

PERFORMANCE OF A LARGE CORRUGATED STEEL CULVERT

Ernest T. Selig, Department of Civil Engineering,
State University of New York at Buffalo; and
Salvatore J. Calabrese, Law Engineering Testing Company, McLean, Virginia

Because few published field data exist to help in the development and evaluation of design criteria for large buried structures, a construction project involving such a structure was instrumented in Thunder Bay, Ontario. The structure was a shallow-buried, elliptical, corrugated-steel pipe with a 16-ft (4.9-m) height and a 27-ft (8.2-m) span. A concrete relief slab was placed on the fill several feet (meters) over the crown to distribute the vehicle loads. Pressures around the structure and under the slab were measured by using embedded stress gauges. Horizontal and vertical extensometers measured strains in the backfill. Radial extensometers inside the structure provided the structural deformation pattern. Data were obtained during construction and during live load tests with heavy vehicles. The results provided information on the magnitudes and distribution of stresses and deformations, the influence of construction procedures, and the apparent moduli of the backfill. Even though the cover over the structure provided by the backfill and slab was only about 20 percent of the span, the deflections and stresses in the pipe from the heavy vehicle loads were much smaller than those produced by the dead weight of material placed over the crown. Many cycles of live loading were required before the culvert system began to respond elastically to the loading. The final soil pressure distribution around the structure and the observed deflections were greatly influenced by the construction procedures.

•THE performance of large buried culverts is difficult to predict because of the complex interaction phenomena involved. The load on the culvert and the deformations are influenced not only by the properties of the structure and the soil but also by the details of the construction process. In addition, few field measurements have been obtained in the past to provide a quantitative evaluation of performance. Therefore, design of most of the large culverts [10- to 50-ft (3- to 15-m) diameter] has involved many assumptions and approximations of unknown validity. This paper describes the results of a field instrumentation study of one such culvert constructed in 1973 in Thunder Bay, Ontario. The purpose of the structure was to provide a road crossing over a stream to replace an old timber bridge.

The culvert was elliptical with a 27-ft (8.2-m) span, a 16-ft (4.9-m) height, and a shallow soil cover (Figures 1 and 2). It was fabricated from 5-gauge, 2 × 6-ft (0.6 × 1.8-m), rolled corrugated-steel plates. Because the design height of soil cover over the crown was initially only 10 percent of the span, the designers specified that a 1-ft-thick (0.3-m), reinforced-concrete slab be placed on top of the soil cover to distribute the concentrated vehicle loads. The structural backfill extending to about 13 ft (4 m) out from each side of the culvert consisted of a compacted granular glacial till.

21. A. A. Sveshnikov. Problems in Probability Theory, Mathematical Statistics and Theory of Random Functions. W. B. Saunders Co., Philadelphia, 1968.
22. T. H. Wu and L. M. Kraft. The Probability of Foundation Safety. Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol. 93, No. SM5, Proc. Paper 5459, 1967, pp. 213-217.

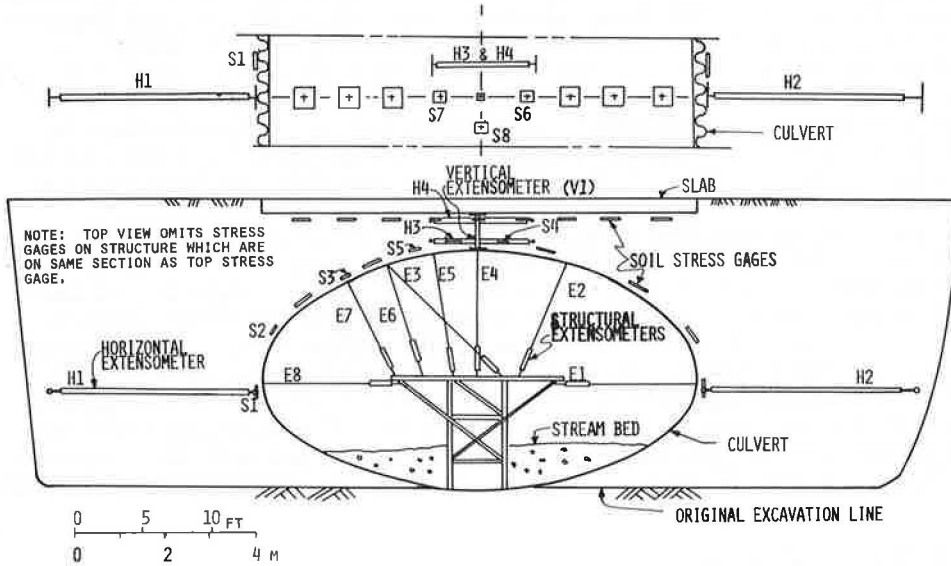
Figure 1. Structure under construction when backfill up to spring line.



Figure 2. End view of completed structure with test load truck, readout station, and relief slab.



Figure 3. Top and end views of instrument layout.



INSTRUMENTATION

The instrumentation layout is shown in Figure 3. Horizontal extensometers measured movements of the sides of the culvert relative to points approximately 13 ft (4 m) away from the structure, at the edge of the granular fill zone. The pressure distribution on the structure from the backfill was measured with embedded stress gauges. The pressure distribution under the slab was also measured with these stress gauges. Horizontal extensometers 6 ft (1.8 m) long were placed in the fill above the crown to help observe how this material deformed. Deflection of the slab relative to that of the crown of the culvert was measured with an embedded vertical extensometer. Radial extensometers inside the culvert gave the magnitude and pattern of deformation of the culvert under vehicle live loads. The instrumentation and installation procedures are described in another paper (1).

