Reinforced-Concrete Pipe Culverts: Design Summary and Implementation

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Research at Mountainhouse Creek and Cross Canyon on reinforced concrete pipe culverts has confirmed the following: (a) loadings 140V:140H and 140V:42H are acceptable for Method A; (b) there is no effective-density increase after fill completion; (c) Method B (baled straw, polystyrene, or uncompacted material) performed well; (d) fill height versus soil pressure is approximately linear for Method A and nonlinear for Method B; (e) there is good correlation between theoretical (soil pressure) and experimental (strain) moments and excellent correlation of the three instrumentation planes placed 3 ft apart; (f) there is asymmetry of loading and moderate success by using Cambridge meters, which measured normal and shear forces on the culvert periphery; (g) adjusted peripheral pressures based on normal and shear forces did not change essential validity of use of normal forces only; and (h) D-loads based on three-edge bearing tests provide valid allowable design overfills. Implementation of this research and future research considerations are discussed. Projected cost savings are $400 000 annually.

In 1963, the California Department of Transportation (Caltrans), in cooperation with the Federal Highway Administration, 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 reinforced-concrete (RC) pipes.

The research program on RC pipe was mandated by the following:

1. Significant distress was observed in RC pipe culverts under earth embankments that ranged up to 300 ft in depth on California highways. Such embankments were used as economical substitutes for long bridges and as convenient sites for excess material from deep cuts. For Method A (compacted structure backfill), requirements for bedding and backfill were restricted to pipes under the roadway only. In the case of long laterals, no controls were placed on bedding and backfill procedures, and subsequent severe distress was observed. For Method-B type installations (soft inclusion in the culvert backfill), unlimited overfills were permissible prior to 1963 based on Marston-Spangler design criteria; indiscriminate use of these criteria led to some of the observed problems.
2. There was conjecture that design criteria, previously employed for culverts with much lower overfills, could not be extrapolated safely.

Caltrans has recently completed the third and final phase of its RC pipe culvert research project at the third location. The three sites are described below:

Location	Culvert Size (in)	Overfill (ft)
Mountainhouse Creek, Part 1	84	136
Mountainhouse Creek, Part 2	84	136
Cross Canyon, RC pipe	84	188

MOUNTAINHOUSE CREEK

Research Summary

RC pipe culverts that Caltrans has tested are a grossly underdesigned 84-in RC pipe culvert (Part 1) and a functional 84-in RC pipe culvert (Part 2) in the same embankment under 136 ft of overfill at Mountainhouse Creek.

Mountainhouse Creek (Part 1) was a grossly underdesigned 1000D dummy pipe that terminated in the embankment at a timber bulkhead. All six test zones were positive projecting. The projection ratios were 0.4 in zones 7 and 8 and 1.0 in zones 9 through 12.

Mountainhouse Creek (Part 2) was a 4000D functional culvert. It was placed in a trench throughout its length and was surmounted by a layer of baled straw in all but one of its six test zones.

The research reports on the 1000D pipe (Part 1) and the 4000D pipe (Part 2) were published in April 1971 and September 1975, respectively (1-8).

Instrumentation consisted of soil-stress meters and displacement-measuring devices in Part 1 and soil-stress meters, strain gauges, and displacement-measuring devices in Part 2.

Design Summary and Applications

All effective-density plots in this paper are based on unadjusted meter readings. Effective density is the density of material, if hydrostatic conditions are assumed, required to produce measured soil stresses for a given overburden. The variations in loading about the periphery of RC pipes are somewhat similar to what was observed on the Caltrans RC arch culvert research. Method A-3 installations are zones 7-12 of Part 1 and zone 1 of Part 2. The plots at zones 7, 8, and 9 (Figures 1 and 2) indicate higher lateral effective densities falling approximately into the 140V:140H band of loading, whereas zone 1 more nearly approximates the 140V:42H band. These individual plots (Figures 1, 3, and 4) fall essentially within the two bands of loading now specified.

The effective density increases subsequent to fill completion were negligible. The total net increase would not justify an increased Beta Sub E for the design of RC pipes. Obviously, the 140V:42H band would be the more critical design value for a circular shape.

Method-B (baled straw) RC pipe tests compared zones 2-5 (Figures 4, 5, and 6) of Mountainhouse Creek, Part 2. This report was completed some four years after the Part 1 research report was completed. Before these Method-B zones are discussed, a further qualification is in order.

The absence of recorded effective densities on the periphery is indicative of the malfunction of soil-pressure meters at specific points on the culvert's periphery. At zone 3, for example, only 5 of the 12 meters on the periphery were functional. This does not, however, negate the research findings at these zones. In fact, there are at least five usable readings at each zone. Further, there was the initial presumption that because the readings were low, they were therefore invalid. However, the fact that five zones (zones 2-6) all shared these common low values attests to their validity. The results of Caltrans Method-B RC pipe research zones indicated a significant reduction in peripheral effective densities. As a consequence, however, the report was delayed several years. Because of this unfortunate experience with the soil-pressure meters, all Caltrans culvert research projects subsequent to Mountainhouse Creek mandated the use

Figure 1. Effective densities at Mountainhouse Creek, zones 7 and 8.

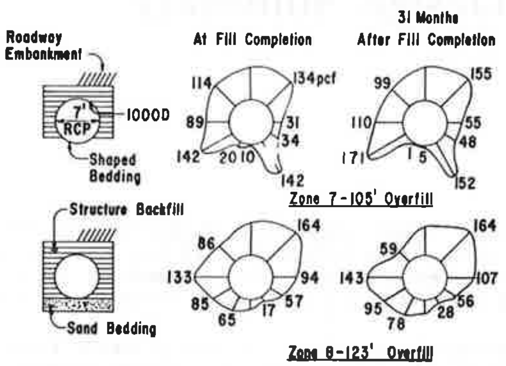


Figure 2. Effective densities at Mountainhouse Creek, zones 9 and 10.

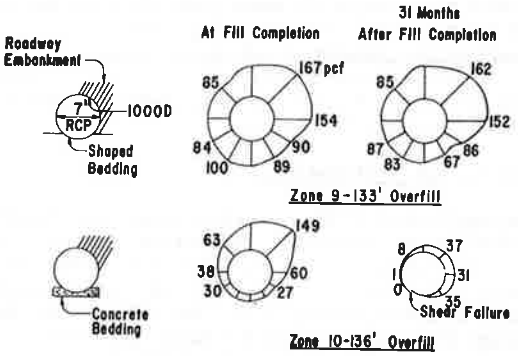


Figure 3. Effective densities at Mountainhouse Creek, zones 11 and 12.

