EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE OF BURIED FLEXIBLE PIPE IN REINFORCED SAND

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Abstract

The experimental work of this study deals with the performance of pipe in sand with various responses subjected to incremental static loading where the backfill is reinforced with two types of reinforcement (geogrid and geocell) to investigate the effects of backfill cover. The pipes considered are installed in sand with different densities; i.e., loose, medium and dense sand, and a constant burial depth (2D, where D is the pipe diameter). It was concluded that the maximum deformation occurs at the crown of the pipe. The deformation increases when the sand density decreases. For a burial depth equal to 1.5 D, the maximum strain on the pipe crown increases by about 22.5% when the sand changes from dense to medium and 36.8% when it changes from dense to loose. The vertical stress above a pipe buried in loose sand is reduced by 6.3% when the geogrid width is 2B where B is the footing width, while it is equal to 22% when the geogrid width is B. When a geocell is used, the percent reduction is equal to 62%. The percent reduction in the vertical stress above a pipe buried in medium sand is about 28% when the geogrid width is 2B and 40% when the geogrid width is B and equal to 68% when the geocell is used.

Key words

- Buried flexible pipe,
- Static loads,
- Soil reinforcement,
- Backfill density,
- Stress transfer,
- Surface settlement.

1 INTRODUCTION

Buried pipes have served to improve living standards since the beginning of civilization. Buried pipes serve in different applications such as drain pipes, sewer pipes, oil pipes, and subway tunnels (Moser and Falkman, 2008). Their actual behavior should be well understood in order to achieve the safety as one of the most important urban facilities (Moghaddas Tafreshi and Khalaj, 2008).

High-density polyethylene pipe has good potential for economical use in view of its inherent chemical and corrosion resistance, light weight, toughness, flexibility, easy splicing, and consequent easy handling (Goddard, 1995).

The analysis of buried plastic pipes is a problem involving soil-structure interaction. Plastic pipe has little inherent strength, so most of its ability to support a vertical load must be supplied by the passive pressure induced as the sides of the pipe move outward against the substantially vertical load, which is then carried by the surrounding soil by the mechanism of an arching action (Selig and Packard, 1987). This clearly means that the structural behavior of buried flexible plastic pipes is not only a property of the pipe, but is also a property of the earth surrounding the pipe.

The structural performance of buried plastic pipe is evaluated through deflection, ring bending, ring compression, strength, maximum strain, and buckling. The calculation and
determination of the structural performance is the essential assignment of the analysis and design of the buried plastic pipe. The deflection of buried plastic pipes is defined as the change in the vertical diameter of the pipe taken with respect to the neutral axis of the pipe wall.

Moghaddas Tafreshi and Khalaj (2008) assessed the behavior of small-diameter high-density polyethylene (HDPE) pipe (110 mm diameter and 4.03 mm wall thickness) buried in reinforced sand, which was then subjected to repeated loading (of an amplitude of 550 kPa). They examined the effect of between 1 to 5 layers of the reinforcement in the soil having relative densities of 42%, 57%, and 72%. The pipe was embedded at depths 1.5-3 times its diameter. Testing was performed in a 550 mm wide trench. It was reported that the proportion of change in vertical pipe diameter and soil surface settlement can be reduced ultimately by about 40% and 51%, respectively, when using the stiffest reinforcement in the backfill of the highest density when the pipe is at its deepest embedment.

Mehrjardi and Moghaddas Tafreshi (2008) also developed a genetic algorithm linked together with a neural network (based on the test results of Tafreshi and Khalaj (2008) and determined that to achieve a 10 mm soil surface settlement and 2% pipe vertical diametric strain, one layer of a geogrid, a 75% soil relative density, and a ratio of 2.5 for the embedment depth of the pipe-to-pipe diameter would be required.

Although other researchers have studied the stress deformation and small strain shear-wave characteristics of rubber and particle mixtures (Lee et al., 2010) and the potential use of rubber as insulating backfill material for buried pipelines (Christ et al., 2010; Moghaddas Tafreshi and Dawson, 2012), there has been an absence of investigation into the protection of buried pipes with the use of geocell reinforcement and rubber waste.

