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Numerical Modeling of Long-Term Performance of Buried Pipes

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ABSTRACT: Flexible pipes such as high density polyethylene (HDPE) and polyvinyl chloride (PVC) pipes deflect under load. In this study, the long-term performance of HDPE and PVC pipes were investigated by using the finite element method. The influence of trench width and creep properties of pipe materials on the pipe performance was investigated for 50 years under different pipe backfill conditions. Fill heights up to 15 m were considered. Controlled low strength material (CLSM) and granular stone were used as pipe backfill materials. Modeling results show that both HDPE and PVC pipes can be buried up to 15 m without any failure when CLSM is used. However, certain sizes of HDPE pipes fail at a depth of 15 m under some circumstances when granular stone was used. Trench widths as low as 1.5 times the pipe diameter can be used without causing failure in most of the pipes considered.

1 INTRODUCTION

1.1 *Background of buried pipes*

Buried pipes are used in various applications, such as highway drainage and sewerage systems. Flexible pipes, such as high density polyethylene (HDPE) and polyvinyl chloride (PVC), deflect under external load (Moser, 1990). Fig. 1 shows a typical cross-section of a buried pipe. When pipes deflect, the horizontal diameter of the pipe increases and compresses the soil laterally so that passive resistance of the soil is mobilized to support applied loads. A buried pipe is a composite system consisting of a ring surrounded by a soil envelope. Therefore, the performance of the buried pipe depends on the soil-pipe interaction (Gassman et al, 2005).

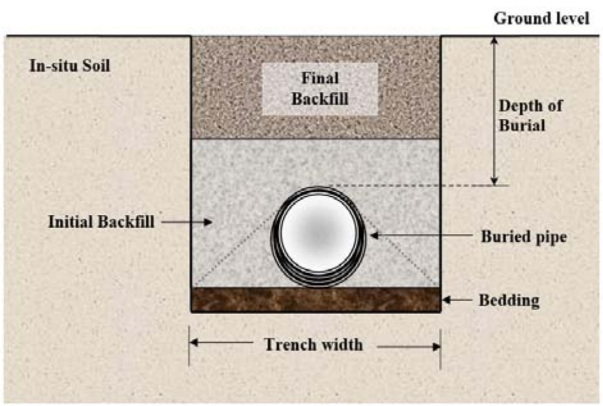


Fig. 1 Schematic diagram of a buried pipe

1.2 *Factors affecting pipe performance*

Various pipe materials with enhanced pipe profiles and backfill materials are being used to improve the durability and serviceability of buried pipes. The deformation of a buried pipe is a function of loads (dead and live loads), pipe geometry, and material properties of both the pipe and soil. The loads acting on the buried pipe vary with the depth of burial and the type of backfill soil. The characteristics of the soil surrounding the pipe influence the structural performance of the pipe.

Time dependent properties like creep are normally associated with thermoplastic pipes, such as HDPE and PVC pipes, which become more critical in evaluation of long-term performance. Creep results in continuous deformation in the pipe when subjected to a constant mechanical load, resulting in the failure of pipe over time. The rate of deformation or failure in a pipe can be a function of exposed time, applied loading, or the environmental conditions. Depending on the applied loading and its duration, the deformation in the pipe may become so large that the pipe can no longer perform its intended function. It is also important to select appropriate materials for trench and pipe backfill soils based on the application.

1.3 *Problem Statement*

In this paper, the long-term performance of double wall corrugated HDPE and solid wall PVC pipes was investigated by using the finite element method. Fig. 2 shows a schematic diagram of a double wall corrugated pipe. In order to evaluate the performance of buried pipes over a long period of time, it is necessary to consider the time dependent properties (creep properties) of pipe materials. The trench width is larger than the pipe diameter, and the trench width ratio is defined as the ratio of trench width to nominal pipe diameter. The influence of trench width and creep properties of pipe materials on the performance of HDPE and PVC pipes was investigated for a time period of 50 years under different loading conditions (dead and live loads).The performance of HDPE and PVC pipes under fill heights ranging from 1 m (3 feet) to 15 m (50 feet), and trench width ratios varying from 1.5 to 2.5 have been analyzed. Three soil types with different properties were considered: trench backfill, pipe backfill, and insitu soil (as shown in Fig. 1). Also, controlled low strength material (CLSM) and granular stone were used as pipe backfill materials. A 5% change in vertical pipe deflection was considered as failure. Failure due to pipe strength was not considered in this study.

