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Experimental investigation of buried flexible HDPE pipe

Rajkumar Ratnaraju*[1)]

[1)] *Associate Professor (Senior Grade), Department of Civil Engineering, Sri Sivasubramaniya Nadar College of Engineering (Autonomous), Kalavakkam – 603110, Tamil Nadu, India*

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ABSTRACT

Buried pipes are used mainly for water supply and drainage, among many other applications such as oil, liquefied natural gas, coal slurries, and mine tailings. The pipes used may be rigid (reinforced concrete, vitrified clay, and ductile iron) or flexible (steel, UPVC, aluminum, fiberglass, and high-density polyethylene), although the distinction between them is blurring. Deflection or buckling determines the design of flexible pipes. HDPE pipes are preferred due to their light weight, long term chemical stability and cost efficiency. This project aims to design and fabricate an experimental setup of the model trench as a steel tank filled with the desired type of soil and flexible pipe with the required depth and loading provisions to simulate uniform loading and record the behavior, i.e., deflection of the flexible plastic pipe, compare the observation with the theoretical results, and infer the findings. The deflection characteristics were to be measured with the help of a dial gauge fixed inside the pipe. Additionally, the objective is to study the load deformation behavior of the buried pipe and stress variation across the cross section of the pipe under static loading, along with the influence of depth of embedment and density of backfill on the deformation and stresses in the pipe and the deformation behavior of the buried pipe when soil is reinforced with geogrid reinforcement, and evaluate the structural performance of the pipe. Based on the conclusions, various recommendations can be made in terms of the application of buried flexible HDPE pipes in place of conventional pipes and thereby reducing the risk of leakage and damage and also compensating the cost of pipe systems economically.

1 Introduction

Pipes are used widely in different walks of life. They are mostly used as service conduits for the transport of natural gas, petroleum, chemicals, and many other fluids. The pipes may be installed above the ground, such as in building service systems, or may be buried underground. For thousands of years, pipelines have been constructed in various parts of the world to convey water for drinking and irrigation. This includes the ancient use in China of pipes made of hollow bamboo and the use of aqueducts by the Romans and Persians. The Chinese even used bamboo pipes to transmit natural gas to light their capital, Peking, as early as 400 B.C.

A significant improvement in pipeline technology took place in the 18th century, when cast-iron pipes were used commercially. Another major milestone was the advent of steel pipe in the 19th century, which greatly increased the strength of pipes of all sizes. The development of high-strength steel pipes made it possible to transport natural gas and oil over long distances. Initially, all steel pipes had to be threaded together. This was difficult to do for large pipes, and they were apt to leak under high pressure [1] .

The application of welding to join pipes in the 1920s made it possible to construct leak-proof, high-pressure, large-diameter pipelines. Today, most high-pressure piping consists of steel pipe with welded joints.

Major innovations since 1950 include the introduction of ductile iron, the use of high-density polyethylene (HDPE) pipe for sewers, and many more. These plastic pipes offer a wide range of benefits over conventional steel and cast-iron pipes. Plastic pipes offer a tremendous weight advantage over alternative piping materials. Less weight also means cheaper transport and, ultimately, a lower transportation cost. This also enables larger payloads (more pipes) to be loaded. Plastic pipe's resistance to fracture is an extremely important performance advantage. While plastic pipes are made from rigid PVC compound, these pipes themselves have the ability to yield under loading without fracturing and can successfully be used where the surface will be subject to external loading, such as road traffic.

A major requirement for all piping applications is joint tightness. Plastic pipes are available with deep-insertion, push-together gasketed, or solvent-cement joints. These

* Corresponding author:
E-mail address: rajkumarr@ssn.edu.in

pipes provide smoother wall surfaces that reduce fluid friction and resistance to flow. This hydraulic smoothness inhibits slime buildup in sewers and virtually eliminates tuberculation and encrustation in water distribution mains. The end results are significantly lower maintenance costs, more efficient initial pipeline design, and superior performance over the lifetime.

