Overstressed Precast Concrete Pipe Arch and Its Redesign

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In 1967, a large precast concrete pipe arch was installed on Trunk Highway 90 in Worthington, Minnesota, under a high fill. Some cracking in the haunches of the pipe arch was observed after a heavy rainfall in 1969. Analyses of the original D-load design and a direct field load design that was completed after the failure are presented. The direct design indicated a need for additional shear steel in the haunch locations. A rehabilitation method that proved successful in keeping the arch pipe functional for the last 23 years is included.

In October 1967 a 3100- × 1980-mm (122- × 78-in.) precast concrete arch pipe was installed under I-90 in Worthington, Minnesota, with an overfill of 7.2 m (24 ft). A Class IV, D-load design pipe was used at this installation (see Figure 1 for details of structural design). After a heavy rain in June 1969, some sections of the pipe were observed to have severe structural distress. Longitudinal cracks were located roughly at the junction of the long-radius base slab and the short-radius lower haunches of the pipe as shown in Figure 2. In general there was only one crack in each cracked pipe section, but they were not all on the same side. Several of the cracks had opened up about 50 mm (2 in.) and were observed to extend diagonally downward and inward toward the centerline of the culvert in an orientation typical of a diagonal tension failure (see Figure 2). However, in most of the 8-ft pipe section, the cracks had not opened up sufficiently to observe crack orientation and depth. A routine inspection conducted several months earlier did not show any signs of distress. Thus, it was concluded that the heavy runoff caused the structural distress. There was no indication of piping or water running alongside or under the culvert. However, saturation of the surrounding soil may have occurred from water flowing through the joints. This may have resulted in loss of lateral soil support and subsequently increased stresses in the pipe.

According to the construction inspector, all pipe sections were placed on a high-quality bedding consisting of about 150 mm (6 in.) of sand/gravel material that overlaid the in situ silty clay soil. To obtain good bearing, the bedding was template shaped for almost the full width of the pipe. Several feet of compacted backfill was placed adjacent to the pipe to an elevation above the springline (see Figure 3). By using the rated three-edge bearing (TEB) strength of a Class IV pipe with 7.2-m (24-ft) overfill and a Class B bedding, the safety factors for loading are 1.0 for a 0.25-mm (0.01-in.) crack and 1.5 for ultimate load. [$D_{0.25\ \mathrm{mm}\ (0.01\ \mathrm{in.})} \leq$ 100 N/lin. m (2,000 lb/lin. ft); $D_{\mathrm{ult.}} \leq$ 150 N/lin. m (3,000 lb/lin. ft) for Class IV pipe.]

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DESIGN PROCEDURES

The original design of precast concrete arch pipes was based on D-loading criteria. These arch pipes were introduced as culvert members in the early 1960s in Minnesota. Their design was based on the standard TEB test method specification in ASTM C497 and ASTM C506. See Figure 4 for original design results of shear steel location and magnitude.

The pipe was not TEB tested but was state inspected to ensure proper steel area was used and placed correctly. Concrete cylinders were taken and tested to meet the minimum requirement of 34.5 MPa (5,000 psi).

For installations under high fills, the indirect design method, based on TEB tests and bedding factors, is inappropriate. TEB tests create a maximum flexural and shear force near the center of the pipe invert. Pipe designers provide the necessary flexural and radial reinforcing steel at these locations so the pipe will pass the TEB test. When a pipe is properly installed, the bedding material provides uniform support to the pipe invert. Uniform support, differing from the TEB test condition, shifts the point of maximum shear out from the center of the pipe toward the edges of the pipe invert. Uniform support also increases the ability of the pipe to support vertical loads that are greater than the load applied during a TEB test. Therefore, installed pipes must resist shear loads at locations different from a similar pipe designed to pass a TEB test. For high overfill installations a direct design method based on actual installed conditions provides a better means of analysis than the traditional indirect design method. See Figure 4 for direct design results of shear steel locations and magnitudes.

DIRECT DESIGN ANALYSIS

A structural direct design analysis of the in-place pipe was made by Minnesota Department of Transportation and a consultant using the actual field loads and bedding conditions as shown in Figure 5. (This included eccentric loadings.) Results indicated shear (diagonal tension) failure where the actual cracking occurred. Lack of shear steel at these locations allowed cracking to occur, which resulted in wall shear failures (see Figures 2 and 4). As a result of these analyses, additional shear reinforcement was added in these locations.

