A R C H I W U M   I N S T Y T U T U   I N Ż Y N I E R I I   L Ą D O W E J
Nr 1   ARCHIVES OF INSTITUTE OF CIVIL ENGINEERING   2007

LABORATORY AND NUMERICAL INVESTIGATIONS OF LARGE-DIAMETER STRUCTURAL PLATE STEEL PIPE CULVERT BEHAVIOR

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Abstract

A 6.4 m (21 ft) diameter, structural plate, corrugated steel pipe culvert was constructed over Nease Creek and placed under a 22.9 m (75 ft) high highway embankment for the construction of a new road in Meigs County, Ohio, U.S.A. The authors inspected the culvert and collected deflection and soil pressure data during construction and beyond the end of construction. The field data showed that, although the corrugated steel plates did not have slotted joints, the bolted seams of the culvert allowed plate movements to occur during construction. This allowed for the circumferential shortening of the culvert under the embankment load and a resultant reduction of the vertical soil pressure acting over the culvert. Numerical and laboratory tests were subsequently performed by the authors to gain insights into the behavior of the structural plate corrugated metal pipe.

Key words: Corrugated Steel Pipe, Soil-Structure Interaction, Culvert

1. INTRODUCTION

The original 1886 invention by Watson and Simpson in the U.S. led to the development of corrugated metal culverts as we know of today. These pipe structures have been manufactured in ever increasing diameters and are often used as an alternative to short-span bridges. This is because they generally present a lower cost option for roadways to cross over streams, creeks, and ravines; and for grade separation structures. Large diameter structural plate corrugated steel structures are quite popular in the western United States because of the structure's ability to resist the load imposed by very high embankments and the relatively low shipping costs. More recently, there is a growing popularity for the use of this structure type in the eastern U.S. and Europe. The cost savings associated with this structure type allows for transportation agencies to further stretch limited funding.

The design of corrugated steel pipe is generally governed by three main performance limits – wall yielding (or crushing), wall buckling, and seam strength. Details on the design of corrugated steel pipe are available from a wide variety of sources.

There are many books, reports, and papers written on corrugated metal culvert structures. Abdel-Sayed et al. (1994) published a comprehensive book titled "Soil-Steel Bridges," in which the design and construction of large span corrugated metal structures are discussed. The book is the result of a collaborative effort of recognized experts in the field. Although originally published in 1994, the text remains an important source of information for the safe design of large span corrugated metal structures.

Chang, et al. (1980) examined the field performance of a corrugated steel arch, which had a 7.9 m (26 ft) span, 4.6 m (15 ft) rise, and 7.0 m (23 ft) of soil cover. During construction, measurements were made for bending and thrust stresses in steel, deflections of the culvert, backfill stresses, and backfill strains. Field data showed a substantial amount of circumferential shortening during the placement of the backfill, especially when the height of the backfill was below the crown of the culvert. Circumferential shortening may have occurred due to slippage in the bolted seams because the holes punched in the corrugated steel plates were larger than the bolts used to connect the corrugated steel plates.

They compared CANDE finite element predictions to the field measurements for a buried corrugated steel arch. The predicted thrust stresses, displacements, and vertical soil stresses at the crown were found to be satisfactory. Vertical and horizontal soil stress at the spring-line showed considerable discrepancy with the field measurements. Major discrepancies were found between the measured and predicted behavior in the earlier stages of construction before the backfill was above the crown. This may have been caused by incorrect modeling, by neglecting the effects of soil compaction during the backfilling, and neglecting the joint slip that occurred at the bolted seams. The discrepancies may also have been caused by the inherent limitations of the finite element stress-strain model assumed for the soil. The behavior calculated by the finite element method was found to agree very well with measured changes after the backfill was above the crown of the structure.

2. LARGE-DIAMETER PIPE CULVERT IN OHIO

Structural plate, corrugated steel structures are made from heavy gauge corrugated steel plates that are prefabricated to various shapes and sizes, including round, elliptical, arch, pipe arch, and long-span configurations. The steel plates are galvanized to improve corrosion resistance and long-term performance. A round structure was utilized at this site.

The structural plate pipe installed for the Nease Creek crossing was 6.4 m (21 ft) in diameter. The structure is located about 5 km (3 miles) southeast of the junction of State Routes 124 and 7. The length of the structure along the pipe invert was 145.4 m (477 ft). In order to improve hydraulics and reduce cost, beveled end sections were provided. This resulted in a crown length of 131.7 m (439 ft). The structural plate utilized for the structure was 9.375 mm (0.375 in) thick and had a 150 mm x 100 mm (6 in x 2 in) corrugation profile. The corrugation profile is shown in Figure 1.

