and to design prismatic structures such as buried box sections, slabs, or one-way spanning footings without web reinforcement.

FURTHER RESEARCH

I am currently directing the next phase of ACPA's long-range research program at Simpson Gumpertz & Heger Inc. (SGH), the development of a direct soil-structure interaction analysis for earth loads, earth pressure distributions, and moments, thrusts, and shears in a buried concrete pipe. This involves development of a finite-element representation of the soil and the pipe and a computerized analysis of the system as it is loaded incrementally by the soil and surface loads. Ernest Selig is consultant to SGH on the soil model and its properties. As mentioned previously, the computer program that results from this effort will be known as SPIDA and will provide a direct design for a buried pipe with specified earth cover, bedding, and pipe conditions.

ACKNOWLEDGMENT

As a part of their long-range research program, ACPA provided financial support to Simpson Gumpertz & Heger Inc., for the tests and investigations that led to the new approaches for shear and radial tension strength and crack control that form the basis of the proposed design method. The continued support and suggestions provided by the ACPA Technical Committee are acknowledged and appreciated. Main Committee Chairman Lee Stockton, Subcommittee Chairman Harry Peck, members Joseph Zicaro and Robert Spiekerman, ACPA Board Chairman Thomas Breitfuss, and Vice President Mike Bealey reviewed the research work and the design method and made valuable suggestions for its implementation. I also acknowledge the many valuable contributions of my associate, Timothy J. McGrath, who served as project manager for SGH, planning and evaluating the extensive test data and making numerous suggestions during development of the design method. Finally, thanks are due Chairman Adrianus Van Kampen and members of the AASHTO Rigid Culvert Liaison Committee, who reviewed the proposed design method and made further valuable suggestions for its implementation as Section 1.15.4 of the AASHTO bridge specifications.

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Abridgment

Behavior of Aluminum Structural Plate Culvert

DAVID B. BEAL

A corrugated aluminum culvert 17 ft 10 in high with a 28-ft 6-in span was instrumented to obtain measurements of strain and displacement during backfilling and under static live load. Values of circumferential bending moment and thrust at 16 locations spaced around the structure's circumference at midspan are reported for each 2 ft of backfill from the springline to 2 ft over the crown. Despite bending moments 70 percent of the fully plastic value and stresses exceeding the nominal yield point of the aluminum, it is concluded that the structural behavior is satisfactory. Discrepancies between measured values and design predictions are discussed.

Corrugated metal culverts can be economical replacements for short-span bridges and have been used for spans as long as 51 ft (1). Traditionally, culvert design has been largely empirical, but with the increasing demand for large-span structures the need for a rational analytical procedure has grown. The purpose of the research described here was to obtain strain and displacement measurements on a typical structure to provide data for comparison with analytical predictions. The work is described completely elsewhere (2). The structure is a 28.5-ft span pipe arch with a rise of 11 ft 9 in and a total height of 17 ft 10 in. The invert length is 140 ft. The structure was manufactured by Kaiser Aluminum and Chemical Sales, Inc., which contributed to this research.

The structure carries Van Campen Creek under State Route 275 in the town of Friendship, New York. With a filled invert, the culvert provides a clear opening of 346 ft². It is constructed of 0.175-in aluminum (5052-H141 alloy) structural plate with corrugations of 9-in pitch and 2.5-in depth. Bulb angle stiffening ribs (6061-T6 alloy) were bolted to the crown on 2-ft 3-in centers. Seven plates were assembled with 0.75-in diameter galvanized steel bolts on 9.75-in centers to form a complete circumference of the structure as shown in Figure 1. Circumferential seams are staggered.

Immediately surrounding the structure, select granular backfill was placed to the limits indicated in Figure 1. Below the invert, 32 ft of a soft-to-firm grey clayey silt was left in place. The backfill was placed in 6-in lifts, and in accordance with construction specifications the difference in backfill elevation from one side of the structure to the other never exceeded 1 ft. Compaction was to 100 percent of the standard Proctor value and was checked after each 2 ft of backfill.

The major effort in this test was to monitor culvert behavior during backfilling. The structure's behavior under live load was also obtained from measurements taken with a single-axle dump truck statically positioned at several locations on the fill.