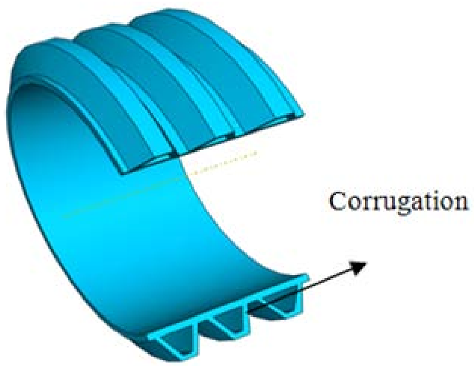


Fig. 2 Double-wall corrugated HDPE pipe

2 METHODOLOGY

2.1 *Background of creep models*

Time dependent elastic modulus, E(t), is one of the important parameters required to model the creep behavior of buried pipes. Power law models can be used to express the elastic modulus as a function of time, as reported in previous studies (Hashash, 1991; Janson, 1995). Such power law models can be obtained from laboratory data by performing stress relaxation tests on pipes. Laboratory measurements related to such stress relaxation tests of HDPE and PVC pipes can be found elsewhere (Hashash, 1991; Janson, 1995). Power law models related to the HDPE and PVC pipe material used in this study are presented in the following sections.

2.2 *Power law model for HDPE pipes*

In the current study, the power law model for HDPE pipe was obtained from laboratory creep data on HDPE pipes (Hashash, 1991). The power law form proposed based on this data is a conservative model to describe the creep behavior of HDPE pipes as it predicts lower values of elastic modulus (i.e., higher displacements) when compared to other creep models for HDPE pipes (Janson, 1985; Chua, 1986). This model can be expressed as (Hashash, 1991):

$$E(t) = 467\,t^{-0.0859} \quad (1)$$

Where E(t) is given in MPa and t is measured in hours. This equation can also be written as:

$$E(t) = 67{,}779\,t^{-0.0859} \quad (2)$$

Where E(t) is given in psi and t is measured in hours.

2.3 *Power law model for PVC pipes*

A power law model was developed for PVC pipes based on stress relaxation data available in the literature (Janson, 1995). This model can be expressed as (Janson, 1995):

$$E(t) = 2{,}716.8\,t^{-0.0859} \quad (3)$$

Where E(t) is given in MPa and t is measured in hours. This equation can also be written as:

$$E(t) = 3{,}904{,}043\,t^{-0.05679} \quad (4)$$

Where E(t) is given in psi and t is measured in hours.

3 TRANSIENT ANALYSES FOR CREEP

3.1 *Finite element modeling*

Two-dimensional transient analyses were performed for a time period of 50 years by using the finite element method to investigate the creep behavior of plastic pipes. A commercially available finite element software was used in the modeling work (ABAQUS, 2007). In general, the power law is described in terms of creep strain rate, which is a function of deviatoric stress (σ) and time (t). This general equation for the time–hardening behavior can beexpressed as (ABAQUS, 2007)

$$\dot{\varepsilon}^{cr} = A\sigma^m t^n \quad (5)$$

Where $\dot{\varepsilon}^{cr}$ is the creep strain rate, A is a constant that determines the overall creep deformation, n is an exponent related to creep rate, and m is a constant that determines how the deviatoric stress influence the creep strain rate.

3.2 *Model geometry*

In order to investigate the creep behavior of plastic pipes, the pipe was modeled by using beam elements and the soil was modeled by using plane strain elements. A structured meshing technique with quadrilateral element shapes was used to mesh the soil geometry. Four-node bilinear plane strain quadrilateral elements were used for the soil and two-node linear beam elements (B21) were used to model the geometry of the pipe.

