Influence of Wall Stiffness on Corrugated Metal Culvert Design

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Recent research has shown that the strength of metal culverts is significantly influenced by the stiffness of the culvert wall. Based on this research, a simple method for determining maximum fill heights for flexible metal culverts is described. This method is used to compare the structural efficiency of two corrugation profiles, namely, the present standard ½- by 2⅔-in. profile and a proposed 1- by 3-in. profile, which has considerably greater stiffness. A table of maximum allowable fill heights based on a safety factor of approximately 2.0 against structural failure is given for steel culverts with the 1-in.-deep profile. It is suggested that the present ½-in.-deep corrugation be used for culverts having diameters of less than approximately 36 in., and that the 1-in.-deep corrugation be used for culverts having diameters of approximately 36 to 108 in. It is also concluded that an aluminum-alloy culvert, because of its lower modulus of elasticity, has a smaller safety factor against structural failure than a steel culvert having the same metal thickness, yield strength, and corrugation profile.

• THE METHODS previously used to determine the strength of flexible metal culverts were generally based on predictions of one or more of the following phenomena: (a) excessive culvert deflection, (b) yielding of the entire cross-section of the culvert wall, and (c) failure of the longitudinal culvert joints. Culvert deflection has usually been predicted by Spangler's formula (1). This formula considers the influence of wall stiffness on the deflection of a culvert, but does not necessarily consider the influence of wall stiffness on the strength of a culvert. Yielding of the entire cross-section and failure of the longitudinal joints have sometimes been predicted by first determining by the ring compression method (2) the forces present in the culvert wall. This method, which is based on an assumed uniform circumferential force in the culvert walls, does not take explicit account of the influence of wall stiffness on the strength of a culvert.

Recent research by Watkins (3) has confirmed that in addition to the three phenomena previously mentioned, the phenomenon of ring buckling, which is greatly dependent on wall stiffness, must also be considered in predicting the strength of corrugated metal culverts. Therefore, this paper describes a simple design method for determining the strength and, consequently, the maximum fill heights for such culverts. This method is based on recent research and takes full account of the influence of wall stiffness on the strength of corrugated metal culverts.

DESIGN CRITERIA

It has been generally recognized for some time that as the height of fill over a corrugated metal culvert increases, the top of the culvert moves downward while the sides of the culvert move outward. This movement causes bending stresses in the culvert

Paper sponsored by Committee on Culverts and Culvert Pipe.

wall that are proportional to the amount of movement, but allows passive pressure to develop along the sides of the culvert so that the soil pressure on the culvert approaches a uniform hydrostatic pressure. This uniform pressure, of course, causes uniform circumferential compressive stresses (hoop stresses) in the culvert wall that can be approximated by the simple ring compression formula (2)

$$f = \frac{PD}{2A} \tag{1}$$

in which P is the vertical soil pressure on top of the culvert, D is the diameter of the culvert, and A is the cross-sectional area of the culvert wall. Therefore, the stress in the culvert wall is the sum of the uniform stress due to ring compression and the bending stresses due to the slight change in shape of the culvert. (For very shallow fill heights, the pressure around the culvert may not be uniform and very large bending stresses may occur. A simplified analysis incorporating ring compression does not necessarily apply in such instances. However, the present report is not concerned with shallow fill heights.)

The soil pressure, P, is the sum of the pressure created by the dead weight of the soil and the pressure created by live loads. The pressure created by the soil alone is usually taken as the product of the density of the soil (frequently estimated to be 1,000 pcf) and the height of fill above the top of the culvert. The live-load pressure for an AASHO-H 20 highway loading is significant only for fill heights of approximately 10 ft and less. The pressures vary with fill height as follows (4): 10 to 8 ft, 100 psf; 6 ft, 200 psf; 4 ft, 400 psf; 2 ft, 800 psf; and 1 ft, 1,600 psf. Intermediate highway-loading values may be determined by interpolation. Live-load pressures resulting from railway loadings can be obtained from National Corrugated Metal Pipe Association (4).

Localized yielding of the outer fibers of the culvert wall due to the combined bending and uniform hoop stresses is not likely to cause failure of the culvert. However, when the uniform ring compression stress in the culvert wall reaches the yield point, yielding occurs over the entire wall cross-section rather than just at the outer fiber, and the culvert cannot carry any additional load. A failure of the longitudinal culvert joints would also constitute culvert failure. Consequently, according to most of the available literature on the design of flexible metal culverts (2), the ring compression stress (Eq. 1) divided by an appropriate safety factor should be limited to whichever is less—the stress at which the longitudinal culvert joint would fail, or the yield point of the culvert material (sometimes referred to as short column strength, or crushing strength).

However, recent research has confirmed that ring buckling strength must also be considered in addition to yield point and joint strength. Ring buckling is a phenomenon similar to column buckling; that is, when the compressive stress in the wall of a culvert reaches a critical value, the culvert wall buckles. Such a structural failure may occur when the ring compression stress is much less than the yield point of the culvert material. On the other hand, it is possible to design efficient longitudinal joints—either riveted or spot-welded—that will allow the stress in the culvert wall to reach the yield point. In the following discussions, therefore, it will be assumed that the joints do not limit the strength of the culvert.

