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Protection of flexible pipes from dynamic surface stresses by Geocell-reinforced sand backfill

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ABSTRACT

Underground conduits or utility pipelines are buried at shallow depths in trenches with the help of flowable fills. These pipes are subjected to deformations and damage due to the application of dynamic traffic loads or heavy static loads from the vehicles. This study presents the results of a pipe model installed in geocell reinforced and unreinforced sand. A PVC pipe of 110 mm diameter and 1.4 mm wall thickness was installed in a rigid tank to simulate a buried pipe. Different types of instrumentation such as earth pressure cell and vibration meter were used to measure the vertical transmitted pressure and displacement amplitude on the pipe crown, respectively. Different factors that affect the performance of pipes installed in sand bedding and backfill were investigated. The factors included the state of compaction of bedding and backfill, the magnitude of the applied surface dynamic pressure, and the load frequency. The results of this study were presented in terms of the vertical transmitted pressure on the crown of the pipe, surface soil settlement, the displacement amplitude of the pipe crown. It was concluded that the performance of the buried pipe depends on the state of compaction of sand bedding and backfill. When the relative density of the sand increases from 30% to 60%, the vertical pressure on the pipe crown, surface settlement, and the amplitude of displacement, decrease by about 30 %, 40 %, and 15 %, respectively. When the relative density of the soil increases from 30% to 60%, more than 40% reduction was recorded in the surface settlement for the unreinforced model while this reduction is about 25% for the model reinforced with geocell.

Keywords: *Flexible pipe, Geocell-reinforcement, Displacement, Dynamic stress, Sand backfill, Relative density*

1. Introduction

Buried pipes are generally used for water supply purposes, wastewater, drainage, oil, and gas transport. The resistance of buried pipes to loading belongs to the pipe stiffness and the surrounding soil. However, the pipe's stiffness typically provides only 5% of the total resistance to deformation. The remaining 95% of the resistance to deformation is supplied by the soil (Watkins et al. 2010). As a result, the bedding and backfill materials play a critical role in the structural deformation and integrity of buried pipelines. In sites where selected bedding and backfill soil are not available, the use of native soils as bedding layers or backfill materials for the installation of buried pipes becomes a realistic choice. The price of importing granular backfill materials can be as high as 2–3.5 times the cost of utilizing native materials (Watkins et al., 2010).

This is particularly true in desert areas that are covered by vast amounts of sand. In these regions, engineers are forced to use sand as a soiled envelope around buried pipes. Besides, the harsh desert environment requires special types of pipes like plastic pipes which are flexible, light-weight, and have earned popularity in civil engineering projects because of their lower cost and resistance to chemical action over the conventional pipes made of concrete and metals (Masada and Sargent, 2007).

Harmonic and periodic vibrations can be generated mostly by heavy machines, moving vehicles, or by running trains, which cause the supporting foundations to behave in a different fashion. When the soil is subjected to dynamic load transferred from the traffic, it deforms and deteriorates, consequently, results in worse support for the structure above it. Hence it is necessary to investigate how the soil is affected under various operating conditions.

The pipes are subjected to deformation and damage due to the application of dynamic traffic loads or heavy vibratory or static loads caused by vehicles. The damage results in the discomfort of the consumers of the pipe function, and also to the travelers on the road. Therefore, to protect these utility lines from the waves caused by dynamic traffic loads, it is proposed to design a shallow reinforcement system using a three-dimensional geosynthetic (geocell).

Many researchers in the past have studied the design and fabrication processes of the buried pipes through small scale and large scale tests (Brachman et al., 2000; Arockiasamy et al., 2006; Moghaddas Tafreshi and Khalaj, 2008; Fattah et al., 2015; Fattah and Mohammed Redha, 2016). In recent times, geocells are showing their efficacy in applications of geotechnical engineering. Geocells are considered 3-dimensional expandable panels, which are made up of ultrasonically welded high strength polymers, or from polymeric alloys, such as Polyethylene, Polyolefin, etc. The interconnected cells that exist in the geocell contribute as a slab that behaves like a large pad that spreads the applied load over a wider area.

