# 1. STRUCTURAL DESIGN OF RIGID AND FLEXIBLE CONDUITS

Designers should refer to the special plans for bedding and backfill requirements for culvert installation with up to 40 ft of fill. For culverts with over 40 ft of fill, designers should contact the **Highway Materials and Tests Manager** of the **Material and Research Division**.

## 1.A General

This section discusses the structural design of rigid and flexible conduits used for storm sewers, culverts, and sanitary sewers. The principles for calculating the external dead and live loads on underground conduits are based on studies conducted at Iowa State University by Marston, Schlick and Spangler. Soil Engineering, (Reference 1), provides additional discussion.

## 1.B Classification of Conduits

ASTM establishes standards for all types of materials.

### 1.B.1 Degree of Rigidity

Types of conduits available on the market today are as follows (classed by rigidity):

Rigid Conduits:

- Vitrified clay pipe (ASTM C 700, AASHTO M 65)
- Non-reinforced concrete pipe (ASTM C 985)
- Reinforced concrete pipe (ASTM C 76)
- Reinforced concrete arch pipe (ASTM C 506, AASHTO M 206)
- Reinforced concrete elliptical pipe (ASTM C 507, AASHTO M 207)
- Reinforced concrete culvert pipe (ASTM C76, AASHTO M 170)

Semirigid Conduits:

- Ductile iron pipe (ASTM A 746)

Flexible Conduits:

- Steel pipe (ASTM A 761)
- Corrugated metal pipe (ASTM A 806, AASHTO M 218)
- High-density polyethylene, HDPE (ASTM F 894, AASHTO M 294)
- Polyvinyl chloride, PVC (ASTM F 679)
- Acrylonitrile butadiene styrene, ABS (ASTM D 2680)
- Corrugated metal pipe, aluminized (ASTM C 76, AASHTO M 36)
- Aluminum corrugated pipe (ASTM B 790, AASHTO M 196)
- Corrugated metal pipe-arch (ASTM A 806, AASHTO M 218)
- Corrugated metal pipe-arch, aluminized (ASTM A 760, AASHTO M 36).

Semirigid conduits are generally considered rigid conduits for determining earth loads. Pipe material selection is a matter of policy (See Appendix C, "Pipe Material Policy").

### 1.B.2 Method of Installation

In order to determine the required design strength of a buried conduit, it is necessary to determine the total load that will be imposed upon the conduit. Calculation of the imposed loads is influenced by the installation condition. Underground conduits are classified into several groups and subgroups based upon the installation condition.

The two major classes are trench conduits and embankment conduits. Trench conduits are placed in natural ground in relatively narrow trenches. Embankment conduits are usually placed on natural ground and are overlaid by a constructed embankment.

The embankment group is further divided into positive projecting, negative projecting and induced trench subgroups, based upon the extent the pipe is exposed to direct embankment loading. Further subdivisions of the positive and negative projecting embankment groups are related to whether or not differential settlements may occur throughout the entire depth of backfill. EXHIBIT I.1 depicts the different features of the various types of installation conditions.

This appendix does not discuss loads on conduits installed in tunnel conditions.

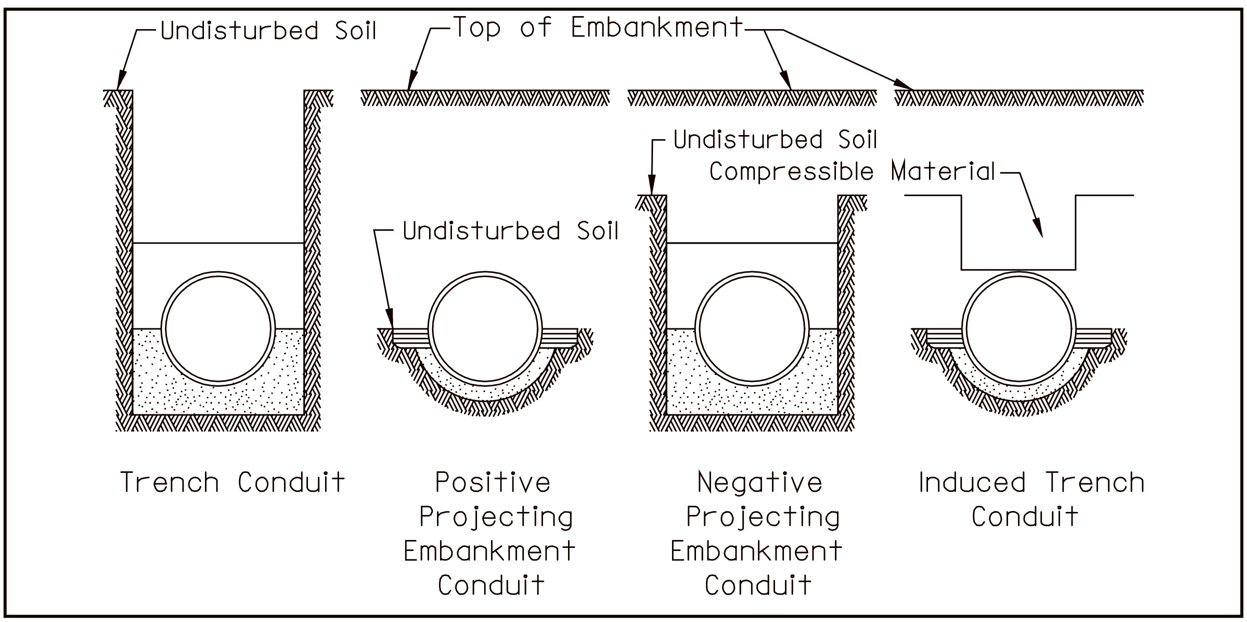


**Exhibit I.1 Features of the Various Types of Underground Conduit Installations**

## 1.C Design of Rigid Conduits

The governing standards most commonly used in the design of rigid conduits are those issued by ASTM. The designer should become familiar with these standards. Projects under design may have site-specific features that require modification of the standard.

