California's Culvert Research Program—Description, Current Status, and Observed Peripheral Pressures

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The California Division of Highways is performing an extensive research program to determine structural behavior of buried conduits. Field studies include observations of three arch culverts, two rigid concrete pipes, and two flexible (structural plate) pipes. Measurements include peripheral and embankment pressures, internal strains, and displacement fields. Parameters include Method B (imperfect ditch) and Method A (positive projection) backfill; well graded and poorly graded structure backfill; and, for the pipes, numerous bedding conditions.

Theoretical studies include a finite element analysis of embankment pressures, taking into account sequence of construction operations and the baled straw layers; and neutral point analyses of arch culvert behavior.

A quasi-theoretical method of inferring soil pressures from a culvert's displacement field has been developed. Model studies for verification are planned.

•THIS paper provides an overall description of the culvert research program and is a preliminary publication of some observed peripheral effective densities acting at the soil structure interfaces and in the embankments.

SCOPE

The program has elicited sufficient interest on the part of various individuals and organizations to warrant publication of a brief resumé describing the nature of the work and some of the results which have been obtained to date. In general, discussion of results is limited to plots of peripheral pressures observed for those prototype culverts for which the work is sufficiently far advanced. Only limited conclusions are offered.

DESCRIPTION OF RESEARCH PROGRAM

The various phases of the project are briefly summarized in Table 1.

RESULTS OBSERVED TO DATE

Arch Culvert Research

Phase 1—San Luis Reservoir—One result of the project was the development of a computerized analysis of arch culvert behavior based on the "neutral point" method (1, 2). The program determines bending moments, thrusts, and shears and resulting internal stresses for individual voussoir loads or assumed hydrostatic loadings. It also takes into account the effects of soil friction acting along the extrados, and differential footing movements. The program is written in FORTRAN IV (E level) for an IBM System/360.

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TABLE 1

SUMMARY OF CULVERT RESEARCH

Phase	Cost ($000)	Parametric Conditions			Parameters Measured
		Bedding	Backfill	Structural Section	
Completed Projects:					
San Luis Reservoir 10-ft RC arch, 200-ft rock fill, broad canyon	86	Bedrock and embankment	Method B (2 types)	Special	Peripheral pressures Internal strains Internal stresses Displacements Embankment pressures Embankment settlements
Current Projects:					
Posey Canyon 8-ft RC arch, 240-ft fill, V canyon	102	Bedrock	Method A & Method B (3 types)	Standard & special	Peripheral pressures Footing displacements Embankment pressures
Chadd Creek 114-in. SPP, 89-ft fill	140	Shaped	Method B		Peripheral pressures Wall strains Embankment pressures Embankment settlements
Apple Canyon 108-in. twin SPP's, 167-ft fill	137	Shaped	Method A		Peripheral pressures Wall strains Embankment pressures Embankment settlements
Mountainhouse Creek 84-in. RCP's, 140-ft fill	194	Shaped flat (sand & embankment); styrofoam concrete cradle	Method A Method B, pea gravel graded aggregate embankment material	4000D & 1000D	Peripheral pressures Internal strains Displacements Embankment pressures Embankment settlements
Cedar Creek 22-ft RC arch, 205-ft fill	160		Method A Method B	Standard & special	Peripheral pressures Internal strains Displacements Embankment pressures Embankment settlements
Soil pressures on buried conduits	16	Theoretical analysis & model studies			Displacements
Proposed Project:					
Culverts under very high fills (200 to 400 ft)	100		Undetermined		
Total	935				

A byproduct of this phase has been another computerized analysis which predicts the pressures surrounding the arch. This program was written by Colin Brown of the University of California, Berkeley, and employs a finite element analysis to determine the effects of boundary conditions, sequence of construction operations, and the influence of the layer of compressible material surmounting the culvert (3).

Empirical results of this phase may be briefly summarized as follows:

Almost without exception, soil pressure meters which functioned properly, whether in the culvert footings or barrel, or in the embankment, and regardless of orientation with respect to the horizon, produced pressures which were linear functions of embankment depth up to the full 200-ft fill height. Pressure changes after completion of the embankment were negligible (Fig. 1).