Moghaddas Tafreshi and Khalaj, (2008) performed laboratory tests on small-diameter high-density polyethylene (HDPE) pipes buried in reinforced sand with geocell subjected to repeated loads to simulate the vehicle loads. The amplitude of applied stress was 5.5 kg/cm^2 in all tests. The variables examined in their study included the sand relative density,

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number of reinforced layers, and depth of embedment of the pipe. The influence of various reinforced layers at 42%, 57%, and 72% relative densities in different depths of embedment of 1.5–3 times of pipe diameter were investigated. The results showed that the percentage of vertical diameter change (ΔD) and settlement of the soil surface (SSS) can be reduced ultimately by 56% and 65% for values of ΔD and SSS, respectively, using geogrid reinforcement, and increase the safety of embedded pipes.

Marto et al. (2013) showed that the addition of planar reinforcement in the sand decreased much both the monotonic and cumulative settlements leading to an economic design of the footings. Generally, the soil has a low tensile strength. The main objective of strengthening the soil mass is to improve stability, increase bearing capacity and decrease total and differential settlements and lateral deformations. A known technique in soil reinforcement is the use of polymeric materials. Using this technique can significantly reduce costs and improve soil performance in comparison with conventional designs.

Hegde et al. (2014) described laboratory tests on PVC pipes with small diameters buried in geosynthetic reinforced and unreinforced sand subjected to static loading. The study's focus was to assess the quality of combining geogrid and geocell reinforcement systems in protecting the underground utilities and buried pipelines. A pipe with a 1.4 mm thickness and a 75 mm outer diameter was found below the footing at different depths ranging from 1B to 2B (B is the width of the footing). The results showed that combining geogrid and geocell reinforcement systems considerably decreases the pipe deformation as compared to unreinforced soil bed. More than 40% reduction in the strain and more than 50% reduction in the pressure values were observed in the reinforced bed as compared to the unreinforced bed at different depths. On the other hand, the foundation bed performance was also found to be highly influenced by the depth of the pipe, even in the presence of the relatively stiff reinforcement system.

Fattah et al. (2018a) presented an experimental study on the effect of geocell reinforcement on soil surface settlement. Some laboratory experiments were conducted using PVC pipes which were buried in a medium sand layer and below a subbase layer reinforced with geocells. The model was subjected to dynamic repeated loading with different amplitudes (0.5 ton and 1 ton) and different loading frequencies (0.5 Hz, 1 Hz, 2 Hz) to study the effects of the geocell reinforcement layer inclusion on the surface settlement. The results of the experimental work showed that the surface settlement increases with the increase of the load amplitude. The reduction of surface settlement due to the geocell reinforcement is about 29 to 43 % when the amplitude of load is 0.5 tons, and this value becomes 32 to 41 % when the amplitude of load is up to (1) ton. The surface settlement value increases proportionally with the increment of frequency amplitude for every tested model.

The present study is intended to investigate the use of sand as backfill and bedding for buried plastic pipes. Geocells are used as sand reinforcement. To achieve this objective, model PVC pipes were installed in a steel tank and tested. Only the effect of the degree of compaction of bedding and backfill soil was considered in this paper.

2. Material Used

2.1. Soil

The soil that is used in this study to simulate the natural ground is sandy. A summary of the test results with the standard specification that was followed in each test is presented in Table 1. According to the grain size distribution curve results presented in Figure 1, it can be seen that the sand is medium to coarse size. According to the Unified Soil Classification System (USCS), the sand is classified as poorly graded sand with the symbol SP.

2.2. Plastic pipe

Although pipe diameters vary over a wide range, a reasonable dimension representing a common small diameter of the pipe for urban services (sewer, drainage, and gas mains, etc.) is adopted. Therefore, based on the dimensions of the model test, the tests were conducted on PVC (Poly Vinyl Chloride) pipe that is commonly used in urban facilities such as water and sewage systems.

The pipe has an outer diameter of 110 mm, and a wall thickness of 1.4 mm. The length of the pipe is 10 mm less than the width of the stiff tank to prevent binding against the end walls. Hence, in order to prevent particles of sand to enter inside the pipe which leads to a reduction in the friction between the pipe and front and back faces of the tank, the two ends of the pipe were closed by two caps before placing it in the tank.

Table 1. Physical properties of used sand.

