Reinforced-Concrete Arch Culvert Research by the California Department of Transportation

ALFRED E. BACHER AND EUGENE G. KLEIN, JR.

Three reinforced concrete (RC) arch culverts were field tested. These three culverts were heavily instrumented with Carlson soil stressmeters at the extrados and with internal SR-4 strain gauges. An evaluation was made of the relative behavior of structural sections subjected to two types of structure backfill: (a) method A, which employs compacted structure backfill in contact with the extrados, and (b) method B backfill, which has either a low-modulus inclusion that surmounts the culvert or baled straw that surrounds the arch barrel at the extrados. Among the observations were that effective-density profiles at the extrados differed greatly and unconservatively from assumed design conditions, method A range of loadings were confirmed at 140V:140H and 140V:42H, soil-pressure-overfill functions were essentially linear for method A and nonlinear for method B, correlation was established between the theoretical moment (soil pressures) and experimental moments (strains), effective densities did not increase after fill completion, and excellent foundation conditions are a prerequisite for RC arch design.

In 1963, the California Department of Transportation (Caltrans), in cooperation with the Federal Highway Administration (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 reinforced-concrete (RC) arch culverts. The research program was mandated by

1. Significant distress observed in culverts under earth embankments ranging up to 300 ft in depth that were used as economical substitutes for long bridges and as convenient disposal sites for waste material from deep cuts (possibly the most dramatic failure occurred at the 15-ft RC arch at West Fork Liebre Gulch, where steel sets were required to repair the ruptured walls),
2. Inexperience of engineers in design of drainage structures that had the expected large overburdens, and
3. Conjecture that design criteria previously employed for culverts that had much lower overfills could not be safely extrapolated.

Caltrans has recently completed the third and final phase of its RC arch culvert research projects at the third location. The three sites are

Location	Culvert Size (ft)	Overfill (ft)
San Luis Reservoir	10	200
Posey Canyon	8	240
Cedar Creek	22	191

Other culvert research programs include three RC pipe structures at Mountainhouse Creek and Cross Canyon, a prestressed pipe structure at Cross Canyon, and three structural-steel-plate pipe structures at Chadd Creek, Apple Canyon, and DB Culvert.

The three RC arch culvert research projects have resulted in certain conclusions about rigid culvert design, especially the unique design aspects of RC arch culverts.

SUMMARY OF RC ARCH CULVERT RESEARCH

Instrumentation for this research included Carlson soil and concrete stressmeters at San Luis Reservoir, Posey Canyon, and Cedar Creek; SR-4 strain gauges at San Luis Reservoir; and SR-4 strain gauges and Carlson strainmeters at Cedar Creek.

Caltrans RC arch culvert research has included both method A installations, which employ compacted structure backfill in contact with the extrados, and method B installations, where there are soft inclusions in the culvert backfill that surmount or surround the arch barrel (1-12). A total of six test sections of method A installations were included in the three phases of the RC arch culvert research, i.e., sections 1, 2, 3, and 7 at Posey Canyon (Figure 1) and stations 4 and 10 at Cedar Creek (Figure 2).

The variation in loading about the RC arch culvert periphery emphasizes the contention that the single idealized loading diagram formerly applied to a rigid culvert is totally unrealistic. It became apparent at the outset of Caltrans' rigid culvert research that these variations in loading for method A installations could best be designed by providing two design bands of loading. The real objective, then, was to identify the magnitude of these variations and to provide design loading envelopes that were compatible with the observed pressure profiles. To emphasize the validity of the two-band loading concept, all Caltrans culvert research projects are shown with unadjusted effective densities based on readings taken at fill completion and from 12 to 26 months afterwards. The term "effective density" was introduced in Caltrans' first culvert research project to help compare zones that had varying overfills. Effective density is the density of material, assuming hydrostatic conditions, required to produce measured soil stresses for a given overburden.

