Performance of a Reinforced Concrete Pipe Culvert Under Rock Embankment

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A 48-in. diameter reinforced concrete pipe installation has been studied to evaluate the performance of both types of bedding conditions currently used by the Kentucky Department of Highways. A portion of the pipe was laid using Kentucky's standard B bedding. The remainder of the pipe culvert was laid using the B_1 bedding (imperfect trench); the design height of the fill (36 ft) was sufficient to require the imperfect trench construction. The embankment was primarily of a rock fill material, with the largest particle size limited to a maximum of 3 ft. The portion of the pipe with the standard B bedding exhibited stress in relation to each additional height of embankment placed. For every fill increment, there was a corresponding change in the vertical and horizontal diameters of the pipe and in the pipe distress as evidenced by cracking. The absence of signs of distress in the B_1 bedding portion indicates that the imperfect trench performed its purpose of relieving load on the pipe.

•WHEN taken as a general classification, underground conduits in some form have been used by mankind for at least 3000 years for drainage or water supply purposes. In recent years Interstate highways with their flatter grades and longer radius curves have required the construction of deeper cuts and higher fills. Concrete pipe culverts under these higher fills require either special methods of installation, such as the imperfect trench, or stronger pipe in order to carry the heavier loadings.

An extensive research program on pipe problems was inaugurated at Iowa State College in 1908, and it has been carried on practically continuously since. Through this research, a comprehensive theory widely known as Marston's Theory of Loads on Underground Conduits (1, 2, 3) has been developed.

Conceivably, it would be possible to compute by modern methods of soil mechanics the various factors that affect the load on a conduit, but such a procedure would involve the expenditure of both time and money that would be prohibitive in relation to the total cost of the structure. Therefore, many of these factors may be evaluated by an accumulation of data obtained from measurement and observation of actual installation performances. Many states have specifications or standard plans permitting the use of the imperfect trench as proposed by Marston, or with modifications. Most of these states have adopted the imperfect trench method of construction within the past two decades.

Advancement of the present knowledge of loads on pipe culverts depends in part on an accumulation of field experience and supporting data. One particular pipe has been chosen for this special study because of its installation conditions and because it may add to the knowledge of the performance of the imperfect trench. This pipe has been

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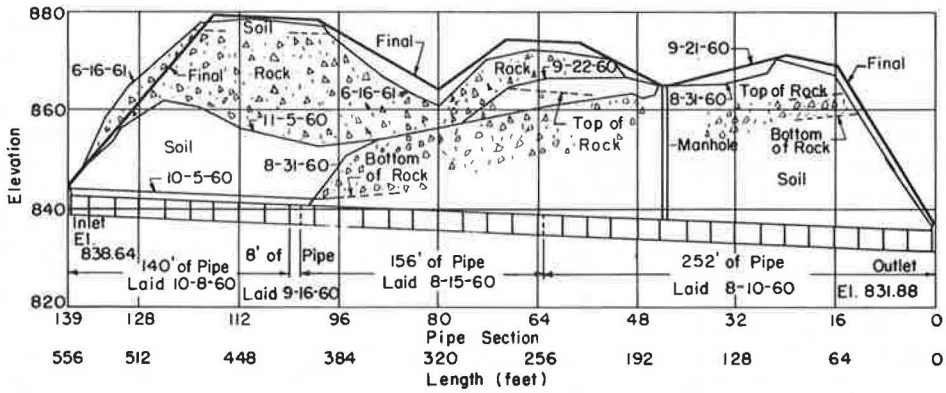


Figure 1. Fill profiles.

constructed using both type beddings that were specified in the 1956 edition of the "Kentucky Department of Highways Standard Specifications for Road and Bridge Construction" and amendments thereto (see Appendix A). Observation of the performance of this installation during and after construction was desirable to check the validity of the imperfect trench theory as applied to rockfill material, which was used in this particular installation.

PIPE INSTALLATION AND PERFORMANCE

A 48-in. diameter pipe installation on Interstate 75 near Georgetown, Kentucky, was selected for special study. This study was inaugurated to take advantage of an opportunity to observe at one location the performance of both bedding conditions as used in Kentucky. Distress was first noted in the pipe in the latter part of August 1960, before the full design length of pipe (560 ft, 140 sections) had been laid. At that time, the fill had not reached full design height (36 ft) and the Class III pipe had hardly been in place a month. This first portion of the pipe was laid using Kentucky's standard B bedding; after a review and check of plans and specifications revealed that Class III pipe with B bedding was an inadequate design, the bedding for the remainder of the pipe was changed to B_1 (imperfect trench) (Fig. 4, Appendix A). Kentucky's standard pipe classes are the same as ASTM designations with reference to strength requirements. Pipe used in this installation was selected from lots accepted as adequate with respect to 3-edge bearing test results.

