Structural Deformation Characteristics of Installed HDPE Circular Pipelines

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Abstract: This study presents a survey of deformation characteristics of the installed high-density polyethylene (HDPE) pipelines. Video and laser inspections are carried out on over 15,000 ft (4,572 m) of buried HDPE pipelines installed across the nation. Different types of deformation failure modes observed in the buried HDPE pipelines are identified in this paper. The results show that the majority of buried HDPE pipelines have deformations in excess of the commonly acceptable limits along multiple locations within each pipeline.

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Introduction

High-density polyethylene (HDPE) pipes are currently used as underground conduits in municipal, transportation, and environmental applications (Mruk 1988). HDPE pipes have the advantage of being lighter in weight and more flexible in their deformation behavior which prevents brittle fractures and cracks when subjected to extensive soil loads. Another main advantage of plastic pipes is their excellent resistance to corrosion and erosion. Despite their aforementioned advantages, plastic pipes generally suffer from large deformations due to their flexibility, particularly, in long time spans (Farshad 2006). This accumulative deformation is due to the stress relaxation inherent in viscoelastic materials (Haddad 2000). The large deformation caused by typical soil loads is considered excessive when it exceeds certain specified limits set by standards (AASHTO 2008). For the case of sewage applications the change in shape and diameter of the pipe changes the assumptions made in hydraulic design of the system such as Manning coefficient. This problem is amplified considering the effect of corrugation growth of these materials which alters the inner surface of the pipelines and hence again the hydraulic design assumptions.

Contrary to their wide range of applications, the structural health of plastic pipelines and especially profiled corrugated pipelines is not yet well accepted among researchers and industry contributors (Trudy 1999). Although there have been many studies to evaluate the behavior of buried HDPE pipelines, the number of reported studies on the deformation characteristics of the installed HDPE pipes are limited.

A pipe deflection criterion was first developed by Spangler (1941), and has remained a dominant part of buried pipe design for decades. Moore et al. (1988) studied the buckling strength of buried flexible culverts. Ayche (2005) studied the effect of profile geometry on performance of HDPE pipelines. Moore (1995) studied the response of profiled plastic pipes under various burial conditions. Zhang and Moor (1998) also have investigated the nonlinear behavior of thermoplastic pipes using different proposed constitutive models in nonlinear finite element method formulation.

There have also been some field test experiments available in the literature. Gassman et al. (2005) studied the effect of installation procedures on the field performance of existing HDPE pipes used for drainage applications on highway projects. The results of this study showed that the installation problems such as poor preparation of bedding soils, inappropriate backfill material, and inadequate backfill cover contributed to the excessive deformation and observed internal cracking in pipes. Sargand et al. (2005) studied the field performance of large-diameter HDPE pipes including the deformation behavior of pipelines under deep soil fill. Madasamy et al. (2006), performed full-scale field tests on flexible pipes under live load applications. The field test results indicated that buried flexible pipes, embedded with highly compacted graded sand with silt, demonstrated good performance without exhibiting any visible joint opening or structural distress.

This study is a part of a major initiation on health monitoring of underground structures in which a new state-of-the-art laser profiler is being employed (http://www.cuesinc.com/Laser-Profiler.html). Ninety-six installed HDPE pipelines with different diameters and lengths were selected randomly throughout five diverse states within the United States. Different modes of structural failure were distinguished and analyzed both qualitatively and quantitatively throughout the study.

The objective of this study is to present the deformation characteristics of HDPE culverts to show that the future research in the health monitoring of the installed underground structures needs to be at the forefronts of federal and state agencies' agenda. This paper does not intend to imply that the HDPE culverts are to be rejected.

