RECLAMATION
Managing Water in the West

Method for Prediction of Flexible Pipe Deflection

M-25 Third Edition

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The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Method for Prediction of Flexible Pipe Deflection

M-25 Third Edition

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Water Conveyance Group

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Contents

Appendices

Tables

Tables (continued)

Figures

Foreword

This is the third edition of the Method for Prediction of Flexible Pipe Deflection. The first edition, released May 1, 1997, was prepared by Amster K. Howard (soils specialist), Leo A Kinney, Jr. (pipe specialist), and Richard P. Fuerst (pipe specialist). The equations and tables were based on the research of Amster Howard and documented in 1981. The second edition was released in December 2013 and was updated by Richard P. Fuerst to use the ATV formula, instead of a table, to determine the correction factor (Sc). In addition, the E' tables were updated based on additional testing by Amster Howard, and the manual was rearranged for better presentation of the material. The third edition removes the ATV formula and restores the correction factor (Sc) table, updates the examples, and makes other minor corrections.

1. Introduction

One of the design considerations for flexible pipe is the deflection of the pipe due to dead and live loads on the pipe. Currently, there are various methods for estimating pipe deflection and various parameters for each method. This manual states the method used by the Bureau of Reclamation (Reclamation), discusses the use of the method, and gives example calculations that apply the method.

There are two basic types of pipe: rigid and flexible. A flexible pipe is generally a pipe that can deflect without structural distress to the pipe or to any coating or lining. Types of flexible pipes used by Reclamation are steel, ductile iron, polyvinyl chloride (PVC), high-density polyethylene (HDPE), bar-wrapped concrete cylinder (old Reclamation designation PT), and fiberglass. The discussions in this report pertain only to flexible pipe.

Terminology used to describe a typical pipe trench cross section differs across various manuals, guides, and standards. Reclamation terminology is illustrated in figure 1. "Bedding" is the soil on which the pipe is laid, and the "embedment" is the soil placed between the sides of the pipe and the trench wall. For flexible pipe, Reclamation typically uses embedment between the bottom of the pipe to a height of 0.7 of the outside diameter (OD) of the pipe. Embedment that may be required above 0.7 OD is not relied upon for deflection control but, rather, local standard requirements, corrosion protection, or buckling issues.
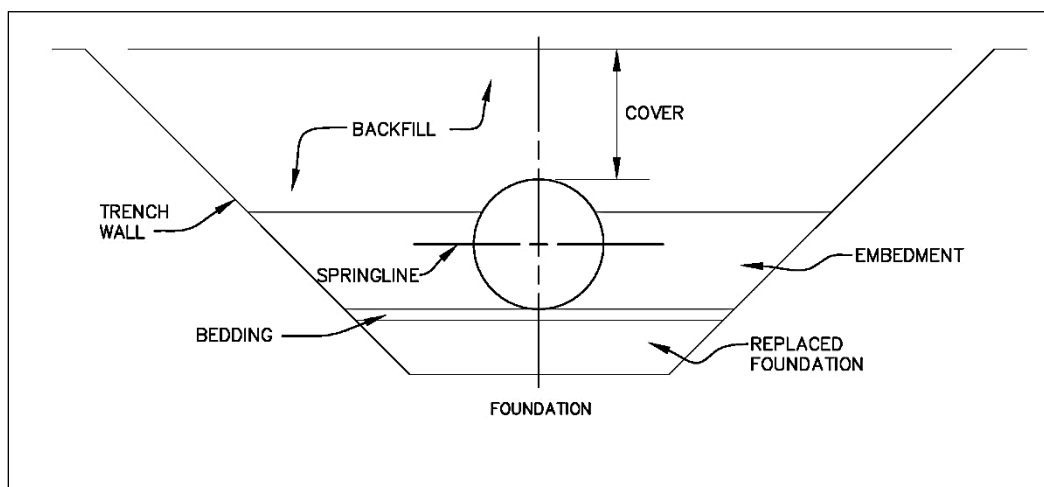

Figure 1. Trench terminology.

For pipes that are 10 inches in diameter and smaller, the embedment around the pipe may be uncompacted (see section 6).

