The Corrugated Metal Conduit As a Compression Ring

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The purpose of this paper is to provide the engineer with knowledge of how a corrugated metal structure functions to support its load. A study has been made of the various ways in which the structure may carry load and the results of this study are presented in a manner directly applicable to a method of rational design.

Brief discussions of the types of loadings on a corrugated metal structure are given. The loads considered are those acting in a plane perpendicular to the longitudinal axis of the structure which tend to change its cross-sectional shape.

Two types of strength in the structure are considered—ring compression strength and ring bending strength. A discussion of requirements for ring compression strength includes the applicable features of a ring compression theory and shows how a corrugated metal conduit carries fill load by means of its ring strength and its ability to utilize support from surrounding earth. A method of applying linear arch theory to the structure is given which will enable a designer to approximate these compression requirements in the periphery of the structure and pressure requirements in the soil surrounding it.

The discussion of requirements for bending strength is presented in three parts dealing with (a) strength for resisting column buckling in the structure's walls and for bridging inconsistencies in the backfill, (b) strength for minimum cover installations, and (c) strength for handling, transporting, erecting and installation of the structure.

A discussion of installation features such as foundation conditions, bedding, imperfect trench methods of construction, is given, including what constitutes adequate backfill and compaction around a structure.

A summary includes step-by-step procedures for the various methods of design and installation of corrugated metal structures as load-carrying conduits.

• THE NORMAL corrugated metal conduit is designed to have sufficient moment strength to permit handling and installation without being unduly flexible. Once it has been installed in a compacted backfill capable of taking reaction pressures, its strength can then be determined as a thin ring in compression.

Notable installations demonstrating this compressive strength have been the three 7-ft diameter structures installed with a 137-ft cover under US 31 near Cullman, Ala., and a 6-ft diameter structure in the ½-in. deep culvert corrugation of 20 gage material (about the thickness of a thin dime) under 33-ft of fill near Lafleche, Saskatchewan. The Cullman structures were of 1-gage Multi-Plate (about $\frac{9}{32}$-in. thick) and Baldwin-Southwark strain gages were used to measure the compression in the ring. Load cells determined the amount of load that went to the vertical timber struts of this particular structure. The Lafleche installation was an experimental structure only and was designed to fail in compression, which it did when the final load of the 33 ft of cover and the filling of the reservoir back of the dam occurred. The latter structure also contained gages

