Comparative Evaluation of Precast Concrete Pipe-Arch and Arch Structures

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In this paper is presented a comparative evaluation of precast concrete pipe-arch and arch structures constructed in Minnesota during the past 20 years. Typical geometrics of these two types of structures are given. Design differences, structural details, load configurations, bedding materials, and foundation considerations for each type of structure are discussed. Comparative evaluation of features and problems associated with construction, maintenance, and repair of these structures is presented. Available information on initial and estimated life-cycle costs is covered in view of known performance history. Conclusions and recommendations are made for improvement in the design and construction of these two types of structures.

During the past two decades, precast concrete pipe-arch structures have been rather extensively used as replacement structures in Minnesota. Precast concrete (BEBO) arch structures were introduced in the United States in 1980–1981. Thirteen such structures have been installed in Minnesota so far and more are being planned. The wide use of precast pipe-arches has been attributed to their economy, ease of construction, and hydraulic efficiency. However, pipe-arches are limited to shorter spans of up to 16 ft. On the other hand, the precast arch structures, in addition to offering economy and ease of construction, can provide spans of up to 50 ft. As a result, their use is increasing.

In this paper are evaluated and compared geometric details, design features, construction techniques, and performance patterns based on construction and subsequent follow-up inspections of these two types of structures. Cost considerations are also examined, and comparative life-cycle costs are discussed.

GEOMETRIC DETAILS

Figure 1 shows typical geometric details of precast concrete pipe-arch structures. Pipe-arches normally span between 6 and 14 ft, beyond which field handling and costs become limiting factors. They are horseshoe shaped in cross section with wall thicknesses that vary from 6 to 11 in. depending on span length. The pipe-arch sections have tapered tongue and groove at their ends, which provide good joints and pipe continuity. Such sections are normally connected end to end with the upstream and downstream ends connected to a flared precast concrete section. Typical reinforcement for pipe-arches consists of two layers or cages of reinforcing bars or mesh, with 1 in. of concrete cover inside and outside. Reinforcement for shear stress, when necessary, is normally provided in the top and bottom floor areas. The lifting or handling hooks for pipe-arch sections are provided in the sides to minimize shear and tensile stresses. Sections of pipe-arches are such that they can be raised and positioned with minimal effort.

Figure 2 shows typical geometric details of precast concrete arch structures. These structures have spans of up to 50 ft, beyond which field handling and costs become prohibitive. Most com-

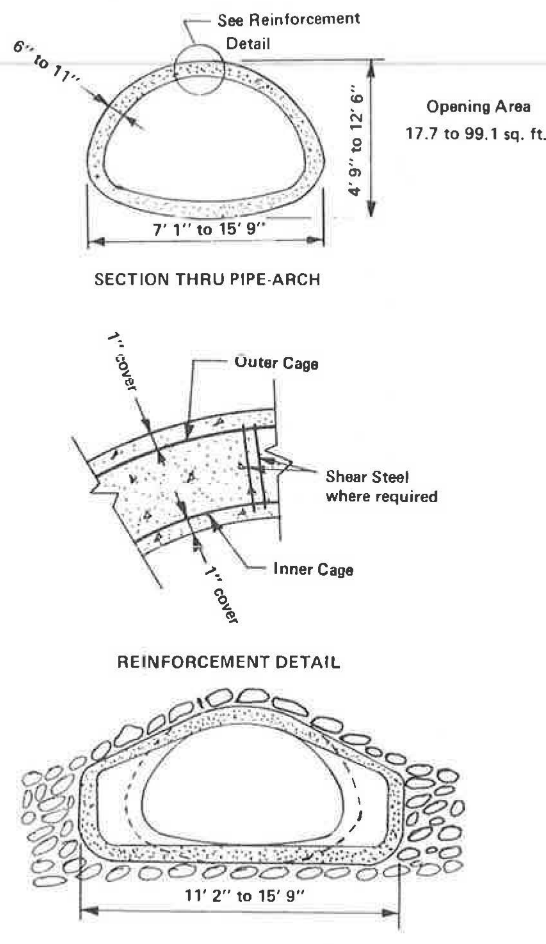

FIGURE 1 Typical geometric details of precast concrete pipe-arch structures.

monly used spans are 24, 30, and 40 ft. The wall thickness of cross sections ranges between 10 and 12 in. Full-span arch sections, 5 to 6 ft wide, are placed side by side (butted together) on top of relatively shallow cast-in-place reinforced concrete footings.

