A Review of

Depth of Cover Tables for Concrete and Corrugated Metal Pipe

Completed for

IOWA DOT

By

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IHRB Project TR-703
December 2016

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16. Abstract Iowa Standard Roadway Plan DR-104 contains maximum embankment fill heights that can be placed above concrete and metal pipes commonly used by the Iowa Department of Transportation. In order to update this tabular data reflective of current design methodologies and recent research findings, this study was undertaken in order to review the topic of allowable embankment cover.		
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Executive Summary

Since the advent of the circular closed conduit, and its use for conveying surface drainage through roadway embankments, methods have been required to determine the limiting magnitude of allowable vertical loads that could be applied to the buried pipes. These allowable load limits were sought to prevent damage to the conduit, or excessive deformation leading to unsatisfactory operation, that might result from these limits being exceeded. With minor modifications, these methods have largely remained unchanged since their inception; and the current 7th Edition of the AASHTO LRFD Bridge Specification continues to support their use.

In general, the problem of allowable pipe cover must be addressed separately for two general categories of section behavior and failure. Concrete, clay, and other rigid materials typically fail by rupture of the pipe wall in flexure, with a majority of the applied vertical load being resisted by the bedding material. Steel, plastic, and other flexible types of conduit will deform under load, and will typically fail by buckling of the pipe wall. The flexible nature of these pipe sections causes a significant portion of the applied vertical load to be resisted by induced lateral passive action of the backfill material, as the vertical loads lead to an ovalization of the pipe cross section.

This report documents the findings of a study conducted to review the history and current practice of establishing allowable pipe fill heights for circular and arched concrete pipe, as well as circular and arched corrugated steel pipe. Concluding this review, recommendations using the latest edition of the AASHTO LRFD Bridge Specification are provided as a basis for updating the tabular pipe cover data currently contained in Iowa DOT Standard Road Plan DR-104.

Concrete Pipe

The determination of allowable fill height over buried concrete pipe can be determined through the use of either the Indirect Design or Direct Design methods. The Indirect Design method is an empirical method developed about 100 years ago using the concept of the D-load to relate insitu pipe strength to the results of a standard laboratory test, while the more recently developed Direct Design method is a rational approach using a more customary limit states design procedure. While both methods are commonly used, and both have been shown to produce satisfactory results, it was found that the majority of agencies still rely on the Indirect Design Method to establish controls on maximum fill height.

Corrugated Steel Pipe

Allowable fill heights for corrugated steel pipe have changed considerably as research into flexible conduit behavior continues to advance. Initially using arbitrarily small deflections for control, more modern methods look at the behavior of the thin pipe wall under complex loading that involves fully engaging the passive soil resistance of the adjacent soil for support. These more recent methods make checks of the stiffness of the pipe wall under ring compression the primary control in determining maximum fill heights.

Current Practice

A review of the current methods and pipe cover values was conducted for the states neighboring Iowa, and the results of that investigation are contained later in this report. Most of the agencies use methods as prescribed by the AASHTO Bridge Specification, but many appear to have cover tables produced by fairly dated editions of the specification.

Recommendations

The recommendations for updating the minimum cover and maximum fill height tables depicted on Iowa DOT Standard Road Plan DR-104 involve employing the current 7th Edition of the AASHTO LRFD Bridge Specification. In many cases, limitations placed on fill height in past editions of the code have been removed, allowing larger values to be used than are currently shown on the standard. In the case of metal pipe, research is ongoing; and it is expected that more refinements to the specification will be forthcoming as the behavior of flexible buried pipe is further understood.

Literature Review

In reviewing the literature produced by the research work completed to date on the topic of buried conduits, the investigations can be categorized as centering on one of two areas: load transmission to the pipe, and pipe strength. These areas of inquiry can be further broken down, in the case of loadings, into dead loads and live loads applied above the pipe, as well as the effect of bedding details on load transmission; and in the case of pipe strength, the research can be separated by the characteristics of the pipe section.

Conduits used to convey surface drainage through roadway embankments can be classified as either rigid or flexible. Rigid pipes are typically defined as culverts that will withstand a deflection of no greater than 2% before experiencing cracking or other permanent section damage, and include materials such as clay and concrete. Flexible culverts are defined as pipes that can experience elastic deformations in excess of 2%, and include steel, aluminum, and various plastics.

Anson Marston and Merlin Spangler pioneered the first formal academic work in the area of loads on buried conduits in the 1910’s at the Engineering Experiment Station of Iowa State College (University) in Ames. This work was prompted by a number of county engineers expressing concerns about the failure of clay tile placed in ditch (trenched) installations, both during construction and after the placement of fill. What follows is a summary of the academic work completed to date on this topic.

Marston and Anderson (1913)

Marston and Anderson (Ref. 1) established the theoretical basis for determining loads that acted on buried conduit for the ditched (trenched) condition. Now widely recognized as Marston’s Load Theory, the concepts established by this work were: 1) the vertical loads on the top of the pipe are comprised of the soil prism above the pipe plus any superimposed live load; 2) that the weight of this soil prism is partially resisted through friction between the trench sidewalls and the backfill material comprising the prism, resulting in a reduction of the effective vertical pressure near the sides of the trench; and 3) an arching effect within the soil prism near the top of the pipe causes the majority of the vertical load to be carried by the pipe approximately from the top of the pipe to +/- 45 degrees. It should be noted that this discussion was confined to ditches of "ordinary" width, and not applicable to "wide" ditches; and that use of the term "ditches" by these researchers is equivalent to what is now referred to as a trenched installation.

The development of the basic equations for loads on culverts in ditches (trenches), based on the assumptions above, followed. The resulting vertical load on the buried pipe was obtained by summing the vertical forces acting on a differential horizontal segment of the soil prism above the pipe, and solving the resulting differential equation.

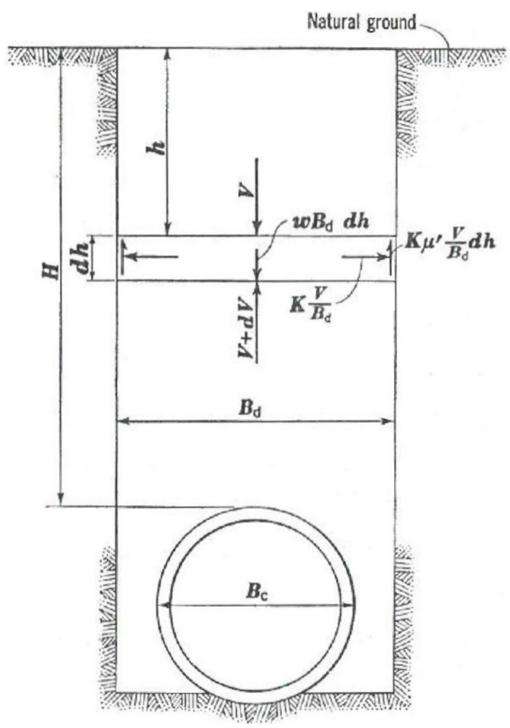

Figure 1. Free Body Diagram for Ditch Culvert (Reproduced from Ref. 8)

The solution of the differential equation produced the following expression for the total vertical load produced by the dead load of backfill on a horizontal plane at depth, h, for a unit length of conduit, of:

$$V = wB_d{}^2 \left[\frac{1 - e^{-2K\mu' \frac{h}{B_d}}}{2K\mu'} \right]$$

where, using consistent units:

V = vertical load on a plane at depth, h, per unit length of pipe

w = unit weight of embankment material

B_d = outside width of ditch (trench)

h = height of fill above the horizontal plane considered

μ' = coefficient of friction of fill material against ditch wall

e = base of natural logarithms

K = Rankine's lateral earth pressure ratio:

$$K = \frac{\sqrt{\mu^2 + 1} - \mu}{\sqrt{\mu^2 + 1} + \mu} = \frac{1 - \sin\phi}{1 + \sin\phi}$$

where:

μ = coefficient of internal friction of fill material

ϕ = friction angle of fill material

Evaluating this expression at the top of the pipe, where $h = H$, gives:

$$W = w{B_d}^2 \left[\frac{1 - e^{-2K\mu'\frac{H}{B_d}}}{2K\mu'}\right]$$

where:

W = vertical load at the top of the pipe, per unit length of pipe

Marston and Anderson further defined the bracketed term in the expression for the vertical load, W, as the coefficient C, producing the widely recognized equation for dead load on a buried culvert of:

$$W = Cw{B_d}^2$$

where:

$$C = \frac{1 - e^{-2K\mu'\frac{H}{B_d}}}{2K\mu'}$$

To simplify the load computations, Marston and Anderson developed working values of C for use in the load formulas above. To accomplish this, they made detailed measurements of the values of both μ and μ' for a number of soil types and degrees of tamping of backfill; and after analyzing the complete data set of wide-ranging values, they reduced the recommended values for characteristic soil properties to six representative backfill types. The values suggested for use in their vertical load formulas for these backfill types are shown in the table below.

Ditch Fill Material	w Unit Wt. of Fill (lbs/ft^3)	K Lateral Earth Pressure Ratio	μ' Coefficient of Ditch Friction
Partially Compacted Top Soil (Damp)	90	0.33	0.50
Saturated Top Soil	110	0.37	0.40
Partially Compacted Damp Yellow Clay	100	0.33	0.40
Saturated Yellow Clay	130	0.37	0.30
Dry Sand	100	0.33	0.50
Wet Sand	120	0.33	0.50

Table 1. Constants to Be Used in Calculating the Loads on Pipes in Ditches (Reproduced from Ref. 1)

Using the characteristic values in the table above, Marston and Anderson produced the following curves for use in determining C, forms of which still appear in current soil engineering textbooks.

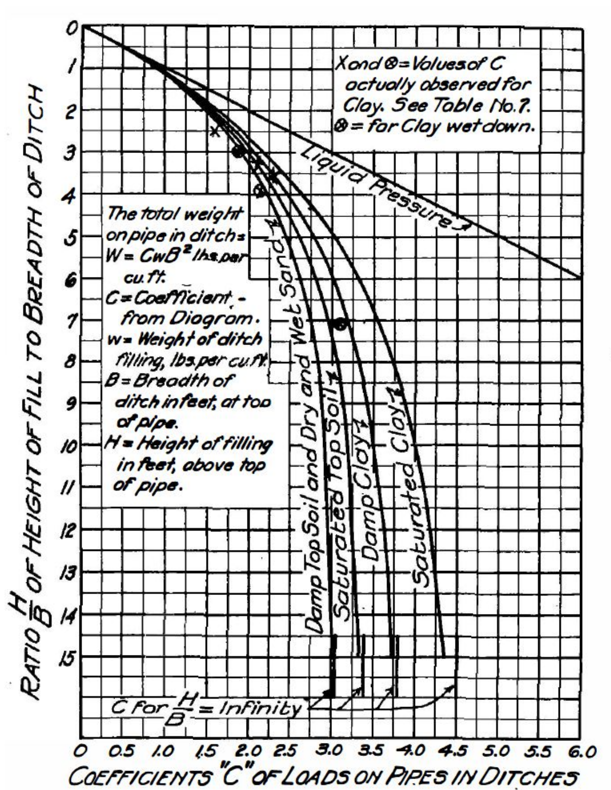

Figure 2. Working Values of C for Use in Determining Maximum Vertical Conduit Load (Reproduced from Ref. 1)

Marston and Anderson also examined the load effects on the buried pipe of what they termed “super loads,” which were loads applied to the top of the backfill (or superimposed loads). They performed a differential analysis, similar to that done for the backfill loads, and produced load effect equations for “long” and “short” super loads. The long super loads were assumed to be those produced by placing piles of material above the finished surface of the backfill for “long” lengths along the axis of the buried pipe, and the short super loads were assumed to be those produced by wheel loads.