### 1.C.1 Earth Loads on Trench Conduits

Trench conduits are installed in relatively narrow trenches excavated in undisturbed soil and then covered with earth backfill that extends to the original ground surface. The backfill load on the conduit is equal to the weight of the backfill material less the summation of the frictional load transfers, and is expressed by the equation:

$$W_c = C_d\ w\ B_d^2 \qquad \text{Eq. I.1}$$

where: $W_c$ = Backfill load on conduit, lbs/lin ft.;
$C_d$ = Load coefficient for trench condition;
$w$ = Unit weight of backfill material, lbs/cu ft.;
$B_d$ = Width of trench at top of conduit, ft.

Equation I.1 indicates the width of the trench at the top of the pipe is the controlling factor in determining the backfill load on the conduit. At any given depth and for any given conduit size, however, there is a certain limiting value to the width of trench beyond which no additional load is transmitted to the conduit. This limiting value is called the “transition width.” There are sufficient experimental data to show that it is safe to calculate the imposed load by means of the trench conduit formula (Eq. I.1) for all widths of trench less than that which gives a load equal to the load calculated by the positive projecting embankment conduit formula (Eq. I.2). In other words, as the width of the trench increases, other factors remaining constant, the load on a rigid conduit increases in accordance with the theory for a trench conduit until it equals the load determined by the theory for a positive projecting conduit. EXHIBIT J.1 in Appendix J, “Nomographs & Charts for Designing Earth Loads on Conduits”, provides load coefficient ($C_d$) for trench condition.

### 1.C.2 Earth Loads on Positive Projecting Embankment Conduits

Positive projecting conduits are installed in shallow bedding with the top of the conduit projecting above the surface of the natural ground, or compacted fill at the time of installation, and then covered with earth fill. The load on a positive projecting conduit is computed by the equation:

$$W_c = C_c\ w\ B_c^2 \qquad \text{Eq. I.2}$$

where: $W_c$ = Fill load on the conduit, lbs/lin ft.;
$C_c$ = Load coefficient for positive projecting embankment condition;
$w$ = Unit weight of fill material, lbs/cu ft.;
$B_c$ = Outside diameter of the conduit, ft.

EXHIBIT J.2 in Appendix J, “Nomographs & Charts for Designing Earth Loads on Conduits”, provides values for the load coefficient ($C_c$) for positive projecting embankment condition. Values to be used for w and $C_c$ are discussed further in Section 1.C.6. The $r_{sd}$ values can be obtained from EXHIBIT I.2.

| Installation and Foundation Condition | Settlement Ratio $R_{sd}$ Usual Range | Design Value |
|---|---|---|
| Positive Projecting............................. | 0.0 to +1.0 | |
| Rock or Unyielding Soil................. | +1.0 | +1.0 |
| *Ordinary Soil............................... | +0.5 to +0.8 | +0.7 |
| Yielding Soil.................................. | 0.0 to +0.5 | +0.3 |
| Zero Projecting................................. | | 0.0 |
| Negative Projecting........................... | -1.0 to 0.0 | |
| p'=0.5........................................... | | -0.1 |
| p'=1.0........................................... | | -0.3 |
| p'=1.5........................................... | | -0.5 |
| p'=2.0........................................... | | -1.0 |
| Induced Trench................................ | -2.0 to 0.0 | |
| p'=0.5........................................... | | -0.5 |
| p'=1.0........................................... | | -0.7 |
| p'=1.5........................................... | | -1.0 |
| p'=2.0........................................... | | -2.0 |

* The value of the settlement ratio depends on the degree of compaction of the fill material adjacent to the sides of the pipe. With good construction methods resulting in proper compaction of bedding and sidefill materials, a settlement ratio design value of +0.5 is recommended.

**Exhibit I.2 Design Values of Settlement Ratio ($r_{sd}$)**

### 1.C.3 Earth Loads on Negative Projecting Embankment Conduits

Negative projecting conduits are those which are installed in shallow trenches of such depth that the top of the conduit is below the surface of the natural ground or compacted fill and then covered with an embankment, which extends above this ground level. The procedure for computing the load on a negative projecting conduit is similar to that used in computing the load on a positive projecting conduit:

$$W_c = C_n \, w \, B_d \, B'_d \qquad \text{Eq. I.3}$$

where:
- $W_c$ = Fill load on the conduit, lbs/lin ft;
- $C_n$ = Load coefficient for negative projecting embankment condition;
- $w$ = Unit weight of fill material, lbs/cu ft;
- $B_d$ = Width of trench at top of the conduit, ft;
- $B'_d$ = Average of the width of trench at the top of the conduit in ft, and the outside diameter of the conduit in ft: $(B_d + B_c)/2$

EXHIBIT J.3 in Appendix J, "Nomographs & Charts for Designing Earth Loads on Conduits", provides values for the load coefficient ($C_n$) for negative projecting embankment conditions and induced trench embankment conditions.

### 1.C.4 Earth Loads on Induced Trench Embankment Conduits

The induced trench method of construction is a practical method for relieving the load on conduits placed under very high fills. The essential features of this method of construction are described as follows:

1. Install the pipe in the same manner as a positive projecting embankment conduit with the desired class of bedding.
2. Compact fill material at each side of the pipe for a lateral distance equal to twice the outside diameter of the pipe or 12 ft, whichever is less. This fill is constructed up to an elevation of at least one pipe diameter over the top of the pipe.
3. Excavate a trench in the compacted fill directly over the pipe. The depth of the trench should be at least one pipe diameter and the width should coincide as nearly as possible with the outside diameter of the pipe.
4. Refill the induced trench with loose compressible material such as straw, sawdust or organic soil.
5. Complete the balance of the fill by normal methods up to the finished grade of the embankment.

The induced trench method of construction can also be obtained by constructing the embankment, before the pipe is installed, to an elevation above the top of the pipe equal to the external diameter of the pipe after which the trench is excavated and the pipe installed. Loose backfill is then placed directly above the pipe and the embankment completed.

The load on a conduit installed by the induced trench method is computed by the equation:

$$W_c = C_n \, w \, B_c^2 \qquad \text{Eq. I.4}$$

where:
- $W_c$ = Fill load on the conduit, lbs/lin ft.;
- $C_n$ = Load coefficient for induced trench condition;
- $w$ = Unit weight of fill material, lbs/cu ft.;
- $B_c$ = Outside diameter of the conduit, ft.

