Influence of Geogrid Reinforcement of Sand in Transfer of Dynamic Loading to Underground Structure

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Abstract. The knowledge of the stress distribution and displacements that occurred in and around the openings is required for the safe design and construction of underground structures. The effect of geogrid reinforcement on the transfer of dynamic load to the underground structure is the subject of this research. Within the soil, a PVC pipe was used to replicate the underground structure. To look at soil, footing, and underground tunnel to dynamic loading, a physical model was created to test the resistance of the soil, footing, and underground tunnel to dynamic loading. There were 58 different models tested in total. With two relative densities, two models are tested under static load. The total number of tests carried out is 58 models using two relative densities (40\% and 80\%). Two models were tested under static load. All the other 56 model tests were tested under dynamic load with two amplitudes corresponding to (0.5 ton and 1 ton) using two frequencies 1 and 2 Hz for each load amplitude. For each amplitude and frequency of the load, the sand models were tested without geogrid and with geogrid of two widths (1B and 2B), where \(B\) is the width of the footing, for each amplitude and frequency of the load. In addition, three geogrid depths from the model surface were verified: 0.5B, 1B, and 1.5B. The pressure above the tunnel's crown was found to be reduced by 13-65\% when geogrid reinforcement was used.

Keywords: Tunnel; dynamic load; geogrid; load transfer.

1. Introduction
In contrast to superstructures, the action of underground structures is typically more complex. This is mainly due to the soil-structure relationship, which is hard to forecast in many circumstances. Lifelines are among the underground systems of considerable significance and sensitivity because they are widely distributed in metropolitan environments and fulfill society's critical needs. Although different codes and provisions are suggested for the safe design of lifelines, the designed and constructed lifelines could not escape damage when subjected to severe dynamic loadings, particularly from strong blasts or earthquakes. Engineers’ desire to optimize geotechnical structures has led to the widespread use of geogrid in recent decades, especially in the form of geosynthetic. Reinforced soil is used in geotechnical engineering applications such as road construction, railway embankments, slope stabilization, and soft soil improvement because of its cost, ease of installation, performance, and reliability. Moghaddas and Khalaj [1] performed laboratory tests on small-diameter high-density polyethylene (HDPE) pipes buried in reinforced sand subjected to repeated loads to simulate the vehicle loads. The amplitude of applied stress was 5.5 kg/cm\(^2\) in all tests. The results showed that the percent vertical diameter change (DD) and settlement of soil surface (SSS) can be reduced up to 56\% and 65\%, respectively, using geogrid reinforcement and increasing the safety of embedded pipes. Also, the efficiency of reinforcement decreased by increasing the number of reinforcement layers, the relative density of the soil and the embedded depth of the pipe.
Mehrjardi et al. [2] used geocell reinforcement (as 3-Dimensional-inclusion reinforcement) with rubber soil mixtures under repeated loading conditions was investigated to mitigate strain in buried flexible service pipes and backfill settlement over such pipes. Two different rubber sizes (chipped and shredded rubbers), three different amounts of rubber content in the mixture, and two different positions were used. Armaghani et al. [3] studied the effect of using geogrid to increase the uplift resistance of buried pipelines, as well as the effect of burial depth, pipe diameter, geogrid layer length, and geogrid layer number on the peak uplift resistance (PUR) of loose sand, were investigated. In the laboratory, 33 small-scale experiments were conducted. Laboratory testing found that the depth of burial and pipe diameter have both increased.

Fattah et al. [4] studied soil-structure interaction issues, the validity of transmitting boundaries was investigated. The proposed Baghdad metro line is used as an example. The effect of several parameters, including the peak value of the horizontal portion of earthquake displacement records and the frequency of the dynamic load, was investigated using a parametric analysis. The research is done with the aid of a computer program called Mod-MIXDYN. Finite boundaries (traditional boundaries), infinite boundaries modeled by infinite elements (5-node mapped infinite element) proposed by [5], and infinite boundaries modeled by dashpot elements were all included in the analysis (viscous boundaries). The transmitting boundary was discovered to absorb the majority of the incident energy. The distinct reflections observed for the "fixed boundaries" disappear by using "transmitted boundaries". This is true for both cases of using viscous boundaries or mapped infinite elements. It was found that the results present significant differences when an earthquake is applied as a base motion or a pressure load is applied at the surface ground. The modular ratio Ec/Es (modulus of elasticity of the concrete lining to that of the surrounding soil) has a considerable effect on the peak value of the horizontal displacement. This paper aims to investigate the influence of geogrid reinforced earth in transfer of dynamic loading to the tunnels and the displacement that occurs. In addition, the determination of the optimum depth and width of geogrid reinforcement in different densities of sandy soils is investigated.

