CHAPTER 4

LOADS AND SUPPORTING STRENGTHS

The design procedure for the selection of pipe strength requires:

I . Determination of Earth Load
2. Determination of Live Load
3. Selection of Bedding
4. Determination of Bedding Factor
5. Application of Factor of Safety
6. Selection of Pipe Strength

TYPES OF INSTALLATIONS

The earth load transmitted to a pipe is largely dependent on the type of installation, and the three common types are Trench, Positive Projecting Embankment, and Negative Projecting Embankment. Pipe are also installed by jacking or tunneling methods where deep installations are necessary or where conventional open excavation and backfill methods may not be feasible. The essential features of each of these installations are shown in Illustration 4.1.

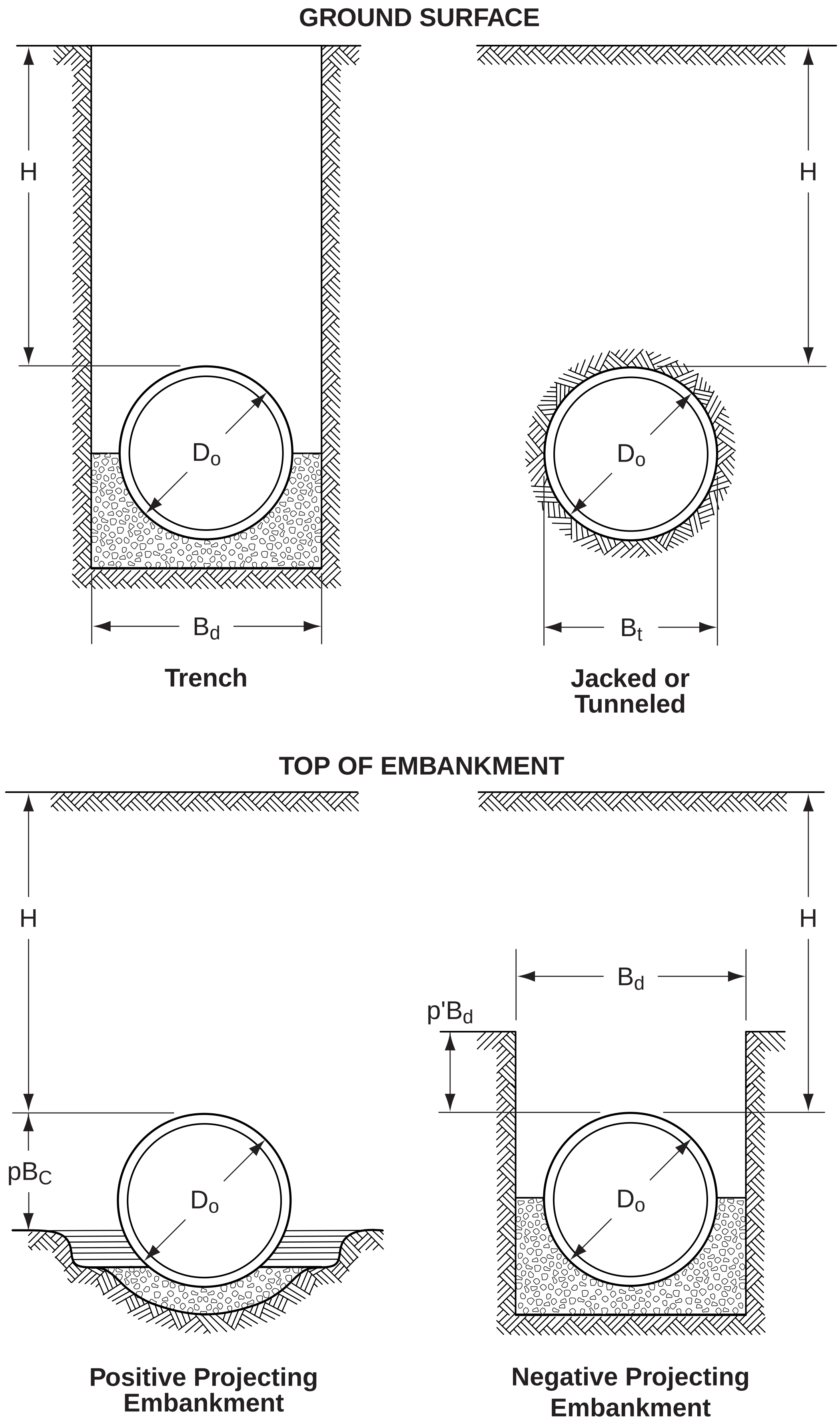
Trench. This type of installation is normally used in the construction of sewers, drains and water mains. The pipe is installed in a relatively narrow trench excavated in undisturbed soil and then covered with backfill extending to the ground surface.

Positive Projecting Embankment. This type of installation is normally used when the culvert is installed in a relatively flat stream bed or drainage path. The pipe is installed on the original ground or compacted fill and then covered by an earth fill or embankment.

Negative Projecting Embankment. This type of installation is normally used when the culvert is installed in a relatively narrow and deep stream bed or drainage path. The pipe is installed in a shallow trench of such depth that the top of the pipe is below the natural ground surface or compacted fill and then covered with an earth fill or embankment which extends above the original ground level.

Jacked or Tunneled. This type of installation is used where surface conditions make it difficult to install the pipe by conventional open excavation and backfill methods, or where it is necessary to install the pipe under an existing embankment.

Illustration 4.1 Essential Features of Types of Installations



Background

The classic theory of earth loads on buried concrete pipe published in 1930 by A. Marston was developed for trench and embankment conditions.

In later work published in 1933, M. G. Spangler presented three bedding configurations and the concept of a bedding factor to relate the supporting strength of buried pipe to the strength obtained in a three-edge bearing test.

Spangler's theory proposed that the bedding factor for a particular pipeline and, consequently, the supporting strength of the buried pipe, is dependent on two installation characteristics:

- Width and quality of contact between the pipe and bedding.
- Magnitude of lateral pressure and the portion of the vertical height of the pipe over which it acts.

For the embankment condition, Spangler developed a general equation for the bedding factor, which partially included the effects of lateral pressure. For the trench condition, Spangler established conservative fixed bedding factors, which neglected the effects of lateral pressure, for each of the three beddings. This separate development of bedding factors for trench and embankment conditions resulted in the belief that lateral pressure becomes effective only at transition, or greater, trench widths. Such an assumption is not compatible with current engineering concepts and construction methods. It is reasonable to expect some lateral pressure to be effective at trench widths less than transition widths. Although conservative designs based on the work of Marston and Spangler have been developed and installed successfully for years, the design concepts have their limitations when applied to real world installations.

The limitations include:

- Loads considered acting only at the top of the pipe.
- Axial thrust not considered.
- Bedding width of test installations less than width designated in his bedding configurations.
- Standard beddings developed to fit assumed theories for soil support rather than ease of and methods of construction.
- Bedding materials and compaction levels not adequately defined.

This section discusses the Standard Installations and the appropriate indirect design procedures to be used with them. The Standard Installations are the most recent beddings developed by ACPA to allow the engineer to take into consideration modern installation techniques when designing concrete pipe. For more information on design using the Marston/Spangler beddings, see Appendix B.

Introduction

In 1970, ACPA began a long-range research program on the interaction of buried concrete pipe and soil. The research resulted in the comprehensive finite element computer program SPIDA, Soil-Pipe Interaction Design and Analysis, for the direct design of buried concrete pipe.

Since the early 1980's, SPIDA has been used for a variety of studies, including development of four new Standard Installations, and a simplified microcomputer design program, SIDD, Standard Installations Direct Design.

The procedure presented here replaces the historical B, C, and D beddings used in the indirect design method and found in the appendix of this manual, with the four new Standard Installations, and presents a state-of-the-art method for determination of bedding factors for the Standard Installations. Pipe and installation terminology as used in the Installations, SIDD, and this procedure is defined in Illustration 4.2.

Illustration 4.2 Pipe/Installation Terminology

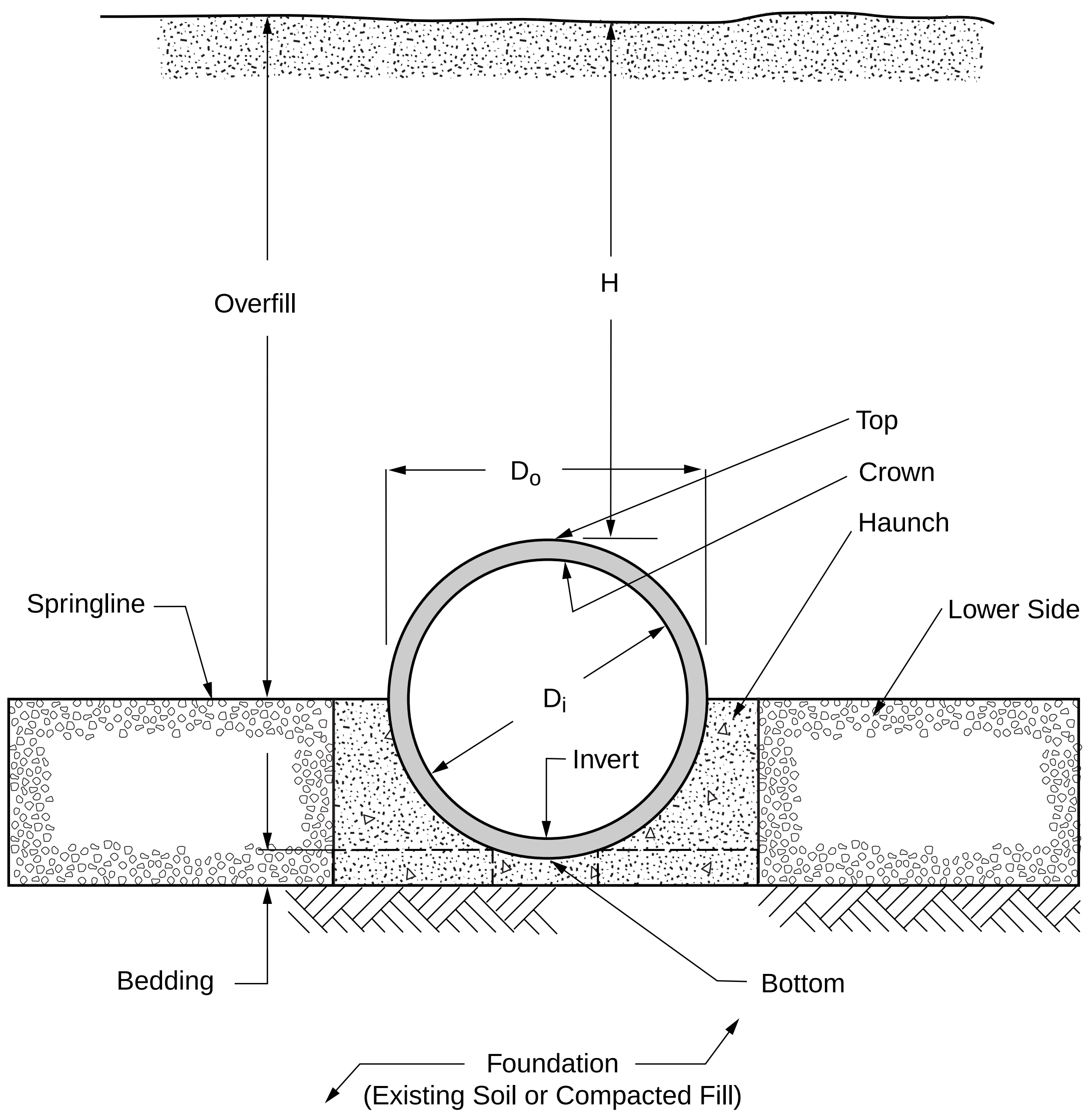
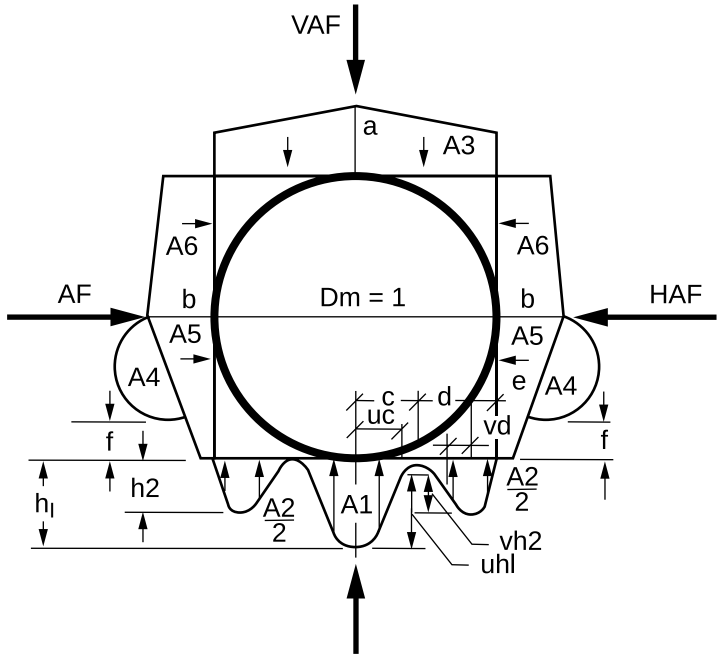


Illustration 4.3 Arching Coefficients and Heger Earth Pressure Distributions



Installation Type	VAF	HAF	A1	A2	A3	A4	A5	A6	a	b	c	e	f	u	v
1	1.35	0.45	0.62	0.73	1.35	0.19	0.08	0.18	1.40	0.40	0.18	0.08	0.05	0.80	0.80
2	1.40	0.40	0.85	0.55	1.40	0.15	0.08	0.17	1.45	0.40	0.19	0.10	0.05	0.82	0.70
3	1.40	0.37	1.05	0.35	1.40	0.10	0.10	0.17	1.45	0.36	0.20	0.12	0.05	0.85	0.60
4	1.45	0.30	1.45	0.00	1.45	0.00	0.11	0.19	1.45	0.30	0.25	0.00	-	0.90	-

Notes:

1. *VAF and HAF are vertical and horizontal arching factors. These coefficients represent non-dimensional total vertical and horizontal loads on the pipe, respectively. The actual total vertical and horizontal loads are (VAF) X (PL) and (HAF) X (PL), respectively, where PL is the prism load.*
2. *PL, the prism load, is the weight of the column of earth cover over the pipe outside diameter and is calculated as:*

$$PL = w\left[\left(H + \frac{D_0\,(4 - \pi)}{96}\right)\right]\frac{D_0}{12}$$

3. *Coefficients A1 through A6 represent the integration of non-dimensional vertical and horizontal components of soil pressure under the indicated portions of the component pressure diagrams (i.e. the area under the component pressure diagrams). The pressures are assumed to vary either parabolically or linearly, as shown, with the non-dimensional magnitudes at governing points represented by h1, h2, uh1, vh2, a and b. Non-dimensional horizontal and vertical dimensions of component pressure regions are defined by c, d, e, vc, vd, and f coefficients.*

4. *d is calculated as (0.5-c-e).*
   h1 is calculated as (1.5A1) / (c) (1+u).
   h2 is calculated as (1.5A2) / [(d) (1+v) + (2e)]

Four Standard Installations

Through consultations with engineers and contractors, and with the results of numerous SPIDA parameter studies, four new Standard Installations were developed and are presented in Illustrations 4.4 and 4.6. The SPIDA studies were conducted for positive projection embankment conditions, which are the worst-case vertical load conditions for pipe, and which provide conservative results for other embankment and trench conditions.

The parameter studies confirmed ideas postulated from past experience and proved the following concepts:

- Loosely placed, uncompacted bedding directly under the invert of the pipe significantly reduces stresses in the 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 pavement structures.
- Installation materials and compaction levels below the springline have a significant effect on pipe structural requirements.