The researchers, in completing this early work, were also compelled to begin thinking about the effects of bedding conditions on the loads transmitted to buried rigid pipe. Based on their experimentation, they produced preliminary design criteria in the use of plain concrete as a bedding material to provide additional support for the buried conduit. Considering the surrounding soils outside of the trench as either yielding (soft) or solid (firm) in nature, Marston and Anderson recommended bedding dimensions based on inside pipe diameter, as illustrated below, respectively.

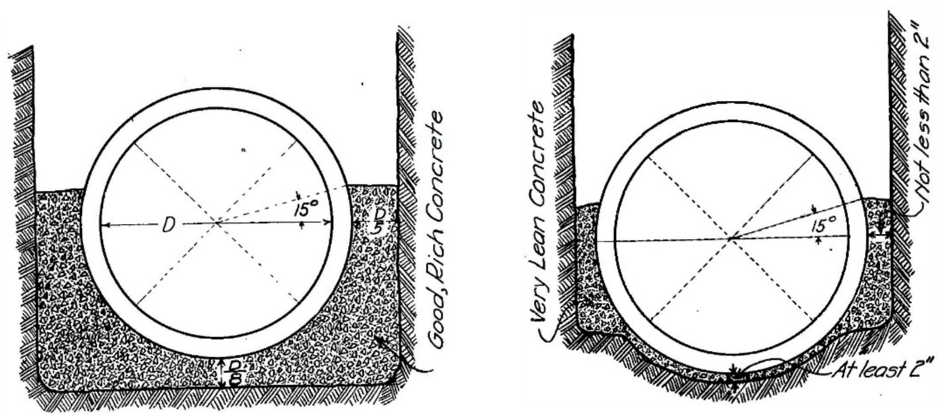

Figure 3. Method of Strengthening Drain Tile and Sewer Pipe to Carry Heavy Loads (Reproduced from Ref. 1)

Marston (1930)

Marston (Ref. 2) expanded on his earlier work in ditched (trenched) culverts by considering projecting culverts, or culverts placed such that a portion of the pipe was seated below the existing ground line with the remainder placed beneath embankment fill.

To distinguish between ditched and projecting conditions, Marston added a subscript to the previous constant, C, so that for the ditched condition:

$$W_c = C_d w {B_d}^2$$

where, with all other variables as previously defined:

$$C_d = \frac{1 - e^{-2K\mu' \frac{H}{B_d}}}{2K\mu'}$$

For the projecting pipe condition, where the pipe was placed partially in embankment fill, Marston theorized that the settlement of material comprising the prism of soil above the pipe would differ from that of the surrounding embankment. This differential settlement would affect the direction and magnitude of the shear forces that develop between the prism of material above the pipe and the surrounding embankment, comparable to the shear force assumed present between insitu material and the ditch backfill for the trenched condition previously analyzed. The relationship of these differential settlements are depicted below.

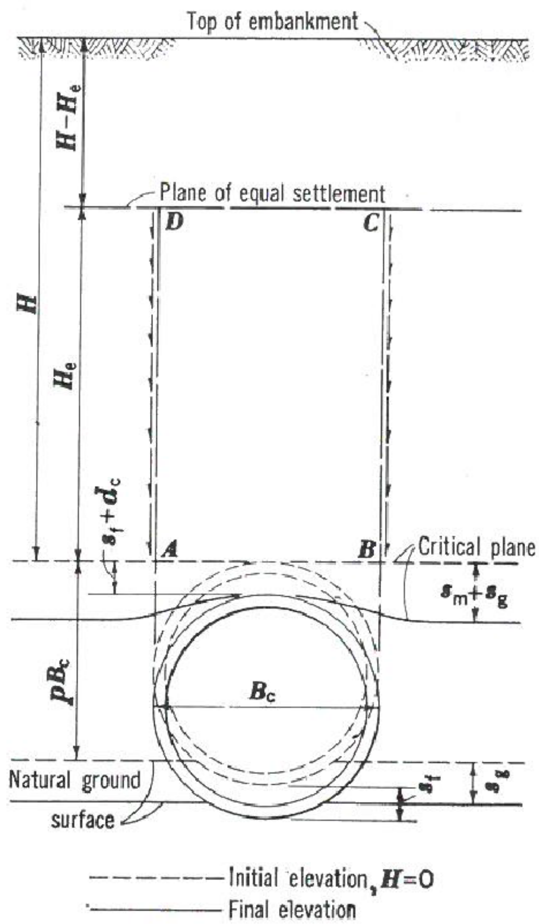

Figure 4. Settlement Values for Determination of Settlement Ratio (Reproduced from Ref. 8)

Marston defined the relationship between these differential settlements by establishing the settlement ratio:

$$r_{sd} = \frac{(s_m + s_g) - (s_f + d_c)}{s_m}$$

where:

r_{sd} = settlement ratio

s_m = compression strain of the side columns of soil over height pB_c

s_g = settlement of natural ground surface adjacent to conduit

s_f = settlement of the conduit into its foundation

d_c = shortening of the vertical height of the conduit

Depending on the direction of the differential settlements, this resulting shear force could add to or reduce the vertical load on the pipe due to the prism of material above the pipe. As shown in Figure 4, the case where the value of (s_m+s_g) exceeds (s_f+d_c), settlement ratio is positive and the movement of the exterior prisms downward relative to the interior prism increases the vertical load resultant on the pipe. Conversely, as shown below, where the value of (s_m+s_g) is less than (s_f+d_c), settlement ratio is negative and the movement of the interior prism is downward relative to the exterior prisms decreases the vertical load resultant.

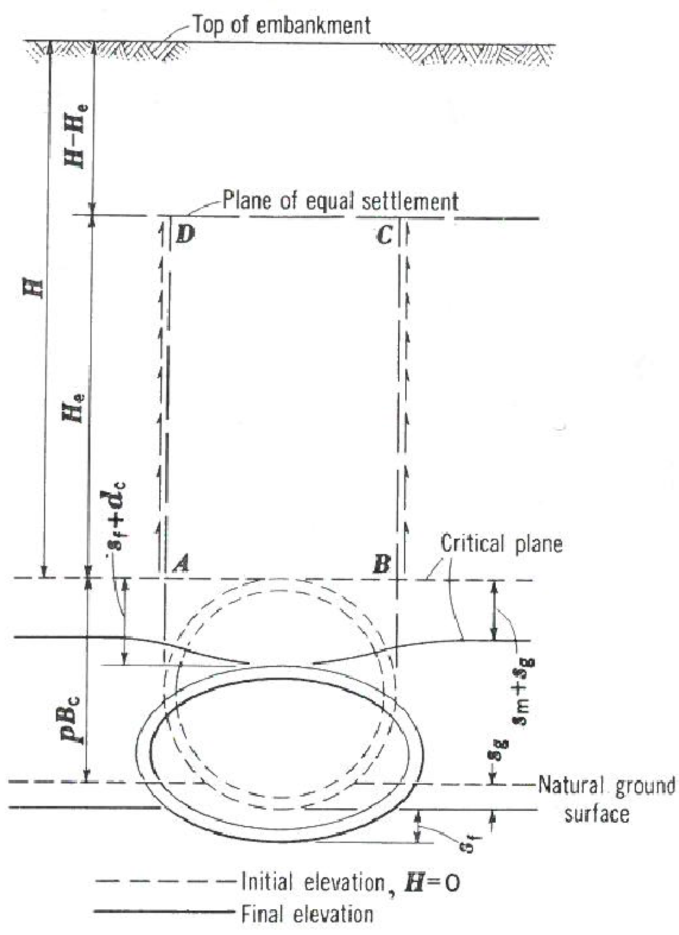

Figure 5. Settlement Values for the Incomplete Ditch Condition (Reproduced from Ref. 8)

For the ditch condition, the shear forces are assumed to extend to the top of the finished ground surface. In a projecting pipe condition, however, the height of the embankment fill may be large enough such that the differential settlements are equalized at a point between the top of the pipe and the finished ground surface. In this case, the shear forces terminate at this plane of equal settlement.

For both of the projecting pipe conditions illustrated above, the top of the embankment is assumed to be higher than the plane of equal settlement. Marston termed these situations as incomplete projection, for the case of the positive settlement ratio, and incomplete ditch, for the case of the negative settlement ratio. When the plane of equal settlement is theoretical, and is calculated to exist above the finished surface of the embankment, the case of positive settlement ratio is termed a complete projection. The case of equal settlement plane above the top of embankment, with a negative settlement ratio, reduces to the ditch situation considered in the earlier work and is designated a complete ditch.

Marston then made modifications to the earlier vertical load formulas to account for these cases involving projecting culverts. Similar to the formula for ditched culverts, the vertical load for projecting culverts is given by:

$$W_c = C_c w {B_c}^2$$

where C_c and B_c have replaced C_d and B_d. B_c is now the outside width of the pipe, and C_c is defined as:

$$C_c = \frac{e^{\pm 2K\mu \frac{H}{B_c}} - 1}{\pm 2K\mu}$$

for the complete projection and complete ditch conditions, with the variables as previously defined. The coefficient of friction between the insitu material and the ditch backfill, μ', is replaced by the coefficient of friction for the embankment material, μ, for the case of a projecting culvert. Note also that the plus signs are to be used in this determination for the case of the complete projection, and the minus signs for the complete ditch situation.

For the case of an incomplete projection or incomplete ditch, the C_c factor must be adjusted to reflect the termination of shear forces between the prisms short of the top of the embankment. This adjustment in the formula produces:

$$C_c = \frac{e^{\pm 2K\mu \frac{H_e}{B_c}} - 1}{\pm 2K\mu} + \left(\frac{H}{B_c} - \frac{H_e}{B_c}\right) e^{\pm 2K\mu \frac{H_e}{B_c}}$$

As for the complete conditions, the sign convention uses the plus signs for the incomplete projection case and the minus signs for the incomplete ditch case. Use of this formula requires the computation of H_e, which is found by implicitly solving the equation:

$$e^{\pm 2K\mu \frac{H_e}{B_c}} \mp 2K\mu \frac{H_e}{B_c} = \pm 2K\mu r_{sd} p + 1$$

where:

$$p \ = \ \text{projection ratio of the culvert, or ratio of the culvert height above existing ground to the total culvert height}$$

with all other variables as previously defined. Where two signs exist in the equation above, the top sign is used for the incomplete projecting condition and the bottom sign is to be used for the incomplete ditch condition.

To facilitate the use of the load formulas for the incomplete projection and incomplete ditch cases, Marston produced a set of curves to be used for the determination of C_c, given assumed values for settlement ratio, r_{sd}, and projection ratio, p. While Marston initially assigned an arbitrarily conservative value for $K\mu$ of 0.1924, he found that use of the formulas for vertical load were relatively insensitive to variations in both variables; and consequently, later refined these curves using $K\mu$ values of 0.13 for the ditch condition and 0.19 for the projecting condition. These refined curves are shown below for various values of settlement and projection ratios.