The induced trench method produces a less severe loading condition than either the positive projecting or negative projecting embankment conditions. The load that the pipe must support is reduced because the fill over the pipe will settle downward relative to the adjacent fill, thus generating shearing forces in an upward direction. This method of construction has another advantage since the sidefill material can be readily compacted adjacent to the sides of the pipe. This high degree of compaction enables development of effective lateral pressure against the sides of the pipe, which increases the in-place supporting strength of the pipe.

### 1.C.5 Live Loads on Buried Conduits

In the structural design of rigid conduits, it is necessary to evaluate the effect of live loads when the conduit is installed with shallow cover (0.5 to 6 ft) under an unsurfaced roadway and subjected to heavy truck traffic. If pavement is designed for heavy truck traffic, the intensity of the live load is usually reduced sufficiently so that the live load transmitted to the conduit is negligible. In the case of flexible pavements designed for light traffic and subjected to heavy traffic, the distribution of the live load through the pavement structure to the subgrade must first be evaluated. The intensity of the distributed load at the subgrade surface should then be used to determine the live load on the conduit.

The distribution of a wheel load applied at the surface to any horizontal plane in the subsoil results in the intensity of the load on any plane in the soil mass being 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.

The total live load transmitted to an underground conduit can be determined by calculating the volume of the pressure intensity diagram. This volume is closely approximated by an elliptical cylinder and ellipsoid.

Based on this loading configuration, the total live load per ft of conduit is obtained from the equation:

$$W_L = \pi WL\ (2P_1 + P_2) / L + 24 \qquad \text{Eq. I.5}$$

where:
- $W_L$ = Total live load transmitted to the conduit, lbs/lin ft.;
- $\pi$ = 3.1416;
- $W$ = Width of loaded area, inches;
- $L$ = Length of loaded area, inches;
- $P_1$ = Vertical unit pressure at the center of the conduit due to applied live load, psi.;
- $P_2$ = Vertical unit pressure at the outside diameter of the conduit due to applied live load, psi.

### 1.C.6 Design Criteria for Calculating Earth Loads and Live Loads on Buried Rigid Conduits

The following section provides general design criteria for the designer when calculating earth loads and live loads on buried conduits.

#### 1.C.6.a Sidewall Clearances and Minimum Design Trench Widths

Designers, in some instances, use trenches that are too narrow in order to reduce the earth load on the conduit. Sidewall clearances need to be established to allow a worker sufficient room to properly place and compact bedding material to avoid pipe failure. Sidewall clearances should include an allowance for construction tolerances since the conduit is not always in the center of the trench.

After sidewall clearances are determined, minimum design trench widths should be established and used for calculation of earth loads on the conduit.

Construction specifications must include the maximum allowable trench width when installing conduits in a trench condition. If the maximum trench width specified is not maintained by the contractor in the field, pipe failure may occur.

### 1.C.6.b Unit Weight of Soil

Unit weight of soil should be obtained from soil borings for the project (See the Roadway Design Manual, Chapter Seven: Earthwork, Section 6, (http://www.roads.nebraska.gov/business-center/design-consultant/rd-manuals/), Reference 2). A unit weight of 120 lb/cu ft is generally sufficient if job specific data are not available.

### 1.C.6.c Load Coefficient (C)

The value for the load coefficient varies with the type of soil (cohesive or non-cohesive) and is also dependent on the product of K and u'. K is the ratio of active lateral unit soil pressure to vertical unit soil pressure, and u' is the coefficient of friction between the backfill material and trench walls.

Values to be used for the load coefficient can be found in EXHIBITS J.1, J.2 AND J.3 in Appendix J, "Nomographs & Charts for Designing Earth Loads on Conduits".

### 1.C.7 Design Strength of Rigid Conduits

The strength of a buried rigid conduit, or the load (dead and live load) that a buried rigid conduit is capable of supporting, is primarily dependent upon the class of pipe bedding utilized and the structural strength of the pipe itself.

### 1.C.7.a Pipe Bedding

The load that a pipe will support depends in part on the width of the bedding contact area and the quality of the contact between the pipe and the bedding. To develop the full load-bearing capacity of a pipe, a segment of the bottom of the pipe equal to or greater than one-fourth of the outside diameter ($B_c$) must be firmly supported. Bell holes must be carefully excavated at proper intervals to ensure that no part of the load is supported solely by the bells.

Pipe bedding should be continuous between manholes or in the case of a roadway cross section, continuous throughout the fill. In addition, the same class of conduit should be maintained throughout the installation. Three classes of bedding for both circular and arch conduits are shown in EXHIBITS I.3 AND I.4 for trench and embankment bedding, respectively. Normally, the installation will be Class C, shaped subgrades; however, in cases where heavy loading is anticipated, such as at railroad crossings or in high fills, two solutions are available:

- Increase the supporting strength of the conduit by specifying a higher pipe class.
- Increase the support capacity by using Class A or Class B bedding.

Load factors ($L_f$) for each class of pipe bedding are indicated on each figure.