Joints between arch sections are packed with mastic rope. Precast concrete headwall sections are connected to the end arch sections by 1-in.-diameter tie rods. A pair of wingwalls butt together with these headwalls in a notch. Typical reinforcement for arch structures consists of two layers of reinforcing bars or mesh, with 1½ in. of concrete cover on the inside and 2 in. on the outside. The height of fill above arch structures is normally maintained at such depths that shear reinforcement is not necessary. The lifting or handling hooks for arch structures are provided in the sides and top of the sections to minimize handling stresses. Sections of arch structures are such, especially because of their narrow widths and long spans, that their handling and placement have to be quite sophisticated.

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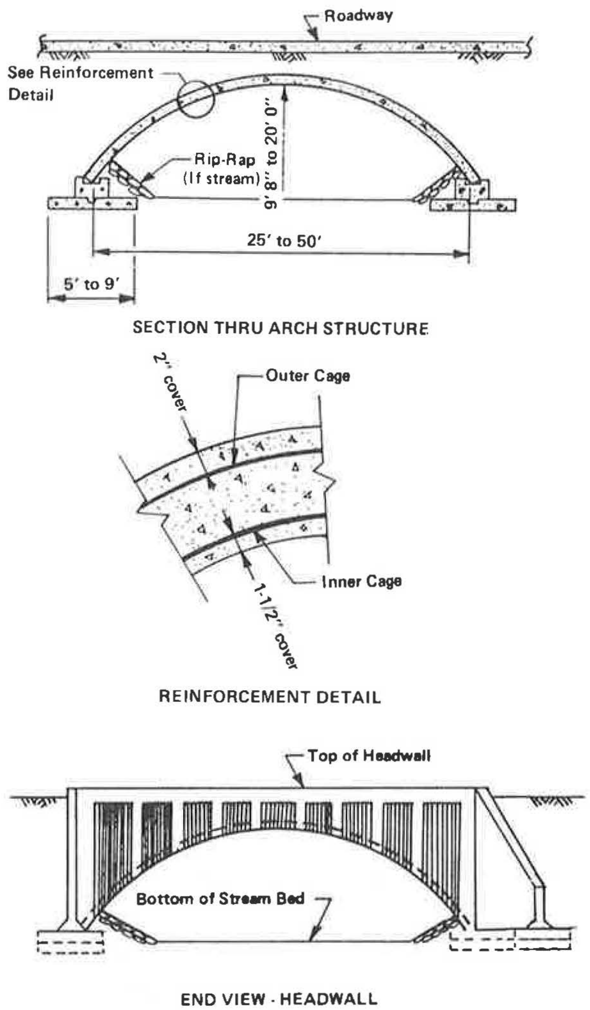

FIGURE 2 Typical geometric details of precast concrete arch structures.

COMPARATIVE EVALUATION

Design

Pipe-arches are designed as a closed-ring system with direct overburden and live loads from above and resisting soil pressures (Figure 3). Actual loads may result in unsymmetrical loading conditions over the life of the pipe-arches, which require greater shear reinforcement. The shape of a pipe-arch is such that the loads are distributed over a large area along its bottom. Typical load, shear, and bending moment diagrams are shown in Figure 3.

Arch structures are designed as two-hinged arches with overburden and live loads from above and resisting soil pressures under footings as well as passive soil pressures from sides. Footing loads consist of a vertical component and a horizontal thrust. The passive soil resistance needs to be mobilized to balance this horizontal thrust. Settlements and outward movements of footings have been found to be significant problems. The critical movements of the footing beneath the arch structures have been one of the major disadvantages in the design of arch structures. Imminent movement conditions have to exist in order to mobilize passive soil resistance that can balance horizontal thrust. Noticeable hairline cracks have been observed along the bottom of concrete at or near arch midspan. These cracks have run transverse to the span and have been located near the reinforcement. These can be attributed to the failure to develop adequate passive soil resistance to lateral movement or to inadequate bearing capacity of soil under the footings, or both. Subcuts as well as better quality and well-compacted bedding and fill materials are therefore necessary for arch structures.