The framework of the study was divided into two steps: the first step was devoted to qualitative inspection of the pipelines, which contained detailed video inspections using the CUES OZ II

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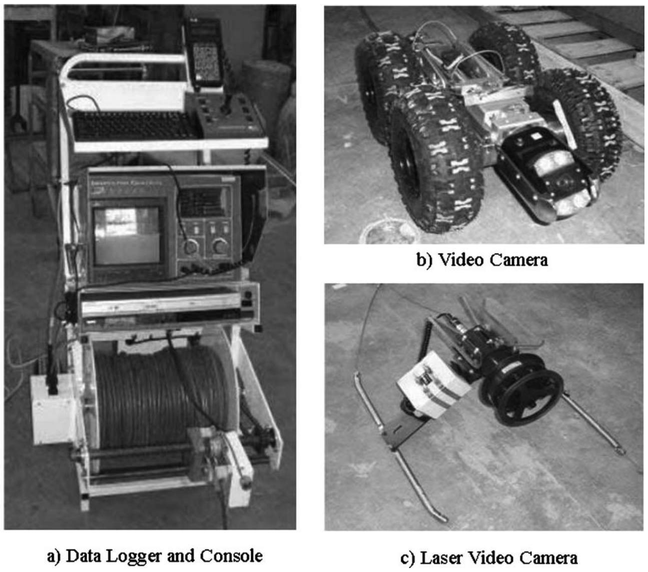

Fig. 1. Different instruments used in pipeline inspections: (a) CUES inspector general instrumentation console; (b) CUES rover with OZII pan/tilt/zoom camera module (P/N CZ902); and (c) 10-head laser ring and skid

high-intensity lighting inspection camera (http://www.cuesinc.com/Laser-Profiler.html). In this step, different failures were observed and recorded accordingly (Abolmaali and Motahari 2007). The view of the implemented video camera is shown in Fig. 1(b).

The second step was devoted to quantitative evaluation of the behavior of the pipelines. In this step the deformed shape profile of the pipelines is calculated along their lengths. The percentage of deformation of each pipeline is calculated by using the data obtained from the laser profiling unit shown in Figs. 1(a and c). In this technique, a laser ring light is projected on the inside surface of the pipe perpendicular to the longitudinal axis of the pipeline (Fig. 2). The laser profiling unit was placed at the far end of the pipeline and was pulled back toward the beginning of the pipeline. Light was not allowed in the pipe to maximize the clarity of the ring. The acquired results were then processed by using special Profiler software (http://www.cuesinc.com/Laser-Profiler.html) provided with the laser profiling unit. A typical view of the Profiler software showing the deformed and undeformed shapes and the acquired deformation graph are shown in Fig. 3.

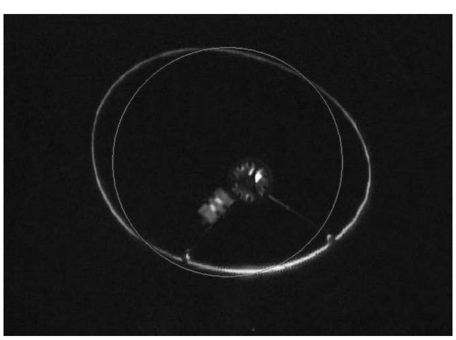

Fig. 2. Example view of laser ring on deformed surface of a pipeline compared to the original undeformed shape of the pipeline section

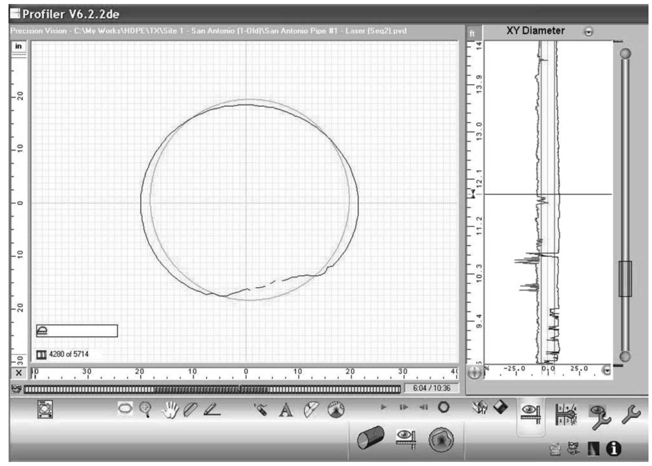

Fig. 3. View of the Profile software used for analyzing the pipeline deformation graphs showing the original undeformed shape of the pipeline section surface and the captured deformed shape of the section on the left side of the figure and deformation graph on the right side of the figure

This paper reports on the deformation characteristics of the HDPE pipelines with different diameters. Excessive deformation is defined as the flattening or change in diameter of the pipe. The change in the pipe's diameter in horizontal and vertical directions, or the respective X and Y deformations of the pipeline, is calculated as a percentage variance from the expected internal diameter. Crown flattening and racking are other cases of excessive deformation described. The common limit of 5% is adopted for indicating excessive deformation (AASHTO 2008).

