THE STRUCTURAL DESIGN OF FLEXIBLE PIPE CULVERTS

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(In Abstract*)

There is no rational method available to the engineering profession for predicting the structural performance of flexible type culvert pipe in advance of installation This paper is a progress report on a research project being conducted by the Iowa Engineering Experiment Station in cooperation with the U S Bureau of Public Roads to study structural performance and to develop a rational theory of design

In the case of flexible pipes, the pipe itself has relatively little inherent strength, and a large part of its ability to support vertical load must be derived from the passive pressures induced as the sides move outward against the earth Analysis of structural behavior, then, must take into account the earth at the sides as an integral part of the structure

Flexible pipe sections of various diameters were loaded in the laboratory at diametrically opposite points and the measured deflections were compared with those calculated by the thin ring elastic theory Results were found close enough to justify the conclusion that even though the deflections and accompanying changes in radius of curvature are relatively large, the elastic theory is applicable to corrugated metal pipes under two point loading within a tolerance probably no greater than that occasioned by variations in the modulus of elasticity of the metal, variations in gage thickness, depth and spacing of corrugations, and other variables inherent in the manufacture of this type of conduit. It seems tenable to assume that the theory will also apply in the case of a corrugated culvert pipe installed under an embankment, since the external pressures on the pipe in the field will be more nearly uniformly distributed around the pipe than in the laboratory An investigation of the structural performance of corrugated metal pipe culverts, therefore, becomes mainly a study of the laws of magnitude and distribution of the loads and pressures to which they are subjected in service. The hypothesis of fill loads on a flexible culvert pipe under an embankment may be summarized as follows

1 The vertical load may be determined by Marston's theory of loads on conduits, and is distributed approximately uniformly over the breadth of the pipe

2 The vertical reaction is equal to the vertical load and is distributed approximately uniformly over the width of bedding of the pipe

3 The horizontal pressures on the sides of the pipe are distributed parabolically over the middle 100 degrees of the pipe and the maximum unit pressure is equal to the modulus of passive resistance of the filling material multiplied by one-half the horizontal deflection of the pipe

Having set up such an hypothesis, it has been possible to develop mathematical expressions for the moments, thrusts, shears and deflections of a pipe in terms of the properties of the pipe and the earth of which the embankment is constructed Finally an equation has been tentatively adopted for use in the design of flexible culvert pipes when the conditions of installation are sufficiently well known to justify the calculation of the vertical load on the pipe by means of Marston's conduit load theory, and

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when the passive resistance of the filling material is known or can be estimated within a reasonable tolerance This equation is expressed as follows

$$\Delta X = \frac{KW_c r^3}{EI + 0\ 061 e r^4}$$

in which

ΔX = horizontal deflection of flexible culvert pipe

$K = 0\ 500\ \sin\alpha - 0\ 082\ \sin^2\alpha + 0\ 080\ \frac{\alpha}{\sin\alpha} - 0\ 160\ \sin\alpha\ (\pi - \alpha) - 0\ 040 \frac{\sin 2\alpha}{\sin\alpha} + 0\ 318\ \cos\alpha - 0\ 208$

W_c = vertical load per unit of length of pipe

r = mean radius of pipe

E = modulus of elasticity of pipe metal

I = moment of inertia per unit of length of cross section of pipe wall

e = modulus of passive resistance of the enveloping earth

α = one half the bedding angle

In order to test the applicability of this design formula, an extensive experimental program has been conducted in which four corrugated metal pipe culverts have been installed at the Experiment Station field laboratory at Ames and loaded with a clay embankment 15 feet high above the top of the culverts The pipes for these experiments and the laboratory studies previously referred to were of four different diameters and U S gage thicknesses namely, 36-in 16-gage, 42-in 14-gage, 48-in 14-gage, and 60-in 12-gage Light gages were chosen so that the diameter changes under the fill loads would be relatively high The embankment was 17 feet wide on top with side slopes about 1 2 on 1 The site for the experimental embankment was the bottom of an old gravel pit The bedding for the culverts was prepared by cutting out a trench with circular shaped cross section and a radius 2 in greater than the pipe, refilled with sand which was struck off with a template of the same radius as the pipe When the pipes were laid they were in contact with the shaped sand bedding for the bottom 90 degrees of the circumference and projected above the subgrade a distance equal to 0 85 of their diameter

Measurements and observations made during the experiments were directed toward three principal objectives First, the settlement of various elements of the pipes and adjacent embankment material was observed in order that the settlement ratio of Marston's theory could be calculated Also the unit weight of the fill material was measured, and all other data necessary to calculate the load on the culverts according to this theory. Second, the distribution of vertical load, vertical reaction and horizontal pressures were measured in order to check the hypothetical distributions and to determine the value of the modulus of passive resistance of the clay filling materials both in the tamped and untamped condition Third, the vertical and horizontal deflections of the pipes were measured for comparison with the hypothetical deflections computed by the design equation