Construction

Pipe-arch sections are normally cast in 4- to 10-ft lengths, weigh up to 15 tons, and are transported to site on flatbed trucks. In general, suitable bedding material for pipe-arches would have a safe bearing capacity of from 1,500 to 4,000 psf. This material is shaped to conform to the bottom of the section so that resulting soil pressures are uniform, thus preventing differential settlements and rotation of sections. A 40- to 50-ton crane is then used to lift, position, and place the sections. Because the pipe-arch sections are not match-cast, some difficulties can arise in achieving a proper fit at the tongue and groove between adjacent sections. A layer of geotextile is placed on top and sides, while a mastic rope is packed in the bottom, of joints to prevent leaking and piping action. Granular backfill is then placed symmetrically in 8-in. lifts and compacted to 95 percent of standard Proctor density to achieve balanced load conditions. A surface wearing course of asphalt or concrete is placed and compacted. A reinforced concrete slab is desirable with shallower overburdens of 2 ft or less to conform to AASHTO requirements.

Sections of arch structures are cast in 5- to 6-ft-wide full-span lengths, weigh up to 20 tons, and are transported to site lying on their side on flatbed trucks. Reinforced concrete footings are cast in place on properly excavated, backfilled, and well-compacted subgrade materials. Such bedding materials would normally be compacted to 100 percent of standard Proctor density and have a safe bearing capacity of 4,000 psf or better. A 75-ton crane, with heavy steel beam, is used to lift and place sections of arch structures on top of the cast-in-place footings. Under normal conditions, placement of an arch section takes from 10 to 15 min depending on construction worker skills and site conditions. Adjacent sections are just butted together with a mastic rope packed in the joints. A layer of geotextile is placed over the joints. Granular material is then placed symmetrically in 8-in. lifts and compacted to 95 percent of standard Proctor density to achieve balanced load conditions. A surface wearing course of asphalt or concrete is placed after all of the design overburden is placed and compacted. A reinforced concrete slab is desirable with shallower overburdens of 2 ft or less.

Erosion protection in the form of a filter material and rock riprap is placed in the channel bottom of arch structures immediately after the concrete footings have cured to the required strength of not less than 45 percent of the design strength. This sequence of operations saves costly hand placement later and permits use of lifting equipment from the stream level.

Maintenance and Repair

Pipe-Arches

Settlements and movements, in the case of pipe-arches, have been the result of inadequate preparation of bedding materials and inadequate compaction of backfill. However, in general, these problems have not caused any critical performance difficulties for pipe-arches.