Note that in each of these effective-density profile plots (Figures 1-3) a common scale has been used for the size of culvert and the magnitude of the observed effective densities. A visual comparison can, therefore, be made of the effective densities of all culverts. It is only by viewing these individual plots at each test section that proper design parameters can be established. The two bands of loading of 140V:140H and 140V:42H provide a range of design loading that satisfies the observed variation in effective density about the RC arch culvert periphery for the method A type of culvert installation. These observed effective densities greatly exceed the previous American Association of State Highway and Transportation Officials (AASHTO) values of 84V:25H.

Increases in effective density subsequent to fill completion were also evaluated. Readings were taken at all test zones after fill completion; readings varied from 12 to 26 months afterwards. At San Luis Reservoir and Cedar Creek, there was no appreciable increase in effective densities subsequent to fill completion. At Posey Canyon, section 2 (Figure 1), the lateral effective densities did increase from approximately 30 percent to 100 percent on the flank portions of the periphery; in effect, the soil lost its shear strength when the soil became saturated, and there was an increase in the lateral pressure from approximately 40 lbf^3 to 136 lbf^3 in a 26-month period. However, these values remained essentially within the two design bands of loading. Therefore, β_E in load factor design, defined as

Figure 1. Effective densities, Posey Canyon (sections 1-7).

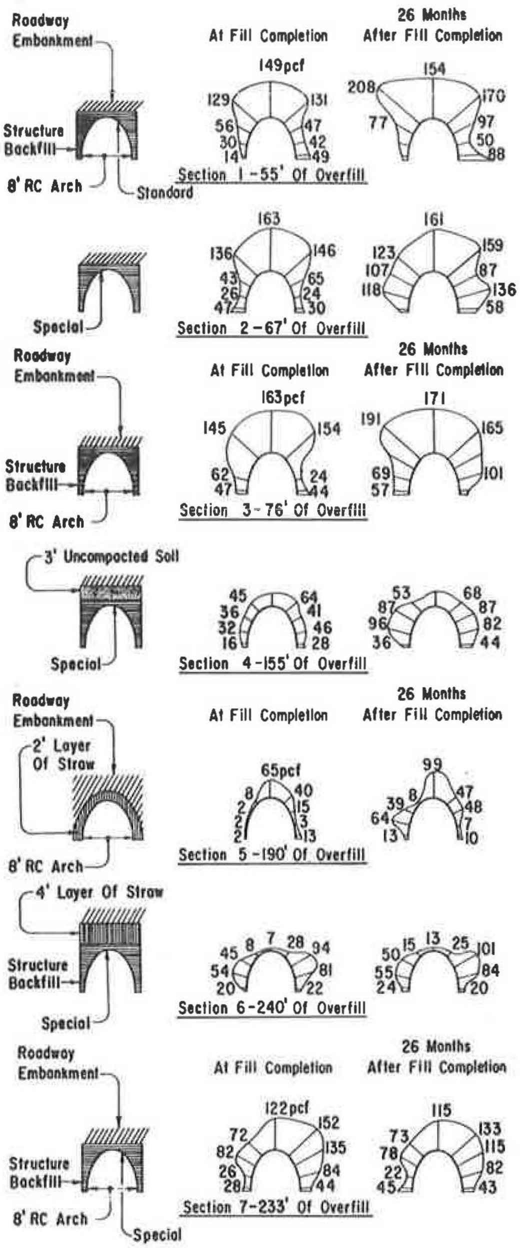
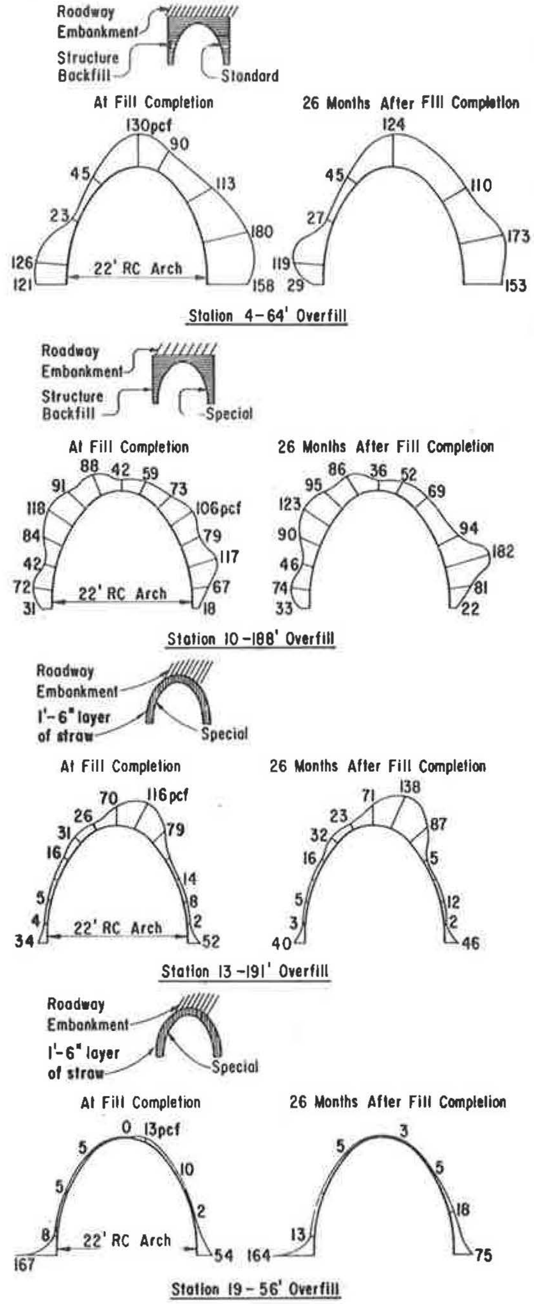