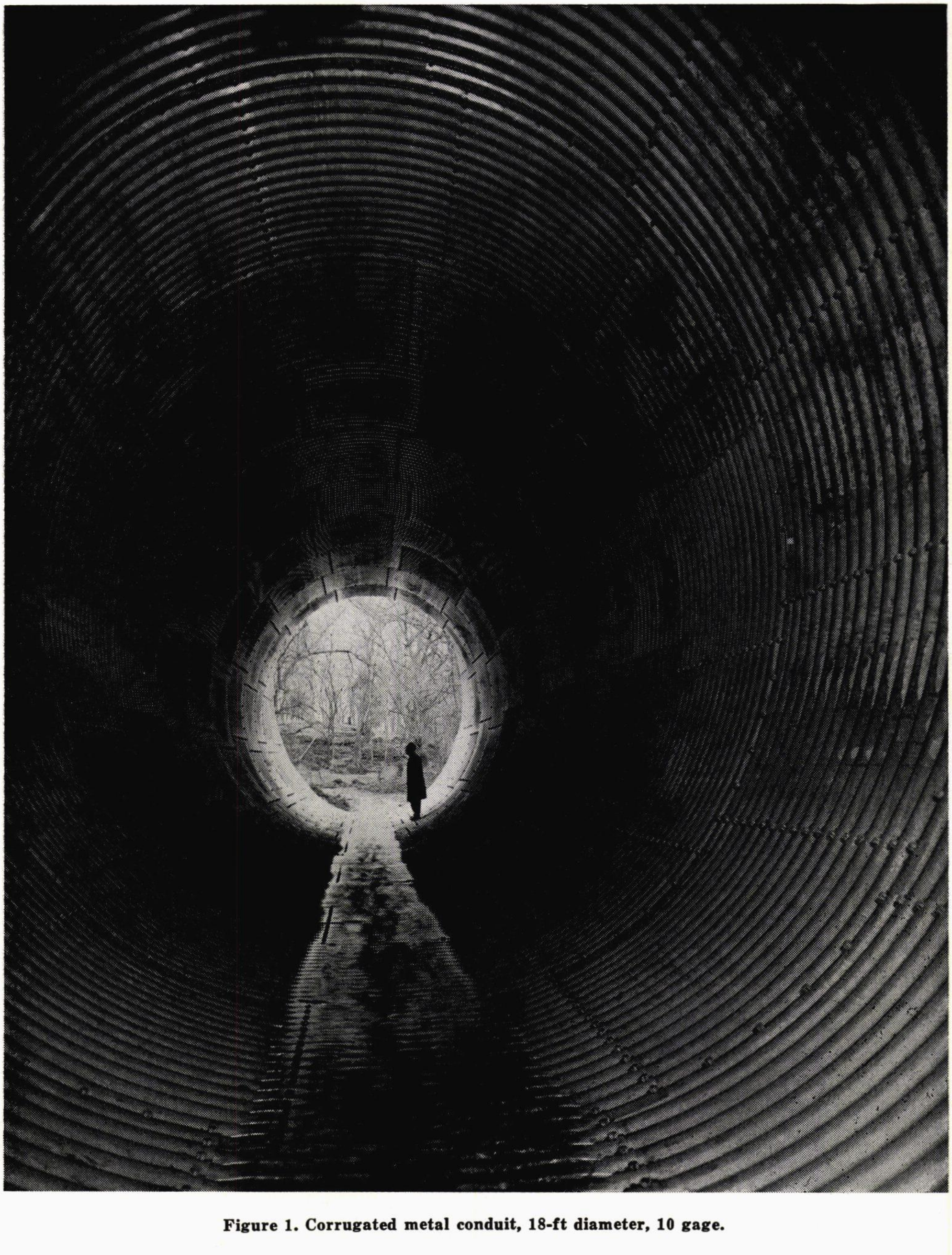

Figure 1. Corrugated metal conduit, 18-ft diameter, 10 gage.

for measuring the strain, pore pressure and extent of influence of the conduit in the embankment. It had no function in the dam, and the dam itself was used merely as a test loading of a structure.

A very recent field experiment has been conducted by the installation of an 18-ft diameter, 5 percent ellipsed, Multi-Plate pipe in 10 gage to carry 12 ft of cover and a highway with H-20 loading over it (Fig. 1). This installation was made by the county engineer in Greene County, Ohio, with the county forces. The inspecting was done by one of Armco's sales engineers. When only 6 in. of cover had been placed on this structure, increasing live loads were applied by means of construction vehicles until the final one consisted of a truck of 46,000 lb gross. Only ⅛-in. deflection took place under this load.

Although many forces are involved in the performance of a conduit other than those tending to crush the ring, this paper deals with the latter only. These forces are the ones determining the required metal thickness of the structure and its seam strength under normal loading conditions.

It is possible to demonstrate the relation between the moment strength and the compressive strength in the normal corrugated metal conduit by selecting a conduit and computing both strengths by engineering formulas. A more vivid physical demonstration can be made by the use of models. An ordinary 1-lb coffee can with bottom and top removed is ideal for the purpose. This model can be crushed with the hand but it has enough strength for installation in the ground as a small conduit. If installed in earth compacted around the sides and covered with about 1 in. of the same material compacted, it will withstand the weight of a man. How much force it actually takes to exceed its moment strength and exactly how much more load than that of the weight of a man it would take to cause the installed structure to fail in compression is not significant. The significance is the difference in strengths and the manner in which this thin ring supports its load. Again, when considered desirable, engineering computations can be made to demonstrate this particular point.

Since it is rather inconvenient to carry around any reasonable size portion of an earth fill, the action of such a fill can be demonstrated by the use of wood clamps made from 2x4's (Fig. 2). The demonstration is not one of quantitative analysis but rather one of qualitative analysis because this wooden clamp represents too nearly perfect a backfill to be subjected to mathematical analysis with any meaning. It does, however, serve to illustrate the action of the fill and structure.