A total of 102 four-foot pipe sections manufactured on different dates, from a design length of 140 sections, was placed with standard B bedding before the change. Plans specified the standard B bedding and it must be assumed that this was obtained. Field data substantiate that the backfill depth requirement above rock (Fig. 3, Appendix A) was obtained before placing the pipe; therefore, one of the factors considered to be a major contributing cause to pipe failure—ledge rock in the foundation too close to the bottom of the pipe—is nonexistent at this location.

For the remaining 37 sections actually placed, a B_1 bedding was used. At least 3 ft of unsuitable material was removed from the foundation area below the bottom of the pipe before the backfill was placed (Fig. 5, Appendix B); the resident engineer estimated a 7-ft soil foundation for camber calculations (4). Plans placed the backfill in approximately 1-ft lifts and a rubber-tire dozer was used to compact it. A sand cushion bedding was prepared in a satisfactory manner.

The pipe was laid in the sand cushion bedding (Fig. 8, Appendix B) and the backfill brought up uniformly in layers not exceeding 6 in. to a minimum height of 18 in. (0.30 times the outside pipe diameter). Each layer was compacted thoroughly by single-action pneumatic tampers under the haunches of the pipe to insure that the backfill was in intimate contact with the sides of the pipe. The embankment was then extended

upward in a normal manner to such an elevation that there was a soil cover equal to the overall height of the pipe plus 12 in. in preparation for construction of the imperfect trench (Fig. 9, Appendix B).

A trench equal in width and height to the outside width and height of the pipe was dug in the compacted embankment with a backhoe (Fig. 10, Appendix B). At this time the alignment of the pipe and the trench were noted to be off approximately 1 ft in some places; this was corrected by refilling and compacting the trench in 6-in. layers and redigging the trench over the centerline of the pipe. The trench was then filled with loose straw to a depth of approximately 24 in. Loose backfill in the remainder of the trench compressed the straw to a thickness of about 16 in. The trench was then covered and bridged by a 2-ft layer of compacted soil to a width of 20 ft on each side of the pipe (Fig. 11, Appendix B).

By this time it was late in the season and construction equipment had been moved from the general construction area. Consequently, the rockfill over the pipe was not completed until the spring of 1961. However, a small volume of earth fill (Fig. 1) was placed the last part of the year as an approach for construction of a nearby overpass pier.

The embankment material placed in 1960, other than that used in the immediate backfill near the pipe and imperfect trench, consisted for the most part of rock. With the placement of the rock material (Figs. 1 and 2) during the latter part of August 1960 over the 102 sections laid with standard B bedding, there developed a series of hairline cracks. A survey of pipe conditions revealed that nearly every section, beginning at section 13 through section 71, had at least one hairline crack in the top and bottom by the last of August. Hairline cracks were visible in section 13 through section 86 by the last of September, with a progressive increase in the size and number of cracks in sections 33 to 76 since the survey made the last part of August.

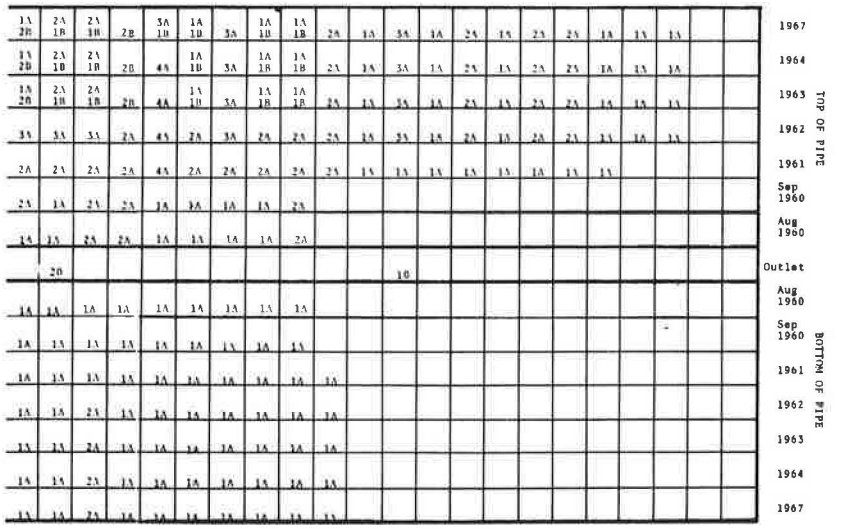
In January 1961 the sections constructed with standard B bedding still exhibited progressive development of hairline cracks under the partial fill load but seemed to be approaching an equilibrium condition with respect to the load. By May 1961 the approximate maximum load appeared to have been reached, since progressive distress was no longer noted in the form of increased size or number of cracks.