The most ovbious method for estimating the critical ring buckling stress is by calculating the critical hydrostatic buckling pressure, P_c, from the classical buckling formula (5) for a cylinder under fluid pressure:

$$P_c = \frac{24EI}{D^3} \tag{2}$$

in which E is the modulus of elasticity of the culvert material and I is the moment of inertia of the cross-section of the culvert wall. (EI, of course, is a measure of the stiffness of the wall of a culvert.) When the value for the critical pressure in Eq. 2 is substituted into Eq. 1, the critical ring buckling stress, f_c, is expressed

$$f_c = \frac{12EI}{D^2A} \tag{3}$$

The buckling behavior of a culvert under soil pressure, however, differs somewhat from the buckling behavior of a cylinder under fluid pressure. Specifically, Eq. 2 does not take into account (a) the increase in the maximum radius of culvert wall curvature that occurs when a culvert deflects under the vertical earth pressure (the top and bottom portions of the culvert become flatter), (b) the bending moment in the culvert that accompanies this change in shape, and (c) the ability of the surrounding soil, unlike fluid, to withstand shearing forces. The behavior described in the first two items decreases the buckling strength of a culvert, but that described in the third item increases the buckling strength and therefore tends to offset the effects of the first two items. To examine the validity of using the hydrostatic-buckling equation (Eq. 2) for estimating the ring buckling stress of a culvert, Watkins (3) conducted tests on models of culverts buried in fine sand. In these tests, the vertical soil pressure on the culvert models was increased in increments until the culvert models failed structurally. Ring buckling was characteristic of each failure.

Watkins' test results were reported in the convenient form shown in Figure 1, where compressive stresses at failure (computed by Eq. 1) are plotted against a culvert flexibility parameter, $10^4D^2A/(EI)$, which is analogous to the slenderness ratio of a column. (The long dashed line, giving the test data, has been modified slightly for flexibility parameters less than approximately 5.0 to take into account the difference between the 40,000-psi yield point of the culvert model material and the 33,000-psi typical minimum yield point of the culvert material herein considered.) Critical stresses calculated by Eq. 3 (based on hydrostatic buckling) and the limitation imposed by yielding of the entire cross-section of the culvert wall are also shown.

Figure 1 shows that culvert models with low flexibility parameters (less than approximately 4 sq in./lb) failed when the ring compression stress was less than either the yield point or the hydrostatic buckling stress. Figure 1 also shows that culvert models with higher flexibility parameters (greater than approximately 4 sq in./lb) failed when the ring compression stress was greater than the hydrostatic buckling stress but less than the yield point. Such behavior can be attributed to the ability of the soil to withstand shearing forces; presumably, tests conducted in soils with weaker shearing strengths or in saturated soils would show stresses at failure that are closer to the hydrostatic buckling stress. Therefore, to estimate the ultimate strength of a culvert, Watkins suggested the use of the curve shown as a solid line in Figure 1. For flexibility parameters greater than 7.27, this curve is defined by the hydrostatic-buckling curve (Eq. 3), and for smaller flexibility parameters, this curve is defined by a straight-line transition that is tangent to the hydrostatic-buckling curve (at a flexibility parameter of 7.27) and passes through the yield point at a flexibility parameter of zero. The following equation defines this transition (which is analogous to the transition curve between the yield point and the Euler buckling curve for columns):

$$f_C \text{ (psi)} = \left[33 - 2.27 \frac{10^4 D^2 A}{EI} \right] 1{,}000 \tag{4}$$

in which D, A, E, and I are expressed in in. and lb.

Figure 2 shows a suggested design-stress curve that provides a safety factor against structural failure of approximately 2.0. The curve was obtained by plotting the hydrostatic buckling stresses divided by 1.5 and a straight-line transition tangent to this curve passing through the yield point divided by 2.0. The curve was plotted for 33,000-psi yield-point steel, which is usually the minimum value found in culvert sheets. The factor of 1.5, rather than 2.0, was applied to the hydrostatic buckling stresses to take into account the fact that, as indicated by Watkins' tests, a culvert surrounded by soil will buckle at stresses somewhat higher than those calculated from the hydrostatic-buckling equation. That is, although a nominal safety factor against hydrostatic buckling of 1.5 was used to construct a portion of the curve, it is suggested that the safety factor against structural failure, which depends on the soil and the compaction methods used, will be at least 2.0 for average culvert installation. (If the surrounding soil becomes saturated and hydraulic conditions are approached, the safety factor may be somewhat less than 2.0. Even under such extreme conditions, however, the suggested