In 1972 the Minnesota Department of Transportation produced a new structural design table for precast concrete pipe arches using the direct design analysis. Pipe sizes ranged in span from 560 to 4290 mm (22 to 169 in.). Standard AASHTO load factors of 1.5 for dead load and 2.5 for live load were used. The analysis assumed a bedding support of 80 percent of the bottom width and

1967 DESIGN DATA OF CLASS IV PIPE			
RISE			1980MM (78 IN.)
SPAN			3100MM (122 IN.)
THICKNESS			230MM (9 IN.)
(1) CONTINUOUS BASIC REINF.	INNER CAGE		16.3 (0.77)
	OUTER CAGE		11.9 (0.56)
(1) ADDITIONAL CAGE REINF.	U (INNER CAGE)	LGTH.	2.1M (6'-10")
			16.3 (0.77)
	V (OUTER CAGE)	LGTH.	4.9M (16'-0")
			11.9 (0.56)
f'c CL. IV			34470KPa (5KSI)
WEIGHT PER M (FT.)			4900Kg (3300 LB.)

(1) REINFORCEMENT AREA SHOWN IS MINIMUM CIRCUMFERENTIAL STEEL AREA IN SQUARE MM (INCHES) PER LINEAL CM (FT.) OF PIPE BARREL.

STIRRUP REQUIREMENTS
X=1.8M (6'), As=16.3 (.77)
Y=2.1M (7'), As=33.2 (1.57)
MINIMUM SPACING 300MM (12 IN.)

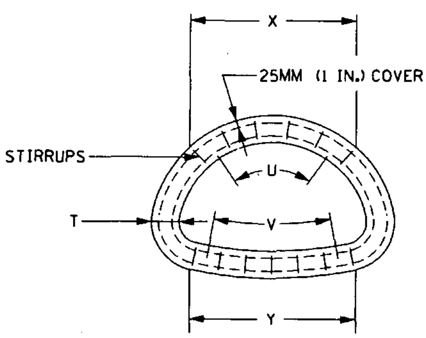

FIGURE 1 Details of structural design, Class IV pipe, 1967.

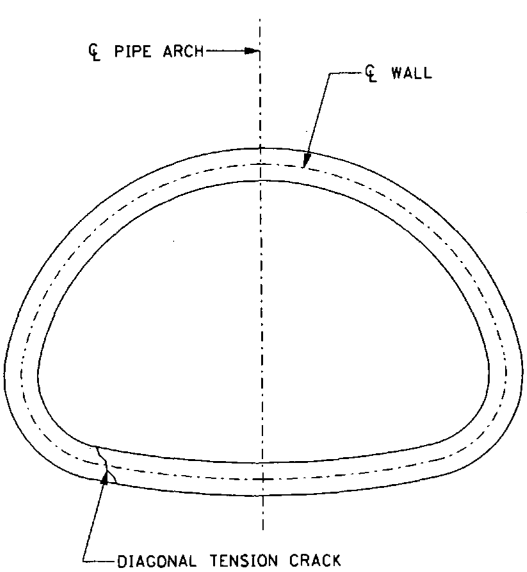

FIGURE 2 Diagonal tension failure.

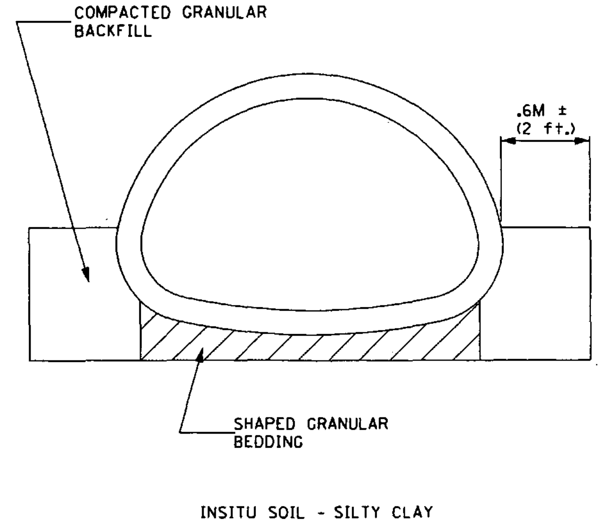

FIGURE 3 Typical installation.