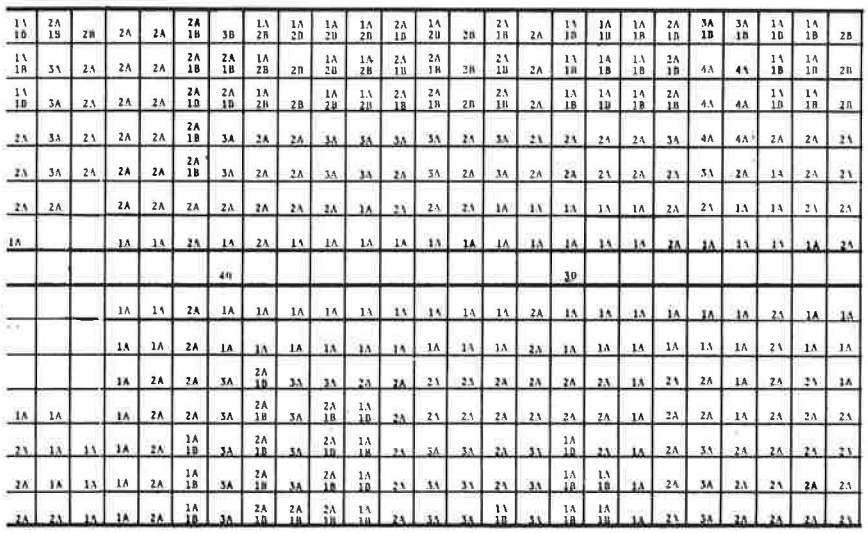
Construction of the rock embankment over the pipe was completed the last of May 1961. The additional load on the pipe sections with standard B bedding resulted in a renewed increase of signs of distress. The amount of additional fill may be seen in Figure 1. Increased distress in the B bedding sections due to the additional embankment was most noticeable in sections 75 through 100. The sections with B_1 bedding, now with nearly full embankment design height, remained in good condition and exhibited no distress.

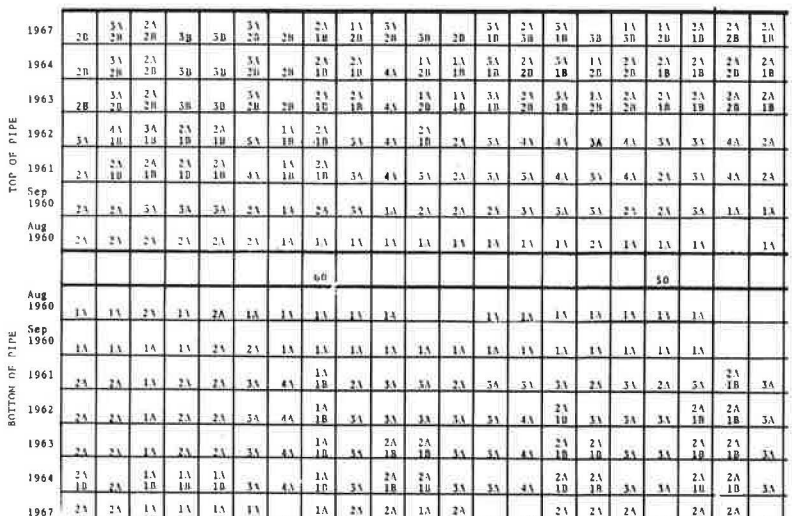
Changes in the inside vertical and horizontal pipe diameters were measured at established checkpoints located in selected sections as the embankment load developed. The ends of the initial vertical and horizontal diameters were marked by punch-marks in the inner surface of the pipe structure. All subsequent measurements were made at these same points. Changes of the vertical and horizontal dimensions measured were less than 1 percent, a change sometimes considered sufficient to cause materially injurious cracks in rigid pipes (5). The maximum change measured over the observational period occurred in section 63 and was only $\frac{1}{4}$-in. vertical and $\frac{3}{8}$-in. horizontal. The pipe diameter changes in section 38 were $\frac{1}{8}$-in. vertical decrease and $\frac{1}{4}$-in. horizontal increase.

RESULTS AND CONCLUSIONS

The development of distress in the sections laid with standard B bedding can be attributed to the 36-ft high fill constructed over the pipe. Formation of a hairline crack, which has been defined as a crack 0.01 in. or less, does not constitute a pipe failure; nevertheless, the existence of hairline cracks was an indication of pipe overload. The 102 sections with standard B bedding have been overloaded and distress may progress to a point that will constitute a failure, but observations to date indicate that equilibrium is being approached. Cracks as wide as $\frac{1}{4}$ in. were often observed.







LEGEND

A - Hairline Crack

B - Crack (0.01 inch or Greater)

Figure 2. Summary of pipe distress.