STRUCTURAL BACKFILL

The backfill material is classified as a coarse-to-fine gravel and coarse-to-fine sand with a trace of cobbles and silt sizes. The designation of the Unified Soil Classification System is GW-SW, and that of the American Association of State Highway and Transportation Officials is A-1-a. The material was compacted in roughly 1-ft-thick (0.3-m) layers and was covered at least four times by using a small vibratory roller. The moisture content, estimated to be from 5 to 10 percent, was accepted as it came from the borrow pit. Laboratory compaction tests (ASTM D 698-70) indicated a maximum dry density of 152 pcf (2430 kg/m³) and an optimum moisture content of 8 percent after correction for the +³/₄-in. (19-mm) material. The average material specific gravity was 2.81.

To indicate the compressibility of the backfill, one-dimensional compression tests were conducted on that portion of the material passing the ³/₄-in. (19-mm) sieve. Because field density and moisture content data were not available, these samples were compacted to 98 percent of the ASTM maximum dry density for the -³/₄-in. (19-mm) material, at the optimum moisture content, or 131 lb/ft³ (2100 kg/m³) and 9.5 percent respectively. The compression tests were conducted in a 12-in.-diameter (30-cm), 8-in.-high (20-cm) cylindrical mold with cycles of pressure between 0 and 11 psi (76 kPa) applied by a 12-in.-diameter (30-cm) circular plate. The one-dimensional compression modulus was 1,200 psi (8300 kPa) for the first load cycle and ranged between about 2,700 and 4,600 psi (18 600 to 31 700 kPa) for the second to nineteenth load cycles.

CONSTRUCTION SEQUENCE

At the location of the structure, the original grade was above the prescribed culvert crown elevation. Therefore the excavation shown in Figure 3 was made first, and then the bottom was shaped to fit the culvert invert. Then assembly of the corrugated plates began, and fill was added to support them. After the entire structure was bolted together, the backfilling was resumed up to the spring line. At this stage (Figure 1), the first instruments were installed. Final bolt tightening with a torque wrench continued toward the crown as the fill elevation increased. By the time the fill reached 70 in. (1.8 m) above the spring line, the bolt tightening was complete, and about 3 ft (0.9 m) of gravel fill was spread, but not compacted, inside the structure to form the streambed. Pairs of heavy timber struts were then wedged upright at 6-ft (1.8-m) intervals along the length of the structure supporting the top plates and butting on the gravel base. The frame for the radial extensometers (Figure 3) was placed inside the culvert and bolted to the invert at the same time. Backfilling over the structure was then completed, and the concrete slab was constructed. The struts were removed after about 1 week of concrete curing. The live load testing of the structure was then conducted, and final grading of the road base over the slab was completed.

MOVEMENTS DURING CONSTRUCTION

The construction events corresponding to the measurements are given in Table 1. Figure 4a shows the change in the two spring-line soil extensometers during construction. The two sides show the same trends. Large inward movement of each side of the culvert [0.35 to 0.5 in. (8.9 to 12.7 mm)] occurred during the 3 ft (0.9 m) of backfilling above the spring-line elevation when the extensometers were placed. Additional fill caused another 0.1-in. (2.5-mm) inward movement on the H1 side but only caused 0.015 in. (0.38 mm) on the H2 side. These differences in magnitude probably resulted from the staging of construction because the filling on the H1 side was usually ahead of the H2 side, and bolt-tightening occurred simultaneously.

Inward movement was small on both sides during the last 2 to 3 ft (0.6 to 0.9 m) of filling up to about 1 to 2 ft (0.3 to 0.6 m) below the crown. Additional fill then caused a movement reversal, and both sides moved outward about 0.15 in. (3.8 mm) by the time the slab was added and the struts removed. During the load test process and final grading, variations within the range of ± 0.01 in. (± 0.25 mm) were observed. The net outward movement in this phase was a result of both the accumulation of residual strain from the load cycles and the addition of fill on top of the slab.

Figure 4b shows the trends for the pressures on the structure and under the slab during construction and subsequent static load testing. The horizontal stress, measured by gauge S1, at the spring line increased continuously as fill was added and sharply increased again when the slab was poured. A similar trend was observed higher on the pipe by stress gauge S2. The pressure reduction at point A for S2 may be a result of inward structure movement caused by the staging of backfilling. Gauges S1 and S2 showed the highest pressures of all the gauges. Gauges S4 and S5 showed an increase of 1 to 2 psi (6.9 to 14 kPa) as the trench above them was backfilled. Some of the pressure increase during the load-testing phase was caused by the addition of fill over the slab. The remainder was possibly caused by stress redistribution.

On two occasions for most gauges (Figure 4b, D, events 13 and 21) a noticeable pressure drop of up to 1 psi (6.9 kPa) was observed. This drop is believed to be a result of an overnight temperature decrease. Cooling of the steel structure would cause a slight shrinkage, and a pressure relief around the structure would result. Therefore, some of the other minor oscillations in the pressure graphs probably are influenced by temperature change.

All of the gauges showed a pressure increase under the first loading by the 32,800-lb (14 900-kg) truck (event 17) with only a small part of this pressure change generally eliminated after unloading. The additional load cycles during the remaining live load testing produced only a small additional net change in pressure.

The vertical extensometer V1 compressed 0.15 in. (3.8 mm), the upper horizontal extensometer H4 shortened by about 0.05 in. (1.3 mm), and the lower horizontal extensometer H3 extended about 0.03 in. (0.8 mm) from the time that these gauges were placed until the slab was poured and the struts removed. The subsequent movements of these extensometers during load testing were small by comparison (Figure 5a). The two horizontal extensometers exhibited approximately the same trends. The compression change in both when the slab was loaded by the truck indicates either (a) that the composite soil-steel-concrete structure deforms in a bending mode with the neutral axis next to the pipe or (b) that the system is deforming in compression like an arch.