Property	Value	Standard of the test
Specific gravity (G_s)	2.64	ASTM D 854
D_{10} (mm)	0.16	ASTM D 422 and ASTM D 2487
D_{30} (mm)	0.23	
D_{60} (mm)	0.38	
Coefficient of uniformity (Cu)	2.37	
Coefficient of curvature (Cc)	0.87	
Soil classification (USCS)	SP	
Maximum dry unit weight (kN/m^3)	18.82	ASTM D 4253
Minimum dry unit weight (kN/m^3)	15.32	ASTM D 4254
Maximum void ratio	0.63	-------
Minimum void ratio	0.38	-------
Angle of internal friction (at R.D =30%)	32º	ASTM D 3080
Angle of internal friction (at R.D =60%)	38º	

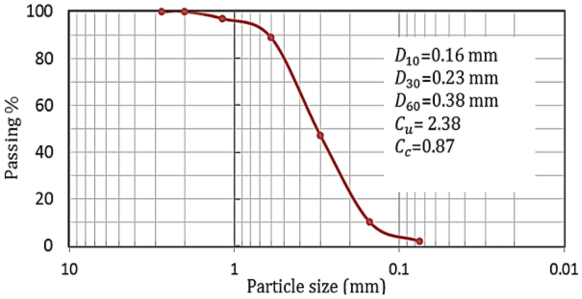


Figure 1. Grain size distribution curve of the sand used.

2.3. Geocell-reinforcement

Geocell reinforcement used for this study was fabricated from planar polymeric taps that are sewn to the adjacent taps periodically in order to form a "honeycomb" arrangement; therefore a non-perforated flexible geocell was manufactured. The height of geocell walls is (25 mm), the pocket-size (d) of geocell is taken as the equivalent circular area diameter of the opening of a pocket (Ag), shown in Figure 2 (i.e. d^2= 4 / =π × Ag). The pocket-size (d) of the geocell used was kept constant (d = 70 mm), and the ratio of the geocell pocket-size (d) to the width of footing model (B) equals 0.7 (i.e. d/B = 0.7). This ratio was reported by Dash et al., (2003) and Fattah and Mohammed Redha, (2016) which is around (0.7 – 0.8) times of footing width it was found to be the one that gives a maximum performance improvement.

3. Instrumentation and data acquisition

A heavy-duty earth pressure cell was used to measure the vertical transmitted pressure, which is suitable for traffic applications. The pressure cell was placed just above the pipe crown. The vertical displacement amplitude of the pipe crown was measured at the surface of the pipe. 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, it is capable of measuring the acceleration, velocity, and displacement of motion depending on the function set before the test. Figure 3 demonstrates the setup stages.

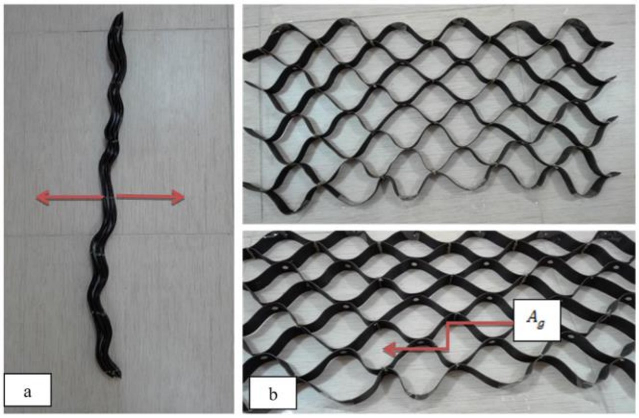
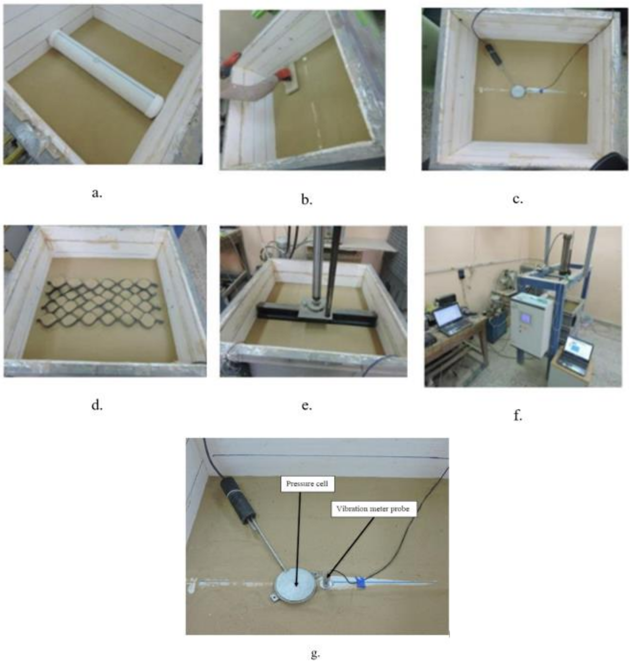


Figure 2. Geocell used. (a) Geocell before expanding. (b) Top view of the geocell mattress after expanding.