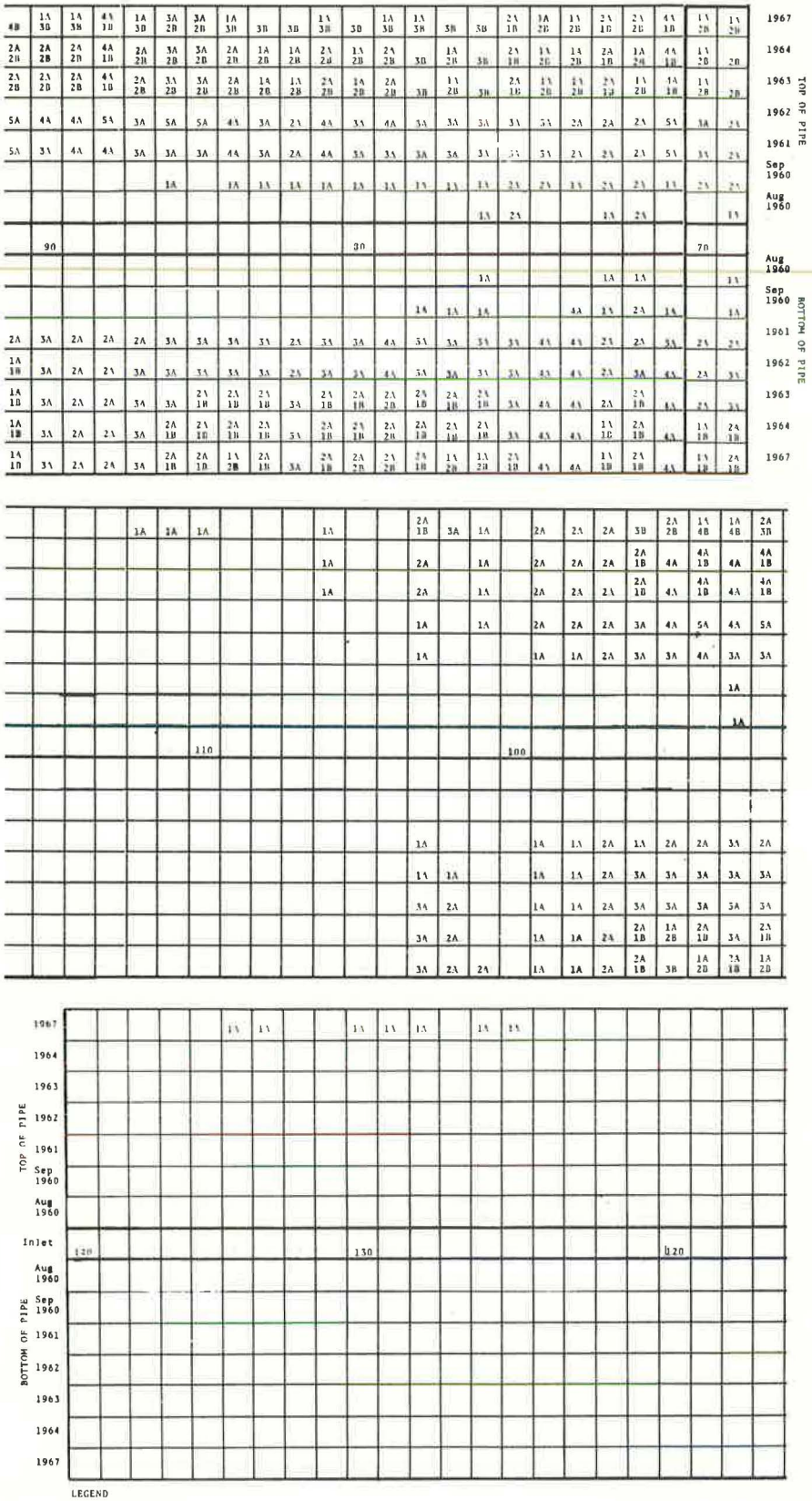


Figure. 2 (continued).

No indications of autogenous healing of cracks have been noted. Field data do indicate a significant difference in performance of pipe placed with standard B bedding and B_1 bedding (imperfrect trench).

Compaction under the haunches of the pipe to insure development of lateral support and prevent settlement of the embankment material in the exterior prisms is most important. Care in compacting the backfill area is important since the stiffer the side supporting material is, the greater will be the tendency of the mass directly above the conduit to arch over the adjacent bodies, thus relieving the top of the structure from part of the overburden pressure.

Specifications now used by the Kentucky Department of Highways give requirements pertaining to the nature of the side supporting material, method of placing the side supporting material, and size of the surrounding mass. The requirements now used appear to be satisfactory, but control presents a problem. Inspection should be continuous during construction to verify that the desired results are being obtained. Pipe bedding must be obtained that is the same as that assumed in design; otherwise, there is no criterion on which to base design methods.

The compressibility of the imperfect trench material must be greater than that of the adjacent compacted mass and should be in the loosest possible state when placed in the trench. The lower one-third of the excavated trench should be filled with loose hay or straw, even when the soil is very compressible, to insure settlement of the interior prism. Settlement of the interior prism was not noticeable at the surface of the embankment at the test site at any time during the observational period.