Reinforcing soil with geosynthetics has been shown to be an effective method for improving the uplift capacity of granular soils. The pull-out resistance of the reinforcing elements is one of the most notable factors in increasing the uplift capacity. Mahdi and Katebia (2015) proposed a new reinforcing element, including elements (anchors) attached to an ordinary geogrid for increasing the pull-out resistance of the reinforcement. Thus, the reinforcement consists of the geogrid and anchors with cylindrical plastic elements attached to it, namely, grid-anchors. A three-dimensional numerical study, which employed the commercial finite difference software FLAC-3D, was performed to investigate the uplift capacity of pipelines buried in sand that were reinforced with this system. The models were used to investigate the effect of the pipe diameter, burial depth, soil density, number of reinforcement layers, width of the reinforcement layer, and the stiffness of the geogrid and anchors on the uplift resistance of the sandy soils. The outcomes revealed that, due to the development of a longer failure surface, the inclusion of a grid-anchor system in a soil deposit increases its uplift capacity to an outstanding degree.

Ahmed et al. (2015) presented the results of an experimental investigation that was conducted to measure the distribution of contact pressure on rigid pipe using tactile sensing technology. The method allows for a continuous pressure profile to be measured around the pipes using flexible sheets that can follow the cylindrical shape of the pipe. The physical model involved a buried pipe installed in granular material subjected to strip surface loading. The effect of introducing a geogrid reinforcement layer above the pipe on the distribution of the contact pressure was also examined. The numerical framework was first validated using the experimental results and then used to investigate the detailed behavior of the soil-pipe system.

The finite element method was employed by Khademi-Zahehi (2019) to evaluate the behavior of buried medium density polyethylene (MDPE) pipes, which had been subjected to damage at the pipe crown. The stress analyses were performed using the ANSYS software finite element package. The stress distribution around the defect was determined under the aforementioned mechanical and thermal loading conditions. Then, the maximum values of the Von Mises stresses in the damaged, buried PE pipes were compared with their correspondingly reduced strength for a safe operation with a life expectancy of fifty years. The stress values increased with the following factors: an increase in the temperature, an increase in the diameter of the hole and a decrease in the elliptical hole diameter ratio (a/b).

Moghaddas Tafreshi et al. (2020) reported full scale experiments, under simulated heavy traffic, of geocell and expanded polystyrene (EPS) geofoam block inclusions to mitigate the pressure on, and deformation of, shallow buried, high density polyethylene (HDPE) flexible pipes, while limiting the surface settlement of a backfilled trench. A geocell of two pocket sizes and an EPS of different widths and thicknesses were used. The soil surface settlement, pipe deformation, and transferred pressure onto the pipe were evaluated under repeated loading. The results showed that using EPS may sometimes lead to larger surface settlements but can also alleviate pressure on the pipe and, consequentially, result in lower pipe deformations.

Three-dimensional finite element models were executed by Elshesheny et al. (2020) and validated to investigate the performance of buried flexible high-density polyethylene (HDPE) pipes, in unreinforced and multiple geogrid-reinforced sand beds, while varying the pipe burial depth, the number of geogrid-layers, and the magnitude of the cyclic loading applied. Soil-geogrid load transfer mechanisms due to interlocked soil in between the apertures of the geogrid-layer were modelled. In unreinforced and reinforced cases, increase in the depth of the pipe burial contributed to the decreasing deformations of the footing and pipe and the crown pressure until reaching an optimum value of the pipe burial’s depth. On the contrary, the strain on the geogrid-layers increased with the increasing the depth of pipe burial.

Alotaibi et al. (2021) discussed the use of stiff three-dimensional geogrids to reinforce sandy soil bridges over existing buried polyvinyl chloride (PVC) pipe at a shallow depth subjected to strip static loading. Twenty-eight large-scale laboratory tests were conducted with variable geogrid geometries using single and double layers of geogrid reinforcement. In general, introducing the geogrid reinforcement reduced the stress transferred to the pipe crown below the center of the loading. For the given stress applied, the increase in the width of the geogrid has resulted in a reduction in the stress transferred to the pipe and the longitudinal strains developed in the pipe. Up to an 80% reduction in the longitudinal strains was observed in the buried PVC pipe as a result of the geogrid reinforcement.

Abdelfateh et al. (2021) presented a method for modeling the behavior of a pipeline based on the finite element analy-
sis by using PLAXIS 3D software, which was aimed at the determination of the pipe bending moment, the displacement over its length, and the evaluation of the vertical stresses in the soil under the pipe. A parametric study was carried out to investigate the effect of the depth of the pipe burial and the soil cohesion. It was found that, unlike laboratory models, the numerical analysis can account for the internal pressure in the pipe and the depth of the pipe burial. The finite-element analysis showed that the presence of fluid pressure inside the pipe results in a decrease in the maximum swelling of the soil by about 95%.