Effective densities were computed from the pressure-height functions. For this phase of the project, where the pressure-height function was linear, the effective density was calculated as the slope of the curve and was constant for the full depth. For those phases where this function was not linear, the effective density was computed using the following equation:

$$\text{E.D.} = \frac{\Delta P}{\Delta H} \times 144 \text{ pcf}$$

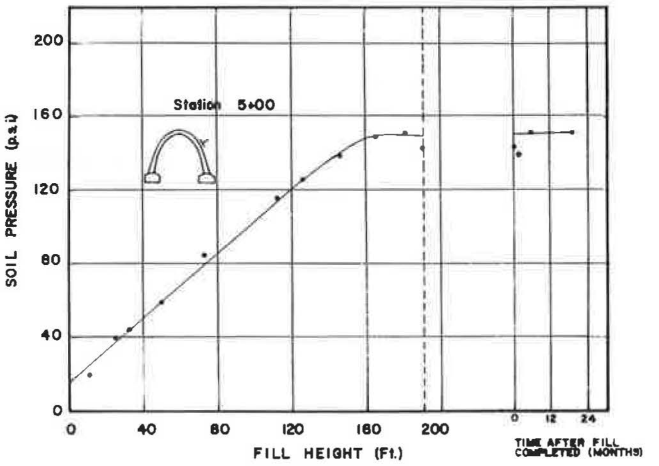

Figure 1. Typical soil pressure-embankment height function for San Luis Reservoir arch (special section, Method B, baled straw, backfill).

where ΔP is the net increase in pressure from the time the embankment is at the level of a given meter until the fill reaches a height, ΔH, above that meter. The plotted values are thus average, rather than instantaneous, effective densities.

Distributions of effective densities around the barrel periphery are shown in Figures 2 and 3.

Effective densities acting on the culvert were vastly different from those used in design. Horizontal densities were much larger; vertical densities, primarily as a result of the layer of straw, much less than had been assumed. Plots of densities acting around the barrel periphery indicated pressure maxima at the springing lines, at the crown, and halfway up the arch, with pressure minima in between.

Pressures observed on three sides of the arch at two stations indicated effective densities of 60 to 70 pcf acting horizontally, 80 to 90 pcf acting at 45 deg, and 62 to 65 pcf acting vertically. Measurements on the fourth side were 105 pcf acting horizontally and 118 pcf at 45 deg. One density near the crown temporarily fell to 42 pcf about a month after embankment completion.

California arch culvert designs have heen based on assumed vertical effective densities of 120 pcf, horizontal densities three-tenths as large or 36 pcf. Specifications permit using 70 percent of the actual weight of earth to effect an increase of allowable design dead load stresses 40 percent more than allowed for live load. The prototype was designed for 84 pcf acting vertically and 25 pcf acting horizontally.

Average overall effective densities acting downward on the culvert, computed from total downward components of pressure forces acting on the barrel and upper footing surfaces and from upward forces on the lower footing surfaces, were 76 to 95 pcf, although the most representative figures ranged from 76 to 83 pcf.

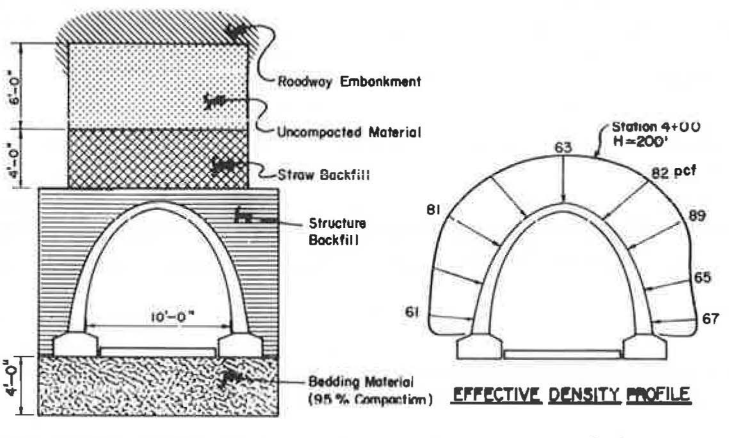

Figure 2. Effective density profile for Station 4, San Luis Reservoir arch (special section, Method B, baled straw, backfill).

