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California Department of Transportation Structural Steel Plate Pipe Culvert Research: Design Summary and Implementation

A. E. BACHER and D. E. KIRKLAND

ABSTRACT

Three structural steel plate pipes (SSPP) have been instrumented and tested as part of an extensive culvert research program by the California Department of Transportation. Two were functional roadway cross drains, at Chadd Creek and Apple Canyon, and one was a grossly underdesigned culvert, the DB culvert. The Chadd Creek culvert was a 114-in. SSPP 0.280 in. thick with 89 ft of overfill and Method B backfill (baled straw surmounting the pipe). The diagram of Method B fill height versus soil stress was nonlinear; strains and strain gradients were large; deflection was 1 percent. The Apple Canyon culvert was a twin 108-in. SSPP 0.375 in. thick with 160 ft of overfill and Method A backfill (structure backfill surrounding the culvert periphery). The diagram of Method A fill height versus soil stress was linear; relatively uniform peripheral pressures were observed; there was an effective density increase of 50 percent subsequent to fill completion and 2 percent deflection. The DB culvert was a 120-in. SSPP 0.109 in. thick with a maximum of 190 ft of overfill and six zones of Method A backfill and two zones of Method B backfill. The six Method A zones suffered excessive deflections or seam failure before fill completion. The two Method B zones (with slotted bolt holes or sprayed polystyrene backpacking) reduced effective densities significantly. Conclusions for Method A are that the design loading should be 140V:140H and that the effective density increase should be 1.5. The Marston and Spangler design methods are not recommended; ring-compression and neutral-point analysis are acceptable designs. The Method B conclusions are that baled straw is not recommended and that slotted bolt holes and sprayed polystyrene show promise.

In 1963 the California Department of Transportation (Caltrans) in cooperation with the FHWA, initiated a $3.5 million culvert research program to assess structural behavior of culverts embedded in deep embankments. Included in this extensive culvert research program were three structural steel plate pipe (SSPP) projects.

The SSPP culvert research program was mandated by

1. Distress observed in flexible culverts under earth embankments ranging up to 150 ft in depth,
2. A proposal by District 1 to use Method B (baled straw) backfill surmounting an SSPP, and
3. Collapse of a contractor's 27-ft-diameter SSPP truck loading chute at Los Banos Reservoir in 1963.

The three SSPP culvert research projects are described as follows:

Location	Plate Thickness (in.)	Culvert Size (in.)	Overfill (ft)
Chadd Creek	0.280	114	89
Apple Canyon	0.280, 0.375	108	160
DB Culvert	0.109	120	190

CHADD CREEK

The initial one of the three Caltrans flexible pipe culvert research projects was a 114-in. functional SSPP surmounted by layers of baled straw (Method B) at Chadd Creek. Instrumentation consisted of Carlson soil stress meters and SR-4 strain gauges.

The effective density profiles based on unadjusted soil pressure readings for the Chadd Creek culvert are shown in Figures 1 and 2. Effective density is defined as the equivalent density of soil that results in the recorded pressure at each meter. It is calculated by multiplying the recorded meter pressure in pounds per square inch by 144 and dividing that value by the fill height in feet. Each point on the plot periphery where an effective density value is shown represents a meter location. The scale of the culvert size and magnitude of the effective densities is common to all effective density plots. The design parameters for each zone (size of culvert, thickness of culvert material, and bedding and backfill parameters) are shown on the left of each figure. The effective densities at the time of fill completion are shown in the center plots, and those recorded 28 months subsequent to fill completion are on the right.

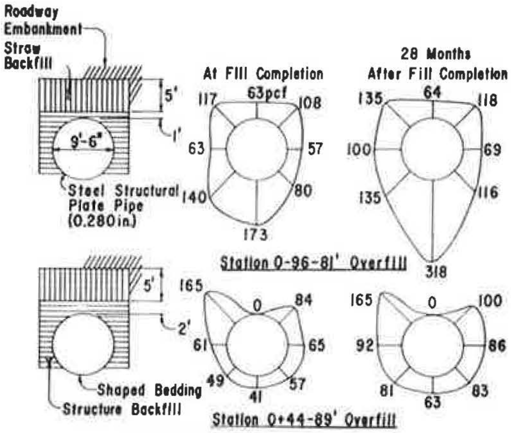

FIGURE 1 Chadd Creek: effective densities, Stations 0-96 and 0+44.