2.   Deflection of Flexible Pipe

The deflection of flexible pipe is the decrease of the vertical diameter of the pipe (and corresponding increase in horizontal diameter) due to load on the pipe. The deflection is expressed in terms of percentage as follows:

$$\text{percent pipe deflection} = \frac{\text{change in diameter}}{\text{pipe diameter}} \times 100 \qquad \text{(Equation 2.1)}$$

or:

$$\Delta Y \, (\%) = \text{percent vertical deflection}$$

Load on a buried pipe is created by placing backfill soil over the top of the pipe and any surcharge and/or live load on the backfill surface over the pipe. Flexible pipe is designed to transmit the load on the pipe to the soil at the sides of the pipe. As the load on the pipe increases, the vertical diameter of the pipe decreases and the horizontal diameter increases. The increase in horizontal diameter is resisted by the stiffness of the soil at the sides of the pipe.

For the design of structural members, the strain or deformation of an element of the material being used can be determined from the ratio of the load or stress on the member to its modulus of elasticity (strain = stress/modulus of elasticity). The modulus is either known for the material or determined by laboratory tests.

The deflection of a buried conduit can be predicted in a similar fashion. The cross-sectional ring deflects according to the ratio of the load on the ring to the modulus of elasticity of the material. The material modulus, however, is more complicated because a soil-structure interaction takes place. The material modulus becomes a combination of the structural elastic modulus (stiffness) of the pipe and the modulus (stiffness) of the soil, so that:

$$\% \text{ pipe deflection} = \frac{\text{load on the pipe}}{\text{pipe stiffness factor} + \text{soil stiffness factor}} \times 100 \qquad \text{(Equation 2.2)}$$

Several variations of this relationship are used to predict the deflection of a buried flexible pipe. The most common variation is the Iowa Formula [1][1] [2], developed by Professor M.G. Spangler of Iowa State University. Reclamation uses the Reclamation Equation, which is a variation of the Iowa Formula. The Reclamation Equation incorporates modifications to the Iowa Formula based on field and laboratory tests, as well as studies on buried flexible pipe. A discussion of the use and background of the Reclamation Equation can be found in reference [3] and in Appendix C, "Reclamation Deflection Equation Development."

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[1] Numbers in brackets refer to references at the end of this report.

3. Reclamation Deflection Equation

The Reclamation Equation is used to predict the average long-term vertical deflection of flexible pipe.

The Reclamation Equation is written as follows:

$$\Delta Y(\%) = \frac{T_f 0.07 \gamma h + 10 W_L}{\frac{EI}{r^3} + 0.061 F_d E'} \qquad \text{(Equation 3.1)}$$

Where:

$\Delta Y\,(\%)$	=	percent vertical deflection
T_f	=	time-lag factor, dimensionless
0.07	=	combination of conversion factor and bedding constant, square feet per square inch per linear inch (ft^2/in^2 per linear inch)
γ	=	backfill unit weight, pounds per cubic feet (lb/ft^3)
h	=	depth of cover, ft
W_L	=	live load, pounds per square inch (lb/in^2)
E'	=	modulus of soil reaction, lb/in^2
F_d	=	design factor, dimensionless
EI/r^3	=	pipe stiffness factor, lb/in^2 per linear inch

Note: The original Iowa formula, and later variations, express load on the pipe with unit pounds per linear inch of pipe instead of lb/in^2 as used in Reclamation's Equation.

The pipe stiffness factor, EI/r^3, can be calculated or obtained from manufacturer's literature. The depth of cover, h, can be determined from the drawings and specifications, the backfill unit weight, γ, from soil reports, and the live load, W_L, from design data.

The values for E' vary according to soil type and density of embedment material, level of ground water obtained from drill logs, trench width, and trench wall stiffness. The time-lag factor, T_f, and design factor, F_d, are discussed in sections 3.2 and 3.6, respectively.

The equation was developed based field tests with cover depths of 50 ft or less, where cover is the distance between the top of the pipe and the constructed ground surface over the pipe.

3.1   Deflection

Deflection is a decrease in the vertical diameter of a pipe. The value ΔY (%) is the average long-term vertical deflection of the pipe and is the final expected change in vertical diameter divided by the nominal pipe diameter, expressed as a percentage.

A flexible pipe changes shape several times during the installation of a pipeline. Generally, the pipe is considered to deform from a perfect circle to an ellipse due to loading. The largest diameter changes usually occur along the vertical diameter and the horizontal diameter, with the vertical diameter change slightly larger than the horizontal diameter change. Performance of the pipe is typically measured by the change in the vertical diameter (a vertical line from invert to crown) divided by the original inside diameter of the pipe, expressed as a percent.