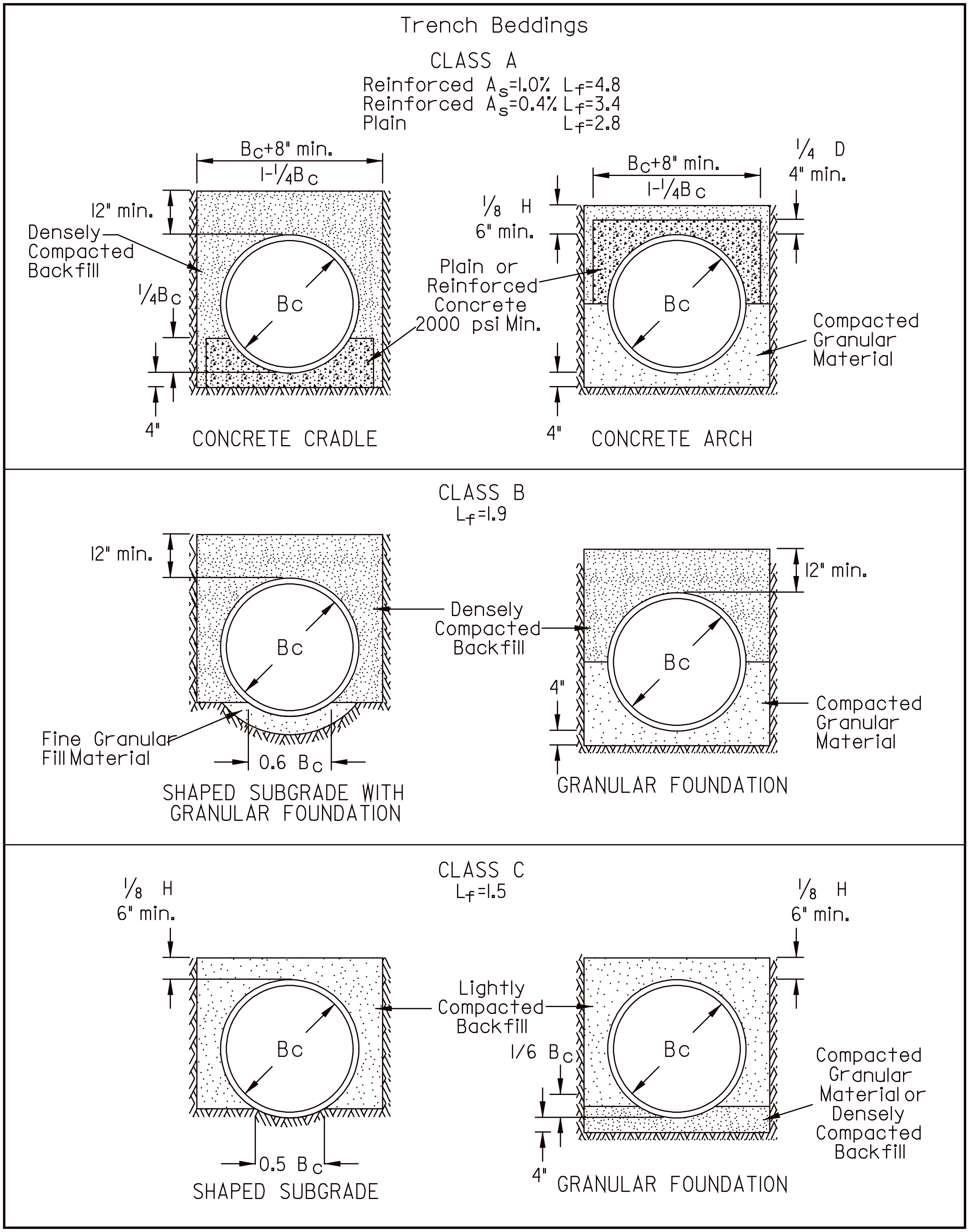


**Exhibit I.3 Trench Beddings**

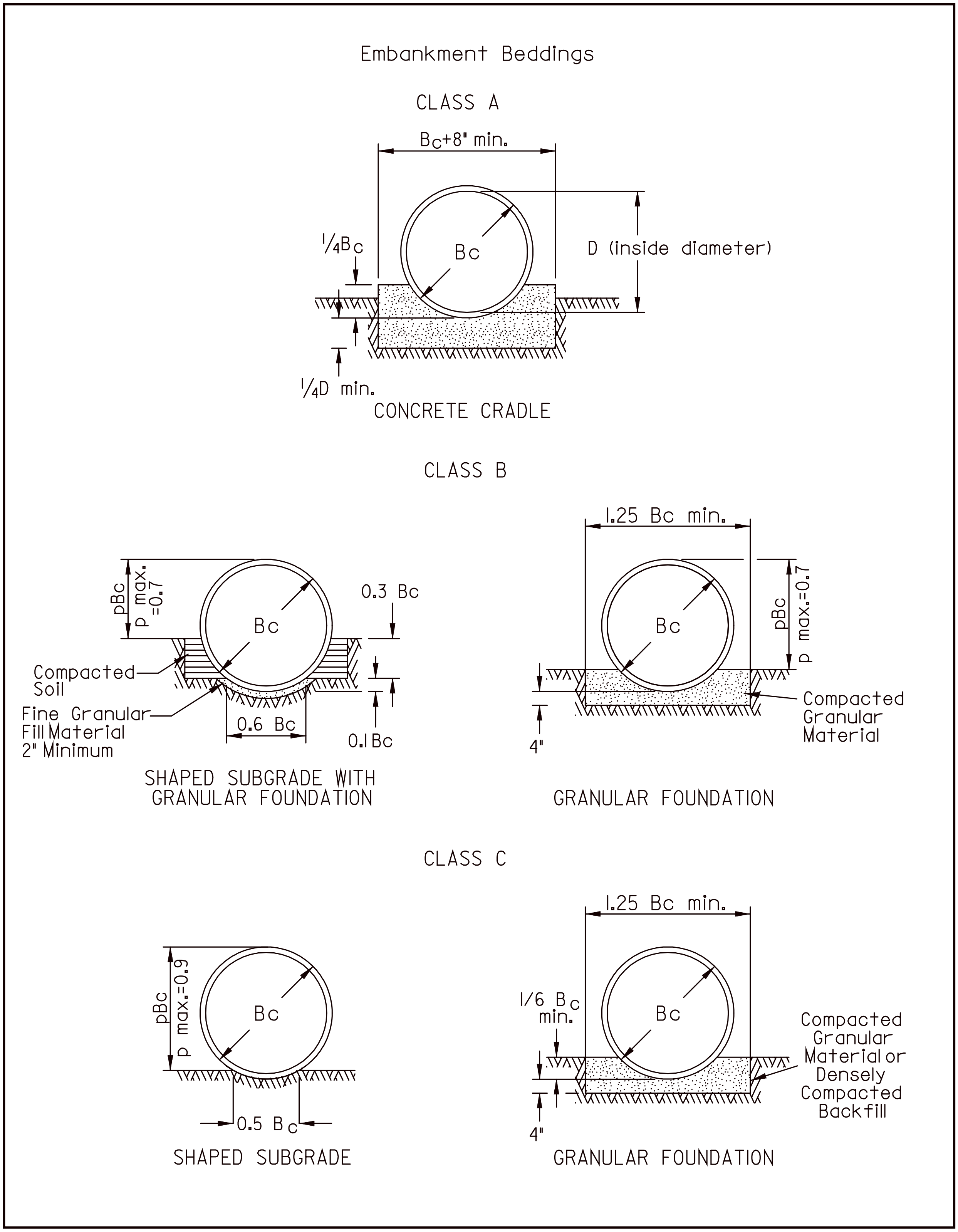


**Exhibit I.4 Embankment Beddings**

### 1.C.7.b Pipe Strength

Rigid conduits are tested for strength by the three-edge bearing test. The testing procedures are given in ASTM C 301 for vitrified clay pipe and ASTM C 497 for non-reinforced concrete pipe and reinforced concrete pipe. The three-edge bearing test is the most severe loading to which a rigid conduit will be subjected since the applied loads are essentially point loads.