When placing the last of the rockfill material in May of 1961, hairline cracks formed in the portion with standard B bedding right up to sections with B_1 bedding. The standard B bedding portion exhibited distress in relation to the additional embankment added. For every fill increment there was a corresponding change in the length of the vertical and horizontal diameters of the pipe and in pipe distress as the load developed. The sections that had complete design fill heights over them before May, and required no additional embankment material, remained in an equilibrium condition of distress. This was expected to be true but could not be verified until this time. The performance of this pipe installation was successful in proving the value of B_1 bedding over the standard B bedding for construction of high fills under rock embankments. Previous work had assumed this to be true but actual verification was desired. The formation of cracks right up to the B_1 bedding portion suggests that the imperfect trench performed its purpose of relieving load on the pipe. Therefore, the rock embankment material appears to act much as soil material does in arching over the pipe.

REFERENCES

1. Marston, Anson. The Theory of External Loads on Closed Conduits in the Light of the Latest Experiments. Iowa State College Eng. Expt. Station Bulletin 96, 1930.
2. Marston, Anson, and Anderson, A. O. The Theory of Loads on Pipes in Ditches and Test of Cement and Clay Drain Tile and Sewer Pipe. Iowa State College Eng. Expt. Station Bulletin 31, 1913.
3. Marston, Anson, Schlick, W. J., and Clemmer, H. F. The Supporting Strength of Sewer Pipe in Ditches and Methods of Testing Sewer Pipe in Laboratories to Determine Their Ordinary Supporting Strength. Iowa State College Eng. Expt. Station Bulletin 47, 1917.
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5. Handbook of Culvert and Drainage Practice. Armco Drainage Products Assn., 1945.