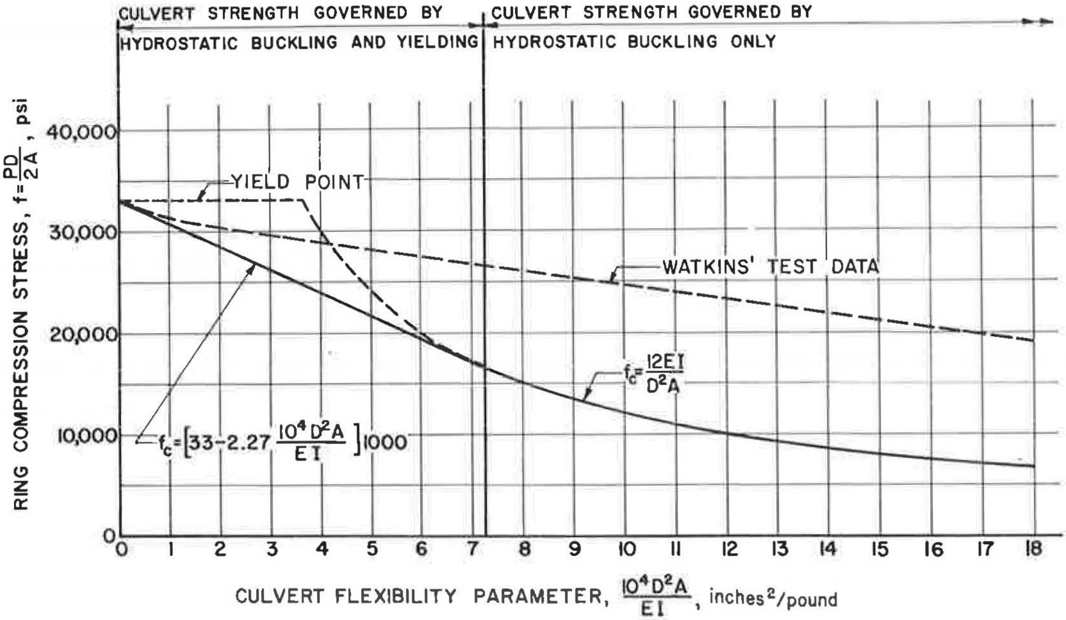

Figure 1. Critical stresses for flexible metal culverts.

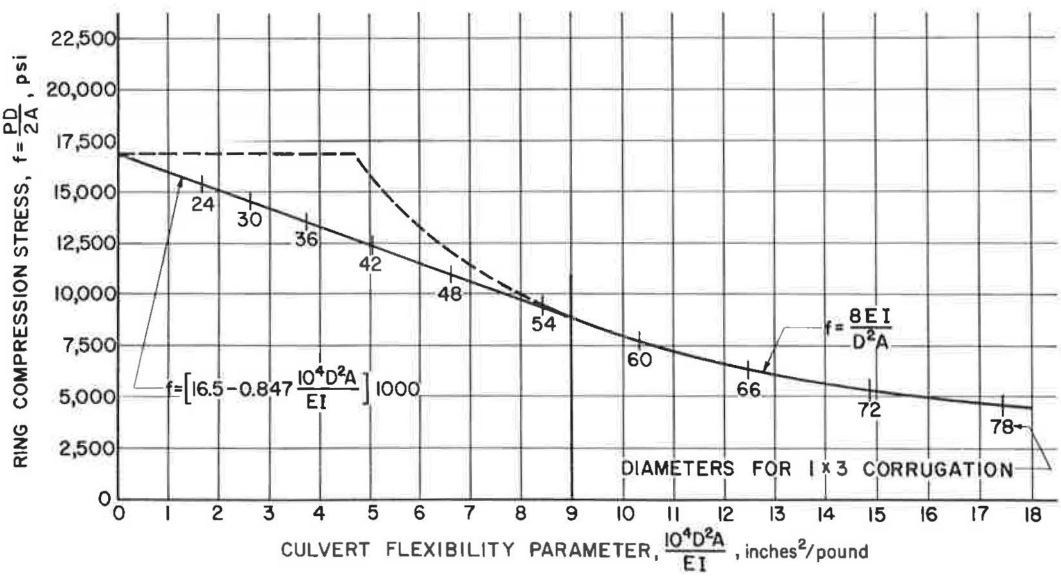

Figure 2. Suggested design stresses for flexible metal culverts.

curves provide an adequate safety factor.) Equations for the design stress corresponding to the curve may be written as follows when $10^4D^2A/(EI) < 9$:

$$f \text{ (psi)} = \left[16.5 - 0.847 \frac{10^4D^2A}{EI} \right] 1,000 \tag{5}$$

or when $10^4D^2A/(EI) \geq 9$, as

$$f\ (\text{psi}) = \frac{8EI}{D^2A} \qquad (6)$$

In addition to the stress limitations, culvert deflections should also be limited so that the predicted critical stresses will not be significantly reduced by bending moments or by an increase in radius. The limitation presently specified for many culvert designs—5 percent of the culvert diameter—appears to be an appropriate limitation. (It is suggested that when ΔX is limited to 5 percent, the effects of bending need not be considered in culvert strength predictions, for reasons previously mentioned.) The culvert deflection can be predicted by Spangler's formula (1)

TABLE 1

SECTIONAL PROPERTIES PER INCH OF WIDTH OF CORRUGATED CULVERT SHEETS[1]

Sheet Gage	Uncoated Thickness (in.)	Area (A) ($in.^2/in.$)		Moment of Inertia (I) ($in.^4/in.$)	
		½ × 2⅔ in.	1 × 3 in.	½ × 2⅔ in.	1 × 3 in.
20	0.0359	0.0388	0.0445	0.00121	0.00515
18	0.0478	0.0516	0.0593	0.00160	0.00689
16	0.0598	0.0646	0.0742	0.00200	0.00866
14	0.0747	0.0808	0.0927	0.00250	0.0109
12	0.1046	0.1130	0.1300	0.00350	0.0154
10	0.1345	0.1454	0.1674	0.00450	0.0202
8	0.1644	0.1775	0.2048	0.00550	0.0251

[1] Properties given based on uncoated thicknesses listed.

$$\Delta X = \frac{D_1 K W_C R^3}{EI + 0.061\, E' R^3} \qquad (7)$$

in which

ΔX = the increase in horizontal diameter of culvert,
D_1 = dimensionless deflection lag factor,
K = dimensionless bedding constant,
W_C = vertical load on culvert,
R = culvert radius, and
E' = modulus of soil reaction.