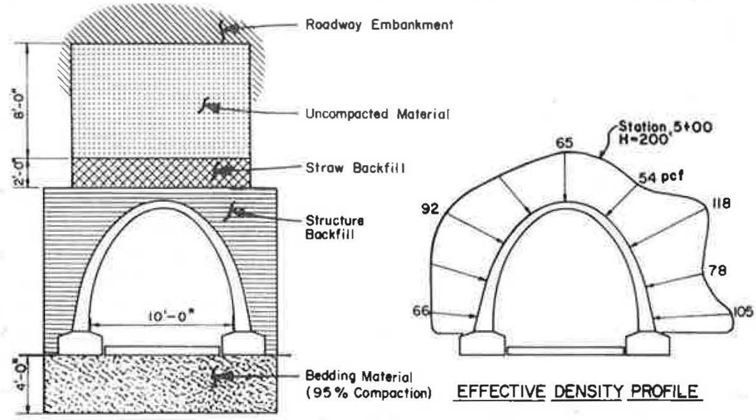

Figure 3. Effective density profile for Station 5, San Luis Reservoir arch (special section, Method B, baled straw, backfill).

Vertical effective densities in the embankment 13 ft from the centerline ranged from 84 to 266 pcf. Densities at 30 ft from the centerline, measured at two locations, were 310 and 740 pcf. The latter figure probably is erroneously high as a result of a concentrated bearing on the Terzaghi-type meter from which it was obtained. The remaining measured embankment densities, though significantly greater than the actual embankment density, are in line with observations at other locations where Method B backfill has been employed, demonstrating dramatically the increases in pressure in the "exterior prisms" as vertical shear forces transfer the load of the settling "interior prism" thereto.

Phase 3—Posey Canyon—Results observed to date at Posey Canyon in part confirmed, and in part controverted, those observed at San Luis. Functioning soil pressure meters at San Luis indicated linear relationships between pressures and embankment depths. Some meters at Posey Canyon indicated distinctly curvilinear functions while others produced linear functions with definite discontinuities.

The most pronounced curvilinear functions were observed at Station 5, where a layer of baled straw was placed around the periphery of the barrel. The increase of effective density acting on the barrel with increasing height undoubtedly results from the curvilinear stress-strain function exhibited by baled straw, which transmits greater soil pressures as it becomes increasingly compact.

A number of soil pressure meters exhibited linear pressure-depth functions up to the point where the embankment reached a height of 130 ft in early November 1966. The November readings and those taken subsequently frequently departed radically from the original linear functions. In some cases, the slope remained the same, while the pressure levels changed; in other instances, there were discontinuities both in slopes and pressure levels. These discontinuities are thought to have resulted from changes in the soil shear strength as the embankment became saturated with heavy rains which began in November.

Figure 4 is the pressure-height plot for Station 7, where no special backfill treatment was employed. Comparing the various curves, it is evident that the effect of saturating the soil was to produce pronounced decreases in effective densities acting vertically and increases in those acting horizontally—effective densities acting at 45 deg at the mid-height of the culvert remained virtually unchanged.

The published curves are not to be construed as typical. At some stations, the increases in soil pressure following saturation were only temporary. At some stations there was no evidence of leveling-off of pressures when the full embankment height was attained. Space limitations preclude publishing all the pressure-height curves at the present time.

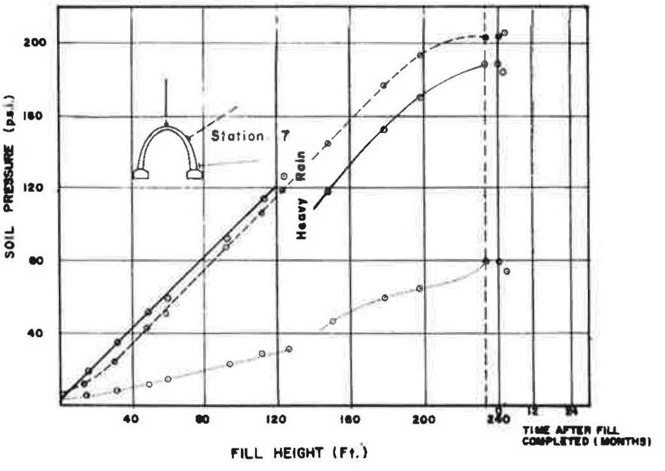

Figure 4. Soil pressure-embankment height function for soil stressmeter at crown, Station 7, Posey Canyon arch.

Calculated effective densities as they were distributed around the arch are plotted in Figures 5 through 9. Several characteristics of the curves are worth noting.

At Station 7 (Fig. 5), with no special backfill treatment, the distribution of effective densities was observed to be somewhat in line with that stipulated in the specifications (120/36), although the magnitudes of the densities were, at two stations, considerably greater.