The shape of a flexible pipe is rarely a perfect circle. The mass of the pipe will cause the pipe to deflect (sag). The amount of deflection depends on the stiffness of the pipe and the type of pipe.

In addition to the initial out-of-roundness, placement and compaction of the soil beside the pipe can cause elongation (an increase in the vertical diameter) of the pipe. The elongation is dependent on the pipe stiffness, the type of compaction, the percent compaction, and whether or not the pipe is strutted [4].

The deflection due to backfill load, live load, and time creates the critical change in pipe diameter, and this is the deflection that is defined and calculated by the method discussed in this report.

Experience has shown that deflection of <u>any</u> flexible pipe can be much higher than predicted by calculation if all design assumptions are not achieved. This requires that the in situ soil conditions, materials selected as embedment, methods and equipment used for compaction, and the care taken during installation be monitored and inspected for compliance with the specifications.

The Reclamation Equation specifically calculates the percent deflection, vertical deflection, initial deflection, long-term deflection, and average deflection. These terms are defined below.

Percent deflection: The percent deflection is the change in vertical diameter divided by the nominal diameter, expressed as a percentage. The "change in diameter" is the difference between the original pipe diameter and the pipe diameter measured at the end of some subsequent event, such as placement of backfill over the pipe or the passage of time.

Vertical deflection: Vertical deflection is the change in the vertical diameter of the pipe. Vertical deflection is calculated because this value is larger than the horizontal deflection and is easier to measure.

Initial deflection: Initial deflection is the deflection occurring on the day the backfilling over the pipe is completed.

Long-term deflection: Long-term deflection is the "final" deflection of the pipe. Although flexible pipe apparently never ceases deflecting (the longest time measurement has been 22 years) [5], there is a point at which the increase in deflection becomes insignificant, and this can be considered the "long-term deflection." The long-term deflection may be very different than the initial deflection, depending on the embedment and native trench materials. For weak soils (low E' values), most of the deflection occurs soon after installation, whereas for stiffer soils (high E' values), the pipe deflection is more gradual.

Average deflection: Average deflection is the average of the pipe vertical deflections that occur along the pipeline. Deflections can vary from point to point along the pipe due to construction variations such as compaction and differences in soil unit weight, moisture, stiffness of the native material, embedment, bedding and backfill materials, and varying trench dimensions.

For pipe installed in soils that are uncompacted or have moderate degrees of compaction, the vertical deflection along the pipe can vary plus or minus 2 percentage points from the average. For pipe installed with a high degree of compaction, the vertical deflection along the pipe can vary plus or minus 1 percentage point from the average. Variation is also dependent upon the stiffness of the pipe. The higher the pipe stiffness factor, the less variability in deflection occurs along the pipeline. If the pipe stiffness factor (EI/r^3) is greater than the soil stiffness factor (0.061 E′), the variability can be assumed as negligible.

Specific points along the pipeline will have higher or lower deflections than the average because of the inherent variability of construction materials and methods. The difference between the average and maximum deflection is only of concern if the calculated average deflection is close to the allowable deflection, and the allowable deflection is a critical value because of cleaning equipment, lining equipment, etc. In that case, the soil stiffness or pipe stiffness factor may need to be increased to ensure that the maximum deflection is less than the allowable deflection.

3.2   Time-Lag Factor, T_f

The time-lag factor, T_f, is used to calculate the increase in deflection of a flexible pipe with time. A flexible pipe continues to deflect over time for two reasons:

1. Increase in the soil load on the pipe.
2. Consolidation of the soil at the sides of the pipe.

Table 5, which appears later in this report, gives values of T_f for use in the Reclamation Equation. The values are the ratio of long-term deflection to the initial deflection. The initial deflection is the deflection on the day the backfill was completed. For calculating initial deflections, a T_f value of 1.0 should be used.

Saturation of the embedment, defined as when the pipeline is below the water table, reduces the stiffness of soils which contain significant fines (silts and clay particles). If the embedment soil will be below the level of the water table, the time-lag factor from table 5 should be doubled for embedment constructed of soils using Class III or IV (soils that contain more than 12 percent fines). This is also true of the native material when it is used in the combined E' equation. If unsaturated native soils have more than 12 percent fines, and where the water table can rise above the pipe due to irrigation or ground water fluctuations, consider increasing the time-lag factor.