1.1 Greenwood and Lang classical theory

Greenwood and Lang [2] found out that the non-uniformity of earth pressure is a function of soil type, degree of compaction, depth of embedment, and pipe stiffness. Greenwood and Lang also presented a modified formula that is more complete than the original formula of Watkins. The modified formula includes the work of Leonhardt (1972-79) [3], who developed a factor to consider the soil resistance of the native soil. The factor that is used to find the soil resistance in Watkins' modified Iowa formula is based on the ratio of the trench width to the pipe diameter and the modulus of the backfill soil around the pipe to the modulus of the native soil. A pipe-soil interaction coefficient, which is an empirical factor, is added to the soil resistance term to reflect the behavior of flexible pipes in the field. The modified formula of Greenwood and Lang [2] is as follows:

$$\Delta X = \frac{K.\,\gamma.\,H}{\frac{EI}{r^3} + 0.061\,\varsigma\,C_I E'} - \delta V_0 \tag{1}$$

- ΔX – horizontal deformation
- K - bedding factor
- $\gamma.$ – unit weight of the backfill
- H - height of the backfill above the pipe
- δV_0- elongation due to compaction of the side fills
- E – modulus of elasticity of pipe material
- I – moment of inertia of the pipe wall per unit length of pipe
- r – mean radius of pipe
- ς – Leonhardt relationship
- C_I – Pipe soil interaction coefficient defined by Greenwood and Lang
- E' – watkins modulus of soil reaction

1.2 Failures in pipes

Performance limits and potential failures must be identified for buried pipe design. Chief among those are excessive deformations of the pipe, wall buckling, and collapse. Maximum allowable pipe deflection is usually not determined by structural failure but by conditions such as clearance for pipe-cleaning equipment, special sections, and pipe appurtenances (attachments).

Pipeline designers classify pipes as “flexible” or “rigid,” depending on how they perform after installation. Flexible pipe can move, or deflect, under loads without structural damage, while rigid pipe cannot deflect significantly without structural distress, such as cracking. In 1930, Marston classified pipes according to their rigidity [4].

In reality, the behavior of a buried pipeline will depend on how its stiffness compares with the stiffness of the soil in which it is to be buried. The soil-pipe system is statistically indeterminate. As a result, using statics alone is not capable of calculating the interface pressure between the soil and pipe.

As soil and surface loads are placed over a buried pipe, the ring tends to deflect, primarily into an ellipse with a decrease in vertical diameter and an almost equal (slightly less) increase in horizontal diameter, leading to collapse as shown in Figure 1. The increase in horizontal diameter develops lateral soil support, which increases the load-carrying capacity of the pipe. The decrease in vertical diameter partially relieves the ring of load since the soil above the pipe takes more of the load in arching action over the pipe.

Figure 1. Failure due to deflection

1.3 Scope of study

In the future, flexible pipes will almost entirely take the place of concrete and clay pipes in buried piping systems that are already in use. This is due to the cheaper costs of flexible plastic pipes and their favorable characteristics, such as ease of replacement, high deflection capacity, etc. Therefore, to predict the behavior and performance of the buried flexible plastic pipes that would be widely used in underground piping systems and to prevent failures of these pipes, this study becomes essential and of prime importance.

2 Objectives

- To study the performance of flexible HDPE pipe buried in a M-Sand backfill subjected to static load.
- The response of the pipes is studied for the influence of deflection on the pipe material.
- To study the performance of flexible HDPE pipe when soil is reinforced with geogrid reinforcement.
- To compare the deflection characteristics with the classical theory devised by Greenwood and Lang.
- However, this study is limited to the pipe material, depth of embedment, pipe without flow, and static loading conditions.