The four Standard Installations provide an optimum range of soil-pipe interaction characteristics. For the relatively high quality materials and high compaction effort of a Type 1 Installation, a lower strength pipe is required. Conversely, a Type 4 Installation requires a higher strength pipe, because it was developed for conditions of little or no control over materials or compaction.

Generic soil types are designated in Illustration 4.4 and Illustration 4.6. The Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO) soil classifications equivalent to the generic soil types in the Standard Installations are presented in Illustration 4.8

Load Pressures

SPIDA was programmed with the Standard Installations and many design runs were made. An evaluation of the output of the designs by Dr. Frank J. Heger produced a load pressure diagram significantly different than proposed by previous theories. See Illustration 4.3. This difference is particularly significant under the pipe in the lower haunch area and is due in part to the assumption of the existence of partial voids adjacent to the pipe wall in this area. SIDD uses this pressure data to determine moments, thrusts, and shears in the pipe wall, and then uses the ACPA limit states design method to determine the required reinforcement areas to handle the pipe wall stresses. Using this method, each criteria that may limit or govern the design is considered separately in the evaluation of overall design requirements. SIDD, which is based on the four

Standard Installations, is a stand-alone program developed by the American Concrete Pipe Association.

The Federal Highway Administration, FHWA, developed a microcomputer program, PIPECAR, for the direct design of concrete pipe prior to the development of SIDD. PIPECAR determines moment, thrust, and shear coefficients from either of two systems, a radial pressure system developed by Olander in 1950 and a uniform pressure system developed by Paris in the 1920's, and also uses the ACPA limit states design method to determine the required reinforcement areas to handle the pipe wall stresses. The SIDD system has been incorporated into PIPECAR as a state-of-the-art enhancement.

Illustration 4.4 Standard Embankment Installations

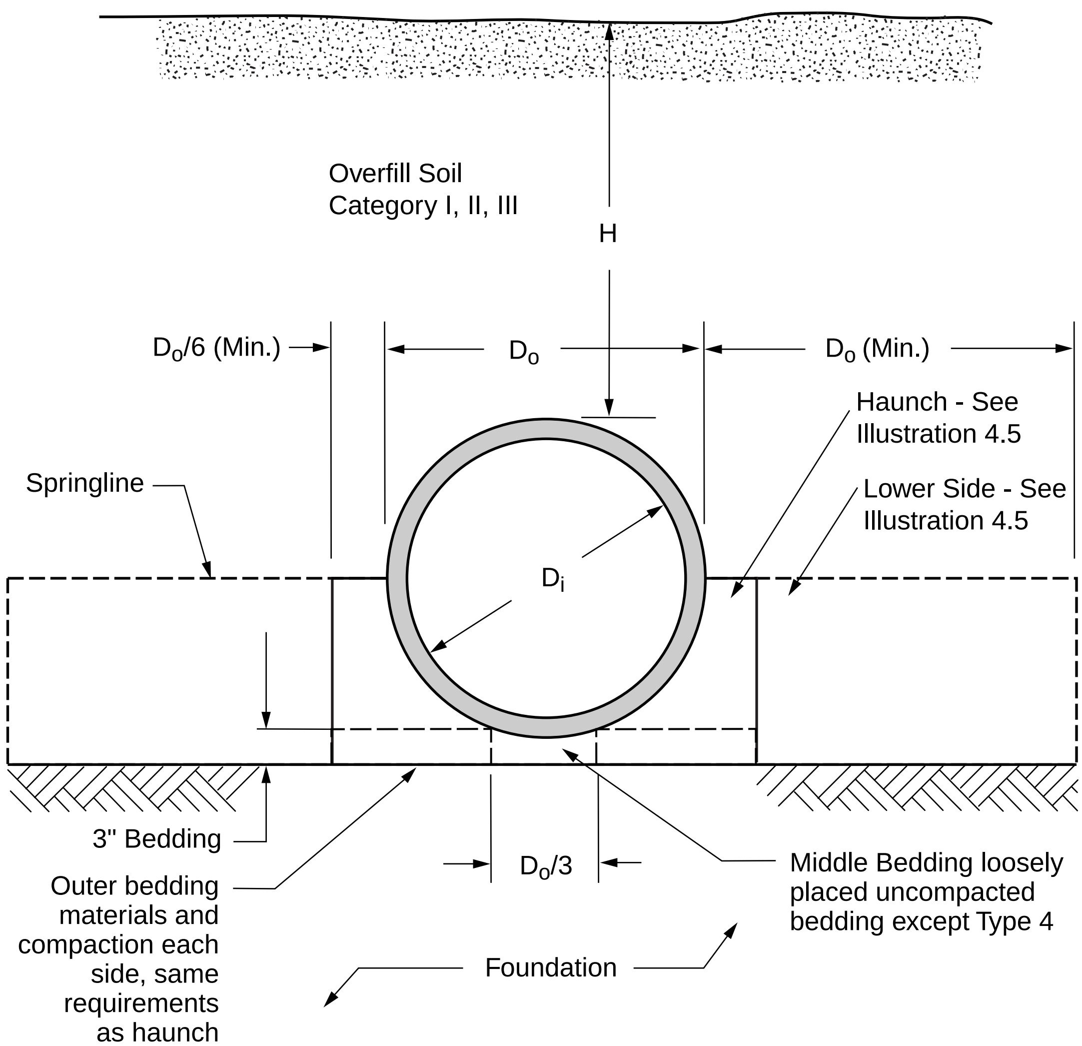


Illustration 4.5 Standard Embankment Installations Soil and Minimum Compaction Requirements

Installation Type	Bedding Thickness	Haunch and Outer Bedding	Lower Side
Type 1	D_o/24 minimum, not less than 75 mm (3"). If rock foundation, use D_o/12 minimum, not less than 150 mm (6").	95% Category I	90% Category I, 95% Category II, or 100% Category III
Type 2	D_o/24 minimum, not less than 75 mm (3"). If rock foundation, use D_o/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	D_o/24 minimum, not less than 75 mm (3"). If rock foundation, use D_o/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 D_o/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 1 soil material with a minimum standard Proctor compaction of 95%. See Illustration 4.8 for equivalent modified Proctor values.*
2. *Soil in the outer bedding, haunch, and lower side zones, except within D_o/3 from the pipe springline, shall be compacted to at least the same compaction as the majority of soil in the overfill zone.*
3. ***Subtrenches***
   - 3.1 *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 0.3 m (1') below the bottom of the pavement base material.*
   - 3.2 *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.*
   - 3.3 *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.*

The SPIDA design runs with the Standard Installations were made with medium compaction of the bedding under the middle-third of the pipe, and with some compaction of the overfill above the springline of the pipe. This middle-third area under the pipe in the Standard Installations has been designated as loosely placed, uncompacted material. The intent is to maintain a slightly yielding bedding under the middle-third of the pipe so that the pipe may settle slightly into the bedding and achieve improved load distribution. Compactive efforts in the middle-third of the bedding with mechanical compactors is undesirable, and could produce a hard flat surface, which would result in highly concentrated stresses in the pipe invert similar to those experienced in the three-edge bearing test. The most desirable construction sequence is to place the bedding to grade; install the pipe to grade; compact the bedding outside of the middle-third of the pipe; and then place and compact the haunch area up to the springline of the pipe. The bedding outside the middle-third of the pipe may be compacted prior to placing the pipe.

As indicated in Illustrations 4.4 and 4.6, when the design includes surface loads, the overfill and lower side areas should be compacted as required to support the surface load. With no surface loads or surface structure requirements, these areas need not be compacted.

Illustration 4.6 Standard Trench Installations

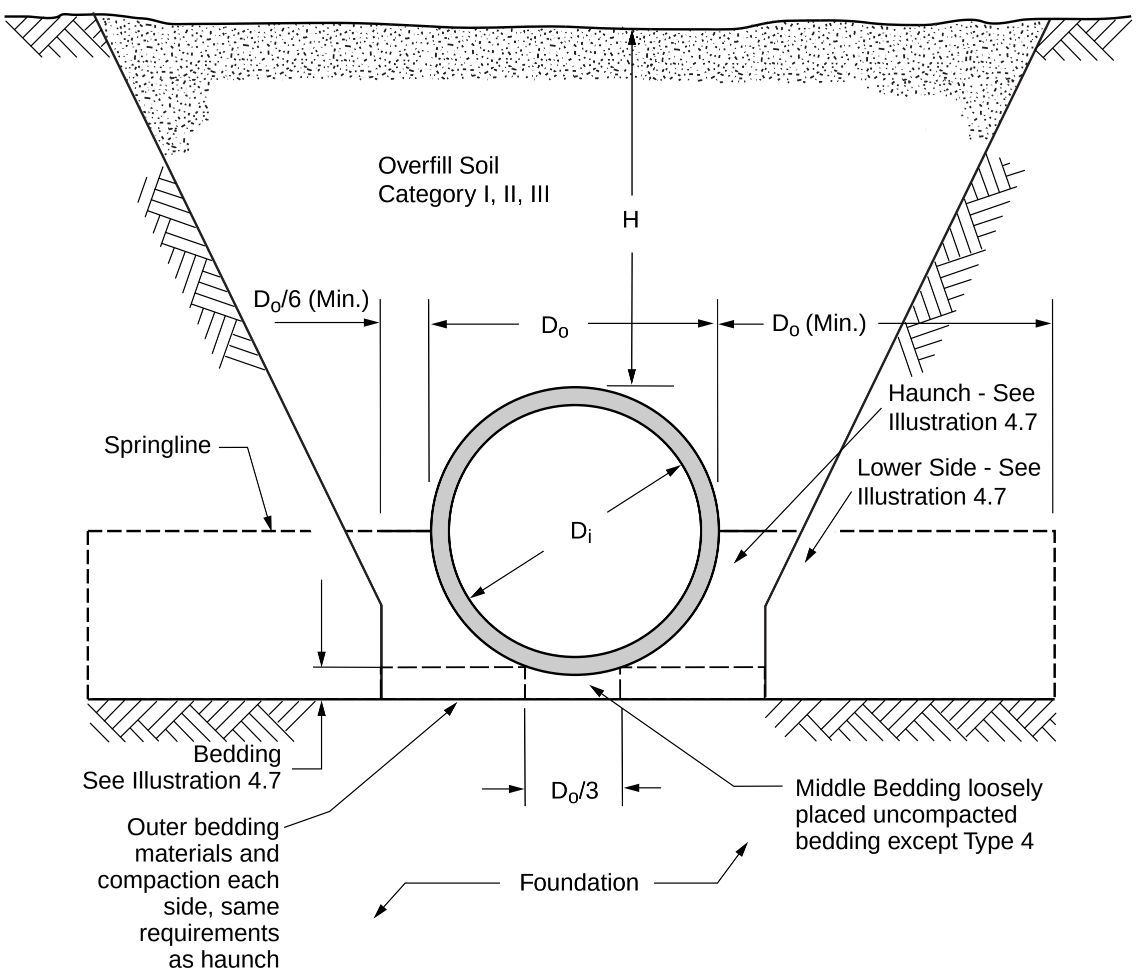


Illustration 4.7 Standard Trench Installations Soil and Minimum Compaction Requirements

Installation Type	Bedding Thickness	Haunch and Outer Bedding	Lower Side
Type 1	D_o/24 minimum, not less than 75 mm (3"). If rock foundation, use D_o/12 minimum, not less than 150 mm (6").	95% Category I	90% Category I, 95% Category II, or 100% Category III
Type 2	D_o/24 minimum, not less than 75 mm (3"). If rock foundation, use D_o/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	D_o/24 minimum, not less than 75 mm (3"). If rock foundation, use D_o/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 D_o/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 4.8 for equivalent modified Proctor values.*
2. *The trench 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 0.3 m (1') below the bottom of the pavement base material.*
3. *Soil in bedding and haunch zones shall be compacted to at least the same compaction as specified for the majority of soil in the backfill zone.*
4. *The trench 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.*

Illustration 4.8 Equivalent USCS and AASHTO Soil Classifications for SIDD Soil Designations

	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

Selection of Standard Installation

The selection of a Standard Installation for a project should be based on an evaluation of the quality of construction and inspection anticipated. A Type 1 Standard Installation requires the highest construction quality and degree of inspection. Required construction quality is reduced for a Type 2 Standard Installation, and reduced further for a Type 3 Standard Installation. A Type 4 Standard Installation requires virtually no construction or quality inspection. Consequently, a Type 4 Standard Installation will require a higher strength pipe, and a Type I Standard Installation will require a lower strength pipe for the same depth of installation.

DETERMINATION OF EARTH LOAD

Embankment Soil Load.

Concrete pipe can be installed in either an embankment or trench condition as discussed previously. The type of installation has a significant effect on the loads carried by the rigid pipe. Although narrow trench installations are most typical, there are many cases where the pipe is installed in a positive projecting embankment condition, or a trench with a width significant enough that it should be considered a positive projecting embankment condition. In this condition the soil along side the pipe will settle more than the soil above the rigid pipe structure, thereby imposing additional load to the prism of soil directly above the pipe. With the Standard Installations, this additional load is accounted for by using a Vertical Arching Factor. This factor is multiplied by the prism load (weight of soil directly above the pipe) to give the total load of soil on the pipe. Unlike the previous design method used for the Marston/Spangler beddings there is no need to assume a projection or settlement ratio. The Vertical Arching Factors for the Standard Installations as well as the equation for soil prism load are as shown in Illustration 4.3 and repeated here.

Prism Load

$$PL = w\left[H + \frac{D_o(4 - \pi)}{8}\right] D_o \qquad (4)$$

w = soil unit weight, (lbs/ft^3)
H = height of fill, (ft)
D_o = outside diameter, (ft)

Vertical Arching Factor (VAF)

Type 1	VAF = 1.35
Type 2	VAF = 1.40
Type 3	VAF = 1.40
Type 4	VAF = 1.45

Trench Soil Load

The backfill load on pipe installed in a trench condition is computed by the equation:

$$W_d = C_d w B_d^2 + \frac{D_o^2(4 - \pi)}{8} w \qquad (5)$$

C_d is further defined as:

$$C_d = \frac{1 - e^{-2K\mu' \frac{H}{B_d}}}{2K\mu'} \qquad (6)$$

Where: B_d = width of trench, (ft)
K = ratio of active lateral unit pressure to vertical unit pressure
μ' = tan ø', coefficient of friction between fill material and sides of trench

The value of C_d can be calculated using equation 6 above, or read from Figure 214.

Typical values of Ku' are:

$K\mu'$ = .1924 Max. for granular materials without cohesion
$K\mu'$ = .165 Max for sand and gravel
$K\mu'$ = .150 Max. for saturated top soil
$K\mu'$ = .130 Max. for ordinary clay
$K\mu'$ = .110 Max for saturated clay

In narrow or moderate trench width conditions, the resulting earth load is equal to the weight of the soil within the trench minus the shearing (frictional) forces on the sides of the trench. Since the new installed backfill material will settle more than the existing soil on the sides of the trench, the friction along the trench walls will relieve the pipe of some of its soil burden. The Vertical Arching Factors in this case will be less than those used for embankment design.

As trench width increases, the reduction in load from the frictional forces is offset by the increase in soil weight within the trench. As the trench width increases it starts to behave like an embankment, where the soil on the side of the pipe settles more than the soil above the pipe. Eventually, the embankment condition is reached when the trench walls are too far away from the pipe to help support the soil immediately adjacent to it. The transition width is the width of a trench at a particular depth where the trench load equals the embankment load. Once transition width is reached, there is no longer any benefit from frictional forces along the wall of the trench. Any pipe installed in a trench width equal to or greater than transition width should be designed for the embankment condition.