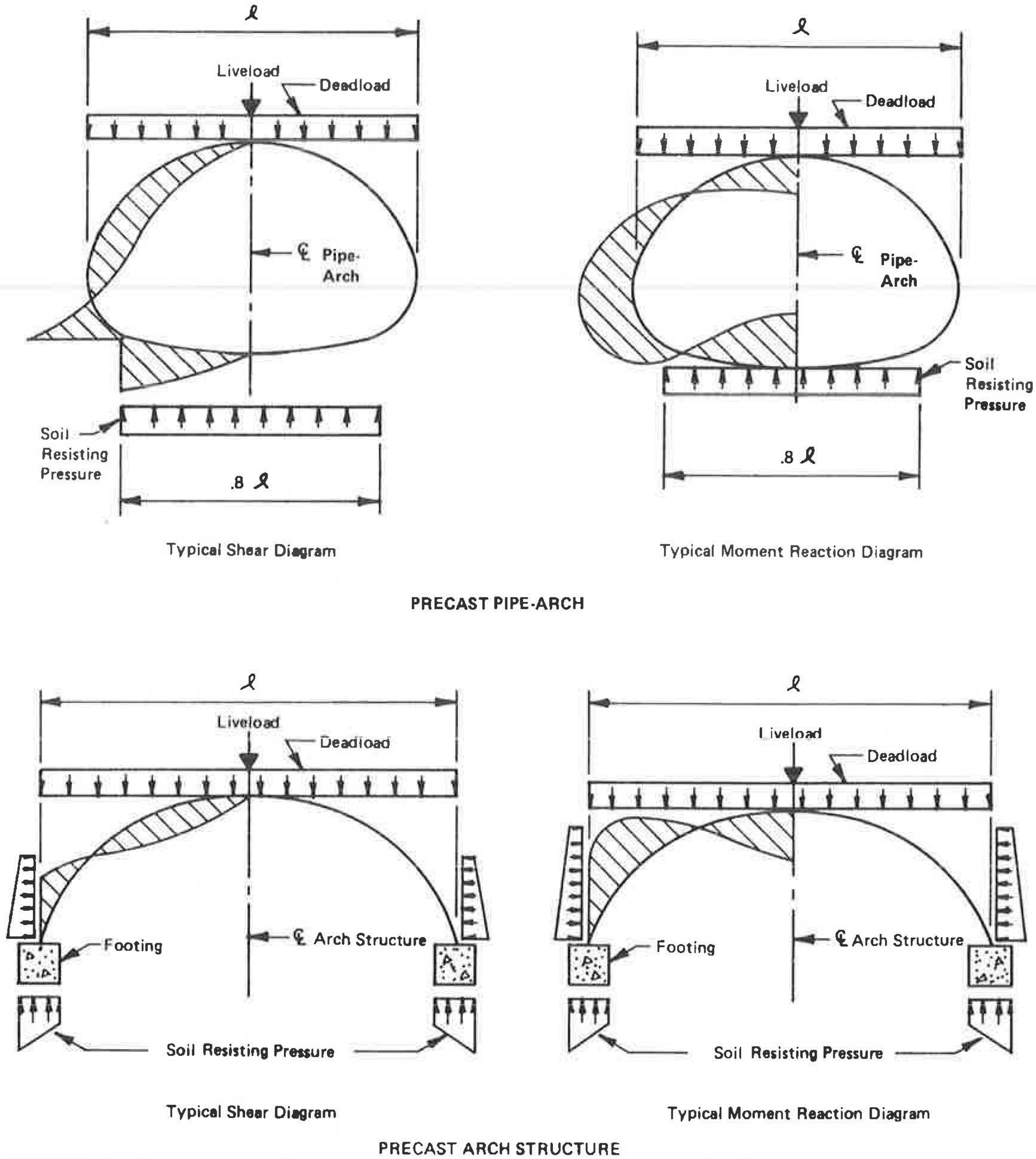

FIGURE 3 Load, shear, and moment diagrams.

The main problem with pipe-arches is scour at inlets and outlets because of excessive flows. Inadequate riprap protection at the base, sides, and top of arch aprons typically results in scour at the base, which progressively causes sliding of the upper soils, thereby enlarging the area of scour. Under extremely high flows scour would normally start further downstream and then progress to the outlet. Properly sizing the pipe-arches to high flows, such as 100-year floods, as well as properly sizing riprap and placing it on filter blankets or geotextiles can effectively minimize or even eliminate scour problems. In some places, where turf grows quickly and abundantly, scouring has not been a problem.

Another problem with pipe-arches is piping underneath the bottom, which erodes away the bedding material that supports it. This action may take place at the apron-inlet or between joints that have opened up. However, this problem has not been extensive for arch-pipes because of the sediment placed on the bottom during low flows that fills the joints. Piping at the inlet and outlet apron sections can be reduced by using a concrete dropwall or similar barrier.

The flat bottom of pipe-arch relates to wider stream flow; however, this wider bottom allows settlements of sediment that fill the waterway. This sediment normally gets washed away under rapid flow conditions. However, occasionally the pipe-arch has to be cleaned using labor-intensive methods that are costly.

Arch Structure

Settlements and movements, in the case of arch structures, have been the results of inadequate preparation of bedding materials under the footings and horizontal thrust as well as rotation at the footings. Cracking has been observed at the bottom of the arch at its crest. This can be explained by reviewing load, shear, and bending moment diagrams (Figure 3). Further, field measurements indicate significant lateral movements as well as some rotation at the footings. This suggests that adequate lateral restraint by the passive earth pressure may not have been activated early enough to prevent lateral movements observed at the footings, thereby causing subsequent crack patterns.