Figure 2. Effective densities, Cedar Creek (stations 4, 10, 13, and 19).

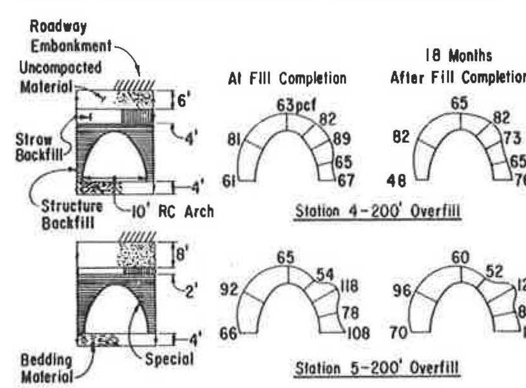


the effective-density increase for rigid culvert design, has been assigned a value of 1.0 for RC arch culverts.

There were also seven test sections of method B installations. Method B is the "imperfect" trench method, as defined by Spangler of Iowa State College (13), where there is a soft inclusion in the culvert backfill, i.e., stations 4 and 5 (Figure 3) at San Luis Reservoir; sections 4, 5, and 6 (Figure 1) at Posey Canyon; and stations 13 and 19 (Figure 2) at Cedar Creek.

At San Luis Reservoir, stations 4 and 5, the observed soil stresses at the crown were half the embankment density, which proved that the low modulus inclusion was effective in reducing vertical soil stresses. However, the neutral-point analysis, based on the observed soil-pressure profile, demonstrated that this density reduction was detrimental to arch behavior since the unmodified lateral soil stresses produced large bending moments and, conse-

Figure 3. Effective densities, San Luis Reservoir (stations 4 and 5).



quently, intrados tensile stresses in the arch flanks. The latter could not be counteracted by compressive stresses because vertical thrusts had been greatly reduced by the load reduction effected by the straw.