Vitrified clay pipe and non-reinforced concrete pipe are tested to the ultimate load the pipe will withstand. Reinforced concrete pipe is tested to a load that will produce a 0.01 inch crack and the ultimate load the pipe will withstand. These loads are used to calculate the three-edge bearing strength.

Pipe classes are designated in the ASTM standards by the D-load where:

$$\text{D-Load} = \frac{TEB}{D} \qquad \text{Eq. I.6}$$

where:
- D-Load = lbs/lin ft/ft of diameter;
- TEB = three-edge bearing strength, lbs/lin ft;
- D = inside diameter of circular pipe (or inside horizontal span of elliptical and arch pipe), in ft.

D-load strength for reinforced concrete pipe can be classified as the 0.01 inch crack strength $D_{0.01}$, and the ultimate strength, $D_{ult}$. D-load strength for vitrified clay pipe and non-reinforced concrete pipe are designated only as ultimate strength, $D_{ult}$.

### 1.C.7.c Determination of Pipe Design Strength

Design strength can be determined from the following:

$$\text{design strength} = \frac{(\text{D-Load} \times D) \times L_f}{FS} \qquad \text{Eq. I.7}$$

where:
- design strength = lbs/lin ft.;
- D-Load = lbs/lin ft/ft diameter;
- D = Inside diameter of circular pipe (or inside horizontal span of elliptical and arch pipe), ft.;
- $L_f$ = Load factor for pipe bedding;
- FS = Factor of safety.

For reinforced concrete pipe, decide if the design strength should be based upon 0.01 inch crack strength ($D_{0.01}$) or ultimate strength ($D_{ult}$). Also determine the factor of safety to be used. Safety factors for rigid conduit design generally range from 1.1 to 1.5.

Solutions for the various equations utilized for the design of rigid conduits are provided in Sections 2.A and 2.B.

## 1.D Design of Flexible Conduits

The following section provides general guidance for the designer regarding the structural design of flexible conduits. Consult the Handbook of PVC Pipe: Design and Construction, (Reference 3), for detailed discussion and design procedures.

The Handbook of PVC Pipe: Design and Construction, (Reference 3), provides theory and procedures for design of PVC pipe. The flexible conduit theory in Reference 3 also applies to PE pipe, however, parameters for PE pipe such as modules of elasticity will be different.

### 1.D.1 Flexible Conduit Theory

A flexible conduit is generally defined as a pipe that will deflect at least 2% without any sign of rupture or cracking. A flexible pipe derives its soil carrying capability from its flexibility. The buried pipe under load tends to deflect. The deflection mechanism transfers the vertical force derived from the load into approximately horizontal forces that are, in turn, opposed by opposite and equal reactions derived from the side support soil.

The amount of deflection that will occur in any buried flexible pipe depends on three factors:

- Pipe stiffness.
- Soil stiffness.
- Earth load and dead load on the pipe.

For further information see Deflection: The Pipe/Soil Mechanism, (Reference 4), (https://www.uni-bell.org/resources/applications/storm-sewer/engineering-design).

### 1.D.2 Pipe Stiffness

Pipe stiffness, as a value for a specific flexible pipe, is the unit load required to produce deflection in parallel plate loading to an arbitrary value, usually 5%.

Three-edge loading to failure is an appropriate measure of load bearing strength for rigid pipe but not for flexible pipe. When considering the load-carrying capability of flexible pipe, the soil stiffness must be considered as well as the pipe stiffness.

Pipe stiffness can be defined by the following equation:

$$PS = F/\Delta Y \geq \frac{EI}{0.149r^3} = 0.559\ E\ (t/r)^3$$ Eq. I.8

where:
- $PS$ = Pipe stiffness, lbs/lin inch/inch or psi.;
- $F$ = Force, lbs/lin inch;
- $\Delta Y$ = Vertical deflection, inch;
- $E$ = Modulus of tensile elasticity, psi.;
- $I$ = Moment of inertia of the wall cross-section per unit length of pipe, $in^4$/linear inch = $in^3$.;
- $r$ = Mean radius of pipe, inch;
- $t$ = Wall thickness, inch.

Theoretical pipe stiffness may be calculated using the following equation:

$$PS = 4.47 \left[ E/(DR-1)^3 \right] \quad \text{Eq. I.9}$$

where:
- E = Modulus of tensile elasticity, psi.;
- DR = Dimension ratio = $\frac{OD}{t}$
- OD = Outside diameter, inch.
- t = Minimum wall thickness, inch.

An arbitrary data point of 5% deflection has been selected to permit meaningful comparison of pipe stiffness in different flexible pipes. Pipe stiffness values for all flexible pipes will vary with deflection. Pipe stiffness values can be obtained from the pipe manufacturer.

### 1.D.3 Soil Stiffness

Soil stiffness is defined as the soil's ability to resist deflection. Because of the ability of flexible pipe to interact with the surrounding soil in supporting a given load, soil stiffness is very important. The measurement of soil stiffness is termed the modulus of passive resistance (e). The modulus of passive resistance of side support soil is considered to be the unit pressure developed as the side of a flexible pipe moves outward against the side fill. The E' value is commonly termed the modulus of soil reaction and is defined as the product of the modulus of passive soil resistance, e, and the mean pipe radius.