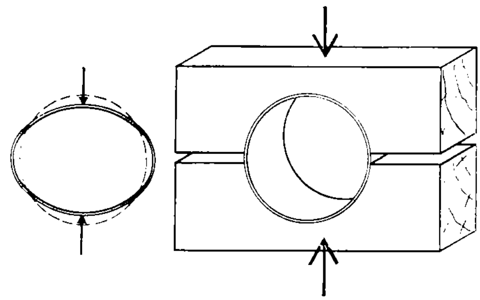

Figure 2. Thin steel ring supports relatively large distributed load when confined (right), but is easily flattened when unsupported (left).

If the model conduit is placed on a table and an attempt made to drive a nail through it, the small amount of moment strength is again vividly portrayed. However, the same model placed within the wooden clamp simulating a perfect earth backfill will remain in its round shape as the load on the nail is increased (Fig. 3). By striking the nail with a hammer, it

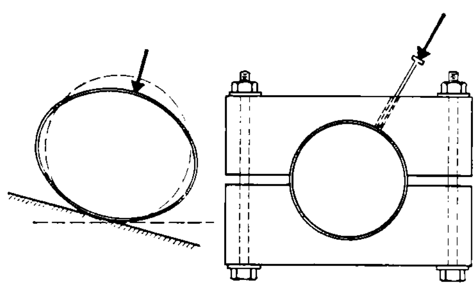

Figure 3. Thin steel ring supports relatively large concentrated load when confined (right), but is easily flattened when unconfined (left).

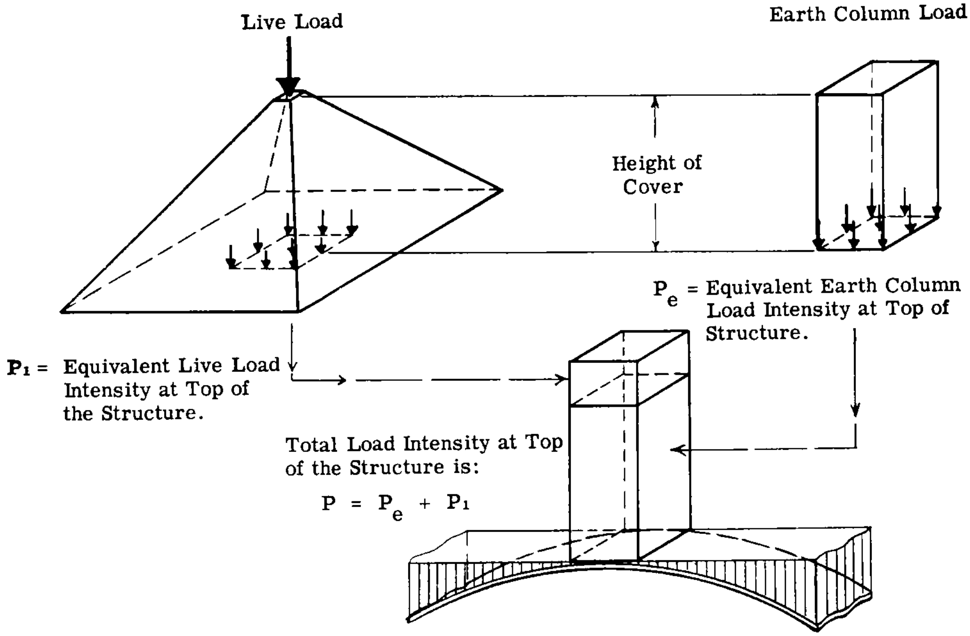

Figure 4. Load intensity at top of corrugated metal conduit.

can be made to penetrate the metal. Since the shape of the can was not materially altered, no moment strength was brought into use to resist the concentrated load of the driven nail point. The fact demonstrated here is that the structure will remain round under the application of heavy concentrated force only if equally heavy radial forces are applied completely around its periphery. In the case of the can within the wooden clamp, these forces were obtained from reaction between the can and the wooden clamp. In the ground, similar reactions are obtained by the addition of the active and passive earth load vectors.

It is conceivable that the corrugated metal conduit could be installed in the ground and, by the action of the normal backfilling process and later application of load, retain exactly the same shape as that with which it left the factory. This has been done in a number of cases by compacting the backfill laterally in such fashion as to increase the vertical elongation of the structure by the amount that the cover load later decreased it. Under such conditions none of the moment strength of the structure is being used to support the final loads. The stresses within the structure are those of compression within the ring. The intensity of the compression within the ring can be computed by the formula that the compression is equal to the intensity of the normal pressure times the radius of the structure. This is the algebraic reverse of the formula used for computing the hoop tension in a pipe subjected to uniform internal pressure.