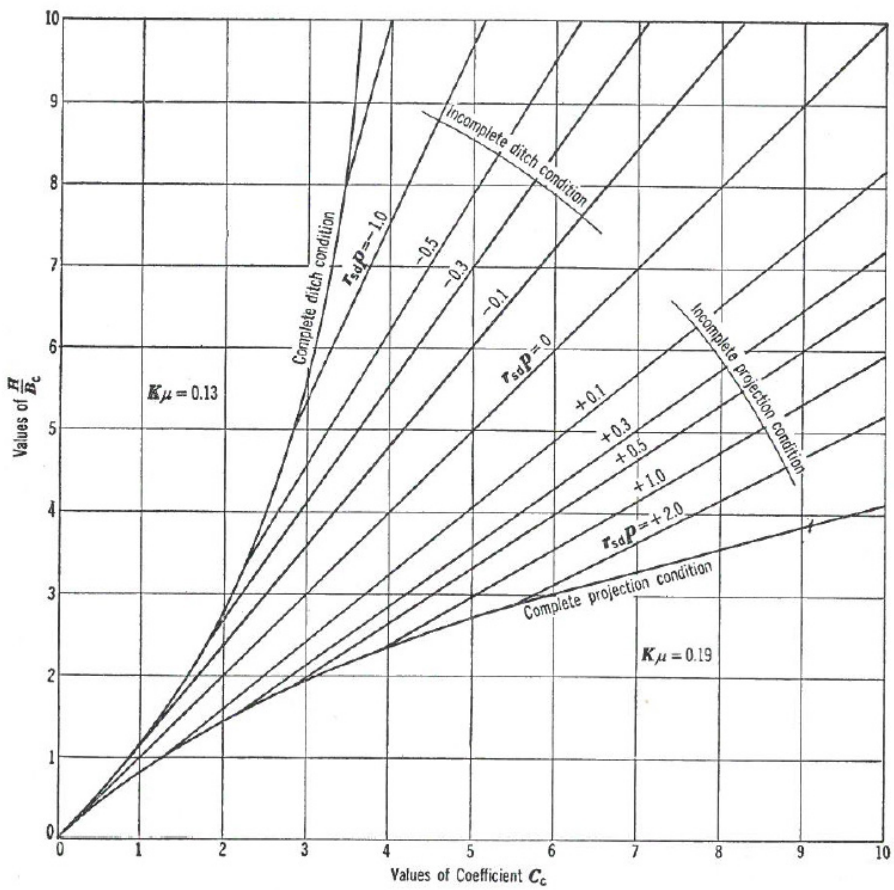

Figure 6. Values of C_c for Projecting Culverts (Reproduced from Ref. 8)

It should be noted that the ray lines for the various combinations of settlement and projection ratios intersect the curves for the complete conditions at a point where $H=H_e$; therefore, the figure above can also be used to obtain values for H_e in lieu of the rigorous use of the implicit equation given above.

This Marston work also took a more detailed look at the vertical reactions imparted to buried pipe by superimposed loads, or as they were referred to in the research, “super-loads,” using an assumed Boussinesq stress distribution. Expressions were developed for determining the effects of these superimposed loads on buried pipes, both uniform and concentrated; and they were shown to become relatively insignificant at depths of cover of about 10 feet.

Schlick (1932)

Schlick (Ref. 3) studied the relationship between the vertical loads predicted by the Marston Formulas and the width of the ditch in which the pipe is placed. His work produced the following findings:

- Marston’s Load Formula for the ditched case gave reasonably correct vertical loads for ditch widths up to approximately 1.5 times the outside diameter of the pipe.
- Marston’s equation for vertical loads in projecting culverts gave reasonably correct vertical loads for ditch widths greater than 3 times the outside diameter of the pipe.
- Loads resulting from pipe placements in ditches of widths between 1.5 and 3 times the outside diameter of the pipe can be accurately predicted by the Marston equations depending on the values of height of fill, H, and settlement ratio, r_{sd}.

Spangler (1933)

Spangler (Ref. 4) sought to establish the service strength of buried rigid pipe, for comparison to the vertical loads predicted by the Marston formulas. Because laboratory conditions replicating the conditions experienced by the buried culvert could not be reasonably produced, he sought to develop a relationship between the insitu pipe strength and the strength determined by readily conducted pipe strength tests in the lab.

The standard laboratory test used by Spangler to determine the strength of rigid pipe was the three-edge bearing (TEB) test, which he determined was the simplest and easiest to perform. The goal of the research was to determine the ratio of the supporting strength of the buried pipe to the strength given by the TEB test. Spangler referred to this ratio as the load factor, which, to avoid confusion with that term and its use in load and resistance factor design, was subsequently termed *bedding factor*.

The limiting strength used by Spangler for both the laboratory tests and the field tests of the buried pipes was determined by an arbitrary service limit state. Spangler termed this strength limit as the cracking load, and further defined the load as that producing a crack width of 0.01” in the pipe wall.

Spangler found that the bedding factor was highly dependent on the details of the pipe bedding. For the purpose of the research, he defined four bedding classes:

- Class A (Concrete Cradle) Bedding – Pipe placed in a concrete cradle
- Class B (First Class) Bedding – Thoroughly tamped below the pipe springline, using fine granular backfill, with a maximum projection of 70%
- Class C (Ordinary) Bedding – Normally placed earth or granular backfill
- Class D (Impermissible) Bedding – Little or no care in placing backfill

These four bedding classes are illustrated below, along with their experimentally determined load (bedding) factors:

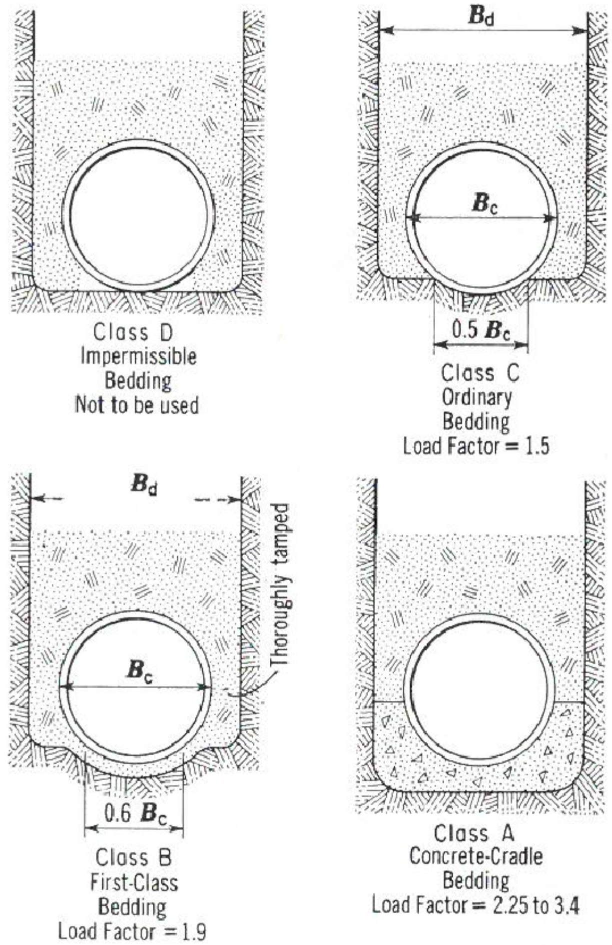

Figure 7. Spangler Bedding Classes (Reproduced from Ref. 8)

Spangler also found that the bedding factor was highly dependent on the magnitude of lateral pressure exerted by the supporting soil, and the portion of the vertical height on which this pressure acted. Spangler proposed the following relationship for the bedding factor:

$$B_f = \frac{1.431}{N - xq}$$

where:

B_f = bedding factor

N = constant depending on distribution of vertical loading and vertical reaction

x = constant depending on distribution of lateral pressure

q = ratio of total lateral pressure to total vertical pressure

The ratio of total lateral pressure to total vertical pressure, q, is found by the formula:

$$q = \frac{mK}{C_c}\left(\frac{H}{B_c} + \frac{m}{2}\right)$$

where:

m = fractional part of B_c over which the lateral pressure acts

with the other variables as previously defined. Note that in many cases the projection ratio, p, is used for m, but this is not necessarily always true.

Spangler's formulations for bedding factor using x and N were developed assuming that cracks in the pipe would initiate in the side wall, which is the common case for most installations. When the pipe is bedded in a concrete cradle, cracking initiates at the top of the pipe; and for this case, Spangler recommended the use of modified values of x and N, namely x' and N'. The values recommended by Spangler for use in determining bedding factor are shown in Table 2, and Table 3 below.

m	x	x'
0.0	0.000	0.150
0.3	0.217	0.743
0.5	0.423	0.856
0.7	0.594	0.811
0.9	0.655	0.678
1.0	0.638	0.638

Table 2. Recommended Values of x and x' (Reproduced from Ref. 8)

Type of Bedding	N	N'
Impermissible	1.310	---
Ordinary	0.840	---
First Class	0.707	---
Concrete Cradle	---	0.505

Table 3. Recommended Values of N and N' (Reproduced from Ref. 8)

Spangler (1941)

Following his earlier work on rigid pipe, Spangler (Ref. 5) later turned his attention to flexible pipe culverts. This research sought to establish rational design criteria for the placement of conduit with flexible, thin-walled sections.

Spangler employed thin-ring elastic analysis to predict horizontal and vertical deflections, and compared these theoretical values with those obtained from laboratory experiments. The idealized loading on the flexible culvert section consisted of distributed vertical pressure loads, assumed consistent with Marston loadings, and variable horizontal pressure loads produced by the passive reaction of the adjacent soil. For mathematical simplification, Spangler assumed this passive reaction to be parabolically applied over 100 degrees of arc on the side of the section (horizontal +/- 50 degrees). Spangler's assumed load distribution is illustrated below.

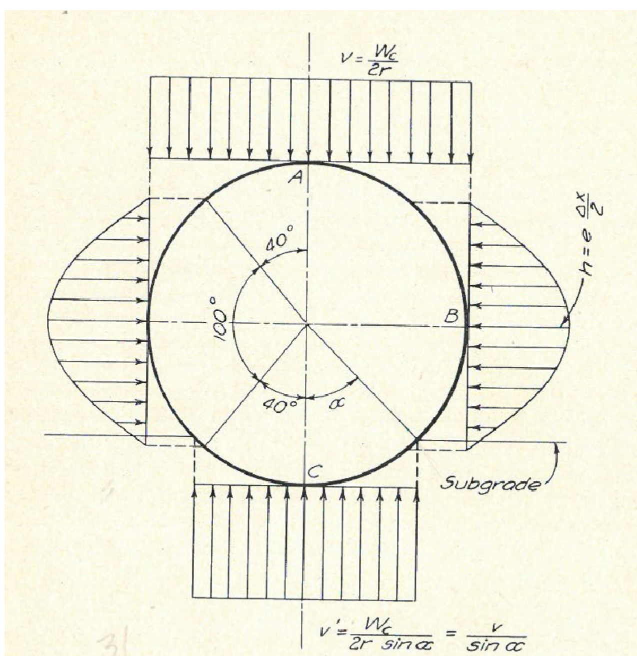

Figure 8. Assumed Pressure Distribution for Flexible Pipe (Reproduced from Ref. 5)

Spangler determined that for the purposes of design, the magnitude of the vertical and horizontal deflections could be considered equal, and developed the original Iowa Formula for the deflection of flexible pipe under buried loading conditions:

$$\Delta x = D_l \frac{K W_c r^3}{EI + 0.061 e r^4}$$

where, using consistent units:

$\Delta x =$ horizontal deflection (considered equal to the vertical deflection)

$D_l =$ deflection lag factor

$K =$ bedding constant

$W_c =$ vertical load per unit length of pipe

$r =$ mean radius of the pipe

$E =$ modulus of elasticity of the pipe material

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

$e =$ modulus of passive resistance of the enveloping soil

The lag factor, D_l, accounts for the observed phenomena that buried flexible pipes continue to deflect slowly with time after initial loading. Spangler found that these values ranged from 1.00 to 2.00, and recommended a value between 1.25 and 1.50 be used for design.