At Posey Canyon, section 5, which had a single-bale thickness of straw surrounding the barrel, the crown effective density was reduced and soil pressures acting laterally were practically eliminated. A theoretical analysis that used only the soil stresses indicated a very favorable soil-pressure profile; however, when the observed footing rotations were included in the analysis, very high barrel stresses were indicated. Such footing rotations are characteristic in arch construction and result from the reaction of an unbalanced column of earth on the cantilever sections of footing outside the extrados. Where a rectangular layer of straw surmounted the arch, at section 6, the results were similar to those of San Luis Reservoir research; i.e., the reduction in crown pressures was indicated by the analysis to be detrimental to the culvert's performance. Where uncompacted material surmounted the arch (section 4) the lack of any readings on the crown, as a result of a malfunction of the soil stressmeter, made the results somewhat inconclusive.

At Cedar Creek, the theoretical method of analysis by the neutral-point method further suggested that certain dangers are inherent in the application of a layer of straw around the arch barrel. At Cedar Creek, station 19, the removal of the passive lateral restraint from the extrados allowed essentially uninhibited outward rotations of the barrel and the footings monolithically attached thereto. The effective-density profile at station 13 confirmed the profile previously observed at Posey Canyon; both exhibited negligible lateral effective densities but nearly hydrostatic densities near the crown.

Another significant conclusion was the essential linearity in loading on all method A Caltrans culvert research projects completed to date. Fill-height pressure plots show that the loads acting on the RC arch culverts vary directly with fill height, indicating that soil arching does not have a significant effect on the design loads for the method A type of culvert installation. Typical fill height versus pressure plots at San Luis Reservoir (Figure 4), Posey Canyon (Figure 5), and Cedar Creek (Figure 6) are shown. In each case the readings of a meter at the 1:30 position on the culvert periphery have been plotted. San Luis Reservoir is a method B installation that exhibited linearity in loading contrary to the usual nonlinearity exhibited on other Caltrans method B culvert research zones.

The extensive instrumentation of the three phases of Caltrans RC arch culvert research gives further assurance that the results achieved are accurate and representative. At San Luis Reservoir and Cedar Creek (Figures 7 and 8), Carlson soil stressmeters and SR-4 strain gauges were both placed. The experimental moments based on SR-4 strain gauges and the theoretical moments based on observed soil stresses had excellent correlation at both San Luis Reservoir and Cedar Creek.

There has also been a phenomenon of asymmetry of loading on all zones of Caltrans culvert research projects. This asymmetry is sometimes quite pronounced, and it is evident that shear forces are acting on the culvert barrel. In research subsequent to these three RC arch culvert studies, Caltrans is attempting to measure these shear forces on other types of culverts.

IMPLEMENTATION OF RC ARCH CULVERT RESEARCH

The implementation of Caltrans RC arch culvert research has been very positive. One result of the arch culvert research has been to require a more conservative design of RC arch culverts. It is

Figure 4. Soil pressures, San Luis Reservoir (station 5).

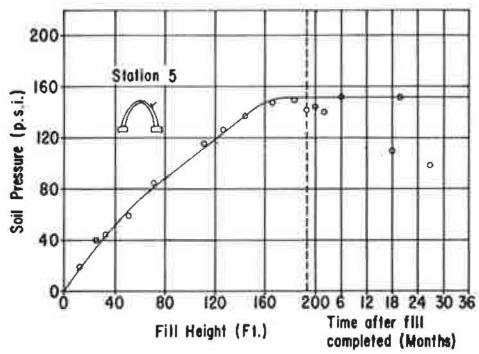


Figure 5. Soil pressures, Posey Canyon (section 7).