Tables 13 through 39 are based on equation (4) and list the transition widths for the four types of beddings with various heights of backfill.

Negative Projection Embankment Soil Load

The fill load on a pipe installed in a negative projecting embankment condition is computed by the equation:

$$W_d = C_n w B_d^2 \qquad (7)$$

The load coefficient C_n is further defined as:

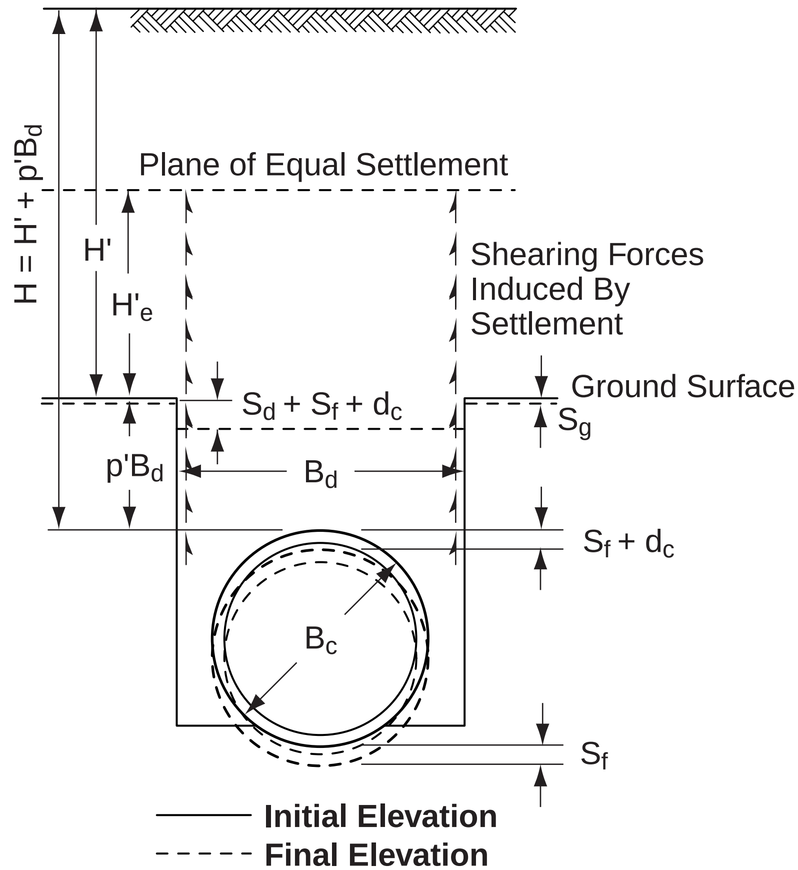
$$C_n = \frac{e^{-2K\mu'\frac{H}{B_d}} - 1}{-2K\mu'} \quad \text{when } H \leq H_e \qquad (8)$$

and

$$C_n = \frac{e^{-2K\mu'\frac{H_e}{B_d}} - 1}{-2K\mu'} + \left(\frac{H}{B_d} - \frac{H_e}{B_d}\right) e^{-2K\mu'\frac{H_e}{B_d}} \quad \text{when } H > H_e \qquad (9)$$

The settlements which influence loads on negative projecting embankment installations are shown in Illustration 4.9.

Illustration 4.9 Settlements Which Influence Loads Negative Projection Embankment Installation



It is necessary to define the settlement ratio for these installations. Equating the deflection of the pipe and the total settlement of the prism of fill above the pipe to the settlement of the adjacent soil:

$$r_{sd} = \frac{S_g - (S_d + S_f + d_c)}{S_d} \qquad (10)$$

Recommended settlement ratio design values are listed in Table 40. The projection ratio (p') for this type of installation is the distance from the top of the pipe to the surface of the natural ground or compacted fill at the time of installation divided by the width of the trench. Where the ground surface is sloping, the average vertical distance from the top of the pipe to the original ground should be used in determining the projection ratio (p'). Figures 194 through 213 present fill loads in pounds per linear foot for circular pipe based on projection ratios of 0.5, 1.0, 1.5, 2.0 and settlement ratios of 0, -0.1, -0.3, -0.5 and -1.0. The dashed H = $p'B_d$ line represents the limiting condition where the height of fill is at the same elevation as the natural ground surface. The dashed H = H_e line represents the condition where the height of the plane of equal settlement (H_e) is equal to the height of fill (H).

Jacked or Tunneled Soil Load. This type of installation is used where surface conditions make it difficult to install the pipe by conventional open excavation and backfill methods, or where it is necessary to install the pipe under an existing embankment. The earth load on a pipe installed by these methods is computed by the equation:

$$W_t = C_t w B_t^2 - 2cC_tB_t \tag{11}$$

Where: B_t = width of tunnel bore, (ft)

The load coefficient C_t is further defined as:

$$C_t = \frac{1 - e^{-2K\mu' \frac{H}{B_t}}}{-2K\mu'} \tag{12}$$

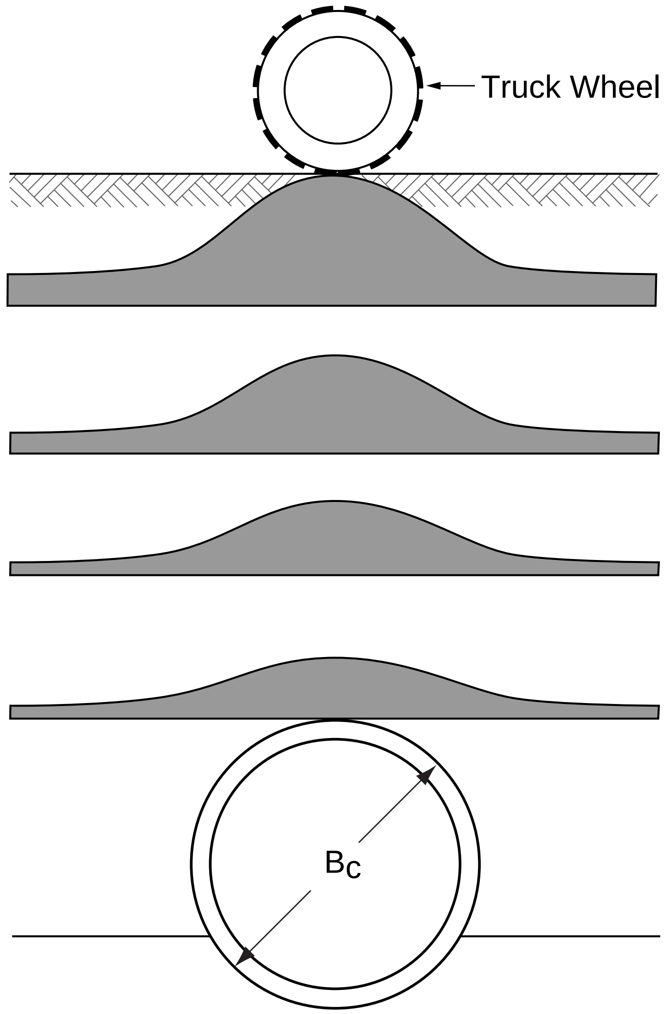
In equation (10) the $C_t w B_t^2$ term is similar to the Negative Projection Embankment equation (6) for soil loads and the $2cC_tB_t$ term accounts for the cohesion of undisturbed soil. Conservative design values of the coefficient of cohesion for various soils are listed in Table 41. Figures 147, 149, 151 and 153 present values of the trench load term ($C_t w B_t^2$) in pounds per linear foot for a soil density of 120 pounds per cubic foot and $K\mu'$ values of 0.165, 0.150, 0.130 and 0.110. Figures 148, 150, 152 and 154 present values of the cohesion term ($2cC_tB_t$) divided by the design values for the coefficient of cohesion (c). To obtain the total earth load for any given height of cover, width of bore or tunnel and type of soil, the value of the cohesion term must be multiplied by the appropriate coefficient of cohesion (c) and this product subtracted from the value of the trench load term.

Determination of Live Load

In the selection of pipe, it is necessary to evaluate the effect of live loads. Live load considerations are necessary in the design of pipe installed with shallow cover under railroads, airports and unsurfaced highways. The distribution of a live load at the surface on any horizontal plane in the subsoil is shown in Illustration 4.10. The intensity of the load on any plane in the soil mass is greatest at the vertical axis directly beneath the point of application and decreases in all directions outward from the center of application. As the distance between the plane and the surface increases, the intensity of the load at any point on the plane decreases.

In typical concrete pipe design, the governing moments and shears in the pipe are at the invert, where the support of the pipe is less uniform then the soil load being applied at the top of the pipe. However, in extremely shallow installations, the governing moments and shears may occur in the crown of the pipe as a result of the concentrated live load. Special live load bedding factors have been developed for this condition and will be explained in more detail later in this chapter.

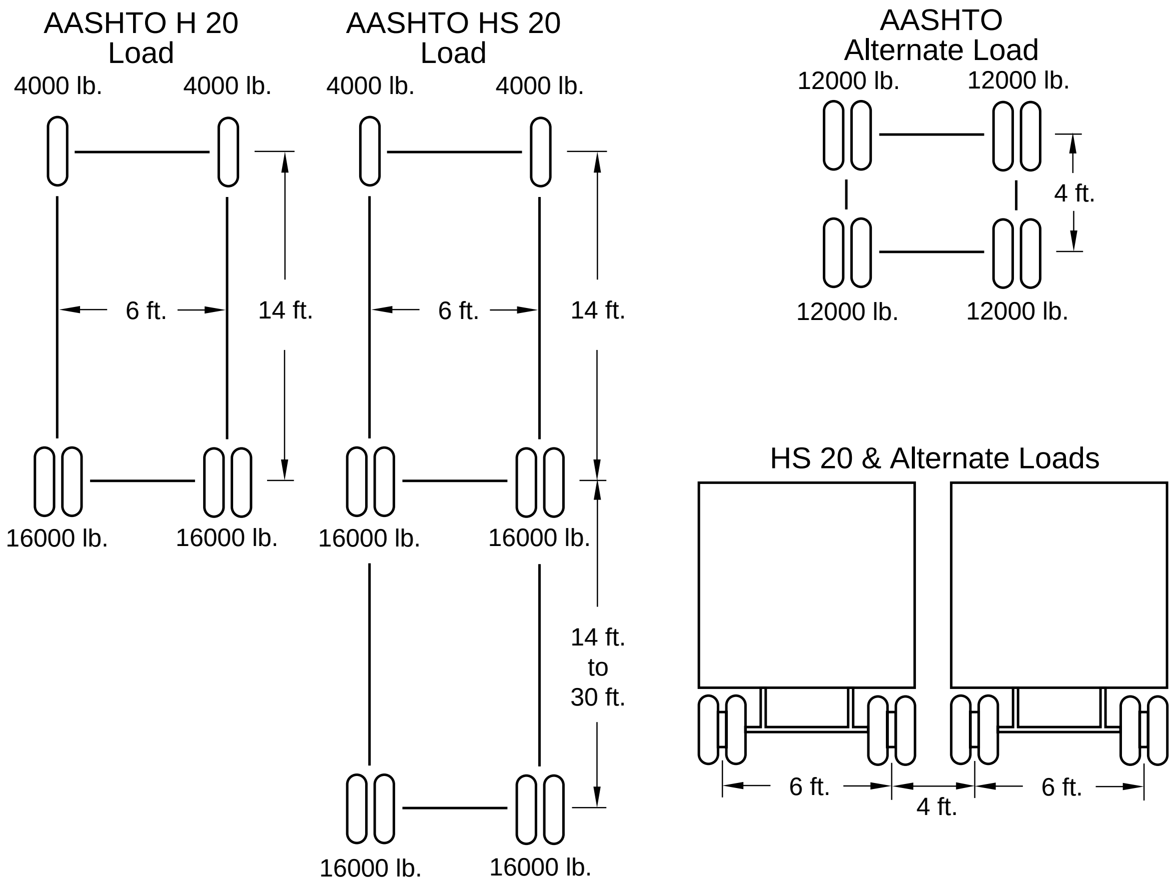
Illustration 4.10 Live Load Distribution



Highways. If a rigid or flexible pavement designed for heavy duty traffic is provided, the intensity of a truck wheel load is usually reduced sufficiently so that the live load transmitted to the pipe is negligible. In the case of flexible pavements designed for light duty traffic but subjected to heavy truck traffic; the flexible pavement should be considered as fill material over the top of the pipe.

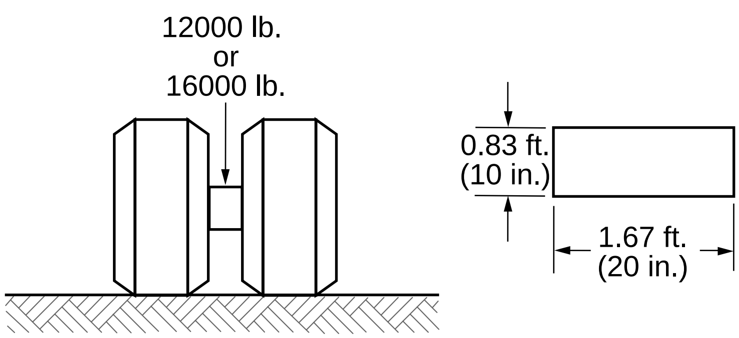
In analyses, the most critical AASHTO loadings shown in Illustration 4.11 are used in either the single mode or passing mode.

Illustration 4.11 AASHTO Live Loads



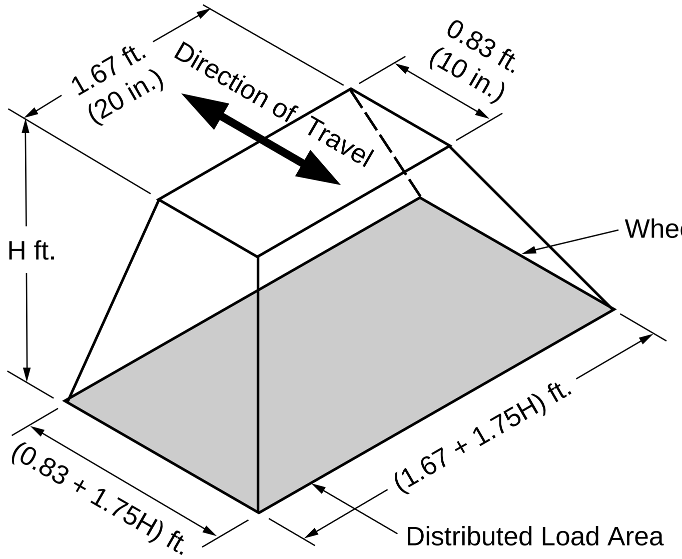
Each of these loadings is assumed to be applied through dual wheel assemblies uniformly distributed over a surface area of 10 inches by 20 inches as shown in Illustration 4.12.

Illustration 4.12 Wheel Load Surface Contact Area



The total wheel load is then assumed to be transmitted and uniformly distributed over a rectangular area on a horizontal plane at the depth, H, as shown in Illustration 4.13 for a single *HS-20* dual wheel.

Illustration 4.13 Distributed Load Area, Single Dual Wheel



Distributed load areas for the alternate load and the passing mode for either loading are developed in a similar manner.

The average pressure intensity on the subsoil plane at the outside top of the pipe at depth, H, is determined by the equation:

$$W_L = \frac{P\,(1 + I_f)}{A_{LL}} \qquad (13)$$

where

W_L = average pressure intensity, pounds per square foot

P = total applied surface wheel loads, pounds

A_{LL} = distributed live load area, square feet

I_f = impact factor

Recommended impact factors, I_f, to be used in determining live loads imposed on pipe with less than 3 feet of cover when subjected to dynamic traffic loads are listed in the accompanying Table.

