and its inclination. Furthermore, tunnel inclination can be a good indication of the magnitude of the tunnel's seismic reaction. When developing shield tunnels for seismic events, the tunnel's inclination may be used to determine how the tunnel's internal forces vary during earthquakes. This method removes the requirement for complex dynamic time-history analysis, considerably improving the efficiency of seismic design for shield tunnels.

Al-Haddad et al. [15] investigate the influence of geosynthetic reinforcement on subsurface pipelines under various loading conditions to reduce stress and prevent leaks. The literature covers the following loads: static load, dynamic load, permanent ground deformation, unintended damage, uplift pressure, explosion, lateral loading, and abrasive shear loading. The study focuses on the use of synthetic earth reinforcements to protect these pipelines. Existing experimental and numerical studies suggest that geosynthetics can mitigate the impact of external loads on buried pipes. The conducted experiments have demonstrated that the utilization of various types of geosynthetics for protecting buried pipes is an effective approach that reduces the transmitted stresses to the pipes. Approximately 45% of the research focused on subterranean pipes that were exposed to static loading. Geogrid (38%) is the typical geosynthetic material employed for safeguarding subterranean pipes.

This research aims to investigate the stresses on the tunnel by reinforcing the above soft soil with different geogrid depths. Two depths of the tunnel are used at 1.5 and 2.5 D, and three geogrid configurations are used at 0.5, 1, and 2 B.

2. Materials

2.1. Soil

The study's soil came from a location north of Baghdad. Standard tests ascertained the physical and chemical characteristics of the soil; the results are given in Table 1. The grain size distribution of the soil used revealed gravel at 0%, sand at 3%, silt at 44%, and clay at 53%, as shown in Figure 1. The USCS has assigned the soil the classification (CL).

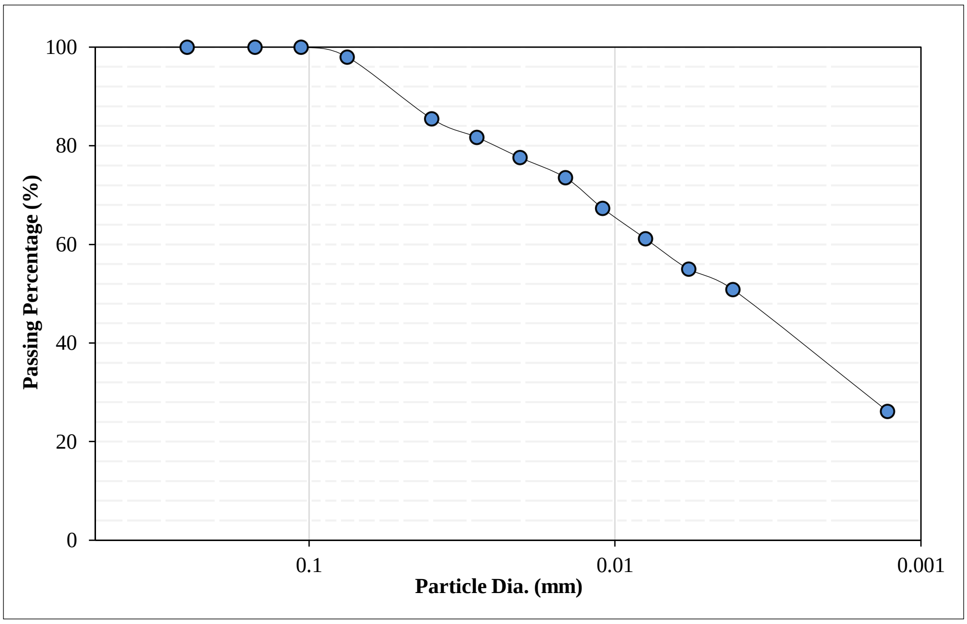

Figure 1. Grain size distribution of the soil used

Table 1. Physical properties of the soil used

Index property	Value
Liquid limit (L.L) %	43.3
Plastic limit (P.L) %	24.6
Shrinkage limit (S.L) %	10.7
Plasticity index (P.I) %	18.8
Specific gravity (GS)	2.68
Gravel %	0
Sand %	3
Silt %	44
Clay %	53
Classification (USCS)	CL
Organic matter (O.M) %	<0.002
Total dissolved salt (TDS) %	2.23
PH Value %	7.3

2.2. Geogrid

Geogrids are materials used in civil engineering to strengthen soil, stabilize slopes, and build roads. They are composed of polyester, polyethylene, or polypropylene and have an open grid structure. Geogrids enhance the mechanical properties of soil by increasing tensile strength and reducing deformation. They improve the effectiveness and longevity of various civil engineering structures. The geogrid used to reinforce the tunnel was manufactured by the Latifah Plastic Mesh factory as described in Figure 2. Table 2 provides a comprehensive overview of the geogrid's characteristics, as specified by the manufacturer [6].

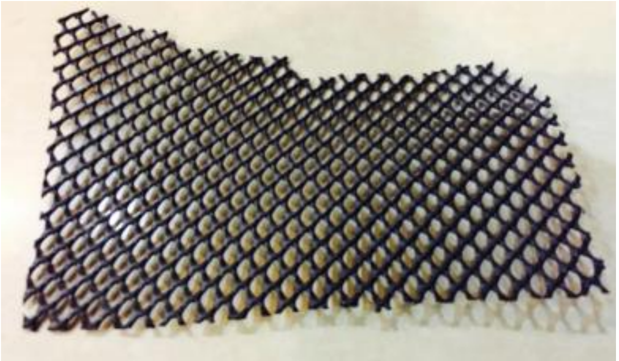

Figure 2. Geogrid reinforcement used

2.3. Tunnel PVC Pipe

This research used a PVC pipe from Amal Al-Sharif Company to represent the tunnel. It had a length of 58 cm, a diameter of 10.16 cm, and a thickness of 10 mm. Figure 3 shows the tunnel used, and Table 3 presents specifications of the PVC pipe used in the experimental study.