2. Experimental work

2.1 Material and tests program

The total number of tests carried out in 58 models. Two models were tested under static load with two relative densities (40% and 80%). According to the literature, all the other 56 model tests were tested under dynamic load, which represents two series were carried out using two relative densities (40% and 80%) corresponding to loose and dense sand, respectively, according to the literature [6]. All the 56 dry sand models were subjected to dynamic load with two load amplitudes corresponding to (0.5 ton and 1 ton) using two frequencies 1 and 2 Hz for each load amplitude. For each amplitude and frequency of the load, the sand models were tested without and with geogrid of two widths (1B and 2B) where B is the footing width. In addition, three series of geogrid depths from the model surface (0.5B, 1B, and 1.5B) were carried out. The sand used in this study was subjected to standard tests to determine its physical properties. The tests were performed on the sand with two relative densities (Dr); loose and dense. The physical properties of soil are summarized in Table 1. A PVC pipe was used in all tests to simulate the underground tunnel. The pipe has a diameter of 110 mm and 700 mm in length, it was placed at a depth equal to 500 mm from the surface. Figure 1 shows the PVC pipe used. The geogrid used in this study is manufactured by Al-Latifia Factory for the plastic mesh (Saudia Arabia). The single sheet was used for more than one test and replaced by a new one when its strands become visibly overstressed.

2.2 Model Design and Devices

To study the effect of geogrid in transfer of dynamic load to the underground structure in sandy soil, it is necessary to simulate the laboratory model as close as possible to the actual condition in the field. To achieve this aim, a special testing apparatus and other accessories were designed and manufactured. The apparatus has the capability of applying different dynamic loads and different frequencies. The general view of the apparatus is shown in Figure 2. The apparatus consists of the following parts:

• Loading steel frame,
Axial model footing,
loading system,
Data acquisition,
Shaft encoder,
Steel container.

Table 1. Physical properties of sand used.

| Index property                       | Index Value | Specification |
|--------------------------------------|-------------|---------------|
| Specific gravity                     | 2.65        | ASTM D854     |
| \(D_{10}\) (mm)                      | 0.175       |               |
| \(D_{30}\) (mm)                      | 0.3         | ASTM D422     |
| \(D_{60}\) (mm)                      | 0.48        |               |
| Coefficient of uniformity (Cu)       | 2.74        | ASTM D2487    |
| Coefficient of curvature (Cc)        | 1.071       |               |
| Maximum void ratio                   | 0.68        |               |
| Minimum void ratio                   | 0.45        |               |
| Maximum dry unit weight (kN/m\(^3\)) | 18.18       | D4253-4254    |
| Minimum dry unit weight (kN/m\(^3\)) | 15.7        |               |
| Angle of internal friction (at Dr. = 40\%) | 34\(^\circ\) | ASTM D3080    |
| Angle of internal friction (at Dr. = 80\%) | 41\(^\circ\) |               |
| Soil classification (USCS)*          | SP          | -             |

*USCS: Unified Soil Classification System.

Figure 1. PVC pipe, pressure cell and vibration meter probe.

Figure 2. General view of the apparatus.

3. Model footing
A strip footing of dimensions 710×110 mm with 30 mm thickness was manufactured to simulate a road or any strip footing above the underground structure and satisfies the requirement of plain strain condition when placed in position with the container.