EXHIBIT I.5 provides E' values for different types of soils, embedment materials, and densities.

| **Soil Type-Pipe Bedding Material (Unified Classification System[a]) (1)** | **E' for Degree of Compaction of Pipe Zone Backfill, psi** | | | |
|---|---|---|---|---|
| | **Loose (2)** | **Slight < 85% Proctor. < 40% relative density (3)** | **Moderate 85%-95% Proctor. 40%-70% relative density (4)** | **High >95% Proctor. > 70% relative density (5)** |
| Fine-grained soils (LL > 50)[b] Soils with medium to high plasticity CH, MH, CH-MH | No data available: consult a competent soils engineer: Otherwise use E' = 0 | | | |
| Fine-grained soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25% coarse-grained particles | 50 | 200 | 400 | 1,000 |
| Fine-grained soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25% coarse-grained particles Coarse-grained soils with fines GM, GC, SM, SC[c] contains more than 12% fines | 100 | 400 | 1,000 | 2,000 |
| Coarse-grained soils with little or no fines GW, GP, SW, SP[c] contains less than 12% fines | 200 | 1,000 | 2,000 | 3,000 |
| Crushed rock | 1,000 | 3,000 | 3,000 | 3,000 |
| Accuracy in terms of percentage deflection[d] | ± 2 | ± 2 | ± 1 | ± 0.5 |

[a]ASTM Designation D 2487, USBR Designation E-3.
[br]LL = Liquid Limit.
[c]Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).
[d]For ±1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%.

Note: Values applicable only for fills less than 50 ft (15 m) . Table does not include any safety factor. For use in predicting initial deflections only, appropriate deflection lag factor must be applied for long-term deflections. If bedding fails on the borderline between two compaction categories, select lower E' value or average the two values. Percentage Proctor based on laboratory maximum dry density from test standards using about 12,500 ft-lb/cu ft (598.000 J/m$^3$) (ASTM D 698, AASHO -T99, USBR Designation E-11), 1 psi = 6.9 kN/m$^2$.

**Exhibit I.5 Average Values of Modulus of Soil Reaction, E'**
**(For Initial Flexible Pipe Deflection) (Source: Reference 5)**

### 1.D.4 Earth Loads on Flexible Conduits

The embankment load is used to calculate earth load on flexible pipe installed in trench conditions and is derived by determining the load imposed by the weight of the vertical prism of soil over the buried pipe, and is calculated as follows:

$$W_c = HwB_c \qquad \text{Eq. I.10}$$

where:
- $W_c$ = Load on the conduit, lbs/lin ft.;
- H = Height of cover over the conduit, ft.;
- w = Unit weight of backfill, lbs/ft$^3$.;
- $B_c$ = Outside diameter of conduit, ft.

When the prism load is expressed in psi, Eq. I.10 becomes:

$$P = \frac{wH}{144} \qquad \text{Eq. I.11}$$

where:
- P = Prism load on conduit, psi.;
- w = Unit weight of backfill, lbs/ft$^3$.;
- H = Height of cover over the conduit, ft.

Earth loads on buried flexible pipe when calculated using the prism load equation (Eq. I.11) provide a conservative design.

### 1.D.5 Live Loads on Flexible Conduits

The effects of live loads on flexible conduits are shown in EXHIBIT I.6. Generally, live loads are only significant at shallow depths.

| Height Of Cover (ft) | Live Load Transferred To Pipe, lb/in$^2$ Highway H20[(A)] | Railway E80[(B)] | Airport [(C)] | Height Of Cover (ft) | Live Load Transferred To Pipe, lb/in$^2$ Highway H20[(A)] | Railway E80[(B)] | Airport [(C)] |
|---|---|---|---|---|---|---|---|
| 1 | 12.50 | N.R. | N.R. | 16 | N.S. | 3.47 | 2.29 |
| 2 | 5.56 | 26.39 | 13.14 | 18 | N.S. | 2.78 | 1.91 |
| 3 | 4.17 | 23.61 | 12.28 | 20 | N.S. | 2.08 | 1.53 |
| 4 | 2.78 | 18.40 | 11.27 | 22 | N.S. | 1.91 | 1.14 |
| 5 | 1.74 | 16.67 | 10.09 | 24 | N.S. | 1.74 | 1.05 |
| 6 | 1.39 | 15.63 | 8.79 | 26 | N.S. | 1.39 | N.S. |
| 7 | 1.22 | 12.15 | 7.85 | 28 | N.S. | 1.04 | N.S. |
| 8 | 0.69 | 11.11 | 6.93 | 30 | N.S. | 0.69 | N.S. |
| 10 | N.S. | 7.64 | 6.09 | 35 | N.S. | N.S. | N.S. |
| 12 | N.S. | 5.56 | 4.76 | 40 | N.S. | N.S. | N.S. |
| 14 | N.S. | 4.17 | 3.06 | ------------ | ------------ | ------------ | ------------- |

1 lb/in$^2$ = 144 lb/ft$^2$

(A) Simulates 20 ton truck traffic + impact.
(B) Simulates 80,000 lb/ft railway load + impact.
(C) 180,000 lb dual tandem gear assembly. 26 inch spacing between tires and 66 inch center-to-center spacing between fore and aft tires under a rigid pavements 12 inches thick + impact.
N.R. Not recommended.
N.S. Live load not significant.

**Exhibit I.6 Live Loads on PVC Pipe**

### 1.D.6 Deflection

The modified Iowa equation is used to determine deflection of buried flexible conduits and is expressed as:

$$\Delta X = D_L \frac{K w_c r^3}{EI + 0.061 E' r^3} \qquad \text{Eq. I.12}$$

where:
- $\Delta X$ = Horizontal deflection, inch;
- $D_L$ = Deflection lag factor;
- $K$ = Bedding constant;
- $w_c$ = Load per unit length of pipe, lbs/lin inch;
- $r$ = Mean pipe radius, inch;
- $E$ = Modulus of tensile elasticity of the pipe material, psi.;
- $I$ = Moment of inertia per unit length, $in^3$.;
- $E'$ = Modulus of soil reaction, psi.

The relationship between horizontal deflection ($\Delta X$) and vertical deflection ($\Delta Y$) in buried flexible conduits can be determined from the following equation:

$$\Delta X = 0.913\,\Delta Y \qquad \text{Eq. I.13}$$

where:
- $\Delta X$ = Horizontal deflection, inch;
- $\Delta Y$ = Vertical deflection, inch.