The question arises then as to what is the intensity of the external radial pressure. Many studies have been made to determine this and the results of these studies indicate that the use of a pressure on top of the structure equal to the height of the fill times its density is the best load to assume as a working load. The distributed pressure of live loads should be added to the dead load (Fig. 4).

The actual normal load on the structure can be varied considerably by the method of treatment of the foundation and backfill: (a) soft foundations under the structure and hard foundations at each side of the structure serve to minimize the load on the structure; (b) hard foundations under the structure and soft foundations either side of the structure tend to increase the load on the structure; and (c) a uniform foundation under the structure and at each side of the structure combined with compaction efforts at the side of the structure, such that deflection is a minimum, will tend to make the load on the structure equal to the height of cover under higher fills. The study of this set of conditions is in itself quite complicated and will not be further discussed here. It is sufficient to make the assumption that the structure carries the column of material above it plus superimposed live loads.

So far in dealing with this round structure, the formula that the compression in the ring is equal to the radius of the ring multiplied by the normal pressure on the ring has been used. Now, the assumption is used that this normal pressure is equal to the height of cover times the density, plus the distributed live load when that is an affecting factor. The intensity of the live load distribution to be added to the dead load should be that intensity at the plane across the top of the structure. If this assumption of loading is used, the vertical component of the compression can be computed by taking one-half of the span of the structure and multiplying it by the height of cover times the density plus the distributed live load. This is important because this will give the compression in the ring for structures of shapes other than circular in which the span occurs at the point where the conduit wall is vertical (Fig. 5).

Since this compression exists throughout the structure, except for the effect of friction forces, any small part of the arc could be removed from the structure as a free body, with its portion of the load and the compression vectors on each end. This furnishes a way to compute the compression in a corrugated metal arch having sufficient cover. The compression becomes the tangential reactions furnishing the horizontals and verticals necessary for abutment design (Fig. 6).

It is well to consider the amount of cover over the structure required to turn it into an essentially compressive struc-

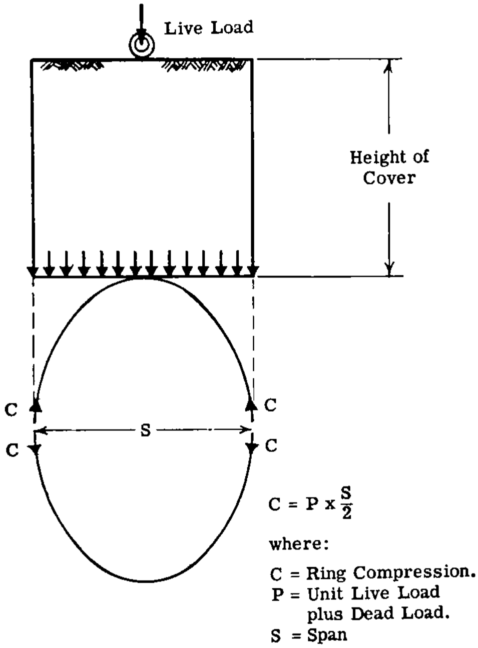

Figure 5. Compression in ring for structures other than circular.

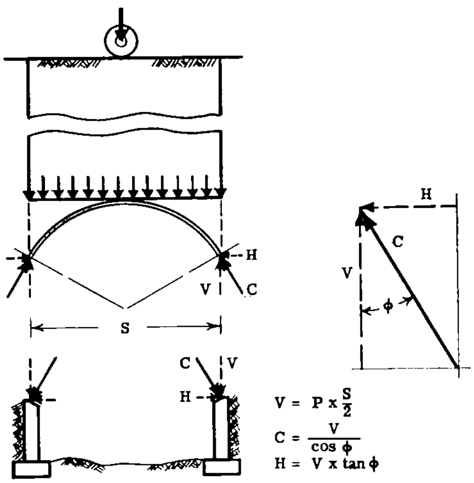

Figure 6. Vertical tangential and horizontal forces at springline of an arch.