Figure 3. The pipe representing the tunnel with the sensors used

Table 2. Engineering properties of the geogrid, [A] including physical, chemical, biological, and [B] technical dimensions [6]

	Property	Test Method	Unit	Data
A	Structure	ASTM D1603		Extruded geogrid
	Mesh type			Square
	Standard color			Green
	Polymer type			HDPE
	Packing			Rolls
	Chemical resistance			All naturally occurring compounds in water and soil do not react with the product.
	Biological resistance			Microorogenesis does not affect the product.
	Sunlight resistance			By adding the right stabilizers, the UV light attack is reduced. It is anticipated that the material will withstand exposure for more than five years without losing more than 20% of its strength in a temperature environment.
	Temperature stability			The material has a lower strength at higher temperatures, yet it remains stable between -60°C and 100°C.
	UV stabilizer			Added with color
B	Aperture size	ISO 9864	mm*mm	6*6
	Mass per unit area		g/m^2	363
	Roll width		m	1
	Roll length		m	30
	Tensile strength at 2 %		KN/m^2	4.3
	Tensile strength at 5 %		KN/m^2	7.7
	Peak tensile strength		KN/m^2	13.5
	Yield point elongation		%	20.0
	Aperture size		mm*mm	6*6
	Mass per unit area		g/m^2	363

Table 3. shows the general specifications of the PVC pipe used in the research

Raw material: PVC.
Wall thickness depends on the pressure rating (e.g., SCH 40 or SCH 80).
The maximum operating pressure depends on the wall thickness and pressure rating.
Corrosion Resistance: The maximum operating temperature varies per rating but ranges typically from 0 to 60 degrees Celsius.
Compliance with Standards: Depending on the pipe's application, it may comply with ASTM D1785 or ASTM D2665 standards and other standards.

3. Experimental Methods

3.1. Steel Container

The tests were carried out using a steel container with dimensions of (600×600×600 mm). The steel container is made of steel plates (4 mm) in thickness. Figure 4 shows the steel container and loading assembly.

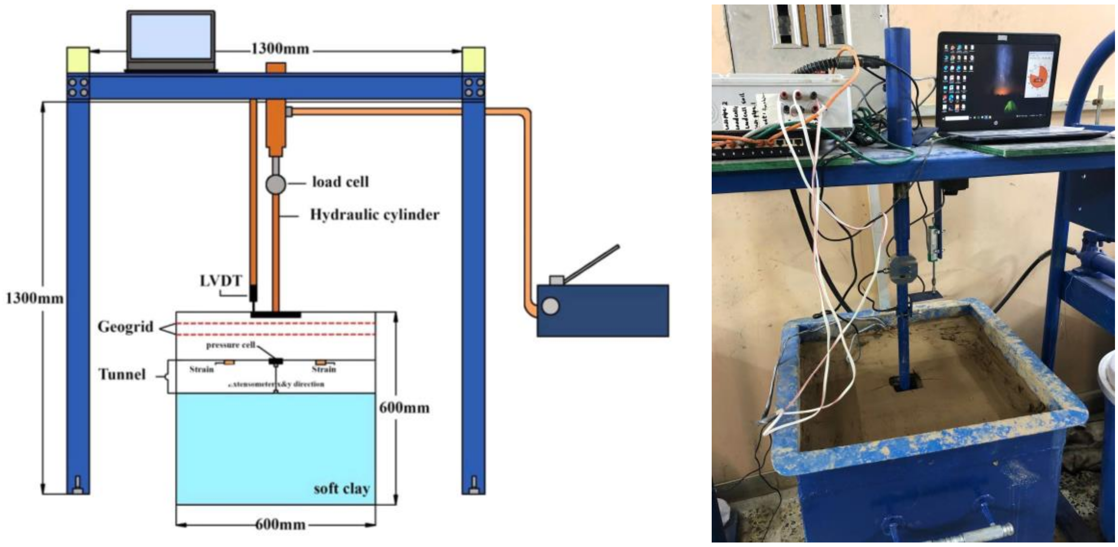

Figure 4. The laboratory model and loading machine

3.2. Steel Footing

All tests employed a square steel foundation measuring 4 mm in thickness and 70 mm in width.

3.3. Loading Assembly

A loading framework was created to apply static vertical loads to the model footing. Figure 4 displays the main components of the loading assembly. The sensors utilized in this research study are: Load cell; Pressure cell; Extensometer (X, Y) Direction; Strain gauge.

4. Testing Program

The flowchart of the research methodology and testing procedure that was used to achieve the study's aims is shown in Figure 5.