The bedding factor, K, is a function of the angle of bedding reaction, α, and is given by:

$$K = 0.5 \sin\alpha - 0.082 \sin^2\alpha + 0.08 \frac{\alpha}{\sin\alpha} - 0.16 \sin\alpha(\pi - \alpha) - 0.04 \frac{\sin 2\alpha}{\sin\alpha} + 0.318 \cos\alpha - 0.208$$

For values of bedding angle, α, between zero and 90 degrees, the bedding factor resulting from the equation is depicted below:

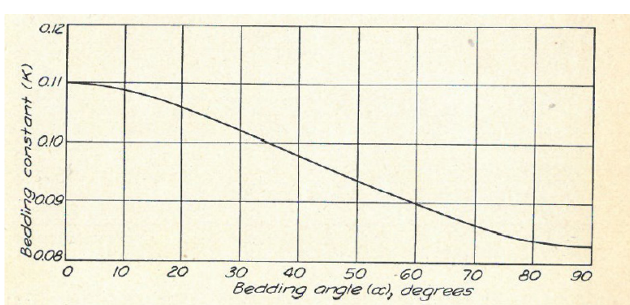

Figure 9. Bedding Constants (Reproduced from Ref. 5)

For practical design, Spangler recommended that the deflection given by the elastic formula above be limited to 5%.

Spangler (1950)

Spangler (Ref. 6) followed Marston's and his earlier work on projecting pipe culverts by completing detailed studies of actual settlement ratios developed by conduits placed in embankments.

The concept of a settlement ratio had been previously incorporated into Marston's load theory, but practical values to be used for the design of culverts had not been established. This work produced representative values to be used for these designs, by measuring the actual differential settlements experienced by a number of rigid and flexible pipes installed in embankments in the field.

Watkins and Spangler (1955)

Watkins and Spangler (Ref. 7) expounded on their earlier work with more detailed study of the interaction between flexible culverts and the surrounding soil. This work brought into question the assumption that the soil property, e, was independent of the pipe properties. As a result, the researchers defined a new parameter, E', the modulus of soil reaction, and replaced the er term in the original Iowa deflection formula with this new parameter. The result was the publication of the widely-recognized Modified Iowa Formula for the deflection of flexible round pipe under buried loading conditions:

$$\Delta x = D_l \frac{K W_c r^3}{EI + 0.061 E' r^3}$$

where, using consistent units as previously defined:

$\Delta x =$ horizontal deflection (considered equal to the vertical deflection)

$D_l =$ deflection lag factor

$K =$ bedding constant

$W_c =$ vertical load per unit length of pipe

$r =$ mean radius of the pipe

$E =$ modulus of elasticity of the pipe material

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

$E' = er =$ modulus of soil reaction

where:

$e \quad =$ modulus of passive resistance of the enveloping soil

Heger (1982)

In 1970, the American Concrete Pipe Association (ACPA) began an extensive research program to study the interaction between buried pipe and surrounding soil. An initial outcome of this work was to develop a rational approach to the design of concrete pipe to be used as buried conduit.

Heger (Ref. 10) presented a design approach, known widely as the Direct Design Method, which employed recognized concepts of reinforced concrete design into the analysis of the pipe section. This Direct Design Method considered flexural strength involving tension in the reinforcement, concrete compression, concrete radial tension, stirrup radial tension, and diagonal tension.

Heger, Liepins and Selig (1985)

Heger (Ref. 11), et al., continued the ACPA work by studying in greater detail the behavior of buried concrete pipe. This work produced a finite-element based program, SPIDA, or Soil-Pipe Interaction Design and Analysis.

Through the use of the SPIDA program, the researchers refined the pressure distributions resulting from loads applied to buried rigid pipes. The Heger pressure distribution is illustrated below:

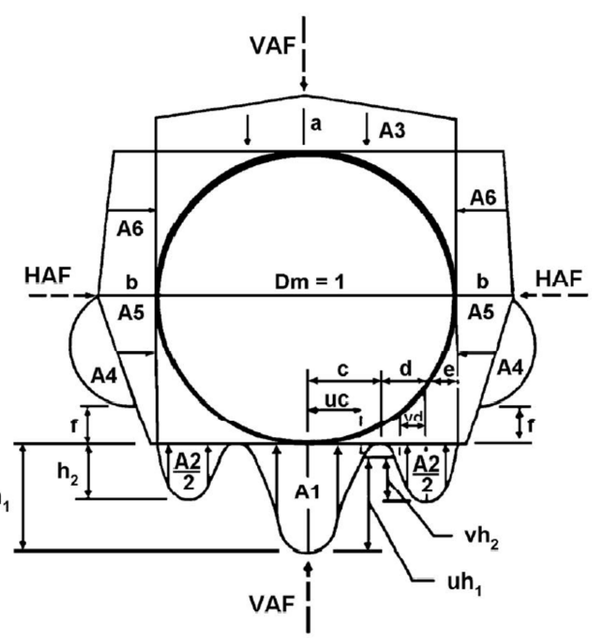

Figure 10. Heger Pressure Distribution (Reproduced from Ref. 22)

Heger (1988)

Heger's continued work (Ref. 12) for ACPA, using the SPIDA program, redefined Spangler's 4 original bedding classes. Through consultations with practicing professionals, and the analysis of numerous SPIDA results, the previous bedding classes were replaced with four Standard Installation Types.

In defining these installations, the following nomenclature was used:

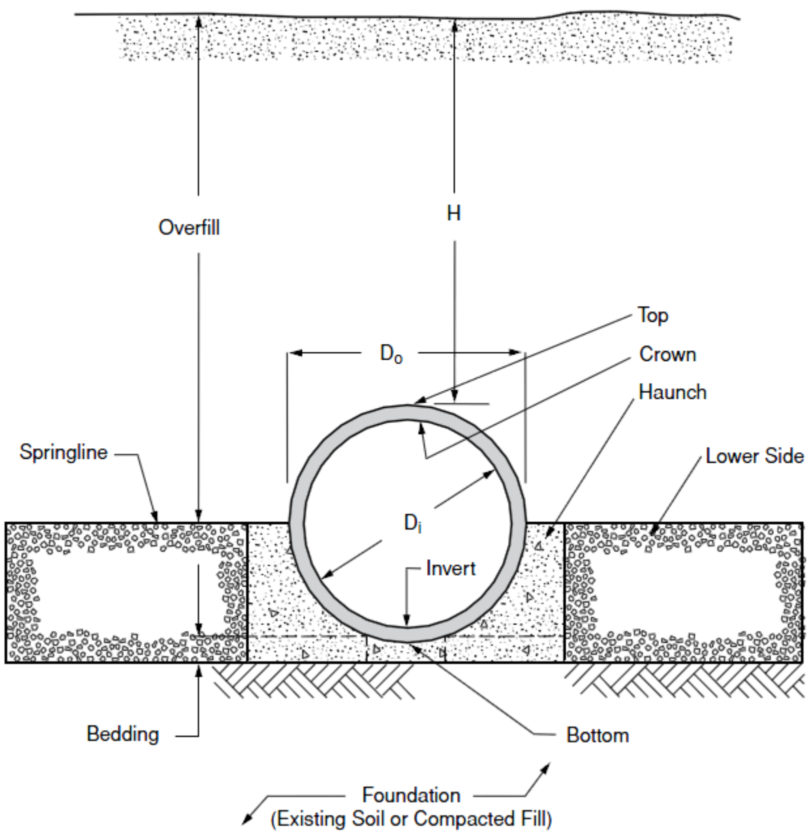

Figure 11. Terminology Used in Defining Standard Pipe Installations (Reproduced from Ref. 20)

The installation types were formulated assuming positive projecting embankment conditions, which multiple applications of the SPIDA models demonstrated to be the worst-case vertical load condition for a buried pipe.

The detailed studies also confirmed the following widely held, but not yet proven, concepts:

- Loosely placed, uncompacted bedding directly beneath the invert of the pipe significantly reduces stresses in the rigid pipe.
- Soil in those portions of the bedding and haunch areas directly under the pipe is difficult to compact.

- The soil in the haunch area from the foundation to the pipe springline provides significant support to the pipe and reduces pipe stresses.
- Compaction level of the soil directly above the haunch, from the pipe springline to the top of the pipe grade level, has negligible effect on pipe stresses. Compaction of the soil in this area is not necessary unless required for the support of pavement structures.
- Installation materials and compaction levels below the springline have a significant effect on pipe structural requirements.

Installation Type	Bedding Thickness	Haunch and Outer Bedding	Lower Side
Type 1	Do/24 minimum, not less than 75 mm (3"). If rock foundation, use Do/12 minimum, not less than 150 mm (6").	95% Category I	90% Category I, 95% Category II, or 100% Category III
Type 2	Do/24 minimum, not less than 75 mm (3"). If rock foundation, use Do/12 minimum, not less than 150 mm (6").	90% Category I or 95% Category II	85% Category I, 90% Category II, or 95% Category III
Type 3	Do/24 minimum, not less than 75 mm (3"). If rock foundation, use Do/12 minimum, not less than 150 mm (6") .	85% Category I, 90% Category II, or 95% Category III	85% Category I, 90% Category II, or 95% Category III
Type 4	No bedding required, except if rock foundation, use Do/12 minimum, not less than 150 mm (6").	No compaction required, except if Category III, use 85% Category III	No compaction required, except if Category III, use 85% Category III

Notes:

1. *Compaction and soil symbols - i.e. "95% Category I"- refers to Category I soil material with minimum standard Proctor compaction of 95%. See Illustration 4.5 for equivalent modified Proctor values.*
2. *Soil in the outer bedding, haunch, and lower side zones, except under the middle 1/3 of the pipe, shall be compacted to at least the same compaction as the majority of soil in the overfill zone.*
3. *For trenches, top elevation shall be no lower than 0.1 H below finished grade or, for roadways, its top shall be no lower than an elevation of 1 foot below the bottom of the pavement base material.*
4. *For trenches, width shall be wider than shown if required for adequate space to attain the specified compaction in the haunch and bedding zones.*
5. *For trench walls that are within 10 degrees of vertical, the compaction or firmness of the soil in the trench walls and lower side zone need not be considered.*
6. *For trench walls with greater than 10 degree slopes that consist of embankment, the lower side shall be compacted to at least the same compaction as specified for the soil in the backfill zone.*
7. ***Subtrenches***
   - *7.1 A subtrench is defined as a trench with its top below finished grade by more than 0.1 H or, for roadways, its top is at an elevation lower than 1ft. below the bottom of the pavement base material.*
   - *7.2 The minimum width of a subtrench shall be 1.33 D_o or wider if required for adequate space to attain the specified compaction in the haunch and bedding zones.*
   - *7.3 For subtrenches with walls of natural soil, any portion of the lower side zone in the subtrench wall shall be at least as firm as an equivalent soil placed to the compaction requirements specified for the lower side zone and as firm as the majority of soil in the overfill zone, or shall be removed and replaced with soil compacted to the specified level.*

Figure 12. Soil and Minimum Compaction Requirements for Standard Installations (Reproduced from Ref. 20)

Categories I through III shown in the table above refer to the soil type surrounding the pipe. For use in the standard installations, commonly found soils were characterized into one of three groups, which are illustrated in the table below.