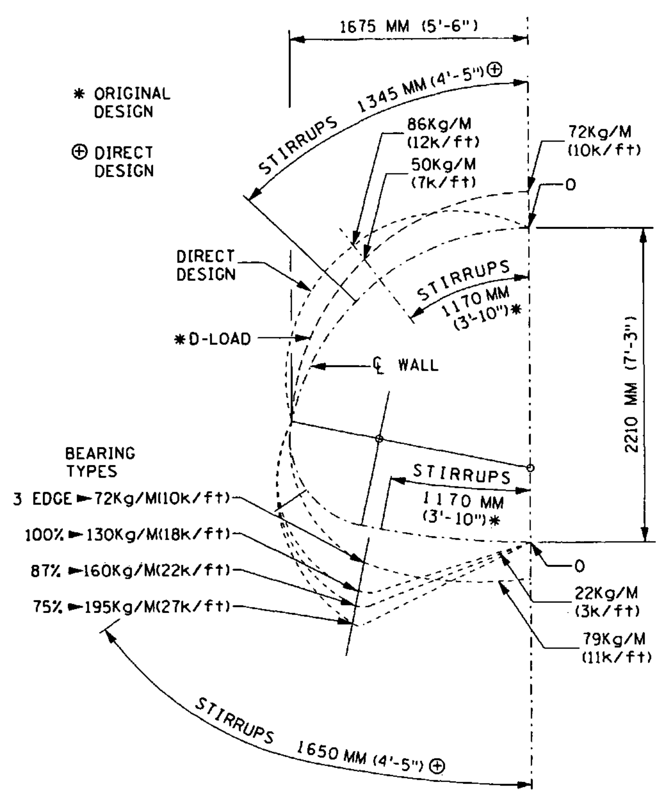

FIGURE 4 Original and direct design results.

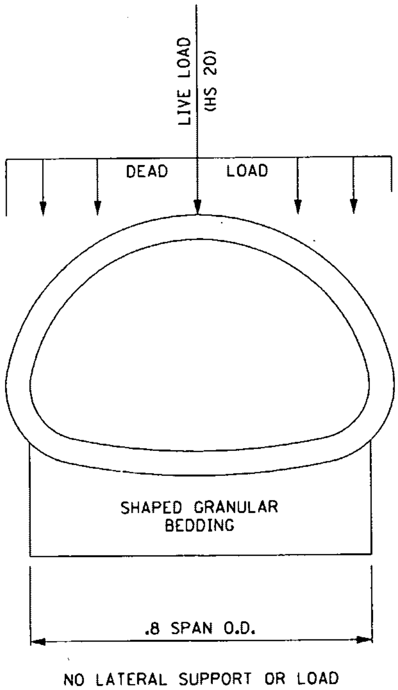

FIGURE 5 Direct design load assumption.

1972 DESIGN DATA OF CLASS IV PIPE			
RISE			1980MM (78 IN.)
SPAN			3100MM (122 IN.)
THICKNESS			230MM (9 IN.)
(1) CONTINUOUS BASIC REINF.	INNER CAGE		19.1 (0.90)
	OUTER CAGE		18.9 (0.89)
(1) ADDITIONAL CAGE REINF.	U (INNER CAGE)	LGTH.	1.2M (3'-10")
			4.7 (0.22) TOP
			19.1 (0.90) BOT
	V (OUTER CAGE)	LGTH.	2.6M (8-6")
			18.8 (0.89)
f'c CL. IV			34.5MPa (5KSI)
WEIGHT PER M (FT.)			4880Kg (3285 LB.)

STIRRUP REQUIREMENTS
X=1.35M (4'-5"), Asl=.14 (.2), MAX. SPCG. 175M (7 IN.)
Y=1.00M (3'-3"), Asl=.47 (.67), MAX. SPCG. 100M (4 IN.)
Z=0.66M (2'-2"), Asl=.14 (.2), MAX. SPCG. 175M (7 IN.)

Asl=MINIMUM STEEL AREA IN SQUARE MM (INCHES) PER SQ. CM. (FT.) OF WALL MEASURED AT ℄ OF WALL.

(1) As=CIRCUMFERENTIAL STEEL AREA IN SQUARE MM (IN.) PER LIN. CM (FT.) OF PIPE BARREL.

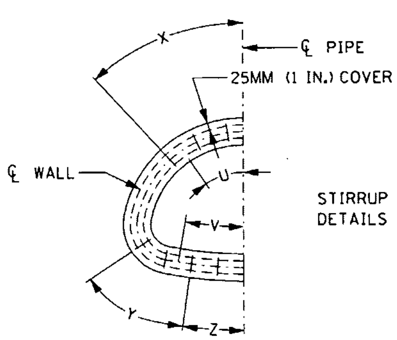

FIGURE 6 Details of structural design, Class IV pipe, 1972.