The factors involved in this equation are discussed in detail by Spangler (1). Like buckling strength, the culvert deflection depends on the wall stiffness, EI.

COMPARISON OF TWO CORRUGATION PROFILES

An examination of Eqs. 3 and 4 shows that for any given culvert diameter the critical buckling stress increases with increasing values of the culvert wall stiffness to cross-sectional area ratio (EI/A). It follows that for a culvert made from any given material, the structural efficiency (strength for a given cross-sectional area) increases with increasing values of I/A. For corrugated metal sheets, the I/A ratio can be readily increased by increasing the depth of the corrugation. For example, the present standard corrugation for shop-fabricated metal culverts—½ (corrugation depth) by 2⅔ in. (corrugation width)—has an I/A ratio of 0.0311, whereas the 1- by 3-in. corrugation has an I/A ratio of approximately 0.117. For a given cross-sectional area, therefore, the deeper corrugation provides more than three times the stiffness of the present standard corrugation. Sectional properties for the two corrugations are given in Table 1.

Figure 3 using two corrugation profiles illustrates where ultimate fill heights (that is, the fill heights that would theoretically cause failure) are plotted against required culvert wall areas. The standard gage number providing the wall areas for each of the profiles is indicated on the abscissa. The sheet thickness required to provide any given culvert wall area is less for the 1- by 3-in. profile than for the ½- by 2⅔-in. profile. This results from the fact that the flat-to-formed-width ratios for the two corrugations are 1.24 and 1.08, respectively.

The strength curves in Figure 3 are for each of two different design assumptions: (a) ring compression stress limited to the yield point (33,000 psi) only—past method, and (b) ring compression stress limited to the critical ring buckling stresses calculated from Eqs. 3 and 4—method suggested by recent research. (For steel culverts with a ½- by 2⅔-in. corrugation, Eq. 3 applies to all culvert diameters greater than 26 in.; for steel culverts with a 1- by 3-in. corrugation, Eq. 3 applies to all culvert diameters greater than 50 in.) An examination of Figure 3 reveals the following:

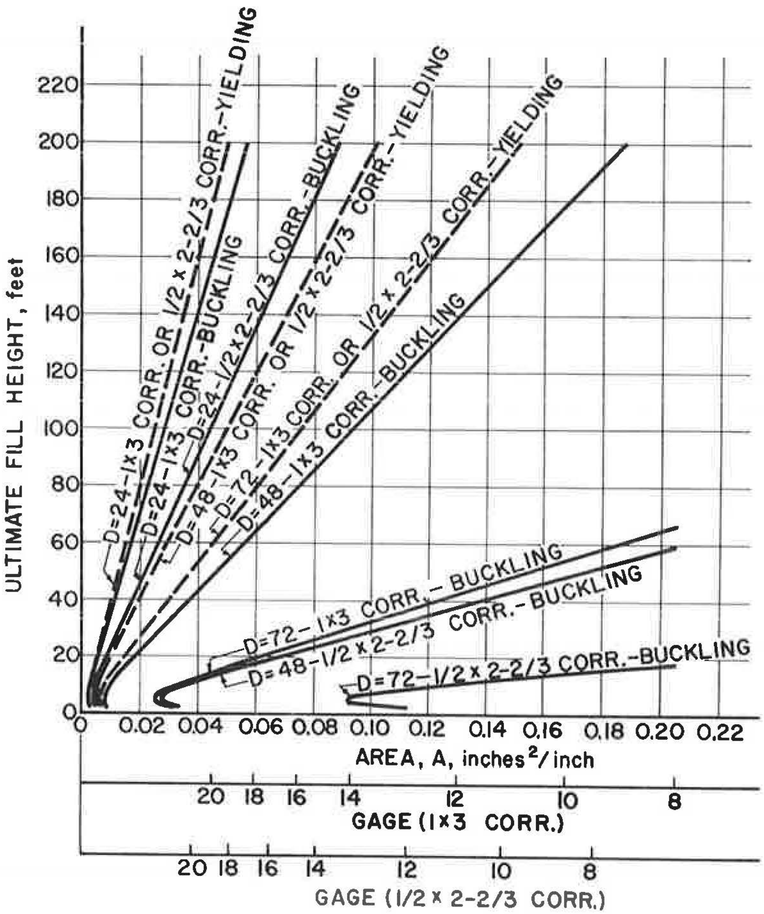

Figure 3. Comparison of ultimate fill heights for two corrugation profiles.

1. If ultimate fill heights are calculated on the basis of yield point only, the same area of metal is required for either of the profiles considered although the metal thicknesses required are different.

2. Ultimate fill heights calculated only on the basis of yield point may be very unconservative.

3. If ultimate fill heights are calculated on the basis of critical ring buckling stresses—as tests have demonstrated should be done—the area of metal (and, consequently, weight of metal) required for the 1- by 3-in. corrugation is considerably less than the area of metal required for the ½- by 2⅔-in. corrugation. (This fact is especially true for the larger culvert diameters.)