	Representative Soil Types		Percent Compaction	
SIDD Soil	USCS,	Standard AASHTO	Standard Proctor	Modified Proctor
Gravelly Sand (Category 1)	SW, SP, GW, GP	A1,A3	100 95 90 85 80 61	95 90 85 80 75 59
Sandy Silt (Category II)	GM, SM, ML, Also GC, SC with less than 20% passing #200 sieve	A2, A4	100 95 90 85 80 49	95 90 85 80 75 46
Silty Clay (Category III)	CL, MH, GC, SC	A5, A6	100 95 90 85 80 45	90 85 80 75 70 40

Figure 13. Soil Classifications, with USCS and AASHTO Equivalents, for Standard Installations (Reproduced from Ref. 20)

ACPA (1991)

The American Concrete Pipe Association (Ref. 13) published updated information on bedding factors for rigid pipes by examining, in greater detail, the impact of lateral loading. The researchers had determined that the initial bedding factors developed by Spangler did not fully recognize the effects of lateral active earth on the insitu strength of the pipe, finding that the previous values were quite conservative in understating the supporting strength of the installed culvert. While this research did address the improved construction methods that had been developed since Spangler's original work, because the updated Heger Standard Beddings had not yet been widely accepted, this study still assumed the use of Spangler's original bedding classes.

Watkins (1999)

Watkins (Ref. 14) reviewed, in detail, the assumptions contained within the Modified Iowa Formula for the deflection of flexible pipes. He found that the elastic theory used to derive the formula should be considered valid only for computing yield stresses and small ring deflections, and should not be used for design. It was determined that the assumption of an elliptical deformed shape, used to derive the Iowa Formula, was not entirely accurate.

Watkins further stated that an appropriate performance limit for flexible pipe would be in the plastic range of ring deflections, and that elastic limits on deflection were not a suitable limiting design criteria. He did, however, state that ring deflection should be controlled because of its effect on other performance criteria.

Erdogmus and Tadros (2006)

Erdogmus and Tadros (Ref. 15) published a report on the behavior and design of buried concrete pipes summarizing their work conducted at the University of Nebraska-Lincoln investigating the methods for determining allowable pipe cover. Erdogmus and Tadros sought to compare the resulting allowable cover produced by the Direct and Indirect Design methods by examining the methods used by other states, evaluating the design criteria used by the Nebraska Department of Roads (NDOR), and tabulating the results for review. Their work included computation by the Direct Design method using AASHTO Allowable Stress Design (ASD), the Direct Design method using AASHTO Load and Resistance Factor Design (LRFD), the American Concrete Pipe Association (ACPA) Indirect Design method, and NDOR's current policy using the Direct Design method.

Pipe Diam. (in)	**Class III Pipe** Fill Height (ft)				**Class IV Pipe** Fill Height (ft)				**Class V Pipe** Fill Height (ft)			
	NDOR DD	ASD DD	LRFD DD	ACPA ID	NDOR DD	ASD DD	LRFD DD	ACPA ID	NDOR DD	ASD DD	LRFD DD	ACPA ID
15	12	12	13	14	15	15	16	22	21	21	22	33
18	12	12	13	15	17	17	18	22	24	24	25	34
21	13	13	13	15	19	19	20	22	26	26	27	34
24	13	13	12	15	19	19	20	22	26	26	27	34
27	13	13	13	14	17	17	17	22	26	26	27	34
30	12	12	12	14	14	14	15	22	25	25	25	33
36	10	10	11	14	16	16	17	22	24	24	25	33
42	10	10	11	14	15	15	16	22	23	23	24	33
48	10	10	11	14	14	15	15	21	22	23	24	33
54	10	10	11	14	14	15	15	21				
60	9	10	10	14	14	15	16	21				
66	9	10	10	14	14	16	16	21				
72	9	10	10	13	14	16	16	21				
78	9	10	11	13								
84	9	10	10	13								
90	9	10	11	13								
96	9	10	11	13								
102	10	11	11	---								
108	10	11	11	---								

Table 4. Comparison of Fill Heights by Computation Method (Reproduced from Ref. 15)

The researchers found that the three variations in application of the Direct Design method produced fairly consistent results, as should be expected, while the ACPA Indirect Design method produced greater values of maximum fill heights that were presumably less conservative. Table 4 above reflects the values for maximum fill height obtained by the study for the methods and pipe classes indicated. It should be noted that these values were all obtained assuming a Type 3 Standard Installation, which is the NDOR standard.

ACPA (2013)

ACPA (Ref. 21) revisited the subject of bedding factors by publishing new values that fully considered the new Standard Installation Types, as well as the Heger pressure distribution for buried pipes. These factors and methodologies are now integrated into the AASHTO LRFD Bridge Design Specification.

Standard Concrete Pipe Class and D-Load

The manufacture and specification of reinforced concrete pipe is governed by ASTM C76, Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe. This specification defines five reinforced concrete pipe strength classes, I to V, and the pipe section details and material strengths necessary to produce them.

The concrete pipe strengths are expressed in terms of D-loads, which are the three-edge bearing test loads, expressed in pounds-force per linear foot per foot of pipe diameter, to produce a 0.01" crack in the pipe wall. Consistent with the concepts of allowable strength design, a factor of safety has been incorporated into the designation of ultimate D-loads. These factors of safety vary from 1.50 for 0.01" D-loads of 2000 and lower, to 1.25 for 0.01" D-loads of 3000 and greater, with a linear interpolation applied between 2000 and 3000. A summary of the 0.01" and ultimate D-loads for the five pipe classes are presented in the table below.

Pipe Class	0.01" Crack D-load (lbs)	Ultimate D-load (lbs)
I	800	1200
II	1000	1500
III	1350	2000
IV	2000	3000
V	3000	3750

Table 5. D-load Values by Pipe Class (Reproduced from Ref. 19)

For each of the five pipe classes, ASTM C76 provides multiple wall thicknesses, reinforcement details, and required material properties to achieve the desired D-load strengths.

Current Practice

The methods used by various agencies to establish minimum and maximum pipe cover heights is a relatively complex topic. While the state of the art is continuing to evolve with regard to buried pipe culvert behavior under embankment load, establishing a singular method of analysis is further complicated by the fact that the various agencies have different bedding standards, have assigned different values to backfill material properties, and in some cases still adhere to outdated methodologies all together. Below is a summary of the methodologies still in use, as encountered in the course of completing this study.

In the case of reinforced concrete pipe, the design methods used by the various agencies include:

- **Indirect Design (Marston/Spangler)** – This method uses the classical Marston Load Theory, D-load pipe strengths, and the original bedding classes.
- **Indirect Design (ACPA/AASHTO)** – This method uses the Marston Load Theory with the updated Heger pressure distribution, D-load pipe strengths, refined values for bedding factors, and the new Standard Installations.
- **Direct Design (AASHTO LRFD)** – This method uses calculated thrusts, moments, and shears, along with the principles of reinforced concrete load and resistance factor design, to specify the pipe section.

In the case of corrugated steel pipe, the prevailing methodologies include:

- **AASHTO Deflection** – This method uses the deflection computed from the Iowa Formula as a limiting criteria for design. This deflection criteria was specified as the controlling factor in the development of metal pipe cover tables by the AASHTO Bridge Specifications prior to 1980.
- **American Iron and Steel Institute (AISI)** – This method checks compression stress in the pipe wall and handling stiffness against prescribed allowable values.
- **AASHTO LRFD** – This method is similar to the AISI method, but also makes a check of the wall buckling strength. The method also employs the principles of LRFD in the use of load and resistance factors.

Iowa DOT

Currently, the Iowa Department of Transportation uses tabular data found on Standard Road Plan DR-104 to specify minimum and maximum cover heights for concrete and steel pipe. No documentation exists to provide a basis for the values shown, outside of the design criteria information appearing on the standard plan sheet. In spite of this lack of documentation, efforts were made to reproduce the existing tabular values to gain an understanding of the methods and assumptions that may have guided their development.

Concrete Pipe

With regard to the tables for circular concrete pipe, the design criteria given as information on the standard plan sheet provided a good deal of guidance toward reproduction of the numbers. The method used to determine the maximum fill heights for concrete pipe appears to have followed the Indirect Design procedure from an earlier version of the ACPA Design Manual.

The design criteria appearing on DR-104, and shown below, state that the tabular data assumes culvert placement in an embankment condition for two bedding classes. The data also shows two distinct values for projection ratio were used in the computations, depending on the bedding class of the pipe, which are labeled Class "B" and Class "C". Values that reasonably match those given in the existing cover tables on DR-104 were reproduced by using the Marston/Spangler Method, along with Marston and Spangler's values for bedding classes B and C.

DESIGN CRITERIA FOR CONCRETE PIPE

The height of cover tables have been prepared from data in the "Concrete Pipe Design Manual" published by the American Concrete Pipe Association using the values listed below.

FOR EMBANKMENT CONDITIONS

Fill Material Density	= w = 120 lbs. per cu. ft.
Settlement Ratio	= rsd = +0.5
*	= ku = 0.13
Projection Ratio	= p = 0.9 (Class "C" bedding)
	= p = 0.7 (Class "B" bedding)
Factor of Safety	= F.S. = 1.33 on Ultimate Strength

* Using a ratio of lateral to vertical earth pressure (k) of 0.37 (saturated yellow clay) and a coefficient of internal friction (u) of 0.34.

The values shown for concrete pipe were calculated for concrete pipe placed under embankment conditions. These values do not apply to to design and installation of sanitary sewer except where sanitary sewer would be placed under embankment conditions.

Figure 14. Design Criteria for Concrete Pipe cover from Iowa DOT Standard Road Plan DR-104

CONCRETE CULVERT PIPE CLASS "B" BEDDING				
DIAMETER OF PIPE 'D' Inches	(H) MAXIMUM ALLOWABLE COVER IN FEET			
	1500D (Class II)	2000D (Class III)	3000D (Class IV)	3750D (Class V)
18	11	13	20	25
24	12	14	21	26
36	13	16	23	28
48	14	16	24	29
60	14	17	24	29
72	14	17	24	30
84	15	17	25	30
96	15	18	25	31
108	15	18	26	32

CONCRETE CULVERT PIPE CLASS "C" BEDDING				
DIAMETER OF PIPE 'D' Inches	(H) MAXIMUM ALLOWABLE COVER IN FEET			
	1500D (Class II)	2000D (Class III)	3000D (Class IV)	3750D (Class V)
18	9	12	18	22
24	10	13	19	23
36	11	14	20	24
48	11	15	21	25
60	12	15	21	26
72	12	16	22	26
84	13	16	22	27
96	13	16	23	27
108	13	17	23	28

Figure 15. Existing Tabular Data for Concrete Pipe from Iowa DOT Standard Road Plan DR-104

Using the assumptions and design data provided on Standard Road Plan DR-104, with the Marston/Spangler Indirect Design procedure, the following values were obtained. As is evident from a detailed review of the Standard Road plan and Table 6, these cover table values very closely match those found in the current standard.

Minor fluctuations in values between the tables can easily be attributed to the rounding and interpolation of intermediate values for bedding factors and the C_c factor in the computations.