CULVERT INSTRUMENTATION

Changes in culvert shape were monitored by measuring the relative movement of four points around the culvert circumference with respect to points at the springline. This measurement was performed at the longitudinal centerline and at two sections 13 ft 6 in on either side of the centerline. Joint slip was monitored at each joint on a complete circumferential ring (seven joints) with linear potentiometers. These measurements were made to 0.001 in and are believed accurate to 0.005 in. Electrical-resistance strain gages were mounted on the inner surface of the structural plate in the circumferential and longitudinal directions at 16 sections around the culvert's centerline circumference (Figure 2). The stiffening rib was instrumented with T-rosette gages at 12 locations. Analysis of the strain-gage data permitted evaluation of the total moment and thrust at 16 circumferential locations. Temperatures were monitored with eight copper constantan thermocouples. Seven of these were mounted to the inner surface of the structural plate, and the remaining device monitored air temperature inside the pipe.

RESPONSE DURING BACKFILLING

The baseline for all measurements was taken with the fill at the springline. Strain, displacement, and temperature were monitored at 2-ft increments of backfill up to a fill depth of 10 ft. Increments from that level raised the fill depth successively to 11 ft 6 in, 13 ft 6 in, and 14 ft 2 in. Measurements were terminated at 14 ft 2 in because of a conflict between construction operations and the experiment.

Maximum stresses at all stages of backfilling occurred on the inner corrugation of the structural plate. The maximum tensile stress of 21 200 psi occurred at Section 10 with the backfill at the crown. Maximum compressive stress was -28 800 psi at Section 16 with full backfill depth. The average yield point of three samples taken from the structure's crown plate was 33 300 psi.

The experimentally determined moment distributions for 8 ft and 14 ft 2 in of fill are shown in Figure 3 as typical examples of the results obtained. In both cases shown and for all increments of backfill, the distribution of moments is regular; changes from positive to negative bending occur at the expected locations. The slight antisymmetry is a result of the backfilling sequence, which resulted in placement of the 6-in lifts on the north side first.

The maximum average crown moment of 5.3 kip•ft/ft occurred at maximum fill depth. Maximum quarter-point moment of 4.4 kip•ft/ft occurred on the north side with the fill at the crown.

Evaluation of thrust was less successful than for bending moment. This is believed to result from the small magnitude of thrust in this low-cover structure.

Interpretation of measured displacements was complicated by the increase in invert elevation. The upward displacement resulted because the large-radius invert plates were unable to resist the pressure from the soft native material underlying the structure. The maximum differential displacement between the crown and invert was 3.4 in. The maximum change in span was 1.6 in; this occurred at 10 ft of backfill.

The joint slip measurements are erratic and show no trend. Most readings were recorded as less than 0.002 in, which is less than the 0.005-in expected accuracy.

Live-load testing was performed by using a truck positioned on the backfill with the centerline of the 20-kip rear axle placed at a series of locations over the crown and quarter point of the structure. The maximum stress recorded on the inner corrugation was 2300 psi and occurred with the rear axle over the crown. At the crown, where the maximum backfill compressive stress was 28 500 psi, a maximum live-load compressive stress of 1700 psi was induced for a net compressive stress of 30 200 psi. This is the absolute maximum stress in the culvert. Live-load stress was always compressive at the quarter point, the location of the maximum dead-load tensile stress.

DISCUSSION OF RESULTS

Table 1 gives maximum values of moment and thrust with fill depth at the crown and at full backfill depth. It should be noted that the completed structure in service will have at least 2 ft of additional fill and asphalt paving. This additional load will decrease the magnitude of the reported bending moments. Thrusts will increase due to this additional load, and these values should be estimated to assess the reliability of the completed structure.

Figure 1. Limits of structural backfill.