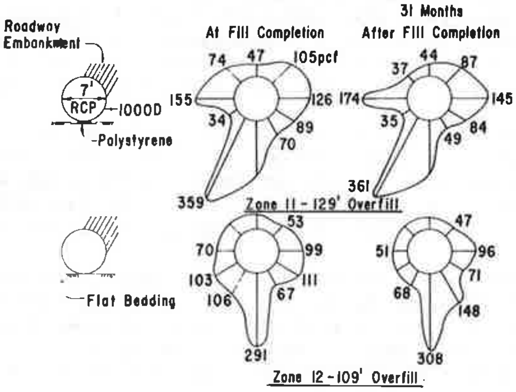
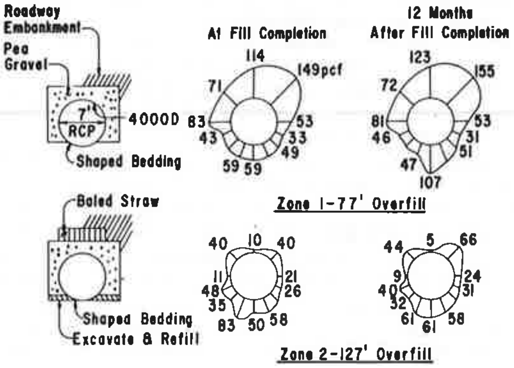


Figure 4. Effective densities at Mountainhouse Creek, zones 1 and 2.



of the more reliable Carlson soil-pressure meters on the culvert periphery.

Caltrans has continued the use of Method B (baled straw) solely on RC pipe designs with the qualification that two layers of reinforcing steel be provided in the pipe. Caltrans has discontinued the application of Method B on the RC box, RC arch, and structural steel-plate pipe culverts based on experience and recent research on RC arch and structural steel-plate pipe.

There was approximate linearity of plots of soil stress versus fill height on RC pipe employing Method A. This is indicated on the plot for meter 12, zone 1 (Figure 7). Some meters in Method-B zones had distinct nonlinearity. Meter 11 at zone 4 (Figure 8) is an example. Initially, there was very little increase in the soil-pressure reading, but there was a significant increase after 65 ft of overfill up to 135 ft of overfill.

As in all other Caltrans culvert research projects, good correlation was established between theoretical moments based on the measured soil pressures and the experimental moments derived from the internal strains at zone 1 (Figure 9). The theoretical and experimental moments were derived from values averaged about the vertical diameter.

The pipes in all four positive projection zones (zones 9-12) exhibited significant distress. This was manifested by an appreciable flattening of the pipes and compression spalling at the sides. Deflections ranged as high as 18 percent.

The most favorable results were observed in the two partly entrenched pipes (zones 7 and 8). Diameter changes were less than 2 percent. Maximum permissible overfill for 1000D pipe was at one time assigned a value of 16 ft in Caltrans specifications. These two pipes developed first hairline cracks at 44 ft and remained serviceable at 140 ft of overfill, which demonstrated that one of the most

Figure 5. Effective densities at Mountainhouse Creek, zones 3 and 4.

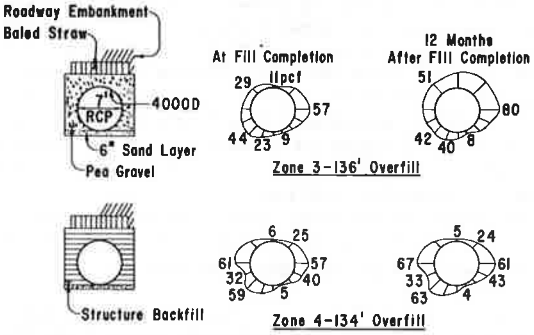
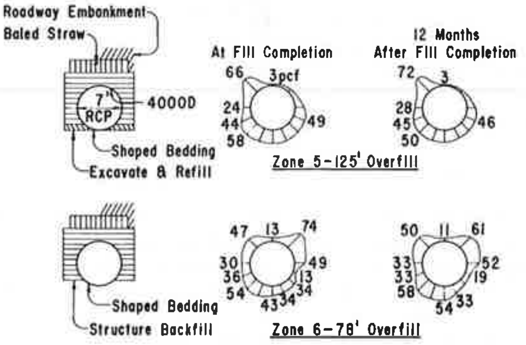


Figure 6. Effective densities at Mountainhouse Creek, zones 5 and 6.



important factors in culvert design and construction is the provision of adequate lateral support. The research indicated no significant advantage in shaped bedding as compared with a flat sand bedding for Method A-3 installations only.

CROSS CANYON

Research Summary

As a consequence of the Mountainhouse Creek research, Parts 1 and 2, an additional RC research project was initiated at Cross Canyon Culvert. It consists of a grossly underdesigned 84-in dummy RC pipe under 188 ft of overfill (9).

The center pipe segment in each zone was instrumented with electric resistance strain gauges at each octant point. Rebar strains in the concrete pipe were measured and also strains in the concrete pipe core. There were two or three planes of instrumentation 3 ft apart at each zone, except for zones 2 and 7.

Figure 7. Soil pressures at Mountainhouse Creek, zone 1.

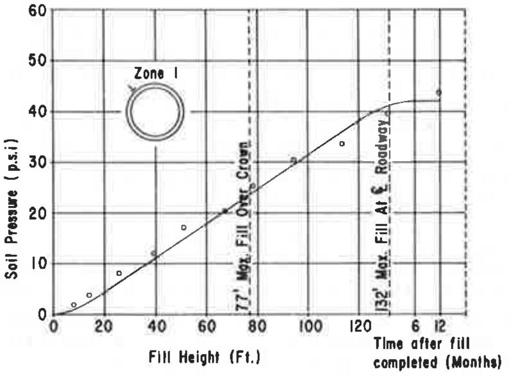


Figure 8. Soil pressures at Mountainhouse Creek, zone 4.

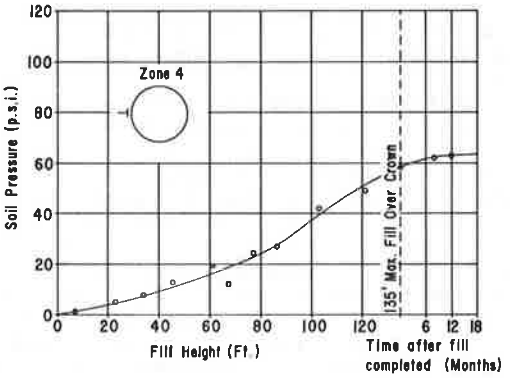
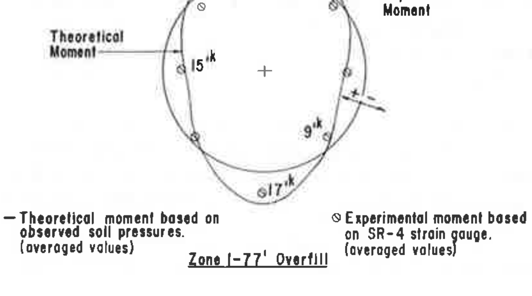


Figure 9. Theoretical and experimental moments at Mountainhouse Creek, zone 1.