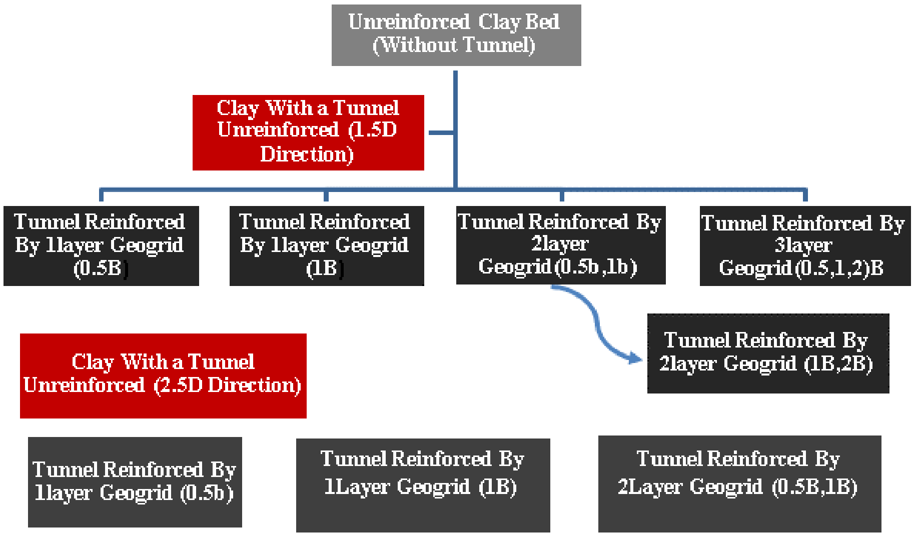

Figure 5. Testing program

4.1. Model Preparation

Seven individual samples were prepared and placed in three layers inside CBR molds to prepare the soft soil used in this study. Each layer was compacted gently using a special hammer to remove trapped air. The test was conducted on a single % water content of 30% to prepare the sample based on Figure 6. Each 25 kg of soil was mixed with enough water to achieve the desired consistency, and the mixing process was done using a sizable 120-liter mixer designed for this purpose. After thorough mixing, the moist soil was kept in tightly sealed polyethene bags for two or three days to obtain a uniform moisture content. Then, the soil was placed in ten layers inside the steel container, and after each layer was placed, it was gently compacted using a wooden piece measuring 75×75 cm to remove trapped air.

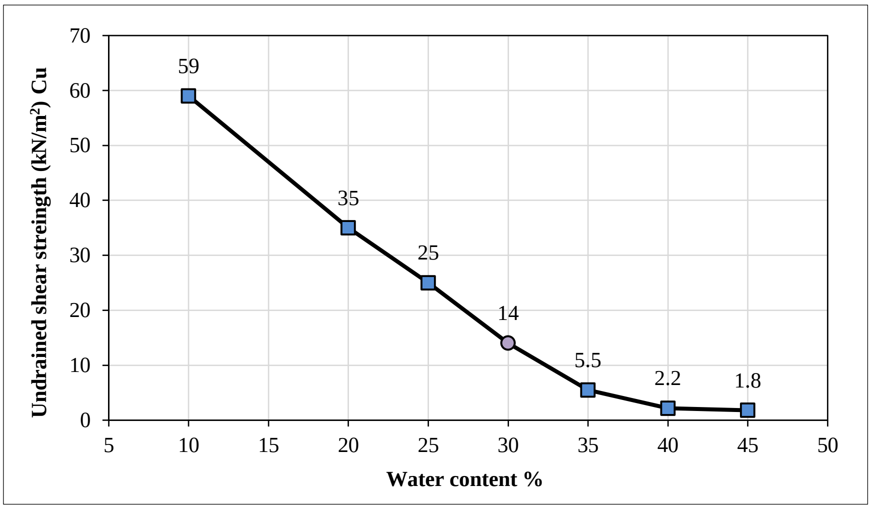

Figure 6. Variation of undrained shear strength versus water content for the remoulade clay after 48 hrs.

5. Results and Discussion

Table 4 provides information on the number of models used to enhance tunnel soil, and the failure ratio is determined by the vertical load needed to produce settlement equal to 10% of the base diameters of the models suggested by Terzaghi (1943) cited by Al-Saudi et al. [3].

Table 4. Results Summaries in Bearing Pressure Q (kPa) Versus Footing Settlement S/B for tunnel at depth 1.5d

s/B (%)	Clay only	Clay +Tunnel (1.5D)	0.5B GR (1layer)	1B GR (1layer)	(0.5B,1B) GR (2layer)	(1B,2B) GR (2layer)	(0.5B,1B,2B) GR (3layer)
5	24.5	25.7	42.6	32.5	45.6	33.6	50.5
10	33.1	40.9	61.6	43.6	67.8	47.4	73.2
15	42.3	52.7	78.1	55.2	88.9	67.9	91.8
20	49.2	60.1	87.4	67.9	102.3	78.5	109.2
25	52.1	71.6	102.5	79.8	113.2	87.7	128.7
30	57.8	76.3	111.2	85.3	125.8	98.2	148.3
35	62.1	82.4	124.8	91.7	138.8	106	164.6
40	66	84.9	130.3	102.9	151.9	113.4	185
45	70.7	86.6	138.4	109.7	163.8	124.5	197.4

In the real world, tunnels may be excavated at different depths based on the project requirements, soil nature, and surrounding environment. The dimensions employed for the tunnel in this study, specifically the two dimensions that have been adopted (1.5D, 2.5D), were derived from prior research conducted by Shaker [16] and Al Khalali [17], as well as the Baghdad Metro project. Hence, it seems that by excavating and reinforcing tunnels at deeper levels, the stresses that reach the tunnel are reduced due to the decreased applied loads. Therefore, the tunnel, which was dug at a depth of 1.5 meters and designed for reinforcement, is deemed the most hazardous in this study because it is more prone to high loads due to its proximity to the surface.