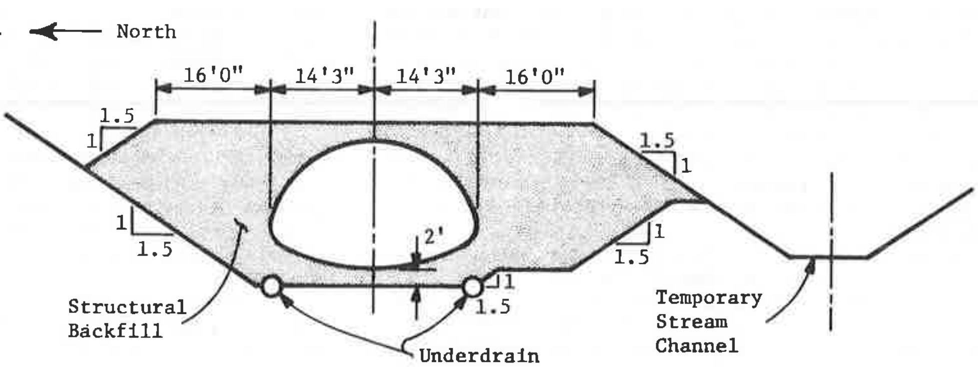
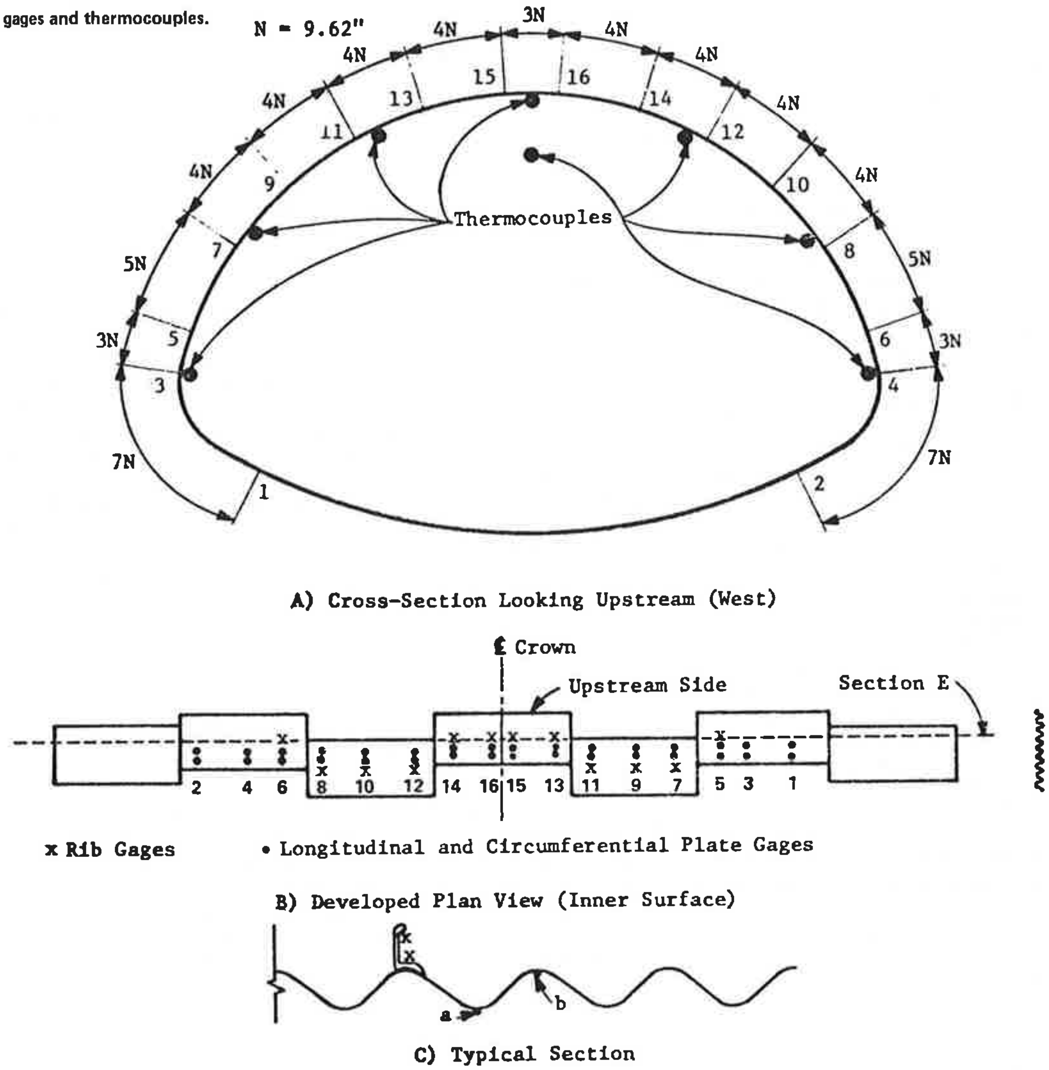


Figure 2. Locations of strain gages and thermocouples.