Although differential settlements can be critical in the case of arch structures, no such cases have been identified in the present short performance history of these types of structures; although settlements of up to 2 in. have been noticed, differential settlements have been less than ½ in.

Arch structures have a circular type of opening without a bottom. The filter blanket and riprap materials are placed in the stream bed to prevent its erosion. To date, extensive scour problems have not occurred. However, settlement and scour around the wingwalls have caused some shear cracks in concrete interconnections. Placement of well-compacted granular material has deterred this problem. The flow through arch structures has been less turbulent and generally controlled by the riprap to prevent scour (Tables 1 and 2).

Total construction costs of pipe-arches and arch structures that have been estimated or are under contract for four sites in Minnesota are given in Table 3.

From the estimates in Table 3 it would appear that two-barrel pipe-arches are less expensive for certain spans and fill heights.

TABLE 1 DATA ON CONCRETE ARCH STRUCTURES

Arch Width	41'	31'	41'	31'	41'	41'	41'	31'	41'	41'	41'
Arch Height	9'-8"	13'-8"	9'-8"	11'-4"	9'-8"	9'-8"	9'-8"	11'-4"	9'-8"	9'-8"	9'-8"
Spreading Footing Width	8'-6"	8'-0"	7'-0"	5'-0"	8'-0"	6'-0"	6'-0"	5'-0"	8'-0"	8'-0"	8'-0"
Spread Footing Depth (Below arch section) (which includes pads)	2'-6"	2'-7"	3'-4"	1'-8"	2'-8"	1'-10"	1'-10"	1'-8"	2'-11"	3'-4"	3'-4"
Type of Scour Protection	Rock Rip Rap	Not Req'd	6' Wide/ Sloped Rip Rap	Rock Rip Rap	Rock Rip Rap	Rock Rip Rap	Rock Rip Rap	Rock Rip Rap	Rock Rip Rap	Rock Rip Rap	Rock Rip Rap
Hydraulic Flow Q_{100}	1350 cfs. @ 5.0 fps.	(None)	1440 cfs. @ 5.1 fps.	860 cfs. @ 4.8 fps.	2200 cfs. @ 7.6 fps.	1450 cfs. @ 5.6 fps.	1700 cfs. @ 6.5 fps.	860 cfs. @ 4.5 fps.	1000 cfs. @ 3.6 fps.	6980 cfs.* @ 5.9 fps.	3710 @ 10.8 fps.
Barrel Length	72'	90'	66'	84'	66'	58'	54'	90'	90'	42'	84'
Cover Over Arch Sections at C/L Roadway	2'-8"	4'-7"	4'-9"	2'-0"	3'-0"	1'-6"	3'-6"	9'-9"	1'-8"	1'-8"	5'-8"
Type Roadway Over	5-1/2" Bit.	Bit.	Bit.	Bit.	Bit.	Bit.	Bit.	Bit.	Bit.	Gravel	Bit.
Traffic Over: ADT	5200 (81)	1750 (80)	472 (99)	400 (87)	475 (82)	1750 (82)	1800 (82)	4850 (81)	6300 (82)	43 (71)	
Angle of Wingwalls to Barrel	Square	Square	Square	Square	30° Flare	30° Flare	30° Flare	Square	30° Flare	30° Flare Parallel	30° Flare
Soil Condition	Peat and Silty Sand	Generally clay loam till	SC stiff to very stiff	Medium to Coarse Sand	Sl. Pl. SiL.	Very Stiff to hard clay loam till	Sand and gravel	Si Clay Very Stiff trace of Sand	Silty Sand Loose to Medium Dense	Silty Sand to Stiff Clay Loam	Gray Clay Till
Subcut Depth Under Ftg.	6 to 8'	4' on North ftg. & 8' on South ftg.	2'	None	Subcut to Elev. 769 3'	2'	1'	None	6'	1'	2'
Backfill Placed Under Footings	Select Granular Borrow Spec. Ø 3149.2B 100% Density	Select Granular Borrow Spec. 3149.2B 100% Density	Select Granular Borrow Spec. 3149.2B 100% Density	Granular Bedding Spec. 3149.2F 100% Density	Granular Bedding Spec. θ 3149.2F 100% Density	Granular Bedding Spec. 3149.2F 100% Density	Granular Bedding Spec. 3149.2F 100% Density	Granular Bedding Spec. 3149.2F 100% Density	Granular Bedding Spec. 3149.2F 100% Density	Granular Bedding Spec. 3149.2F 100% Density	Granular Bedding Spec. 3149.2F 100% Density

* An overflow channel is used to handle the 6980 cfs. flow.