TABLE 1 Pipe Properties

Nominal Pipe Diameter(in)	124
Concrete Compressive Strength(psi)	5000
Concrete Elastic Modulus(psi)	4286826
Concrete Poisson Ratio	0.17
Density of Pipe(pcf)	0
Steel Yield Strength(psi)	60000
Steel Elastic Modulus(psi)	29000000
Steel Poisson Ratio	0.3
Concrete Cracking Strain	0
Concrete Yielding Strain	0.000566
Concrete Crushing Strain	0.002
Steel Yielding Strain	0.001883
Wall Thickness(in)	9

TABLE 2 Properties of In Situ Material (Duncan Soil Model Parameters)

Soil Classification	sc 100
Density	120
Cohesion Intercept	3.472
Friction Angle	0.576
Scaled Modulus Number	400
Modulus Exponent	0.6
Failure Ratio	0.7
Bulk Modulus Number	200
Bulk Modulus Exponent	0.5

TABLE 3 Properties of Bedding and Backfill Material (Duncan Soil Parameters)

Soil Classification	sm100
Density(pcf)	120
Cohesion Intercept	0
Friction Angle	0.628
Scaled Modulus Number	600
Modulus Exponent	0.25
Failure Ratio	0.7
Bulk Modulus Number	450
Bulk Modulus Exponent	0

TABLE 4 Stresses in Culvert Wall (psi)

Nodes	Inner Cage Steel	Outer Cage Steel	Concrete Compression	Shear Stress
1	12583	-6433.8	-1397.8	0
2	10141	-5535.1	-1184.3	28.92
3	3608	-3105.4	-609	47.59
4	-2382.9	2281.2	454.3	53.04
5	-5512.9	14098	-1286	46.88
6	-7744.4	22871	-1888.3	9.3
7	-6243.1	18134	-1514.2	-54.77
8	-425.6	-297.6	-62.4	-84.5
9	10530	-4565.9	-1034.6	-65.2
10	17240	-6849.4	-1590.5	-32.83
11	19529	-7616.3	-1778.1	0

TABLE 5 Strains in the Inner and Outer Fiber of the Culvert Wall

NODES	INNER STRAIN	OUTER STRAIN
1	0.00050959	-0.00031664
2	0.00041281	-0.00026828
3	0.00015373	-0.00013796
4	-0.00010292	0.00099729
5	-0.00029133	0.00056071
6	-0.00042776	0.00090242
7	-0.00034301	0.00071614
8	-0.00014129	-0.00000856
9	0.00042151	-0.00023437
10	0.00068635	-0.0003603
11	0.0007766	-0.0004028

no lateral support on the sides (see Figure 5). An 80 percent bearing width is more realistic because of the difficulty in obtaining compaction under the haunches. If good installation methods are used, lateral side support may be used in the analysis. Spans of 2590 mm (102 in.) or more required shear steel to be extended into the haunches where the diagonal cracks had occurred. Previous D-load designs had only required shear steel in the bottom and top of the arch. (See Figures 4 and 6 for new stirrup requirements.)

A recent analysis of 3100- × 1980-mm (122- × 78-in.) arch pipe was made using CANDE (culvert analysis and design software) version 1980. The Duncan soil model was used. The properties of the in situ silty clayey sand used in the model were as follows:

Location	*Type of Soil*	*Relative Compaction (%)*
In situ soil	Silty clayey sand	100
Bedding	Silty sand	100
Backfill	Silty sand	100

Density of in situ soil, bedding, and backfill was taken as 1.54 kg/m^3 (120 pcf).

The Duncan model is a nonlinear stress-strain model. The interface model, which takes into consideration the relative movement of the soil with respect to the pipe at the pipe-soil interface, was adopted for the analysis. Thus at each load step, tensile separation, frictional movement, and complete bond of the interface are possible. The pipe wall was divided into 10 elements that gave

TABLE 6 Safety Factors

Parameter	Ratio	Safety Factor	
		Desired	Compute
Concrete Crushing	Concrete Strength/ Max. Compressive Stress	>=2	2.648
Steel Yielding	Steel Yield Stress/ Max. Steel Stress	>=2	2.623
Diagonal Cracking	Wall Shear Capacity/ Max. Shear	>=2	1.32
Crack Width	0.01 inch/ Max Crack width	1	2.493
Bowstringing	Tensile Strength/ Stress From Bow String	1	4.897
Displacement	Allowable Displacement /Max. Disp	1	0.63