The pairs of struts, installed at 6-ft (1.8-m) intervals along the length of the structure, supported the points shown in Figure 6. These struts were positioned prior to any backfilling over the top of the structure. The struts were removed after the slab was poured and partially cured. The nonuniform pressure distribution shown in Figure 6 was believed to be created under the slab and around the culvert as a result of the stress relief at the strut points when the struts were removed. This distribution did not change when additional fill was placed over the slab. The cross section on which the gauges were located was halfway between two strut cross sections. The average pressures under the slab of 2.9 to 6.8 psi (20 to 47 kPa) for the two situations shown in Figure 6 were about twice the average overburden stress. This indicates a longitudinal redistribution of stress accompanying strut removal, in which the stress

Table 1. Description of construction events corresponding to instrument readings.

Event	Description
0 to 6	Backfill elevation increased from spring line to 40 in. above spring line (56 in. below crown)
7	Backfill increased to 70 in. above spring line (26 in. below crown) and then struts added
8 to 10	Backfill increased to slab level, about 2 ft above crown
11 to 13	Trench dug for installation of gauges above structure and then backfilled
14 to 15	Slab poured and partially cured, then struts removed
17	After first loading with 32,800-lb truck conducted
18 to 21	Additional live load tests conducted
22 to 24	Several more live load tests conducted and addition of 1 to 2 ft of gravel fill placed over slab

Note: 1 in. = 2.5 cm. 1 lb = 0.45 kg.

Figure 4. Measured pressures and deformations during construction.

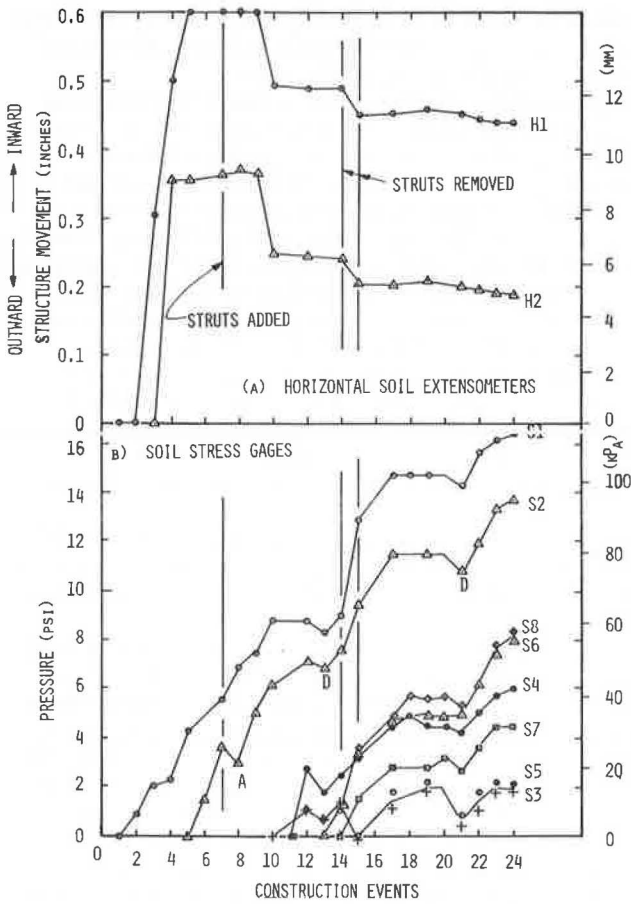


Figure 5. Movements after slab constructed and struts removed.

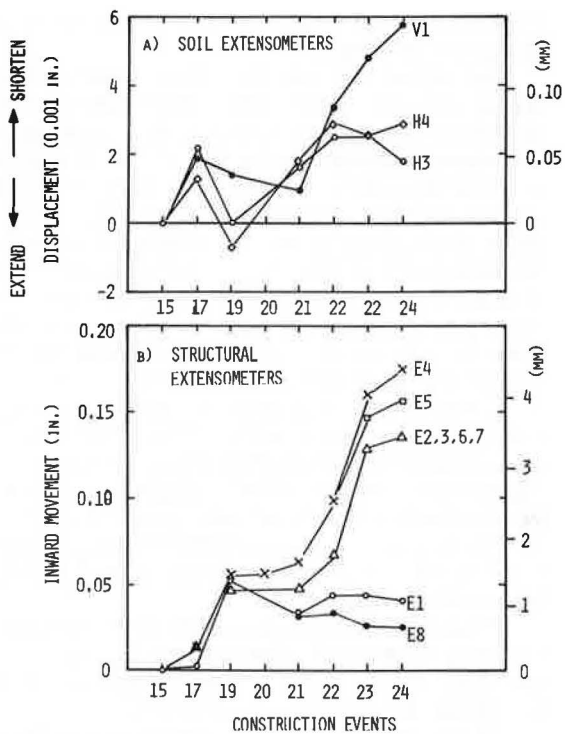


Figure 6. Final pressure distribution around structure and under slab.

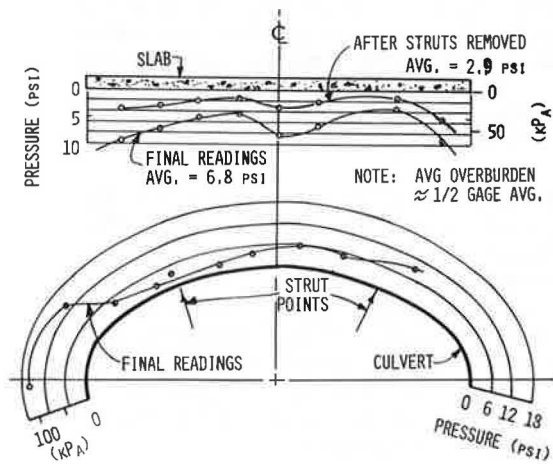
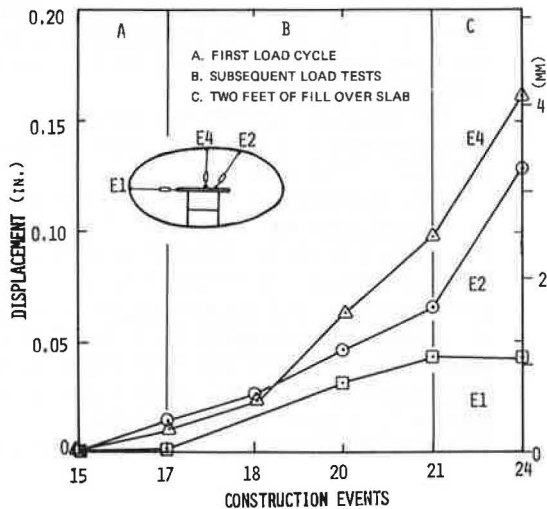