3.1 Data acquisition
A PLC (Programmable Logic Controller) is employed. A Programmable Logic Controller (PLC) is a digital device used to simulate electro-mechanical processes known as a high-tech process machine. According to the research goals, this device digitally analyzes the data. Unlike general-purpose computers, PLCs can be configured for a variety of inputs and outputs.
3.2 Shaft encoder
A shaft encoder type (Rotary) can be defined as an electro-mechanical device that converts the angular positions or motion of the shaft to an analog or digital code. The incremental encoder output provides information about the motion of the shaft, which is typically further processed elsewhere into information such as speed, displacement, revolution per minute (rpm) and position. In this study, the shaft encoder was used to measure the settlement of strip footing. For further information about encoder is found in references [7,8].

3.3 Steel container
The container used to contain the soil and the underground structure. The internal dimensions are 1000 mm length, 750 mm width, and 700 mm depth. The container was made of steel plates 5 mm thick.

3.4 Earth pressure cell
Earth pressure cells provide a direct means of measuring total pressure in the soil. They may also be used to measure earth-bearing pressure on foundation slabs and footings and at the tips of piles. Figure 1 shows the earth pressure cell model 4800 manufactured by GEOKON, which is used in this study.

3.5 Vibration meter
The vertical amplitude of the tunnel was measured at the surface of the tunnel. The vibration meter (VT-8204) of one channel was used in the test. This vibration meter has a working capacity of 0.001 to 2.217 mm, and capable of measuring displacement, velocity, and acceleration of motion depending on the function set prior to the test. The components of the VT-8204 vibration meter probe on pipe is shown in Figure 1.

4. Sand deposit preparation
Karbala sand is used in this study. The sand deposit was prepared using a steel tamping hummer manufactured for this purpose. Two cases of relative density are chosen (40% for loose sand and 80% for dense sand). This means that the weight required to achieve the relative density is predetermined since the unit weight and the volume of the sand are also predetermined. The sand is divided into equal weights. Each weight represents the quantity of sand required for each layer. The soil of each layer was compacted to a predetermined depth. A PVC pipe that simulates a tunnel was installed on a soil bedding of 250 mm. After that, the pressure cell and vibration meter probe was installed above the pipe crown, and then the soil deposit preparation was completed. Then, the geogrid was placed in the desired depth and width. After finishing the final layer, the top surface was scraped and leveled with a sharp edge ruler to achieve a smooth surface as closely as possible. The model's top surface was then brought into contact with the strip footing.

5. Loading test
The static loading was applied gradually through an axial loading system. The system operates at a controlled displacement of 0.03 mm/sec. The process of the loading is continued till failure occurs. After the preparation of footing on the surface of the sand layer, a dynamic load was applied throughout a predetermined sequence. The application of dynamic load continues for 20 minutes. The following equation represents the function of the dynamic load:

\[ F(t) = a_0 \sin(\omega t) \]  

(1)

Where:
\( a_0 \) = amplitude of load,
\( \omega \) = frequency of load
\( t \) = time, and
\( T \) = period.

The shape of the dynamic wave loading applied is of the form of sinusoidal compressive type as shown in Figure 3.
Figure 3. Dynamic load wave.

5.1 Model test results under static load
As a reference, two model tests are performed under static load using sand of two different relative densities 40% and 80%, which are corresponding to loose and dense sand, respectively. According to the proposal given by [8], failure is characterized as a load causing a settlement corresponding to 10% of the footing width in all model tests. The relationship between the applied vertical stress (q) and the settlement of the two model tests is depicted in Figure 4. Local shear failure is shown to be the mode of failure for Dr = 80%, and punching shear failure is shown to be the mode of failure for Dr = 40%. Table 2 shows that the theoretical bearing capacity equation underestimates bearing capacity values since it is conservative. This result agrees well with Terzaghi equation [8].

\[ Q_{ult} = cN_c + qN_q + 0.5 \gamma BN_y \]  \hspace{1cm} (2)

For the soil used in this study, the value of \( c = 0 \) (cohesionless soil) and \( (D_f = 0) \) (footing at the surface), so Eq. 2 becomes:

\[ q_{ult} = 0.5 \gamma BN_B \]  \hspace{1cm} (3)