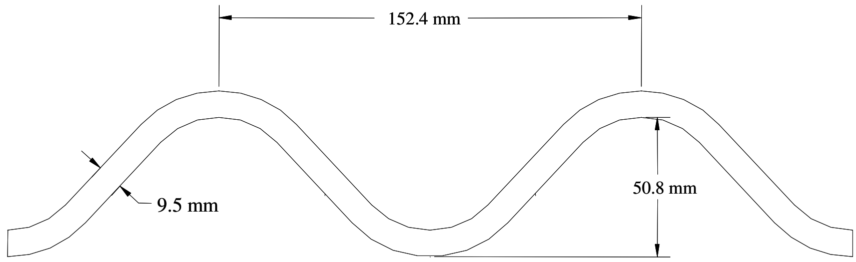

Figure 1. Profile View of Corrugated Steel Pipe

Physical properties of the plate sections are summarized in Table 1.

Table 1. Physical Properties of Corrugated Steel Plates

Physical Property	Data
Plate Corrugation Size	150 mm (6 in) pitch x 50 mm (2 in) depth
Wall Thickness (t)	9.5 mm (0.375 in)
Wall Area (A)	11.88 mm^2/mm (0.46775 in^2/in)
Wall Moment of Inertia (I)	3,802 mm^4/mm (0.232 in^4/in)
Wall Section Modulus (S)	125.8 mm^3/mm (0.195 in^3/in)
Unit Weight (γ)	76.8 kN/m^3 (0.283 lb/in^3 or 489 pcf)
Modulus of Elasticity (E)	E = 207 GPa (30 x 10^6 psi)
Poisson's Ratio (υ)	0.30
Yield Strength (σ_y)	227.5 MPa (33.0 ksi)

A total of twelve curved plates were needed to form the circumference of the culvert structure. The plates were joined together at the seams by overlapping them and tightening the bolts to a torque of 237 to 271 N-m (175 to 200 lb-ft).

Construction of the Nease Creek culvert began September of 2001 with the excavation of the pipe bed. A 152 mm (6 inch) thick layer of ODOT Item 304 crushed limestone was placed in the bottom of the channel as bedding for the culvert. The gradation specification for the Item 304 material is given in Table 2.

Table 2. Gradation Specifications of Ohio DOT Item 304

Sieve Size	% Passing by Mass	Sieve Size (No.)	% Passing by Mass
50 mm (2.0 in)	100	4.75 mm (No. 4)	30 to 60
25 mm (1.0 in)	70 to 100	0.60 mm (No. 30)	9 to 33
19 mm (0.75 in)	50 to 90	0.075 mm (No. 200)	0 to 13

Ref: Ohio DOT (2005).

Assembly of the culvert was completed in October of 2001. Upon completion of the pipe assembly, instrumentation was installed and shape measurements were recorded. Data were collected at frequent intervals while the pipe was backfilled. Backfilling began the same week. ODOT Item 304 crushed limestone was placed in compacted 152 mm (6 inch) lifts to a distance of approximately 1.8 m (6 ft) outside the springline of the pipe and to 0.6 m (2 ft) above the crown of the pipe. A vibratory plate compactor was used to compact the backfill. The compacted backfill had an average compaction of 96% SPD for all tests. The unit weight was 21.2 kN/m^3 (135 lb/ft^3) at an average moisture content of 4.4%. The pipe backfill was completed on November 14, 2001. Placement of the embankment began immediately following the backfill placement. The embankment extended to a height of approximately 23 m (75 ft) over the crown of the pipe at the highest point. The embankment was placed in approximately 0.6 to 0.9 m (2 to 3 ft) lifts and compacted by a sheep's foot roller to an approximate moist unit weight of 21.7 kN/m^3 (138 lb/ft^3) (exceeded 100% compaction). The embankment foreslope from the roadway to existing grade was constructed at a 2:1 (H:V) slope. The profile view of the pipe and embankment is given in Figure 2.

The structure had the overall length of 145 m (477 ft) at a slope of 0.27%. Additional details regarding installation procedure, site geometry, and in-situ soil characteristics can be found in the final research report by Sargand, et. al. (2004). Construction was completed in the fall of 2002.