In addition to the weight savings possible with the proposed 1- by 3-in. corrugation, a culvert of this profile will deflect less under a given load than a culvert with the same cross-sectional area made from the ½- by 2⅔-in. corrugation, if both culverts have similar earth backfills. A better quality soil or more compaction—corresponding to a larger value of E′—must be used for culverts with ½-in. corrugations than with the deeper corrugations to make the deflection the same.

To illustrate these facts, culvert deflections at increasing fill heights were computed from Spangler's equation (Eq. 7) for 48-in. diameter culverts with each of the two corrugations. The results are shown in Figure 4. The values assumed for the terms in Spangler's equation were $D_1 = 1.5$, $K = 0.10$, and $E' = 700$ and 2,000 psi.

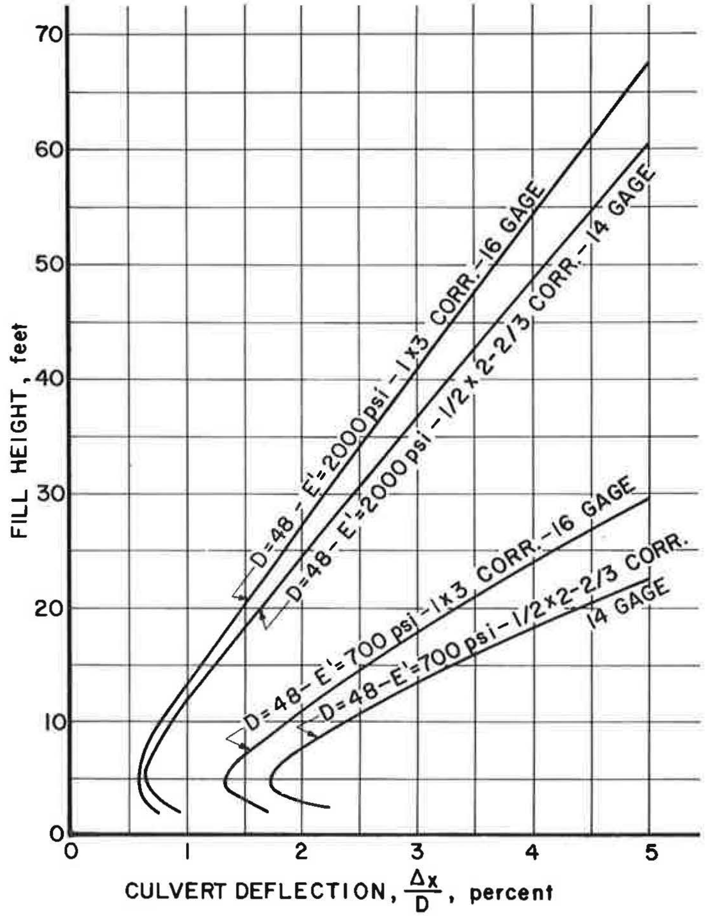

Figure 4. Comparison of culvert deflections for two corrugation profiles.

Although the 16-ga culvert with a 1- by 3-in. corrugation had about 10 percent less wall area than the 14-ga culvert with a $\frac{1}{2}$- by $2\frac{2}{3}$-in. corrugation, the culvert with the $\frac{1}{2}$-in. corrugation deflected more than the culvert with the 1-in. corrugation for the same fill height. Before reaching a culvert deflection of 5 percent, the culvert with the 1-in. corrugation withstood about 35 percent more fill for $E' = 700$ psi and 10 percent more fill for $E' = 2{,}000$ psi than the culvert with the $\frac{1}{2}$-in. corrugation. For the same fill height and a deflection of 5 percent, a greater value of E' is required with the $\frac{1}{2}$-in. corrugation than with the 1-in. corrugation. The value of E' can be increased only by better compaction around the culvert or by using a better quality backfill. Either of these operations would add substantially to culvert installation costs.

From the previous discussions it might appear that the 1- by 3-in. corrugation, because of its favorable I/A ratio, would require less culvert material than the $\frac{1}{2}$- by $2\frac{2}{3}$-in. corrugation for all culvert diameters. However, this is not true. A minimum thickness (larger than the calculated thickness which is quite small that would apply to either corrugation is frequently specified for small-diameter culverts because of practical considerations, such as local indentation resistance. Thus, if the same minimum thickness is specified for the two corrugations, the $\frac{1}{2}$-in. corrugation will require about 13 percent less material than the 1-in. corrugation because of previously mentioned flat-to-formed-width ratios.