Ø Specification 3149.2B allows select granular borrow material (one inch maximum size down to a maximum of 15% passing a #200 sievé) to be used in backfill.

θ Specification 3149.2F is the same as Spec. 3149.2B, except that only a maximum of 10% may pass a #200 sieve and the material is a graded aggregate product.

TABLE 2 DATA ON CONCRETE PIPE-ARCHES

Width (Inches) (Clearance span)	102	115	115	138	138	154	154	169	169
Height (Inches) (Clear Height)	62	72	72	87	87	97	97	107	107
Hydraulic Flow Q_{100} (CFS) / V_{100} (FPS)	460/ 6.5	717/ 5.5	763/ 8.71	640/ 5.9	762/ 7.47	1300/ 8.0	1483/ 9.06	1495/ 7.54	1920/ 10.7
No. of Barrels	2	3	2	2	2	2	2	2	2
Barrel Length (Feet)	44	50	40	50	64	38	76	72	52
Cover over Pipe (Feet)	2.38	1.00	2.30	2.60	1.95	2.39	5.0	7.5	3.50
Type of Roadway Surface	Gravel	Gravel	Gravel	Bit.	Gravel	Gravel	Gravel	Gravel	Bit.
Subcut Depth Under Pipe (Ft.)	1.0	4.0	2.0	1.5	2.0	2.0	1.0	2.0	2.0
Type Backfill Under Pipe*	Class A	Class A	Class A	Class A	Class A	Class B	Class A	Class A	Class A

*Per specification 2451

All pipe-arches Class A riprap as scour protection.

TABLE 3 CONSTRUCTION COSTS

Fill Height Above Arch (ft)	Site (county)	Length of Pipe-Arch (ft)	No. of Barrels	Size (in.)	Water Way Area (ft2)	Total Cost ($)	Size (ft)	Water Way Area (ft2)	Cost ($)
7.0	Lake	122	2	154	163	129,470	24	190	150,700
2.5	Dakota	86	3	169	297	130,100	40	300	109,210
15.0	Murray	152	3	169	297	289,755	30	330	181,388
12.0	Clearwater	120	3	169	297	181,100	30	330	129,050

Note: Length of pipe-arch includes the aprons.

However, when three-barrel pipe-arches are used, the arch structure appears to be less costly. When long spans and deep fills are encountered, the arch structure is definitely more economical than pipe-arches. Additional comparisons need to be made to determine the competitiveness of two-barrel pipe-arches and the 24-ft arch structure.

No significant maintenance and repair costs related to the structure of the pipe-arches have yet been experienced. There have been costs associated with erosion and sedimentation. However, these can be substantially minimized by adequate sizing of the pipe-arch to handle extreme flow conditions, such as the 100-year flood, and proper selection as well as placement of appropriate erosion protection.

Significant problems related to settlement, movement, and rotation of footings have come to light in the short performance history of arch structures. Should current design practices for arch structures be maintained, the levels of maintenance and repair activities can be expected to be greater than those for the pipe-arches. The crack patterns may become more serious. Another area for maintenance would be the connections with the headwall and between the headwall and wingwalls. Cracking and spalling of concrete sections can be expected to develop in those areas.

Another area of concern is the potential damage to footing support due to scour under extreme flow conditions. Settlement and movements can worsen unless stronger requirements for bearing capacity, depth of burial to reduce adverse effects of potential scour, and better means of preventing footing movements and rotations are specified. Consideration of piling support would be in order. Under the current practice, however, maintenance costs can be expected to be higher than those for pipe-arches.

CONCLUSIONS

1. Pipe-arches with low, wide bottoms are suitable for flat, shallow stream crossings, and arch structures are more adaptive to narrow, deep channels.

2. Pipe-arches have not experienced structural or scour problems of any significance. There has been some localized scour at their inlet and outlet apron sections.