Figure 7. Inward movement of structure during load tests and final filling.



relief at the strut sections caused a stress increase at the intermediate points including the gauge locations.

The structural extensometers were installed after the slab was constructed and the struts removed (event 15). Therefore no information was obtained on the magnitude of structure deflection caused by the construction phases. The measurements for the structural extensometers are shown in Figure 5b. The two horizontal structural extensometers showed little movement during the first loading with the 32,800-lb (14 900-kg) truck (change from event 15 to 17). All of the other extensometers moved about the same amount and generally indicated inward movement under load and a small amount of rebound on unloading. A much larger residual inward movement of about 0.05 in. (1.3 mm) occurred for all extensometers after many additional load cycles in event 18 were completed. The effect of the next series of live load tests (events 19 to 21) appeared to be small. Addition of fill on top of the slab (events 22 to 24) caused outward movement at E1 and E8 and inward movement at the other structural extensometers.

Extensometers E1 and E8 were in good agreement, and this indicates symmetry of conditions on the two sides of the structure. The maximum movement was registered by the vertical extensometer E4, as expected, and the nearest extensometer to it, E5, showed the same trend with slightly smaller deflections. The remaining, vertically inclined extensometers were grouped together in magnitude of movement.

The residual structural deformation after the load tests and final grading was about 0.16 in. (4.1 mm) vertically downward and 0.04 in. (1.0 mm) horizontally inward on both sides (Figure 7).

From the construction measurements for the vertical soil extensometer V1 and the vertical structural extensometer E4, it is apparent that the relative deflection between the slab and the structure is negligible compared with the deflection of the crown of the structure (Figures 5a and 5b).

The readings of the horizontal soil extensometer H measured outside the structure at the spring line are roughly consistent in trend with those for the horizontal structural extensometer E (Figures 4 and 6a). Outward movement of the structure would cause H compression and E extension, for example. However, the magnitudes of the H and E readings are different: Much smaller changes are indicated for H than for E on both sides of the structure. One possible explanation is that the zone of deformation in the soil extends well beyond 13 ft (4 m) from the structure. In addition, the cohesive soil beyond the backfill zone is most likely more compressible than the granular backfill.

The relationship between the pressure under the slab and the crown deflection from the construction process is shown in Figure 8. The average modulus is approximately 26 lb/in.³ (7070 kPa/m).

Most commonly used design procedures for culverts require some measure of the horizontal passive resistance of the soil to outward movement of the structure. The dimensions of the associated modulus are pressure per unit deflection. An estimate of this modulus was obtained by plotting the spring-line pressure as a function of the corresponding soil extensometer movement (Figure 9). During the live load test phase, the modulus increased from 17 to 170 lb/in.³ (4620 to 46 200 kPa/m). However, because the structural extensometers showed larger lateral movement than the soil extensometers, the actual moduli are probably lower than those shown in Figure 9. During the initial stages of backfilling, the modulus was about 4 lb/in.³ (1090 kPa/m). This can be thought of as the active coefficient of backfill reaction.

LIVE LOAD TESTS

Most of the live load tests were conducted by using a gravel-filled dump truck with a gross weight of 32,800 lb (14 900 kg) (Figure 2). The load positions relative to the structure and the instrumented cross section are shown in Figure 10. The first load test consisted of positioning the truck successively in positions D, C, and E and then moving it off the slab to the starting position A. Residual deformations and net pressure increases were observed after the load was removed (Figure 11). The residual

Figure 8. Pressure under slab S8 related to crown deflection E4.

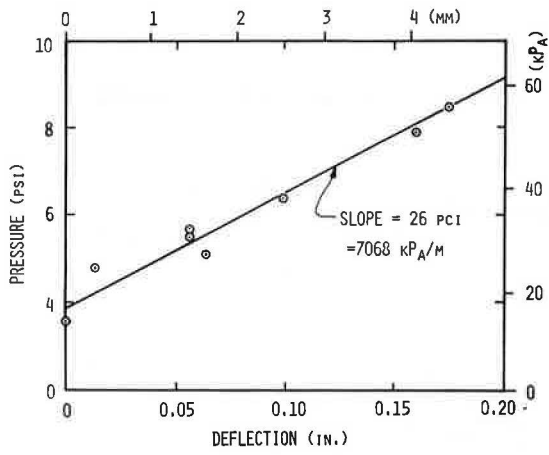


Figure 9. Relationship of spring-line pressure to deformation during construction.