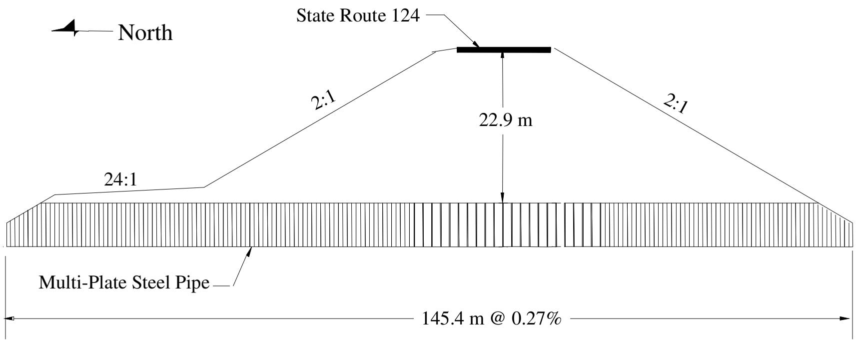

Figure 2. Profile View of Pipe Culvert Placed Under Embankment

The culvert structure was instrumented at two cross-sections with soil pressure cells. During and after the installation, horizontal and vertical inside diameters were measured at nineteen stations established along the culvert length, using a telescoping rod and a magnetic steel tape. Collection of the soil pressure cell and insider diameter measurements continued after the initial back-filling was complete and for an additional 1.5 years after construction.

3. NUMERICAL MODELING

Numerical modeling of the culvert field performance was carried out using CANDE-89 incremental finite element computer program. CANDE is an abbreviation for Culvert ANalysis and DEsign. It was originally developed by Katona et al. in the 1970s specifically for the analysis of buried culverts. It has become one of the standard analytical tools for culvert structures in the U.S. The current PC version CANDE-89 was made available by Musser (1989).

The half-mesh used in the analysis is shown in Figure 3.

The culvert and its surrounding soil are represented by 14 beam elements and 146 quadrilateral/ triangular elements. The bottom boundary of the mesh coincided with the actual depth of shale bedrock. The location of the upper boundary and width of the mesh were specified such that the boundary conditions would have a minimum impact on the culvert performance. A total of 13 construction stages were created to trace the actual culvert installation methods practiced in the field. The first construction stage introduced the foundation soil, bedding layer, and the culvert structure. The second to ninth construction stages were needed for the placement of initial backfill material and the embankment up to a height of 9.6 m (31.5 ft) over the pipe. The last four construction stages were used to create the overburden stress generated by the remaining 13.3 m (43.5 ft) of soil fill.

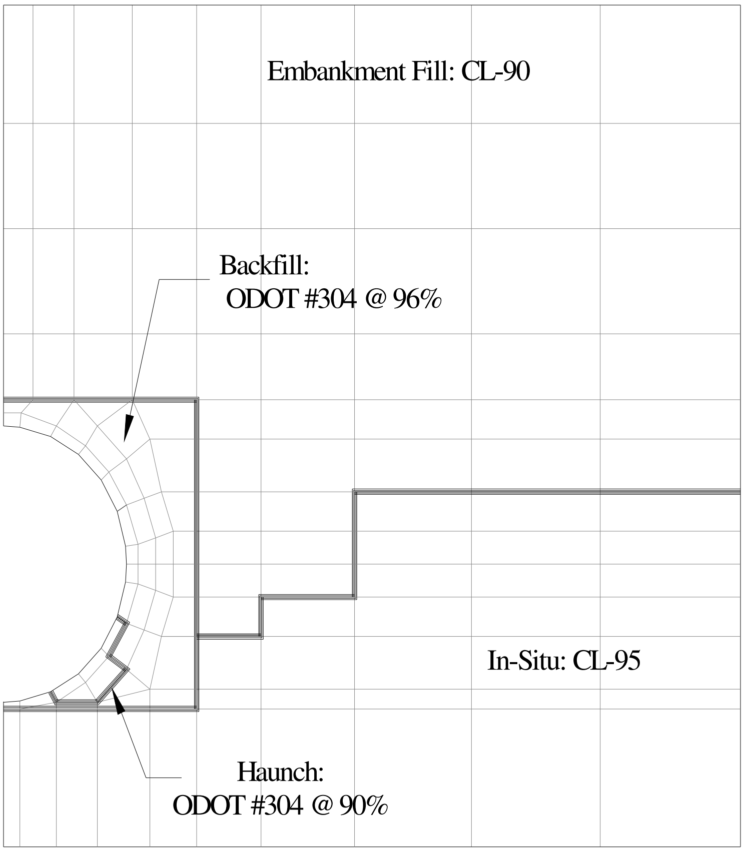

Figure 3. Half-Mesh Used in Numerical Simulation

In the numerical simulation, four soil types were assigned to different regions of the half-mesh (see Figure 3). CANDE-89 utilizes the Duncan-Selig hyperbolic soil model to simulate the soil behaviors and has a library of default model parameter values for several different soil types. The foundation soil above bedrock was represented by the default material CL-95. The backfill material (Ohio DOT Item 304 crushed limestone) was designated by a set of parameters previously determined by the authors. A relative compaction (R) of 96% was specified for all of the backfill regions, except for the haunch region where R was set to 90%. The embankment soil was represented by the default material CL-90. Table 3 summarizes the hyperbolic model parameter values used in the numerical simulations.