5.1. Effect of Reinforcement on the Surface Settlement Above the Tunnel

(1.5D) Tunnels are considered important structures due to their significant role in transportation operations, as mentioned earlier. The loads generated by tunnel constructions and the surface affect the surrounding soil. Soil loads can distort the tunnel if not sufficiently reinforced. The results of reinforcement using geogrid are illustrated in Figure 7. Also, as shown in Tables 4 and 5, adding a single layer of geogrid to the soil at a depth of 0.5B below the base (where B is the base width) led to a 1.50 improvement at the previously specified s/B=10%, and at the end of the test, the soil improvement was 1.59 in strength. When adding a single layer at a depth of 1B, it is also indicated that the geogrid has less effect, with a 1.06 improvement at the specified 10% failure ratio. At the end of the test, the improvement ratio was 1.26. This explains the decreased efficiency of the geogrid in enhancing the tunnel stability in the soil because the geogrid is farther from the load source.

As we can see from Tables 4 and 6, using two layers of geogrid to reinforce the tunnel led to an improvement of 1.65 at s/B=10%, and at the end of the inspection, the improvement ratio was 1.89. Using two layers can improve the tunnel's stability, strengthen the tunnel walls, and reduce the chance of deformations by adding more support and distributing loads more evenly. In this study, we also added two geogrid layers to the tunnel soil at 1B and 2B depths for comparison. Here, we can see from the table data that there was some interference between the layers, resulting in less improvement. As we have previously explained, the effect of the geogrid diminishes with increasing layer depth. When adding three layers of geogrid reinforcement, the geogrid was added at depths of 0.5B, 1B, and 2B. We can see from the table that this led to an improvement of 1.78 at the specified failure ratio and 2.27 at the end of the examination because it improves load distribution and enhances soil strength. Although using three layers of geogrid may be more costly than using two or one layer, it can be more effective in improving tunnel stability than using fewer layers. The reinforcement with two layers has been adopted as the best based on previous research by Karim et al. [6] and Mohammed et al. [18], including those who have reached It may be inferred that adding more than two layers is pointless as it did not result in any improvement and yielded the same data.

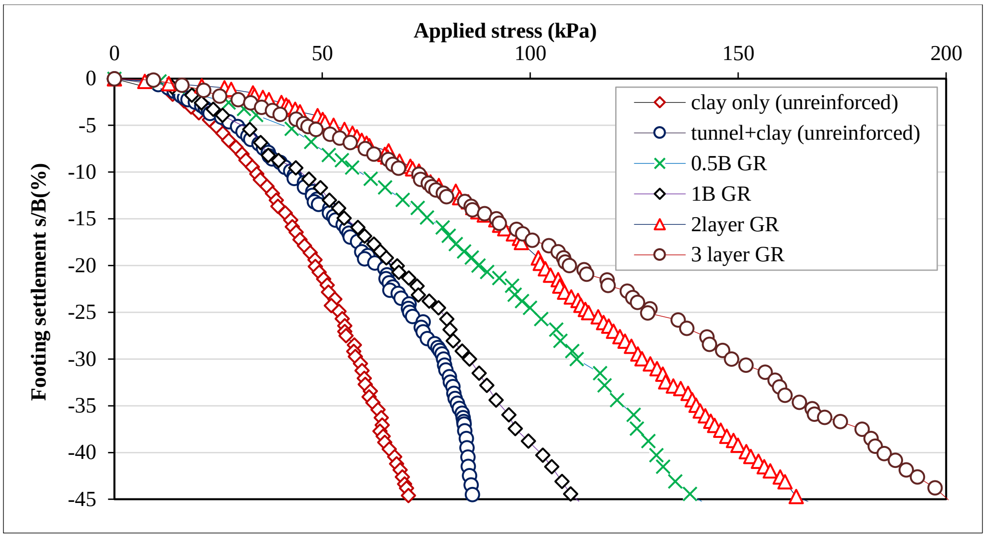

Figure 7. Effect of geogrid on the footing the settlement above the tunnel in 1.5D dimension

Table 5. Summary of Improvement Factors (IF) Versus Footing Settlement S/B From for tunnel at depth 1.5d

s/B (%)	Clay +Tunnel (1.5D)	0.5BGR (1layer)	1B GR (1layer)	(0.5B,1B) GR (2layer)	(1B,2B) GR (2layer)	(0.5B,1B,2B) GR (3layer)
5	1.18	1.65	1.26	1.77	1.30	1.96
10	1.24	1.50	1.06	1.65	1.15	1.78
15	1.24	1.48	1.04	1.68	1.28	1.74
20	1.29	1.45	1.12	1.70	1.30	1.81
25	1.30	1.43	1.11	1.58	1.22	1.79
30	1.34	1.45	1.12	1.64	1.28	1.94
35	1.33	1.51	1.11	1.68	1.28	1.99
40	1.28	1.53	1.21	1.78	1.33	2.17
45	1.22	1.59	1.26	1.89	1.43	2.27

(2.5D) Tunnel excavation and reinforcement with large dimensions can reduce the harmful effects of loads on the tunnel and make it more stable. In this study, we observed that the loads borne by the soil without reinforcement were lower than the excavated tunnel at a depth of 1.5D. Figures 8 and Tables 6 and 7 show that reinforcing the tunnel soil with a single layer of geogrid placed at a depth of 0.5B improves the soil bearing capacity and reduces deformations by 1.43 at s/B=10%. At the end of the test, with an increase in loads, soil improvement increases by 1.55. As shown in the table, when a single layer was used at a depth of 1B, the soil improvement initially was 1.18 at the failure ratio. Still, at the end of the test, the improvement decreased to 1.33 due to the diminishing effect of the geogrid at greater depths. When enhanced with two layers of geogrid at depths of 0.5B and 1B, the soil was improved by 1.82 at s/B=10%, and upon completion of the test, it showed an improvement of 1.84. Therefore, using two layers of reinforcement is also considered a good and economical enhancement.