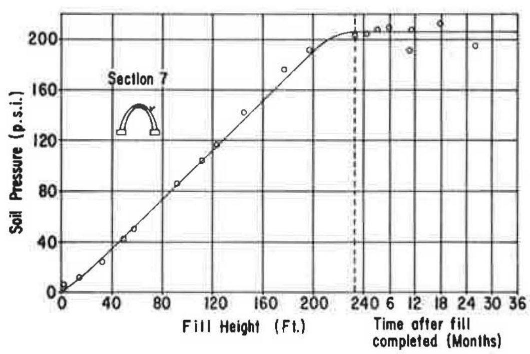


Figure 6. Soil pressures, Cedar Creek (station 10).

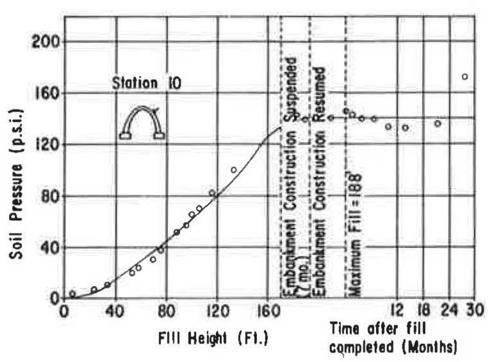


Figure 7. Theoretical and experimental moments, San Luis Reservoir (station 5).

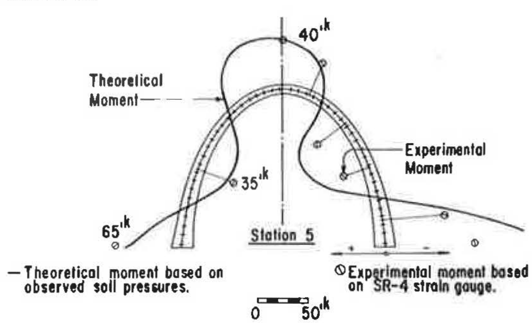


Figure 8. Theoretical and experimental moments, Cedar Creek, (station 10).

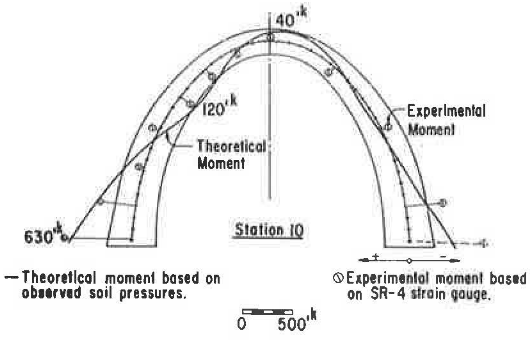
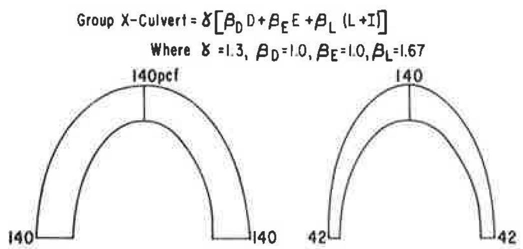


Figure 9. Load factor design for RC arches.



necessary to provide a design that satisfies two bands of loading for RC arch culverts (Figure 9). Caltrans currently applies two bands--140V:140H and 140V:42H. AASHTO, on the most recent bridge ballot, revised article 1.2.2A (Loads on Culverts), which now specifies two bands--120V:120H and 120V:30H.

It has also become apparent that the application of load factor design to the design of RC arches is a logical implementation of the RC arch culvert research. Caltrans has revised Standard Plan D95 (Reinforced Concrete Arch) based on load factor design, specifying loadings of 140V:140H and 140V:42H and improved steel details. [Copies of Standard Plan D95 are available from Caltrans.] AASHTO Standard Specifications for Highway Bridges now includes Section 1.15.5 (Reinforced Concrete Arch, Cast-in-Place) as part of Section 1.15 (Soil-Reinforced Concrete Structure Interaction Systems).

Most significant in the present use of method A backfill has been the profound influence of differential footing settlement and footing rotation of RC arches, which has placed greater emphasis on the necessity of a complete geological investigation at each potential site for an RC arch culvert. Excellent foundation conditions are a necessary prerequisite to preclude footing rotations or differential displacements.