ture when it has been installed in the same shape as received from the factory. During installation the structure must contain enough moment strength so that it can resist the forces of handling and the compaction of the earth against it. Once the fill has been placed to the top of the structure, additional fill begins to exercise pressure on the top so as to reduce the requirement for moment strength. At some point above the structure, this fill reaches an amount which exactly overcomes the active lateral pressure on the structure and the structure then becomes completely a compression ring. Analysis of the normal components of the active pressures on a structure using the active component of the vertical weight as one-third, shows this point of height of cover to be approximately one-quarter the diameter of a round structure or one-half its radius. In practical applications this amount can be reduced to at least one-eighth the diameter because the structure does contain moment strength. The only data available on this at present are obtained from the experience record of the structures and have been summarized in minimum heights-of-cover tables. Experimental work is now being carried on by the Corps of Engineers at the Vicksburg, Miss., and Mariemont, Ohio, laboratories which will help determine more precise data in regard to very light cover and very heavy live load. As a part of their experimental work at Sharonville, Ohio, a 48-in. diameter, 16-gage culvert with 1-ft of cover over it and a 24-in. concrete slab has been subjected to many passes of exceedingly heavy wheel loads without noticeable movement of the structure. This experiment has not been finished, but when it is, the results will be published as a part of the general program.

Some analytical theory here will serve for the approximation to be made in using these calculations to design a structure. Because of the vast difference in compressive strength of the conduit as compared with its moment strength, the culvert will be designed on the basis of compressive strength only as a sufficiently accurate approximation to enable competent design of such structures. Knowledge of earth pressures and earth ability to withstand pressures generally is not sufficiently exact to warrant a greater degree of precision. At any plane section taken transverse to such a conduit and at any point on this transverse section, the forces operating on the section can be represented completely by two mutually perpendicular vectors. If one of these vectors is chosen as radial, the other vector will be tangential and will represent the friction force of the soil on the conduit. This force may or may not exist, depending on whether or not relative motion between the two is impending (Fig. 7).

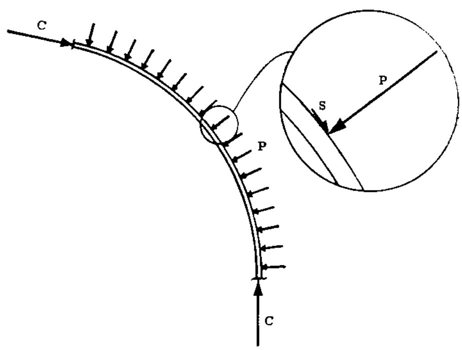

Figure 7. Tangential force S depends on relative motion between conduit wall and soil.

In any case it is limited either by the friction coefficient of the soil on the structure or by the shear within the soil itself. In exceedingly light shells it should be taken into account, but the safety factors used with conduits are such as to render the accounting of the friction force unnecessary.

It has been noted previously that any small portion of the arc of a circular structure could be removed as a free body. Applying this principle to the shape of structure known as elliptical (it is actually an oval), a very close approximation of the compression within the ring and of the distribution of the soil reactions around the ring can be made. The compression within the ring is computed by multiplying the height of cover by the span and the density and dividing by 2, assuming that the structure carries the entire height of cover. From the formula that the normal forces on the circular arcs times the radius of the arch equals the compression, the normal forces on each arc in the structure can be determined. Since the top arc is smaller than it would be in a round structure of equivalent periphery, the pressures on this arc will be very slightly more than those obtained from the formula that *P* equals the height of cover times the density. If the arc covered 180 deg, as it does in a half-circle arch, the pressure would exactly equal the height of cover times the density. Some passive reaction above the structure is permissible. In turn, the pressures on the larger radii side arcs are considerably less than they would be for a round structure of the same periphery. This illustrates why the elliptically formed structure suffers less vertical deflection under the same fill loading conditions than a round structure. The pressure diagram around the structure obtained from this close approximation is shown in Figure 8.

The same process of calculation applied to the structure known as the pipe-arch will result in the pressure diagrams shown in Figure 9. A structure very similar to that of the pipe-arch but containing one more radius in the top plates, has been known as the underpass shape. The pressure diagram for it, computed by the same means, is shown in Figure 10.