At Station 6 (Fig. 9), where a horizontal layer of straw surmounted the arch, the computed density distribution was similar to that at San Luis, although the vertical and horizontal densities were considerably less than those observed at San Luis.

Station 5 (Fig. 8), where a bale thickness of straw was placed around the entire barrel periphery, showed the most promise, inasmuch as the lateral pressures were almost negligible and vertical densities were about half that of the embankment.

The observed pressure distribution at Stations 1 and 2 (Figs. 5 and 6), comprising standard and special structural sections, respectively, differed inappreciably from one another, except that effective densities acting on the more rigid section may have been slightly greater. The effective density distributions at these three stations, where no special backfill treatment was employed, are somewhat comparable to the 120:36 pcf ratio which has been used in design, except that observed vertical densities are greater than the design figures.

At Station 4 (Fig. 7), where a layer of uncompacted soil surmounted the arch, the vertical densities acting at the crown were little less than under Method A conditions; however, comparisons with Stations 1, 2, and 3 indicate greatly decreased densities 2 or 3 ft from the crown on either side. Horizontal densities differed little among the four stations.

In general, the effective densities acting on the right side of the arch exceeded those on the left. This phenomenon probably was influenced by boundary conditions since the right slope of the canyon, over much of the culvert's length, was nearly unbroken, whereas the left slope was characterized by a natural bench 30 to 50 ft above the stream level, which was converted into a haul road during construction. It is not unlikely that such discontinuities provide some support for the embankment, inhibiting its full settlement, and decreasing acting pressures below the broken slopes.

Readings for soil stressmeters placed in the embankment 6 ft above the crown and 8 to 20 ft out from the culvert centerline were also converted to effective densities. Many of these readings were erratic after the onset of heavy rains in November, so the

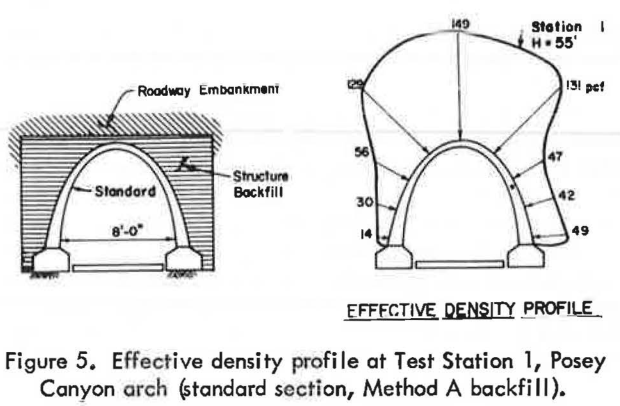

Figure 5. Effective density profile at Test Station 1, Posey Canyon arch (standard section, Method A backfill).

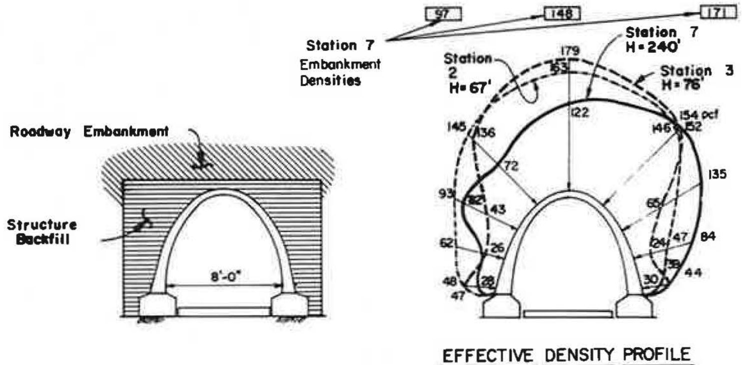

Figure 6. Effective density profiles, Stations 2, 3, and 7, Posey Canyon arch (special section, Method A backfill).

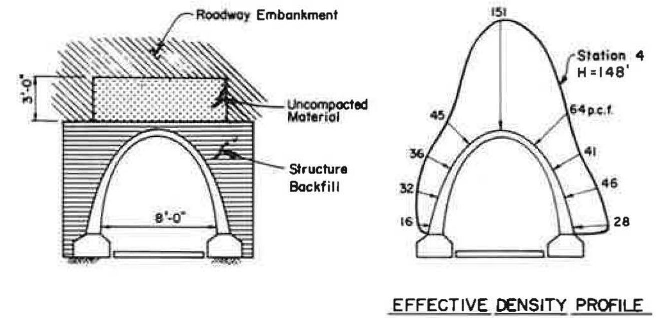

Figure 7. Effective density profile, Station 4, Posey Canyon arch (special section, Method B, uncompacted soil, surmounting culvert).