Table 3. Hyperbolic Soil Model Parameter Values

Soil Type	Triaxial Test Parameters:						Hydrostatic Parameters:	
	K MPa (psi)	N	R_f	c kPa (psi)	ϕ_0 (deg.)	$\Delta\phi$ (deg.)	Bi/Pa	εv
CL-90 (soil fill)	0.52 (75)	0.54	0.94	48 (7)	17	7	25.5	0.121
CL-95 (in-situ soil)	0.83 (120)	0.45	1.00	62 (9)	15	4	53.0	0.092
304-90 (backfill-haunch)	11.62 (1,685)	0.145	0.64	55 (8)	42	7.5	102.0	0.036
304-96 (backfill-general)	11.81 (1,713)	0.14	0.86	69 (10)	46	5.6	187.0	0.014

Ref. CANDE-89 Manual (1989)

Although the culvert structure did not have slotted joints, the slotted joint option available in CANDE-89 was used in the computer simulations. This is because the circular holes punched into the corrugated steel plates were 3.2 mm (0.125 in) larger than the bolts. The gap between the bolt and the plate could act as a slotted joint and relieve thrust stress by circumferential contraction of the bolted plates. With twelve longitudinal seams located around the culvert circumference, a maximum circumferential contraction of 38.1 mm (1.5 in) could possibly take place. Furthermore, individual joint movement could exceed 3.2 mm (0.125 in) if there were some gaps between the plates which provide room for the bolts to rotate. In the current project, evidence of joint looseness was detected in the field.

The culvert joints were modeled as slotted joints with varying joint travel lengths of 3.2, 6.4, 9.5, and 12.7 mm (0.125, 0.25, 0.375, and 0.50 in) to make comparisons. When the slotted joints are modeled in CANDE-89, a joint slipping stress must be entered into the program. The joint slipping stress recommended by the CANDE-89 manual (Musser, 1989) is 34.1 MPa (5.0 ksi). The exact stress is difficult to determine due to the variability of conditions that induce joint slipping in seams without slotted joints. Because of this, the joint slipping stress was varied from 6.9 to 34.1 MPa (1.0 to 5.0 ksi).

Attempts were made to take advantage of the feature in CANDE-89 to utilize thin interface elements. Different friction coefficients and tensile strengths were used in a mesh created with interface elements. However, CANDE-89 was unable to produce an acceptable output due to numerical convergence problems. Others have reported similar problems with interface elements not converging in the analysis (ex. Chang, et al. 1980). The CANDE simulations results are summarized in the final research report by Sargand, et. al. (2004).

4. FIELD AND NUMERICAL MODELING RESULTS

Conclusions reached during the large-diameter culvert project in Ohio were as follows:

- Peaking behavior was experienced by the steel pipe during the initial backfilling, with the horizontal diameter decreasing by 0.9% and the vertical diameter increasing by 1.0%.
- Field measurements of pipe deflections were – 3.3% (vertical) and 2.5% (horizontal) at the end of the construction.
- Vertical soil pressure measured at the crown of the steel pipe ranged from 184 to 250 kPa (26.7 to 36.2 psi) at the end of construction. This corresponded to about 42% of the geostatic pressure.
- Lateral soil pressure at the springline ranged from 99 to 190 kPa (14.3 to 27.5 psi) at the end of construction.
- Circumferential shortening was experienced by the steel pipe culvert due to joint slippage. Based on the finite element modeling, the magnitude of each individual joint travel length was at least 3.2 mm (0.125 in) and possibly greater.
- Field measurements and observations suggest that positive soil arching may have been induced by a combination of ring compression (bending) and circumferential shortening experienced by the steel pipe.
- The culvert's behavior stabilized during the 1.5-year time period after the end of construction.
- CANDE-89 was unable to predict the peaking behavior experienced by the culvert during the initial backfilling. Simulated compaction effects had very little effect in helping to predict the peaking behavior.
- CANDE-89 had a tendency to underpredict the steel pipe deflections and overpredict the soil pressure acting against the pipe. This is understandable, considering the facts that – 1) CANDE-89 is based on small displacement theory and displacement formulations; 2) the use of interface elements was

abandoned due to persistent convergence problem; and 3) CANDE-89 cannot incorporate bolt rotation in simulating joint slippage.

- Increased positive soil arching was predicted by CANDE-89 with the increasing joint travel length and decreasing joint slippage stress.
- The numerical results reflect complex nature of the joint slippage mechanism. A single value of joint travel length or joint slippage stress cannot realistically simulate field performance.