Note: The time-lag factor, as used in the Reclamation Equation, is not the same as the deflection lag factor used by Spangler in the Iowa Formula [1]. The deflection lag factor reflects the increase in deflection from the time the **maximum load on the pipe is achieved**, not from the time of final backfilling over the pipe [6]. The maximum load is usually reached about 3 to 6 months following final backfilling due to soil settlement and moisture changes in the backfill over the pipe. Spangler reported values of deflection lag of 1.0 to 1.5. If his data is reevaluated in terms of time-lag, the increase in deflection that he reported over time is about 200 percent, or a **time-lag factor of 2.0**.

3.3   Earth Loads

The dead load on the pipe is represented by 0.07 γh, which assumes a prism load on the pipe. The prism load is the weight of a column of soil that is the width of the pipe (outside pipe diameter) for the full height of the backfill for a 1-ft unit length of pipe. The value, γ, is the unit weight of the soil placed over the pipe, including the water in the soil (wet unit weight). If the water content of the soil will change, the maximum anticipated unit weight value should be used. When γ is not known, a value of 120 lb/ft^3 can be used for design purposes. In areas where trench material will be compacted to 95-percent compaction over the top of the pipe, wet soil unit weights may reach 135 lb/ft^3. Soils containing a significant

amount of gravel, cobbles, or boulders can have a unit weight much higher than 120 lb/ft^3 and should be evaluated. The depth of cover, h, is the vertical distance from the top of the pipe to the ground surface over the pipe.

Note: While there are other methods of calculating the load on a pipe, the prism load must be used with the values shown in tables 5 and 6 because the values were developed assuming a prism load.

3.4   Live Loads

Appendix E, "Live Loads (W_L)," includes a complete explanation of the designs for highway and railroad loadings. Tables 1, 2, and 3 summarize the live loading pressures (W_L), and the values include the live load pressures plus the recommended impact factors.

Table 1. HS-20 Live Loads for Rigid Pavement (lb/in^2)

Depth (ft)	W_L (lb/in^2)	Depth (ft)	W_L (lb/in^2)
2	11.1	5	3.2
2.5	8.5	6	2.5
3	6.7	7	2.0
4	4.3	8	1.6

Table 2. HS-20 Live Loads for Flexible Pavement (lb/in^2)

Depth (ft)	W_L (lb/in^2)	Depth (ft)	W_L (lb/in^2)
2	16.8	5	2.5
2.5	11.5	6	1.6
3	7.6	7	1.1
4	4.2	8	0.9

Table 3. Railroad Live Loads (lb/in^2)

Depth (ft)	W_L (lb/in^2)	Depth (ft)	W_L (lb/in^2)
2.5	16.7	7	8.8
3	15.8	8	7.6
4	13.9	9	6.5
5	12.1	10	5.6
6	10.4	20	2.2

3.5   Pipe Stiffness Factor, EI/r³

Pipe stiffness factor, EI/r³, represents the resistance to deformation solely by the pipe (without any soil support). In most cases, the pipe stiffness factor has very little influence on the pipe deflection because the soil stiffness factor is much greater. Considering the magnitude of the variations that can occur in the load on the pipe and in the soil stiffness, the use of nominal values for E, I, and r provides sufficient accuracy for the Reclamation Equation. Table 4 shows typical values for E. The values for PVC and HDPE are for solid wall pipe only.

Table 4. Typical Modulus of Elasticity Values (E)

Pipe type	E (lb/in²)
HDPE	28,250 *
PVC	400,000 **
Steel	29,000,000 ***
Ductile iron	24,000,000
Bar-wrapped concrete cylinder	4,000,000 ****
Fiberglass	Varies *****

    * PE3408 and PE4710 material at 73 degrees Fahrenheit (°F) (long-term E).
     ** Class 12454 Material.
     *** American Society for Testing Materials (ASTM) A1011 or A1018, Grade 36.
     **** Cement mortar lining and coating. Use transformed section for steel cylinder and bars.
     ***** Pipe stiffness may be determined by the parallel plate test or be provided by the manufacturer.