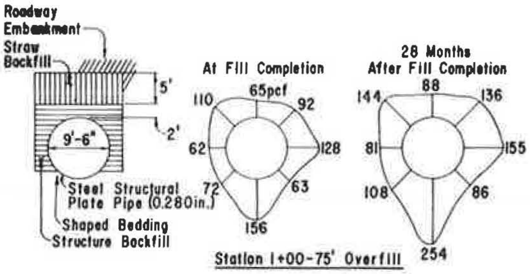

FIGURE 2 Chadd Creek: effective densities, Station 1+00.

The method B type installations of SSPP at Chadd Creek had baled straw as the soft inclusion in the backfill (Stations 0-96, 0+44, and 1+100).

Although the Chadd Creek pipe did not exhibit any noticeable distress and pipe displacements remained relatively small (e.g., 1 percent), it is apparent from viewing the effective density profiles that there is an adverse effect on the pipe from the straw backfill. As one can see from Figures 1 and 2, the peripheral effective densities are not uniform, and a relatively uniform loading condition about the periphery is considered essential to the performance of a flexible culvert. Care also has to be taken to control deflections for a flexible culvert.

The plot of soil pressure versus fill height for the Chadd Creek culvert indicates a distinct nonlinearity in loading (Figure 3). There was also an increase in effective densities subsequent to fill completion.

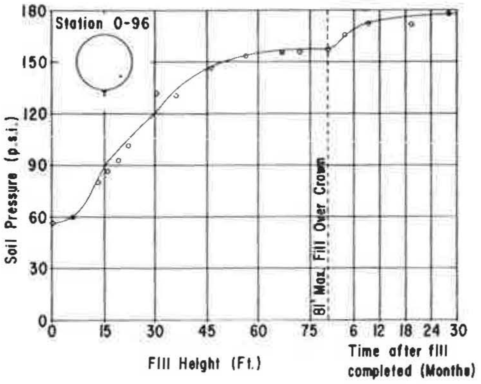

FIGURE 3 Chadd Creek: soil pressures.

Marston's theory predicted higher crown pressures than observed and failed to predict the pressure increases after fill completion. Spangler's Iowa deflection formula (1,2) resulted in calculated deflections that ranged from 10 to 16 times larger than the measured vertical displacements. Ring-compression theory predicted thrusts that correlated well with observed thrusts. Neutral-point analysis (Figure 4) also resulted in excellent correlation between the theoretical and experimental bending moments. The moment gradient, however, was too large.

Method B baled straw backfill surmounting SSPP is not recommended (3-5).

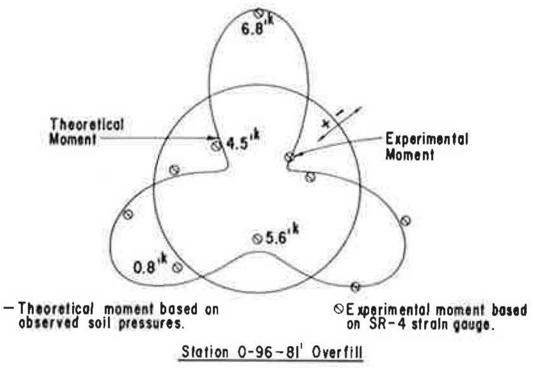

FIGURE 4 Chadd Creek: theoretical and experimental moments.

APPLE CANYON

The second research project on flexible pipe culverts was at Apple Canyon. It was a twin 108-in. functional SSPP under Method A backfill. Instrumentation consisted of Carlson soil stress meters and SR-4 strain gauges.