3 Literature review

Arokiaswamy et al. [5] performed a field test subjecting high-density polyethylene (HDPE), PVC, and metal large-diameter pipes to a design truck loading. The finite element method was used to determine how the pipe soil system responded to live load application. The above results were taken for comparison. Good performance was demonstrated by using buried flexible pipes embedded with highly compacted graded sand and silt. Under shallow burial conditions, the specified deflection limit for the installation of flexible pipes was found to be 5%, and for vertical deflection, was found to be 2%, according to the AASHTO specification.

Mohammed Hoosseini and Moghaddas Tafreshi [6] studied the behavior of buried pipes under cyclic loading conditions experimentally; a physical model of the buried pipe trench condition was developed. The steel flexible model pipes were placed inside a soil trench of medium silica sand. The trench was prepared by the raining technique at three different relative densities inside the testing tank. The depth of the pipes in the trench was changed, and cyclic loads with different amplitudes were applied to the trench surface centrally and eccentrically. From the experimental investigation, the deflection and the failure condition were determined.

Neelam and Vipulanandan [7] investigated the behavior of flexible PVC pipes with sand and controlled low-strength materials (CLSM) as backfill materials in the soil box. Pipe deflections were compared against the modified Iowa formula, and an appropriate modification factor was introduced in the modified Iowa formula to better represent the test data.

Babu et al. [8] presented a critical appraisal of the mechanical behavior of buried flexible pipes and proposed a design methodology for the prediction of the performance of buried flexible pipes using finite element analysis for simple loading and boundary conditions.

Suleiman et al. [9] modeled the pipe-soil system using ANSYS. Small and larger deflection theories of ANSYS were used in the analysis, and the results were compared with CANDE, one of the most commonly used programs for buried pipe analysis, and found to be satisfactory.

Zhan and Rajani [10] carried out a non-linear finite element analysis to assess the effects of different trench backfill materials, pipe burial depths, and pipe materials on the amount of traffic load transferred to buried pipe and found that the results were in good agreement with those obtained from field truck load tests.

4 Materials

4.1 M-sand

The M-sand as shown in Figure 2 used for this particular project is homogenous in nature. The sand is made to attain a density of around 18 kN/m^3 by means of controlled tamping using a plunger for preparing the dense sand bed. The sand above the bedding is of ordinary loose density, around 13.5 kN/m^3 and the properties of used M-Sand are given in Table 1.

Figure 2. M-Sand

Table 1. Properties of M-sand

Parameter	Value
Density of dense bed (kN/m^3)	18.036
Density of loose backfill (kN/m^3)	13.5
Specific gravity [11]	2.730
Angle of internal friction [12]	29.89º

4.2 HDPE Pipe:

HDPE pipes of 200 mm outer diameter and 6 mm thickness as shown in Figure 3, were used in the study. The pipes used conform to the Indian standard IS 14333 (1996) [11] and are characterized by a black color. The specifications of the pipe are listed below in Table 2.

Figure 3. HDPE pipe

Table 2. Properties of HDPE pipes

Properties	**Values**
Diameter	200.00 mm
Young's modulus	800.00 MPa
Thickness	6.00 mm
Moment of inertia	18.00 mm^3
D/T ratio	33.33
EI	14400.00 N.mm

4.3 Geogrid

The geogrid, as shown in Figure 4, is used to effectively reduce the stress on the pipes. These geogrids are black in color. The properties of the geogrid obtained from the manufacturer are listed below in Table 3.

Figure 4. Geogrid

Table 3. Properties of geogrid

Properties	Values
Ultimate tensile strength	30 kN/m
Aperture dimension	40 mm
Rib thickness	1.5 mm
Rib width	2.3 mm
Junction efficiency	95%
Resistance to UV degradation	100%

4.4 Specially fabricated tank

The steel tank of dimension 600 mm x 800 mm x 1200 mm shown in Figure 5 was fabricated with side plates consisting of holes of diameter 200mm with suitable tolerance for the pipe to fit. The steel tank is fabricated with a manual loading arrangement that produces a uniform load on the soil, which is dispersed to the pipe, which in turn gives the deflection reading.