Under most soil conditions, flexible pipe tends to deflect into a nearly elliptical shape and the horizontal and vertical deflections may be considered equal for small deflections ($\Delta$). Since most flexible pipe is described by either pipe stiffness ($F/\Delta Y$) or outside diameter to thickness ratio (DR), the modified Iowa equation (Eq. I.12) can be rewritten as follows:

$$\%\ \text{Deflection} = \%\ \frac{\Delta Y}{D} = \frac{D_L K P\,(100)}{0.149\,\frac{F}{\Delta Y} + 0.061E'} \qquad \text{Eq. I.14}$$

or,

$$\%\ \text{Deflection} = \%\ \frac{\Delta Y}{D} = \frac{D_L K P\,(100)}{[2E/3(DR - 1)^3] + 0.061E'} \qquad \text{Eq. I.15}$$

Where
- $P$ = Prism load, psi.;
- $w$ = Unit weight of soil, $lbs/ft^3$.;
- $H$ = Height of cover over the pipe, ft and the rest as defined before.

When live loads must be considered, the following equation should be used:

$$\% \text{ Deflection} = \% \frac{\Delta Y}{D} = \frac{(D_L KP + K W')(100)}{[2E/3(DR - 1)^3] + 0.061E'} \qquad \text{Eq. I.16}$$

where:

- $P$ = Prism load, psi.;
- $K$ = Bedding constant;
- $W'$ = Live load, psi.;
- $DR$ = Dimension ratio;
- $E$ = Modulus of tensile elasticity of the pipe material, psi.;
- $E'$ = Modulus of soil reaction, psi.;
- $D_L$ = Deflection lag factor.

The deflection lag factor ($D_L$) accounts for the fact that, in pipe/soil systems, the soil consolidation at the sides of the pipe continues at an ever decreasing rate with time, after the maximum load reaches the buried pipe. Experience demonstrates that deflection of buried flexible pipe will continue for a period of time after completion of pipe installation before final equilibrium is achieved.

The full load on any buried pipe is not reached immediately after installation unless the final backfill is compacted to a high density. For a pipe with good flexibility, the long term load will not exceed the prism load. The increase in load with time is the largest contribution to increasing deflection. Therefore, for design, the prism load can be used to compensate for the increased trench consolidation load with time and resulting increased deflection. When deflection calculations are based on prism loads, the deflection lag factor, $D_L$, should be 1.0.

The bedding constant (K) accommodates the response of the buried flexible pipe to the opposite and equal reaction to the load force derived from the bedding under the pipe. The bedding constant varies with the width and angle of the bedding achieved in the installation. The bedding angle (θ) is shown in EXHIBIT I.7.

EXHIBIT I.8 presents a list of bedding constant values dependent on the bedding angle. As a general rule, when using the modified Iowa equation, a value of K = 0.1 is assumed.

Equations I.14, I.15, and I.16 do not apply to profile wall flexible pipe, which is pipe similar to corrugated metal pipe in that it has corrugations on the inside or outside or both.

## 1.E Manufacturer Literature

Pipe manufacturers of rigid and flexible conduits often publish tables and other literature that include maximum recommended heights of cover for various classes and combinations of pipe and bedding. Before utilizing the above information, the designer should satisfy himself/herself that the tables are based upon acceptable design criteria and procedures.

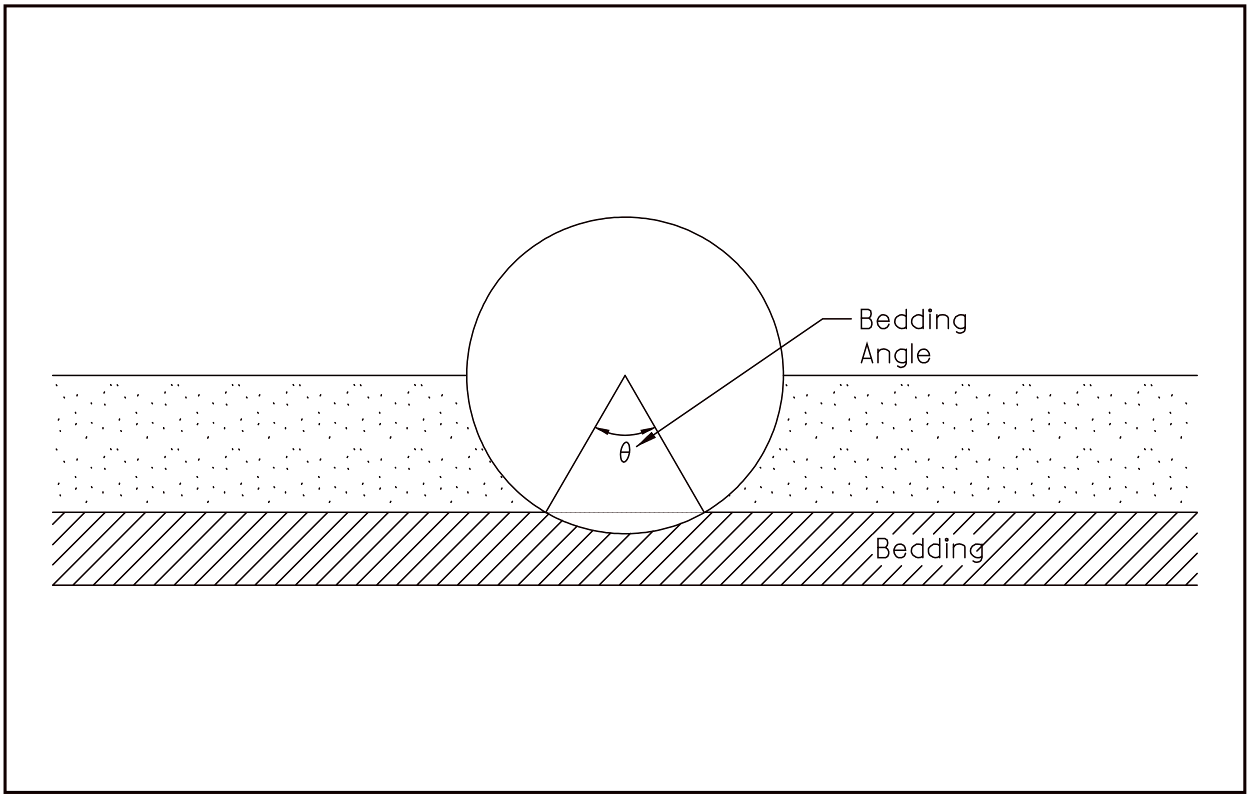


**Exhibit I.7 Bedding Angle (Source: UNI-BELL PVC Pipe Association)**

| Bedding Angle (Degrees) | K |
|---|---|
| 0 | 0.110 |
| 30 | 0.108 |
| 45 | 0.105 |
| 60 | 0.102 |
| 90 | 0.096 |
| 120 | 0.090 |
| 180 | 0.083 |

**Exhibit I.8 Values of Bedding Constant, K**

## 2. EXAMPLE PROBLEMS

### 2.A Earth Loads on Rigid Trench Conduits

Determine the backfill load on a 24-inch diameter reinforced concrete pipe that is beneath 14 ft of cover installed in a trench. Backfill material is saturated topsoil.