The effective density profiles for the Apple Canyon culvert are shown in Figure 5. These represent two Method A type installations, where structure backfill surrounds the pipe periphery (Stations 7+25 and 10+00). It is apparent from viewing the two effective density profiles for this flexible pipe that a single band of loading should be applied to a flexible culvert. Because a flexible culvert can deflect, a relatively uniform loading condition is created about the periphery. However, care has to be taken to assure controlled deflections for a flexible culvert.

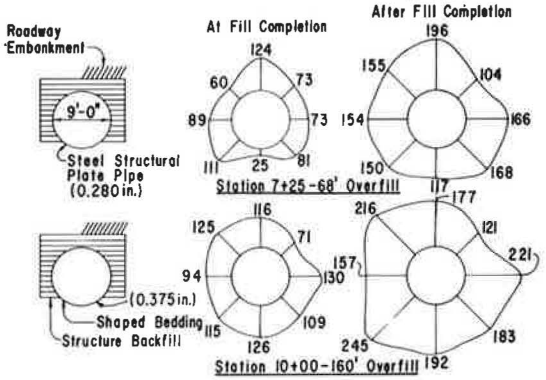

FIGURE 5 Apple Canyon: effective densities, Stations 7+25 and 10+00.

The effective density increase with time was quite significant. At Apple Canyon, the increase on the average was approximately 50 percent; at Station 10+00, for example, the effective density at the lowest left meter increased from 115 to 245 pcf in the 24 months subsequent to fill completion. Similarly, Station 7+25 also exhibited the same dramatic increases in effective density. There is essential linearity in loading for Apple Canyon with Method A backfill, as shown in the diagram of fill height versus soil stress (Figure 6). Of particular significance is the increase in soil stress after fill completion. By contrast, there was distinct nonlinearity in the plot of fill height versus soil pressure for Chadd Creek with Method B backfill.

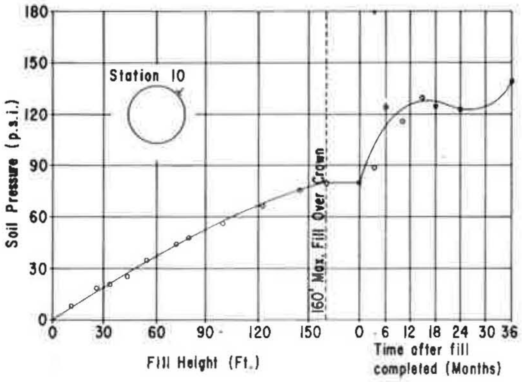

FIGURE 6 Apple Canyon: soil pressures.

Previously specified yield strains (57,000 psi observed versus 28,000 psi specified) were common at Apple Canyon, but the pipe displacements remained relatively small with less than a 2 percent change from the initial installed peripheral shape.

Marston's theory failed to predict the pressure increase after fill completion. Spangler's Iowa deflection formula resulted in theoretical deformations 8 to 11 times larger than those observed. Ring-compression theory had calculated thrusts that were only 50 percent of the measured thrusts. There is an effective density increase subsequent to fill completion; that is, $B_e = 1.50$. Neutral-point analysis (Figure 7) provided fair correlation between the theoretical and experimental bending moments. The moment gradient was far less than that observed at Chadd Creek; in fact, the moment gradient at Chadd Creek was 50 percent higher. Finite-element analysis yielded poor correlations between measured and theoretical displacements and pipe stresses (6,7).

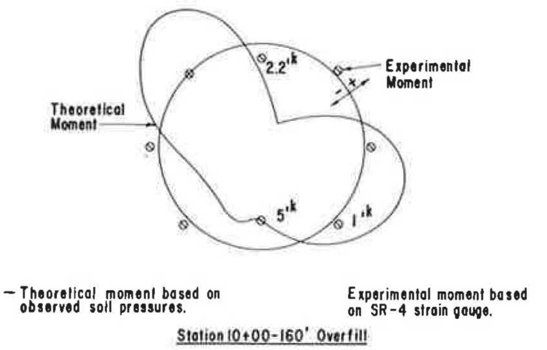

FIGURE 7 Apple Canyon: theoretical and experimental moments.