Appendix A

KENTUCKY DEPARTMENT OF HIGHWAYS STANDARD DRAWINGS SHOWING PIPE BEDDING DETAILS AND ALLOWABLE FILL HEIGHTS

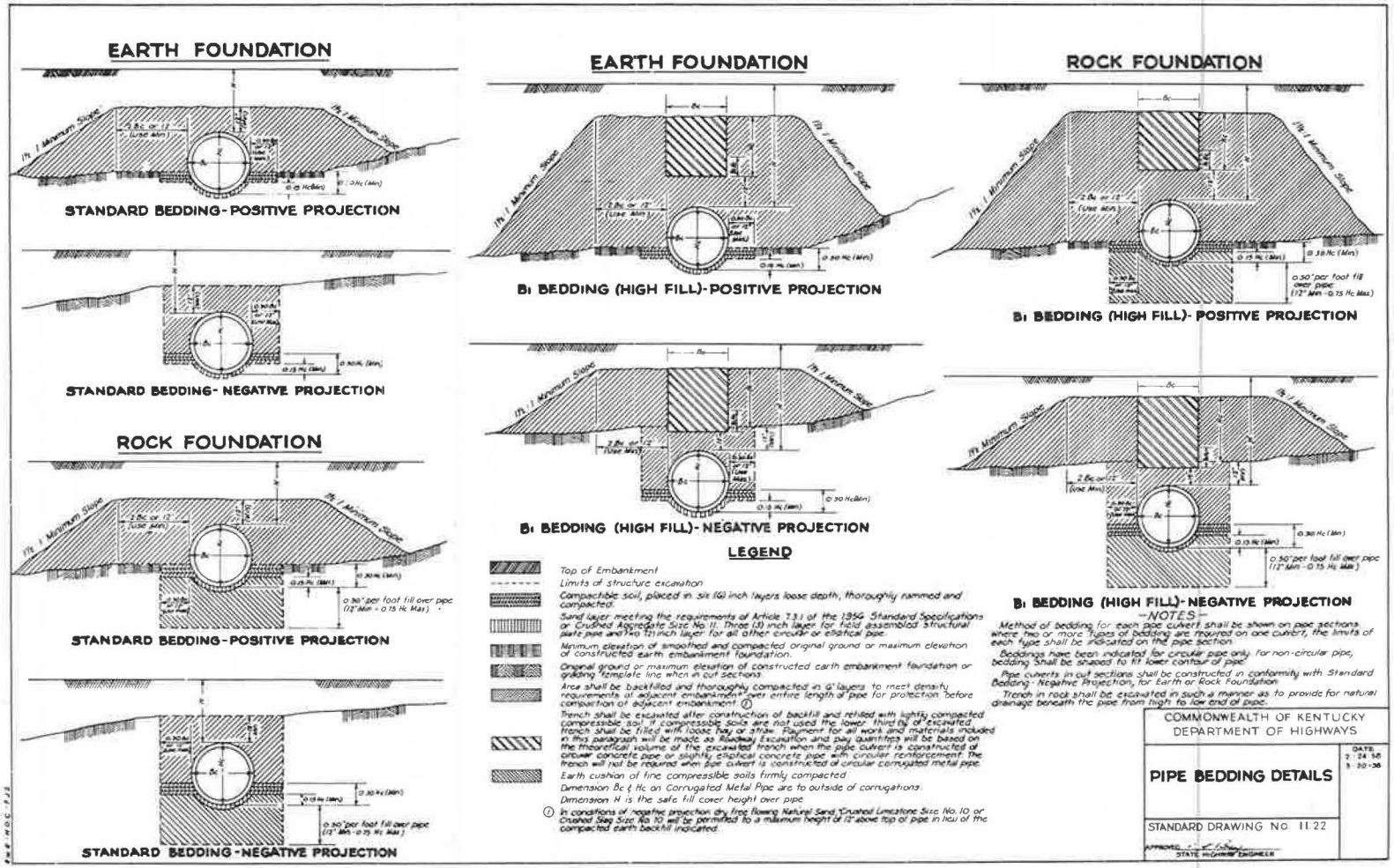

Figure 3. Kentucky pipe bedding details.

TABLE FOR SAFE FILL COVER HEIGHTS AND GAGES FOR CORRUGATED METAL CIRCULAR PIPE

SIZE OF PIPE	Height of Fill Cover Over Top of Pipe (Dimension H of Standard Drawing No. 11.22)											
	Standard Bedding			B₁ (High Fill) Bedding								
	1.5' to 10'	11' to 15'	16' to 20'	21' to 25'	26' to 30'	31' to 35'	36' to 40'	41' to 45'	46' to 50'	51' to 55'	56' to 60'	61' to 65'
	GAGE											
15"	16	16	16	16	16							
18"	16	16	16	16	16							
24"	14	14	14	14	14	14	14	14	12	12	12	12
30"	14	14	14	14	14	12	12	12	10	10	10	10
36"	12	12	12	12	12	10	10	10	8	8	8	8
42"	12	12	12	12	10	10	8	8	8	8	8	8
48"	12	12	12	10	8	8	8	8	8	8	8	8
54"	12	12	10	8	8	8	8	8	8	8	8	8
60"	10	10	8	8	8	8	8	8	8	8	8	8
66"	10	10	8	8	8	8	8	8	8	10	8	8
72"	10	8	8	8	8	8	8	8	8	8	8	7
78"	8	8	8	12	12	12	10	10	8	8	8	5
84"	8	12	12	12	12	12	10	10	8	8	7	5

▨ Factory Riveted Corrugated Metal Pipe - 5% Ellipsed - Held with wire struts

▨ Field Assembled Structural Plate Pipe, Factory Fabricated with 5% Ellipse

CORRUGATED METAL PIPE ARCH

Nominal End Area (Sq Ft)	Span (Inches)	Rise (Inches)	Gage	Diameter of Circular Pipe of Equal Periphery (Inches)	Dimension "B" (Inches) ②	Minimum Radius of Curvature (Inches)
1.1	18	11	16	15	3.5	2.5
1.6	22	13	16	18	4	3
2.8	29	18	14	24	5.5	4
4.4	36	22	14	30	6.5	4.5
6.4	43	27	12	36	8	5.5
8.7	50	31	12	42	9	6.5
11.4	58	36	12	48	10.5	7.5
14.3	65	40	12	54	12	8.5
17.6	72	44	10	60	13	9.5

② Dimension "B" is the vertical distance from the lowest portion of the base to a horizontal line drawn across the widest portion of the arch. Permissible variations in dimension "B" of plus one inch for 18" x 11" and 22" x 13" pipe arch and plus or minus one inch for 29" x 18" to 72" x 44" pipe arch. Permissible variation in span or rise of one inch for 18" x 11" to 36" x 22" pipe arch and two inches for 43" x 27" to 72" x 44" pipe arch.

GENERAL NOTES

See Division V, Sections 11 & 12 of the 1956 Standard Specifications as amended for more detailed information as to construction, basis for payment etc.

When fill cover height over circular pipe, including slightly elliptical concrete pipe with circular reinforcement, is 30 feet or more the minimum size of pipe shall be 24 inches.

The maximum safe fill cover height for non-circular pipe, excluding slightly elliptical concrete pipe with circular reinforcement, is 15 feet.

Pipe shown within the shaded portion of the chart for "Table for Safe Fill Cover Heights and Gages for Corrugated Metal Circular Pipe" require a 5% ellipse. Both inlet and outlet ends of the ellipsed pipe shall be fabricated circular. Transition from the circular ends to the ellipsed portion of the pipe shall be accomplished in a distance of not more than 18 feet.