The pipe stiffness factor is the product of the modulus of elasticity, E, of the pipe wall material (lb/in²) and the moment of inertia, I, (inch⁴/inch) of a unit length of pipe divided by the mean pipe radius, r, (inches) cubed. For a unit length of straight wall pipe of homogeneous material, the moment of inertia is equal to $t^3/12$ where t is the wall thickness. The EI value may be found using assumed or empirical values for E and t, or EI can be determined by conducting parallel plate tests on a section of pipe as defined in American Society for Testing Materials (ASTM) D2412. During the test, deflections due to line loads on the top and bottom of the pipe are measured, and EI is calculated using either:

$$EI = 0.149 \, \frac{Pr^3}{\Delta Y} \qquad \text{(Equation 3.2)} \qquad or \qquad EI = 0.136 \, \frac{Pr^3}{\Delta X} \qquad \text{(Equation 3.3)}$$

Where:

    P   = load per linear inch
    r   = pipe radius, inches
    ΔY = vertical deflection, inches
    ΔX = horizontal deflection, inches

In the parallel plate tests, the pipe deforms elliptically with the horizontal deflection (theoretically about 91 percent of the vertical deflection).

The correlations between <u>pipe stiffness factor</u> and other published expressions are as follows:

1. For fiberglass pressure pipe, a pipe stiffness (PS) is calculated and published for the various diameters and wall thicknesses. <u>The pipe stiffness factor</u> can be determined from the pipe stiffness using the following expression:

$$\frac{EI}{r^3} = 0.149 \; PS \qquad \text{(Equation 3.4)}$$

Where:

PS = the value $P/\Delta Y$ from a parallel plate test, with P equal to the force necessary to deflect the pipe 5 percent.

Example: If a fiberglass pipe has a pipe stiffness of 18 lb/in^2 from manufacturer's literature, then the $EI/r^3 = 0.149 \; (18) = 2.682$ lb/in^2

2. The stiffness of PVC and HDPE pipe is usually stated in terms of the Dimension Ratio (DR) (sometimes referred to as the Standard Dimension Ratio [SDR]), which is equal to the ratio D/t where "D" is the average outside pipe diameter, and "t" is the minimum pipe wall thickness. <u>The pipe stiffness factor</u> can be determined from the DR using the following expression [7]:

$$\frac{EI}{r^3} = \frac{2E}{3(DR-1)^3} \qquad \text{(Equation 3.5)}$$

Example: For a PVC pipe with a DR ratio of 18, the EI/r^3 would be
2 (400,000) / 3 (18-1)^3 = 54.3 lb/in^2

3.6 Design Factor, F_d

Each E′ value in tables 5 and 6 is a typical value (i.e., for each category of soil type and classification, about one-half of the measured deflections were higher, and about one-half were lower, than the deflection predicted using the E′ value shown). To reduce the possibility that the actual deflection will exceed the predicted value, a design factor, F_d, is applied to E′$_b$ and listed in table 5.

Table 5. Embedment Material Parameters

Soil Class	Soil classification of embedment (USCS)	Percent compaction of embedment (E'_b)		
		Uncompacted	Moderate (≥ 85 to <95% C)	High (≥ 95% C)
I	**CRUSHED ROCK:** Not more than 25% passing 3/8-inch sieve and not more than 12% fines; maximum size not to exceed 1½ inches.	$E'_b = 1000$ $F_d = 0.67$ $T_f = 2$ Sat. $T_f = 2$	$E'_b = 6000$ $F_d = 1$ $T_f = 2$ Sat. $T_f = 2$	
II	**CLEAN COARSE-GRAINED SOILS:** Sands, gravels with 12% or less fines GW, GP, SW, SP, or any soil beginning with one of these symbols (i.e., GP-GM). Does not apply to SP soils with ≥ 50% fine sand (passing No. 40 sieve). Treat as ML soils.	$E'_b = 500$ $F_d = 0.67$ $T_f = 1.5$ Sat. $T_f = 1.5$	$E'_b = 2000$ $F_d = 0.75$ $T_f = 2$ Sat. $T_f = 2$	$E'_b = 4000$ $F_d = 1$ $T_f = 2$ Sat. $T_f = 2$
III	**SANDY OR GRAVELLY FINE-GRAINED SOILS:** Silts and clays with 30% or more coarse-grained particles CL, ML (or CL-ML, CL/ML, ML/CL). **COARSE-GRAINED SOILS WITH FINES:** Sands, gravels with more than 12% fines GC, GM, SC, SM, or any soil beginning with one of these symbols (i.e., SC/CL).	$E'_b = 200$ $F_d = 0.5$ $T_f = 1.5$ *Sat. $T_f = 3$	$E'_b = 1000$ $F_d = 0.67$ $T_f = 2$ *Sat. $T_f = 4$	$E'_b = 2500$ $F_d = 0.75$ $T_f = 2$ *Sat. $T_f = 4$
IV	**FINE-GRAINED SOILS:** Silts and clays with less than 30% coarse-grained particles CL, ML (or CL-ML, CL/ML, ML/CL).	$E'_b = 100$ $F_d = 0.5$ $T_f = 1.5$ *Sat. $T_f = 3$	$E'_b = 400$ $F_d = 0.67$ $T_f = 2$ *Sat. $T_f = 4$	$E'_b = 1500$ $F_d = 0.75$ $T_f = 2$ *Sat. $T_f = 4$
V	**HIGHLY COMPRESSIBLE FINE-GRAINED SOILS:** CH, MH, OH, OL, or any soil containing one of these symbols (i.e., CL/CH).	Soils with medium to high plasticity or with significant organic content No data available **Not Recommended**		