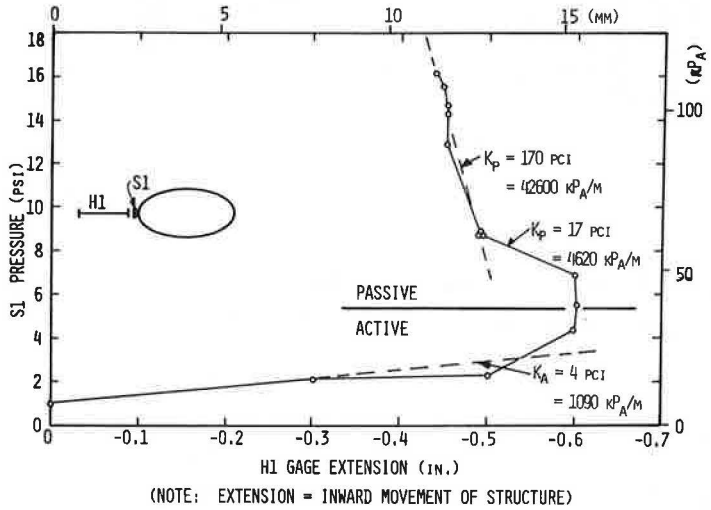


Figure 10. Load positions for 32,800-lb (14 900-kg) truck.

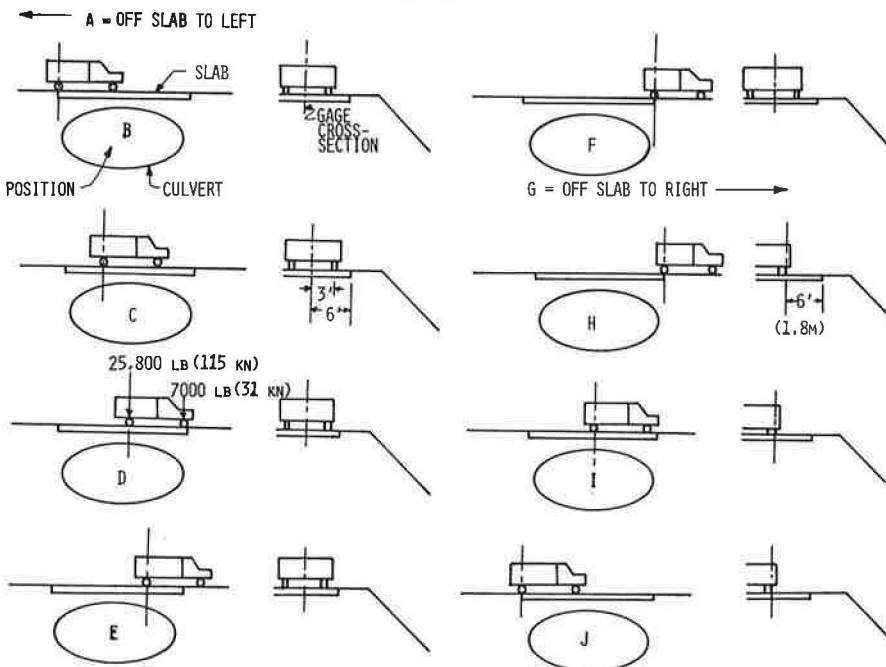


Figure 11. Residual pressures and deflections after first live load test.

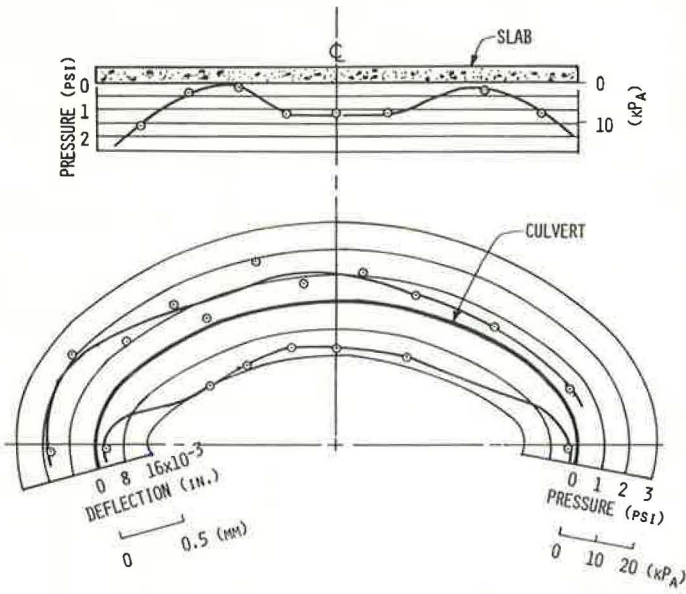
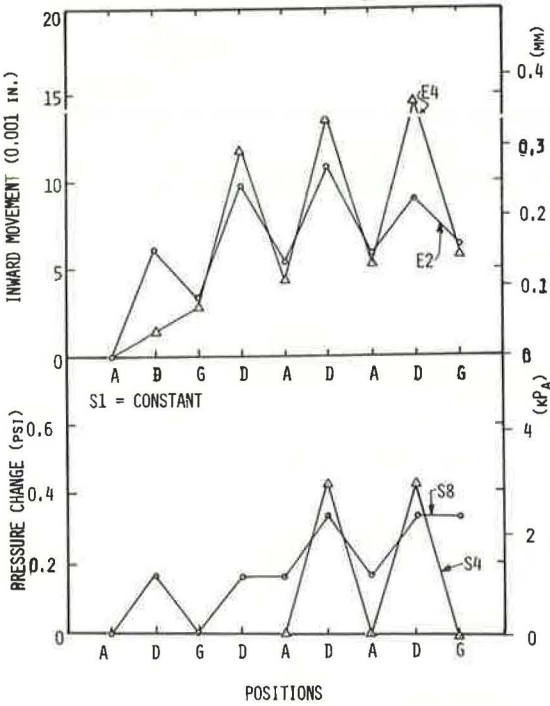


Figure 12. Results from second live load test.



radial deformations were all inward, amounting to 0.003 in. (0.008 mm) at the spring line and 0.014 in. (0.36 mm) at the crown. This pattern suggests slippage at the longitudinal bolted joints in the structure. At the same time residual pressure increases of about 0 to 2.2 psi (0 to 15 kPa) occurred on the structure.