Class "B" Bedding				
Pipe Diam. (in)	Maximum Allowable Cover (ft)			
	1500D (Class II)	2000D (Class III)	3000D (Class IV)	3750D (Class V)
18	12	16	24	30
24	13	17	25	31
36	13	17	26	32
48	13	17	26	32
60	13	18	26	33
72	14	18	27	33
84	14	18	27	33
96	14	18	27	33
108	15	19	27	34

Class "C" Bedding				
Pipe Diam. (in)	Maximum Allowable Cover (ft)			
	1500D (Class II)	2000D (Class III)	3000D (Class IV)	3750D (Class V)
18	10	14	20	25
24	11	14	21	26
36	11	15	22	27
48	11	15	22	27
60	12	15	22	28
72	12	15	23	28
84	13	16	23	28
96	13	16	23	28
108	14	17	23	29

Table 6. Allowable Concrete Pipe Cover Values Using Marston/Spangler Procedure

Corrugated Steel Pipe

The allowable pipe cover values shown on Standard Road Plan DR-104 for metal pipes, unlike those for concrete pipes, are not accompanied by any assumptions or design data. During the review of adjacent states' standards, it was apparent the Iowa values were typically more conservative.

Because the tabular values appeared to reflect a sensitivity to pipe deflection, a study using the Modified Iowa Formula for flexible pipe deflection was conducted to determine the deflection values that would correlate to the values currently shown on the standard sheet. It was found that the allowable cover values currently listed in the tables reflect a 3-5% deflection, as given by the Modified Iowa Formula. This would be consistent with the 5% value originally recommended by Spangler in the 1940's.

The existing metal pipe tables also list maximum allowable covers for both "round" and "elongated" placements. This is presumably in regard to a former practice to increase the vertical pipe diameter in the fabricating shop by 3-5%, as depicted on Iowa DOT Standard Road Plan DR-101. Making this adjustment to the pipe material before placing it in the ground would eliminate the significance of the arbitrary 5% deflection limitation, enabling one of the other conditions to control the design, whether it be wall area, wall buckling, or flexibility.

As mentioned earlier, more recent research has demonstrated the use of an arbitrary deflection value as a limiting control tends to produce overly conservative pipe cover restrictions for flexible pipe culverts. The Iowa Formula, as originally derived, has been shown to significantly underestimate the passive lateral earth pressure that is produced by the ovalization of flexible pipe under applied vertical load in actual installations.

Surrounding States

An informal survey was conducted as part of this study to ascertain the methods used by the state agencies surrounding Iowa to establish maximum pipe cover heights. It was found that the states typically utilize one of the finite number of methodologies for generating limiting values previously summarized.

While the design methods are relatively few, the assumptions made by the various agencies on a number of the supporting design parameters vary greatly. Standard beddings, assumed consolidation and projection ratios, and even standard pipe classes that are allowed for use, vary significantly among the agencies.

Concrete Pipe

The Direct and Indirect Design Methods have been covered previously in this report, along with the Marston procedure for determining vertical pipe loads in a buried condition. Given the terminology background provide earlier, the table below summarizes the methods and assumptions used by the neighboring states in establishing maximum cover values for concrete pipe.

State	Method	Beddings	Pipe Class	Notes
Iowa	Indirect Design (Marston/Spangler)	Marston Class B and C	Class II to IV	Assumed $r_{sd} = +0.5$ Projection Ratios: Class B = 0.7 Class C = 0.9
Minnesota	Indirect Design (Marston/Spangler)	Marston Class A to D	Class II to IV	Assumed $r_{sd} = +0.7$ Projection Ratios: Class A = 0.7 Class B = 0.5 Class C = 0.7 Class D = 0.9
Wisconsin	Indirect Design (Marston/Spangler)	Marston Class A to D	Class I to IV	Projection Ratios: Class C = 0.0
Illinois	Indirect Design (ACPA/AASHTO)	Standard Type 2	Class II to V	Table lists design fill heights at 5' increments with required pipe class, or D-Load.
Missouri	Indirect Design (ACPA/AASHTO)	Standard Types 1-4	Class I to IV	MODOT uses single value for a given pipe class and installation type.
Kansas	Indirect Design (ACPA/AASHTO)	Standard Type 3	Class II to V	Assumed $r_{sd} = +0.7$ *Note: The specification of r_{sd} would indicate use of an edition of AASHTO predating incorporation of the Heger findings.*
Nebraska	Direct Design (AASHTO LRFD)	Standard Types 1-3	Class III to V	Standard Installation Type 3 is NDOR Minimum Standard
South Dakota	Indirect Design (ACPA/AASHTO)	Standard Type 3	Class II to V	Tabular Values Match Those for a Type 3 Standard Installation.

Table 7. Summary of Concrete Pipe Allowable Cover Methodology for Surrounding States

Corrugated Steel Pipe

The table below summarizes the methods and assumptions used by the neighboring states in establishing maximum cover values for corrugated steel pipe.

State	Method	Notes
Iowa	AASHTO Deflection	Based on Tabular Data, Deflection Limited to 3-5%
Minnesota	AISI	Data Provided from Manufacturer (CONTECH) ANSI Load Reduction Factor = 1.00 (Assumed Backfill Compacted to 80% of AASHTO T-99 Density)
Wisconsin	AASHTO Deflection	Based on Tabular Data, Deflection Limited to 3-5%
Illinois	AASHTO Deflection	Based on Tabular Data, Deflection Limited to 3-5%
Missouri	AISI	ANSI Load Reduction Factor = 0.90 (Assumed Backfill Compacted to 85% of AASHTO T-99 Density)
Kansas	AASHTO Deflection	Deflection Limited to 5%, Maximum Allowable Fill = 50'
Nebraska	AASHTO Deflection	Based on Tabular Data, Deflection Limited to 3-5%
South Dakota	AISI	ANSI Load Reduction Factor = 1.00 (Assumed Backfill Compacted to 80% of AASHTO T-99 Density)

Table 8. Summary of Metal Pipe Allowable Cover Methodology for Surrounding States

The current edition of the AASHTO LRFD Bridge Specifications does not subject corrugated steel pipe to a deflection limit. This brings the AASHTO Specification into better agreement with the AISI Design Procedure, by making design checks on wall area compression, wall area buckling, longitudinal seam strength, and flexibility for handling and installation.

The primary difference between the AISI procedure and the current AASHTO LRFD method, is the use by AISI of a load reduction factor. This factor has been used by AISI to reduce the calculated vertical prism load over flexible pipes in recognition of the soil arching effect, and is dependent on the assumed compaction conditions of the backfill (See Ref. 16, Figure 7.9). For this reason, the AISI procedure should be considered slightly less conservative than the currently detailed AASHTO procedure.

Recommendations

The primary goal of this study was to produce recommendations for the update of the material provided on Iowa DOT Standard Road Plan DR-104. Those recommendations, essentially utilizing Section 12 of the current edition of the AASHTO LRFD Bridge Specifications, are found below.

Values were produced using the AASHTO procedures for maximum allowable fill height. Because these values typically exceeded 8', no consideration was made for a live load contribution to the vertical loadings for the computation of the maximum values. According to AASHTO Article 3.6.1.2.6a, live load has been found to be insignificant in structures buried under more than 8' of fill (Ref. 22).

The newly tabulated values for allowable fill height used, as guidance, the pipe sections that were listed in the existing DR-104 plan sheet. Computations were completed for all available pipe sizes of a particular material and cross section as part of this work, but only values for the sections appearing in the existing tables are presented below.

A terminology distinction must be made here, as part of these recommendations. The term "pipe cover" appears to have been used interchangeably with "fill height" in prior work related to this topic. The current AASHTO Specification differentiates between "minimum cover" and "maximum fill" heights, and this distinction will be maintained for the remainder of this report.

While AASHTO Article 12.10.2.1 places a minimum limit of 110 pcf for the unit weight of backfill material when determining fill loads, an assumed weight of 120 pcf was used for the development of all the tables below.

Concrete Pipe

For the design of concrete pipe, it is our recommendation that Iowa DOT continue to use the Indirect Design Method, as described in AASHTO Article 12.10.4.3, with updates to the procedure to reflect current practice using the 7th Edition of the AASHTO Specification. This method has proven reliable over time, and considering the results of the Tadros research conducted for NDOR, there appears to be relatively insignificant over-conservatism built into the technique when compared to the Direct Design Method.

The AASHTO procedure for the design of concrete pipe is described in the following Articles of the AASHTO Specification, neglecting live load as previously stated:

- 12.6.6.3 Minimum Cover
- 12.10.2.1 Standard Installations
- 12.10.2.2 Pipe Fluid Weight
- 12.10.4.3.1 Bearing Resistance
- 12.10.4.3.2 Bedding Factors

AASHTO Equation 12.10.2.1-1 gives the expression for unfactored vertical earth load as:

$$W_E = F_e w B_C H$$

where:

$W_E =$ unfactored earth load per unit length of pipe (kips/ft)

$F_e =$ soil-structure interaction factor for the specified installation. For standard embankment and trench installations of pipe, this value is the vertical arching factor, VAF, found in AASHTO Table 12.10.2.1-3. For Standard Installation Types 2, 3, and 4, this value is 1.40, 1.40, and 1.45, respectively.

$B_C =$ out-to-out horizontal dimension of pipe (ft)

$H =$ height of fill over pipe (ft)

$w =$ unit weight of soil (pcf)

AASHTO Article 12.10.2.2 specifies that the weight of fluid be added to the vertical pipe loads for concrete culverts. The assumed fluid weight should use 62.4 pcf unless another value is indicated.

For the Indirect Design Method, the 0.01" crack D-load is the assumed bearing resistance value, and the unfactored earth and fluid loads are the applied actions. The resulting relationship is given by AASHTO Equation 12.10.4.3.1-1:

$$D = \left(\frac{12}{S_i}\right)\left(\frac{W_E + W_F}{B_{FE}}\right)$$

where the live load term has been removed, and:

$D =$ pipe D-load to produce 0.01" crack

$W_E =$ unfactored earth load per unit length of pipe (kips/ft)

$W_F =$ unfactored fluid load per unit length of pipe (kips/ft)

S_i = internal diameter of the pipe (in)

$B_{FE} =$ earth load bedding factor based on pipe diameter and Standard Installation Type. Bedding factors are given for circular pipe in AASHTO Table 12.10.4.3.2a-1 for five discrete pipe diameters, with guidance to interpolate between given values.

Combining the two preceding equations and rearranging terms gives a general form for finding the maximum fill height, H, based on the given criteria:

$$H = \left(\frac{DS_iB_{FE}}{12} - W_F\right)\frac{1}{F_e w B_C}$$

or for filled circular pipe contents of weight 62.4 pcf,

$$H = \left(DB_{FE} - \frac{49}{12}S_i\right)\frac{S_i}{12F_e w B_C}$$

A critical factor in designing concrete pipe involves the selection of standard installation conditions. In the course of this study, it was found that some ambiguities exist in correlating the Iowa DOT standard pipe bedding details to the standard installation types used by the AASHTO Specification. It is therefore recommended that the standard details governing culvert placement be updated to definitively conform to one of these Standard Installation practices, as parameters tied to these conditions have a direct effect on the calculated maximum fill values.

For purposes of this study, the Iowa DOT Class “B” and Class “C” beddings were assumed to be roughly equivalent to the Standard Type 3 and Type 4 Installations, respectively. Both of these standard installations indicate embankment compaction to 95% of maximum density, which is the Iowa DOT standard, along with the possible use of Category III soils within the embankment. The Type 4 Standard Installation does not specify the placement of a particular bedding material, which is consistent with the current construction detail for Class “C” bedding shown in Standard Road Plan DR-101. It should be noted that both Nebraska DOR and South Dakota DOT have specified Standard Installation Type 3 as their typical minimum pipe installation detail.

The table below summarizes the values obtained for maximum fill height from the expression above for Class II, III, IV, and V concrete pipe. While it is recommended that values for a Type 3 Standard Installation be used for the current Class “B” bedding details, and Type 4 values for the current Class “C” bedding details, the computed values are also shown for a Type 2 Standard Installation for comparison.