5. LABORATORY TESTING

The field and numerical modeling implicitly suggested that movement in the bolted connections of corrugated steel plate culverts may be taking place. A laboratory experiment was devised to determine if such a phenomenon could be reproduced and quantified.

Two panels of the corrugated steel plate were acquired from Lane Enterprises. Each of the plates was cut into a few smaller size plates such that there was a total of six specimen. The six plates were arranged in pairs to form three bolted assemblies, which could be tested in the laboratory. Each plate assembly was then instrumented with two 90° CEA-Series strain rosettes, manufactured by Micro-Measurements, and two LVDTs. The strain gages were placed in the corrugation crest and valley. The crest rosette consists of gages 1 through 3 and the valley rosette consists of strain gages 4 through 6. They were installed 12.7 mm below the bolt holes in the lower plate. This provided 6.8 mm of clearance between the strain gage and the head of the bolt. The rosettes were aligned with gage 2 and gage 5 of the respective rosettes in a vertical alignment (parallel with the applied load). The plate assemblies were then bolted together using 237, 251, and 271 N-m (175, 185, and 200 lb-ft) of torque, respectively. This is the range of bolt torques recommended by plate manufacturers' for proper field construction of structural plate corrugates steel structures. It is important to note that no attempt was made to influence the orientation of the bolts with respect to the two plates. In other words, the plates could be fully compressed against the bolts, fully extended against the bolts, or somewhere between these limits. Two LVDT mounting brackets were welded to each plate assembly. The LVDTs were then mounted between the brackets. Figure 4 shows the location of the strain gages and the LVDTs. Each plate assembly was then placed in a compression loading machine and loaded until well past the joint slippage stress recommended by the CANDE-89 User Manual. A servo-controlled MTS hydraulic loading system was used to load each plate assembly at a constant ramp function of 21.35 kN/min (4800 lb/min).

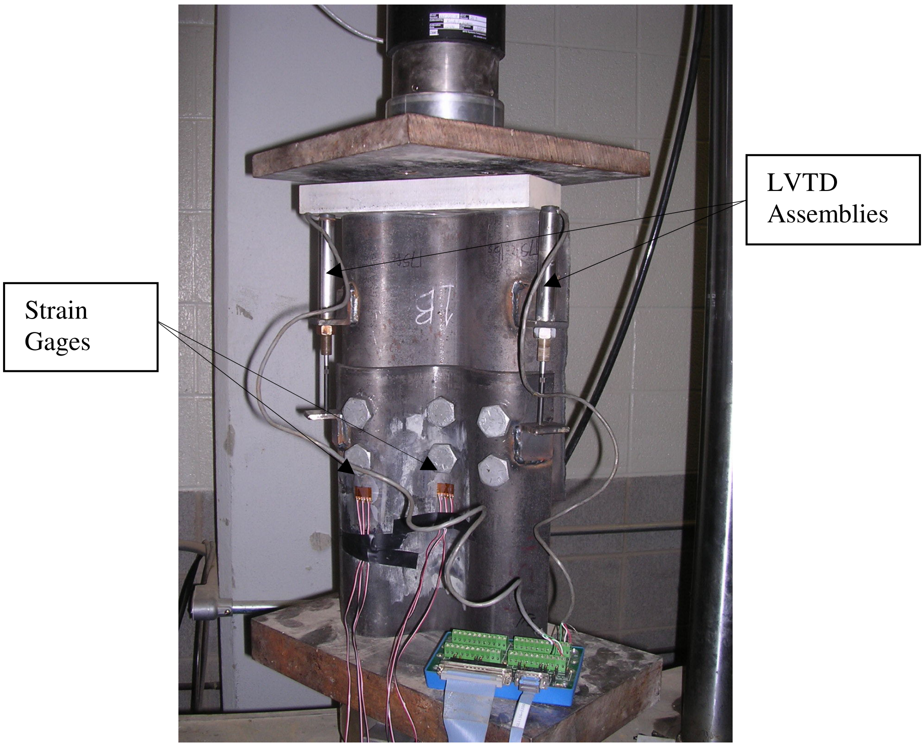

Figure 4. Testing of Instrumented Corrugated Plate Assembly

A maximum load of 93.4, 117.9, and 186.8 kN (21000, 26500 and 42000 pounds) was applied to the plate assemblies, respectively, resulting in a maximum applied stress of 43.4, 51.0 and 86.2 MPa, (6300, 7400 and 12500 psi) for each of the plate assemblies.

Joint slippage began at approximately 25.9, 33.1 and 35.2 MPa, (3750, 4800 and 5100 psi) respectively. Total joint travel for each of the tests was 2.24, 2.06 and 3.81 mm, (0.088, 0.081, 0.15 inches) respectively. Figures 5 through 7 show the displacement of the plates as a function of applied stress.