Figure 5. Front and side view of tank

Figure 6. Proving Ring

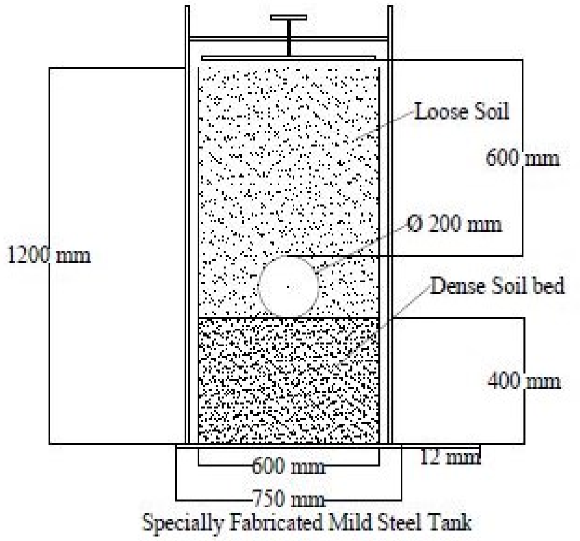

Figure 7. Line diagram of steel tank

4.5 Dial Gauge

The dial gauges are used to record the amount of deflection which are placed both in crown and spring line direction at 300 mm from the center on either side.

4.6 Proving Ring

The proving arrangement shown in Figure 6 is facilitated to find the amount of load applied on the soil.

The line diagram of the proposed steel tank with appropriate dimensions to be specially fabricated, used as a reference in the fabrication process is shown below in Figure 7.

5 Experimental Procedure

The basic concept behind the experiment involves measuring the deflection values of the pipe for different loads in the presence and absence of geogrids. The sequence and process to be followed are explained below:

- The steel tank with loading arrangement and the pipe hole were fabricated. The dimensions of the tank are 600 mm x 800 mm x 1200 mm.
- A dense bed with M-Sand was prepared up to 400 mm (the height of the fixed plates), and thereby the bulk density was maintained to a dense level by suitable compaction.
- The HDPE pipe of diameter 200 mm was fitted with two dial gauges, one for the crown deflection and the other for the springing line deflection.

- The HDPE pipe was inserted through the sand test tank through the plates with the hole.
- The loose backfill was prepared by pouring M-Sand by raining technique into the tank without any alterations. This backfill was prepared up to the height of the hollow plates.
- The deflection in the crown was recorded for every increment of 15 kg of load above the crown level of the HDPE pipe.
- The side plates were then placed, and the loose backfill was filled simultaneously, taking the readings of deflection for the corresponding sand load. Thus, values for the plot load vs. deflection graph for the self-weight condition were obtained.
- The tension-proving ring, along with the magnetic base, was attached to the loading frame in order to determine the load corresponding to the downward movement of the loading plate.
- The lever arm was rotated to provide loading for the loose bed. As the lever turned, the loading plate moved downwards by a thread rod mechanism, and loading was applied to the loose backfill.
- The load value was determined from the proving ring dial gauge, and the deflection value both for the springing line and the crown was determined using the deflection dial gauge.
- The values were tabulated in order to obtain the load vs. deflection graph without a geogrid reinforcement case.
- The same procedure was repeated after placing the geogrid, and the deflection readings were observed for the reinforcement case as well.
- The values are tabulated, and graphical results are plotted.
- The experimental values were correlated with the theoretical reviews, and thereby a comparison study was obtained.

6 Preparation of a dense bed

- The sand was filled in layers and compacted using the rammers to a depth of 400 mm, as shown in figure 8.
- The density of the dense bed is maintained within the range of 17 kN/m^3 to 20 kN/m^3.