The fully plastic moment and thrust for this structure are 7.9 kip•ft/ft and 85.4 kips/ft, respectively. The maximum total measured thrust is 11 kips/ft, only 13 percent of the plastic value. By contrast, the maximum total moment is 70 percent of the plastic value. If we ignore thrust, the factor of safety against formation of a plastic hinge is 1.49 with 2 ft of cover and 1.44 with live load in place.

The high stresses observed are not unexpected but may alarm engineers accustomed to stress values less than 55 percent of the yield point. This concern is unfounded, however, because even at the stress levels observed, the structure is under no danger of collapse. Duncan (3,4) has suggested controlling the factor of safety against formation of a plastic hinge as a design requirement for flexible culverts with shallow fill and has given three reasons why structure collapse will not occur at this point: (a) multiple plastic hinges are required to form a collapse mechanism, (b) the soil will restrain deformations after formation of a mechanism, and (c) the design estimates are based on minimum values of yield stress.

Measured live-load bending moments were small. Nevertheless, based on design estimates (3), the bending moment induced by an HS 20 truck with 4-ft cover would be only 62 percent of those produced experimentally. Thus, despite the noted inaccuracies in the experimental force determination, it is unlikely that service loads will have a significant influence on culvert behavior.

CONCLUSIONS

From the test results presented, the following conclusions can be made about the behavior of this structural-plate culvert:

1. The backfill placement sequence resulted in distortion of culvert shape and increased positive bending moments on the north side of the structure;
2. The total change in height of the structure was less than the change in rise because of the upward movement of the invert;
3. Maximum compressive stresses at the crown exceeded the nominal yield point of the aluminum plate; the actual yield point was not exceeded;
4. The variation of dead-load moments around the circumference of the structure was consistent with intuitive expectation; the maximum moment was 70 percent of the fully plastic value;
5. The apparent irregularities in measured thrust values are greater than assumed measurement accuracies;
6. In-service bending moments due to backfilling will be less than the values reported due to the placement of an additional 2 ft of cover;

7. Live-load stresses were small with respect to dead-load stresses; and
8. Design estimates of thrust were greater than measured values and estimates of moment were less.

ACKNOWLEDGMENT

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Figure 3. Distribution of moment around circumference.