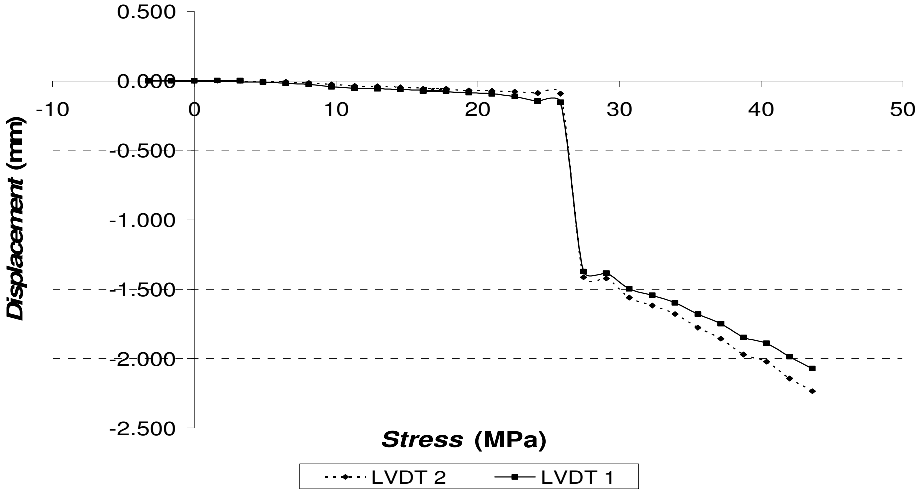

Figure 5. Stress vs. Displacement (237 N-m plates)

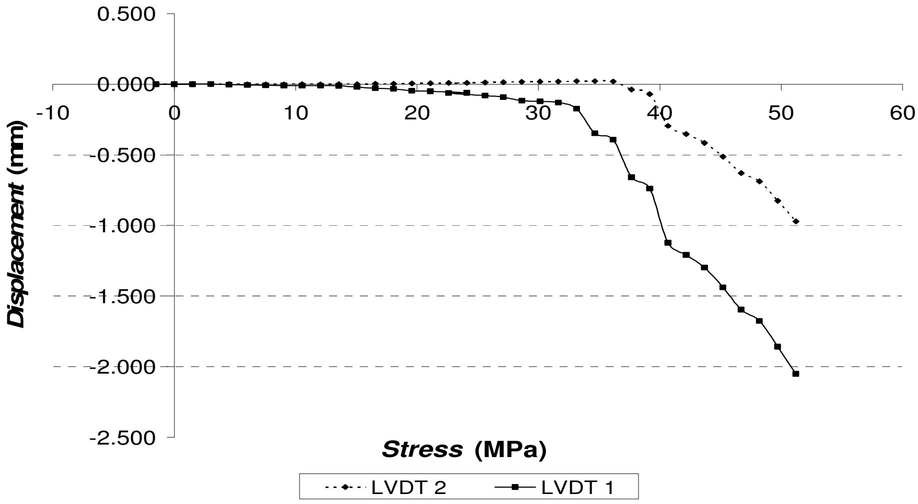

Figure 6. Stress vs. Displacement (251 N-m plates)

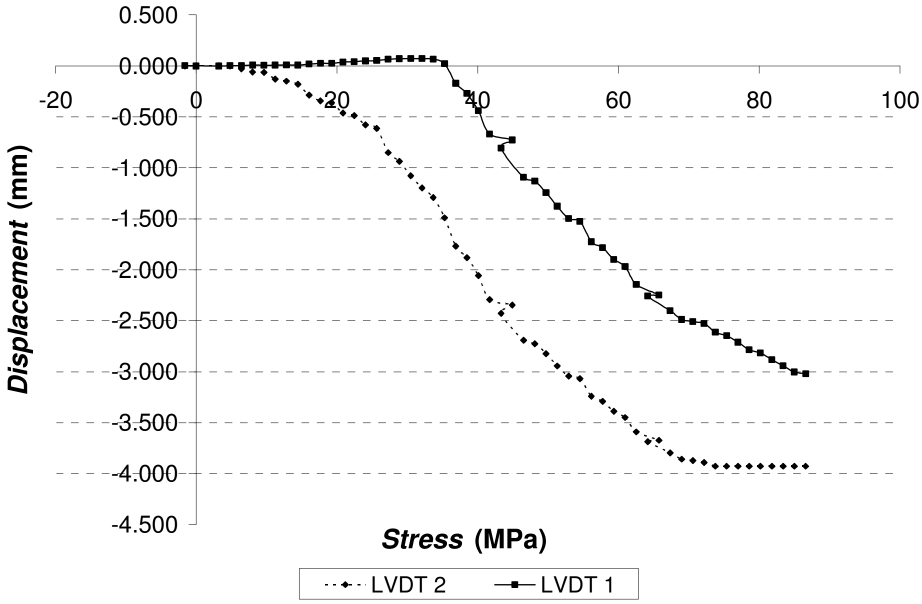

Figure 7. Stress vs. Displacement (271 N-m plates)

The average measured strain in the plate assemblies, just below the bolt holes was, 340, 278 and 663 micro-strains, respectively. Figures 8 through 10 plot the recorded strains as a function of applied stress.