Impact Factors For Highway Truck Loads

H, HEIGHT OF COVER	I_f, IMPACT FACTOR
0'-0" to 1'-0"	0.3
1'-1" to 2'-0"	0.2
2'-1" to 2'-11"	0.1
3'-0" and greater	0.0

NOTE: *Impact Factors recommended by the American Association of State Highway and Transportation Officials in "Standard Specifications for Highway Bridges."*

As the depth, *H*, increases, the critical loading configuration can be either one HS-20 wheel load, two HS-20 wheel loads in the passing mode or the alternate load in the passing mode. Since the exact geometric relationship of individual or combinations of surface wheel loads cannot be anticipated, the most critical loading configurations and the outside dimensions of the distributed load areas within the indicated cover depths are summarized in the accompanying Table.

Critical Loading Configurations

H, feet	P, pounds	A_{LL}, Distributed Load Area
$H < 1.33$	16,000	$(0.83 + 1.75H)\ (1.67 + 1.75H)$
$1.33 \leq H < 4.10$	32,000	$(0.83 + 1.75H)\ (5.67 + 1.75H)$
$4.10 \leq H$	48,000	$(4.83 + 1.75H)\ (5.67 + 1.75H)$

The total live load acting on the pipe is determined by the following formula:

$$W_T = W_L L S_L \qquad (14)$$

where

W_T = total live load, pounds

L = Length of A_{LL} parallel to logitudinal axis of pipe, feet

S_L = outside horizontal span of pipe or width of A_{LL} transverse to longitudinal axis of pipe, whichever is less, feet.

The live load acting on the pipe in pounds per linear foot is determined by the following equation:

where

$$W_L = \frac{W_T}{L_e} \qquad (15)$$

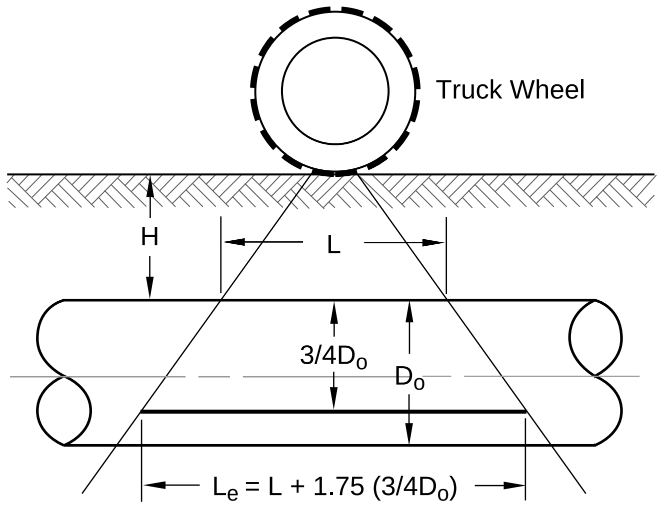
W_L = live load on pipe, pounds per linear foot

L_e = effective supporting length of pipe, feet

Since the buried concrete pipe is similar to a beam on continuous supports, the effective supporting length of the pipe is assumed as in Illustration 4.14 and determined by the following equation:

$$L_e = L + 1.75 \left(\frac{3D_o}{4} \right) \qquad (16)$$

Illustration 4.14 Effective Supporting Length of Pipe



Analysis of possible pipe alignments relative to load orientation confirms the most critical loading can occur when the longitudinal pipe axis is either parallel or transverse to the direction of travel and centered under the distributed load area. Tables 42 through 45 present the maximum highway live loads in pounds per linear foot imposed on circular, horizontal elliptical, vertical elliptical and arch pipe with impact included.

Airports. The distribution of aircraft wheel loads on any horizontal plane in the soil mass is dependent on the magnitude and characteristics of the aircraft loads, the aircraft's landing gear configuration, the type of pavement structure and the subsoil conditions. Heavier gross aircraft weights have resulted in multiple wheel undercarriages consisting of dual wheel assemblies and/or dual tandem assemblies. The distribution of wheel loads through rigid and flexible pavements are shown in Illustrations 4.15 and 4.16.

If a rigid pavement is provided, an aircraft wheel load concentration is distributed over an appreciable area and is substantially reduced in intensity at the subgrade. For multi-wheeled landing gear assemblies, the total pressure intensity is dependent on the interacting pressures produced by each individual wheel. The maximum load transmitted to a pipe varies with the pipe size under consideration, the pipe's relative location with respect to the particular landing gear configuration and the height of fill between the top of the pipe and the subgrade surface.

For a flexible pavement, the area of the load distribution at any plane in the soil mass is considerably less than for a rigid pavement. The interaction of pressure intensities due to individual wheels of a multi-wheeled landing gear assembly is also less pronounced at any given depth of cover.

In present airport design practices, the aircraft's maximum takeoff weight is used since the maximum landing weight is usually considered to be about three-fourths the takeoff weight. Impact is not considered as criteria are not yet available to include dynamic effects in the design process.

Rigid Pavement. The pressure intensity is computed by the equation:

$$p(H,X) = \frac{CP}{R_s^2} \qquad (17)$$

R_s is further defined as:

$$R_s = \sqrt[4]{\frac{E_h^3}{12\,(1 - {}_u^2)\,k}} \qquad (18)$$

Tables 46 through 50 present pressure coefficients in terms of the radius of stiffness as developed by the Portland Cement Association and published in the report "Vertical Pressure on Culverts Under Wheel Loads on Concrete Pavement Slabs." [3]

Values of radius of stiffness are listed in Table 52 for pavement thickness and modulus of subgrade reaction.

Flexible Pavement. The pressure intensity is computed by the equation:

$$p(H,X) = Cp_o \qquad (19)$$

Illustration 4.15 - Aircraft Pressure Distribution Rigid Pavement

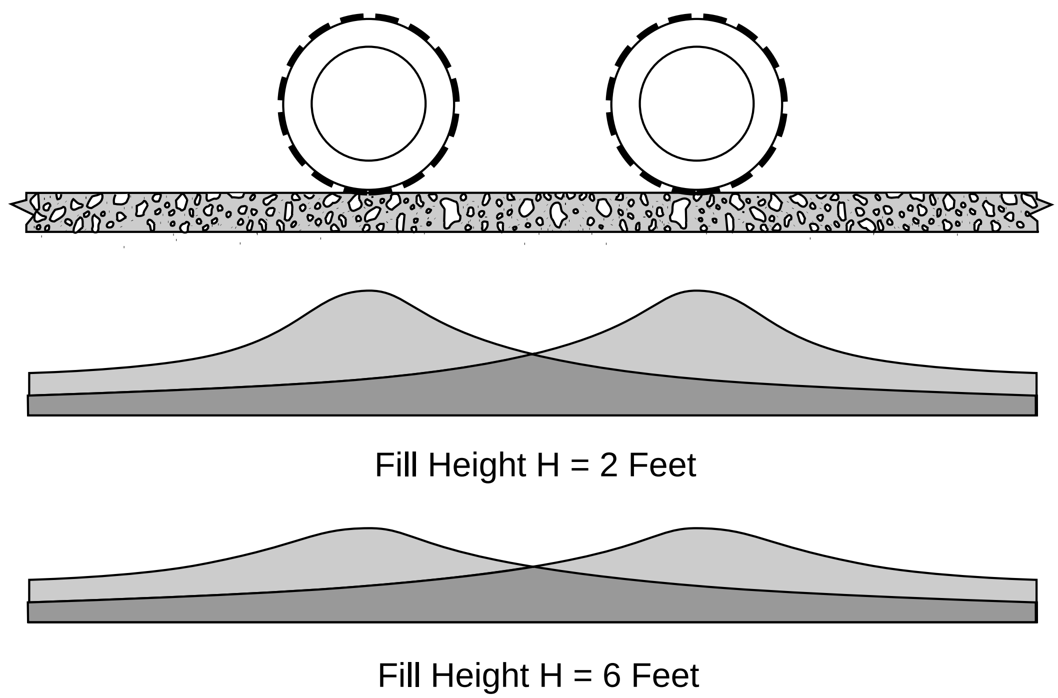
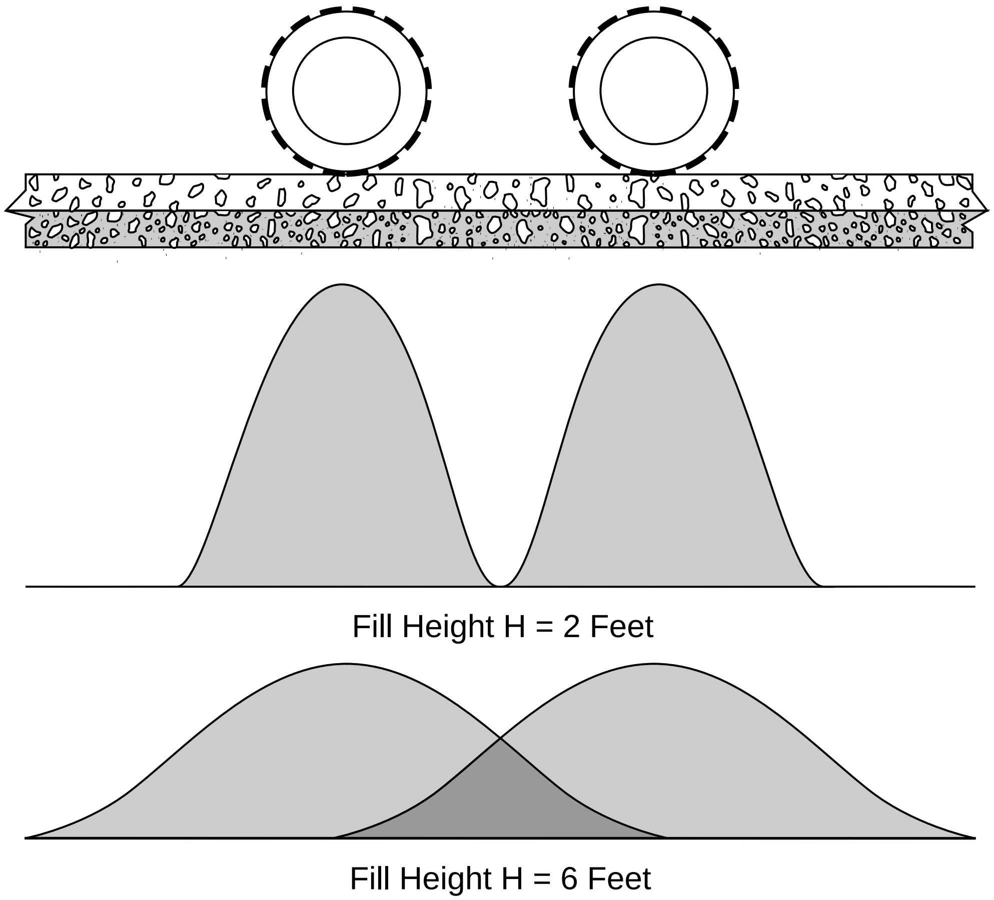


Illustration 4.16 - Aircraft Pressure Distribution Flexible Pavement



The values given in Tables 46 through 50 are the pressures on planes at depth H in a semi-infinite elastic body. The presence of a pipe introduces a boundary condition which theoretically creates a problem approaching that of an elastic layer of depth H resting on a rigid base. Although pressures based on this assumption are somewhat higher than those given, uncertainties as to the exact elastic properties of the backfill over the pipe, the rigidity of the pipe and other factors are such that theoretically more accurate computations are not considered justified.

The pressure coefficient, C, is dependent on the horizontal distance (X), the vertical distance (H) between the pipe and surface load and the radius of the circle of pressure at the surface (r).

r is further defined as:

$$r = \sqrt{\frac{P}{p_o \pi}} \qquad (20)$$

Pressure coefficients in terms of the radius of the circle of pressure at the surface (r) are presented in Table 51.

For rigid and flexible pavements, Tables 53 through 55 present aircraft loads in pounds per linear foot for circular, horizontal elliptical and arch pipe. The Tables are based on equations (18) and (19) using a 180,000 pound dual tandem wheel assembly, 190 pounds per square inch tire pressure, 26-inch spacing between dual tires, 66-inch spacing between tandem axles, k value of 300 pounds per cubic inch, 12-inch, thick concrete pavement and an R_s, value of 37.44 inches. Subgrade and subbase support for a rigid pavement is evaluated in terms of k, the modulus of subgrade reaction. A k value of 300 pounds per cubic inch was used, since this value represents a desirable subgrade or subbase material. In addition, because of the interaction between the pavement and subgrade, a lower value of k (representing reduced subgrade support) results in less load on the pipe.

Although Tables 53 through 55 are for specific values of aircraft weights and landing gear configuration, the tables can be used with sufficient accuracy for all heavy commercial aircraft currently in operation. Investigation of the design loads of future jets indicates that although the total loads will greatly exceed present aircraft loads, the distribution of such loads over a greater number of landing gears and wheels will not impose loads on underground conduits greater than by commercial aircraft currently in operation. For lighter aircrafts and/or different rigid pavement thicknesses, it is necessary to calculate loads as illustrated in Example 4.9.

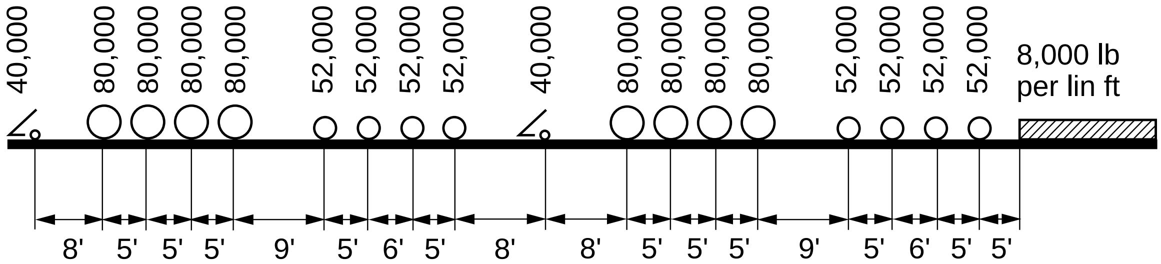
Railroads. In determining the live load transmitted to a pipe installed under railroad tracks, the weight on the locomotive driver axles plus the weight of the track structure, including ballast, is considered to be uniformly distributed over an area equal to the length occupied by the drivers multiplied by the length of ties.

The American Railway Engineering and Maintenance of Way Association (AREMA) recommends a Cooper E80 loading with axle loads and axle spacing as shown in Illustration 4.17. Based on a uniform load distribution at the bottom of the ties and through the soil mass, the live load transmitted to a pipe underground is computed by the equation:

$$W_L = Cp_oB_cI_f \qquad {}^4(21)$$

Tables 56 through 58 present live loads in pounds per linear foot based on equation (20) with a Cooper E80 design loading, track structure weighing 200 pounds per linear foot and the locomotive load uniformly distributed over an area 8 feet X 20 feet yielding a uniform live load of 2025 pounds per square foot. In accordance with AREMA “Manual of Recommended Practice” an impact factor of 1.4 at zero cover decreasing to 1.0 at ten feet of cover is included in the Tables.

Illustration 4.17 - Cooper E 80 Design Load



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3 Op. cit., p. 28

4 Equation (21) is recommended by WPCF-ASCE Manual, The Design and Construction of Sanitary Storm Sewers.

Construction Loads. During grading operations it may be necessary for heavy construction equipment to travel over an installed pipe. Unless adequate protection is provided, the pipe may be subjected to load concentrations in excess of the design loads. Before heavy construction equipment is permitted to cross over a pipe, a temporary earth fill should be constructed to an elevation at least 3 feet over the top of the pipe. The fill should be of sufficient width to prevent possible lateral displacement of the pipe.