To study and investigate the real behavior of the tested models during the application of the dynamic load, it is necessary to find a procedure to measure and sense the occurring displacement due to the dynamic load during the test. This procedure, which enables the tester to obtain the total accurate information that, consists of a huge data of readings in a very short time. For this reason, a data acquisition system was used.

The Programmable Logic Controller (PLC) can be defined as a digital computer used for automation of electromechanical processes, which are considered as a highly technical process unit. This system analyzes the data digitally, according to the research requirement. PLC, unlike general-purpose computers, can be designed for multiple inputs and outputs arrangements extend temperature ranges and immunity to electrical noise. PLC program is generally executed repeatedly as long as the controlled system is running and the data is saved in the memory in case of the electrical current was turned off.



a. Placement of the pipe, b. Filling the soil above the pipe, c. Installation of pressure cel, d. Placement of geocell, e. Model preparation for loading, f. Loading machine, g. Measurement instruments.

Figure 3. Preparation stages of the test model.

4. Testing program and methodology

The laboratory model tests provide a less expensive alternative to the field tests, more control on the system components such as instrumentations and loading, and more control on soil placement and compaction. In addition, the laboratory ensures an ideal environment for testing (e.g. avoiding the effects of winds, rain, and temperature variation).

A series of laboratory model tests were tested under the effect of traffic dynamic load represented by half-sine function (only positive phase). For comparison, the tests were conducted with and without geocell reinforcement. The depth of placement (u) and the width of geocell (b) were chosen as (0.1B and 3.2B, respectively, where B is the width of footing) these adopted values were recommended by Dash et al., (2001) who stated that the optimum depth of geocell placement (u) is (0.1B) from the bottom of the footing.

The model was manufactured in such a way as to simulate the real situation of the buried pipe in geocell reinforced and unreinforced sand. The pipe was tested in a large tank made up of 6 mm thick steel plates. The tank was cubed in shape with 800 mm height as shown in Figure 4. This test setup was intended to simulate the plane strain condition for buried pipes. The main concern in simulating the condition as plane strain is to avoid the effects of the test tank sides. This was accomplished by maintaining the test tank rigidity and placing the model pipe at a reasonable distance from the sides of the tank. All the tank sides were strongly supported by three steel U-sections to provide rigid walls.

The dynamic load was applied for 1000 seconds for each test. The half-sine wave dynamic function was utilized in this study. The shape of the function is displayed in (Figure 6); so, the equation of the applied dynamic load (F) at any time (t) is:

$$F(t) = \boldsymbol{a}_o * \sin \quad * t \qquad (1)$$

where:

F = applied force,

t = time,

$\boldsymbol{a}_o$ = the amplitude of load, and

= the load frequency.

The positive part (half of the sine wave) is the only part that was applied to the test models.

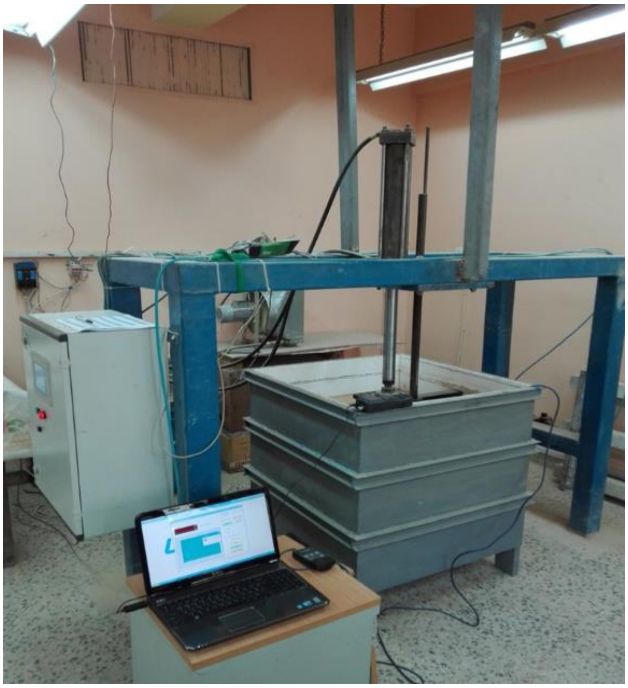


Figure 4. Preparation stages of the test model.