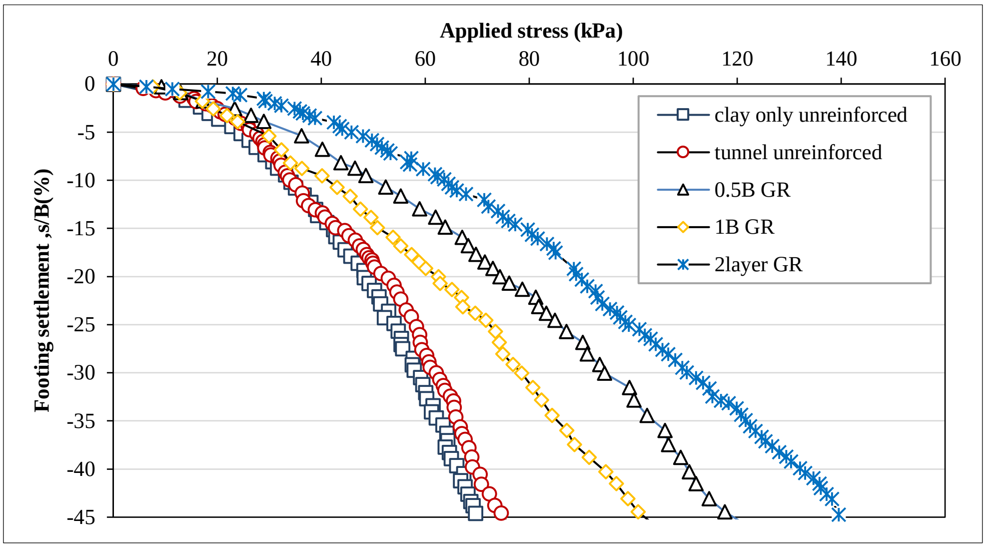

Figure 8. Effect of geogrid on the footing the settlement above the tunnel in 2.5D dimension

Table 6. Results Summaries in Bearing Pressure Q (kPa) Versus Footing Settlement S/B for tunnel at depth 2.5d

s/B (%)	Clay only	Clay +Tunnel (2.5D)	0.5B GR (1layer)	1B GR (1layer)	(0.5B,1B) GR (2layer)
5	22.7	27.5	36.2	29.9	42.4
10	33.1	33.9	48.5	40.1	61.8
15	42.3	44.6	63.8	50.7	77.3
20	48.2	53.9	73	60.2	88.6
25	54	58.3	83.3	69.6	98.4
30	57.8	62.7	93.5	76.9	109.4
35	62.1	66.7	102.6	84.4	120.7
40	65	70.5	110.7	94.7	130.3
45	69.6	75.6	117.6	100.9	139.5

Table 7. Summary of Improvement Factors (IF) Versus Footing Settlement S/B From for tunnel at depth 2.5d

s/B (%)	Clay +Tunnel (2.5D)	0.5B GR (1layer)	1B GR (1layer)	(0.5B,1B) GR (2layer)
5	1.21	1.31	1.08	1.54
10	1.02	1.43	1.18	1.82
15	1.05	1.43	1.14	1.73
20	1.11	1.35	1.12	1.64
25	1.08	1.42	1.19	1.68
30	1.08	1.49	1.22	1.74
35	1.07	1.53	1.26	1.81
40	1.08	1.57	1.34	1.84
45	1.08	1.55	1.33	1.84

Shakir [16] studied the effect of increasing the depth of the tunnel and its diameter on the vertical stress and displacement by using the finite element method. The results showed that the increasing depth decreases both vertical stresses and displacements, and this agrees with this research.

Al-Kalali et al. [19], in their study on buried pipes in sandy soil, found that the settlement of the pipe, which is buried in loose sand, decreases by 30% when the width of the geogrid is equal to B and by 40% when the geogrid width is equal to 2B. However, when a geocell is utilized, the settlement decreases by 50%. When geogrids are used, the proportion of settlement reduction increases. The breadth is increased by a small percentage (10%). The usage of geogrid with a width of B minimizes surface settlement by around 41%, which is consistent with this research. When the geogrid width is raised to 2B, the reduction in surface settlement climbs to 46%, which is consistent with the findings. However, using geocell reduces surface settling in thick sand by 60%. Surface settling is reduced by 45% when using a geogrid with a width of B in thick sand. When the geogrid width is raised to 2B, surface settlement is reduced by 68%. Finally, using geocell reduces surface settlement by 79%, which is consistent with the findings of Jebur et al. [20].

Mahfouz et al. [21] studied the pressure transferred strategy to the tunnel and the reduction in this pressure by using rubber sand and geogrid. The results showed that using rubber sand can reduce the pressure on the tunnel by about 27%, but when using Geogrid, the pressure is reduced by more than 45%, and this agrees with this research.