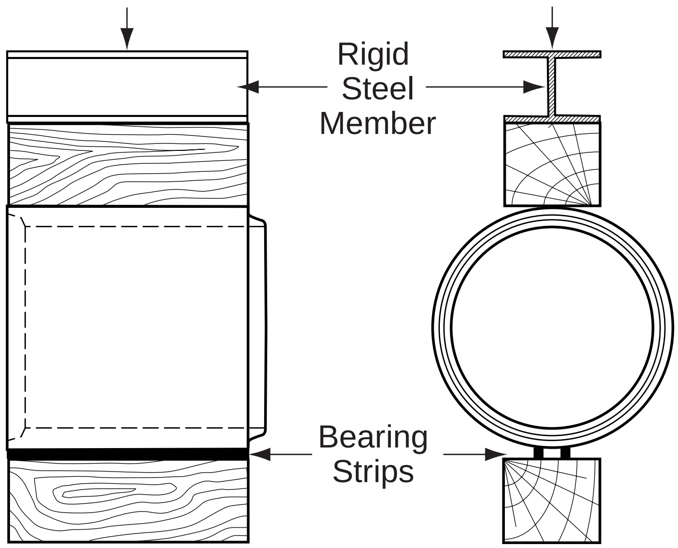
SELECTION OF BEDDING

A bedding is provided to distribute the vertical reaction around the lower exterior surface of the pipe and reduce stress concentrations within the pipe wall. The load that a concrete pipe will support depends on the width of the bedding contact area and the quality of the contact between the pipe and bedding. An important consideration in selecting a material for bedding is to be sure that positive contact can be obtained between the bed and the pipe. Since most granular materials will shift to attain positive contact as the pipe settles an ideal load distribution can be attained through the use of clean coarse sand, well-rounded pea gravel or well-graded crushed rock.

BEDDING FACTORS

Under installed conditions the vertical load on a pipe is distributed over its width and the reaction is distributed in accordance with the type of bedding. When the pipe strength used in design has been determined by plant testing, bedding factors must be developed to relate the in-place supporting strength to the more severe plant test strength. The bedding factor is the ratio of the strength of the pipe under the installed condition of loading and bedding to the strength of the pipe in the plant test. This same ratio was defined originally by Spangler as the load factor. This latter term, however, was subsequently defined in the ultimate strength method of reinforced concrete design with an entirely different meaning. To avoid confusion, therefore, Spangler's term was renamed the bedding factor. The three-edge bearing test as shown in Illustration 4.18 is the normally accepted plant test so that all bedding factors described in the following relate the in-place supporting strength to the three-edge bearing strength.

Illustration 4.18 - Three-Edge Bearing Test



Although developed for the direct design method, the Standard Installations are readily applicable to and simplify the indirect design method. The Standard Installations are easier to construct and provide more realistic designs than the historical B, C, and D beddings. Development of bedding factors for the Standard Installations, as presented in the following paragraphs, follows the concepts of reinforced concrete design theories. The basic definition of bedding factor is that it is the ratio of maximum moment in the three-edge bearing test to the maximum moment in the buried condition, when the vertical loads under each condition are equal:

where: $$B_f = \frac{M_{TEST}}{M_{FIELD}} \qquad (22)$$

B_f = bedding factor
M_{TEST} = maximum moment in pipe wall under three-edge bearing test load, inch-pounds
M_{FIELD} = maximum moment in pipe wall under field loads, inch-pounds

Consequently, to evaluate the proper bedding factor relationship, the vertical load on the pipe for each condition must be equal, which occurs when the springline axial thrusts for both conditions are equal. In accordance with the laws of statics and equilibrium, M_{TEST} and M_{FIELD} are:

where: $M_{TEST} = [0.318N_{FS}] \times [D + t]$ (23)

$M_{FIELD} = [M_{FI}] - [0.38tN_{FI}] - [0.125N_{FI} \times c]$ (24)

N_{FS} = axial thrust at the springline under a three-edge bearing test load, pounds per foot
D = internal pipe diameter, inches
t = pipe wall thickness, inches
M_{FI} = moment at the invert under field loading, inch-pounds/ft
N_{FI} = axial thrust at the invert under field loads, pounds per foot
c = thickness of concrete cover over the inner reinforcement, inches

Substituting equations 22 and 23 into equation 21.

$$B_f = \frac{[0.318N_{FS}] \times [D + t]}{[M_{FI}] - [0.38tN_{FI}] - [0.125N_{FI} \times C]} \quad (25)$$

Using SIDD, bedding factors were determined for a range of pipe diameters and depths of burial. These calculations were based on one inch cover over the reinforcement, a moment arm of 0.875d between the resultant tensile and compressive forces, and a reinforcement diameter of 0.075t. Evaluations indicated that for A, B and C pipe wall thicknesses, there was negligible variation in the bedding factor due to pipe wall thickness or the concrete cover, c, over the reinforcement. The resulting bedding factors are presented in Illustration 4.19.

Illustration 4.19 Bedding Factors, Embankment Conditions, B_{fe}

Pipe	Standard Installation			
Diameter	**Type 1**	**Type 2**	**Type 3**	**Type 4**
12 in.	4.4	3.2	2.5	1.7
24 in.	4.2	3.0	2.4	1.7
36 in.	4.0	2.9	2.3	1.7
72 in.	3.8	2.8	2.2	1.7
144 in.	3.6	2.8	2.2	1.7

Notes:
1. *For pipe diameters other than listed in Illustration 4.19, embankment condition factors, B_{fe} can be obtained by interpolation.*
2. *Bedding factors are based on the soils being placed with the minimum compaction specified in Illustrations 4.5 and 4.7 for each standard installation.*

Determination of Bedding Factor

For trench installations as discussed previously, experience indicates that active lateral pressure increases as trench width increases to the transition width, provided the sidefill is compacted. A SIDD parameter study of the Standard Installations indicates the bedding factors are constant for all pipe diameters under conditions of zero lateral pressure on the pipe. These bedding factors exist at the interface of the pipewall and the soil and are called minimum bedding factors, B_{fo}, to differentiate them from the fixed bedding factors developed by Spangler. Illustration 4.20 presents the minimum bedding factors.

Illustration 4.20 Trench Minimum Bedding Factors, B_{fo}

Standard Installation	Minimum Bedding Factor, B_{fo}
Type 1	2.3
Type 2	1.9
Type 3	1.7
Type 4	1.5

Note:

1. *Bedding factors are based on the soils being placed with the minimum compaction specified in Illustrations 4.5 and 4.7 for each Standard Installation.*
2. *For pipe installed in trenches dug in previously constructed embankment, the load and the bedding factor should be determined as an embankment condition unless the backfill placed over the pipe is of lesser compaction than the embankment*

A conservative linear variation is assumed between the minimum bedding factor and the bedding factor for the embankment condition, which begins at transition width.

The equation for the variable trench bedding factor, is:

$$B_{fv} = \frac{[B_{fe} - B_{fo}][B_d - B_c]}{[B_{dt} - B_c]} + B_{fo} \qquad (26)$$

where:

B_c	=	outside horizontal span of pipe, feet
B_d	=	trench width at top of pipe, feet
B_{dt}	=	transition width at top of pipe, feet
B_{fe}	=	bedding factor, embankment
B_{fo}	=	minimum bedding factor, trench
B_{fv}	=	variable bedding factor, trench

Transition width values, B_{dt} are provided in Tables 13 through 39.

For pipe installed with 6.5 ft or less of overfill and subjected to truck loads, the controlling maximum moment may be at the crown rather than the invert. Consequently, the use of an earth load bedding factor may produce unconservative designs. Crown and invert moments of pipe for a range of diameters and burial depths subjected to HS20 truck live loadings were evaluated. Also evaluated, was the effect of bedding angle and live load angle (width of loading on the pipe). When HS20 or other live loadings are encountered to a significant value, the live load bedding factors, B_{fLL},, presented in Illustration 4.21 are satisfactory for a Type 4 Standard Installation and become increasingly conservative for Types 3, 2, and 1. Limitations on B_{fLL} are discussed in the section on Selection of Pipe Strength.

Application of Factor of Safety

The indirect design method for concrete pipe is similar to the common working stress method of steel design, which employs a factor of safety between yield stress and the desired working stress. In the indirect method, the factor of safety is defined as the relationship between the ultimate strength D-load and the 0.01inch crack D-load. This relationship is specified in the ASTM Standards C 76 and C 655 on concrete pipe. The relationship between ultimate D-load and 0.01-inch crack D-load is 1.5 for 0.01 inch crack D-loads of 2,000 or less; 1.25 for 0.01 inch crack D loads of 3,000 or more; and a linear reduction from 1.5 to 1.25 for 0.01 inch crack D-loads between more than 2,000 and less than 3,000. Therefore, a factor of safety of 1.0 should be applied if the 0.01 inch crack strength is used as the design criterion rather than the ultimate strength. The 0.01 inch crack width is an arbitrarily chosen test criterion and not a criteria for field performance or service limit.

SELECTION OF PIPE STRENGTH

The American Society for Testing and Materials has developed standard specifications for precast concrete pipe. Each specification contains design, manufacturing and testing criteria.

ASTM Standard C 14 covers three strength classes for nonreinforced concrete pipe. These classes are specified to meet minimum ultimate loads, expressed in terms of three-edge bearing strength in pounds per linear foot.

ASTM Standard C 76 for reinforced concrete culvert, storm drain and sewer pipe specifies strength classes based on *D*-load at 0.01-inch crack and/or ultimate load. The 0.01-inch crack *D*-load ($D_{0.01}$) is the maximum three-edge-bearing test load supported by a concrete pipe before a crack occurs having a width of 0.01 inch measured at close intervals, throughout a length of at least I foot. The ultimate *D*-load (D_u) is the maximum three-edge-bearing test load supported by a pipe. *D*-loads are expressed in pounds per linear foot per foot of inside diameter.

ASTM Standard C 506 for reinforced concrete arch culvert, storm drain, and sewer pipe specifies strengths based on D-load at 0.01-inch crack and/or ultimate load in pounds per linear foot per foot of inside span.

Illustration 4.21 Bedding Factors, B_{fLL}, for HS20 Live Loadings

Fill Height, Ft.	Pipe Diameter, Inches										
	12	24	36	48	60	72	84	96	108	120	144
0.5	2.2	1.7	1.4	1.3	1.3	1.1	1.1	1.1	1.1	1.1	1.1
1.0	2.2	2.2	1.7	1.5	1.4	1.3	1.3	1.3	1.1	1.1	1.1
1.5	2.2	2.2	2.1	1.8	1.5	1.4	1.4	1.3	1.3	1.3	1.1
2.0	2.2	2.2	2.2	2.0	1.8	1.5	1.5	1.4	1.4	1.3	1.3
2.5	2.2	2.2	2.2	2.2	2.0	1.8	1.7	1.5	1.4	1.4	1.3
3.0	2.2	2.2	2.2	2.2	2.2	2.2	1.8	1.7	1.5	1.5	1.4
3.5	2.2	2.2	2.2	2.2	2.2	2.2	1.9	1.8	1.7	1.5	1.4
4.0	2.2	2.2	2.2	2.2	2.2	2.2	2.1	1.9	1.8	1.7	1.5
4.5	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	1.9	1.8	1.7
5.0	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	1.9	1.8
5.5	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	1.9
6.0	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.1	2.0
6.5	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2

Note:

1. For pipe diameters other than listed in illustration 4.21, B_{fLL} values can be obtained by interpolation.

ASTM Standard C 507 for reinforced concrete elliptical culvert, storm drain and sewer pipe specifies strength classes for both horizontal elliptical and vertical elliptical pipe based on *D*-load at 0.01-inch crack and/or ultimate load in pounds per linear foot per foot of inside span.

ASTM Standard C 655 for reinforced concrete *D*-load culvert, storm drain and sewer pipe covers acceptance of pipe design to meet specific *D*-load requirements.

ASTM Standard C 985 for nonreinforced concrete specified strength culvert, storm drain, and sewer pipe covers acceptance of pipe designed for specified strength requirements.

Since numerous reinforced concrete pipe sizes are available, three-edge bearing test strengths are classified by *D*-loads. The *D*-load concept provides strength classification of pipe independent of pipe diameter. For reinforced circular pipe the three-edge-bearing test load in pounds per linear foot equals *D*-load X inside diameter in feet. For arch, horizontal elliptical and vertical elliptical pipe the three-edge bearing test load in pounds per linear foot equals *D*-load X nominal inside span in feet.

The required three-edge-bearing strength of non-reinforced concrete pipe is expressed in pounds per linear foot, not as a *D*-load, and is computed by the equation:

$$T.E.B = \left[\frac{W_E}{B_{fe}} + \frac{W_L}{B_{fLL}} \right] \times F.S. \qquad (27)$$

The required three-edge bearing strength of circular reinforced concrete pipe is expressed as *D*-load and is computed by the equation:

$$D\text{-load} = \left[\frac{W_E}{B_{fe}} + \frac{W_L}{B_{fLL}} \right] \times \frac{F.S.}{D} \qquad (28)$$

The determination of required strength of elliptical and arch concrete pipe is computed by the equation:

$$D\text{-load} = \left[\frac{W_E}{B_{fe}} + \frac{W_L}{B_{fLL}} \right] \times \frac{F.S.}{S} \qquad (29)$$

where:

S = inside horizontal span of pipe, ft.

When an HS20 truck live loading is applied to the pipe, use the live load bedding factor, B_{fLL}, as indicated in Equations 26-28, unless the earth load bedding factor, B_{fe}, is of lesser value in which case, use the lower B_{fe} value in place of B_{fLL}. For example, with a Type 4 Standard Installation of a 48 inch diameter pipe under 1.0 feet of fill, the factors used would be B_{fe} = 1.7 and B_{fLL} = 1.5; but under 2.5 feet or greater fill, the factors used would be B_{fe}= 1.7 and B_{fLL}, = 1.7 rather than 2.2. For trench installations with trench widths less than transition width, B_{fLL} would be compared to the variable trench bedding factor, B_{fv}.

The use of the six-step indirect design method is illustrated by examples on the following pages.

EXAMPLE PROBLEMS

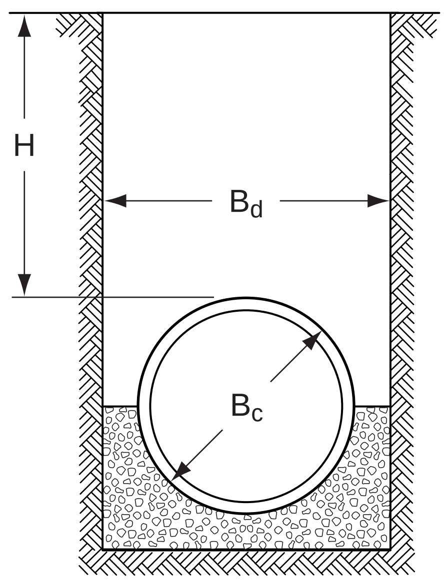
EXAMPLE PROBLEMS

EXAMPLE 4-1
Trench Installation

Given: A 48 inch circular pipe is to be installed in a 7 foot wide trench with 10 feet of cover over the top of the pipe. The pipe will be backfilled with sand and gravel weighing 110 pounds per cubic foot. Assume a type 4 bedding.

Find: The required pipe strength in terms of 0.01 inch crack D-load.

Example 4-1



1. Determination of Earth Load (W_E)

To determine the earth load, we must first determine if the installation is behaving as a trench installation or an embankment installation. Since we are not told what the existing in-situ material is, conservatively assume a Ku' value between the existing soil and backfill of 0.150. Also, since there is limited room for compaction with a trench this narrow. Assume a Type 4 Installation.