The effect of a rectangular soft inclusion that surmounts an RC arch culvert or a soft inclusion placed around an RC arch culvert barrel was, at best, unpredictable and sometimes resulted in structural distress. As a consequence, Caltrans no longer uses method B on RC arch culverts. There may, however, be a possibility of using method B on special RC arch culvert designs under carefully controlled conditions.

SUMMARY

The comprehensive RC arch culvert research by Caltrans has resulted in changes in AASHTO bridge design specifications, has demonstrated the necessity of applying more conservative loadings to RC arch culverts, has led to the logical application of load factor design to rigid culverts, and has assured that RC arch culverts do offer an economical alternative to long bridge structures where site conditions are favorable.

REFERENCES

1. R. E. Davis. Structural Behavior of a Reinforced Concrete Arch Culvert. Bridge Department, California Division of Highways, Sacramento, Rept. SSR 9-66, 1966.
2. R. E. Davis and A. E. Bacher. California's Culvert Research Program: Description, Current Status, and Observed Peripheral Pressures. HRB, Highway Research Record 249, 1968, pp. 14-23.
3. R. E. Davis and A. E. Bacher. Discussion of paper, Forces on Rigid Culverts Under High Fills, by C. B. Brown. Structural Division Journal of ASCE, Vol. 94, No. 4 ST7, July 1968, pp. 1840-1845.
4. R. E. Davis and L. R. Patterson. Structural Behavior of a Reinforced Concrete Arch Culvert: Phase 2, Posey Canyon. Bridge Department, California Division of Highways, Sacramento, Rept. SSR 2-68, 1968.
5. R. E. Davis. Structural Behavior of a Reinforced Concrete Arch Culvert. Structural Division Journal of ASCE, Vol. 95, No. ST12, Dec. 1969, pp. 2665-2686.
6. A. E. Bacher. Discussion of paper, Structural Behavior of Concrete Arch Culvert, by R. E. Davis. Structural Division Journal of ASCE, Vol. 96, No. ST9, Sept. 1970, pp. 1970-1972.
7. R. E. Davis and A. E. Bacher. Structural Behavior of a Reinforced Concrete Arch Culvert: Phase 2, Posey Canyon (Supplemental). Bridge Department, California Division of Highways, Sacramento, Rept. R&D 6-70, 1970.
8. R. E. Davis. Closure and errata to Structural Behavior of a Concrete Arch Culvert. Structural Division Journal of ASCE, Vol. 97, No. ST4, April 1971, pp. 1348-1350.
9. R. E. Davis and A. E. Bacher. Concrete Arch Culvert Behavior: Phase 2. Structural Division Journal of ASCE, Vol. 98, No. ST11, Nov. 1972, pp. 2329-2350.
10. R. E. Davis, H. D. Nix, and A. E. Bacher. Structural Behavior of a Reinforced Concrete Arch Culvert: Phase 3, Cedar Creek. Division of Structures and Engineering Services, California Department of Transportation, Sacramento, Repts. FHWA-CA-ST-4120-77-01 to FHWA-CA-ST-4120-77-11, June 1977.
11. R. E. Davis, H. D. Nix, and A. E. Bacher. Arch Culvert Research: Phase 3. Structural Division Journal of ASCE, Vol. 105, No. ST4, April 1979, pp. 739-749.
12. R. E. Davis, H. D. Nix, and A. E. Bacher. Arch Culvert Footing Movements. Structural Division Journal of ASCE, Vol. 105, No. ST4, April 1979, pp. 729-737.
13. M. G. Spangler. A Theory on Loads on Negative Projecting Conduits. Proc., HRB, Vol. 30, 1950, pp. 153-161.

Publication of this paper sponsored by Committee on Subsurface Structures Design.