Figure 8. Compacted a dense M-Sand bed

Observation:

Volume of sand used = 0.192 m^3

Mass of the sand = 353 kg

Achieved density $= \frac{353 *10^{-3}*9.81}{0.192}$ = 18.036 kN/m^3

7 Preparation of loose backfill

The sand was filled in a loose condition using the raining technique to a depth of 800 mm, including the pipe material, as shown in Figure 9.

The density of the loose soil is maintained within the range of 12 kN/m^3 to 15 kN/m^3

Observation:

Volume of sand = 0.359 m^3

Mass of sand = 495 kg

Achieved density $= \frac{495 *10^{-3}*9.81}{0.359}$ = 13.5 kN/m

Figure 9. Filling of loose M-Sand bed

8 Orientation of HDPE pipe

The geogrid is placed in a parabolic shape above the circumference of the pipe, extending along the spring line as shown in Figure 10.

This orientation of the geogrid facilitates the pipe´s ability to transfer the load along the spring line and increases its ability to resist deflection.

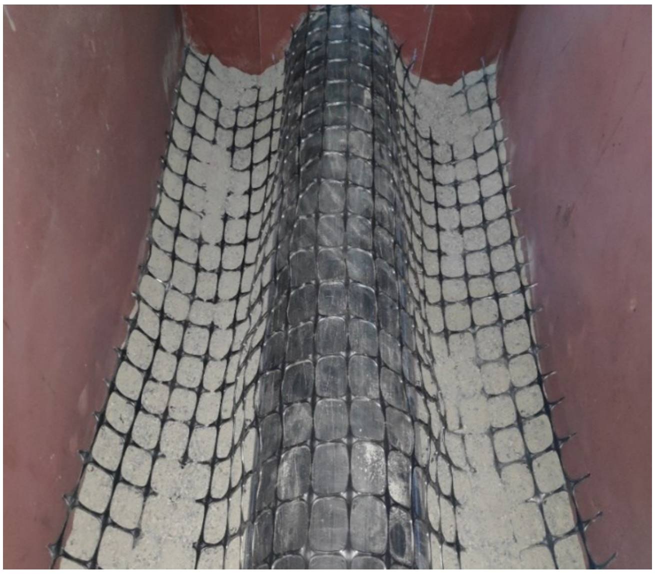

Figure 10. Orientation and placement of geo-grid over HDPE Pipe

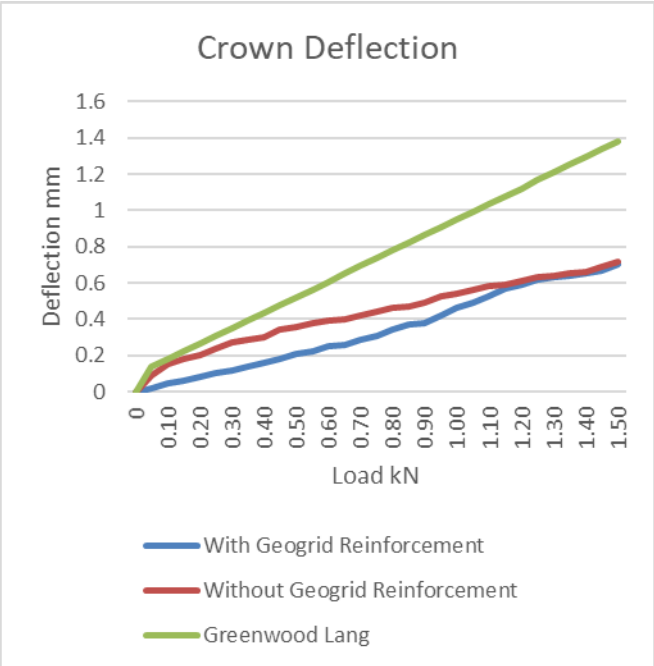

Figure 11. Load vs Crown Deflection Comparison

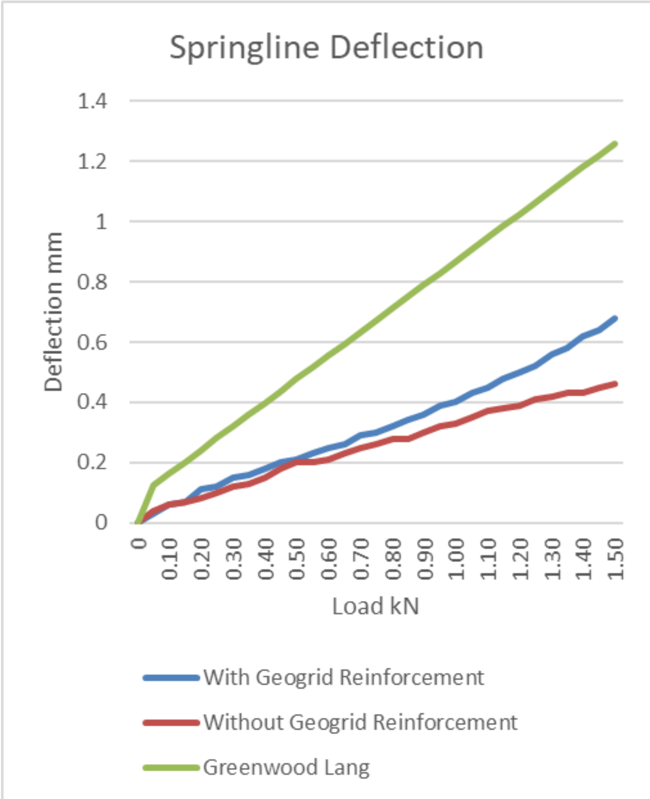

Figure 12. Load vs spring line deflection comparison

9 Results and discussion

- The deflections obtained at the crown and spring lines of the pipe with and without the presence of geogrid reinforcement are presented graphically in figures 11 and 12, respectively, and the following results are discussed.
- The deflection on the pipe due to the filling of M-sand up to the crown of the pipe was found to be insignificant, and therefore, the values were neglected.
- The M-sand was filled above the crown level of the pipe in increasing amounts of 15 kg, the deflection readings were recorded for each increment of sand filling.
- In the case of pipe without geogrid reinforcement, the deflection due to self-weight was found to be 1.18 mm.