Table 2. Bearing capacity of strip footing over sandy soil.

|          | Experimental | Theoretical (Eq. 3) |
|----------|--------------|---------------------|
| Loose sand | 15           | 7.2                 |
| Dense sand| 43           | 20.8                |
5.2 Model test results under dynamic load

5.2.1 Effect of depth of the reinforcement on the vertical pressure

The vertical pressure was measured by a pressure cell. Figures 5 and 6 show the relationship between the vertical pressure on the tunnel crown and (d/B) ratio. For loose sand, it can be noticed that when the geogrid is placed at a depth equal to (0.5B) from the surface, the pressure will decrease by about 10-33%. This decrement is because the soil with geogrid reinforcement will behave like a stiff bed and redistributes the pressure over a wide area, as stated by [2] who studied the effect of the geocell to improve the performance of buried pipes, but this percentage decreased to about 7-13% when the geogrid is placed at a depth equal to (1B) because the distribution of load at a depth (1B) gives smaller pressure intensities than at a depth of (0.5B), whereas no decreasing in pressure was noticed when the geogrid is placed at depth equal to (1.5B) because the geogrid was placed at a depth out of the bulb of stresses below the strip footing in comparison with the results of geogrid and without geogrid. These percentages are different according to the state of load and geogrid width.

On the other hand, for dense sand, it can be noticed that when the geogrid is placed at a depth equal to (0.5B) from the surface, the pressure decreases by about 13-60% in comparison with the results without geogrid. This percentage is greater than in loose sand because pressure redistribution in dense state is better than in a loose state due to the rearrangement of soil particles in loose sand, which does not occur in dense sand. However, when the geogrid is at a depth (1B and 1.5B), there is no decrease in the pressure compared with the results of pressure without geogrid because the geogrid was placed at a depth out of the active zone of stresses below the footing. This percentage varies depending on the load and geogrid condition. Since rigid pipes are stiffer than soils, soil columns on both sides of the rigid pipe are more compressive than soil columns on top of the rigid pipe when a tunnel is built in soil. As a result, soil columns on both sides of the rigid pipe appear to settle more than soils on top of the rigid pipe, and this is a problem.

5.2.2 Effect of depth of reinforcement on the surface settlement

Sensors in the dynamic load apparatus measured the surface settlement. Figures 7 and 8 show the relationship between the surface settlement and (d/B) ratio. The results show that the vertical settlement can be reduced by about 20-44% when using geogrid reinforcement at a depth equals to (0.5 B). This decrease is attributed to the smaller soil mass above the reinforcing layer, which could have insufficient overburden to generate enough friction and tension resistance at the soil reinforced interface, according to [9], who studied the laboratory tests of small diameter pipes buried in reinforced sand under repeated load. Furthermore, this percentage will decrease to about 13-37% when the geogrid is placed at a depth equal to (1B) because the soil mass increases, so the friction and tension resistance decreases. Also, when the geogrid is placed at a depth equals to (1.5B), the results of vertical settlement without geogrid
are approximately close to the results of vertical settlement with geogrid. This indicates that the efficiency of geogrid decreases when the depth increases.

The geogrid has no efficiency at a depth equal to (1.5B). This can be attributed to the stress zone below the foundation. When the geogrid is placed at a depth of 0.5B or 1B, it is within the stress bulb so that its presence considerably affects the values of displacements induced by the dynamic load. These percentages are different according to the state of load and geogrid. The same behavior was also noticed by [10], who observed an increase in the bearing capacity up to approximately 2.7 times by placing the reinforcement within homogenous sand at a depth within the range of u/B= 0.25-0.75 (u is the reinforcement depth and B is the footing width). On the other hand, for dense sand, the results show no significant effect of using geogrid on the surface settlement in dense sand, and that is compatible with the results of [10], who found that the reinforcement at lower relative density is more effective than higher relative density.

Figure 7. Relationship between the surface settlement and (d/B) ratio for b=1B.

Figure 8. Relationship between the surface settlement and (d/B) ratio for b = 2B.