The present study is aimed at a determination of the effects of the mechanical parameters characterizing the soil-structure interaction developed in buried pipe installations in order to investigate the effects of using a geocell reinforcement on a buried pipe and evaluating this concept by laboratory scale modeling. The static loading has been investigated using a laboratory model to carry out a series of experimental tests for different parameters affecting the behavior of buried UPVC pipe. The pipes considered were installed in sand with different densities; i.e., loose, medium and dense sand, and a constant burial depth. Soil pressure cells and special data acquisition system were used for measuring stresses in the soil around the pipe and to measure the deformation of the pipe. The surface settlement was also measured by LVDT. The novelty comes from direct measurement of the stresses below the geocells to investigate any change in the stress transfer upon using these geocells.

2 EXPERIMENTAL WORK

In order to determine the required soil parameters, a soil-testing program was carried out. Routine soil tests were carried out to characterize the soil properties, namely, the grain size analysis, specific gravity, direct shear test, modified Proctor compaction test and the maximum and minimum dry density. The granular backfill materials used in this study were supplied from a site in the city of Karbala in Iraq. A relatively well-graded sand was passed through sieve No. 10 (maximum size is 2 mm). The mechanical grain size analysis according to ASTM D422-07 was performed on the backfill material. The physical and mechanical properties of the sand are summarized in Table 1.

The tensile tests were conducted on PVC pipe that complies with BSI (2000) for underground sewer and drainage services. The pipe has an outer diameter of 110 mm and a wall thickness of 4 mm and, hence, a Standard Dimension Ratio (SDR) = D/t = 27.5. The length of the pipe was selected to be 750 mm. This pipe was subjected to tensile force, and the axial deformation was recorded. The tensile strength at a 10% axial strain of the pipe was measured to be 21 MPa and considered to be the ultimate tensile strength of the pipe material.

2.1 Description of experimental apparatus

A steel container was used to host the soil bed and pipe. The internal dimensions of the container were of a length of 1200 mm, a width of 1000 mm and a height of 1000 mm. One face of the steel had Plexiglas windows with 500 x 500 mm dimensions, which were used for monitoring the pipe deformation during the test. The soil box was used to study the behavior of the buried UPVC pipe as shown in Figure 1.

A steel loading frame was manufactured to support the piston. The stress and displacement patterns in the sand can be affected by the side boundaries of the soil container. In addition, due to the friction between the container walls and soil grains, the vertical stress in the sand can be reduced with the depth. To avoid the side friction of the walls, the ratio between the container’s height and its diameter must be equal to or less than one (Garnier, 2002). The setup dimensions of the present study are within the influence zone found by previous investigators such as Springman (2007) and completely satisfy the influence zone determined from the theory of elasticity.

The axial load was applied through a hydraulic jack system as shown in Figure 1. The hydraulic jack frame had a

<table>
<thead>
<tr>
<th>Index Property</th>
<th>Standards</th>
<th>Value</th>
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<tbody>
<tr>
<td>Specific gravity (Gs)</td>
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<td>D10 (mm)</td>
<td>ASTM D 422</td>
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<td>D30 (mm)</td>
<td>ASTM D 422</td>
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<tr>
<td>D60 (mm)</td>
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<td>Coefficient of uniformity (Cu)</td>
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<tr>
<td>Coefficient of curvature (Cc)</td>
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<td>2.94</td>
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<tr>
<td>Maximum dry unit weight (kN/m³)</td>
<td>ASTM D 4253-00</td>
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<td>Loose state: μ = 33°</td>
</tr>
<tr>
<td>Friction angle</td>
<td>ASTM D 3080-03</td>
<td>Medium state: μ = 36°</td>
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<tr>
<td>Friction angle</td>
<td>ASTM D 3080-3</td>
<td>Dense state: μ = 39°</td>
</tr>
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</table>
The maximum load that could be applied was about 5 tons. A manual system was fixed on the right column of the frame to control the hydraulic intensity. A plastic tube was used to pump the hydraulic oil from the manual system to the piston. An abreaction system was used to expel the air from the hydraulic system.