This method of approximating the compression within the ring of a metal conduit now permits balancing the compression against the laboratory tests of seam strength or short column strength of the culvert material. The pressure distribution provides the soils engineer with data from which to determine what type of soil will be needed around the various shape structures to insure support without undue deformation.

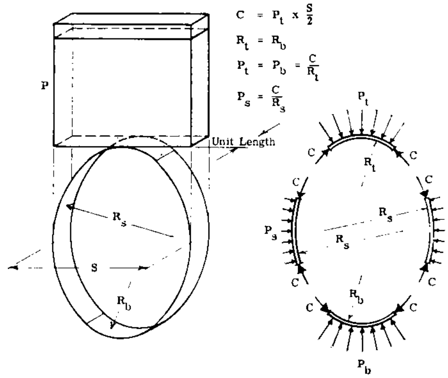

Figure 8. Typical loading and pressure diagrams for elliptical structure.

In regard to the safety factors in respect to seam or wall compression strength, it would be desirable to know in precise terms the compression under which such a structure would fail by a compressive buckle. So far this precise information does not exist. An approximation can be had by applying Timoshenko's analysis for buckling of circular rings and tubes under extreme external

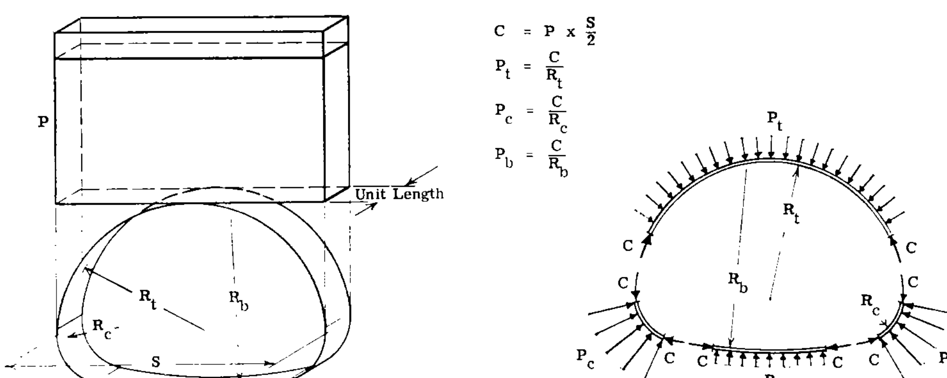

Figure 9. Typical loading and pressure diagrams for pipe-arch structure.

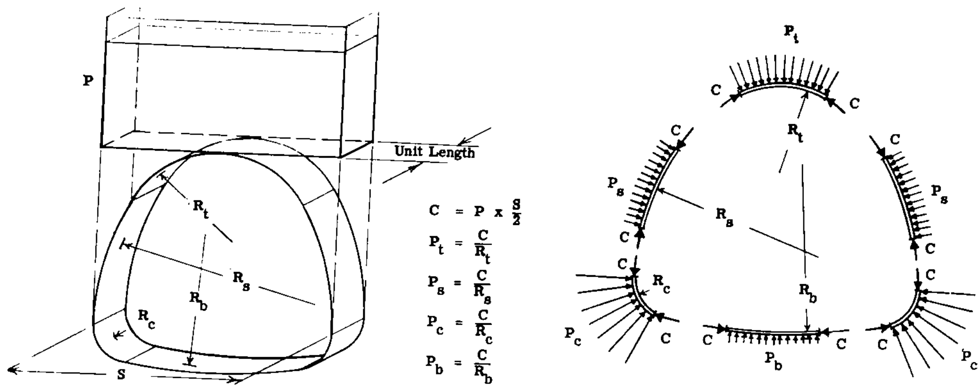

Figure 10. Typical loading and pressure diagrams for underpass structure.

pressure. This analysis is predicated upon a uniform pressure exerted on the rings as by water; earth does not behave in quite this manner. Some laboratory model trials have indicated that this ultimate compressive strength in earth might be on the order of 10 percent less than the yield strength of the metal. Sufficient data do not exist for use with any certainty. Practical reasons demand a safety factor in excess of this and such ultimate collapse computations are of little value except in extreme hazard-type conditions, for example, those associated with blast loadings. For carefully controlled and well-engineered installations, a safety factor of 2 based on the seam strength or wall strength has been found adequate. For handbook-type installations in which a reasonable chance of average backfilling practice can be expected, a safety factor of 4 has been in use.