Step 1: Determine the outside diameter of pipe ($B_c$).

Assume wall thickness is 2 inches. Refer to appropriate ASTM for actual wall thickness.

$B_c$ = 24 in + 2 (2 in) = 28 in = 2.33 ft.

Step 2: Calculate the width of the trench at the top of the pipe ($B_d$).

Allow 12-inch sidewall clearance on each side of the pipe.

$B_d$ = 2.33 ft + 2 ft = 4.33 ft.

Step 3: Find the load coefficient for trench conditions ($C_d$) using EXHIBIT J.1 in Appendix J, "Nomographs & Charts for Designing Earth Loads on Conduits".

$H/B_d$ = 14 ft/4.33 ft = 3.23. Therefore, $C_d$ = 2.1.

Step 4: Determine the backfill load on the pipe ($W_c$) using Eq. I.1.

Assume unit weight of backfill material (w) is 120 lbs/cu ft.

$W_c = C_d w B_d^2$

$= 2.1 \times 120 \times (4.33)^2$

= 4,725 lbs/lin ft.

## 2.B Rigid Conduit Design

A 24-inch diameter reinforced concrete pipe will be placed in a trench with Class C shaped subgrade bedding. Determine the class of pipe required to support a backfill load of 4,725 lbs/lin ft. Assume that live load is negligible.

Step 1: Select a trial class of pipe and determine the D-Load value from ASTM C-76.

For Class IV pipe, $\text{D-Load}_{ult}$ = 3000 lbs/lin ft/ft diameter.

Step 2: Determine the load factor ($L_f$), for the specified trench bedding from EXHIBIT I.3.

$L_f = 1.5$.

Step 3: Calculate the design strength of the pipe using Eq. I.7.

$$\text{Design Strength} = \frac{(\text{D-Load} \times D) \times L_f}{FS}$$

$$= \frac{(3000 \text{ lbs/lin ft/ft diameter} \times 2 \text{ ft}) \times 1.5}{1.5}.$$

= 6000 lbs/lin ft

Step 4: Evaluate trial class of pipe.

6000 lbs/lin ft > 4,725 lbs/lin ft.

Therefore, Class IV pipe with Class C shaped subgrade bedding is adequate.

## 2.C Earth Loads on Flexible Trench Conduits

Determine the backfill load on an 18-inch PVC pipe beneath 11 ft of cover installed in a trench. Backfill material is saturated topsoil.

Step 1: Determine the outside diameter of the pipe ($B_c$).

From manufacturer's literature:

$B_c$ = 18.70 in = 1.56 ft.

Step 2: Determine the unit weight of the backfill material (w).

Assume unit weight is 120 lbs/cu ft.

Step 3: Determine the backfill load on the pipe ($W_c$) using Eq. I.10.

$W_c = HwB_c = 11 \times 120 \times 1.56 = 2{,}059$ lbs/lin ft.

## 2.D Flexible Conduit Design

Determine the amount of deflection (percent) that will occur in an 18-inch PVC pipe installed under the following conditions. Evaluate if the amount of deflection is acceptable.

| | |
|---|---|
| Pipe Size and Material: | 18-inch (nominal) PVC |
| Outside Diameter: | 18.70-inch (average) |
| Wall Thickness: | 0.534-inch |
| Modulus of Tensile Elasticity, E': | 400,000 psi |
| Installation Conditions: | trench condition |
| Cover Depth: | 11 ft |
| Backfill Material: | saturated topsoil |
| Unit Weight of Backfill Material: | 120 lbs/cu ft |

Pipe Bedding Material: fine-grained soils (LL <50) with more than 25 coarse-grained particles.

90% compaction (Proctor)

Live Load: H20 (highway).

Step 1: Determine the modulus of soil reaction (E') from EXHIBIT I.5.

E' = 1000 psi.

Step 2: Calculate the dimension ratio (DR).

$$DR = \frac{OD}{T} = \frac{18.70}{0.534} = 35.02$$

Step 3: Find the prism load (P) using Eq. I.11.

$$P = \frac{wh}{144}$$

$$P = \frac{120 \times 11}{144} = 9.17 \text{ psi}$$

Step 4: Obtain bedding constant (K) from EXHIBIT I.8.

Bedding angle is assumed to be approximately zero, thus, K = 0.110.

Step 5: Calculate percentage of deflection using Eq. I.15.

Deflection lag factor ($D_L$) is 1.0 since calculations are based on prism load.

$$\% \text{ Deflection} = \frac{D_L KP(100)}{[2E/3(DR - 1)^3] + 0.061E'}$$

$$= \frac{1.0 \times 0.110 \times 9.17 \times 100}{[2(400{,}000)/3(35-1)^3] + 0.061(1000)}$$

$$= 1.48\%.$$

Allowable deflection is generally 5%, therefore 1.48% is acceptable.

## 3. REFERENCES

1. Spangler, M.G. and R.L. Handy, Soil Engineering, 4th Edition, Harper and Row, 1982.

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3. Handbook of PVC Pipe: Design and Construction; Uni-Bell PVC Pipe Association; Dallas, Texas; 1986.

4. Deflection: The Pipe/Soil System Mechanism; Uni-Bell PVC Pipe Association; Dallas, Texas; 1990. (https://www.uni-bell.org/resources/applications/storm-sewer/engineering-design).

5. Amster Howard, Soil Reaction for Buried Flexible Pipe, ASCE Journal of Geotechnical Engineering Division, January, 1977.