In the second live load test, the truck made a series of passes on and off the slab. The observed elastic and residual pressures and deformations at several locations (Figure 10) are shown in Figure 12. The average ratio of pressure increase under the center of the slab to the crown deflection under the vehicle loading was approximately 47 lb/in.³ (12 800 kPa/m). Spring-line movements were less than 0.001 in. (0.025 mm).

In the third live load test, the truck made a pass over the slab from position A to G at a constant speed of about 5 mph (8 km/h). The results are shown in Figures 13, 14, and 15. The residual readings are minor compared with the peak values; therefore, the response is essentially elastic. A reverse pass from G to A gave almost the same results; however, the curves in Figure 13 are not symmetrical about the center position D. The peak dynamic stress around the structure was about 0.15 psi (1.0 kPa) at the crown. The peak stress under the center of the slab was about 0.5 psi (3.4 kPa). The maximum crown deflection was 0.009 in. (0.23 mm), and deflections at all other locations were smaller. None of the soil extensometers changed by more than 0.0005 in. (0.013 mm). The ratio of pressure increase under the center of the slab to crown deflection was 34 lb/in.³ (9230 kPa/m).

In the fourth live load test, the vehicle was positioned for a moment in each location in Figure 10. This test gave numerical results similar to those for the previous test with the continuously moving truck for positions A through G. For the reverse pass (positions H through J) in this case, the truck wheels on the right side passed over the gauge section rather than a straddle pass. The trends were similar, but the magnitudes of the peak readings were smaller by an average of 34 percent. The pressure distribution and deflection pattern produced by the truck in position D (center of slab) is shown in Figure 16. The maximum deflection under the 32,800-lb (14 900-kg) load was about 0.012 in. (0.3 mm) at the crown. The maximum pressure on the structure was 0.3 psi (2.1 kPa), and the maximum under the center of the slab was 0.8 psi (5.5 kPa).

The structure was also tested under a live load of 162,000 lb (73 500 kg) produced by the combined weight of three gravel trucks positioned side by side on the slab. The crown deflection under this load was 0.052 in. (1.3 mm), and the ratio of pressure increase under the slab to crown deflection was 33 lb/in.³ (8960 kPa/m).

INTERPRETATION OF DIAMETER CHANGES

In interpreting the field data related to the structural extensometers consideration should be given to: (a) the effects of a temperature change on the shape of the structure and the lengths of the connecting cables and metal support frame of the extensometers, (b) a change in the shape of the structure due to bolt slippage, and (c) a change in shape due to the hoop stress in the structure.

A decrease in temperature would cause the cables of the structural extensometers to shorten, which would move the sensing elements of the extensometer apart. The same decrease in temperature would also cause the perimeter of the structure to shorten, which would decrease the lengths of its axes. This will cause the sensing elements of the extensometers to move together so that essentially no net change in extensometer reading would be observed. However, the steel would not be likely to change in temperature as readily as would the structural extensometers because it is in contact with the backfill on one side. Thus air temperature decrease inside of the culvert would show an apparent increase in culvert diameter.

The observed overnight deformation changes with the structural extensometers are shown in Figure 17 both with and without the 0.30-in. (7.6-mm) adjustment for the estimated temperature effect on the extensometers. The adjusted readings indicate a shrinkage of the structure. These readings are consistent with those for the observed pressure reductions (Figure 4).

Figure 13. Soil stress changes during third live load test.

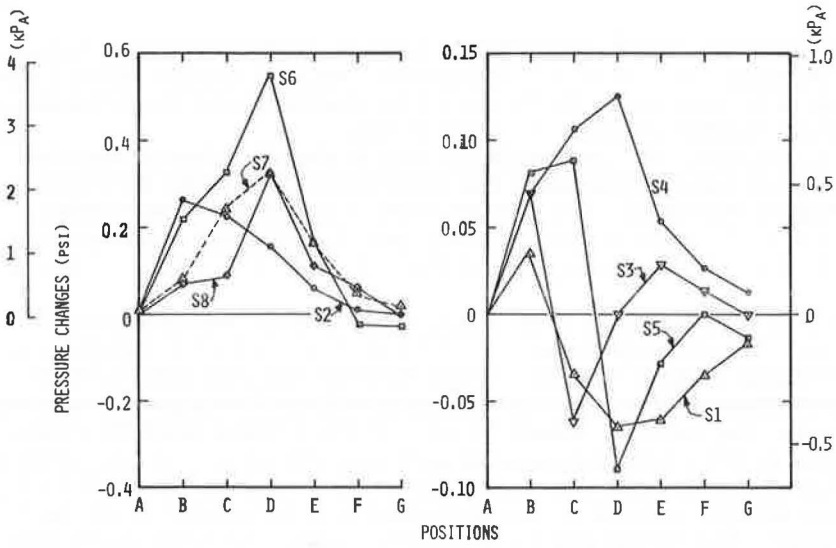


Figure 14. Extensometer changes during third live load test.

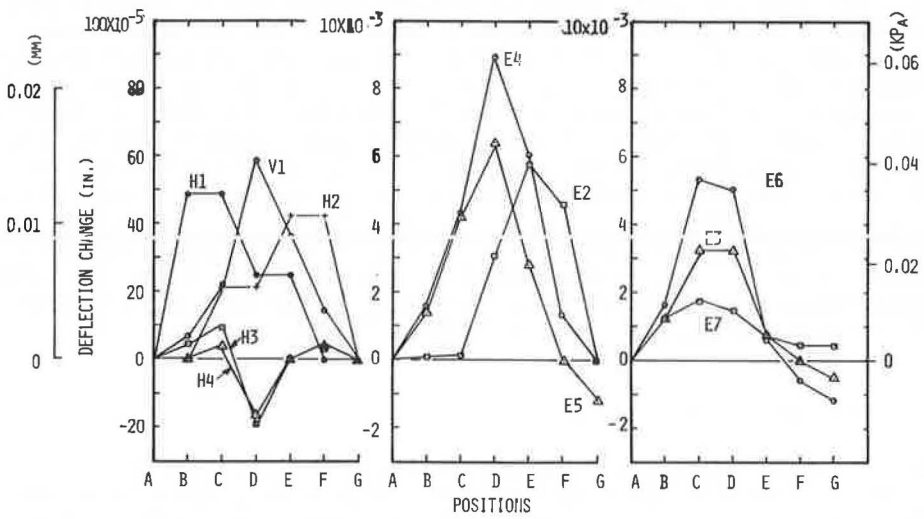


Figure 15. Culvert deflection pattern based on structural extensometers for truck moving over positions indicated.