Table 6. Native Trench Wall Material Parameters

Trench wall soil classification (USCS)	Stiffness of trench wall (E'_n)		
	Slight (< 85% C)	Moderate (≥ 85 to < 95% C)	High (≥ 95% C)
HIGHLY COMPRESSIBLE FINE-GRAINED SOILS: CH, MH, OH, OL. Peat, swamps, bogs, or other unsuitable material	E'_n < 500 Material Type 3		
FINE-GRAINED SOILS: Silts and clays with less than 30% coarse-grained particles CL, ML (or CL-ML, CL/ML, ML/CL)	E'_n = 200 Material Type 3	E'_n = 500 Material Type 2	E'_n = 1500 Material Type 2
SANDY OR GRAVELLY FINE-GRAINED SOILS: Silts and clays with 30% or more coarse-grained particles CL, ML (or CL-ML, CL/ML, ML/CL) **COARSE-GRAINED SOILS WITH FINES:** Sands, gravels with more than 12% fines GC, GM, SC, SM, or any soil beginning with one of these symbols (i.e., SC/CL)	E'_n = 400 Material Type 3	E'_n = 700 Material Type 2	E'_n = 2500 Material Type 1
CLEAN COARSE-GRAINED SOILS: Sands, gravels with 12% or less fines GW, GP, SW, SP, or any soil beginning with one of these symbols (i.e., GP-GM). Does not apply to SP soils with ≥ 50% fine sand (passing No. 40 sieve). Treat as ML soils.	E'_n = 700 Material Type 2	E'_n = 1000 to 2000 Material Type 2*	E'_n = 4000 Material Type 1
ROCK, SANDSTONE, SHALE: Highly cemented soils, etc.	Not applicable	E'_n >> 4000 Material Type 1	

Notes:
*E'_n = 1000 for normally consolidated sands and 2000 for overconsolidated sands.
E' is shown as lb/in^2.
C is compaction (ASTM D698 and D7382) from in-place density.

The design factor effectively reduces the E′ value. Using the design factor values shown in table 5, there is a 95-percent probability that the actual pipe deflection will not exceed the predicted value by more than 0.5 percentage points.

Appendix D, "Design Factor (F_d) Variations," discusses other circumstances in which different sets of design factor values should be used.

3.7   Modulus of Soil Reaction, E′

The E′ value represents the composite resistance of the soil beside the pipe to outward movement of the pipe wall. E′ is based on the width of the trench, the embedment material ($E′_b$), and the trench wall material ($E′_n$). Therefore, the type of soil and the percent compaction or density of both the embedment and trench wall materials must be determined, and the appropriate value must be used in the Reclamation Equation. Table 5 gives the $E′_b$ values for the embedment, which vary significantly based on the type of soil (USCS) and the percent compaction. Table 6 gives the $E′_n$ values for the native trench wall stiffness.

E′ is an empirical number based on measured deflections of many actual pipe installations [3] [8] [9]. **$E′_b$ does not vary with depth based on an evaluation of the empirical data** [10].