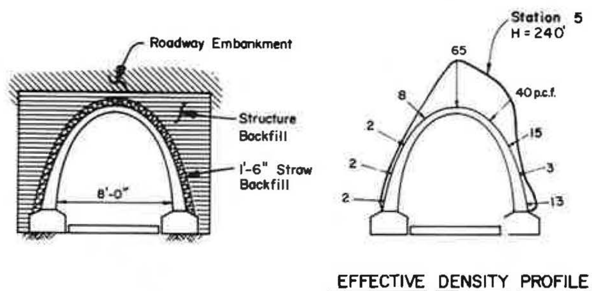

Figure 8. Effective density profile, Station 5, Posey Canyon arch (special section, Method B, baled straw surrounding culvert).

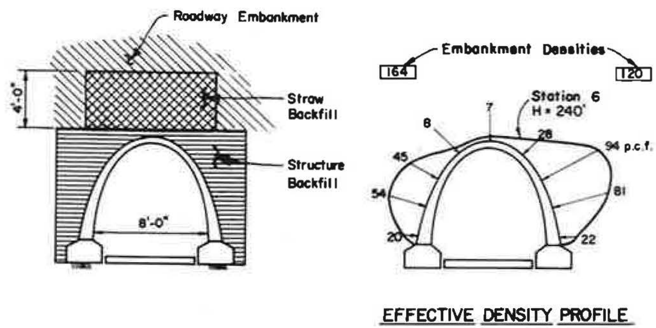

Figure 9. Effective density profile, Station 6, Posey Canyon arch (special section, Method B, baled straw, surmounting culvert).

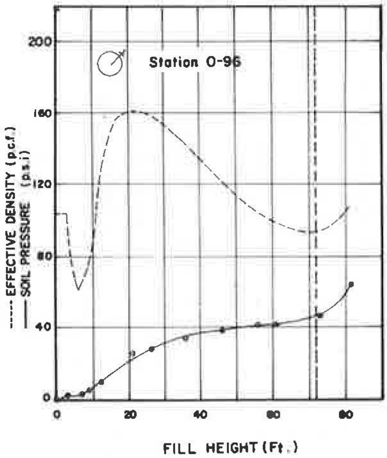

Figure 10. Soil pressure and effective density-embankment height functions at midpoint of upper quadrant; Chadd Creek steel structural plate pipe, Station 0-96 (Method B, baled straw, surmounting culvert).

pressures at the 120-ft level have been used in computing densities (Figs. 6 and 9).

Seven of the measured effective densities are appreciably higher than the embankment density, which approximated 120 to 130 pcf. Some of these excessive densities may have resulted from the longitudinal and transverse distribution of the weight of the interior prism over the straw layers to the exterior prisms. As mentioned previously, this phenomenon was observed at San Luis and Chadd Creek.

Pipe Culvert Research

Soil pressures and effective densities have been plotted as functions of embankment depths for the structural plate pipes at Chadd Creek and Apple Canyon. At the time of writing, the rigid pipe culvert study is still in its early stages.

Flexible Pipe Research (Phase 1—Chadd Creek)—Figure 10 is a plot of soil pressure and effective density as functions of embankment depth for the upper octant point on one side of the pipe. Marked similarities of configuration between symmetrically oriented meters on the left and right sides were observed. Similar configurations occurred for other locations; however, amplitudes of variation differed greatly among various octant points.

The effective density plots clearly demonstrate that, in the case of a flexible pipe using Method B backfill, design criteria may vary greatly with ultimate embankment depth, and more critical conditions may occur at lower depths.

A certain similarity of configuration of the effective density-height relationships for all orientations was evident, with distinct density maxima occurring with 20 to 30 ft over the meters, and minima with 70 to 90 ft over the meters.

Densities acting on the crown, under the straw, and at the ends of the horizontal diameter were sub-hydrostatic and remained less than 60 pcf Super-hydrostatic densities as great as 160 pcf were observed at the upper quadrant points; those observed at the invert were well over twice the embankment density. The aforementioned densities were maximum values observed at the 20 to 30-ft levels. All observed densities except that at the invert were sub-hydrostatic for the maximum fill height.