Soil-stress meters were imbedded in the surface of the concrete pipe in two or three planes at each zone and in the soil surrounding the concrete pipe. The upper half of the pipe contained meters at 45° intervals. The lower half had meters at 30° circumferential spacings. Strain gauges were placed in one plane at each zone.

A new specially designed Cambridge meter, obtained from Robertson Research Ltd., was installed in these culverts. This device measures both normal pressures and circumferential shears on the pipe wall. Displacement, settlement, rigid body rotation, and joint movement were measured manually.

The dummy pipe contains 10 zones. All zones are positive projecting. The projection ratios were 1.0 for zones 1 and 2 and approximately 0.5 for the other zones. Four pipe strength classes and five backfill conditions were employed. The four zones of different pipe strengths were installed to assess their relative structural capacities; Method B (imperfect trench conditions), which consisted of baled straw, loose soil, and polystyrene plank backpacking, comprised three more zones. One zone had soil cement backfill. Another zone had horizontal tension pipe struts, and one zone had vertical compression pipe struts.

Design Summary and Applications

The plots of the unadjusted effective densities of the 10 zones of Cross Canyon are conclusive in the following respects.

The magnitude of the effective densities and the peripheral effective-density plot of Method A, zones 1, 3, 4, 5, and 6 (Figures 10-12), fall within the two bands previously projected for RC pipe design. This is in basic conformity with the Mountainhouse Creek research projects, Parts 1 and 2, Method A. Effective-density profiles indicated by the instrumentation verify that the two bands of loading are an acceptable, conservative design. The lesser pressure at the crown in zones 4, 5, and 6 may be attributed to the overzealous concern for the instrumentation by the contractor during backfill, which resulted in less compaction over the crown than that specified.

The effective-density increases subsequent to fill completion were negligible, which affirmed the use of a Beta Sub E factor of 1.0 for Method-A RC pipe design.

The three Method-B test zones (with soft inclusions in the backfill) all performed well--zone 8 (Figure 12), 2-6 in of polystyrene surrounding the upper 240° of the pipe; zone 9 (Figure 13), uncompacted material surmounting the RC pipe; and zone 10, baled straw surmounting the pipe. The uncompacted material gave the optimum results of the three types tested even though the uncompacted material had the largest soil gradients. The good performance of zone 9 can be attributed to the high compressive thrusts that resulted from the retention of large lateral soil stresses. The effective densities ranged between 27 and 96 pcf. The baled straw had effective densities that varied from 4 to 41 pcf around the periphery, except for the high invert effective density of 194 pcf. Excluding the invert, the effective densities were somewhat less than the average 50 pcf observed at five sections of research on Mountainhouse Creek RC pipe, Part 2. In effect, the low effective densities of baled-straw

Figure 10. Effective densities at Cross Canyon, zones 1 and 3.

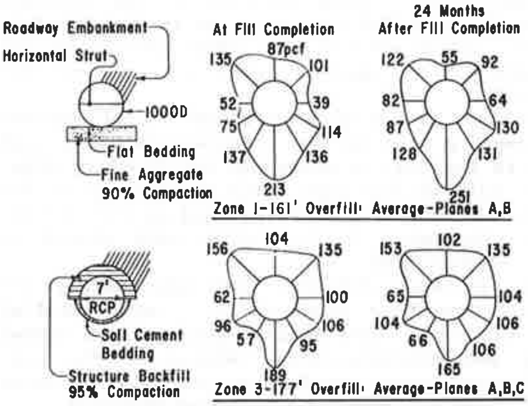


Figure 11. Effective densities at Cross Canyon, zones 4 and 5.

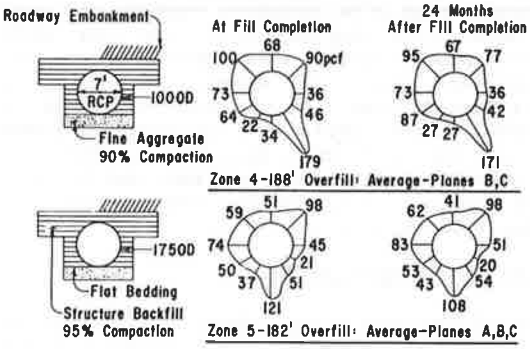


Figure 12. Effective densities at Cross Canyon, zones 6 and 8.

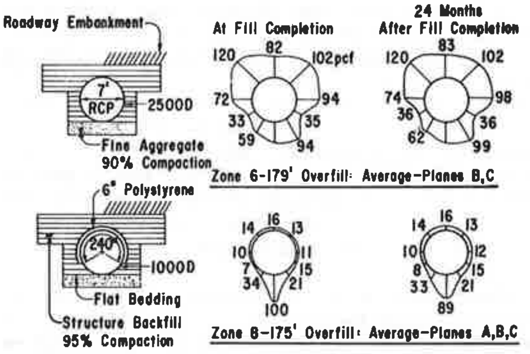
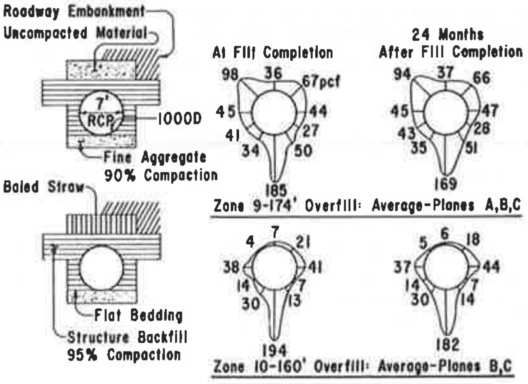


Figure 13. Effective densities at Cross Canyon, zones 9 and 10.



Method-B backfill observed in zones 2-6 at Mountainhouse Creek were affirmed by zone 9 Cross Canyon research, except for the invert effective density (meter 6). The beneficial effects of the 6-in polystyrene soft inclusion, with readings approximately 20 pcf at meters 1-5 and 7-10, were partly negated by the hard spot at meter 6 of 100 pcf on the bottom of the pipe.

In this research project, the effective densities for Method B (uncompacted material) were somewhat higher than for the other two Method-B alternatives. One further word of caution--the uncompacted earth can range between 70 and 95 percent relative compaction on individual projects. The introduction of the straw-backfill, Method-B alternative on Caltrans culverts was prompted by the inability to control the density of uncompacted earth during construction and the adverse reaction by contractors to the construction sequence required for its installation. The most recent specifications for Method-B RC pipe permit baled straw only.