Arch structures have settled and moved horizontally outward at their footing lines, until the passive soil resistance has been activated. These conditions have caused hairline cracks at the midspan of the arches. Use of piling in the concrete footings should be considered.

3. Use of adequate scour protection is essential to arch structures that have spread concrete footings.

4. Pipe-arches are easy to place using normal construction equipment. Arch structures require more sophisticated handling equipment and techniques because of their size, shape, and weight.

5. Pipe-arches have only experienced some scour and sedimentation problems. Arch structures are relatively new and somewhat experimental in nature, but to date they have not directly presented similar maintenance or repair problems.

6. It appears that up to two lines of pipe-arches are as economical to use as a single arch structure. However, three or more lines of pipe-arches are significantly more expensive than a single arch structure.

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Measurements and Analyses of Compaction Effects on a Long-Span Culvert

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Earth pressures that result from compaction of backfill can induce stresses and deformations, which are not amenable to analysis by conventional analytical methods, in flexible metal culverts. In this paper are presented the results of a study in which deformations of a 39-ft-span flexible metal culvert were measured at various stages of backfill placement and compaction. These field measurements were then compared with the results of finite element analyses in order to investigate the influence of compaction effects on culvert stresses and deformations. Two types of finite element analyses were performed: *(a)* conventional analyses that make no provision for modeling compaction effects and *(b)* analyses that incorporate recently developed models and analytical procedures that permit modeling of compaction-induced stresses and deformations. The results of these finite element analyses indicate that compaction effects significantly increased structural deformations during backfilling and also significantly affected bending moments within the culvert. Axial thrust around the culvert perimeter was also affected by compaction-induced earth pressures, but to a lesser degree. The results of this study provide a basis for assessing the potential importance of considering compaction effects in evaluating culvert stresses and deformations during and after backfill placement and compaction.

Earth pressures that result from compaction of backfill can produce stresses and deformations, which are not amenable to analysis by conventional analytical methods, in flexible metal culverts. These compaction-induced stresses and deformations can significantly influence the stress state and geometry of a culvert at various stages of backfill placement and compaction.

In this paper are presented the results of a study in which deformations of a large-span flexible metal culvert structure were measured during backfill operations. Detailed records of backfill placement procedures were maintained and care was taken to prevent the operation of large construction equipment in close proximity to the culvert, so this field study represents a case in which the influence of compaction effects on culvert stresses and deformations was less pronounced than for more typical cases in which the proximity of large equipment to the culvert structure is less rigorously controlled.

Two types of finite element analyses were performed: (*a*) conventional analyses that are well able to model incremental placement of backfill in layers but that cannot model compaction-induced stresses and deformations and (*b*) analyses that incorporate recently developed models and analytical procedures that permit modeling of compaction effects (*1*, *2*). Comparison of the results of these two types of analyses with each other, as well as with field measurements, provides a basis for assessing the potential importance of considering compaction effects in analyzing culvert stresses and deformations.

PROMONTORY CULVERT STRUCTURE

The Promontory culvert structure is located in Mesa, California, and is designed to perform as a bridge providing grade separation between two otherwise intersecting roadways. Figure 1 (top) shows a cross section through the structure. The culvert is a low-profile arch, with a span of 38 ft 5 in., a rise of 15 ft 9 in., and a length of 80 ft, founded on 3-ft-high reinforced concrete stem walls with a reinforced concrete base slab. The culvert consists of 9- x 2 1/2-in. corrugated aluminum structural plate 0.175 in. thick, and the crown section is reinforced with Type IV aluminum bulb angle stiffener ribs that occur at a spacing of 9 in. The culvert haunches are grouted into a slot at the top of the stem walls, providing a rigid connection for moment transfer at this point.

The existing foundation soil at the site was a stiff, silty, sandy clay of low plasticity (CL-SC). Chemical tests indicated that this sandy clay was potentially corrosive with respect to the culvert structure. As a result, a crushed basalt material (select fill) was imported for use as a protective backfill envelope within 3 to 4 ft of the culvert. This crushed basalt was an angular silty sand (SM) and was placed to a minimum width of 4 ft at both sides of the culvert and continued to the final fill surface as shown in Figure 1 (top).

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