The distribution of the vertical and horizontal pressures on the pipes was measured by means of stainless steel friction ribbons During the loading period the settlements, deflections and ribbon pulls were observed at least once for every one foot increment of fill

It appears from examination of the deflection and foundation settlement curves that the maximum load on the culverts was reached within a very short time after the fill was completed, probably within less than a week

The relationship between the lateral pressure on the pipes and the horizontal movement of the sides of the pipes was determined, that is, the modulus of passive resistance of the fill material For the untamped clay it was 13 4 lb per sq in per in movement and for the tamped filling material 27 0 lb per sq in per in It appears, therefore, that tamping the side fills practically doubled their capacity to assist the pipes in carrying the vertical earth load

Having determined the modulus of passive resistance of the side fill materials, and knowing the physical properties of the pipes, the deflection of the pipes under the calculated load may be determined by the tentative design formula

An interesting phenomenon is the fact that the pipes continue to deflect slowly long after the fill is completed and the maximum vertical load attained More than a year after completion of this fill deflection continued, the average amount of this lag being 0 25 per cent of the nominal diameter with the tamped side fills and 0 38 per cent for the pipes with untamped side fills.

In these experiments the straight-line increase of both deflections and side pressures as the fill was constructed justifies the use of a constant ratio between deflection and pressure in this ordinary method of construction The effect of vertical pressure on the ratio of deflection to side pressure is not revealed in these studies, however, so that when a flexible pipe is "strutted" before the fill is placed and the strutts afterwards removed, a different situation is presented Much remains to be learned, furthermore, regarding characteristics of the side fill materials and their effect on the modulus of passive resistance Study is also needed of other bedding conditions

DISCUSSION OF FLEXIBLE PIPE CULVERTS

Mr George E Shafer, *Armco Culvert Manufacturers Association:* We have followed with a great deal of interest Dean Marston's very complete investigation of loads on closed conduits and the design of rigid pipe We naturally have an even greater interest in Mr Spangler's continuation of this excellent type of work and the effect it will have on the design and acceptance of corrugated metal pipe There is a great contrast between Mr Spangler's comprehensive understanding of flexible pipe and the original ideas of the inventor, who 41 years ago made the first corrugated metal pipe with the corrugations running parallel with the pipe instead of circumferentially The correct way to run the corrugations was soon found and a new industry started to grow, slowly at first because many questioned the structural strength of a pipe with walls so thin

Records show a continual battle on the part of producers to prove to the public that the pipe was strong enough even though no one could figure out why They resorted to borrowing elephants from side shows to stand on corrugated pipe at fair exhibits, or threshing machines to run over the pipe

Just after Professor Talbot published his classic report on the design of Cast Iron and Concrete Pipe, he was asked to test corrugated metal pipe to see if it was as strong as the rigid pipe, hoping to find a reason for its ability to stand up under high fills These and other tests were made, not to determine the correct gage of metal to use under certain height fills, but to answer the question—why does corrugated metal pipe develop so much field strength?

What producers thought was the proper gage was determined by experience just like bridges were designed prior to 1840 when truss analysis was first introduced It was not until 1924 when Mr Lacher, Managing Editor of *Railway Engineering and Maintenance,* stated that railroads were beginning to recognize the merits of corrugated metal pipe and that a scientific analysis of strength would be helpful, that the subject of analysis received much serious consideration

The exact load on a flexible pipe from a fill was unknown until determined in 1925 by the A R E A 's Farina test Dean Marston soon followed with a complete mathematical theory, presented to this group in 1929

Two independent research groups have tried to design corrugated metal pipe by mechanically loading the pipe to failure

Deflection being so important we have naturally observed many installations of various fill heights over a long period of time Some data on the question of "deferred" deflection, mentioned by Mr Spangler, may be of interest here.

Unless a corrugated metal pipe does deflect, it is not functioning correctly or utilizing all the available natural resources The deflection must and does eventually cease, but at what rate does it proceed? Several outstanding installations will serve to illustrate this point and answer the question