### 2.2 Soil preparation and measurement devices

The method used to deposit the soil in the testing tank at a known and uniform density was based on a method developed by Koulhubzewski (1948), which is known as the “raining technique”. A moveable steel tank 300 mm long, 300 mm wide, and 450 mm high and ending in an inclined funnel system outlet, was mounted above the testing tank, and used as a hopper to pour the testing material from different heights. A simple sliding system of a perforated plate was provided in the outlet of the funnel to start or stop the raining of the soil.

The “raining technique” applied to deposit the soil in the testing tank at a known and uniform density was used in preparing the test soil. An inclined funnel was mounted above the testing tank and used as a hopper to pour the testing material from different heights through two rollers. In order to facilitate the horizontal movement of the steel tank, a simple sliding system was prepared for this purpose.

The height of the drop and the rate of discharge of the sand mainly affect the density of the sand layer in the raining method (Turner and Kulhawy, 1987). Two rollers fixed at the top of the box were used to adjust the height of the raining device.
to control the height of the free fall of the sand. Several trials with different heights of the falls were performed in order to achieve the relative density desired.

The depth of the embedment of the pipe was adjusted by limiting the top of the tank by means of a temporary wooden wall. The free end of the pipe was then sealed, and the soil was poured into the tank. The surface of the soil was then leveled. At this stage, the loading plate (a steel plate with dimensions of 800 x 200 x 20) mm was placed on the surface of the soil at the desired position, and the system was ready for testing under different loading conditions.

A data acquisition system was used by which all the strains could be read and automatically recorded. The system is able to read the data from eight channels simultaneously. Three contact pressure transducers were used to scan the normal and shear stresses on the base and sides of the pipe. A displacement transducer was used to detect the surface settlement. A load cell was also placed in the loading shaft to detect the pattern of the loads applied on the footing surface accurately.

A number of pressure cells, 100 mm in diameter, were used to measure the total pressure acting on their point of installation. Figure 2a shows the earth pressure cells used in this study. Figure 2b illustrates the method of the installation of the pressure cell above the pipe. The pressure cell consists of two circular stainless-steel plates welded together around their periphery, leaving a narrow cavity between them. The cavity is filled with antifreeze fluid. Model CF-350-20AA-(II)-C20 strain gauges were used in all the tests. A gauge with a length of 20 mm was designed for measuring the strain on the surface of the PVC pipe.

The geogrid material used in this study is Pars Mesh Polymeric (PMP), Type SQ12. Tension tests were performed on the geogrid as per ASTM D6637 to determine its strength and tensile modulus. The tensile modulus (the secant slope of a stress-strain curve) was found to be 79 kN/m², and its yield strength is 0.47 kN/m at a 10% strain level. The aperture size was 14x20 mm.

Testing Procedure

The preparation of the soil bed (bedding materials) requires that any stable soil will act adequately as a bedding material, provided that it is placed and compacted around a pipeline. From a practical point of view, granular material is more readily compacted; it has become widely accepted. The bedding material should be of a similar particle size to that in the trench sides. In the present study, a layer of sand with a 300 mm height was well compacted before the laying of the pipe, which was instrumented by four strain gauges in four places on the perimeter of the pipe opposite and connected to a strain indicator by wire. Then one pressure cell was placed horizontally on the crown of the pipe. The second cell pressure was put vertically on the side of the pipe, while the last one was placed horizontally beneath the surface of the sand by the same width of strip footing in case there was no geocell reinforcement or geogrid. When they exist, a third soil pressure cell will be placed beneath them. Figure 3 shows the schematic diagram of the buried pipe system model with its instrumentation.

After the instrumented pipe was laid, the sand was then poured by hopper according to the height to achieve the required density off either dense, medium or loose, and with three embedment depths (1.5, 2, 3) times the diameter of the pipe. When the sand level reached the required height, then the strip footing, which was made from steel plate with a thickness of 20 mm and a width and height off 110 x 750 mm, was placed. Throughout the test, the soil surface settlement was monitored by two LVDTs placed on the opposite edges of the loading plate to measure the average settlement of the surface. The pipe wall’s circumferential strain was recorded by four strain gauges on the external crown and sides of the pipe invert. Then, a load cell was placed at the center of the strip loading plate under the piston of the hydraulic jack. Weirs connected with channels were checked before the indicator started to apply the loading with constant increments of 1 kPa. All the strain readings were transferred automatically to a laptop; the other readings were manually recorded for the three soil pressures and two LVDTs.