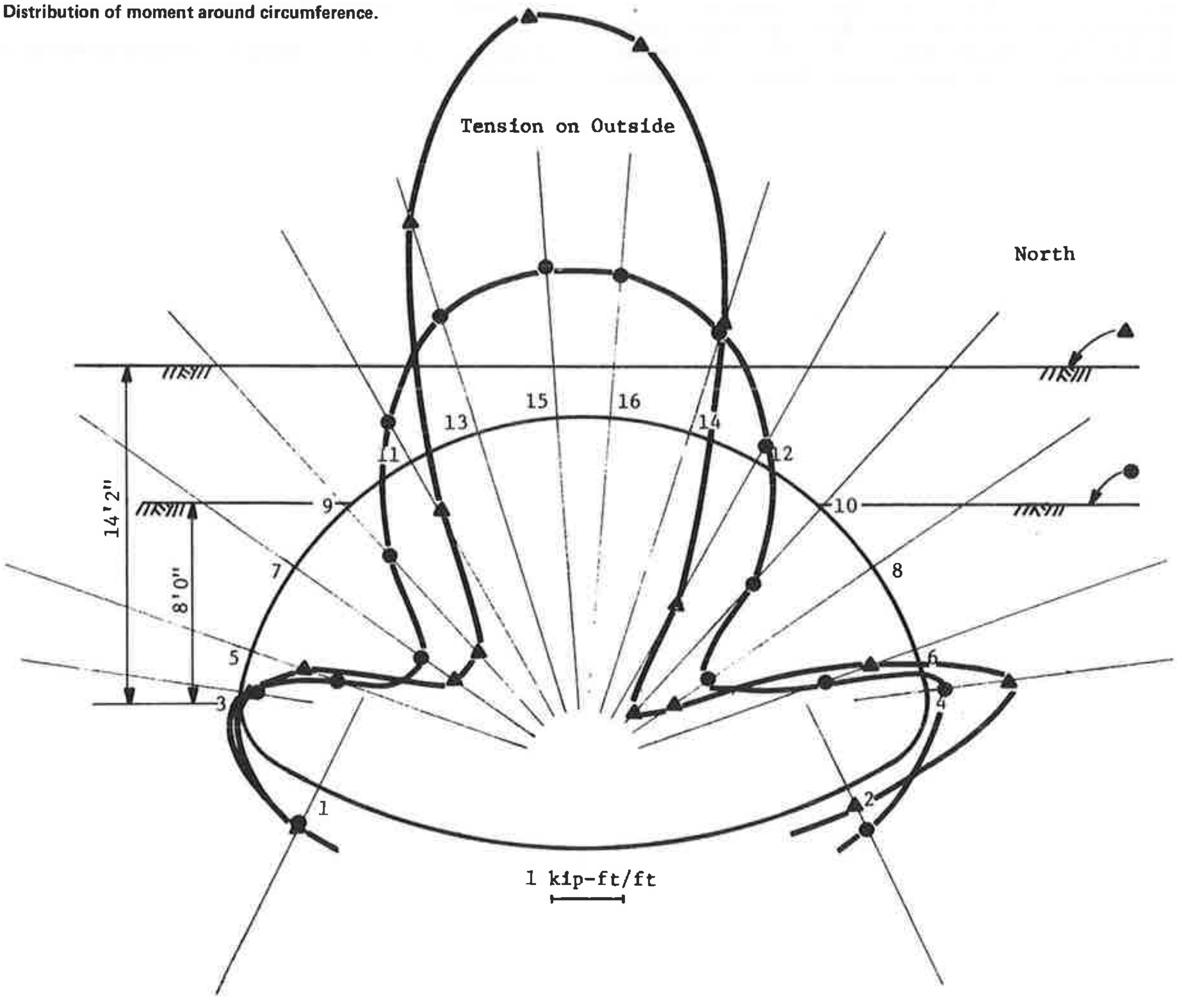

Table 1. Maximum experimental and calculated moment and thrust.

Location	Backfill				Live Load				Total			
	Moment (kip·ft/ft)		Thrust (kips/ft)		Moment (kip·ft/ft)		Thrust (kips/ft)		Moment (kip·ft/ft)		Thrust (kips/ft)	
	Experimental	Calculated	Experimental	Calculated	Experimental	Calculated[a]	Experimental	Calculated[a]	Experimental	Calculated	Experimental	Calculated
H = 0 ft												
Crown	-4.8	-2.6	0.8	-[b]	-	-	-	-	-4.8	-	0.8	-
Quarter point		2.6		8.9	-	-	-	-		2.6		8.9
North	4.4		2.5						4.4		2.5	
South	3.3		1.5						3.3		1.5	
Springline		-		9.3	-	-	-	-		-		9.3
North	-1.0		3.7						-1.0		3.7	
South	0.2		4.7						0.2		4.7	
H = 2 ft												
Crown	-5.3	-	3.0	-	-0.2	-	4.1	-	-5.5	-	7.1	-
Quarter point		1.9		14.1		1.4		2.8		3.3		16.9
North	4.0		6.4		0.0		1.6		4.0		8.0	
South	2.8		9.4		0.0		1.6		2.8		11.0	
Springline		-		14.9		-		2.9		-		17.8
North	-1.0		7.8		0.0		1.0		-1.1		8.9	
South	-0.2		8.1		0.0		1.0		0.2		9.1	

[a] Equivalent live load = 2.94 kips/ft. [b] Dash indicates that no value was available.

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