From Table 23, The transition width for a 48 inch diameter pipe with a Kμ' value of 0.150 under 10 feet of fill is:

B_{dt} = 8.5 feet

Transition width is greater than the actual trench width, therefore the installation will act as a trench. Use Equations 6 and 5.

$w = 110$ pounds per cubic foot
$H = 10$ feet
$B_d = 7$ feet
$K\mu' = 0.150$

$$D_o = \frac{48 + 2 \times (5)}{12}$$

Note: Wall thickness for a 48 inch inside diameter pipe with a B wall is 5-inches per ASTM C 76.

$D_o = 4.83$ feet

The value of C_d can be obtained from Figure 214, or calculated using Equation 5.

$$C_d = \frac{1 - e^{-2 \times (0.150) \times \left(\frac{10}{7}\right)}}{(2) \times (0.150)} \qquad \text{Equation 6}$$

$C_d = 1.16$

$$W_d = (C_d \times w \times B_d^2) + \frac{D_o^2 \times (4 - \pi)}{8} \times w \qquad \text{Equation 5}$$

$W_d = 6538$ pounds per linear foot

2. Determination of Live Load (W_L)
From Table 42, live load is negligible at a depth of 10 feet.

3. Selection of Bedding

Because of the narrow trench, good compaction of the soil on the sides of the pipe would be difficult, although not impossible. Therefore a Type 4 bedding was assumed.

4. Determination of Bedding Factor

The pipe is installed in a trench that is less than transition width. Therefore, Equation 26 must be used to determine the variable bedding factor.

$B_c = D_o$ B_C = 4.83 outside diameter of pipe in feet

B_d = 7 width of trench in feet

B_{dt} = 8.5 transition width in feet (taken from Table 23)

B_{fe} = 1.7 embankment bedding factor (taken from Illustration 4.19)

B_{fo} = 1.5 minimum bedding factor (taken from Illustration 4.20)

$$B_{fv} = \frac{(1.7 - 1.5)\,(7 - 4.83)}{8.5 - 4.83} + 1.5 \qquad \text{Equation 26}$$

B_{fv} = 1.62

5. Application of Factor of Safety (F.S.)
A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength
The D-load is given by Equation 28

$W_E = W_d$ W_E = 6538 earth load in pounds per linear foot

W_L = 0 live load is negligible

$B_{fe} = B_{fv}$ B_{fe} = 1.62 earth load bedding factor

B_{fLL} = N/A live load bedding factor is not applicable

D = 4 inside diameter of pipe in feet

$$D_{0.01} = \left(\frac{6538}{1.62}\right)\left(\frac{1.0}{4}\right) \qquad \text{Equation 28}$$

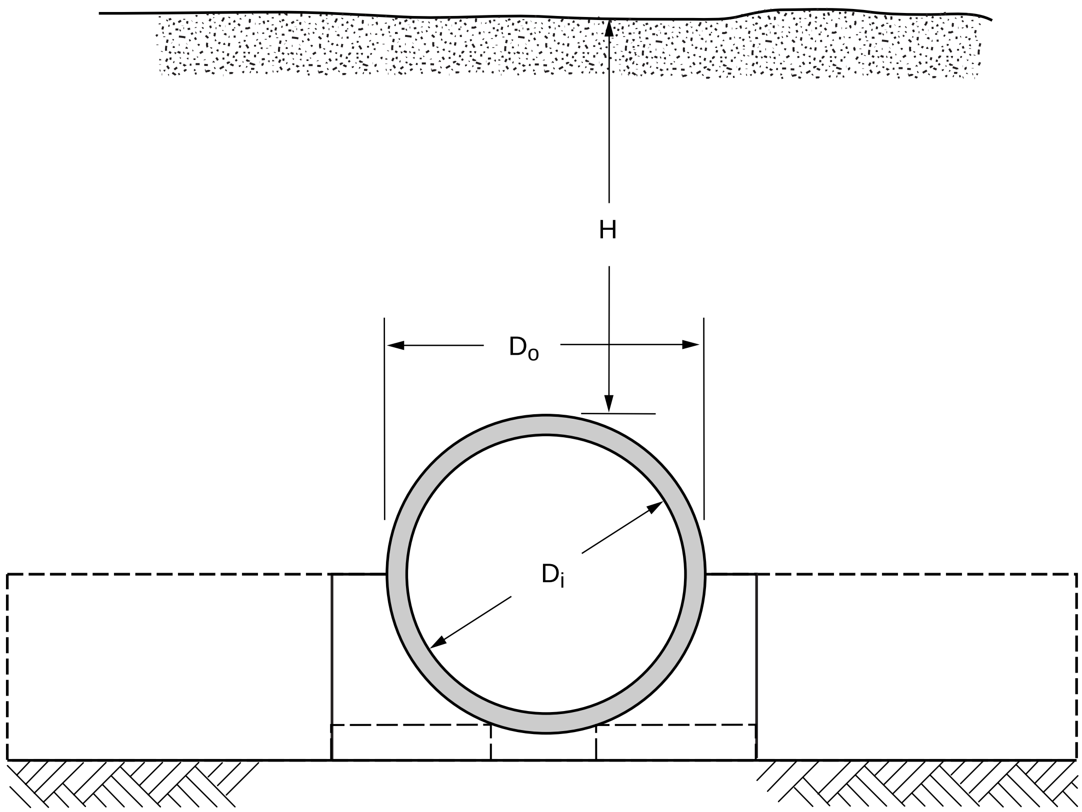
$D_{0.01}$ = 1009 pounds per linear foot per foot of diameter

Answer: A pipe which would withstand a minimum three-edge bearing test load for the 0.01 inch crack of 1009 pounds per linear foot per foot of inside diameter would be required.

EXAMPLE 4-2
Positive Projection Embankment Installation

Given: A 48 inch circular pipe is to be installed in a positive projecting embankment condition using a Type 1 installation. The pipe will be covered with 35 feet of 120 pounds per cubic foot overfill.

Find: The required pipe strength in terms of 0.01 inch D-load



1. Determination of Earth Load (W_E)
Per the given information, the installation behaves as a positive projecting embankment. Therefore, use Equation 4 to determine the soil prism load and multiply it by the appropriate vertical arching factor.

$$D_o = \frac{48 + 2\,(5)}{12}$$

Note: Per ASTM C 76 the wall thickness for a 48-inch diameter pipe with a B wall is 5 inches.

D_o = 4.83 outside diameter of pipe in feet

w = 120 unit weight of soil in pounds per cubic foot

H = 35 height of cover in feet

$$PL = 120\left[35 + \frac{4.83\,(4 - \pi)}{8}\right]4.83 \qquad \text{Equation 4}$$

PL = 20586 pounds per linear foot

Immediately listed below Equation 4 are the vertical arching factors (VAFs) for the four types of Standard Installations. Using a VAF of 1.35 for a Type 1 Installation, the earth load is:

$W_E = 1.35 \times 20586$

$W_E = 27791$ pounds per linear foot

2. Determination of Live Load (WL)
   From Table 42, live load is negligible at a depth of 35 feet.

3. Selection of Bedding
   A Type 1 Installation will be used for this example

4. Determination of Bedding Factor
   The embankment bedding factor for a Type 1 Installation may be interpolated from Illustration 4.19

$B_{fe36} = 4.0$
$B_{fe72} = 3.8$

$$B_{fe} = \frac{72 - 48}{72 - 36}(4.0 - 3.8) + 3.8$$

$B_{fe} = 3.93$

5. Application of Factor of Safety (F.S.)
   A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength
   The D-load is given by Equation 28

$W_E = 27791$ earth load in pounds per linear foot

$W_L = 0$ live load is negligible

$B_{fe} = 3.93$ earth load bedding factor

$B_{fLL} = \text{N/A}$ live load bedding factor is not applicable

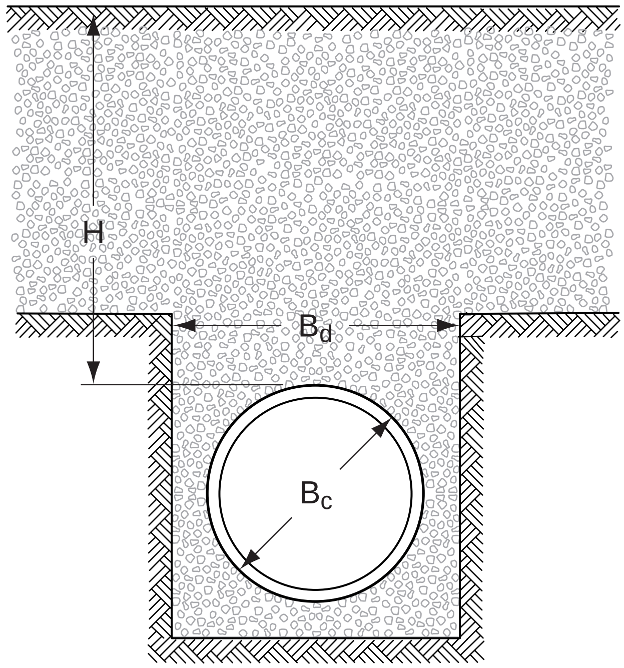
$D = 4$ inside diameter of pipe in feet

$$D_{0.01} = \left(\frac{27791}{3.93}\right)\left(\frac{1.0}{4}\right) \qquad \text{Equation 28}$$

$D_{0.01} = 1768$ pounds per linear foot per foot of diameter

Answer: A pipe which would withstand a minimum three-edge bearing test for the 0.01 inch crack of 1768 pounds per linear foot per foot of inside diameter would be required.

EXAMPLE 4-3
Negative Projection Embankment Installation



Given: A 72 inch circular pipe is to be installed in a negative projecting embankment condition in ordinary soil. The pipe will be covered with 35 feet of 120 pounds per cubic foot overfill. A 10 foot trench width will be constructed with a 5 foot depth from the top of the pipe to the natural ground surface.

Find:

1. Determination of Earth Load (W_E)
   A settlement ratio must first be assumed. The negative projection ratio of this installation is the height of soil from the top of the pipe to the top of the natural ground (5 ft) divided by the trench width (10 ft). Therefore the negative projection ratio of this installation is p' = 0.5. From Table 40, for a negative projection ratio of p' = 0.5, the design value of the settlement ratio is -0.1.

   Enter Figure 195 on the horizontal scale at H = 35 feet. Proceed vertically until the line representing B_d = 10 feet is intersected. At this point the vertical scale shows the fill load to be 27,500 pounds per linear foot for 100 pounds per cubic foot fill material. Increase the load 20 percent for 120 pound material.

   W_n = 1.20 x 27500

   W_n = 33000 pounds per linear foot

2. Determination of Live Load (W_L)
From Table 42, live load is negligible at a depth of 35 feet.

3. Selection of Bedding
No specific bedding was given. Assuming the contractor will put minimal effort into compacting the soil, a Type 3 Installation is chosen.

4. Determination of Bedding Factor
The variable bedding factor will be determined using Equation 26 in the same fashion as if the pipe were installed in a trench.

$$B_c = \frac{72 + 2 \times 7}{12}$$

Note: Per ASTM C 76 the wall thickness for a 72-inch diameter pipe with a B wall is 7 inches.

B_c = 7.17 outside diameter of pipe in feet
B_d = 10 trench width in feet
B_{dt} = 14.1 transition width for a Type 3 Installation with $K\mu'$=0.150
Interpolated from Table 27
B_{fe} = 2.2 embankment bedding factor (taken from Illustration 4.19)
B_{fo} = 1.7 minimum bedding factor (taken from Illustration 4.20)

$$B_{fv} = \frac{(2.2 - 1.7)\ (10 - 7.17)}{14.1 - 7.17} + 1.7 \qquad \text{Equation 26}$$

B_{fv} = 1.9

5. Application of Factor of Safety (F.S.)
A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength
The D-load is given by Equation 28

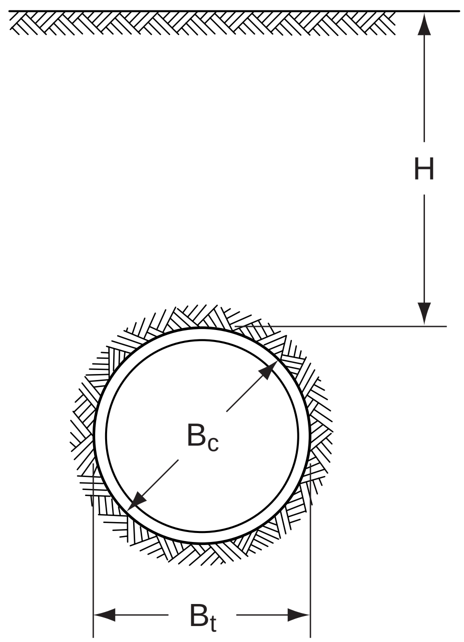
$W_E = W_n$ W_E = 33000 earth load in pounds per linear foot
W_L = 0 live load is negligible
$B_{fe} = B_{fv}$ B_{fe} = 1.9 earth load bedding factor
B_{fLL} = N/A live load bedding factor is not applicable
D = 6 inside diameter of pipe in feet

$$D_{0.01} = \left(\frac{33000}{1.9}\right)\left(\frac{1.0}{6}\right) \qquad \text{Equation 28}$$

$D_{0.01}$ = 2895 pounds per linear foot per foot of diameter

Answer: A pipe which would withstand a minimum three-edge bearing test load for the 0.01 inch crack of 2895 pounds per linear foot per foot of inside diameter would be required.

EXAMPLE 4-4
Jacked or Tunneled Installation



Given: A 48 inch circular pipe is to be installed by the jacking method of construction with a height of cover over the top of the pipe of 40 feet. The pipe will be jacked through ordinary clay material weighing 110 pounds per cubic foot throughout its entire length. The limit of excavation will be 5 feet.

Find: The required pipe strength in terms of 0.01 inch crack D-load.

1. Determination of Earth Load (W_E)
A coefficient of cohesion value must first be assumed. In Table 41, values of the coefficient of cohesion from 40 to 1000 are given for clay. A conservative value of 100 pounds per square foot will be used.

Enter Figure 151, Ordinary Clay, and project a horizontal line from H = 40 feet on the vertical scale and a vertical line from B_t = 5 feet on the horizontal scale. At the intersection of these two lines interpolate between the curved lines for a value of 9,500 pounds per linear foot, which accounts for earth load without cohesion. Decrease the load in proportion to 110/120 for 110 pound material.

$$W_t = \frac{110}{120} \times 9500$$

$$W_t = 8708 \text{ pounds per linear foot}$$

Enter Figure 152, Ordinary Clay, and project a horizontal line from H = 40 feet on the vertical scale and a vertical line from B_t = 5 feet on the horizontal scale. At the intersection of these two lines interpolate between the curved lines for a value of 33, which accounts for the cohesion of the soil. Multiply this value by the coefficient of cohesion, c = 100, and subtract the product from the 8708 value obtained from figure 151.

W_t = 8708 - 100 x 33

W_t = 5408 pounds per linear foot

2. Determination of Live Load (W_L)
   From Table 42, live load is negligible at 40 feet.

3. Selection of Bedding
   The annular space between the pipe and limit of excavation will be filled with grout.

4. Determination of Bedding Factor (B_{fe})
   Since the space between the pipe and the bore will be filled with grout, there will be positive contact of bedding around the entire periphery of the pipe. Because of this beneficial bedding condition, little flexural stress should be induced in the pipe wall. A conservative bedding factor of 3.0 will be used.

5. Application of Factor of Safety (F.S.)
   A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength
   The D-load is given by Equation 28.