Three soil pressure cells were placed around the pipe; one of them was placed above the pipe in the horizontal direction, the second was placed next to the pipe in the vertical direction, while the third one was put beneath the loading plate at a depth equal to the width of the loading plate as shown in Figure 3. The loading plate was placed on the surface of the model. The test was first carried out without a geogrid. Then the test was repeated with the geogrid. Once its width was equal to 1B, then it was equal to 2B, where B is the width of the loading plate (footing). The soil pressure cell was placed directly beneath the geogrid.

3 Results and Discussion

3.1 Effect of the soil density on the pipe

Figure 4 shows the effect of soil density on the crown strain at an embedment depth equal to 2d, where d is the diameter of the pipe. It can be seen from this figure that the maximum deformation occurs on the crown of the pipe. Referring to Figure 4, when the burial depth equals 2d, the maximum strain on the pipe crown increases by about 26.6% when the sand changes from dense (Dr = 75%) to medium (Dr = 60%) and by 35.3% when it changes from dense to loose (Dr = 35%). These results are expected and compatible with those obtained by Hosseini and Moghaddas Tafreshi (2002), who conducted laboratory tests of small diameter pipes buried in reinforced sand and de-
terminated that the deflection behavior and failure mechanism of the system highly depend on the soil density.

The results are also compatible with the findings of Arockiasamy et al. (2006) who studied the soil-pipe interaction and noted that whatever the soil is well compacted, it absorbs the bulk of the load transferred to the pipe and thus reduces the strain of the pipe’s wall. However, in relatively loose soils, due to the weak contacts and poor interlocking of the grains and the special arrangement of the soil fabric, regardless of the embedment depth, even under low loads, the failure of the system usually occurred in a low load applied due to local buckling or the large deflection of the pipe together with excessive settlement of the loading plate.

Figure 5 shows the effect of the buried soil density on the pipe invert strain. It can be seen that the invert strain is less than the crown strain by about 75%. This is because the movement of the bottom of the buried pipe is restricted by the soil, where the lateral movement is limited by the soil, which the pipe tries to push, and the axial movement is limited by the soil-pipe friction. The decrease in the strain with the increase in the soil density can also be clearly seen. The maximum strain on the pipe invert decreases by about 4% when the sand changes from loose to medium and by 23.5% when it changes from loose to dense when the embedment depth equals 2D. This explains the decrease in the effect of the density on the strain as we move away from the loading source. All these percentages were calculated for the last load increment.

A good understanding of the behavior of buried UPVC pipes is obtained from measurements of the pipe wall strain, which indicates variations in the deformed shape of the pipe. The springline area is the edge side of the pipe in the diameter area, and there are two sides for the pipe. So in this section, when the term “springline strain” is used, it means the average value of the right and left spring line strains. Figure 6 displays the effect of the soil density on the springline strain at different burial depths; it is evident from the results that increasing the backfill quality affords the pipe greater protection in terms of circumferential strain. The springline strain decreases by about 7% when the sand changes from loose to medium and by 22% when it changes from loose to dense for an embedment depth equals 2D. It can also be seen that the sign of the springline strain is negative or, in other words, it is the opposite sign of the crown strain, which explains that the pipe is suffering from compression in the crown while it is exposed to tension in the springline area.

Figures 7 to 9 present the variation of the crown strain with a surface load applied for the pipe buried in loose, medium, and dense sand, respectively. The pipe was embedded at a depth of 1.5 D, which is kept constant to investigate the effect of the geogrid width placed at a depth of 0.5 B below the loading plate. The geogrid location is also kept constant. The results show that the reduction in the crown strain in loose sand, when the geogrid width equals 1B, is 13% compared with the test results without a geogrid, but this percentage decreases to 11% when the geogrid width equals 2B. While the reduction percent in medium sand becomes 14% and 12% when the geogrid width was B and 2B, respectively, in dense sand, it becomes 15% and 11% when the width of the geogrid changes from B to 2 B. These results are attributed to the full interaction that will ripen between the soil beneath a geogrid and the geogrid itself so that the pressure transferred through the system is small.