3.8   Compaction of Embedment

The soil stiffness ($E′_b$) parameters vary according to the percent compaction of the embedment soil. The percent compaction is determined by comparing the density of the embedment soil to a maximum density from a standardized laboratory test. "Percent compaction" is used for cohesive soils (generally, soils containing more than 12% fines) as described in ASTM D698. Percent compaction is the ratio, expressed as a percentage, of: (1) dry unit weight of a soil, to (2) maximum dry weight obtained in a laboratory compaction test (ASTM D653). Percent compaction is also used for cohesionless soils. Percent compaction compares the in-place field density to both a minimum and maximum density from laboratory tests. The laboratory test for cohesionless soils is described in ASTM D7382. The maximum density is based on a vibratory hammer test and represents the most effective method to increase the density of the soil. Soils containing between 5 and 12 percent fines must be evaluated using both methods, and the method that results in a higher in-place density should be used.

3.9   Stiffness of Trench Wall

The performance of flexible pipe depends on the resistance of the soil at the sides of the pipe. This side soil support results from the combination of the embedment soil and the trench wall soil. The width of the trench, to prevent excessive deflection, depends on the firmness of the embedment soil relative to the firmness of the trench wall material.

Previously, Reclamation determined the width of the trench based on a comparison of the compacted select material embedment stiffness and the trench wall material stiffness. This resulted in three possible trench widths (see Appendix B, "Pipe Deflection for Standard Installation Method"). For weak trench walls, a trench width of five pipe diameters was required.   Reclamation now uses a composite E' for design which accounts for any difference in stiffness (see section 3.10). The composite E' method may result in reduced trench widths.

The new composite E' method is based on the relative stiffness of the embedment material stiffness and the trench wall material. The E'_n value of the in situ trench wall material at the level of the pipe springline must be determined. Native trench materials have an inherent structural stiffness, which is shown by a Standard Penetration Test (SPT) blow count of 5 or greater, except when the trench excavation is in a swamp, peat bog, or other unsuitable material classification listed in table 6. The E'_n can also be determined using the soil classification and percent compaction of the native material in the trench wall evaluated during investigations.

The material types are categorized below:

> **Material Type 1:** Based on SPT, Cone Penetrometer Test (CPT), or in-place field density tests, the trench wall material has an $E'_n \geq 2500$. Minimum clearance between the pipe and the trench is all that is required.

> **Material Type 2:** Based on SPT, CPT, or in-place field density tests, the trench wall material has an $E'_n \geq 500$ and $E'_n < 2500$. The trench width will vary depending on the deflection requirements and the ratio of the stiffness between the embedment material and the trench wall material.

> **Material Type 3:** When the trench walls are extremely soft ($E'_n < 500$) and provide minimal pipe support.

When Material Type 3 soil conditions are identified prior to construction, design methods can be used to avoid a five pipe diameter wide trench. These methods are:

1. Specify only rigid pipe on an improved foundation.

2. Increase the pipe stiffness factor (EI/r^3) by increasing the wall thickness or increasing the thickness of mortar coatings, or both. Note: The haunch area still requires compaction.

3. Encase the pipe in reinforced concrete (foundation bearing pressures must be examined).

4. Use a composite E′ value.

3.10 Determination of Composite E′

To determine the composite E′ for a buried pipe, separate E′ values for the native soil, E'_n, and the embedment soil, E'_b, must be determined and then combined using the following equation:

$$E' = S_c\, E'_b \qquad\qquad \text{(Equation 3.6)}$$

Where:

    E′   = composite modulus of soil reaction, lb/in^2
    S_c = soil support combining factor (table 7)
    E'_b = modulus of soil reaction of the pipe embedment (table 5)

The composite E′ combining factors in table 7 are based on work by Leonhardt and the Abwassertechnishce Vereinigung e.V. (ATV) A 127 formula [11]. The values in table 7 are the inverse of the values used in the German standard (ATV 2000). The values in table 7 are similar to the ones used in AWWA M23, PVC Pipe – Design and Installation Manual [12]; and AWWA M55, PE Pipe – Design and Installation Manual [13]. See Appendix A, "Example Calculations."