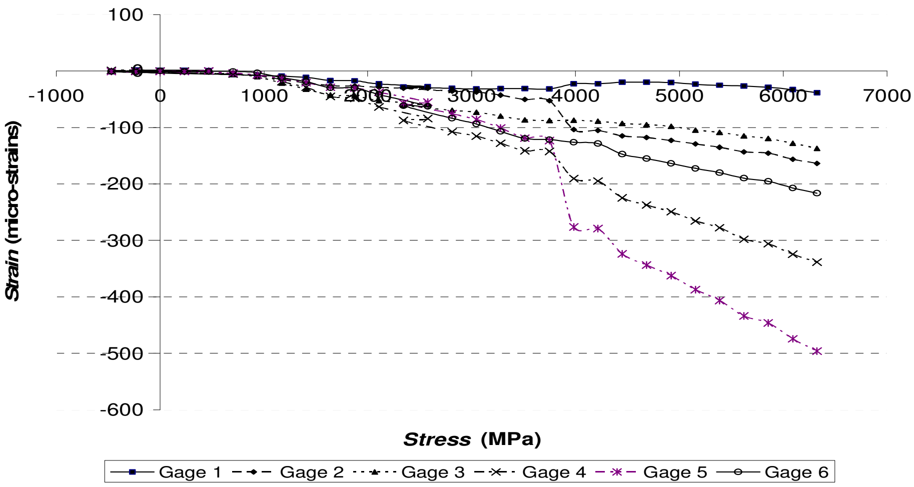

Figure 8. Stress vs. Strain (237 N-m plates)

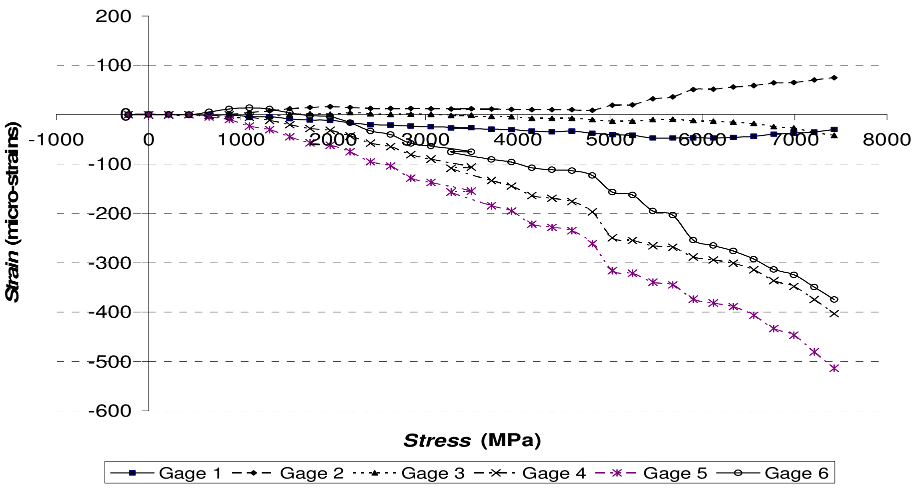

Figure 9. Stress vs. Strain (251 N-m plates)