Effective density profiles are plotted for the three stations in Figure 11, which shows large pressure bulbs at the invert and midpoints of the upper quadrants, with distinct minima at or just below the ends of the horizontal diameter and under the straw. With increasing depths, maximum densities decrease, and minima increase, so that some tendency toward a more uniform distribution is indicated.

Flexible Pipe Research (Phase 2—Apple Canyon)—Figure 12 depicts a typical soil pressure-embankment depth and effective density function for the crown of one of the 108-in. twin culverts at Apple Canyon. Of particular significance is the increase in observed pressure after fill completion on the periphery of this steel structural plate pipe. The effective density increased from 120 to 160 pcf in the period of a year after the fill was placed. This phenomenom was observed at other points about the periphery with overall increases ranging from 30 to 60 percent.

Figure 13 shows the effective density profile for Station 7+25 at the maximum fill height of 60 ft, and at Station 10+00 for the 160-ft fill height. It is evident that the structural behavior of the Apple Canyon pipe with Method A backfill differs radically from that of the Chadd Creek pipe where the baled straw was used. The Apple Canyon pressure-height curves are essentially linear, with some decreases in effective densities beginning at the 100-ft level. A slight upward curvature of some curves was evident for low depths of cover. The radical changes in effective density which accompanied

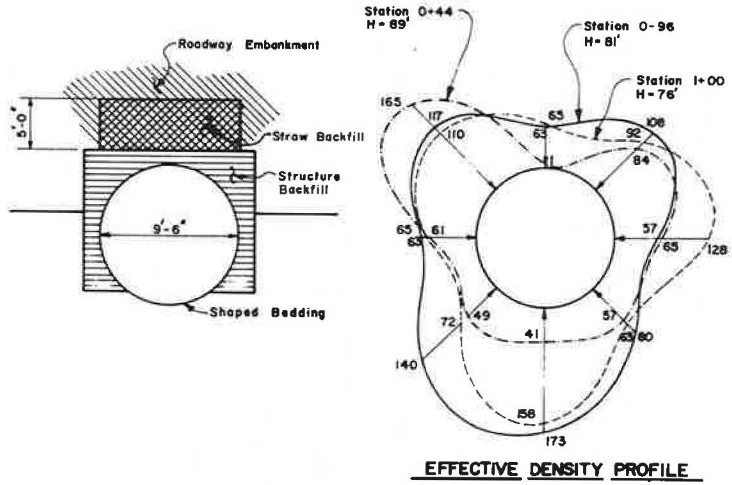

Figure 11. Effective density profiles, Stations 0+44, 0-96, 1+00, Chadd Creek steel structural plate pipe (Method B, baled straw, surmounting culvert).

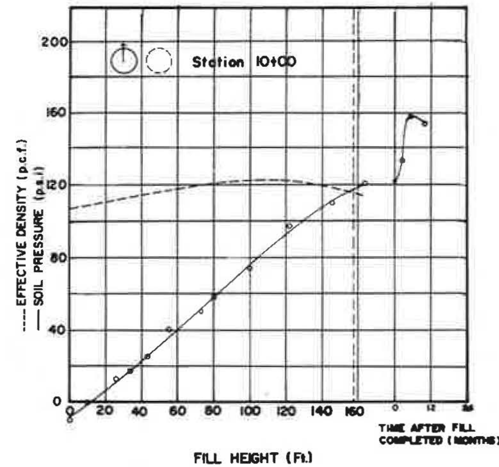

Figure 12. Soil pressure and effective density-embankment height functions at crown; Apple Canyon, 108-in. steel structural plate pipe, Station 10+00 (Method A backfill).

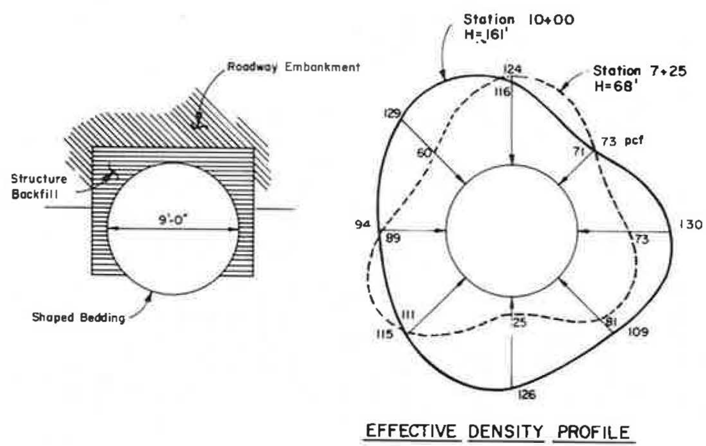

Figure 13. Effective density profiles for the Apple Canyon, 108-in. structural plate pipe (Method A backfill).