5. Results and Discussion

5.1. Effect of relative density of sand on the vertical pressure

The influence of various soil relative densities on the transmitting of dynamic vertical pressure to the buried pipe with time in loose and medium sand densities are present in Figures 5 and 6. From these figures, it can be seen that when the relative density increases from 30% to 60%, the vertical pressure transmitted to the pipe crown increases by about 30%.

Conditions of the soil have a considerable influence on the transmission of pressure to the pipe crown. A flexible pipe installed in loose sand deflected more than the pipe installed in medium sand. It can be stated that as the relative density of the backfill increased, the vertical pressure on the pipe crown decreased. Thus greatest reduction in strain occurs vertically. The experiences that have been gained from the utilization of PVC flexible pipe prove that, in most cases, the appearance of local plastic strain does not indicate any risk of the transition of a pipeline system into a limiting state followed by the loss of its load-carrying capacity.

A geocell reinforced soil is stronger and stiffer and gives more strength than the equivalent soil without geocell reinforcement. The presence of geogrid in the soil makes the relationship between the settlement and applied pressure of the reinforced soil almost linear until reaching the failure stage. The reinforcement efficiency-related conversely to geogrid width as concluded by Marto et al. (2013).

Geocell functions in two ways: reinforcement and separation which are the techniques of improving the poor soil with geocell, to increase the stiffness and load-carrying capacity of the soil through frictional interaction between the soil and geocell material.

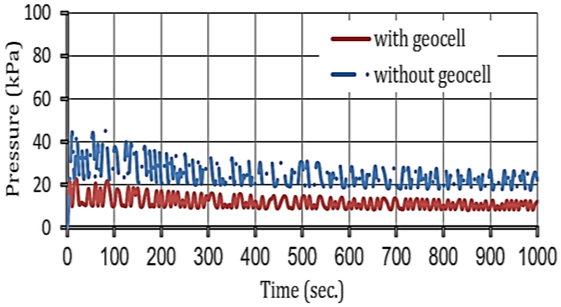


Figure 5. Variation of the vertical pressure with time under a = 0. 5 ton, ω = 2 Hz, and RD. = 30%, without and with geocell.

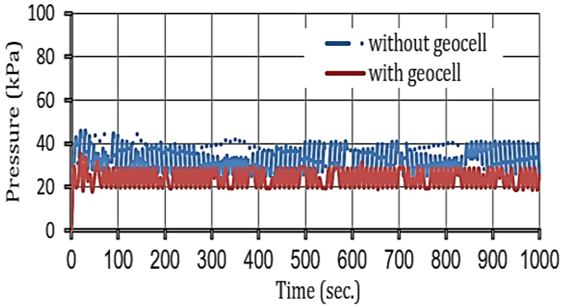


Figure 6. Variation of the vertical pressure with time under a = 0. 5 ton, ω = 2 Hz, and RD. = 60%, without and with geocell.

5.2. Effect of relative density of sand on the surface settlement

The effect of relative density on the surface settlement under different frequencies is shown in Figures 7 and 8. In general, the settlement decreases with increasing relative density; when the relative density of the soil increases from 30% to 60%, more than 40% reduction was recorded in the surface settlement for the unreinforced model while this reduction is about 25% for model reinforced with geocell.

Also from the test results, it is evident that the percent decrease in the surface settlement is substantially greater for loose reinforced sand than for medium reinforced sand. This indicates that the reinforcement in the sand at a loose state (lower relative density) is more effective than at a dense state (higher relative density).

Geocell mesh provides better interlocking with the soil particles thus ensuring adequate anchorage during loading. The improvement in the load-carrying capacity could be attributed to improved load dispersion through the reinforced subbase onto the subgrade. This, in turn, results in a lesser intensity of stresses getting the transfer to subgrade, thus leading to lesser subgrade distress.

5.3. Effect of relative density of sand on the displacement above the pipe crown

The variation of displacement amplitude (A_z) during traffic dynamic load application with time at different relative densities and load amplitudes is shown in Figures 9 and 10. It can be observed from the above figures that, with an increase in the relative density of soil, the amplitude of displacement (A_z) at the crown of the pipe decreased. The percent of the decrease in (A_z) when the soil relative density increased from 30% to 60% is about 15%, which is approximately the same at all load amplitudes.