CONCRETE ROUND PIPE												
Pipe D (in)	Maximum Allowable Fill Height (ft)											
	Class II Pipe			Class III Pipe			Class IV Pipe			Class V Pipe		
	Type 2 Install	Type 3 Install	Type 4 Install	Type 2 Install	Type 3 Install	Type 4 Install	Type 2 Install	Type 3 Install	Type 4 Install	Type 2 Install	Type 3 Install	Type 4 Install
18	14	11	7	19	15	10	29	22	15	43	34	23
24	14	11	7	19	15	10	28	22	15	42	34	23
36	13	10	7	18	14	10	28	22	15	42	33	23
48	13	10	7	18	14	10	27	21	15	41	33	23
60	13	10	7	18	14	10	27	21	15	41	32	23
72	12	9	7	17	13	10	26	20	15	40	31	23
84	12	9	7	17	13	10	26	20	15	40	31	23
96	12	9	6	17	13	9	26	20	15	40	31	23
108	12	9	6	17	13	9	26	20	14	40	31	23

Table 9. Proposed Maximum Allowable Fill Height Values for Circular Concrete Pipe

Minimum cover for concrete pipe is given by AASHTO Article 12.6.6.3, and Table 12.6.6.3-1, as the greater of $B_c/8$ or 1', measured from the top of flexible pavements or unpaved areas, or 9" measured from the bottom of rigid pavements. For the pipe diameters in the table above, therefore, all minimum cover values are 1', when rounded to the nearest whole foot.

In addition to obtaining updated maximum fill height values for circular concrete pipe, Iowa DOT sought to determine whether a separate table of values were necessary to address limits on fill height when using concrete arch pipe.

For concrete arch and concrete elliptical pipe, AASHTO requires the computation of bedding factor based on orientation of the pipe placement, Standard Installation Type, and the assumed projection ratio. Based on these parameters, AASHTO Table 12.10.4.3.2b-1 contains values to be used in the computation of bedding factor for the Type 2 and Type 3 Installations only.

The bedding factor equation for concrete arch and elliptical pipe given in AASHTO Article 12.10.4.3.2 is:

$$B_{FE} = \frac{C_A}{C_N - xq}$$

where:

B_{FE} = bedding factor for installation of arch and elliptical concrete pipe

C_A = constant corresponding to the pipe shape

C_N = parameter related to distribution of vertical load and vertical reaction

x = parameter related to effective area of vertical projection acted on by lateral pressure

q = ratio of total lateral pressure to total vertical fill load

which, for arch and horizontal elliptical pipe is given by:

$$q = 0.23\frac{p}{F_e}\left(1 + 0.35p\frac{B_c}{H}\right)$$

where, as previously defined:

p = projection ratio of the installed pipe

F_e = soil-structure interaction factor, which when using the Indirect Design Method is equal to the vertical arching factor, VAF, found in AASHTO Table 12.10.2.1-3.

B_C = out-to-out horizontal dimension of pipe (ft)

H = height of fill over pipe (ft)

These AASHTO equations for bedding factor and ratio of lateral pressure to vertical load for non-circular concrete pipe can be recognized as being of the same form as Spangler's general equations previously presented.

The parameters given by AASHTO Article 12.10.4.3.2 for determining bedding factor for concrete arch and elliptical pipe are given in the table below.

Pipe Shape	C_A	Installation Type	C_N	Projection Ratio, p	x
Horizontal Elliptical and Arch	1.337	2	0.630	0.9	0.421
				0.7	0.369
		3	0.763	0.5	0.268
				0.3	0.148
Vertical Elliptical	1.021	2	0.516	0.9	0.718
				0.7	0.639
		3	0.615	0.5	0.457
				0.3	0.238

Table 10. Design Values of Parameters in Bedding Factor Equation (Reproduced from Ref. 22)

The limited number of values given in the table above reflects the state of current research into bedding factors for non-circular concrete pipe. A sensitivity analysis using the various parameter values from the table indicated that, in general, larger values of projection ratio produce slightly greater values for allowable fill height.

In computing the fill height numbers shown in the table below, the bedding factor parameters for a projection ratio of 0.7 were used for the Type 2 Installation, and values for a projection ratio of 0.5 were used for the Type 3 Standard Installation. While the case could be made to use the smaller of the projection values for each installation, due to this producing slightly more conservative values for the maximum fill height, a projection value of 0.3 for the Type 3 installation did not seem appropriate given current practice of placing pipe in the field.

CONCRETE ARCH PIPE										
Span (in)	Rise (in)	Round Equivalent Diameter (in)	Maximum Allowable Fill Height (ft)							
			Class II Pipe		Class III Pipe		Class IV Pipe		Class V Pipe	
			Type 2	Type 3	Type 2	Type 3	Type 2	Type 3	Type 2	Type 3
22.00	13.50	18	11	8	15	12	22	17	33	26
28.50	18.00	24	11	9	15	12	22	17	33	26
43.75	26.63	36	11	9	15	12	22	18	34	27
58.50	36.00	48	11	8	15	12	22	18	34	27
73.00	45.00	60	11	8	15	12	22	18	34	27
88.00	54.00	72	11	8	15	11	22	17	34	27
102.00	62.00	84	10	8	15	11	22	17	34	27
122.00	77.25	96	10	8	14	11	22	17	34	26
138.00	87.13	108	10	8	14	11	22	17	34	26

Table 11. Proposed Maximum Allowable Fill Height Values for Concrete Arch Pipe

The values obtained for concrete arch pipe, given the assumptions stated, show that the allowable fill heights for the Type 2 and Type 3 arch installations roughly match the numbers for Type 3 and Type 4 installations of circular concrete pipe. While this may be coincidence or a computational anomaly, comparing values for each pipe shape using Type 3 Standard Installations for both reveals that a separate table of values is likely warranted at this time.

Corrugated Steel Pipe

For the design of corrugated steel pipe, it is our recommendation that Iowa DOT use the procedure described in AASHTO Article 12.7 for metal pipe and pipe arches. The current edition of the AASHTO Specification does not impose a deflection limit on metal pipe, but computations using the Modified Iowa Formula are included below to demonstrate the effect that this limitation would have on the tabulated values.

The AASHTO procedure for the design of metal pipe is described in the following Articles of the AASHTO Specification, again neglecting any live load contribution for the reasons previously stated:

- 12.6.6.3 Minimum Cover
- 12.7.2.2 Thrust

- 12.7.2.3 Wall Resistance
- 12.7.2.4 Resistance to Buckling
- 12.7.2.5 Seam Resistance
- 12.7.2.6 Handling and Installation Requirements

The AASHTO procedure for the design of steel pipe culverts begins with computation of pipe thrust. This is the load that produces ring compression in the pipe section. The factored thrust is given by:

$$T_L = \frac{P_{FD}S}{2}$$

where, neglecting the live load contribution:

T_L = thrust per unit length of wall (kips/ft)

P_{FD} = factored dead load vertical crown pressure (ksf)

S = culvert span (ft)

The factored dead load vertical crown pressure is simply the factored vertical backfill pressure. This is found from:

$$P_{FD} = \gamma_{EV}\gamma_{soil}H$$

where:

γ_{EV} = load factor for vertical earth load, 1.95, from AASHTO Table 3.4.1-2

γ_{soil} = unit weight of backfill (kcf)

H = height of fill over pipe (ft)

The calculated factored thrust is checked against the factored wall resistances based on yielding of the section area, buckling of the corrugations; and for the case of annular pipe, strength of longitudinal seams. The factored axial wall resistance is given by:

$$R_n = \phi F_y A$$

where:

R_n = factored axial wall resistance per unit length of wall (kips/ft)

ϕ = resistance factor, 1.00, for both minimum area and buckling from AASHTO Table 12.5.5-1

F_y = minimum yield strength of the pipe material (ksi)

A = area of the pipe wall per unit length of pipe (in^2)

Combining equations and rearranging terms gives an expression for maximum fill height of:

$$H = \frac{2\phi F_y A}{1.95\gamma_{soil} S}$$

The same resistance formula is used by the AASHTO Specification for both minimum area and buckling checks. Due to the fact that the buckling check uses either F_y or F_{cr}, which is a critical buckling stress less than F_y, the minimum area check for the pipe sections commonly used by Iowa DOT is somewhat redundant. The critical buckling stress is computed according to AASHTO Article 12.7.2.4, with the metal pipe properties given below (See Table 7.1 from Ref. 16).

F_y = 33 ksi, yield strength of the pipe material

F_u = 45 ksi, tensile strength of the pipe material

E_m = 30,000 ksi, elastic modulus of the pipe material

The maximum fill height values are given in the tables below for the various configurations of steel pipe used by Iowa DOT. The tables contain both a computed value based on buckling of the pipe wall, and a value based on the 5% deflection criteria.

For determining the fill height limitation based on deflection, the Modified Iowa Formula was utilized. In terms of the maximum fill height, the expression used was:

$$H = 7.2\left(\frac{EI + 0.061E'r^3}{D_L K w_s r^3}\right)$$

where:

H = fill height (feet)

E = modulus of elasticity of the pipe material (psi)

I = moment of inertia per unit length of the pipe wall (in^4/in)

r = mean radius of the pipe (in)

w_s = unit weight of backfill material (pcf)

E' = = modulus of soil reaction (psi)

D_L = deflection lag factor, dependent on E'

K = bedding constant, assumed to be 0.10.

For the computation of limiting values of fill height for metal pipes based on a deflection criteria, reasonably conservative values for E' and D_L were assumed. A modulus of soil reaction of 400 psi was assumed, corresponding to moderately-compacted fine-grained soils. Similarly, a deflection lag factor of 1.75 was assumed. See Section 16.3 of Ref. 17 for background on these assumptions.

As part of the AASHTO design procedure, a flexibility check for handling stability during construction is to be done according to Article 12.7.2.6. The tabulated values shown below have been checked for flexibility per this requirement.

Minimum cover for metal pipe is given by AASHTO Article 12.6.6.3, and Table 12.6.6.3-1, as the greater of S/8 or 12", where S is the pipe span in inches. The limiting minimum pipe cover values are also listed in these tables.

Using the assumptions previously stated, the minimum cover and maximum allowable fill heights for the section properties typically used by Iowa DOT for circular steel pipe are shown below. Table 12, Table 13, and Table 14 contain recommended design values for 2 ⅔" x ½", 3" x 1", and 5" x 1" corrugations, respectively; and values are given for both deflection control and wall stress control.