3.3 *Boundary and loading conditions*

A combination of the HS-25 loading at the ground surface (live load) along with the self-weight of the soil (dead load) was used. The magnitude of an HS-25 loading was taken as 689.5 kPa (100 psi) applied on a rectangular area of 0.5 m (20 in) x 0.25 m (10 in) at the ground surface. Fig. 3 shows the finite element mesh with loading and boundary conditions used in this modeling study.

3.4 *Material properties*

Different soil properties were selected for the pipe backfill, trench backfill, and in-situ soil. The properties of soil and the pipes used in the study are presented in Table 1 and Table 2, respectively. Table 3 shows the creep parameters of the two pipe materials corresponding to the power law models used in the current study.

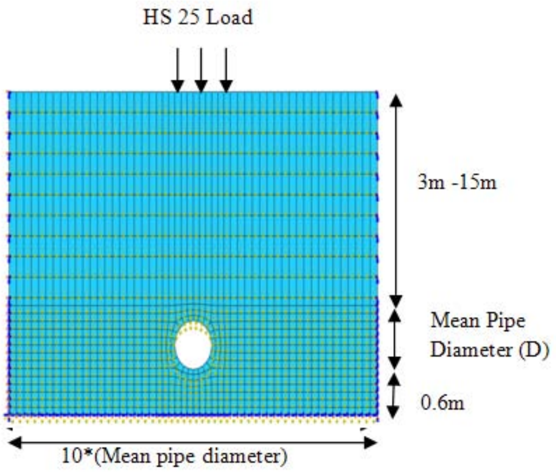


Fig. 3 Loading and boundary conditions

4 MODELING RESULTS

4.1 *Long-term pipe deflections*

The pipe deflections were computed by taking the difference between the magnitudes of vertical displacement at the crown and base of the pipe. Fig. 4 shows the distribution of vertical displacements for a typical HDPE pipe due to HS-25 loading and self-weight of the soil.

Table 1. Soil properties

Material	Elastic Modulus (kPa)	(psi)	Poisson's ratio
Insitu soil	8,273	1,200	0.3
Trench Backfill	13,789	2,000	0.3
Pipe Backfill	20,684	3,000	0.3

Table 2. Pipe properties

Material	Elastic Modulus (kPa)	(psi)	Poisson's ratio
HDPE	758,423	110,000	0.46
PVC	2,757,902	400,000	0.41

Table 3. Creep parameters

Material	A	n	m
HDPE	1.2735×10^{-6}	1	-0.9141
PVC	1.4396×10^{-7}	1	-0.9433

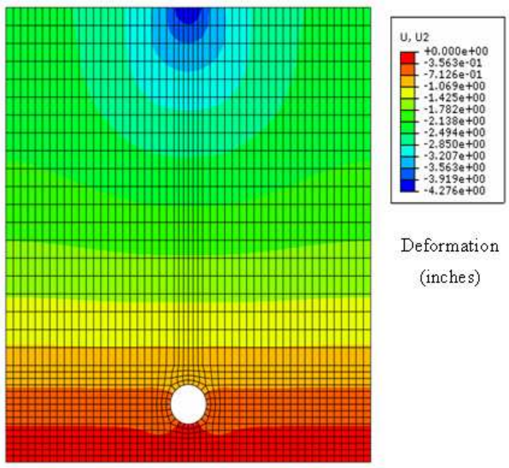
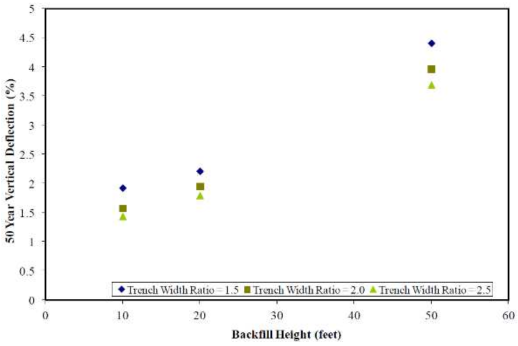
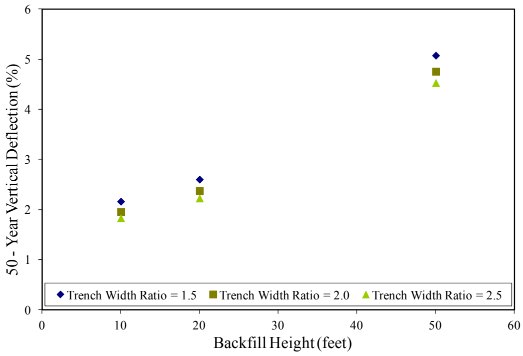