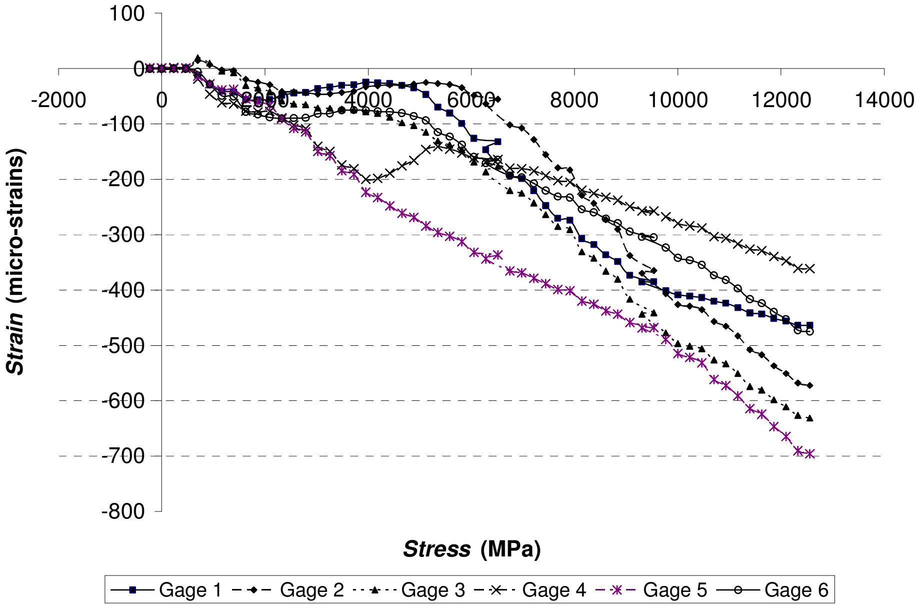

Figure 10. Stress vs. Strain (271 N-m plates)

Of particular importance are strain gages 2 and 5. These are the gages parallel with the applied load. The extreme difference between the measured displacement and the measured strain is a sure indicator that plate slipping occurred.

For the second test (251 N-m torque), the strain rosette located on the corrugation crest (strain gages 1 through 3) did not appear to be functioning properly during the testing. These three gages recorded positive strains thought out the test. Because of this, the strain readings from this gage were not utilized for data analysis.

6. SUMMARY AND CONCLUSIONS

A 6.4 m (21.0 ft) diameter structural plate steel pipe culvert structure was recently installed under a maximum soil fill height of 22.9 m (75.0 ft) in Meigs County, Ohio, U.S. This steel pipe culvert was the first of its kind to be constructed in the southeastern region of Ohio. The culvert structure was selected by Ohio DOT over a conventional 5-million US dollar bridge structure, because it would cost about 3.4 million US dollars less. The field performance of the culvert was monitored by measuring the earth pressure distribution around the pipe as well as the deflections of the pipe culvert during and after construction. The culvert study also included numerical simulations of the field culvert performance and controlled laboratory load testing of corrugated steel plate joint sections.

The controlled laboratory load test results confirmed the investigators believe that circumferential shortening and resultant positive soil arching was taking place in the field installation, even though slotted joints were not supplied. The joint slippage assumption used in the original CANDE-89 analysis was confirmed as valid. The following specific conclusions and recommendations can be drawn:

- In all three tests, significant joint slippage occurred. The onset of joint slippage occurred between 25.9 and 35.2 MPa (3750 and 5100 psi). This is well in line with the 34.1 MPa (5000 psi) value recommended by CANDE.
- Total joint travel was between 2.06 and 3.81 mm (0.081 and 0.15 inches). This in reasonable conformity with the CANDE-89 predicted 3.18 mm (0.125 inches) of individual joint travel.
- The average joint movement of 2.7 mm (0.11 in), extrapolated about the sixteen joints forming the culvert result in a total circumferential shortening of 43 mm (1.7 in). The CANDE-89 analyses indicate that this magnitude of joint slip can account for the load relief experienced during the field testing.
- With additional field and laboratory investigation, it may be possible to refine the design method for corrugated steel plate pipe. The current geostatic design stress may be able to be reduced because of the positive soil arching caused by joint slippage in the bolted connections of structural plate corrugated steel culverts.

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LABORATORYJNE I NUMRYCZNE BADANIA DUŻEJ ŚREDNICY KONSTRUKCJI Z BLACH FALISTYCH

Streszczenie

Przepust ze stali karbowanej o średnicy 6.4 m (21 ft) został zbudowany nad Nease Creek i usytuowany pod nasypem o wysokości 22.9 m (75 ft) w Meigs Country, Ohio, U.S.A. Autorzy zbadali przepust oraz zebrali informacje dotyczące odkształceń w powłoce i naprężeń gruntowych podczas budowy i po jej zakończeniu. Wyniki z badań polowych ujawniły ze pomimo tego ze konstrukcje z blach falistych nie posiadały złączy umożliwiających swobodny przesuw śrub (slotted joints) to jednak połączenia śrubowe umożliwiły wzajemny przesuw płaszczy stalowych podczas budowy. To pozwoliło na skrócenie obwodowe konstrukcji pod obciążeniem nasypem i w efekcie zredukowanie pionowych naprężeń w gruncie nad przepustem. Następnie przeprowadzane zostały przez autorów testy numeryczne i laboratoryjne, dla rozpoznania zachowania się stalowego przepustu z blachy karbowanej.

Słowa kluczowe: Karbowane rury stalowe, współdziałanie grunt-konstrukcja, przepust