5.2.3 Effect of width of reinforcement on the vertical pressure

Figure 9 and 10 show the relationship between the vertical pressure on the tunnel crown and (b/B). In general, it can be noticed that when the geogrid width equals (1B), the pressure decreases by about 15-46% compared with test results without geogrid, but this percentage decreases to 8-33% when geogrid width equals to (2B). These results can be discussed as follows: when the geogrid reinforcement width is 1 B, full interaction will be mobilized between the geogrid and the soil beneath it so that the pressure transferred through the system is small, while geogrid of 2B width will be subjected to bending and its edges will be raised (this was observed through the experiments), leading to decrease in the mobilized friction and interaction with the underlying soil. This behavior was also noticed by [2] who observed that the geocell layer was pulled down under the plate settlement; however, at a remote distance from the loading plate periphery, no tension in the geocell was observed.

It can be noticed that when the geogrid width equals to (1B), the pressure decreases by about 13-68% compared with the results without geogrid; on the contrary, for loose sand, this percentage increases to 25-70% when the geogrid width equals to (2B). The high density of the sand causes this, full mobilization of interaction will be developed between the geogrid and the soil, which inhibits bending of the geogrid during loading so that the geogrid reinforcement of 2B width will produce a stiff layer which does not allow propagation of waves and stresses will not be transmitted to the pipe zone. Moghaddas and Khalaj [11] found that the value of PDRF (pipe diameter reduction factor) and SRF (settlement reduction factor) depends on the width of reinforcement because adequate width of the reinforcement should be provided to mobilize the required frictional resistance. Moghaddas and Khalaj [11] found that with an increase of the b/D (where b is the width of reinforcement and D is the pipe
diameter), the value of PDRF and SRF decreases, reaching a minimum value at b/D approximately 4-5. All the tests in loose and dense sand with geogrid at depth (d= 1.5 B) revealed results similar or near to the results of tests without geogrid.

5.2.4 Effect of width of reinforcement on the surface settlement
Figures 11 and 12 show the relationship between the surface settlement and (b/B) ratio variation of the surface settlement for model footing on loose sand. The results show that the vertical settlement can be reduced by about 24-44% when using geogrid reinforcement of width equals to (2B), while when the width equals to (1B), the results show that the vertical settlement is reduced to about 13-36%, this indicates that when the width of geogrid increases, the surface settlement decreases because the geogrid of width (2B) can mobilize frictional resistance more than (1B) these results are compatible with the findings of [11]. For dense sand, there is no effect of geogrid on the surface settlement.

5.2.5 Effect of load amplitude on the vertical pressure
Two different amplitudes of dynamic load (a) were chosen (1 ton and 0.5 ton). Figures 5 and 6 in the previous sections show the relationship between the vertical pressure on the tunnel crown and (d/B) ratio. In loose sand, it can be noticed that when the load amplitude decreases from 1 ton to 0.5 ton, the pressure decreases too by about 57%. Comparing the pressure results with and without geogrid, it can be noticed that when the load amplitude equals 1 ton, the pressure decreases by about 11-46%, but this percentage decreases to about 7-38% when the applied load equals 0.5 ton. On the other hand, in dense sand, it can be noticed that when the load amplitude equals 1 ton, the pressure decreased by about 13-27% compared with test results without geogrid, but when the load amplitude decreases to 0.5 ton, the percentage increases to about 68-71%. In dense sand, when the load amplitude is high, dilation may take place, leading to decreased interaction between the geogrid and the sand, which reduces the geogrid’s efficiency in spreading the dynamic waves.

5.2.6 Effect of load amplitude on the surface settlement
Figures 7 and 8 show the relationship between the surface settlement and (d/B) ratio. It can be noticed that the vertical settlement can be reduced by about 25-40% when using a geogrid under an applied load amplitude equal to 1 ton. The percent vertical settlement can be reduced by about 13-35% when a geogrid layer is used under an applied amplitude load (0.5 ton). The results show that the vertical settlement can be reduced by about (64) % when the load amplitude decreases from (a = 1 ton to a = 0.5 ton). All of these percentages are different according to the state of load and geogrid. These results are compatible with the results of [11] who found that the vertical settlement of soil surface can be reduced up to 65% by using geogrid reinforcement and increase the safety of embedded pipes. Also, the
efficiency of reinforcement was decreased by increasing the number of geogrid layers, the relative density of the soil, and the embedded depth of the pipe.