There is approximate linearity on the plots of soil stress versus fill height of Method-A installations. Of the 50 individual plots of soil stress versus height, 34 were approximately linear; 80 percent of the readings were within 20 percent of a straight line. An example is zone 4 of Cross Canyon (Figure 14). This again correlates with the Mountainhouse Creek research, parts 1 and 2.

An attempt also has been made on this and all previous Caltrans culvert research to assess Spangler's settlement ratio. The results were unsatisfactory (Figure 14); the settlement ratio that predicts twice the crown pressure is actually observed at zone 4. However, there is a distinct nonlinearity on many of the meter readings of the Method-B backfill (zones 8, 9, and 10). A plot of meter 2, zone 9 (Figure 15), is indicative of this nonlinearity.

The external pressures and the internal strains had good correlation for moment and displacements. A comparison of the theoretical (soil-pressure) and experimental (strain) moments is shown for zone 4 (Figure 16).

Also of significance is the fact that where there were three planes of instrumentation, 75 percent of the sections (sections 1, 4, 6, 8, 9, and 10) had remarkably good correlation. For example, the plots shown on the three planes at zone 4 (Figure 17) of the observed peripheral pressures show virtually identical tracings. Experience in other culvert research projects has emphasized the fact that variations in the foundation, the side fill, and the embankment surmounting the culvert can occur along the length of any culvert installation; as a consequence, significant changes in the effective-density profiles have been observed. However, with a spacing of 3 ft between planes, there is assurance that these conditions did not change at this research site.

The asymmetry of effective-density profiles, common to all Caltrans rigid-culvert research projects thus far, was found in the Method-A test sections. Cambridge-meter circumferential shear readings were but one of the indications of the condition of asymmetrical loading. A considerable computational effort was exerted to establish rotational, horizontal, and vertical equilibrium at all zones.

A comparison has been made between an unadjusted effective-density profile and an effective-density profile based on the shear and normal soil stresses at zone 6 (Figure 18). It is of interest to note that the variations are generally less than 20 percent; all previous Caltrans culvert research conclusions are therefore valid despite the fact

Figure 14. Soil pressures at Cross Canyon, zone 4.

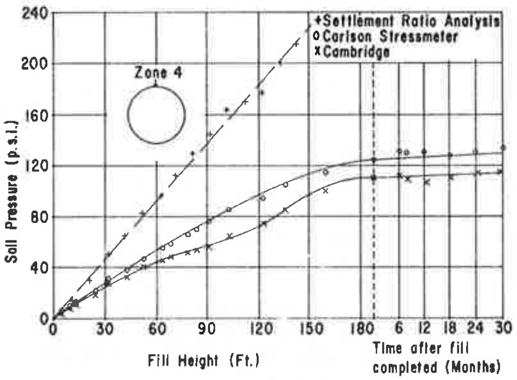


Figure 15. Soil pressures at Cross Canyon, zone 9.

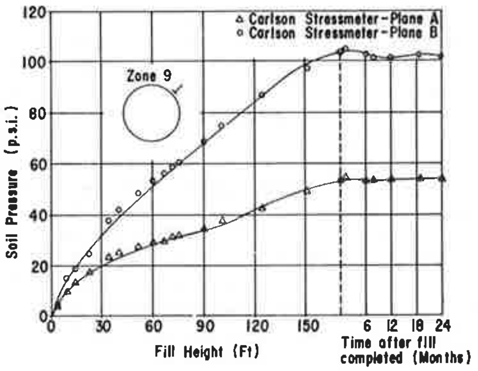


Figure 16. Theoretical and experimental moments, Cross Canyon, zone 4.

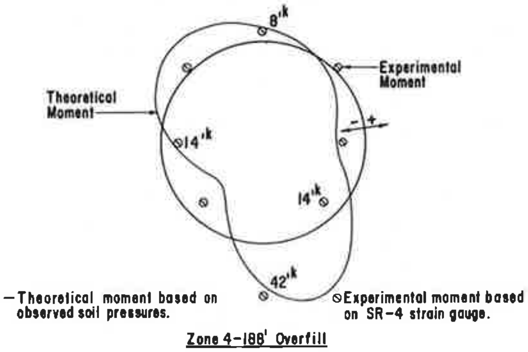


Figure 17. Soil stress meters at Cross Canyon, zone 4.

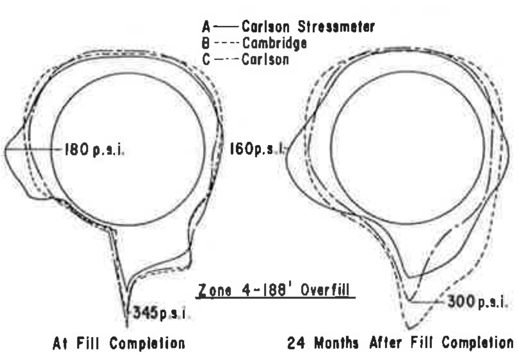


Figure 18. Effective densities at Cross Canyon, zone 6 (unadjusted, Cambridge-modified).

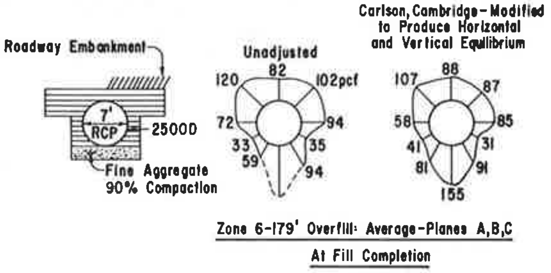
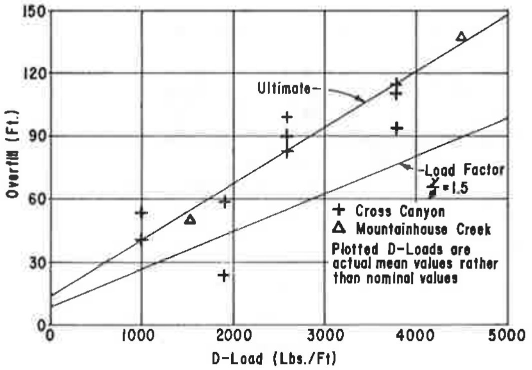


Figure 19. Limiting overfill: Method A-3 backfill.



that no measurement of shear stresses was made.