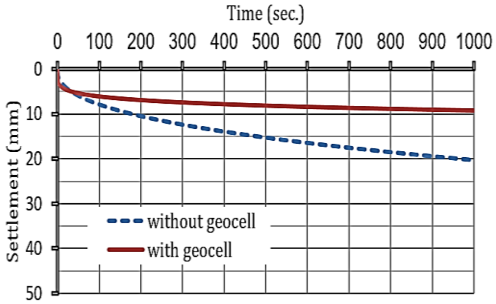


Figure 7. Variation of the surface settlement with time under a = 0. 5 ton, ω = 2 Hz, and RD. = 30%, without and with geocell.

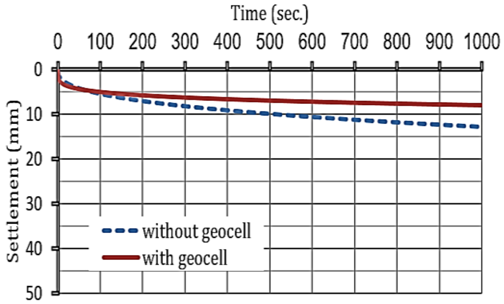


Figure 8. Variation of the surface settlement with time under a = 0. 5 ton, ω = 2 Hz, and RD. = 60%, without and with geocell.

This is similar to the installation of pipes by different compaction stresses, as the loose relative density is similar to the low stiffness of the backfill and poor support provided by soil during pipe installation, while the medium relative density is corresponding to the high stiffness of the backfill and good soil support. The high displacement amplitude increasing in the case of loose state sand is attributed to the increase in the modulus of elasticity and soil stiffness in the case of medium state sand which leads to an increase in soil material damping. Geogrids or geocells reinforce by laterally restraining the base or subbase and improving the bearing capacity of the system, thus decreasing shear stresses on the weak subgrade (Hassan et al., 2018).

Fattah et al. (2018b) found that the geocell reinforcement is effective in reducing surface settlement, hence the deflection of the pipe is also reduced. The plastic points are significantly reduced below the geocell layer.

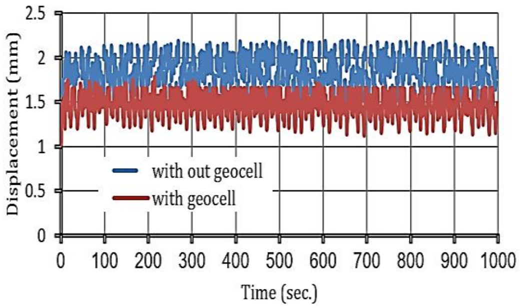


Figure 9. Displacement of the pipe crown with time under a = 0.5 ton, ω = 2 Hz, and RD. = 30%, without and with geocell.

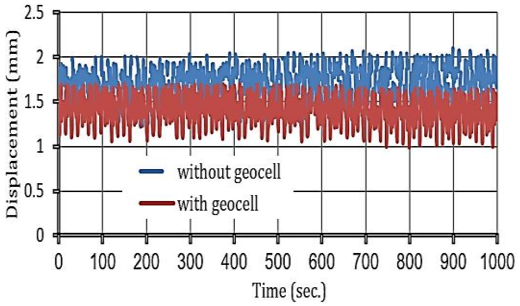


Figure 10. Displacement of the pipe crown with time under a =0.5 ton, ω = 2 Hz, and RD. = 60%, without and with geocell.

6. Conclusions

The conclusions listed below can be drawn from the results of the experiments:

1. The performance of the buried pipe depends on the state of compaction of sand bedding and backfill. The sand compacted at lower relative density transmits higher stresses to underground pipelines.
2. When the relative density of the soil increases from 30% to 60%, more than 40% reduction was recorded in the surface settlement for the unreinforced model while this reduction is about 25% for the model reinforced with geocell.
3. When the relative density of the sand increases from 30% to 60%, the vertical pressure on the pipe crown, surface settlement, and the amplitude of displacement, decrease by about 30 %, 40 %, and 15 %, respectively.

In general, reinforcing the sandy soils with geocell leads to a beneficial reduction in dynamic response (displacement amplitude, surface settlement, and transmitted dynamic pressure) for all states of soil in different percentages. This condition is accompanied by an increase in soil strength.

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