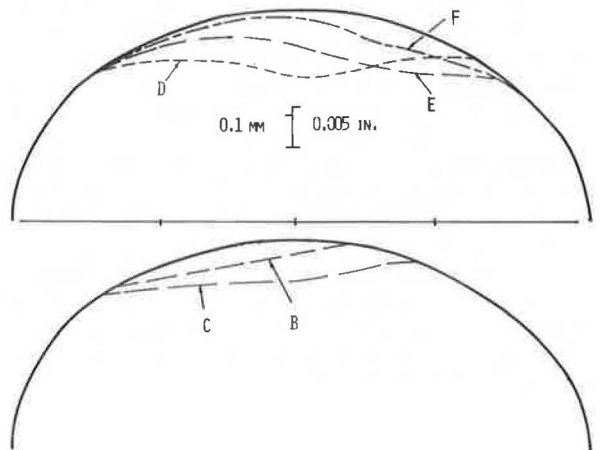


Figure 16. Pressures and deflections for 32,800-lb (14 900-kg) truck in position D.

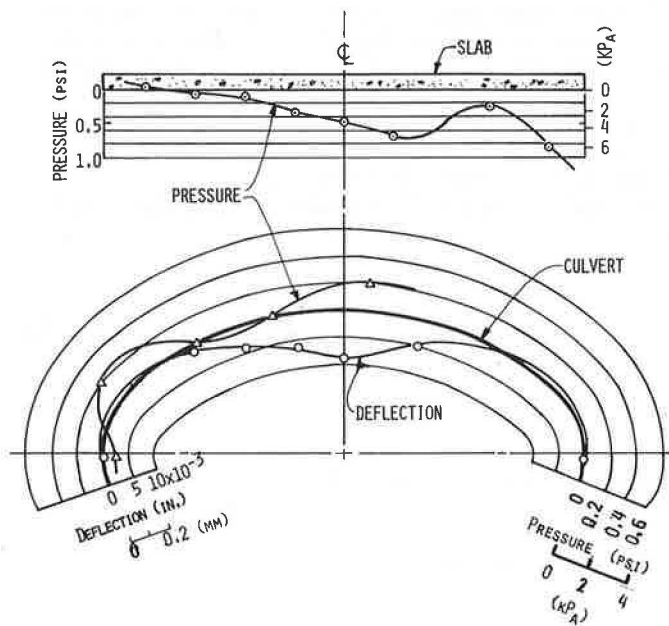
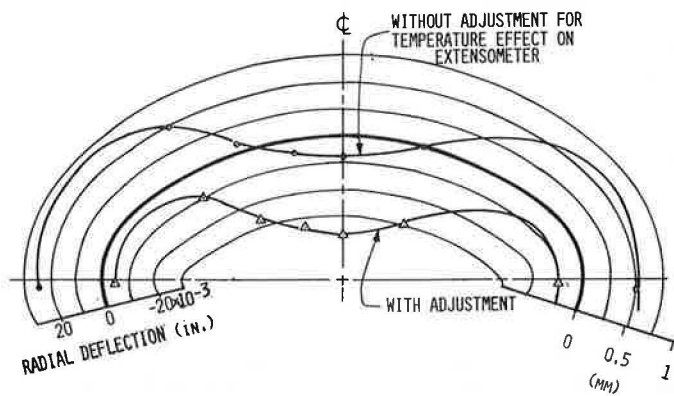


Figure 17. Radial deformations of structural extensometers caused by overnight temperature drop.



The bolt hole diameter in the plates is 1 in. (2.5 mm), and the bolt diameter is 0.75 in. (19 mm). This leaves an average clearance of 0.125 in. (3.2 mm)/joint. There are a total of 14 longitudinal joints in the pipe. Hence, an average perimeter shortening of 1.75 in. (44 mm) could be expected from slippage if friction were overcome. This would result in a change of 0.35 to 0.19 in. (8.9 to 4.8 mm) in the major and minor diameters respectively. These are much larger movements than those needed to explain the apparent net inward movement at the spring line in Figure 11. Based on an average soil pressure of 8 psi (55 kPa) around the pipe, calculations show that the assumption of slippage at one joint, at least, is reasonable.

If the ring compression theory is used, the thrust T in pounds per foot (kilograms per meter) of length of culvert is

$$T = \frac{pD}{2} \quad (1)$$

where

p = average pressure on pipe from soil in lb/ft² (Pa), and
 D = average pipe diameter in ft (m).

The stress-strain relationships in the pipe wall give

$$\frac{T}{A} \left(\frac{P}{\Delta P} \right) = E \quad (2)$$

where

$E = 30 \times 10^6 \times 144$ in lb/ft² (Pa),
 P = length of perimeter in ft (m), and
 A = area of section in ft²/ft (m²/m).