DB CULVERT

The DB culvert was a 320-ft-long, grossly underdesigned dummy SSPP divided into eight zones, each having different bedding and backfill parameters. Various levels of backfill compaction, the effects of shaped versus flat bedding, and trench installations were among the parameters considered. In addition, two recent Method B innovations--circumferentially slotted bolt holes and sprayed polystyrene backpacking--were incorporated into the project. Instrumentation consisted of Kyowa and Ormand soil stress meters and SR-4 strain gauges that measured the pipe wall strains.

At the DB culvert the instrumentation was supplemented by Cambridge meters that measured soil shear stresses at the culvert-soil interface in addition to normal soil stresses. Further, there were three planes of meters spaced approximately 2 ft apart at each instrumented section, which provided added reliability for the test results.

The effective density profiles for Zones 1 through 8 (Figures 8-11) have been plotted based on the unadjusted soil-pressure readings.

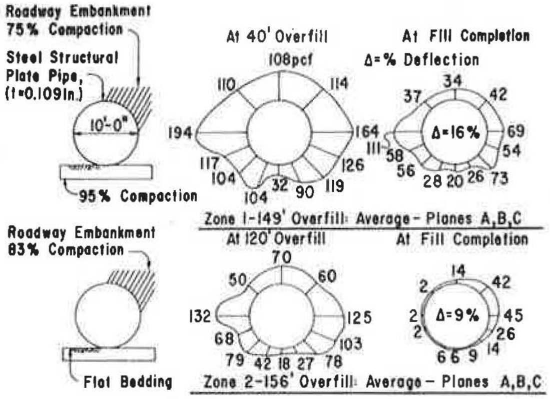

FIGURE 8 DB culvert: effective densities, Zones 1 and 2.

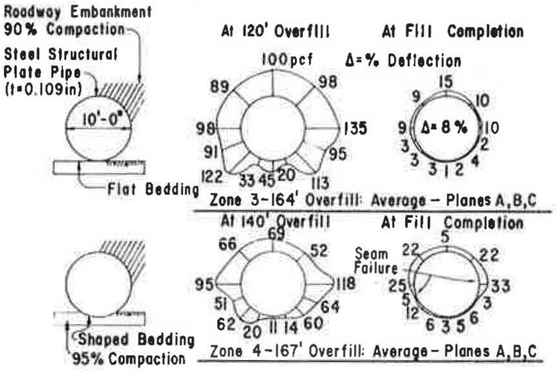

FIGURE 9 DB culvert: effective densities, Zones 3 and 4.

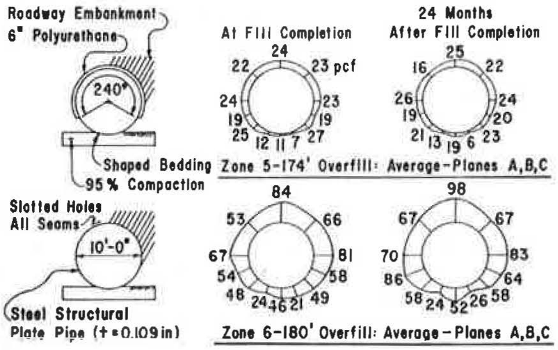

FIGURE 10 DB culvert: effective densities, Zones 5 and 6.

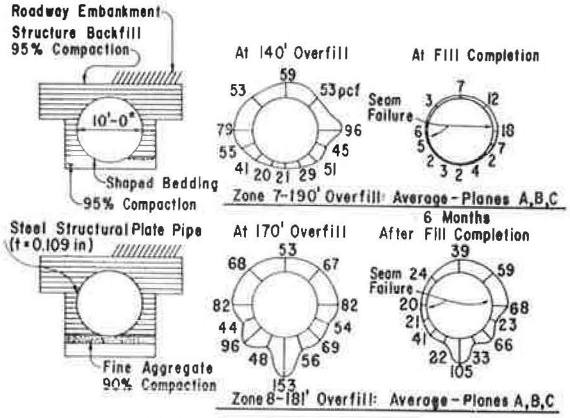

FIGURE 11 DB culvert: effective densities, Zones 7 and 8.