TABLE 2

SUGGESTED STANDARD GAGES FOR ROUND CORRUGATED STEEL CULVERTS UNDER EARTH FILLS AND AASHO-H20 HIGHWAY LOADING[a]

Fill Height (ft)	Sheet Gages for Culvert Diameters (in.)													
	36	42	48	54	60	66	72	78	84	90	96	102	108	
1[b] - 10	20	20	20	20	20	18	18	16	14	12	12	10	8	Zone[d] A
11 - 15	20	20	20	20	20	18	16	14	12	12	10	8		
16 - 20	20	20	20	20	18	16	14	12	10	10	8			
21 - 25	20	20	20	20	16	14	12	10	8	8				
26 - 30	20	20	20	18	16	12	12	10	8		E ′ = 700 psi[c]			
31 - 35	20	20	18	16	14	12	10	8						Zone[e] B
36 - 40	20	20	18	16	12	10	8							
41 - 45	20	18	16	14	12	10	8				E ′ = 1,000 psi[c]			
46 - 50	20	18	16	14	12	8								Zone[f] C
51 - 60	18	16	14	12	(10)	(8)								
61 - 70	16	14	12	(12)	(8)						E ′ = 1,500 psi[c]			
71 - 80	16	14	12	(10)	(8)									
81 - 100	14	(12)	(10)	(8)										

[a]Sheet gages are for steel sheets (33,000-psi yield point) with a 1- by 3-in. corrugation and have been calculated to provide a safety factor of approximately 2.0 against structural failure. Structural failure by yielding, ring buckling, and joint failure have been considered. Two ³/₈-in. diameter rivets per corrugation are required except for gages shown in parentheses, for which two ¹/₂-in. diameter rivets per corrugation are required.
[b]Minimum fill height is 1 ft for diameters up to 48 in. Minimum fill heights for larger culverts are ¹/₄ the culvert diameter.
[c]Values of modulus of soil reaction, E′, required to limit ultimate culvert deflection to 5 percent.
[d]Zone A: good backfill compaction required.
[e]Zone B: excellent backfill compaction required.
[f]Zone C: superior compaction of selected backfills or use of 5 percent vertically elongated pipe required.

SUGGESTED CULVERT DESIGNS

Table 2 gives suggested sheet thicknesses for steel culverts (33,000-psi typical minimum yield point) with the 1- by 3-in. profile under an earth fill weighing 100 pcf and AASHO-H20 highway loading. The culvert designs, which include diameters of 36 to 108 in., are based on Eqs. 5 and 6, which are shown plotted in Figure 2 for the 1- by 3-in. profile. Because the EI/A ratio is nearly constant for any given culvert material and corrugation profile, the design stress varies only with the culvert diameter. Twenty gage was used as a reasonable although arbitrary minimum thickness. (On the basis of this minimum thickness, the ½-in. corrugation because of its smaller flat-to-formed-width ratio is generally more efficient than the 1-in. corrugation for culverts having diameters less than 36 in. Therefore, no suggested thicknesses are given in Table 2 for the 1- by 3-in. corrugation in culverts with diameters less than 36 in.) When compared with the presently specified thicknesses (4) for the ½- by 2⅔-in. profile, the culvert designs shown in Table 2 represent significant weight savings.

Longitudinal joint design was also considered for the culvert designs given in Table 2. The joint designs were based on the following ultimate joint strengths for various culvert gages, rivet diameters, and rivets per joint ft: (a) 20 ga, ⅜-in. diameter, 8/joint ft, 17,100 lb/joint ft; (b) 18 ga, ⅜-in. diameter, 8/joint ft, 22,200 lb/joint ft; (c) 8 to 16 ga, ⅜-in. diameter, 8/joint ft, 27,600 lb/joint ft; and (d) 8 to 12 ga, ½-in. diameter, 8/joint ft, 49,000 lb/joint ft. Two ⅜-in.-diameter rivets per corrugation (8 rivets/ft) were found sufficient to provide a joint having a safety factor of 2.0, except for a few instances in which two ½-in.-diameter rivets per corrugation (8 rivets/ft) were required. The joint design for the 1- by 3-in. profile compares favorably with the joint presently used for culverts with a ½- by 2⅔-in. profile—two ⅜-in.-diameter rivets per corrugation (9 rivets/ft) for culvert diameters of 42 in. and larger. Joints can also be obtained by automatic spot-welding techniques.

As previously mentioned, it is desirable to prevent excessive culvert deflection. This can usually be accomplished by compacting the soil as it is backfilled around the culvert. As a guide to the degree of compaction required for the culvert designs given in Table 2, the value of the modulus of soil reaction, E′, required to limit the culvert deflection to 5 percent was calculated by using Spangler's formula with the following assumed values: D_l = 1.25 and K = 0.10. On the basis of the values calculated for E′, Table 2 was then divided into three zones: Zone A, in which an E′ of 700 psi is satisfactory; Zone B, in which an E′ of 700 to 1,000 is required; and Zone C, in which an E′ greater than 1,000 psi is required.

Unfortunately, no detailed information is available on the degree of compaction required in different types of soil to obtain these values of E′. However, the values of E′ that were developed in a number of actual culvert installations were reported by Watkins and Spangler (7) and are discussed briefly by Spangler (1). For five culverts with compacted sandy-clay-loam or clayey-sandy-silt backfills, the E′ values ranged from 502 to 1,320 psi, the average value being 765 psi. However, a value of 7,980 psi was reported for a culvert with a crushed-sandstone backfill compacted to full Proctor density. As a result of these measurements, Spangler recommended a value of 700 psi for design use when the soil is compacted to 90 percent of Proctor density for a distance equivalent to two diameters on each side of the pipe. (It is assumed that the compaction would extend vertically to approximately the top of the pipe.) Consequently, such compaction, which is probably typical of present practice, is indicated for Zone A of Table 2. For Zone B, values of E′ up to 1,000 psi are required, and therefore, the backfill must be placed more carefully and compacted more fully. For Zone C, where E′ values of more than 1,000 psi are required, it is suggested—unless the backfill is of a select quality and is compacted to full Proctor density—that the culvert be vertically elongated to 5 percent of its diameter. Of course, vertically elongated pipe could also be used in Zone A or Zone B if soil conditions were such that the required E′ values indicated in Table 2 could not be easily obtained. If the pipe is vertically elongated to 5 percent of its diameter, the following maximum E′ values would be required to limit the final culvert deflection to 5 percent: Zone A, 250 psi; Zone B, 375 psi; and Zone C, 700 psi. These values were calculated by Spangler's equation based on a total culvert deflection of 10 percent.