In normal conduit conditions the fill material may weigh up to an extreme of possibly 130 lb. From the Farina tests it was shown that the pressure exerted on the top of corrugated metal conduit under normal installation conditions may be as low as 60 percent of the height of cover times the density. It is considered conservative to use the density of the soil above the conduit as 100 lb per cu ft and use the entire height of cover. When this height of cover with a density of 100 lb is multiplied by 4 and balanced against the compression strength of the seam, then the thickness of the conduit metal will be as determined in most handbooks.

Installations of these structures can be scrutinized for the pressure distribution by soils engineers and the type of backfilling material determined accordingly. In some cases it has been found desirable when placing pipe-arch or underpass-type structures under high fills to replace the native soil by a granular backfill around the corners or high-pressure points of the structure. Successful installations under fills higher than those shown in handbooks have been made. One pipe-arch structure carries a cover height of 40 ft under highway loading.

Studies are under way to determine the amount of moment strength required for installation purposes. For the present the best answer can be found in published experience tables. For average conditions, conduits should not be made much larger than those shown for any given metal thickness. The application of this engineering approximation for the rational computation of the strength of a corrugated metal structure and the determination of the type of soil and compaction to surround it are easily and quickly made as the sample computations show.

Many structures of different shapes, sizes and installation conditions have been designed using this approximation in the last five or six years with complete success.

APPENDIX

EXAMPLE No. 1

Given: A 144-in. diameter pipe in the 6″x2″ corrugation, ellipsed 5 percent, to be installed under 30 ft of fill which weighs approximately 100 pcf. Dimensions of the structure are: span, 137.9-in.; top radius, 59.7-in.; side radius, 79.2 in.

To Determine:

(1) The gage required to provide a safety factor of 4 in ring compression in longitudinal seams of structure.
(2) Approximate reacting soil pressures around structure.

Solution (Refer to Fig. 7):

(1) Average unit load on a plane at top of the structure is:

$$P = HC \times W = 30 \times 100 = 3{,}000 \text{ psf.}$$

Ring compression is:

$$C = P \times \frac{\text{Span}}{2} = 3{,}000 \times \frac{137.9}{2 \times 12}$$

$$= 17{,}240 \text{ lb per lin ft.}$$

For a safety factor of 4 in ring compression, seam strength minimum should be:

$$C_4 = 17{,}240 \times 4 = 68{,}960 \text{ lb per lin ft.}$$

From manufacturers' strength charts, 8 gage in 4-bolt construction is found to supply the required seam strength.

(2) Reacting soil pressures are:

$$P_s = \frac{C}{R_s} = \frac{17{,}240 \times 12}{79.2} = 2{,}610 \text{ psf}$$

$$P_t = P_b = \frac{C}{R_t} = \frac{17{,}240 \times 12}{59.7}$$

$$= 3{,}465 \text{ lb per sq ft.}$$

EXAMPLE NO. 2

Given: A 7′–11″ span × 5′–7″ rise pipe-arch in the 6″×2″ corrugation, to be installed under 12 ft of cover which weighs approximately 100 pcf. Radii are: top, 47.7 in.; corner, 18.0 in.; bottom, 137.9 in.

To determine:

(1) Axial compression in the ring.
(2) Approximate reacting soil pressures around the structure.

Solution (Refer to Fig. 8):

(1) $P = HC \times W = 12 \times 100$

$$= 1{,}200 \text{ psf.}$$

$$C = P \times \frac{\text{Span}}{2} = 1{,}200 \times \frac{7.92}{2}$$

$$= 4{,}750 \text{ lb per lin ft.}$$

(2) Reacting soil pressures are:

$$P_t = \frac{C}{R_t} = \frac{4{,}750 \times 12}{47.7} = 1{,}195 \text{ psf.}$$

$$P_c = \frac{C}{R_c} = \frac{4{,}750 \times 12}{18.0} = 3{,}165 \text{ psf.}$$

$$P_b = \frac{C}{R_b} = \frac{4{,}750 \times 12}{137.9} = 413 \text{ psf.}$$