$W_E = W_t$ W_E = 5408 earth load in pounds per linear foot

W_L = 0 live load is negligible

B_{fe} = 3.0 earth load bedding factor

B_{fLL} = N/A live load bedding factor is not applicable

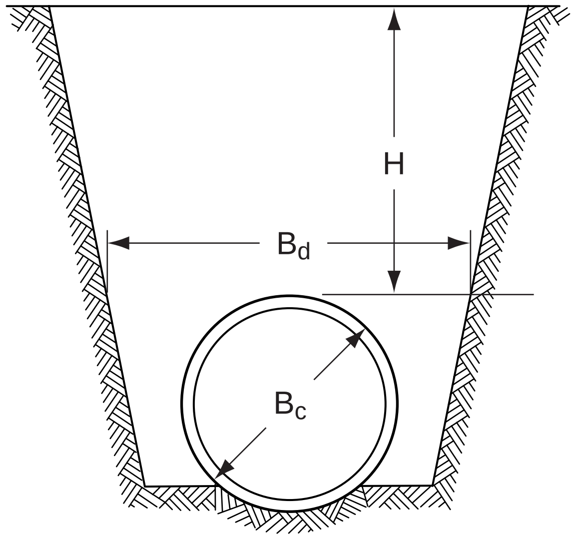
D = 4 inside diameter of pipe in feet

$$D_{0.01} = \left(\frac{5408}{3.0}\right)\left(\frac{1.0}{4}\right) \qquad \text{Equation 28}$$

$D_{0.01}$ = 451 pounds per linear foot per foot of diameter

Answer: A pipe which would withstand a minimum three-edge bearing test load for the 0.01 inch crack of 451 pounds per linear foot per foot of inside diameter would be required.

EXAMPLE 4-5
Wide Trench Installation



Given: A 24 inch circular pipe is to be installed in a 5 foot wide trench with 10 feet of cover over the top of the pipe. The pipe will be backfilled with ordinary clay weighing 120 pounds per cubic foot.

Find: The required three-edge bearing test strength for nonreinforced pipe and the ultimate D-load for reinforced pipe.

1. Determination of Earth Load (W_E)
   To determine the earth load, we must first determine if the installation is behaving as a trench installation or an embankment installation. Assume that since the pipe is being backfilled with clay that they are using in-situ soil for backfill. Assume a Kμ' value between the existing soil and backfill of 0.130. We will assume a Type 4 Installation for this example.

   From Table 17, the transition width for a 24 inch diameter pipe with a Kμ' value of 0.130 under 10 feet of fill is:

   $B_{dt} = 4.8$

   Since the transition width is less than the trench width, this installation will act as an embankment. Therefore calculate the prism load per Equation 4 and multiply it by the appropriate vertical arching factor (VAF).

$$D_o = \frac{24 + 2\,(3)}{12}$$

Note: Per ASTM C 76 the wall thickness for a 48-inch diameter pipe with a B wall is 3 inches.

D_o = 2.5 outside diameter of pipe in feet

w = 120 unit weight of soil in pounds per cubic foot

H = 10 height of cover in feet

$$PL = 120 \times \left[10 + \frac{2.5\,(4 - \pi)}{8}\right] \times 2.5 \qquad \text{Equation 3}$$

PL = 3080 pounds per linear foot

Immediately listed below Equation 3 are the vertical arching factors (VAF) for the four types of Standard Installations. Using a VAF of 1.45 for a Type 4 Installation, the earth load is:

W_E = 1.45 x 3080

W_E = 4466 pounds per linear foot

2. Determination of Live Load (W_L)
   From Table 42, live load is negligible at a depth of 10 feet.

3. Selection of Bedding
   A Type 4 Installation has been chosen for this example

4. Determination of Bedding Factor
   Since this installation behaves as an embankment, an embankment bedding factor will be chosen. From Illustration 4.19, the embankment bedding factor for a 24 inch pipe installed in a Type 4 Installation is:

   B_{fe} = 1.7

5. Application of Factor of Safety (F.S.)
   A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength

W_E = 4466 earth load in pounds per linear foot

W_L = 0 live load is negligible

B_{fe} = 1.7 earth load bedding factor

B_{fLL} = N/A live load bedding factor is not applicable

D = 2 inside diameter of pipe in feet

The ultimate three-edge bearing strength for nonreinforced concrete pipe is given by Equation 27

$$TEB = \left(\frac{4466}{1.7}\right) x\ 1.5 \qquad \text{Equation 27}$$

$$TEB = 3941 \text{ pounds per linear foot}$$

The D-load for reinforced concrete pipe is given by Equation 28

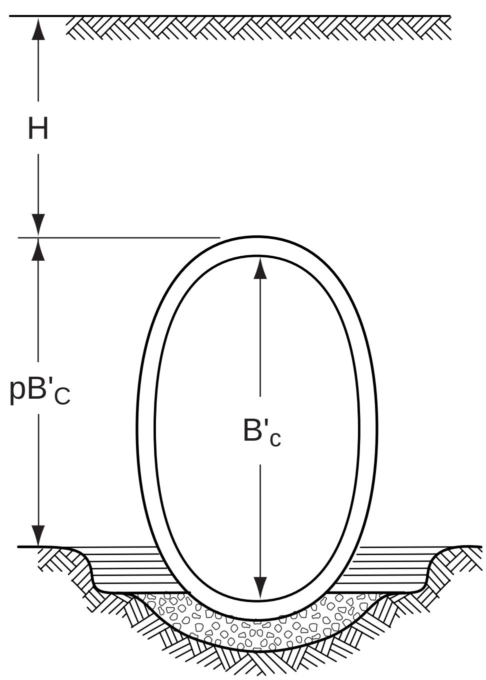
$$D_{0.01} = \left(\frac{4466}{1.7}\right)\left(\frac{1.0}{2}\right) \qquad \text{Equation 28}$$

$$D_{0.01} = 1314 \text{ pounds per linear foot per foot of diameter}$$

Answer: A nonreinforced pipe which would withstand a minimum three-edge bearing test load of 3941 pounds per linear foot would be required.

A pipe which would withstand a minimum three-edge bearing test for the 0.01 inch crack of 1314 pounds per linear foot per foot of inside diameter would be required.

EXAMPLE 4-6
Positive Projection Embankment Installation
Vertical Elliptical PIpe



Given: A 76 inch x 48 inch vertical elliptical pipe is to be installed in a positive projection embankment condition in ordinary soil. The pipe will be covered with 50 feet of 120 pounds per cubic foot overfill.

Find: The required pipe strength in terms of 0.01 inch crack D-load.

1. Determination of Earth Load (W_E)
   Note: The Standard Installations were initially developed for circular pipe, and their benefit has not yet been established for elliptical and arch pipe. Therefore, the traditional Marston/Spangler design method using B and C beddings is still conservatively applied for these shapes.

   A settlement ratio must first be assumed. In Table 40, values of settlement ratio from +0.5 to +0.8 are given for positive projecting installation on a foundation of ordinary soil. A value of 0.7 will be used. The product of the settlement ratio and the projection ratio will be 0.49 ($r_{sd}p$ approximately 0.5).

   Enter Figure 182 on the horizontal scale at H = 50 feet. Proceed vertically until the line representing R x S = 76" x 48" is intersected. At this point the vertical scale shows the fill load to be 41,000 pounds per linear foot for 100 pounds per cubic foot fill material. Increase the load 20 percent for 120 pound material.

   $W_c = 1.20 \times 41000$

   $W_c = 49200$ per linear foot

2. Determination of Live Load (W_L)
   From Table 44, live load is negligible at a depth of 50 feet.

3. Selection of Bedding
   Due to the high fill height you will more than likely want good support around the pipe, a Class B bedding will be assumed for this example.

4. Determination of Bedding Factor (B_f)
   First determine the H/B_c ratio.

   $H = 50$

   $$B_c = \frac{48 + 2\,(6.5)}{12}$$

   Note: Per ASTM C 507 the wall thickness for a 76"x48" elliptical pipe is 6.5 inches.

   $$\frac{H}{B_c} = 9.84$$

   From Table 59, for an H/B_c ratio of 9.84, $r_{sd}p$ value of 0.5, p value of 0.7, and a Class B bedding, a bedding factor of 2.71 is obtained.

   $B_{fe} = 2.71$

5. Application of Factor of Safety (F.S.)

A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength
The D-load is given by Equation 29

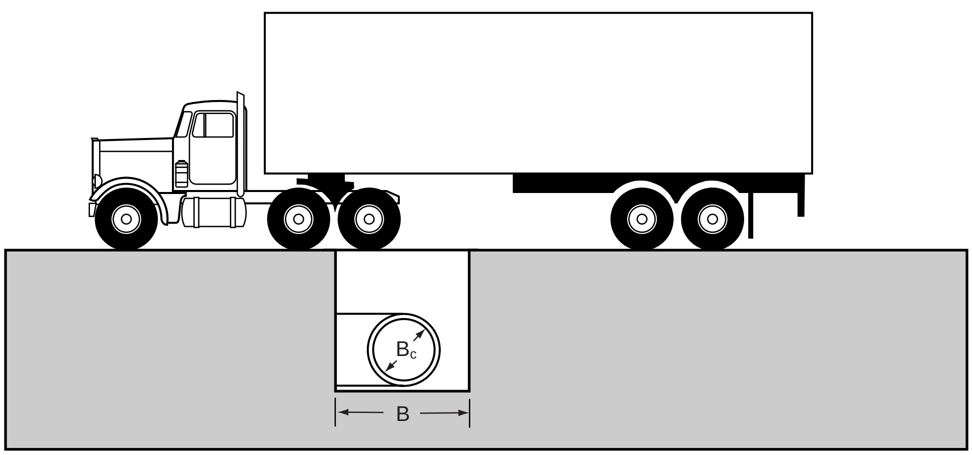
$W_E = W_c$ W_E = 49200 earth load in pounds per linear foot
W_L = 0 live load is negligible
B_{fe} = 2.71 earth load bedding factor
B_{fLL} = N/A live load bedding factor is not applicable
S = 4 inside diameter of pipe in feet

$$D_{0.01} = \left(\frac{49200}{2.71}\right)\left(\frac{1.0}{4}\right) \quad \text{Equation 29}$$

$D_{0.01}$ = 4539 pounds per linear foot per foot of inside horizonal span

Answer: A pipe which would withstand a minimum three-edge bearing test load for the 0.01 inch crack of 4539 pounds per linear foot per foot of inside horizontal span would be required.

EXAMPLE 4-7
Highway Live Load



Given: A 24 inch circular pipe is to be installed in a positive projection embankment under an unsurfaced roadway and covered with 2.0 feet of 120 pounds per cubic foot backfill material.

Find: The required pipe strength in terms of 0.01 inch crack D-load.

1. Determination of Earth Load (W_E)
   Per the given information, the installation behaves as a positive projecting embankment. Therefore, use Equation 4 to determine the soil prism load and multiply it by the appropriate vertical arching factor.

$$D_o = \frac{24 + 2 \times 3}{12}$$

Note: Per ASTM C 76 the wall thickness for a 24 inch diameter pipe with a B wall is 3 inches.

D_o = 2.5 outside diameter of pipe in feet

w = 120 unit weight of soil in pounds per cubic foot

H = 10 height of cover in feet

$$PL = 120 \times \left[2 + \frac{2.5 (4 - \pi)}{8}\right] \times 2.5 \qquad \text{Equation 4}$$

PL = 680 pounds per linear foot

Assume a Type 2 Standard Installation and use the appropriate vertical arching factor listed below Equation 4.

VAF = 1.4

W_E = 1.40 x 680

W_E = 952 earth load in pounds per linear foot

2. Determination of Live Load (W_L)
   Since the pipe is being installed under an unsurfaced roadway with shallow cover, a truck loading based on AASHTO will be evaluated. From Table 42, for D = 24 inches and H = 2.0 feet, a live load of 1780 pounds per linear foot is obtained. This live load value includes impact.

   W_L = 1780 pounds per linear foot

3. Selection of Bedding
   A Type 2 Standard Installation will be used for this example.

4. Determination of Bedding Factor
   a.) Determination of Earth Load Bedding Factor

   B_{fe} = 3.0

   From Illustration 4.19, the earth load bedding factor for a 24 inch pipe installed in a Type 2 positive projecting embankment condition is 3.0.

b.) Determination of Live Load Bedding Factor
From Illustration 4.21, the live load bedding factor for a 24 inch pipe under 2 feet of cover is 2.2.

$B_{fLL} = 2.2$

5. Application of Factor of Safety (F.S.)
A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength
The D-load is given by Equation 28

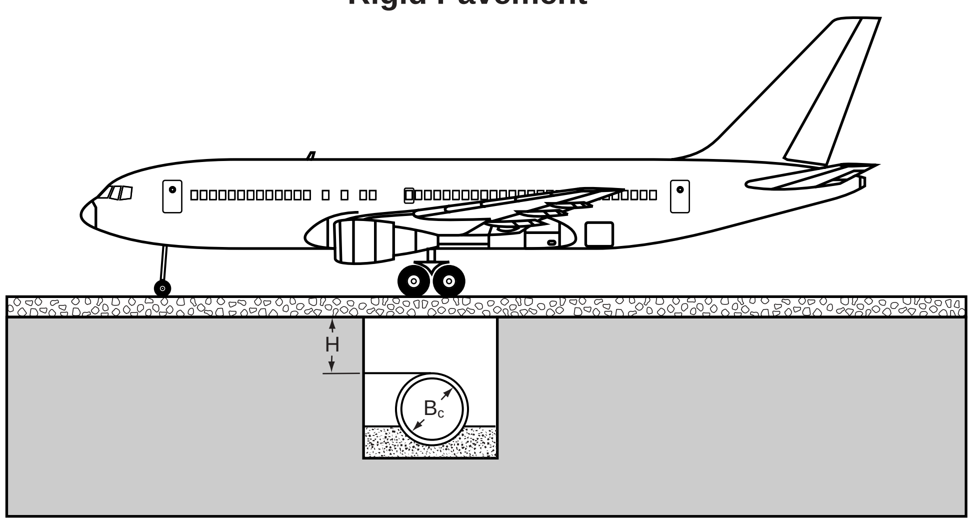
$W_E = 952$ earth load in pounds per linear foot
$W_L = 1780$ live load in pounds per linear foot
$B_{fe} = 3$ earth load bedding factor
$B_{fLL} = 2.2$ live load bedding factor
$D = 2$ inside diameter of pipe in feet

$$D_{0.01} = \left[\left(\frac{952}{3}\right) + \left(\frac{1780}{2.2}\right)\right]\left(\frac{1.0}{2}\right) \qquad \text{Equation 28}$$

$D_{0.01} = 597.3$ pounds per linear foot per foot of diameter

Answer: A pipe which would withstand a minimum three-edge bearing test for the 0.01 inch crack of 563.2 pounds per linear foot per foot of inside diameter would be required.

EXAMPLE 4-8
Aircraft Live Load
Rigid Pavement



Given: A 12 inch circular pipe is to be installed in a narrow trench, B_d = 3ft under a 12 inch thick concrete airfield pavement and subject to heavy commercial aircraft loading. The pipe will be covered with 1.0 foot (measured from top of pipe to bottom of pavement slab) of sand and gravel material weighing 120 pounds per cubic foot.

Find: The required pipe strength in terms of 0.01 inch crack D-load.

1. Determination of Earth Load (W_E)
   Per review of Table 13, the 3 ft. trench is wider than transition width. Therefore, the earth load is equal to the soil prism load multiplied by the appropriate vertical arching factor.

$$D_o = \frac{12 + 2\,(2)}{12}$$

Note: Per ASTM C 76 the wall thickness for a 12 inch diameter pipe with a B wall is 2 inches.