When the relative density increases, the percentage of the reduction increases because the friction and interaction between the soil and geogrid has increased; therefore, the deformation was lower. But when the geogrid width increased, the pipe showed a somewhat lower reduction in the strain. This behavior was also noticed by Mehrjadi et al. (2012a), who observed that the geocell layer was pulled down under the plate (footing) settlement; however, at a remote distance from the loading plate periphery, no tension in the geocell was observed. Therefore, the reinforcement efficiency in reducing the deformation of the pipe lessened as the width of the geogrid increased. This is also compatible with the findings of Marto et al. (2013), who studied the effect of the geogrid reinforcement on the bearing capacity properties of soil under a static load and found that the presence of a geogrid in the soil makes the
3.2 Effect of a reinforcement on stresses in soil around a pipe

In general, soils possess a low tensile strength. The main objective of strengthening the soil mass is to increase the bearing capacity, improve the stability and decrease settlements and lateral deformations. One of the approaches is the use of polymeric materials. Geosynthetic is a well-known technique in soil reinforcement. Its use can significantly improve the soil’s performance and reduce costs in comparison with conventional designs. In the present study, two types of reinforcement were used: a geogrid and a geocell. A geogrid is made from polymer materials; it may be woven or knitted from yarns, heat-welded from strips of material, or produced by punching a regular pattern of holes in sheets of material and then stretched into a grid (Khatib, 2010). A geocell is a honeycomb with a three-dimensional cell structure that provides for the containment of compacted fill soils. The reinforcement decreases the lateral movement of the soil particles and forms a mat or rigid layer for the distribution of loads applied to a wider area footing (Dash et al., 2003).

Figures 10 to 12 show the relation between the surface pressure applied with the soil pressure measured by a soil pressure cell when the pipe is buried in loose sand, while Figures 13 to 15 and Figures 16 to 18 show the same relation when the pipe is buried in medium and dense sand, respectively.

In all the tests, the reinforcement depth was kept constant and equal to B. The improvement of the soil strength when a geogrid and geocell are used in the soil is clear.

It can be seen from Figure 10 that the vertical stress above the pipe buried in loose sand, is reduced by 8.3% when the geogrid width is 2B, while it is reduced to 22% when the geogrid width is B. When the geocell was used, the percent reduction is equal to 62%.

On the other hand, Figure 13 shows the percent reduction in the vertical stress above the pipe buried in medium sand; the reduction is 28% when the geogrid width was 2B and 40% when the geogrid width was B and equal to 68% when a geocell was used.

Figure 16 shows that the reduction in the vertical stress above the pipe buried in dense sand is 32.7% when the geogrid width was 2B, 42.3% when the geogrid width was B, and 75% when the geocell was used.

It can be concluded from these percentages that the efficiency of a geocell in reducing the stress transfer to the buried pipe is more than the efficiency of a geogrid; this is because the structure of a geocell and its third dimension, which gives the soil more interaction with the geocell and prevents it from sliding by confining the soil between the wall of the geocell and the soil, which leads to an increase in the strength and thus reduces the transmission of stress to the pipe.

The geocell reinforcement keeps the encapsulated soil from being displaced from directly beneath the load applied by confining the material by hoop action in the cell walls, thereby increasing the shear strength of the composite system. The load redistribution that occurs within the confined zone involves a three-dimensional interaction between the sand infill material and the cellular structure as stated by Moghaddas Tafreshi and Dawson, (2010).

Vertical stress applied to the infill induces horizontal active pressure at the perimeter of the cell. The interface friction of the infill wall transfers the load into the cell structure which, in turn, mobilizes the resistance in the surrounding cells. It is also evident that the cells that surround a loaded cell offer greater passive resistance due to the greater lateral strain in the vicinity of the load. The combined effect of these mechanisms acts like a large mat that spreads the applied load over an extended area, instead of directly at the point of contact, and thus provides a composite lab with high flexural stiffness and load support capabilities within the geocell reinforcement, consequently leading to an improvement in the overall settlement performance.

Figure 11 shows the effect of the reinforcement on the horizontal pressure beside the pipe buried in loose sand. The percent reduction in horizontal stress is 48% when the sand was reinforced by a geogrid of width B, 50% when the geogrid width was 2B, and 75% when a geocell was used. Figure 14 shows...
the same relation but in medium sand, and the percent of the reduction in horizontal stress was 28.6% when the geogrid width was B, 42.8% when the geogrid width was 2B, and 85% when the geocell was used. Also Figure 17 shows that the percent reduction in the horizontal stress in dense sand is 66% when the geogrid width was B, 75% when the geogrid width was 2B, and 90% when a geocell was used instead of a geogrid.

Figure 12 presents the effect of reinforcement on the vertical stress under the reinforcement in loose sand; the percent reduction in the stress was 20% when the geogrid width was B, 28% when the geogrid width was 2B, and 57% when a geocell was used.