Reinforced Concrete Elliptical Pipe (exclusive of slightly elliptical concrete pipe with circular reinforcement) shall meet the same strength requirements specified for Class III Reinforced Concrete Circular Pipe of equivalent nominal end area.

TABLE FOR SAFE FILL COVER HEIGHTS AND CLASSES FOR REINFORCED CONCRETE CIRCULAR PIPE.

SIZE OF PIPE	Height of Fill Cover Over Top of Pipe (Dimension H of Standard Drawing #22)				
	Standard Bedding	B₁ (High Fill) Bedding			
	1.5' to 20'	21' to 30'	31' to 40'	41' to 65'	
	CLASS OF PIPE				
15"	III	III			
18"	II	II			
24"	II	III	II	II	
30"	III	III	II	II	
36"	II	III	III	II	
42"	II	III	III	III	
48"	II	II	III	III	
54"	III	II	III	III	
60"	II	III	III	III	
66"	III	III	III	III	
72"	III	III	III	III	
78"	III	III	III	III	
84"	II	III	III	III	

REINFORCED CONCRETE ELLIPTICAL PIPE

Nominal End Area (Sq Ft)	Span (Inches)	Rise (Inches)	Wall Thickness (Inches)	Nominal Weight (Pounds per Lineal Foot)	10 Round Pipe Equivalent (Inches)
1.8	23	14	2½	195	18
3.3	30	19	3½	300	24
4.1	34	22	3½	365	27
5.1	38	24	3½	430	30
6.3	42	27	3½	475	33
7.4	45	29	4½	625	36
8.8	49	32	4½	720	39
10.2	53	34	5	815	42
12.9	60	38	5½	1000	48
16.6	68	43	6	1235	54

① Includes Slightly Elliptical Concrete Pipe with Circular Reinforcement.

② Excludes Slightly Elliptical Concrete Pipe with Circular Reinforcement.

COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS

FILL COVER HEIGHTS GAGES AND DIMENSIONS FOR ① CIRCULAR PIPE AND ② NON CIRCULAR PIPE

DATE 2-24-58

STANDARD DRAWING NO. 11.23

APPROVED _____ STATE HIGHWAY ENGINEER

Figure 4. Kentucky allowable fill heights.

Appendix B

PHOTOGRAPHIC SEQUENCE OF CONSTRUCTION OF PIPE INSTALLED WITH B_1 BEDDING (IMPERFECT TRENCH)

Figure 5. Pipe bedding prepared: Undesirable material removed and replaced with selected compacted backfill.

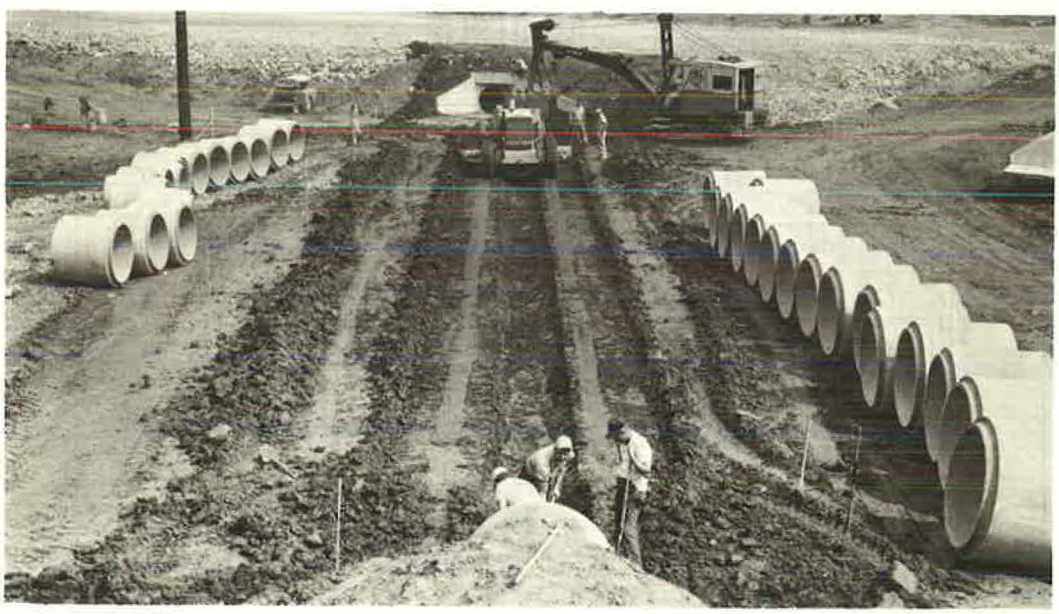

Figure 6. Patrol grader with special blade preparing soil for laying pipe.

Figure 7. Close-up of special blade on patrol grader.

Figure 8. Placing pipe in sand cushion bedding.

Figure 9. Placing backfill before construction of the imperfect trench (when specified).