Fig. 4 Displacements due to HS-25 loading and self-weight of the soil

Fig. 5 shows the influence of trench width ratio on the long-term vertical pipe deflections for a 1.50 m (60-inch) HDPE pipe under CLSM and granular stone backfill. Modeling results show that pipe deflections decreased with an increase in trench width ratio from 1.5 to 2.5. Results also show that a 1.50 m (60-inch) corrugated HDPE pipe can be installed up to a depth of 6 m (20 feet) with the trench width ratio as small as 1.5 without causing failure. Computed pipe deflections appear to be larger when granular stone was used as pipe backfill.



(a) with CLSM as pipe backfill



(b) with granular stone as pipe backfill

Fig. 5 Influence of trench width ratio on vertical deflections of a 1.50 m (60 inch) HDPE pipe

Fig. 6 shows the influence of trench width ratio on the long-term pipe deflections for a 0.6 m (24-inch) PVC pipe under granular stone backfill. Modeling results show that a 0.6 m (24-inch) PVC pipe can be installed up to a depth of 15 m (50 feet) with the trench width ratio as small as 1.5 without causing pipe failure.

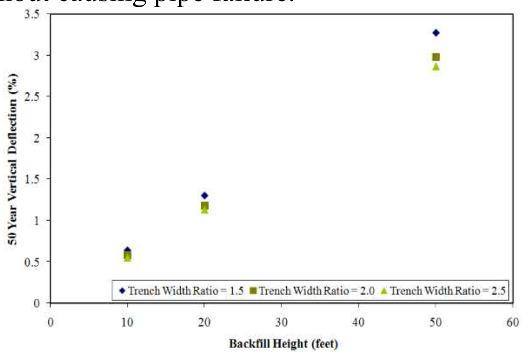


Fig. 6 Influence of trench width ratio on vertical deflections of a 0.6 m (24 inch) PVC pipe

To validate the model, an alternative approach was used since measured field or laboratory data over long-term performance of buried pipes is not available in the published literature. As an alternative to a comprehensive creep analysis, finite element modeling was performed using a reduced elastic modulus to simulate long-term pipe degradation. Reduced moduli of 151,684 kPa (22,000 psi) and 965,266 kPa (140,000 psi) were used for HDPE and PVC pipes, respectively. These reduced modulii values were consistent with those reported elsewhere (AASHTO, 2007). The results obtained from such simplified analyses show similar results to those obtained from comprehensive analyses.

5 CONCLUSIONS

The influence of trench width and creep properties of pipe materials on the performance of HDPE and PVC pipes was investigated for a time period of 50 years under different backfill materials. In this study, only the pipe deflections were considered. Fill heights up to 15 m (50 feet) were analyzed. Trench width ratios were varied from 1.5 to 2.5. Modeling results show that pipe deflections decreased with an increase in trench width ratio from 1.5 to 2.5. Also, computed pipe deflections showed larger pipe deflections when granular stone was used as pipe backfill. Based only on deformation consideration for pipe failure, both HDPE and PVC pipes can be buried up to 15 m (50 feet) without any failure when CLSM is used as a pipe backfill. However, when granular stone was used as a pipe backfill, modeling results show that certain sizes of HDPE pipes fail at a depth of 15 m (50 feet) under the combination of live and dead loads for a trench width ratio of 1.5.

ACKNOWLEDGMENTS

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