The Method A zones (Zones 1-4, 7, and 8) all exhibited distress at some fill less than the maximum overfill. The effective density plots have therefore been drawn based on the overfill at the time that this distress occurred, whether the distress was manifested by excessive deformation or seam failure. Deflections were significant: 18 percent at Zone 1 with 75 percent relative compaction, 9 percent at Zone 2 with 83 percent compaction, and 8 percent at Zone 3 with 90 percent compaction. A deflection in excess of 5 percent is considered structurally unacceptable based on Spangler's Iowa deflection formula (Zones 1, 2, and 3). Deflections at 75, 83, and 90 percent relative compaction were also compared with observed deflections in Watkins test cell at Utah State University. Horizontal diameter changes in the test cell were valid for high standard densities, but the limiting boundary conditions of the test cell resulted in poor correlation at lower densities, of 75 and 83 percent relative compaction. Zones 4, 7, and 8 exhibited seam failure. Where slotted holes were provided (Zone 6) and polystyrene was sprayed on the upper 240 degrees of the culvert periphery (Zone 5), the results were promising. The slotted holes closed prematurely when less than 20 ft of overfill had been placed. The relatively uniform effective density of approximately 25 pcf at Zone 5 with 6-in. polystyrene backing provided an excellent means of controlled reduction of peripheral pressures.

In the plot of soil pressures from the three planes of stress meters at Zone 3 (Figures 12 and 13), a wide disparity was exhibited between the Cambridge stress meters and the Kyowa and Ormond stress meters. The peripheral pressures at Zone 3 also were reduced because of overstress when the overfill exceeded 120 ft. Cambridge meter shear readings are shown in Figure 14. Note that some tangential shears were clockwise; others were counterclockwise. The tangential shear readings did not materially alter the recommended design effective densities.

Because of the excessive deflection or seam failure occurring at overfills less than the maximum overfill for Zones 1, 2, 3, 4, 7, and 8 during construction, no attempt was made to apply Marston's theory, Spangler's Iowa deflection formula, ring-compression theory, or neutral-point analysis. Finite-element analyses were made for Zones 2, 5, and 8. The finite element was not applicable when the overfill exceeded 120 ft, that is, after there was a seam failure. Further, the reality of probable variable soil parameters at a given culvert site emphasizes that finite-element applicability is contin-

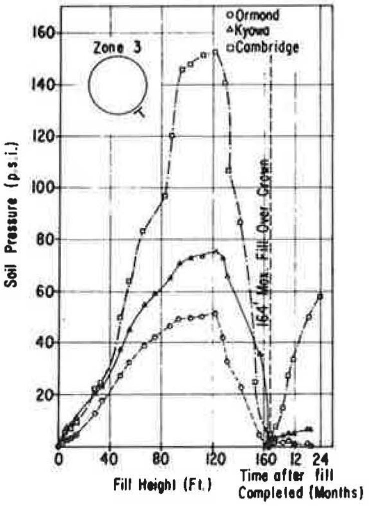

FIGURE 12 DB culvert: soil pressures.

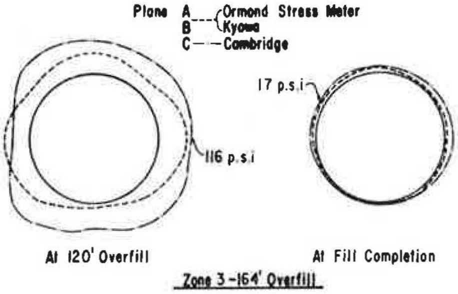

FIGURE 13 DB culvert: soil stress meters, normal pressures.

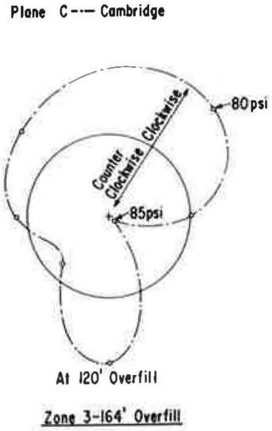

FIGURE 14 DB culvert: soil stress meters, tangential shears.

gent on the availability of adequate and complete soil data at each site.