STEEL ROUND PIPE – 2 ⅔" x ½" Corrugations											
Pipe D (in)	Min Cover Above Pipe (in)	Maximum Allowable Fill Height (ft)									
		16 Gage (0.064")		14 Gage (0.079")		12 Gage (0.109")		10 Gage (0.138")		8 Gage (0.168")	
		Deflect	Buckling	Deflect	Buckling	Deflect	Buckling	Deflect	Buckling	Deflect	Buckling
12	12	98	219	122	273						
15	12	54	175	67	218						
18	12	35	146	42	182	57	255				
24	12	20	109	23	137	29	191				
30	12			16	109	19	153	22	197		
36	12			13	91	14	127	16	164		
42	12					12	109	13	141	15	172
48	12					11	96	12	123	13	150
54	12					10	85	11	109	11	134
60	12							10	98	11	120
66	12							10	89	10	109
72	12							9	82	10	100
78	12									9	90
84	12									9	78

Table 12. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Round Steel Pipe (2 ⅔" x ½" Corrugations)

STEEL ROUND PIPE – 3” x 1” Corrugations											
Pipe D (in)	Min Cover Above Pipe (in)	Maximum Allowable Fill Height (ft)									
		16 Gage (0.064”)		14 Gage (0.079”)		12 Gage (0.109”)		10 Gage (0.138”)		8 Gage (0.168”)	
		Deflect	Buckling	Deflect	Buckling	Deflect	Buckling	Deflect	Buckling	Deflect	Buckling
36	12	24	84	28	105	36	147				
42	12	18	72	20	90	26	126				
48	12	15	63	16	78	20	110				
54	12	13	56	14	70	16	98				
60	12	12	50	13	63	14	88				
66	12	11	46	11	57	13	80				
72	12	10	42	11	52	12	73				
78	12	10	39	10	48	11	68				
84	12			10	45	11	63	11	81		
90	12					10	59	11	76	11	92
96	12					10	55	10	71	11	87
102	13							10	67	10	82
108	14							10	63	10	77
114	15							9	60	10	73
120	15							9	57	10	69

Table 13. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Round Steel Pipe (3” x 1” Corrugations)

The existing tabular data for maximum fill height shown on Standard Road Plan DR-104 uses identical values for both 3” x 1” and 5” x 1” corrugations. From a review of the literature, this likely is a reflection of past practice where manufacturers’ data was presented for the lighter 5” x 1” section, and values were arbitrarily to be increased by 12% for the heavier 3” x 1” pipes. As shown in the tables below, there are significant value differences between the two pipe wall sections, due to this difference in pipe wall area. In the event these tables are to remain combined, it is recommended that the more conservative values from the table for the 5” x 1” corrugations continue to be used.

STEEL ROUND PIPE – 5” x 1” Corrugations											
Pipe D (in)	Min Cover Above Pipe (in)	Maximum Allowable Fill Height (ft)									
		16 Gage (0.064”)		14 Gage (0.079”)		12 Gage (0.109”)		10 Gage (0.138”)		8 Gage (0.168”)	
		Deflect	Buckling	Deflect	Buckling	Deflect	Buckling	Deflect	Buckling	Deflect	Buckling
36	12	24	75	28	93	36	128				
42	12	18	64	21	80	26	110				
48	12	15	56	17	70	20	96				
54	12	13	50	14	62	17	85				
60	12	12	45	13	56	14	77				
66	12	11	41	12	51	13	70				
72	12	10	37	11	47	12	64				
78	12	10	34	10	43	11	59				
84	12			10	40	11	55	11	72		
90	12					10	51	11	67	11	82
96	12					10	48	10	63	11	77
102	13							10	59	10	73
108	14							10	56	10	69
114	15							9	53	10	65
120	15							9	50	10	62

Table 14. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Round Steel Pipe (5” x 1” Corrugations)

Using the same assumptions for metal pipe, the minimum cover and maximum allowable fill heights for circular structural steel pipe with 6” x 2” corrugations are shown below. Table 15 contains recommended design values based on the 5% deflection criteria, while Table 16 contains values based on limiting compressive wall stress.

STEEL ROUND PIPE – 6” x 2” Corrugations								
Pipe D (in)	Min Pipe Cover (in)	Maximum Allowable Fill Height (ft) For 5% Deflection						
		12 Gage (0.110”)	10 Gage (0.140”)	8 Gage (0.170”)	7 Gage (0.188”)	5 Gage (0.218”)	3 Gage (0.249”)	1 Gage (0.280”)
60	12	31	38	45				
66	12	26	31	36				
72	12	22	26	30				
78	12	19	22	25	27			
84	12	17	19	22	23			
90	12	15	17	19	21			
96	12	14	16	17	18			
102	13	13	14	16	17			
108	14	12	13	15	15			
114	15	12	13	14	14	15		
120	15	11	12	13	14	14		
126	16	11	12	12	13	14		
132	17	11	11	12	12	13		
138	18	10	11	11	12	12		
144	18	10	11	11	11	12		
150	19	10	10	11	11	11	12	
156	20	10	10	10	11	11	12	
162	21	10	10	10	10	11	11	12
168	21	9	10	10	10	11	11	11
174	22	9	10	10	10	10	11	11
180	23	9	9	10	10	10	10	11

Table 15. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Round Structural Steel Pipe for 5% Maximum Deflection (6” x 2” Corrugations)

STRUCTURAL STEEL ROUND PIPE – 6” x 2” Corrugations								
Pipe D (in)	Min Pipe Cover (in)	Maximum Allowable Fill Height (ft) For Limiting Wall Stress						
		12 Gage (0.110”)	10 Gage (0.140”)	8 Gage (0.170”)	7 Gage (0.188”)	5 Gage (0.218”)	3 Gage (0.249”)	1 Gage (0.280”)
60	12	88	113	138				
66	12	80	103	126				
72	12	73	94	115				
78	12	68	87	106	119			
84	12	63	81	99	110			
90	12	59	75	92	103			
96	12	55	71	86	97			
102	13	52	66	81	91			
108	14	49	63	77	86			
114	15	46	59	73	81	95		
120	15	44	56	69	77	90		
126	16	42	54	66	74	86		
132	17	40	51	63	70	82		
138	18	38	49	60	67	78		
144	18	37	47	58	64	75		
150	19	35	45	55	62	72	82	
156	20	34	43	53	59	69	79	
162	21	33	42	51	57	67	76	86
168	21	31	40	49	55	64	74	83
174	22	30	39	48	53	62	71	80
180	23	29	38	46	52	60	69	77

Table 16. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Round Structural Steel Pipe for Limiting Wall Stress (6” x 2” Corrugations)

Like the design of circular metal pipe, the design of metal arch pipe is also governed by AASHTO Article 12.7. The primary design control is again the pipe wall stiffness, and its ability to resist ring compression without yielding or buckling.

The AISI Design methodology, and much of the available manufacturers’ literature, contains additional limitations on fill height for arch pipe based on the corner radius of the pipe section. Because of the action of the arch section, vertical loads carried by the pipe crown have been shown to concentrate in this region. Using an arbitrary limit on the resisting soil pressure at the base of the arch, by assuming the thrust load was carried entirely by the soil adjacent to the corner radius, maximum fill heights were computed. These values are typically noted with the allowable soil pressure, with guidance to increase the value in proportion to the actual allowable soil bearing specific to the site.

The existing tables for metal arch pipe given on Standard Road Plan DR-104 show the minimum base radius for the pipe sections. This fact would seem to indicate the current values have been obtained using a limit on corner bearing. The 11th Edition of the AASHTO ASD Bridge Specification did impose a 4 ksf (2 tons/sq ft) bearing limit to be used when computing maximum fill heights (See Article 1.8.8, Ref. 9). This value used as a limiting value under the AISI design method. The current edition of the AASHTO LRFD Specification does not apply this limitation; however, Article 12.6.3.2 does recognize the soil stress concentration that results at the base of an arch section by indicating that the soil must be able to resist the computed pipe thrust.

The tables below for maximum fill height for metal arch pipe show both values for comparative purposes, heights allowed based on limiting wall stress and the 4 ksf bearing limit. It should be noted that the factored thrust is used to check the bearing, and that the 1.95 load factor applied to the vertical soil load is comparable to the 2.0 factor of safety used by older editions of the AASHTO ASD to check the same condition.

STEEL ARCH PIPE – 2 ⅔" x ½" Corrugations													
Span (in)	Rise (in)	Equiv Round Pipe D	Min Cover (in)	Maximum Allowable Fill Height (ft)									
				16 Gage (0.064")		14 Gage (0.079")		12 Gage (0.109")		10 Gage (0.138")		8 Gage (0.168")	
				Wall	Soil	Wall	Soil	Wall	Soil	Wall	Soil	Wall	Soil
17	13	12	12	154	7	193	7						
21	15	15	12	125	7	156	7						
24	18	18	12	109	7	137	7						
28	20	24	12	94	7	117	7						
35	24	30	12	75	7	94	7						
42	29	36	12	62	7	78	7						
49	33	42	12					94	7	120	7	147	7
57	38	48	12					81	7	104	7	127	7
64	43	54	12					72	7	92	7	113	7
71	47	60	12							83	7	102	7
77	52	66	12									92	7
83	57	72	12									80	7

Table 17. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Steel Arch Pipe (2 ⅔" x ½" Corrugations)

STEEL ARCH PIPE – 3” x 1” Corrugations											
Span (in)	Rise (in)	Equiv Round Pipe D	Min Cover (in)	Maximum Allowable Fill Height (ft)							
				16 Gage (0.064”)		14 Gage (0.079”)		12 Gage (0.109”)		10 Gage (0.138”)	
				Wall	Soil	Wall	Soil	Wall	Soil	Wall	Soil
60	46	54	12	50	11	63	11				
66	51	60	12	46	11	57	11				
73	55	66	12	41	11	52	11				
81	59	72	12			47	9	65	9		
87	63	78	12			43	9	61	9		
95	67	84	12			40	9	56	9		
103	71	90	13					51	9		
112	75	96	14					47	8		
117	79	102	15					45	9		
128	83	108	16							53	8

Table 18. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Steel Arch Pipe (3” x 1” Corrugations)

STEEL ARCH PIPE – 5” x 1” Corrugations											
Span (in)	Rise (in)	Equiv Round Pipe D	Min Cover (in)	Maximum Allowable Fill Height (ft)							
				16 Gage (0.064”)		14 Gage (0.079”)		12 Gage (0.109”)		10 Gage (0.138”)	
				Wall	Soil	Wall	Soil	Wall	Soil	Wall	Soil
60	46	54	12	45	11	56	11				
66	51	60	12	41	11	51	11				
73	55	66	12	37	11	46	11				
81	59	72	12			41	9	57	9		
87	63	78	12			39	9	53	9		
95	67	84	12			35	9	48	9		
103	71	90	13					45	9		
112	75	96	14					41	8		
117	79	102	15					39	9		
128	83	108	16							47	8

Table 19. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Steel Arch Pipe (5” x 1” Corrugations)

STRUCTURAL STEEL ARCH PIPE – 6" x 2" Corrugations											
Span (in)	Rise (in)	Equiv Round Pipe D	Min Cover (in)	Maximum Allowable Fill Height (ft)							
				12 Gage (0.110")		10 Gage (0.140")		8 Gage (0.170")		7 Gage (0.188")	
				Wall	Soil	Wall	Soil	Wall	Soil	Wall	Soil
73	55	66	12	72	8						
84	61	72	12	63	7						
95	67	84	12	55	6						
106	73	90	14	50	6						
117	79	96	15	45	5						
131	85	108	17	40	5						
142	91	114	18	37	4						
154	100	120	20	34	4						
159	112	132	20	33	7						
170	118	144	22	31	6						
184	124	150	23			37	6				
195	130	156	25			35	5				
206	136	168	26			33	5				
217	142	180	28					38	5		
231	148	186	29					36	5		
239	154	192	30					35	4		
247	158	198	31							38	4

Table 20. Proposed Minimum Cover and Maximum Allowable Fill Height Values for Structural Steel Arch Pipe (6" x 2" Corrugations)

As can be seen from the tables above, allowable maximum fill heights based on the 4 ksf base bearing match reasonably well with the values currently used in Standard Road Plan DR-104 for metal arch pipe. This value is highly conservative, as recognized by AASHTO in removing the limitation from more recent editions, as the vertical pipe load is not carried in its entirety by the supporting soil under the corner radius. For this reason, and in compliance with the current AASHTO Specification, it is our recommendation that that values based on limiting wall stress be used for design with notation added that the corner pressure needs to be checked per Article 12.6.3.2.

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