Combining equations 1 and 2 gives

$$\frac{\Delta P}{P} = \frac{pD}{2AE} \quad (3)$$

For the five-gauge, 2 × 6-ft (0.6 × 1.8-m) corrugation, $A = 0.022$ ft²/ft (0.0068 m²/m). The average final backfill pressure on the culvert was about $p = 8 \times 144$ lb/ft² (55 kPa). The average diameter is $D = 22.5$ ft (6.9 m). Thus $\Delta P/P = 0.000135$. The corresponding average diameter change would thus be $\Delta D = 0.003$ ft (0.0009 m) or about 0.04 in. (1 mm). This diameter change is also large enough to account for the apparent residual inward movement at the spring line that resulted in permanent pressure increases around the pipe (Figure 7) after a series of live load tests.

OBSERVATIONS

1. Although a comparison of results with live load tests without the slab was not possible, the results with the slab indicate that the slab was effective in distributing the vehicle load and in stiffening the soil-steel structure. A vehicle load of 162,000 lb (73 500 kg) caused a crown deflection of only about 0.050 in. (1.3 mm).

2. The total inward movement of the spring line of the structure during the stages

of backfilling above the spring line was about 0.3 to 0.6 in. (7.6 to 15 mm). This was much larger than the 0.16 to 0.19-in. (4.1 to 4.8-mm) outward movement accompanying the remainder of construction and load testing. The outward movement of the structure increased the pressure against the fill. The zone of passive resistance apparently extended beyond the 13-ft (4-m) granular fill into the more compressible natural clay stratum at the site.

3. The granular backfill provided stiff lateral support to the structure. The outward movement during the final stages of filling over the crown showed a modulus of 17 lb/in.³ (4620 kPa/m). However, during the load testing and final grading after the struts were removed, the modulus increased to 170 lb/in.³ (46 200 kPa/m).

4. The stiffness of the fill over the top of the structure was great enough compared with the stiffness of the structure so that the deflection of the slab over the crown was essentially the same as the crown deflection. The subgrade modulus for the center of the slab was thus equal to the pressure under the slab divided by the crown deflection. After a few load cycles, when the soil-structure system began to behave elastically, the modulus under the center of the slab was 25 to 70 lb/in.³ (6790 to 19 000 kPa/m). This modulus will increase with distance from the center.

5. The pressures around the structure in the live load tests were an order of magnitude smaller than the dead load values from the slab and fill after construction. The maximum pressure at the center under the slab from the 32,800-lb (14 900-kg) vehicle was estimated to be about 0.7 psi (4.8 kPa). The corresponding maximum pressure on the crown was about 0.3 psi (2.1 kPa). Higher values of pressure were observed under the ends of the slab when the vehicle load was at the quarter point of the slab.

6. The changes in structure diameter in the live load tests were also an order of magnitude less than those from the dead load. When the 32,800-lb (14 900-kg) truck was in the center of the slab, the vertical deflection of the crown was about 0.01 in. (0.25 mm) compared with a total accumulative residual deflection of about 0.2 in. (5.1 mm) during the testing and addition of fill on top of the slab.

7. The first live load test caused a significant residual increase of 0.3 to 1.8 psi (2.1 to 12.4 kPa) in pressure under the slab and an increase of 0.4 to 2.1 psi (2.8 to 14.5 kPa) around the structure. A residual radial inward deformation of the structure also occurred, increasing from 0.004 in. (0.1 mm) at the spring line to 0.016 in. (0.41 mm) at the crown. Apparently this resulted from inelastic soil behavior and possibly from joint movement in the structure.

8. Bolt slippage at the joints of the structure could easily permit a reduction in perimeter of the structure. The timing of construction backfilling with the bolt tightening process could have a big influence on the magnitude and distribution of final pressures. The deformations resulting from thermal strains could also be as large as the live load deformations.

9. Considering the errors inherent in soil pressure measurements, the best estimate of the pressure distributions around the structure and under the slab at the completion of the tests is as shown in Figure 6. Under the slab, the average pressure was 6.8 psi (47 kPa), but it increased from about 8 psi (55 kPa) in the center, to 4 psi (28 kPa) at the quarter points, and to 10 psi (69 kPa) near the ends. The average pressure over the center of the structure was about 4.2 psi (29 kPa), and the maximum at the crown was 5.6 psi (39 kPa). These correspond to an overburden density of about 116 to 155 lb/ft³ (1860 to 2480 kg/m³) with a depth of 5.2 ft (1.6 m). This is in the range of the existing average density. The final crown pressure was about 5.6 psi (39 kPa). The pressure decreased to about 2.8 psi (19 kPa) at the strutting support point and increased again to 15.4 psi (106 kPa) at the spring line. The final horizontal pressure at the spring line was about equal to the vertical geostatic stress at that level.

10. The slab-fill-steel pipe composite section at the top of the structure was considered to act as a beam or an arch. The data obtained do not really clarify this; however, a combination of the two models is probably more correct.

11. Field stress measurements in soil are difficult to make accurately, and an uncertainty of ± 50 percent exists. Careful laboratory calibration of the gauges in soil is needed, and in-place field calibration checks are desired. For this study, a limited laboratory evaluation was performed. Although this is much more than is usually done,

an additional gauge evaluation program is desirable that includes the effect of having the gauges close to the concrete slab.

12. The staging of strut installation and removal appears to be one of the most important factors in determining the pressure distribution around the structure and under the slab. The slab, when freshly poured, applied a uniform surcharge to the fill. Deflection under this surcharge and the fill on top of the structure was limited at the strut points and probably maximum at the crown. The struts were removed after the slab concrete had hardened. Resulting deflection at the strut points relieved the pressure there and transferred it to the center and haunch zone. The total load carried by the structure also increased and thereby increased the lateral pressure at the spring line.

13. All of the field measurements provided in this study contributed useful information to understanding the soil-structure interaction. It is desirable to obtain similar data on several other projects before generalizing the results. The primary reason is that the results are affected to an unknown degree by the construction details. In such tests, close coordination of the measurements and construction is urged. The influence of the struts should be carefully examined. Temperatures of the structure should also be measured.

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