Large deflections and buckling observed in the grossly underdesigned DB culvert indicate that current safety factors are not overly conservative. On Method A sections, the observed effective densities were approximately half those observed at Apple Canyon. Because DB is a nonfunctional culvert, there was no continuously saturated condition at the perimeter of the culvert caused by stream flow, which effectively reduced the external pressures. At the DB culvert distress occurred at approximately 120 ft of overfill. With an allowable design overfill of 33 ft, there was therefore a safety factor of only 2 because the observed effective densities at the DB culvert were only half those observed at Apple Canyon (8).

IMPLEMENTATION

The following Caltrans criteria were developed from the three research projects (9).

Method A

A uniform effective density of 140V:140H should be applied. An effective density increase of 1.5 (B_e) should also be applied. Ring-compression theory is considered to be an acceptable approximate design method for SSPP. Marston's theory and Spangler's Iowa deflection formula are not recommended. Neutral-point analysis is an acceptable alternative design method. Application of the ring-compression method by using load factor design is shown in Figure 15. AASHTO requirements are far less stringent, as shown in Figure 16. This criterion should specify a higher factor of safety.

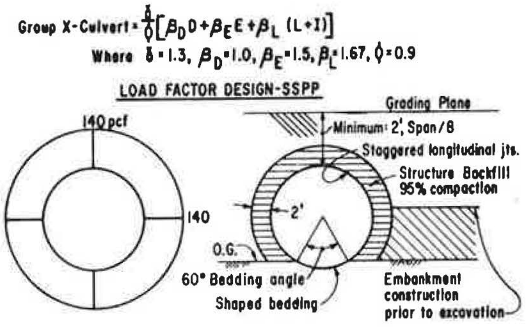

FIGURE 15 Caltrans criteria: unit load on culverts.

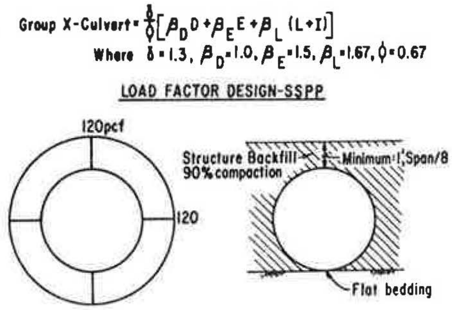

FIGURE 16 AASHTO 1.2.2(A): unit load on culverts.

Method B

Baled straw is not recommended for use on flexible steel pipe. Slotted bolt holes with proper keyhole designs may be used to reduce the loading. It is possible that sprayed polystyrene could be used to advantage because the DB culvert research showed that this technique resulted in an 80 percent reduction in current design effective densities. An assessment of its cost-effectiveness would have to be made.

COST SAVINGS

Based on Caltrans SSPP culvert research, the allowable overfill for a 60-in. (0.109-in.-thick) SSPP has been increased from 42 to 57 ft; for a 240-in. (0.280-in.-thick) SSPP it has been increased from 36 to 44 ft. The estimated savings over the full range of pipe sizes used in California is $150,000 per year.

ACKNOWLEDGMENT

Al Banke and Craig Chatelain of Caltrans also contributed to the development of the rational design method for SSPP now used in California.

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Construction and Field Evaluation of Precast Concrete Arch Structures

JAMES J. HILL

ABSTRACT

A construction and field evaluation is presented of the precast concrete arch structures (BEBO of America) that have been constructed in Minnesota since 1980. Fabrication, construction, and follow-up inspections of the arch structures have revealed certain construction techniques and structural deficiencies that require correction. Settlement and movement of selected arch structures have been monitored to determine deformation and related results. A construction time frame and an estimated cost comparison of alternative structures are also included.

The details and design of the precast concrete arch structures built in Minnesota are presented. The locations of these structures and their individual data are given in Figure 1 and Table 1. The plant fabrication and material specifications are related in general terms.

Field installation and follow-up inspections are presented that disclose structural inadequacies