The three-edge bearing test also was given a further assessment. Pipe strengths of 1000D, 1750D, 2500D, and 3600D were compared; all had approximately 180 ft of overfill. The results were rather surprising. Although the strength of pipe did not have a direct relationship with the D loading (i.e., the 3600D pipe does not support 3.6 times as much overfill as the 1000D), it did have remarkable validity with respect to allowable overfills used by Caltrans based empirically on the Mountainhouse Creek research. Method A-3 application of a load factor of 1.5 (Figure 19) provided confirmation of the current values used by Caltrans. Also of interest is the fact that values of allowable overfill based on the Design Manual of the American Concrete Pipe Association (ACPA) are 60 percent of the Cross Canyon D-load values.

A crack survey was made of the magnitude and frequency of cracking and the magnitude of the deformation in each zone, which are summarized as follows:

Zone	Maximum Crack Width (in)	Vertical Deformation (in)
1	0.05	0.9
3	0.05	0.6
4	0.07	0.6
5	0.05	1.2
6	0.03	1.1
7	0.02	0.8
8	0.01	0.3
9	0.02	0.0
10	0.03	0.1

Maximum cracks in all zones were less than 0.10 in. Maximum deformation for Method A was 1.4 percent; for Method B it was 0.4 percent and less.

Figure 20. Load factor design: RC pipe, Caltrans.

$$\text{Group X-Culvert} = \gamma\left[\beta_D D + \beta_E E + \beta_L (L+I)\right]$$

$$\text{Where } \gamma = 1.3,\ \beta_D = 1.0,\ \beta_E = 1.0,\ \beta_L = 1.67$$

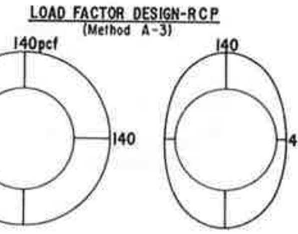
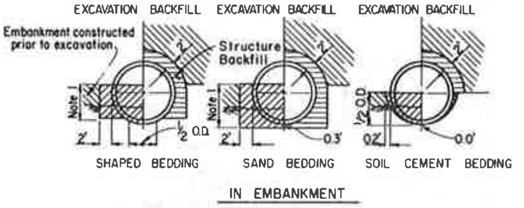


Figure 21. Portion of standard plan A62-D, excavation and backfill details, concrete and asbestos cement pipe culverts.



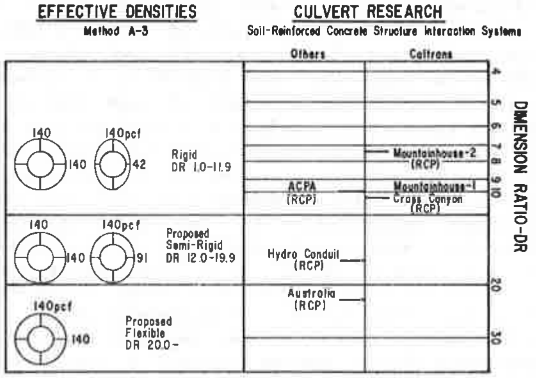
MINIMUM ALLOWABLE CLASSES OF RCP FOR METHOD A-3

Cover (in feet)	Minimum Class & D-Load
Less than 26.0	Class II 1000D
26.0-31.9	Class III 1350D
32.0-37.9	Class III Special 1700D
38.0-44.9	Class IV 2000D
45.0-55.9	Class IV Special 2500D
56.0-67.9	Class V 3000D
68.0-80.0	Class V Special 3600D

Notes 7, 8 and 9

A62-D

Figure 22. Dimension ratio.



IMPLEMENTATION

Caltrans has implemented the following from this RC pipe research:

For Method A-3, two bands of loading (Figure 20) are now specified for RC pipe special designs--design loadings 140V:140H and 140V:42H. Allowable overfills are determined by D-loads based on the three-edge bearing tests. There is excellent correlation between the projected allowable overfills for Method 3 based on the Mountainhouse Creek research and the most recent RC pipe research at Cross Canyon. The soil-cement option for Method 3 (Figure 21) is specified as an alternative on Standard Plan A62. The maximum crack width observed at zone 3 was 0.05 in and there was a uniform soil gradient in the lower quadrants. The continued application of the soil-cement option is supported by the successful use of this option by contractors on recent Caltrans projects.

For Method B (baled straw surmounting the pipe), allowable overfills are specified by D-loads based on the three-edge bearing tests. Double cage reinforcement should be provided, and the bedding should be shaped.

The American Association of State Highway and Transportation Officials (AASHTO) has recently revised Article 1.2.2A (Loads on Culverts) to specify two loading conditions (120V:120H and 120V:30H). AASHTO specifications now include Section 1.15 (Soil-Reinforced Concrete Structure Interaction Systems) with input by Caltrans based on these three Caltrans RC pipe culvert research projects. AASHTO specifications also include Section 2.28 (Installation and Construction of Soil-Reinforced Concrete Structure Interaction Systems); active participation was provided by California in the development of these construction specifications.

FUTURE CONSIDERATIONS

Caltrans will introduce a new criterion, the dimension ratio (DR), for RC pipe design (Figure 22). DR is defined as the internal diameter in inches divided by the wall thickness in inches. Caltrans RC pipe research at Mountainhouse Creek and Cross Canyon and Caltrans special RC pipe designs have used pipes with dimension ratios that range between 3.7 and 10.5. ACPA has also conducted research on RC pipe in embankment and trench conditions with a DR of 10.0. Hydro Conduit Corporation has performed RC pipe research (10,11) on pipes with DRs that range between 14.9 and 19.2. Since 1962, the Australian Concrete Pipe Association has used RC pipe with DRs that range between 13.8 and 20.9 (Australian Standard CA-33-1962).

Phases of RC pipe load-factor design to be considered are as follows:

1. For Method A-3, develop load-factor design specifications: (a) rigid culvert design--DR 1.0-11.9, design loadings 140V:140H and 140V:42H; (b) semirigid culvert design--DR 12.0-19.9, design loadings 140V:140H and 140V:91H; and (c) flexible culvert design--DR 20.0-, design loading 140V:140H.
2. For Method B, develop load-factor design specifications. Consider application of earth effective-density profiles consistent with Mountainhouse Creek and Cross Canyon research projects.

AASHTO Bridge Specification 1.15.4, RC pipe, precast, has recently been approved. Caltrans is developing a standard plan based on the direct design method for RC precast pipe.

Caltrans is currently studying the applicability of the finite-element method to culvert design.

COST SAVINGS

A saving of $390 000 would have been realized at Cross Canyon had a 96-in RC pipe been used instead of the 96-in prestressed concrete pipe.

Savings projected for Caltrans RC pipe installations are as follows:

1. $100 000/year due to increased allowable overfills for conventionally designed RC pipes, and
2. $300 000/year due to use of concrete pipe with thinner walls.