5.2.7 Effect of load frequency on the vertical pressure
Two different frequencies of load were applied; 2 Hz and 1 Hz. Figures 5 and 6 in the previous sections show the relationship between the vertical pressure on the tunnel crown and (d/B) ratio. In loose sand, it can be noticed that the pressure decreases when the frequency decreases. This means that the intensity of the applied load within a limited time will be increased. This leads to an increase in the pressure transferred to the tunnel. The percentage of decrement in pressure when the frequency decreased is about 20% for a =0.5 ton and 45% for a = 1 ton. This can be attributed to the time lag of dissipation of elastic waves transfer to the tunnel, increasing the amplitude of dynamic load and its frequency. While in dense sand, the percentage decreases to 9% for a = 0.5 ton and 18% for a = 1 ton. Also, it can be noticed that the percentage of decrease in vertical pressure of tests without and with geogrid for a load frequency equal to 2 Hz is approximately close or similar to the percentage of tests with frequency equals to 1 Hz.

5.2.8 Effect of load frequency on the surface settlement
Figures 7 8 show the relationship between the surface settlement and (d/B) ratio. For loose sand, the results show that the vertical settlement can be reduced by about 4% when the frequency decreased from 2 Hz to 1 Hz. This means that the intensity of applied load within a limited time will be increased, which leads to an increase in the surface settlement. It can also be noticed that the vertical settlement can be reduced by about 13-36% when using a geogrid under an applied frequency equal to 2 Hz, while the vertical settlement is reduced by about 27-44% when the applied frequency equals 1 Hz.

5.2.9 Effect of relative density on the vertical pressure
Two different soil relative densities were used 40% and 80%. Comparing test results, Figures 5 and 6 in the previous sections show the relationship between the vertical pressure on the tunnel crown and (d/B) ratio. It can be noticed that when the relative density increases from 40% to 80%, the vertical pressure decreases by about 55%. This behavior due to the arching phenomena which occurs as the stress transfer in a tunneling problem from moving parts of the soil (settle more) to adjacent parts (settle less) that can be achieved by considering the vertical stress redistribution in the soil mass above the spring line [11].

5.2.10 Effect of relative density on the surface settlement
Figures 7 and 8 represent the relationship between surface settlement and the (d/B) ratio. The results show that increasing the relative density of sand from 40% to 80% will reduce vertical settlement by about 80%. This is due to the loose relative density, which is equivalent to low backfill stiffness and weak soil support during pipe construction, while the dense relative density is due to the dense relative density.

6. Conclusions
- Geogrid put at 0.5B and 1B decreased the pressure on the tunnel by (10-33) and (7-13) percent for loose sand, respectively. When geogrid is positioned 1.5B from the surface, there is no noticeable reduction in strain. The pressure was decreased by (13-60) percent for dense sand when the geogrid was placed at a depth of 0.5B from the surface, but there was no reduction in the pressure when the geogrid was placed at a depth of 0.5B from the surface.
- In loose sand, placing the geogrid at depths of 0.5B and 1B reduces vertical settlement by around (20-44) and (13-37) percent, respectively, whereas placing the geogrid at 1.5B from the surface has no impact. Furthermore, using geogrid for dense sand has no discernible effect on vertical settlement.
- For loose sand, the best effective width of geogrid for lowering pressure is 1B, and for dense sand, 2B. In loose sand, the most effective width for reducing surface settlement is 2B, and using geogrid has no impact on surface settlement in dense sand.
The pressure drops by about 57 percent, and the settlement drops by about 64 percent when the load amplitude drops from 1 to 0.5 ton. Furthermore, when the load frequency is reduced from 2Hz to 1Hz, the pressure drops by a percentage depending on the state of the load amplitude, and the settlement falls by about 4%.

When the soil density increases from 40% to 80%, the pressure decreases by 55%, and the surface settlement decreases by 80%.

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