the use of Method B backfill at Chadd Creek were absent at Apple Canyon, and the Apple Canyon curves were very similar to those for Station 7 at Posey Canyon, where Method A backfill was employed. Thus, the shape of the pressure-height functions for the flexible culvert without straw were comparable to those for a rigid arch; however, the distribution of effective densities was very different, approaching a more uniform configuration around the pipe periphery.

In general, the pressure-height functions for meters surrounding rigid structures level off as soon as the maximum fill height is reached. Observations to date indicate that large changes in soil pressure acting on a flexible pipe may continue after completion of the fill over the meter.

CONCLUSIONS

For the San Luis Reservoir arch, where a rigid concrete culvert was buried in a 200-ft deep rock fill in a broad canyon:

1. The pressure-height curves were linear up to the full fill height.
2. The pressure configuration was vastly different from that assumed in the initial design.
3. Changes in effective densities after embankment completion were negligible.

The Posey Canyon culvert is a rigid arch buried in a 240-ft deep, crushed shale embankment in a V-shaped canyon.

1. Soil pressure-embankment height plots were essentially linear up to the full fill depth with exceptions as follows: (a) At Station 5, where baled straw surrounded the barrel periphery, a distinct upward curvature reflected the curvilinear stress-strain function of baled straw, which transmits greater pressures to the extrados as the straw becomes increasingly compact. (b) Some decrease in effective density began to occur when the embankment depth reached 180 ft. (c) Severe discontinuities in the linear functions were evidenced when the embankment depth reached 130 ft. These discontinuities are thought to have resulted from changes in soil shear strength due to embankment saturation with the onset of heavy rains.

2. For the condition where baled straw surrounded the barrel, lateral densities were negligible, vertical densities about half that of the embankment—these latter, however, would become greater proportions of embankment density with greater depths due to the curvilinear stress-strain function of the straw.

Pressure-height functions for the case where a layer of straw surmounted the arch were of somewhat the same configuration as those for the San Luis arch; however, horizontal and vertical densities were both much less than those measured at San Luis.

Where no special treatment was given to the backfill, the effective density distribution was much like the 120 pcf/36 pcf (horizontal:vertical) distribution used in design, although the vertical densities were somewhat higher. The super-hydrostatic densities are believed to result in part from the transference of load from the interior prism surmounting the straw at an adjacent station and in part from boundary conditions in the V-shaped canyon.

3. In general, effective densities increased after fill completion where the imperfect ditch was used, but remained essentially constant for stations with Method A backfill.

For Phase 1—Chadd Creek, flexible pipe research:

1. Effective density curves for a 114-in. structural plate pipe surmounted by a layer of baled straw were distinctly nonlinear. Maximum densities occurred with 20 to 30 ft of soil over the meter, minima with 70 to 90 ft over the meter. Configurations are similar for meters on the upper half of the pipe, for side meters, and for those at midpoints of the lower quadrants.

2. The effective density profiles show super-hydrostatic pressure bulbs at the invert; maxima at midpoints of the upper quadrants with densities slightly sub-hydrostatic; effective densities at the crown, sides, and midpoints of the lower quadrants about half that of the embankment, showing that the straw is effective in reducing vertical pressures at least up to full embankment depth.

3. Behavior of pressures after embankment completion cannot be evaluated at the present time.

For Phase 2—Apple Canyon, flexible pipe research:

1. For a 108-in. structural plate pipe with Method A backfill (positive projection), pressure-height curves were very similar to those observed for the rigid arch at Posey Canyon for the station with Method A backfill. Functions were essentially linear although some decrease in effective density began to occur at a lower level than at Posey Canyon, about 100 ft. The soil-structure interaction was thus very different from that where the Method B backfill was employed.

2. The effective density profile when embankment construction was complete exhibited more uniformity than in the case of any of the other structures tested.

3. Distinct increases in the effective densities have occurred during the five months since the embankment was completed. Transducer readings will continue until two years after embankment completion.

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

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