Figure 10. Construction of the imperfect trench (when specified).

Figure 11. Loose backfilling of imperfect trench: Straw placed to a depth of one-third trench depth.

Figure 12. Completion of the imperfect trench: Embankment placed 2 ft above top of trench.

Figure 13. Embankment material placed over culvert: Line between soil and rock material shown.

Discussion

M. G. SPANGLER, Iowa State University, Ames—John Tyndal, a famous British physicist of the 19th century, once said: "The brightest flashes in the world of thought are incomplete until they have been proved to have their counterparts in the world of fact." In other words, a theory, to be proved valid, must yield results that agree with the facts of a situation.

The writer has had a number of opportunities to compare the results obtained by the Marston theory of loads on underground conduits with the structural performance of pipe culverts under earth embankments, and in all cases it has been demonstrated that the theory yields reasonably good and reliable results. However, opportunities to judge the applicability of the theory to pipe culverts under rock embankments are relatively rare. Mr. Deen's paper is a welcome addition to the literature because it provides an opportunity for a comparison of this kind.

The subject culvert was constructed in accordance with two of the Marston classifications relative to installation environment. The downstream 408 ft (102 four-foot sections) was installed as a positive projecting conduit. This portion of the pipeline suffered extensive damage in the form of longitudinal cracks, some as wide as $\frac{1}{4}$ in., and deflections of the pipes were excessive. The remaining 38 pipe sections at the upstream end of the culvert were installed by the imperfect ditch method of construction, and, although the height of fill over this portion of the structure was slightly greater than on the downstream section, these pipes did not suffer any structural damage or distress.

It is of interest to calculate loads and supporting strengths of the pipes in the two installation environments (7). For the downstream section load calculation, H = 35 ft, $B_C = 4.67$, $H/B_C = 35/4.67 = 7.5$. Assume $p = 0.7$, $r_{sd} = +0.7$, $r_{sd}p = +0.5$, $w = 120$ pcf, $C_C = 11.25$. Then

$$W_c = 11.25 \times 120 \times (4.67)^2 = 29{,}500 \text{ plf}$$

For calculation of supporting strength, assume $K = 0.33$, $m = 0.7$, $x = 0.594$, and class B bedding $N = 0.707$. Then

$$q = \frac{0.7 \times 0.33}{11.25} (7.5 + 0.35) = 0.161$$

$$\text{Load factor} = \frac{1.43}{0.707 - (0.594 \times 0.161)} = 2.34$$

$$\text{Required 3-edge bearing strength} = \frac{29{,}500}{2.34} = 12{,}600 \text{ plf}$$

$$\text{Required D-load strength} = \frac{12{,}600}{4} = 3{,}150D$$

The pipe used was Class III, which has a D-load strength at 0.01-in. crack of 1,350D. Thus it is indicated that the theoretical load on the pipe was about $2\frac{1}{3}$ times the minimum strength of the pipe. This accounts for the extensive damage in the form of longitudinal cracking in this portion of the culvert.

Similar computations of load and supporting strength for the imperfect ditch portion of the culvert have been made. For the load calculation, H = 38 ft, $B_C = 4.67$, and $H/B = 8.14$. Assume $p' = 1.0$, $r_{sd} = -0.5$, $C_n = 4.8$, and $w = 120$ pcf. Then

$$W_c = 4.8 \times 120 \times (4.67)^2 = 12{,}600 \text{ plf}$$

For calculation of supporting strength, assume K = 0.33, m = 0.7, x = 0.594, and Class B bedding N = 0.707. Then

$$q = \frac{0.7 \times 0.33}{4.8} (0.14 + 0.35) = 0.408$$

$$\text{Load factor} = \frac{1.43}{0.707 - (0.594 \times 0.408)} = 3.08$$

$$\text{Required 3-edge bearing strength} = \frac{12,600}{3.08} = 4,100 \text{ plf}$$

$$\text{Required D-load strength} = \frac{4,100}{4} = 1,025D$$

It is indicated that the theoretical required strength of pipe in this section of the culvert is only about three-fourths of the minimum strength of the pipe at 0.01-in. crack. This result agrees with the observed fact that the pipes installed by the imperfect ditch method did not crack.

The comparison between theoretical and actual performance of the two portions of this culvert also indicates that the Marston theory is applicable to rock embankments as well as to those constructed of soil. About 40 years ago the writer (6) investigated the structural performance of three cast iron pipe culverts under rock embankments in northeastern Iowa and arrived at the following conclusion, among others: "There is every evidence that the rock embankments acted in a manner entirely analogous to the action of ordinary earth embankments." These observations are in complete harmony with the conclusion: "Therefore, the rock embankment material appears to act much as soil material does in arching over the pipe."

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7. Spangler, M. G. Soil Engineering, 2nd ed. International Textbook Co., Scranton, Pa., 1960.