The use of thinner-wall RC pipe will save material and result in more economical RC pipe designs.

ACKNOWLEDGMENT

The initiation of the RC pipe research of Mountainhouse Creek and Cross Canyon and the determination of design parameters were with the full cooperation and participation of the Caltrans Culvert Committee and the California Precast Concrete Pipe Association (CPCPA). It was a mutual involvement by both CPCPA and Caltrans.

Walt Creasmon of Ameron and Joe Zicaro of the Hydro Conduit Corporation contributed significantly to the Mountainhouse Creek research proposal and Ernie Rogers, managing engineer of the CPCPA, to the Cross Canyon research proposal. Tom Breitfuss of the Hydro Conduit Corporation and Bob Spickerman of the California Concrete Pipe Corporation have been particularly instrumental in the recent implementation aspects.

Discussion

R.E. Davis

As principal investigator on all Caltrans' major culvert research for 15 years, I believe that readers of this paper might misinterpret findings of the subject research.

The effective-density plots in Figures 1-4 do not resemble the two specified bands of loading. The phraseology "falling approximately into" and "fall essentially within" may lead the reader to believe (erroneously) that specified effective-density profiles that encompass all observed profiles will produce more conservative designs.

The use of Mountainhouse Creek soil stress data as a basis for important conclusions is questionable. At project inception, TRANSLAB purchased a bank of stress meters from two untried sources. Laboratory tests made of stress meters of the variety used in Mountainhouse Creek, Part 1, subsequent to project completion indicated 100 percent failure. Of 72 meters used in Mountainhouse Creek, Part 2, 15 failed at low overfills, no stress readings were reported for an additional 4, and 22, after producing small, finite stress readings, dipped to zero or negative stress ranges. Subsequent culvert tests have employed not only Carlson, but Kyowa, Ormond, and Cambridge stress meters.

Experimental moments shown in Figure 9 were averaged about the vertical diameter. Actual, omitted experimental moments departed significantly from the quasi-theoretical curve. High mortality rates for the stress meters and lack of valid correlations make all Mountainhouse soil-stress data suspect.

Promulgation of the baled-straw overlayer is polemic to many Cross Canyon observations, as follows:

1. Cost per foot: zone 9, \$171.75; zone 8, \$184.44; zone 10, \$193.01, or 12 percent more than the uncompacted soil;
2. 0.01-in-crack overfill: zone 9, never reached; zone 8, 61 ft; zone 10, 37 ft;
3. Total length of cracking: zone 9 consistently one of the best;
4. Maximum vertical diameter change: zone 9, 0.041 in; zone 10, 0.080 in; zone 8, 0.326 in;
5. Material availability: uncompacted soil, always; baled straw, not always, and cost at time of testing was \$27/ton; polystyrene plank is a petroleum derivative, cost \$3/ft^3 at time of test;
6. Ease of construction: zone 9, embankment material handled three times, but all work by machines; zone 10, baled straw unloaded and placed by hand; zone 8, much work in hand placing, gluing, tacking, and winding ropes to prevent planks from being dislodged;
7. Theoretical assessment of behavior: zone 9, exhibited healthy compressive thrust at crown; zones 8 and 10, negligible thrust at crown conducive to cracking;
8. Uncompacted soil inorganic and not subject to decomposition, whereas baled straw is; and
9. Radial tension stress by Heger's criteria: zone 9, 65 psi; zone 8, 69 psi; zone 10, 82 psi.

Downgrading of the uncompacted-soil overlayer in the paper should be reconsidered.

The uppermost curve in Figure 14 is a hypothetical curve based on Marston-Spangler settlement ratio analysis and does not contain experimental data. If the ordinate scales in Figures 14 and 15 are matched, the uppermost curve in the latter correlates very well with experimental data from the lower curve on Figure 14, with a slight transposition of the origin; the authors' suggestion that one of these typical curves proves linearity while the other demonstrates "distinct nonlinearity" should be clarified. The argument is more than semantic. The mathematical definition of effective density is the slope of the secant joining the origin to points along the function of soil stress and overfill. For linear curves, the secants would degenerate into tangents, effective densities would be the same at all levels, and effective-density profiles at ultimate overfills could be considered representative of all levels. Typical effective-density maxima at 1:30, 6:00, and 10:30 o'clock dampen more rapidly with increasing overfill than minima at 12:00, 4:30, and 7:30 o'clock, which results in decreased soil-stress gradients. Use of the authors' ultimate-density profiles will produce unconservative designs for almost all construction methods at lower overfills where the soil-stress gradients are more severe.

Description of the Cross Canyon project as "an assessment of the three-edge bearing test" is questionable. The assertion that it verified with remarkable validity the results of the Mountainhouse Creek research is unclear. Zone 5 (the 1750D pipe) was a fluke (primarily because of the use of undeformed bars); the primary mode of failure at zones 6 (2500D) and 7 (3600D) and the 4000D pipe at Mountainhouse Creek was incipient delamination, not a three-edge bearing test criterion. The fact that an approximate linear function could be established between the various modes of failure and the D-strength of the pipe is only coincidental.

The table of maximum crack widths is invalid because it includes widths from all segments. Buffer segments were included on either side of each instrumented pipe (except in zones 1 and 2), and only "representative" center segments should be considered to eliminate the effects of longitudinal bridging between zones. Maximum crack widths (in inches) taken only from these segments are as follows: zone 1, 0.050; zone 2, 0.020; zone 4, 0.050+; zone 5, 0.035; zone 6, 0.040; zone 7, 0.015; zone 8, 0.020; zone 9, 0.005; zone 10, 0.020. The correct figures suggest superiority of uncompacted overfill at zone 9.

The authors suggest use of the 0.01-in crack as a failure criterion for Method 3 and a 0.05-in crack in zone 3 and also attach significance to the fact that all cracks were less than 0.1 in. Readers may fail to perceive the research project objective to assess relative structural behavior and economy of 10 construction modes.

It should be carefully noted that the suggestion concerning DR bears no relationship to Caltrans pipe research. Excluding consideration of the prestressed pipe at Cross Canyon, the range of DRs studied by Caltrans is 7.3 to 10.5. The only valid data available pertinent to the low end of this range are from the noninstrumented zone 7 at Cross Canyon. All other pipe segments were of a single value of 10.5, yet structural behavior ranged from total failure to excellent. Since the DR does not consider the significant effects of soil-structure interaction, its value as a design criterion needs further explanation.