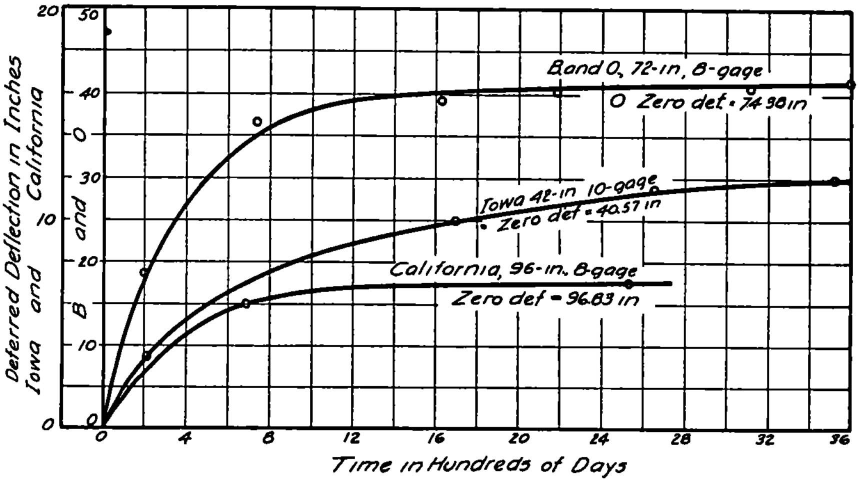

Figure 1

using the distribution of pressure determined from field tests

The producers of one group have attempted to check their gage table by developing an empirical equation for the deflection of the pipe Here you have heard the first systematic attempt to design rationally a commonly used structure, the analysis of which has bothered many—not because of the structure itself but because of the lateral pressure developed against the side of the pipe, which depends upon so many variables Mr Spangler's approach is logical because the design must be based upon deflection, the real measure of failure

Figure 1 shows the deferred deflection plotted against time for three installations where accurate measurements have been recorded for from 7 to 10 years The upper curve is for a 72-in 8-gage pipe installed under 3 ft of cover on the B & O R R A huge hot metal ladle (Fig 2) weighing 343 tons passes over this culvert several times each day This ladle produces the heaviest known axle load in regular railroad use today The bottom curve of Figure 1 is for a 96-in 8-gage pipe under 25 ft fill on the Calaveras Branch of the Southern Pacific Railroad (Fig 3) Both these installations were strutted; that is, the vertical diameter was elongated while the fill was being made. The side fills were compacted but not especially tamped.

The center curve is for a 42-in. 10-gage pipe installed at Ames, Iowa under a 15 ft. untamped fill (Fig. 4). The fact that the Ames culvert was not strutted and the side fills not tamped probably accounts for the different shape of the curve.

These data which are typical, show how the pipe deflects rather rapidly at first and in so doing builds up sufficient side support to counterbalance its part of the load, then the deflections slow up

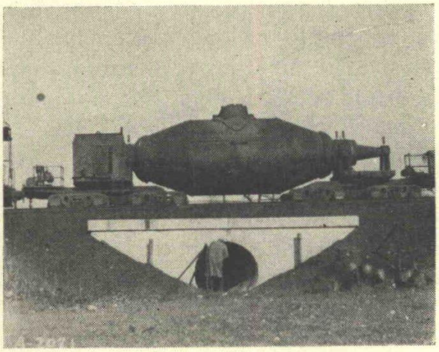

Figure 2. A hot metal ladle weighing 343 tons passes over this culvert several times a day

and eventually cease. The thousands of existing installations are proof that the deflection does cease, but at what rate is of interest.

If the inherent strength of the pipe is more than the load on the pipe, the deflection may cease very soon, at least before final settlement of the fill alongside the pipe. If the inherent strength is less than the load, deflection may continue as long as there is settlement in the fill and that, of course, depends upon the type of embankment material and how placed, etc.

Since deflection is so important on this type of construction, as brought out so clearly by Mr. Spangler, the next desire is to know how far the pipe can deflect, in percentage of the diameter, before collapse will occur. From field studies of old existing installations made of gages far lighter than are good practice today, this point of pending failure has been

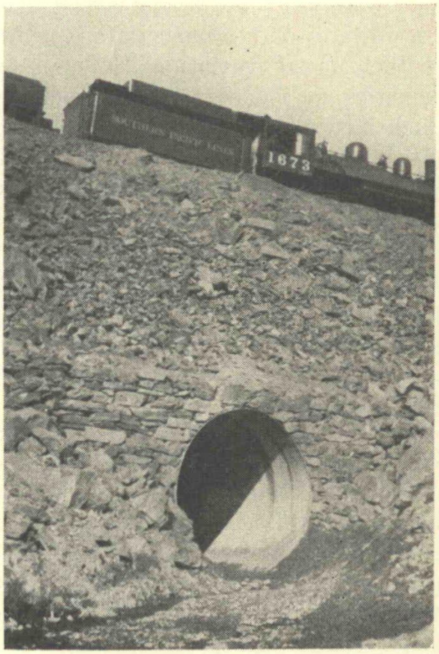

Figure 3. A 96-in. 8-gage culvert 100 ft. long

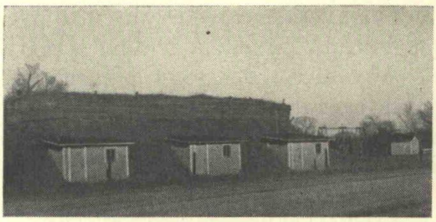

Figure 4. An experimental installation of 42-in. 8-gage pipe under 15 ft. untamped fill at Ames, Iowa.

fixed at 20 per cent. That is a 60-in. pipe can deflect 12 in. before failure. Most designs should be made on the basis of 5 per cent deflection when the fill is practically consolidated, giving a factor of safety of from 3 to 4.