Classification of Deformation Types

Based on different loading conditions and severity of the loading, different types of deformation behaviors are observed in pipelines. These deformation behaviors are categorized as follows and are depicted in Figs. 4 and 5.

Symmetrical Deformation along Horizontal (X) Axis

This is the most common case which happens when symmetrical vertical loads are transmitted to the pipeline from the backfill soil above them and the deformation of the pipe occurs in a way to cause elongation of diameter along horizontal (X) axis [Figs. 4(a) and 5(a)].

Symmetrical Deformation along Vertical (Y) Axis

In cases where soil is compacted at the sides of the pipe, the pressures transmitted to the surface of the pipes from the horizontal direction cause the pipeline to deform in a way that elongation occurs along vertical (Y) axis [Figs. 4(b) and 5(b)].

Ovality (Racking) Deformation

Typically, the maximum deformation of a given pipeline section occurs in the X or Y diameter, however, the pipeline may deform in a skew manner (racking behavior), so as to have the maximum deformation in the diagonal direction of the pipe [refer to Figs. 4(c) and 5(c)]. In such a case, the maximum deformation is cap-

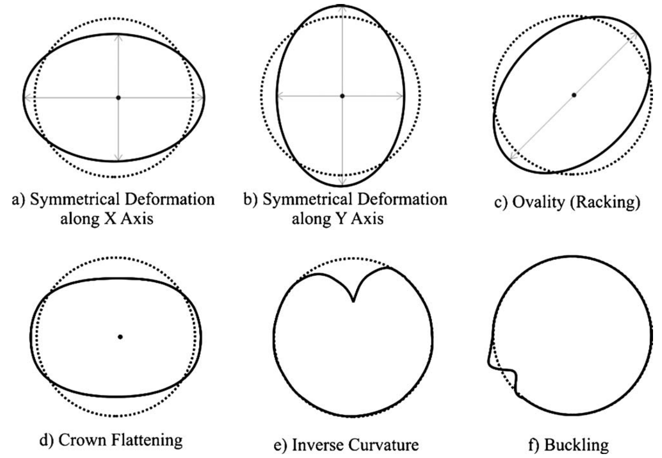

Fig. 4. Different types of observed deformation types (schematic view)

tured only by the ovality graphs. Thus, the maximum of X and Y deformations and the ovality of the pipe are considered as the maximum deformation of the pipeline in this study.

The ovality shows how oval or "out of round" a pipe's cross section has become due to deformation. This is displayed as a positive percentage, and the 0% represents a perfectly round pipe. The formula is based upon the ASTM F1216 (ASTM 2008)

$$\text{Ovality} = 100 \times \frac{\text{Maximum inside diameter} - \text{Mean inside diameter}}{\text{Mean inside diameter}}$$

For obtaining the mean inside diameter, the actual diameters are calculated over 90 different directions at each section.

Crown Flattening

There are special cases due to the type of loading and the type and compaction of backfill soil in which the deformed shape does not deform in an elliptical shape and the crown of the section flattens and deflects downward [Figs. 4(d) and 5(d)].

Buckling

Buckling mode is defined as the out-of-plane deformation due to large circumferential stresses which causes longitudinal and/or radial waves on the surface of the pipe [Figs. 4(e) and 5(e)].