- In the case of pipe with geogrid reinforcement, the deflection due to self-weight was found to be 0.50 mm.
- In the case of pipe without geogrid reinforcement, the applied uniform load of 1.50 kN yielded a crown deflection of 0.72 mm and a spring-line deflection of 0.46 mm.
- In the case of pipe with geogrid reinforcement, the applied uniform load of 1.50 kN yielded a crown deflection of 0.70 mm and a spring-line deflection of 0.68 mm.
- The load-versus-deflection characteristics of the HDPE pipe were computed using the theoretical equation derived by Greenwood and Lang.
- In the case of theoretical computation, the application of a uniform load of 1.50 kN yielded a crown deflection of 1.38 mm and a spring-line deflection of 1.26 mm.

10 Conclusion

- The introduction of Geogrid Reinforcement exhibited an improvement in the characteristics of HDPE pipe in loose M-sand backfill, i.e., the deflection due to the load imposed by the self-weight of M-sand applied to the pipe was considerably reduced by 0.68 mm, i.e., a 58 % decrease.
- Similarly, the crown deflection due to the application of a uniform load was reduced by 35 % due to the introduction of Geogrid reinforcement.
- The spring line deflection characteristics did not show satisfactory behavior, which suggests that this specific orientation of geogrid reinforcement is not suitable for reducing of spring-line deflection.
- The Greenwood and Lang theoretical computation of the load vs deflection characteristics of HDPE pipe in loose M-sand backfill under uniform load overestimates the experimental findings.
- Therefore, the results suggest that this orientation of geogrid reinforcement is best suited for reducing the crown deflection of HDPE pipe in loose M-sand backfill under uniform loading and self-weight.

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