The recommendations for two bands of loading reflect the dangerous assumption described earlier. The 140V:140H uniform loading will produce zero moments and shears in a round pipe and can scarcely be critical. The 140V:42H loading may produce maximum stresses comparable with some of those observed at Cross Canyon but will produce designs that are unconservative for other failure modes, e.g., diagonal and radial tension failures. The authors' manifest philosophy that certain "bands of loading" that encompass all observed bands will produce conservative designs is incorrect. Stresses in the pipe result from moments, shears, and thrusts, which depend on soil-stress gradients rather than the absolute magnitudes of stress, and one profile may encompass another one completely and yet produce a much less conservative design.

Thus, the most serious deficiency in the paper is the fact that the recommended design profiles are not "representative" of anything observed in the field tests and particularly of the low-modulus inclusion installations. The recommended profiles will therefore produce unconservative designs for some significant failure modes.

Opinions, findings, and conclusions expressed in this discussion are mine and do not necessarily reflect the official views or policies of the California Department of Transportation or the Federal Highway Administration. This discussion does not constitute a standard, specification, or regulation.

CLOSURE

This closure by Bacher is in response to certain issues raised by R.E. Davis. Readers are urged to address further discussion directly to Bacher. Response to such discussion or inquiries relative to implementation of the research into Caltrans practice will be made directly by him. Davis' comments will be addressed in paragraph order.

PARAGRAPH 2

Davis essentially states that the two conditions of loading now specified will not provide a conservative RC pipe design. As background, in 1967 the Bridge Department Culvert Committee first specified that RC arch culverts be designed for two conditions of loading, applying a service load design of 120V:36H for overfills from 0 to 60 ft and 84V:84H for higher overfills. Subsequently, load-factor design was initiated and developed for all culverts. Similar rigid culvert loadings were implemented in 1967. Two conditions of loading are currently specified for Caltrans rigid culvert design, 140V:140H and 140V:42H. To my knowledge, there have been no RC pipe culvert failures attributable to underdesign since 1967.

PARAGRAPHS 3 AND 4

Davis refutes RC pipe research of record for Mountainhouse Creek research, which he coauthored. To date, there have been no published disclaimers by Davis of the Mountainhouse Creek research documents. These research documents have been widely disseminated and accepted by the design profession.

PARAGRAPH 5

The comparative costs of the three Method-B type installations are representative of the Cross Canyon research project only. The soil cement method used on a recent pipe contract was fully machine placed. Hand methods used on the Cross Canyon research are not representative of full-scale projects.

The retention of the baled-straw Method-B alternative is a decision shared by members of the Caltrans Culvert Committee. However, in the last three years, only 2 percent of the total RC pipes installed specified Method B. It is still made available as an option to designers where the overfill exceeds 50 ft.

PARAGRAPH 6

Davis has chosen to apply his own revised interpretation of effective density. The two research-project approaches used were as follows:

Mountainhouse Creek: p (pcf) = [144 x p (psi)]/ h (ft).

Cross Canyon: Δp (pcf) = [144 x Δp (psi)/ h (ft).

At Cross Canyon, emphasis has been placed on the incremental change in pressure reading with each corresponding incremental change in fill height. Considering the number of readings taken at Cross Canyon, Davis states that Method-A readings are not essentially linear. The fact is that by taking soil-pressure readings at increasing fill heights, there is approximate linearity; 80 percent of Method-A peripheral pressure plots have 80 percent of the interim soil pressures within 20 percent of a straight line between the origin and the maximum reading.

The issue is much more fundamental. Traditionally, there has been a basic belief of some engineers in the field of soil-structure interaction that soil arching takes place on Method-A installations. Caltrans RC arch culvert research, now completed, has reached the unequivocal conclusion that there is no observed soil arching on Method-A type installations.

The reality is that at 180 ft of overfill, there is approximately twice as much earth load acting on an underground structure as there is at 90 ft of overfill for Method-A installations.

The contention by Davis that the present specified effective-density profile (140V:140H, 140V:42H) will produce unconservative designs for rigid culverts is not supported by 15 years of experience. Davis further contends that during construction of RC pipes, severe soil-stress gradients can occur. The necessity of considering the possible handling and installation stresses for culverts has always been recognized in design practice. It is of such importance for flexible culverts (i.e., steel and aluminum corrugated-metal pipe) that a minimum flexibility factor is specified; in the case of long-span metal culverts, deflection controls are specified during construction and temporary internal strutting is frequently required. Similarly, a minimum pipe stiffness is specified for plastic pipe culverts in ASTM specifications. In the case of RC pipe, minimum wall thicknesses are specified in the materials specifications.

In the figures shown for zone 4 (Figures 23-28), delineation has been made to emphasize that the current design for 1000D pipe permits only 26 ft of overfill. A neutral-point analysis has been applied with extrapolations to 188 ft of overfill. The specified 140V:42H for rigid culvert design has resulted in excellent correlation with the observed stresses. As stated previously, by using the three-edge bearing test, the 1000D pipe was considered adequate for a maximum of only 26 ft of overfill. The measured inner and outer steel reinforcing tensile stresses and the inner and outer concrete fiber tensile and compression stresses are approximately the same as the design specified, and during construction they did not exceed the minimum specified design stresses.

Finally, had Davis taken the opportunity to inspect the Cross Canyon research culvert four years after its completion, he would have observed the remarkably good condition of this grossly underdesigned RC pipe culvert.

PARAGRAPH 7

Davis was responsible for initiating the research of

Figure 23. Quasi-theoretical versus specification stresses: steel tensile stress, inner reinforcing bar, zone 4.

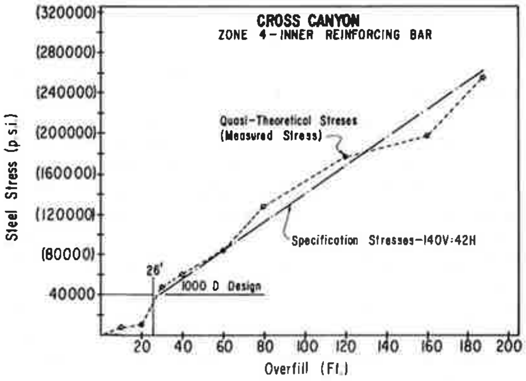


Figure 24. Quasi-theoretical versus specification stresses: steel tensile stress, outer reinforcing bar, zone 4.

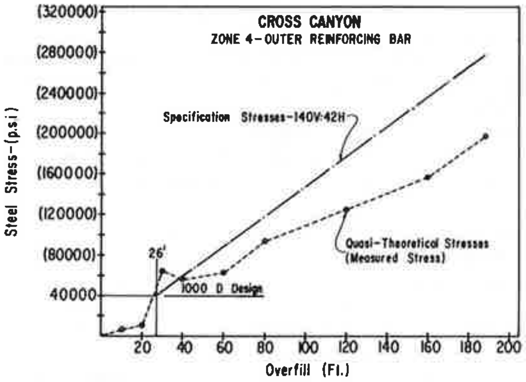


Figure 25. Quasi-theoretical versus specification stresses: concrete compressive stress, concrete inner fiber, zone 4.