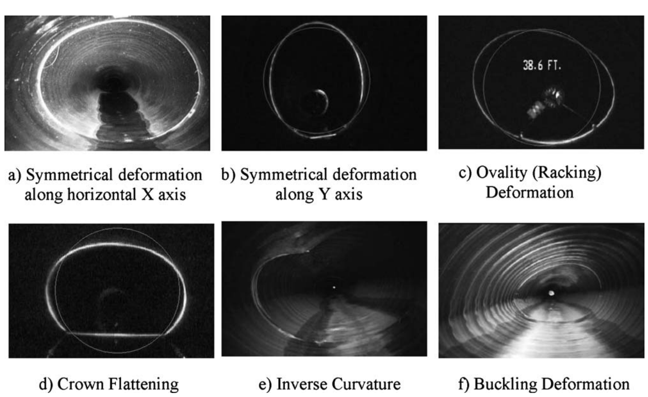

Fig. 5. Different types of observed deformation types (real examples)

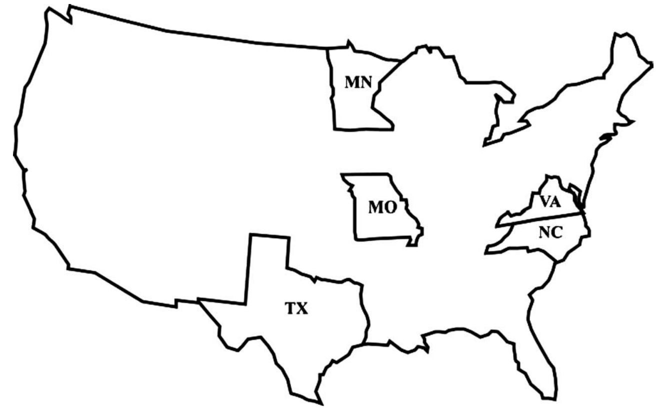

Fig. 6. Schematic view of pipeline inspection site locations

Inverse Curvature (Snap Through)

Inverse curvature (snap through) is a loss of stability phenomenon which creates inverse curvature by deforming into reversed shapes by undergoing tensile instead of compressive deformation. This deformation type is known as the inward projection and bulging of the surface of a pipe surface due to the external pressure on the pipe [Figs. 4(f) and 5(f)].

Deformation Analysis Results and Discussions

In this section statistical results of all pipelines inspected are summarized and discussed briefly, and examples of the complete deformation analysis of pipelines along their length are presented in detail.

Statistical Study

A total of 96 pipelines were investigated in five different states to cover a wide range of geographical data. Pipelines varied in di-

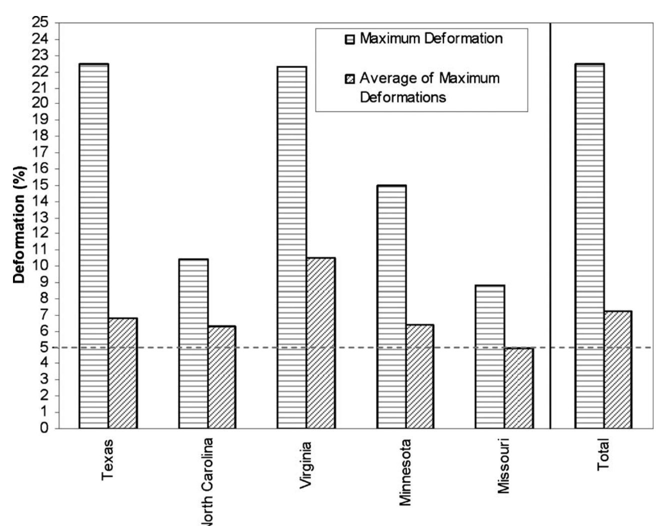

Fig. 7. Maximum and average values for maximum deformations of pipelines inspected in each state and the average and maximum of the total pipes inspected

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Table 1. Information of Inspected Sites and Pipelines at Each State

		Texas	North Carolina	Virginia	Minnesota	Missouri	Total
Number of site locations		9	6	8	9	4	36
Number of pipelines		22	11	21	31	13	98
Total length of the pipelines	(ft)	2,800	600	3,000	7,600	1,400	15,400
	(m)	853	183	914	2,316	427	4,694
Maximum deformation (%)		22.5	10.4	22.3	15	8.8	22.5
Average of maximum deformation (%)		6.8	6.3	10.5	6.4	5	7.2
Percentage of pipelines with excessive deformation (>5%)		38%	75%	100%	53%	56%	63%

ameter (15–60 in.; 38.1–152.4 cm) and length (50–440 ft; 15.24–134.1 m). Fig. 6 shows a schematic view of inspection site locations.