Nonferrous Metal Culverts

As previously mentioned, EI is a measure of culvert wall stiffness. The discussion presented thus far has been conducted only in terms of relative I values, and the advantage of using a greater I to increase the stiffness has been clearly indicated. Obviously, the use of a greater E is also advantageous in increasing stiffness. For example, when a culvert is constructed from aluminum alloy, which has an E about one-third that of steel, the culvert will have a stiffness one-third that of a steel culvert if both culverts have the same corrugation profile and sheet thickness. Consequently, if an aluminum-alloy culvert is used that has the same thickness, corrugation profile, and diameter as a steel culvert, and the yield strength of aluminum alloy is the same as the yield point of the steel, the steel culvert will in all cases have a greater safety factor against structural failure than the aluminum-alloy culvert. Furthermore, the aluminum-alloy culvert will deflect considerably more than the steel culvert under the same loading and soil conditions.

SUMMARY

The significant results of this study can be summarized as follows:

1. Because culvert wall stiffness is an important consideration in the structural design of flexible metal culverts, Eqs. 5 and 6 represent a convenient method for determining design stresses and, consequently, maximum allowable fill heights for a culvert with a given stiffness.

2. The proposed 1- by 3-in. corrugation profile, because of its favorable ratio of wall stiffness to cross-sectional area (EI/A), generally is structurally more efficient than the present standard ½- by 2⅔-in. profile for culverts with diameters of approximately 36 in. and larger. Minimum thickness limitations favor the ½- by 2⅔-in. profile for culverts with diameters of approximately 36 in. and less.

3. Under similar load and backfill conditions, a culvert made from the 1-in. deep profile deflects less than a culvert with the same cross-sectional area made from the ½-in. deep profile. A better quality soil or more compaction must be used with the ½-in. deep profile to limit the deflection to the same amount that would occur with the 1-in. deep corrugation.

4. An aluminum-alloy culvert having the same diameter, thickness, corrugation profile, and yield strength as a steel culvert will have a smaller safety factor against structural failure than the steel culvert. Furthermore, the aluminum-alloy culvert will deflect considerably more than the steel culvert under the same loading and soil conditions.

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Discussion

T. F. DE CAPITEAU, Drainage Products Engineer, Republic Steel Corporation, Youngstown, Ohio—The significance of wall stiffness in the design of corrugated metal pipe structures has been recognized since this product was first produced more than 60 years ago, but a satisfactory method of using the value EI in designing a flexible structure has been quite elusive.

Spangler's deflection formulas permit correlation of the wall stiffness with an anticipated adequacy of the earth envelope to predict defelction under any load. However, wall stiffness contributes very little in comparison to compaction of the soil in limiting deflection, and deflection can theoretically be held to an acceptable value by proper selection of fill material and adequate compaction when the pipe wall itself is entirely inadequate.

The importance of a good installation procedure is becoming more evident each year, and better techniques for selecting, placing, and compacting the backfill around flexible conduits have greatly reduced the hazard of excessive deflection.

Mr. Brockenbrough's report on the influence of wall thickness on the design of corrugated metal pipe gives an excellent means of determining the adequacy of the pipe wall in the interaction range where wall area and seam strength may be suspect as well as in the elastic buckling range where stiffness is the limiting factor.

It should be recognized, however, that the hydrostatic buckling formula which is the basis of this report is not strictly applicable to the problem, even though it does provide a useful tool for investigating the elastic buckling design concept. Hydrostatic pressure is active and uniform and is also capable of following the movement of a pipe wall as deflection leading to buckling is developed. A culvert, on the other hand, is subjected to active vertical pressures and passive horizontal pressures. When deflection occurs the passive pressures build up to a value sufficient to establish equilibrium between the vertical pressures, the horizontal pressures, and the inherent strength of the pipe. While the pressures may develop so as to be nearly uniform the slight difference will be of a nature to constrain buckling.