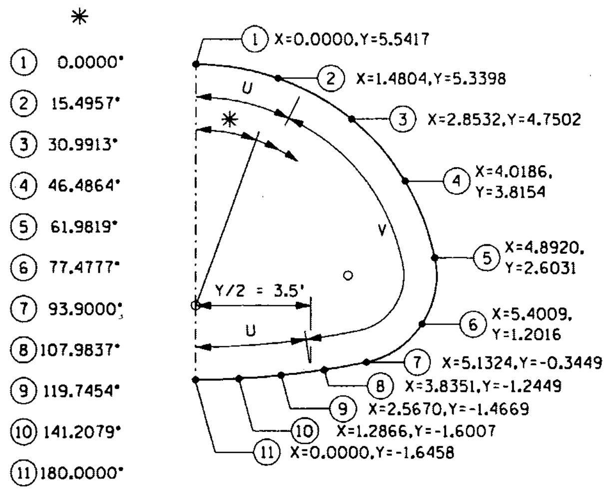

FIGURE 7 Computer analysis, 122-in. span.

output results corresponding to the 11 pipe nodes. (See Tables 1 through 6 and Figure 7 for input and output parameters.)

In the 1967 pipe design under consideration, a major crack was observed in the bottom of the pipe just outside the stirrup zone Y. From our CANDE analysis it was found that maximum shear stress was at Node 8, which is just outside the 1967 designed stirrup zone Y. The magnitude of this shear stress is 12.25 kPa (84.5 psi) > 0.95 $\sqrt{f'}$ c = 9.75 kPa (67.2 psi)—the allowable shear stress for concrete.

The safety factor for tensile stress was 1.32 (less than desirable value of 2), and the performance factor for bowstringing was 0.63 (less than desirable value of 1.0), suggesting that failure could have been due to a combination of diagonal tension and bowstringing action. See accompanying CANDE program input and output.

REHABILITATION OF ARCH PIPE

The distressed pipe and culvert sections were rehabilitated in 1970 with a vertical strut system using wide flange steel supports (see Figure 8). Galvanized sheets were placed over both sides of the vertical struts to reduce the potential for debris accumulation.

Holes were cored through the wall haunch areas to facilitate pressure grouting of haunch voids. About 5.5 m^3 (7 yd^3) of grout was used, indicating that considerable voids existed. As a result of these rehabilitation measures, the culvert is still functioning adequately.

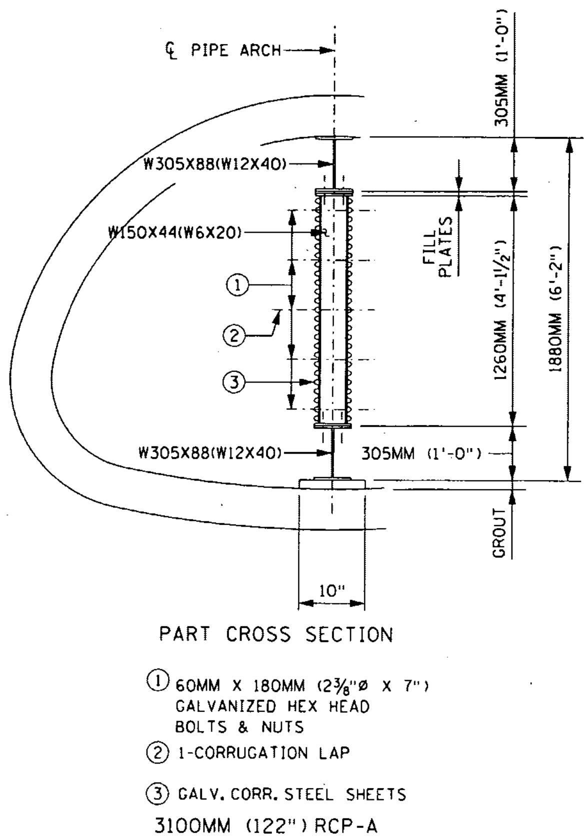

FIGURE 8 Rehabilitation of distressed arch pipe.

None of the arch pipe produced and installed since 1972 using the direct design analysis shows any signs of structural distress.

CONCLUSIONS

- Use an adequate amount of shear steel in top and bottom of arch pipe based on direct design loadings.
- Allow for loss of side support in questionable fill materials. To obtain lateral support, good fill materials and adequate compaction are required.
- Shaped granular beddings (0.8 span outside diameter) beneath arch pipes will provide uniform bearing pressures, which can be realistically achieved.
- Design of arch pipes with about 0.60 m (2 ft) of fill over them should include varying locations of concentrated live loads.

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