Table 1 shows the information with regard to the number of pipelines and the site locations inspected in each state and reports the maximum and average values of the maximum deformations observed along the pipelines. The results are also shown in Fig. 7 in clustered column format for ease of comparison. The results show that deformation of more than the accepted 5% limit are observed in pipelines in all states and the average of the maximum deformation over all pipelines in each state is equal to or more than 5%. The percentage of pipelines with excessive deformations varies between 38 and 100% among the states, and an average percentage of 63% is calculated for the pipelines with excessive deformation in all states.

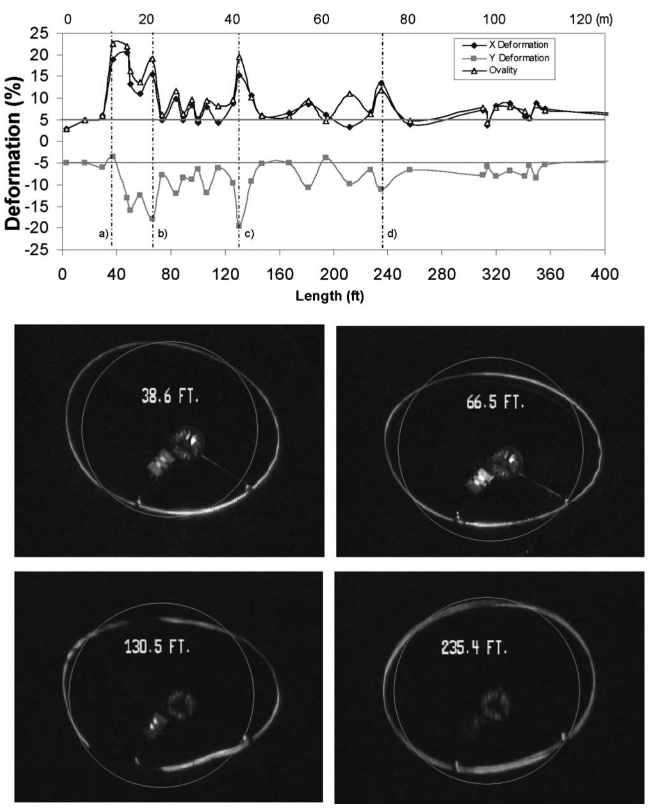

Fig. 8. Vertical, horizontal, and ovality deformations along the length of a pipeline and corresponding views of sections showing the laser ring on deformed shape of the section compared with the original undeformed ring for a 36 in. (91.44 cm) pipeline

Deformation Analysis

In this section one example of the analysis results for each state is reported. The first case is a 36 in. (91.44 cm) drain pipeline with a length of approximately 400 ft (121.92 m) located in the state of Texas. The results of the analysis are shown in Fig. 8 with a graph of the horizontal, vertical, and ovality deformations along the length of the pipeline and the corresponding views of specified sections showing the laser ring on the deformed shape of the section compared with the original undeformed shape. As it is shown in this figure, different types of deformation are observed along the length of the pipeline. Sections B and D show the most common behavior of symmetrical deformation along the x axis. Section A shows racking or ovality-type deformation while Section C shows a completely disordered unsymmetrical large deformation along with fracture of the surface of the pipeline.

The next example is a 36 in. (91.44 cm) drain pipeline with a length of about 180 ft (54.86 m) in the state of Virginia. The results of the analysis of this pipeline is shown in Fig. 9 which shows the vertical, horizontal, and ovality deformations along the length of the pipeline and includes a view of the laser ring on the deformed shape of the specified section compared with the origi-