D_o = 1.33 outside diameter of pipe in feet

w = 120 unit weight of soil in pounds per cubic foot

H = 1 height of cover in feet

$$PL = 120 \times \left[1 + \frac{1.33 \times (4 - \pi)}{8}\right] \times 1.33$$

PL = 182 pounds per linear foot

Immediately listed below Equation 4 are the vertical arching factors (VAFs) for the four types of Standard Installations. Using a VAF of 1.40 for a Type 2 Installation, the earth load is:

W_E = 1.40 x 182

W_E = 255 pounds per linear foot

The weight of concrete pavement must be included also. Assuming 150 pounds per cubic foot unit weight of concrete, the total weight of soil and concrete is:

W_E = 255 + 150 x 1.0 x 133

W_E = 455 pounds per linear foot

2. Determination of Live Load (W_L)
   It would first be necessary to determine the bearing value of the backfill and/or subgrade. A modulus of subgrade reaction, k = 300 pounds per cubic inch will be assumed for this example. This value is used in Table 53A and represents a moderately compacted granular material, which is in line with the Type 2 Installation we are using.

Based on the number of undercarriages, landing gear configurations and gross weights of existing and proposed future aircrafts, the Concorde is a reasonable commercial aircraft design loading for pipe placed under airfields. From Table 53A, for D = 12 inches and H = 1.0 foot, a live load of 1,892 pounds per linear foot is obtained.

$W_L = 1892$ pounds per linear foot

3. Selection of Bedding
   Since this installation is under an airfield, a relatively good installation is required, therefore use a Type 2 Installation.

4. Determination of Bedding Factor
   a.) Determination of Earth Load Bedding Factor

   From Illustration 4.19, the earth load bedding factor for a 12 inch pipe installed in a positive projecting embankment condition is 3.2.

   $B_{fe} = 3.2$

   b.) Determination of Live Load Bedding Factor

   From Illustration 4.21, the live load bedding factor for a 12 inch pipe under 2 feet of cover (one foot of pavement and one foot of soil) is 2.2.

   $B_{fLL} = 2.2$

5. Application of Factor of Safety (F.S.)
   A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength
   The D-load is given by Equation 28

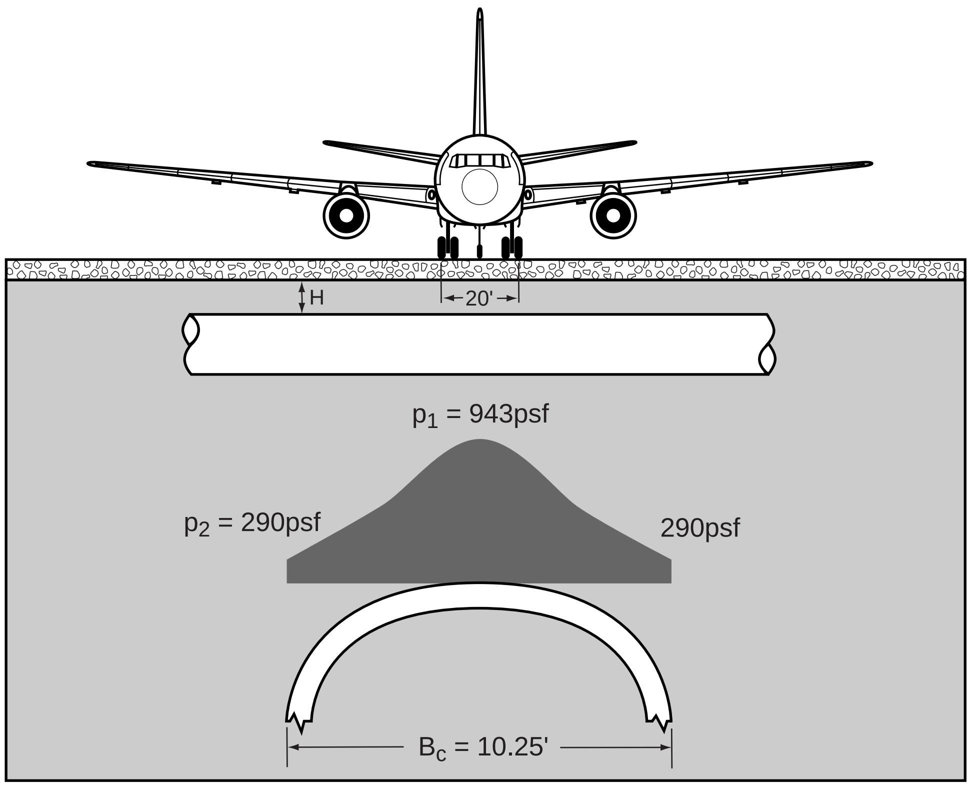
$W_E = 455$ earth load in pounds per linear foot
$W_L = 1892$ live load in pounds per linear foot
$B_{fe} = 3.2$ earth load bedding factor
$B_{fLL} = 2.2$ live load bedding factor
$D = 1$ inside diameter of pipe in feet

$$D_{0.01} = \left[\left(\frac{455}{3.2}\right) + \left(\frac{1892}{2.2}\right)\right]\left(\frac{1.0}{1}\right) \qquad \text{Equation 28}$$

$D_{0.01} = 1002$ pounds per linear foot per foot of diameter

Answer: A pipe which would withstand a minimum three-edge bearing test for the 0.01 inch crack of 1002 pounds per linear foot per foot of inside diameter would be required.

EXAMPLE 4-9
Aircraft Live Load
Flexible Pavement



Given: A 68 inch x 106 inch horizontal elliptical pipe is to be installed in a positive projecting embankment condition under a 7 inch thick concrete airfield pavement and subject to two 60,000 pound wheel loads spaced 20 feet, center to center. The pipe will be covered with 3-feet (measured from top of pipe to bottom of pavement slab) of sand and gravel material weighing 120 pounds per cubic foot.

Find: The required pipe strength in terms of 0.01 inch crack D-load.

1. Determination of Earth Load (W_E)
   Note: The Standard Installations were initially developed for circular pipe, and their benefit has not yet been established for elliptical and arch pipe. Therefore, the traditional Marston/Spangler design method using B and C beddings is still conservatively applied for these shapes.

A settlement ratio must first be assumed. In Table 40, values of settlement ratio from +0.5 to +0.8 are given for positive projecting installations on a foundation of ordinary soil. A value of 0.7 will be used. The product of the settlement ratio and the projection ratio will be 0.49 ($r_{sd}p$ approximately 0.5).

Enter Figure 187 on the horizontal scale at H = 3 ft. Proceed vertically until the line representing R x S = 68" x 106" is intersected. At this point the vertical scale shows the fill load to be 3,400 pounds per linear foot for 100 pounds per cubic foot fill material. Increase the load 20 percent for 120 pound material.

$W_d = 3400 \times 1.2$

$W_d = 4080$ pounds per linear foot

outside span of pipe is:

$$B_c = \frac{106 + 2\,(8.5)}{12}$$

Note: Wall thickness for a 68"x106" elliptical concrete pipe per ASTM C 507 is 8.5 inches.

$B_c = 10.25$ feet

Assuming 150 pounds per cubic foot concrete, the weight of the pavement is:

$$W_p = 150 \times \frac{7}{12} \times 10.25$$

$W_p = 897$ pounds per linear foot

$W_E = W_d + W_p$

$W_E = 4977$ pounds per linear foot

2. Determination of Live Load (W_L)

Assuming a modulus of subgrade reaction of k = 300 pounds per cubic inch and a pavement thickness of h = 7 inches, a radius of stiffness of 24.99 inches (2.08 feet) is obtained from Table 52. The wheel spacing in terms of the radius of stiffness is 20/2.08 = 9.6 Rs, therefore the maximum live load on the pipe will occur when one wheel is directly over the centerline of the pipe and the second wheel disregarded. The pressure intensity on the pipe is given by Equation 17:

$$p_{(H,X)} = \frac{C \times P}{R_S^2} \qquad \text{Equation 17}$$

The pressure coefficient (C) is obtained from Table 46 at x = 0 and H = 3 feet.

For $x/R_s = 0$ and $H/R_s = 3/2.08 = 1.44$, C = 0.068 by interpolation between $H/R_s = 1.2$ and $H/R_s = 1.6$ in Table 46.

$$p_3 = \frac{(0.068)(60{,}000)}{(2.08)^2} \qquad \text{Equation 17}$$

p_3 = 943 pounds per square foot

In a similar manner pressure intensities are calculated at convenient increments across the width of the pipe. The pressure coefficients and corresponding pressures in pounds per square foot are listed in the accompanying table.

Point	x/R_S								
	0.0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2
Pressure Coefficient C	0.068	0.064	0.058	0.050	0.041	0.031	0.022	0.015	0.010
Pressure psf	943	887	804	693	568	430	305	208	139

For convenience of computing the load in pounds per linear foot, the pressure distribution can be broken down into two components; a uniform load of 290 pounds per square foot and a parabolic load with a maximum pressure of 653 pounds per square foot.

$$W_L = p_2 \times B_c + \frac{2}{3}(p_1 - p_2)\,B_c$$

$$W_L = 290 \times 10.25 + \frac{2}{3}(943 - 290)\,10.25$$

W_L = 7435 pounds per linear foot

3. Selection of Bedding
   A Class B bedding will be assumed for this example.

4. Determination of Bedding Factor
   a.) Determination of Earth Load Bedding Factor

   From Table 60, a Class B bedding with p = 0.7, H/B_c = 3 ft/10.25 ft. = 0.3, and $r_{sd}p$ = 0.5, an earth load bedding factor of 2.42 is obtained.

   $B_{fe} = 2.42$

b.) Determination of Live Load Bedding Factor

Live Load Bedding Factors are given in Illustration 4.21 for circular pipe. These factors can be applied to elliptical pipe by using the span of the pipe in place of diameter. The 106" span for the elliptical pipe in this example is very close to the 108" pipe diameter value in the table. Therefore, from Illustration 4.21, the live load bedding factor for a pipe with a span of 108 inches, buried under 3.5 feet of fill (3 feet of cover plus 7 inches of pavement is approx. 3.5 feet) is 1.7.

$B_{fLL} = 1.7$

5. Application of Factor of Safety (F.S.)
A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of pipe strength
The D-load given is given by Equation 29

$W_E = 4977$ earth load in pounds per linear foot

$W_L = 7435$ live load is negligible

$B_{fe} = 2.42$ earth load bedding factor

$B_{fLL} = 1.7$ live load bedding factor

$$S = \frac{106}{12}$$

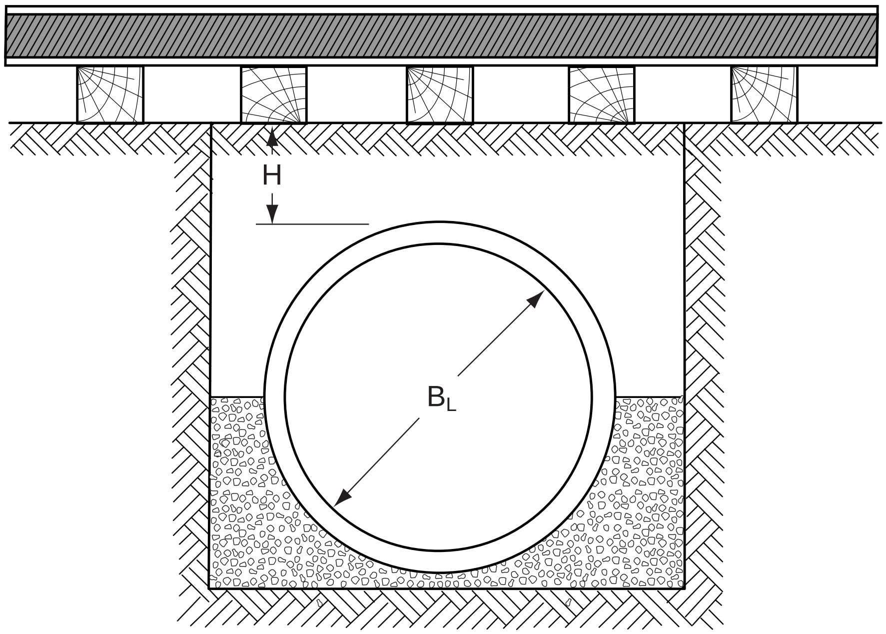
$S = 8.83$ inside span of pipe in feet

$$D_{0.01} = \left[\left(\frac{4977}{2.42}\right) + \left(\frac{7435}{1.7}\right)\right]\left(\frac{1.0}{8.83}\right) \qquad \text{Equation 29}$$

$D_{0.01} = 728$ pounds per linear foot per foot of inside horizontal span

Answer: A pipe which would withstand a minimum three-edge bearing test load for the 0.01 inch crack of 728 pounds per linear foot per foot of inside horizontal span would be required.

EXAMPLE 4-10
Railroad Live Load



Given: A 48 inch circular pipe is to be installed under a railroad in a 9 foot wide trench. The pipe will be covered with 1.0 foot of 120 pounds per cubic foot overfill (measured from top of pipe to bottom of ties).

Find: The required pipe strength in terms of 0.01 inch crack D-load.

1. Determination of Earth Load (W_E)
   The transition width tables do not have fill heights less than 5 ft. With only one foot of cover, assume an embankment condition. An installation directly below the tracks such as this would probably require good granular soil well compacted around it to avoid settlement of the tracks. Therefore assume a Type 1 Installation and multiply the soil prism load by a vertical arching factor of 1.35.

$$D_o = \frac{48 + 2\,(5)}{12}$$

Note: Per ASTM C 76 the wall thickness for a 48 inch diameter pipe with a B wall is 5 inches.

D_o = 4.83 outside diameter of pipe in feet

w = 120 unit weight of soil in pounds per cubic foot

H = 1 height of cover in feet

$$PL = 120 \times \left[1 + \frac{4.83 \times (4 - \pi)}{8}\right] \times 4.83 \qquad \text{Equation 4}$$

PL = 880 pounds per linear foot

Immediately listed below Equation 4 are the vertical arching factors (VAFs) for the four types of Standard Installations. Using a VAF of 1.35 for a Type 1 Installation, the earth load is:

$W_E = 1.35 \times 880$

$W_E = 1188$ pounds per linear foot

2. Determination of Live Load (W_L)
   From Table 56, for a 48 inch diameter concrete pipe, H = 1.0 foot, and a Cooper E80 design load, a live load of 13,200 pounds per linear foot is obtained. This live load value includes impact.

   $W_L = 13200$ pounds per linear foot

3. Selection of Bedding
   Since the pipe is in shallow cover directly under the tracks, a Type 1 Installation will be used.

4. Determination of Bedding Factor
   a.) Determination of Earth Load Bedding Factor

   The embankment bedding factor for 48 inch diameter pipe in a Type 1 Installation may be interpolated from Illustration 4.19.

   $B_{fe36} = 4.0$
   $B_{fe72} = 3.8$

   $$B_{fe} = \frac{72 - 48}{72 - 36}(4.0 - 3.8) + 3.8$$

   $B_{fe} = 3.93$

   b.) Determination of Live Load Bedding Factor

   From Illustration 4.21, the live load bedding factor for a 48 inch pipe installed under 1 foot of cover is:

   $B_{fLL} = 1.5$

5. Application of Factor of Safety (F.S.)
   A factor of safety of 1.0 based on the 0.01 inch crack will be applied.

6. Selection of Pipe Strength
   The D-load is given by Equation 28

W_E = 1188 earth load in pounds per linear foot
W_L = 13200 live load is negligible
B_{fe} = 3.93 earth load bedding factor
B_{fLL} = 1.5 live load bedding factor
D = 4

$$D_{0.01} = \left[\left(\frac{1188}{3.93}\right) + \left(\frac{13200}{1.5}\right)\right]\left(\frac{1.0}{4}\right)$$

$D_{0.01}$ = 2276 pounds per linear foot per foot of diameter

Answer: A pipe which would withstand a minimum three-edge bearing test for the 0.01 inch crack of 2276 pounds per linear foot per foot of inside diameter would be required.