Hydrostatic pressure as considered in the buckling formula represents the condition most conducive to buckling and would only be encountered by a culvert if installed in a completely saturated plasticized clay backfill. All other conditions of backfill material

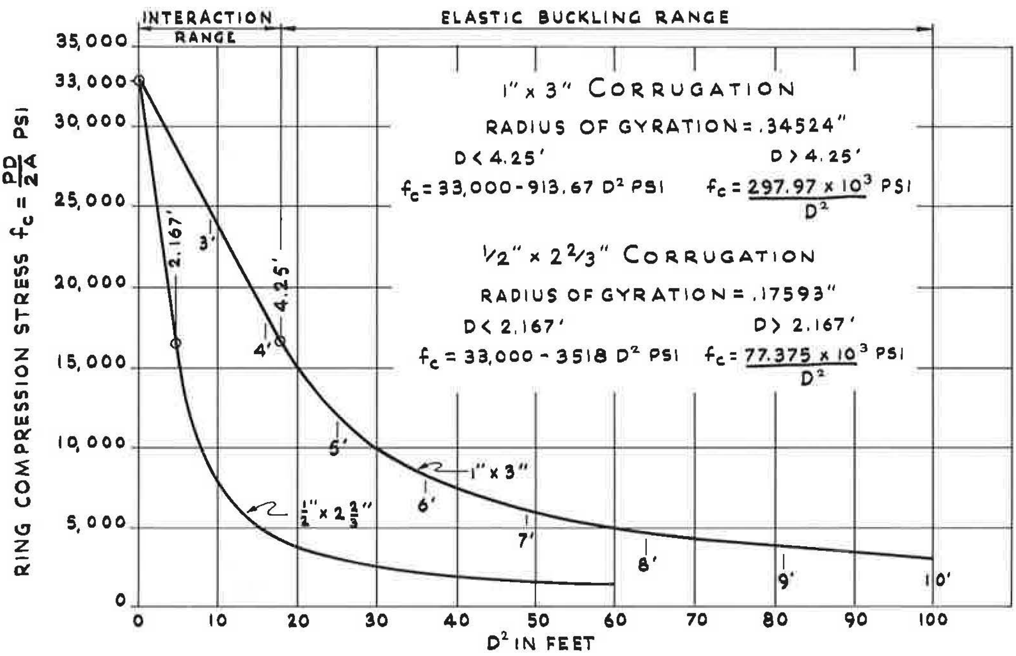

Figure 5. Critical stresses for flexible steel culverts.

and compaction would render the conduit less vulnerable to buckling. A factor accounting for the effect of soil properties on the hydrostatic buckling formula would make its use more rational.

The author has introduced a safety factor of 2.0 in the allowable stress formula for the interaction range and 1.5 for the elastic buckling range. These values may be adequate but the basis for choosing them is not clear and introducing them into the formulas confuses the issue. The formulas expressed for critical stress without the safety factors would permit a designer to use a safety factor of his own choosing based on his knowledge of the installation. It is doubtful that an appropriate safety factor can be justified for general use in a design method so recently developed. A gage table on this basis may not be acceptable. Actually, a safety factor of 2.5 was objected to as being too low about two years ago, indicating that a higher value should be used for a flexible metal culvert. The bases for this opinion were valid and are just as substantial today.

The critical stress in the interaction range where ring compression combines with hydrostatic buckling is

$$f_c = \left(33 - 2.27 \frac{10^4 D^2 A}{EI}\right) 1,000 \text{ psi} \tag{8}$$

In the elastic buckling range the critical stress from the hydrostatic buckling formula is

$$f_c - \frac{12EI}{D^2 A} \text{ psi} \tag{9}$$

It is interesting to note that because the radius of gyration does not vary appreciably for a particular corrugation, r^2 can be substituted for I/A to facilitate computations. For the steel culvert with 1- by 3-in. corrugations in Brockenbrough's paper, r^2 = 0.11919, and for diameters less than 51 in.

$$f_c = (33{,}000 - 6.34491D^2)\ \text{psi} \tag{10}$$

and for diameters greater than 51 in.

$$f_c = \frac{42.9084 \times 10^6}{D^2}\ \text{psi} \tag{11}$$

This makes it possible to plot critical stress versus D^2 instead of the parameter $10^4 D^2 A/(EI)$, and if the diameter, D, is expressed in feet, the graph becomes more comprehensive (Fig. 5).

R. L. BROCKENBROUGH, Closure—Mr. deCapiteau indicates that the safety factor against structural failure suggested, approximately 2.0, may be too low. Safety factors as high as 3.0 or 4.0 have been used in the past. However, these safety factors were generally against only one failure condition, either uniform yielding of the culvert wall or failure of longitudinal joints, and were necessarily high because failure by buckling was not considered in the design calculations. Information regarding the elastic stability of flexible metal culverts under earth fills was lacking at that time. The recent model tests referred to by the author show that flexible culverts will buckle at stresses higher (for the flexibility parameters indicated) than those predicted by the hydrostatic buckling equation and thus substantiate the use of the hydrostatic buckling equation as a conservative lower limit for the strength of such culverts. Because this new information is available, it is possible to use a safety factor against all modes of structural failure (including buckling) that is closer to the safety factors used for other engineering structures.

The allowable stresses for uniform compression suggested by the author for the 1- by 3-in. corrugation, Eqs. 5 and 6 and Figure 2, decrease from 13,400 psi for a 36-in.-diameter culvert, the smallest diameter suggested for the 1-in.-deep corrugation, to 2,400 psi for a 108-in.-diameter culvert, the largest culvert diameter suggested for the 1-in.-deep corrugation. Thus, although the culvert designs suggested by the author (Table 2) have a safety factor of approximately 2.0 against structural failure, the designs have a safety factor against uniform yielding of 2.46 to 13.7 (based on a typical minimum yield point of 33,000 psi), and therefore, are generally more conservative culvert designs than those suggested in the past.