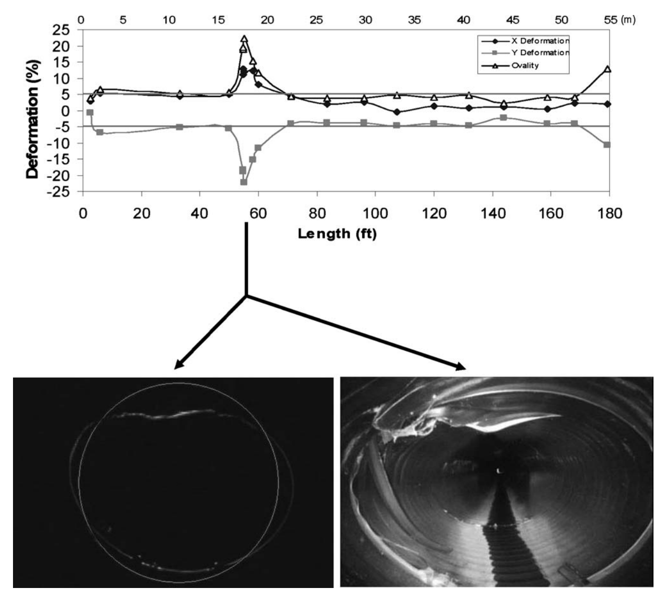

Fig. 9. Vertical, horizontal, and ovality deformations along the length of a 36 in. (91.44 cm) pipeline showing the laser ring on deformed shape of the section compared with the original undeformed ring and snapshot of the section showing the maximum deformation along the length of the pipeline

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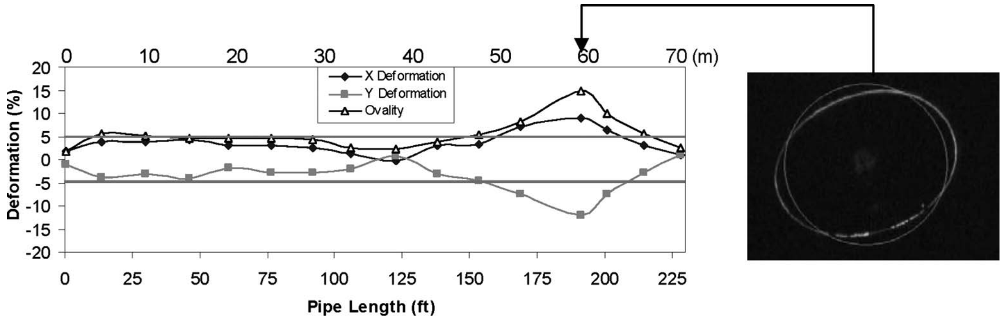
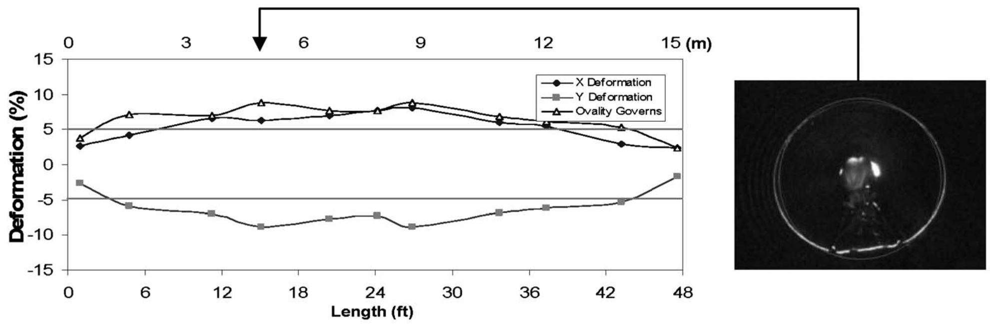
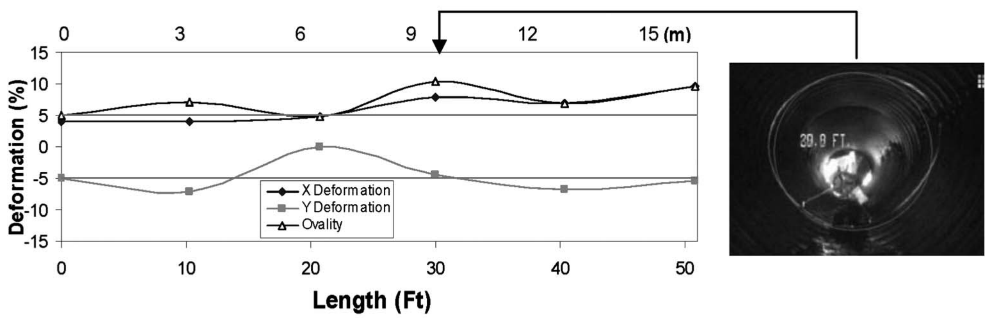