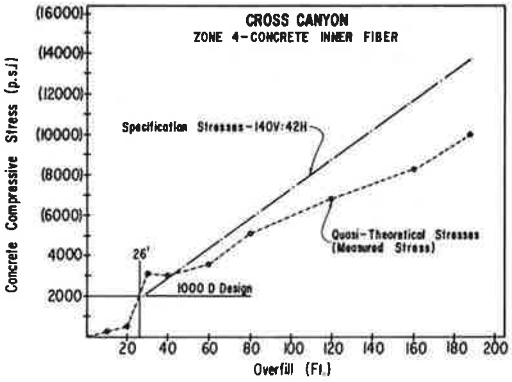


Figure 26. Quasi-theoretical versus specification stresses: concrete compressive stress, concrete outer fiber, zone 4.

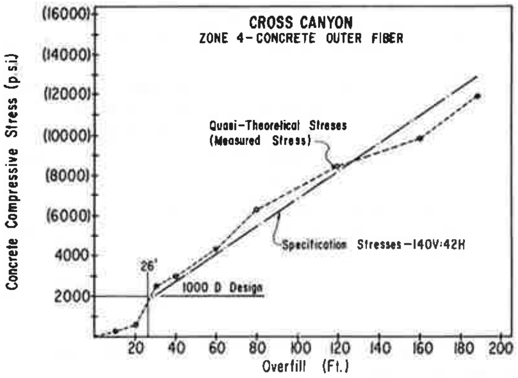


Figure 27. Quasi-theoretical versus specification stresses: concrete tensile stress, concrete inner fiber, zone 4.

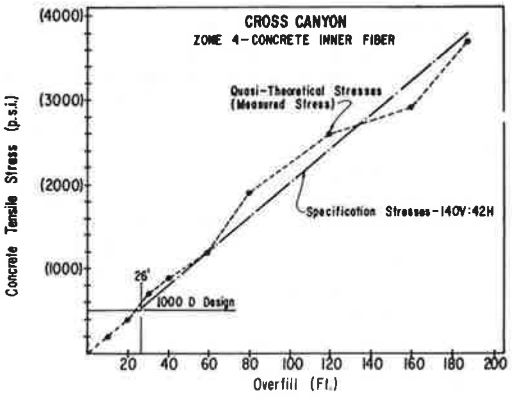
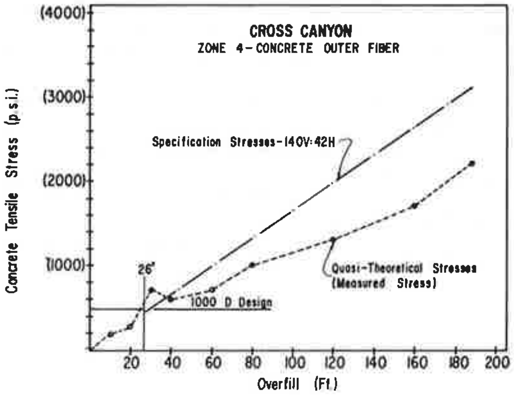


Figure 28. Quasi-theoretical versus specification stresses: concrete tensile stress, concrete outer fiber, zone 4.



the 1000D, 1750D, 2500D, and 3600D specified D-load pipes at Cross Canyon. The 1000D and 4000D three-edge bearing test values witnessed on the Mountainhouse Creek research resulted in the interim allowable-overfill tables in the Caltrans Design Manual. The most recent research at Cross Canyon confirms these allowable-overfill tables.

PARAGRAPHS 8 AND 9

Apparently Davis is not familiar with the current Caltrans and AASHTO RC pipe construction specifications. In a corrosive environment, a 0.01-in crack is specified. However, from a structural standpoint, cracks of 0.10 in are considered acceptable in a noncorrosive environment.

It should be emphasized that the tentative AASHTO design specifications for RC pipe are based on a 0.01-in crack.

When the cracking reaches 0.10 in, the structure becomes hinged, which relieves the moment and creates a new interface condition that has thrust as the only significant design consideration. The structure continues to function, since the soil retains the peripheral shape of the pipe, similar to the stone arch construction dating back to the Roman era.

PARAGRAPH 10

Davis offers no alternative or constructive discussion to Bacher's proposed DR concept. The simple reality is that if an 84-in pipe with an 8-in wall can successfully support 180 ft of overfill, it is probable that a thinner-wall pipe can be used to support a 20-ft overfill. Initial design calculations based on the direct design criteria of AASHTO Section 1.15.4 (Reinforced Concrete Pipe, Precast) indicates that an 84-in RC pipe with a 5.25-in wall would safely support 20 ft of overfill.

Australia has successfully placed RC pipe with DRs ranging between 14 and 22 since 1962 (Australian Standard CA-33-1962); also, Hydro Conduit has performed research on pipes with DRs varying between 14.0 and 19.2. Finally, zones 3 and 4 of Cross Canyon research performed better than zones 5 and 6 (1750D and 2500D), which were more heavily reinforced. The fact that zones 3 and 4 were more flexible improved their structural performance; in effect, the moment considerations become less significant because there is moment relief under loading if the pipe is more flexible.

PARAGRAPHS 11 AND 12

The current AASHTO specification, Section 1.15 (Soil-Reinforced Concrete Structure Interaction System) in both Sections 1.15.2 (Service Load Design) and 1.15.3 (Load Factor Design) defines RC pipe as circular pipe, elliptical pipe, and arch pipe. It should be apparent to Davis that a vertical ellipse or pipe arch should be designed for the more critical 140V:140H loading.

The continued allegation by Davis that "two bands of loading reflect the dangerous assumption described earlier" is not supported by our experience.

Elementary logic tells one that a pipe designed for 180 ft of overfill will not suffer distress at 90 ft of overfill under conditions of interim loading with normal construction procedures and when reasonable care is taken by the contractor.

Application of the 140V:42H loading to a rigid culvert with a DR of 1-11.9 by using a neutral-point analysis has affirmed the validity of our current RC pipe design specifications. Application of the AASHTO and ACPA design method to semirigid RC pipe by using DRs of 12.0-19.9 will inevitably lead to future reduced wall thickness for RC pipe installations.

In conclusion, it is my opinion that, in dealing with the many variables of a soil-culvert interaction system, the establishment of a reasonable range of vertical and horizontal pressures for design consistent with variations in DRs and appropriate bedding and backfill parameters offers the most promising solution to safe, cost-effective RC pipe culvert installations.

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