Similarly, Figure 15 shows the percent reduction in the vertical stresses beneath the reinforcement embedded in medium sand; the percent reduction when the geogrid width equals B is 24%, 33% when the width equals to 2B, and 60% when a geocell was used.

Figure 18 shows the effect of reinforcement on the vertical stress under a reinforcement in dense sand; the percent reduction in stress was 27% when the geogrid width was B, 37% when the geogrid width was 2B, and 67% when the geocell was used.

It can be seen that when the density of sand increased, the percent of reduction increased, which can be interpreted by the interlocking of the sand particles with the reinforcement, which gives a more strength to bear the loads applied.

Obviously, the use of a geocell as a reinforcement in loose sand can reduce the vertical pressure on the pipe crown. The pattern of the strain variations in the geocell walls indicated that the geocell mattress behaves as a composite beam supported by the subgrade soil. The load dispersion in the geocell mattress was found to be governed by factors such as geometry of the geocell layer and the position of its placement under the footing.

When the geocell reinforcement is filled with soil, it appears to behave as a stiff bed, which redistributes stress over a wider area, instead of a narrow stressed area at the point of the load applied when no reinforcement is used.

The geocell reinforcement keeps the encapsulated soil from being displaced from directly beneath the load applied by confining the material by hoop action in the cell walls, thereby increasing the shear strength of the composite system. The load redistribution that occurs within the confined zone involves a three-dimensional interaction between the infill materials and the cellular structure. The vertical stress applied to the infill induces a horizontal active pressure at the perimeter of the cell. The interface friction of the infill wall transfers the load into the cell structure which, in turn, mobilizes resistance in surrounding cells as indicated by Mehrjardi et al. (2012b).
Fattah et al. (2018b) found that the vertical pressure on the crown of a buried pipe decreased between 13-41% due to reinforcement of the sub-base layer by the geocell under different load frequencies. The vertical pressure reaching the pipe was increased when the frequency was increased, for the same load amplitude, with or without a geocell. Moghaddas Tafreshi et al. (2020) concluded that with the increase in the geocell’s width beyond the optimal width of (expanded polystyrene) EPS (i.e., 1.5 times the pipe diameter), not only is no further improvement generated, but it also counteracts the beneficial effect of an EPS block, as the negative influence of the pipe’s behavior would be expected with the increase in the width of an EPS block more than 2.5 times the pipe diameter. This could be attributed to diminishing the arching effect over the pipe due to the use of a wider EPS width, which extends the soil prism over the pipe (Fattah et al., 2016; Witthoeft and Kim, 2016).

3.3 Effect of reinforcement on the surface settlement

The improvement in reducing the surface settlement by adding a geogrid reinforcement is clearly seen in Figures 19 to 21, which represent the relation between the surface load applied with the surface settlement for a soil-pipe system buried in loose, medium or dense sand, respectively. It can be seen in Figure 19 that the surface settlement of the footing above the buried pipe embedded in loose sand decreases by about 25 to 35% when the geogrid width equals B, and 40 to 45% when the geogrid width equals 2B, while this percent becomes 50 to 57% when a geocell is used.

It can be seen that the percent decrease in a settlement is increased when the geogrid width is increased, but in the small amount of 10%. This is compatible with the results reached by Marto et al. (2013), who found that the reinforcing efficiency in reducing the maximum footing settlement is reduced as the width of a geogrid was increased. They also found that if the width of a geogrid is greater than five times the width of a footing, it had no significant effect.

These results are compatible with those of Fattah et al. (2018a), who found that a geocell reinforcement greatly reduces the soil surface settlement above buried pipes. The surface settlement increases with the increase in the load amplitude. The reduction of a surface settlement due to the geocell reinforcement is about 29 to 43 % when the amplitude of load is 0.5 ton. This value became 32 to 41% when the amplitude of the load was up to 1 ton.

The geocell reinforcement keeps the encapsulated soil from being displaced directly beneath the load applied by confining the material via hoop action in the cell walls, thereby increasing the shear strength of the composite system. The load redistribution that occurs within the confined zone involves a three-dimensional interaction between the infill sand and the cellular structure.