5.2. Effect of Reinforcement on the Surface Pressure above the Tunnel

The main goal of strengthening the soil with a geogrid is to enhance its bearing capacity and reduce the pressure reaching the tunnel due to external loads that may lead to instability and deformation. A pressure cell was placed in the middle of the tunnel from above to measure the applied pressures. (1.5D) Figure 9 and Table 8 show that the pressure applied to the tunnel reached 13.6 kPa in the soil without reinforcement at the specified failure ratio s/B=10%. However, when reinforced with a single layer of geogrid at distances of 0.5B and 1B from the foundation, the tunnel's pressures decreased to 7.4 and 8.9 kPa. Furthermore, the pressure decreased by a ratio of 7.1kPa when reinforced with two layers and three layers of geogrid, which was 6.5 kPa. Figure 10 and Table 9 show that the excavated tunnel, which is reinforced at a distance of 2.5D from the foundation, experiences a significant decrease in pressure when excavated and reinforced due to its distance from the foundation. It shows that the soil without reinforcement, when subjected to load, had pressures equal to 10.5 kPa in the case of not using any reinforcement. However, when reinforced with a single layer either at a distance of 0.5B or 1B, it was observed that the pressure reaching the tunnel at the failure depth equals 3.84

and 5 kPa at s/B=10%. Finally, when the tunnel was reinforced with two geogrid layers, the pressure reaching the tunnel at the failure depth was s/B=3.5 kPa. This indicates that geogrid is an excellent and cost-effective method for soil improvement projects.

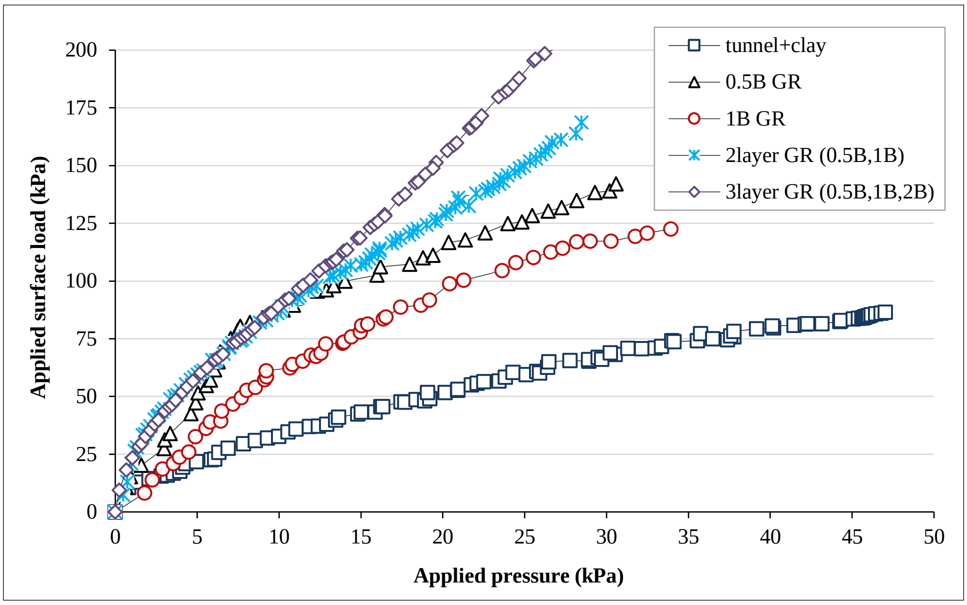

Figure 9. On a 1.5D tunnel, the vertical applied pressure and surface settlement of a footing vary

Table 8. Summaries of Results in Pressure (kPa) Versus Footing Settlement S/B for the tunnel at depth 1.5d

s/B (%)	Clay +Tunnel (1.5D)	Clay +tunnel 0.5B Geogrid	Clay +tunnel +1B Geogrid	Clay +tunnel +2layer Geogrid	Clay +tunnel +3layer Geogrid
5	6.8	4.6	4.9	3.7	3.3
10	13.9	7.4	8.9	7.1	6.5
15	20.9	9.6	13.9	10.3	9.8
20	26.4	11.9	19.1	13.8	13.2
25	32.1	14.8	22.8	16.5	16.1
30	37.7	18.8	27.3	19.2	19
35	43.1	22.6	30.6	23.3	21.2
40	45.9	27.4	32.8	25.2	24.1
45	47	30.5	33.9	28.4	26.9

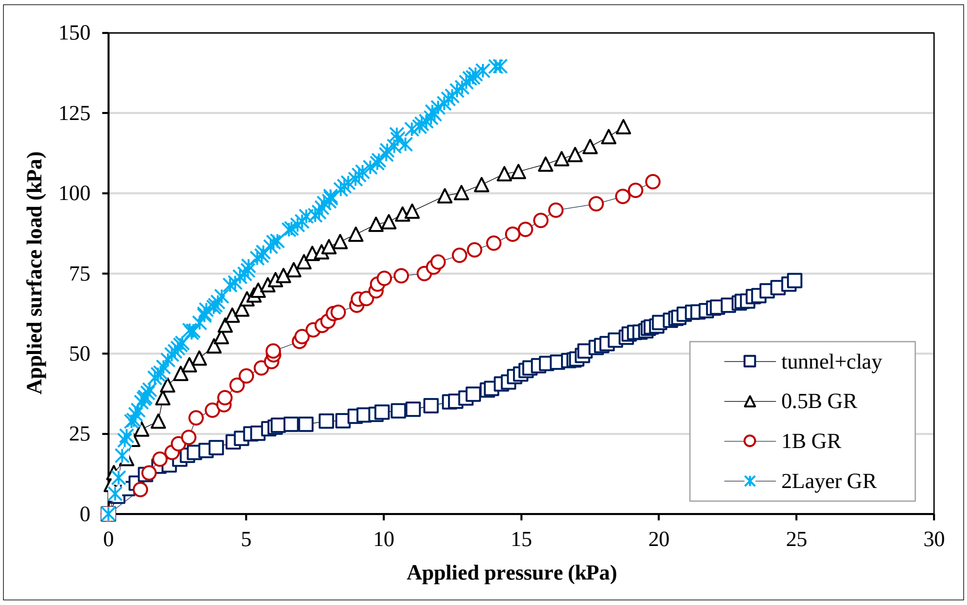

Figure 10. On a 2.5D tunnel, the vertical applied pressure and surface settlement of a footing vary