a) Minnesota



b) Missouri



c) North Carolina

Fig. 10. Vertical, horizontal, and ovality deformations along the length of pipelines in different states and corresponding views of sections showing the laser ring profile on the deformed shape of the section compared with the original undeformed ring

nal undeformed ring and a snapshot of the same section at the point of maximum deformation along the length of the pipe. As shown in this figure, unlike in the previous case, the large deformation occurs at a specific range of the pipe length, and other sections of the pipeline show relatively low or average deformations. This is due to failure at a joint between two different sections due to malfunction of the joint detail. Three other examples from the states of Minnesota, Missouri, and North Carolina are also depicted in Fig. 10.

Summary and Conclusions

Deformation characteristics of the HDPE pipelines are studied by analyzing the data from the laser video inspection of 96 pipelines in five states, namely, Texas, Minnesota, Missouri, Virginia, and North Carolina. A wide range of deformation types were observed, from the more common moderate symmetrical deformation to harsh and unsymmetrical deformation. Cases of buckling and inverse curvature deformations were also observed in some pipelines in the investigation. The statistical data extracted from the results of inspection revealed that 63% of pipelines experienced excessive deformation in excess of the AASHTO (2008) specified 5% limit. The maximum deformation of pipelines in each state, along with their average maximum deformation, is reported. The maximum and the average maximum of all the pipelines inspected are shown to be 22.5 and 7.2%, respectively. The results of this study are not indented to either accept or reject HDPE pipes but merely report the deformation characteristics and the observed failure modes of the installed pipelines in service using video and laser inspections.

References

AASHTO. (2008). *AASHTO LRFD bridge design specifications, customary U.S. units*, 4th Ed.

J. Transp. Eng. 2010.136:298-303.

Abolmaali, A., and Motahari, S. A. (2007). *University of Texas at Arlington Publication*, ⟨http://www.uta.edu/ce/abolmaali/hdpe%20report.pdf⟩.

ASTM. (2008). "Standard practice for rehabilitation of existing pipelines and conduits by the inversion and curing of a resin-impregnated tube." *F1216-07b*, West Conshohocken, Pa.

Ayche, N. (2005). "The effect of high density polyethylene (HDPE) pipe profile geometry on its structural performance." MS thesis, Ohio Univ.

Farshad, M. (2006). *Plastic pipe systems: Failure investigation and diagnosis*, Elsevier Science, New York.

Gassman, S. L., Schroeder, A. J., and Ray, R. P. (2005). "Field performance of high density polyethylene culvert pipe." *J. Transp. Eng.*, 131(2), 160.

Haddad, Y. M. (2000). *Mechanical behavior of engineering materials*, Springer, New York.

Madasamy, A., Omar, C., and Terdkiat, L. (2006). "Full-scale field tests on flexible pipes under live load application." *J. Perform. Constr. Facil.*, 20, 21–27.

Moore, D., Selig, E. T., and Haggag, A. (1988). "Elastic buckling strength of buried flexible culverts." *Transp. Res. Rec.*, 1191.

Moore, I. D. (1995). "Three-dimensional response of deeply buried profiled polyethylene pipe." *Transp. Res. Rec.*, 1514, 49.

Mruk, S. (1988). *Pipe. Encyclopedia of polymer science and technology*, Vol. 11, H. F. Mark, N. M. Bikales, C. G. Overberger, G. Menges, and J. I. Kroschwitz, eds., Wiley, New York.

Sargand, S. M., Masada, A. M., Tarawneh, B., and Gruver, D. (2005). "Field performance and analysis of large-diameter HDPE pipes under deep soil fill." *J. Geotech. Geoenviron. Eng.*, 131, 39–51.

Spangler, M. G. (1941). "The structural design of HDPE pipe culverts." *Rep. No. 153*, Iowa State Univ., Ames, Iowa.

Trudy, C. L. (1999). "Influence of local support of local support on corrugated HDPE pipe." MS thesis, The Univ. of Western Ontario, London, Ont.

Zhang, C., and Moor, I. D. (1998). "Nonlinear finite element analysis for thermoplastic pipes." *Transp. Res. Rec.*, 1624, 225.

J. Transp. Eng. 2010.136:298-303.