Using a reinforcement in soil would control and decrease the vertical settlement and progressive densification would be induced. The reinforcement can contribute to increase the bearing capacity through significantly changing the geometry of the collapse pattern, thereby preventing the mechanism from reaching deep into the soil. The reinforcement prevents the most adverse mechanisms from occurring, thereby leading
to an increase in the limit load. The main role of the inclusion is to reduce the distortion rate in the sheared zone and reduce the ultimate shear stress mobilized in the shear zone. The reinforcement provides an effective restraint and has a useful role in preventing vertical spreading of the soil. As a result, the shear strength is distinctly increased and the failure pattern is modified as stated by Michalowski and Shi, (2003).

Figure 20 presents the surface settlement above a pipe embedded in medium sand. It can be seen that the surface settlement decreases by about 41% when a geogrid with a width of B was used, decreases by 46% when the geogrid width equals 2B, and by 60% when geocell was used. Figure 21 presents the same relation but in dense sand, which indicates that the surface settlement decreases by 45% when the geogrid width equals B, 68% when the geogrid width equals 2B, and 79% when a geocell is used.

It can be seen that the geocell reinforcement is more efficient in reducing the surface settlement than a geogrid reinforcement, which is due to the inherent strength of the geocell material and its own structure (the third dimension of a cell), which prevents the lateral movement of the soil particles and forms a rigid slab for the distribution of loads applied to a wider area vertically. Confinement of the soil between the cells also causes an increase in the strength.

Fattah and Mohammed Redha (2016, 2022) found that reinforcing the sandy soils with a geocell leads to a beneficial reduction in the dynamic response (surface settlement, displacement amplitude, and dynamic pressure transmitted) for all the soil states at different percentages. This is accompanied by an increase in the soil strength, as well as reducing the hazards of a traffic load by decreasing the stresses transmitted to the pipe. This behavior can be attributed to the geocell reinforcement that is acting as an interconnected cage; its vertical walls are serving as a series of plate anchors, which mobilizes substantial resistance against the footing settlement, as well as increasing in the improvement performance.

4 CONCLUSIONS

• The maximum deformation occurs at the crown of the pipe. The deformation increases when the density decreases. For a burial depth equal to 1.5 d, the maximum strain on the pipe crown increases by about 22.5% when the sand changes from dense to medium and 36.8% when it changes from dense to loose. When the burial depth equals 2D, the maximum strain on the pipe crown increases by about 26.6% when the sand changes from dense to medium and 35.3% when it changes from dense to loose. The maximum strain on the pipe crown increases by about 19.35% when the sand changes from dense to medium and 33.3% when it changes from dense to loose.

• The invert strain in the tunnel is less than the crown strain by about 75%. The maximum strain on the pipe invert decreases by about 36% when the sand changes from loose to medium and 39.6% when it changes from loose to dense for the case of n embedment depth equal to 1.5. This percent becomes 4% when the sand changes from loose to medium and 23.5% when the sand changes from loose to dense for an embedment depth equal to 2D.

• The vertical stress above a pipe buried in loose sand is reduced by 8.3% when the geogrid width is 2B, while it is equal to 22% when the geogrid width was B. When a geocell was used, the percent reduction was equal to 62%. The percent reduction in the vertical stress above a pipe buried in medium sand is about 28% when the geogrid width was 2B, 40% when geogrid width was B and equal to 68%, when the geocell was used. The reduction in vertical stress above the pipe buried in dense sand was 32.7% when the geogrid width was 2B, 42.3% when the geogrid width was B, and 75% when a geocell was used.

• There is a decrease in stress beneath the geogrid layer in loose sand; the percent reduction in the stress was 20
% when the geogrid width was B, 28% when the geogrid width was 2B, and 57% when a geocell was used. Similarly, the percent reduction in the vertical stresses beneath a reinforcement embedded in medium sand, the percent reduction when the geogrid width equal B was 24%, 33% when the width equal to 2B, and 60% when a geocell was used. In dense sand, the percent reduction in stress was 27% when the geogrid width was B, 37% when the geogrid width was 2B, and 67% when a geocell was used.

• The surface settlement of a buried pipe embedded in loose sand decreases by 30% when the geogrid width equals B and 40% when the geogrid width equals 2B, while this percent becomes 50% when a geocell is used. The percent decrease in settlement is increased when the geogrid width is increased but in a small amount (10%). The surface settlement decreases by about 41% when a geogrid is used with a width of B and decreases by 46% when the geogrid width equals 2B and by 60% when a geocell is used, but in dense sand the surface settlement decreases by 45% when the geogrid width equals B, 68% when the geogrid width equals 2B, and 79% when a geocell is used.
REFERENCES