Table 9. Summaries of Results in Pressure (kPa) Versus Footing Settlement S/B for the tunnel at depth 2.5d

s/B (%)	Clay +Tunnel (2.5D)	Clay +tunnel 0.5B Geogrid	Clay +tunnel +1B Geogrid	Clay +tunnel +2layer Geogrid
5	5.17	1.97	3.18	1.89
10	10.5	3.84	5	3.5
15	14.5	5.03	5.9	5
20	17.2	6.72	8.35	6.65
25	19.1	8.41	10	8.07
30	20	11	11.9	9.82
35	21.9	13.5	13.8	11.3
40	23.4	16.1	16.4	12.6
45	24.7	18.5	19.1	14.1

A tunnel with a reinforced concrete liner that is 350 mm thick was completed by Khan et al. [22]. The analyses have taken into account the degree of saturation and the impacts of soil stratification using the finite element method. In stratification analysis, it was found numerically that as the soil layer migrated in the direction of the liner, the stresses and deformation decreased to 15%. The presence of groundwater above the crown caused a 24% increase in tangential and radial stresses.

5.3. Effect of Reinforcement on the Surface Deflection in the Tunnel

The Extensometer is a precise measuring device used to detect deformations, changes in dimensions, and tension within tunnels. Our current research uses an extensometer to monitor deformations in the x and y directions. Figure 11 illustrates that when a tunnel is reinforced at a distance of 1.5D, the ratio of tension and compression inside the tunnel, without any reinforcement, does exceed 0.5 mm. When the tunnel is reinforced with a single layer of geogrid (0.5B and 1B), the deformation values in both directions decrease to 0.4 mm. Furthermore, the deformation ratio decreases to 0.25 mm when comparing two or three geogrid layers. This indicates that the geogrid significantly improves the tunnel soil and reduces deformations in the surrounding soil over time. Figure 12 illustrates that when reinforcing a tunnel at a distance of 2.5D, the loads reach the top of the tunnel to a lesser extent. This suggests that the deformation ratio here will be lower. Thus, the figure shows that the deformation ratio without tunnel reinforcement was 0.15 mm. The deformation ratio decreased to approximately 0.09 mm when reinforcing the tunnel with geogrid layers. This means that the stress applied to the tunnel was significantly reduced in both cases due to the reinforcement with geogrid. It is noteworthy that horizontal displacements increase with increasing applied pressure. This means that using the geogrid and extensometer network to reduce and monitor deformations in the tunnel contributes significantly to ensuring its long-term safety and stability.

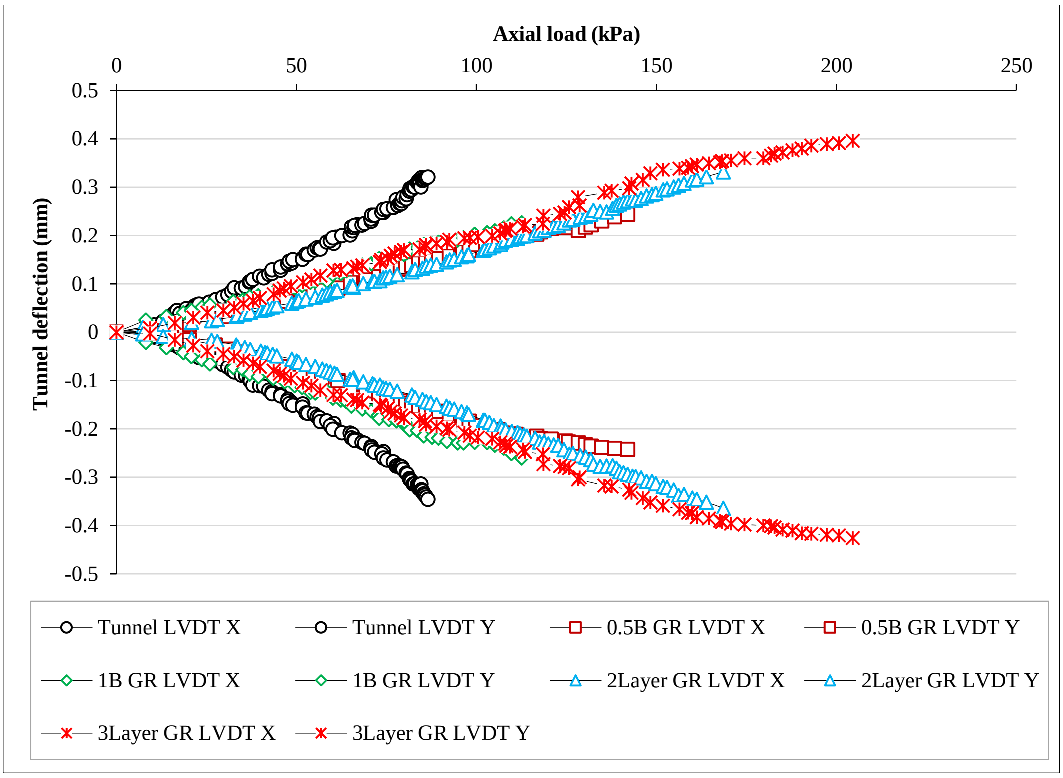

Figure 11. On a 1.5D tunnel, the Impact of Reinforcement on Deformation Under Loading

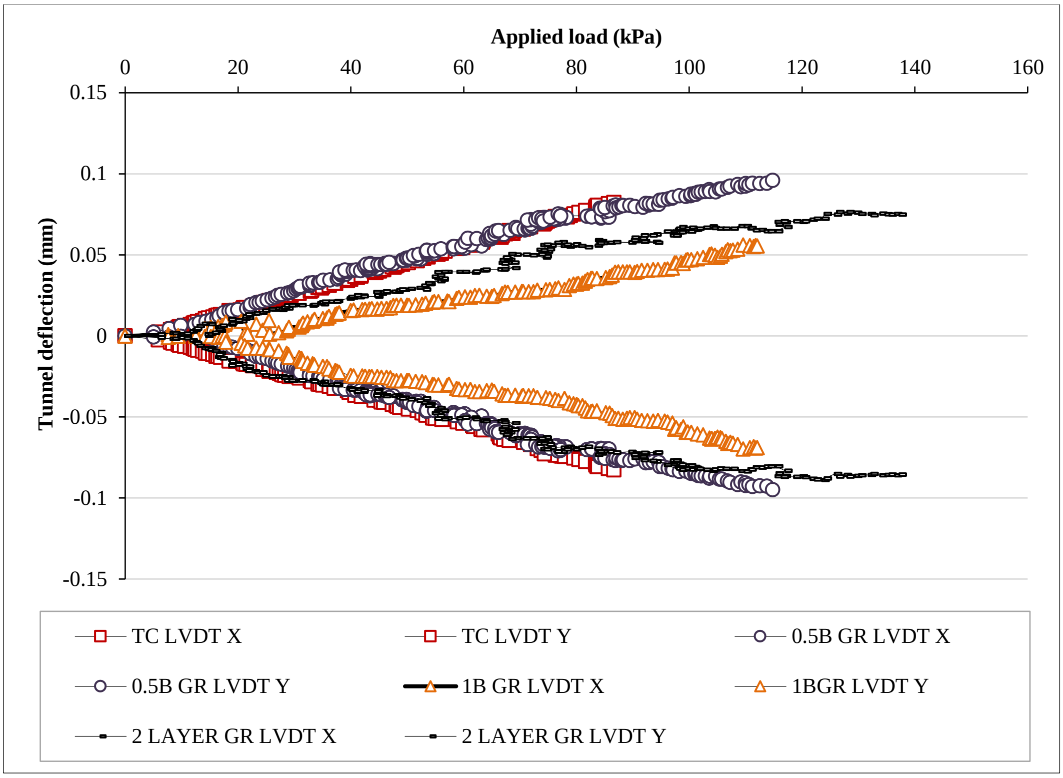

Figure 12. On a 2.5D tunnel, the Impact of Reinforcement on Deformation Under Loading

Al-Haddad et al. [23] used plastic bottles as a reinforcement layer for sand, effectively reducing loads on the sand and leading to decreased deformation. The researcher found this when using the sensors' LVDT. The comparison revealed that soil reinforcement in any way effectively reduces deformations and that the sensors used gave almost the same results.

6. Conclusions

Conclusions gained from extensive laboratory testing on soil samples with geogrid reinforcement at different depths for the tunnel and geogrid are as follows:

- The geogrid improves the ability of tunnel soil to bear loads. Reinforcing the soil with two layers of geogrid improves it by 1.65, while reinforcing it with three layers improves it by 1.78, although it is quite expensive. As a result, we rely on two-layer reinforcement since it is more cost-effective. These are the results of a 1.5D tunnel excavation. For the tunnel dug, scheduled to be reinforced at a depth of 2.5D, the improvement ratio with two layers of the geogrid network was 1.82 at (s/B=10%).
- Enhancing the geogrid helps to better disperse the load on the tunnel, which means that employing geogrid reinforcement lessens the pressure reaching the tunnel owing to the loads. When reinforcing the tunnel with two layers of geogrid on the excavated tunnel soil to be reinforced at a depth of 1.5D, the pressure reaching it was 7.1kPa, while the tunnel excavated at a depth of 2.5D had a pressure ratio of 3.5kPa due to the weights.
- Reinforcing the geogrid net contributes to the tunnel's straightness, structural strength, and capacity to sustain severe loads over time. When a 1.5D deep tunnel is reinforced with two geogrid layers, the deformation ratio drops dramatically to 0.25. The tunnel dug at a depth of 2.5D had a deformation ratio of 0.09 when reinforced with two layers of geogrid. charges, as indicated in the paper submission guidelines.

7. Declarations

7.1. Author Contributions

Conceptualization, A.S.A.-G.; methodology, A.S.A.-G. and H.H.B.; validation, Z.H.F.; formal analysis, Z.H.F.; investigation, Z.H.F., A.S.A.-G., and H.H.B.; resources, Z.H.F.; data curation, Z.H.F.; writing—original draft preparation, Z.H.F.; writing—review and editing, A.S.A.-G. and H.H.B.; visualization, Z.H.F. and A.S.A.-G.; supervision, A.S.A.-G. and H.H.B.; project administration, A.S.A.-G. and H.H.B.; funding acquisition, Z.H.F. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

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