To use table 7 for S_c values, the following numbers must be determined:

    E'_n = modulus of soil reaction of native soil at pipe elevation (table 6, 8, or 9)
    B = trench width at pipe springline, inches
    D = outside pipe diameter, inches

Table 7. Values for Soil Support Combining Factor, S_C [14]

E'_n/E'_b	B/D = 1.5	B/D = 2	B/D = 2.5	B/D = 3	B/D = 4	B/D = 5
≤0.1	0.15	0.30	0.60	0.80	0.90	1.00
0.2	0.30	0.45	0.70	0.85	0.92	1.00
0.4	0.50	0.60	0.80	0.90	0.95	1.00
0.6	0.70	0.80	0.90	0.95	1.00	1.00
0.8	0.85	0.90	0.95	0.98	1.00	1.00
1.0	1.00	1.00	1.00	1.00	1.00	1.00
1.5	1.30	1.15	1.10	1.05	1.00	1.00
2.0	1.50	1.30	1.15	1.10	1.05	1.00
3.0	1.75	1.45	1.30	1.20	1.08	1.00
>=5.0	2.00	1.60	1.40	1.25	1.10	1.00

Notes: E'_n values should be obtained from tables 6, 8, or 9, depending on how data was obtained. In-between values of S_c may be determined by straight line interpolation from adjacent values. For values of E'_n/E'_b less than 0.1, use 0.1 S_c factors.

Table 8. E'_n Based on SPT Test [14]

Soil description and classification - USCS	N_{60} value from SPT test (blows/foot)					
	0-4	5	10	20	30	≥ 50
Clays and silts with <30% sand/gravel: CL, ML	0	500	750	1250	1500	2500
Sandy silts, clays with ≥ 30% sand: sCL, sML Silty or clayey sand: SM, SC	0	700	1000	1500	2000	3000
Normally consolidated sands: SP, SP-SM, SP-SC	0	1000	1500	2500	3000	5000
Overconsolidated sands: SP, SP-SM, SP-SC	0	2000	3000	4000	5000	8000
Gravels, soils with gravel: GW, GP, GM, GC	0	Results unreliable; use another test method				

Table 9. Values of E'_n for Native Soils [14]

q_u (ton/ft²) (ASTM D2166	Description	E'_n lb/in²
> 0 - 0.25	Very soft	200
0.25 - 0.50	Soft	700
0.50 - 1.00	Medium	1500
1.00 - 2.00	Stiff	3000
2.00 - 4.00	Very stiff	5000
> 4.00	Hard	> 5000

Note: ton/ft² = tons per square foot

4. Allowable Long-Term Deflections

The predicted long-term deflection should be compared to the allowable long-term deflections for each pipe type, as shown in table 10. If the predicted deflections exceed what is allowable, then the soil stiffness or the pipe stiffness must be increased. If the pipe stiffness (EI/r^3) value for the pipe is small compared to the soil stiffness ($0.061F_dE'$) value, increasing the pipe wall thickness may be very expensive compared to increasing the trench width or embedment compaction. Increasing the thickness of mortar coatings on bar-wrapped concrete cylinder pipe and steel pipe has been used to increase the pipe stiffness for some cases. The mortar coating thickness for steel pipe, however, should not exceed 2 inches due to handling and durability concerns.

Table 10. Allowable Long-Term Pipe Deflections

Type of pipe	Allowable long-term vertical deflection[1] (ΔY)
Factory cement-mortar-lined and/or cement-mortar-coated steel pipe	3 percent
Flexible lined and coated steel pipe	5 percent
Flexible coated and cement-mortar-lined, in-place steel pipe	5 percent
Fiberglass pipe	5 percent
PVC pipe	5 percent
Ductile iron pipe	3 percent
Polyethylene pipe	Varies based on DR[2]
C303 bar-wrapped concrete cylinder pipe (72 inches maximum diameter) [15]	D/40 percent

[1] The deflection allowed by some pipe manufacturers may be different and should be compared to the above numbers. Special designs (e.g., casing pipe) may require smaller allowable values than those defined in the above table.
[2] Allowable deflections for HDPE pipe [13]:
   7.5% for DRs ≥ 21
   6.0% for DRs ≥13.5 and < 21
   5.0% for DR 11
   4.0% for DR 9
   3.0% for DR 7.3

5. CLSM

Reclamation specifications allow for pipe to be constructed using controlled low strength material (CLSM) for embedment. CLSM is often referred to in other publications and documents as flowable fill, soil-cement slurry, controlled density fill, soil-crete, or flowable mortar.

The designated trench wall material type determines how the CLSM installation method can be used. For Material Type 1, the trench is excavated so that a minimum annular space (usually around 3 inches) exists between the pipe and the in situ soil (as illustrated in figure 2). CLSM is used to fill the space between the pipe and the native soil to ensure complete contact between the pipe and the soil; thus, the sidewall support for the pipe to resist deflection will come only from the in situ trench wall material, not from the CLSM. **Because the width of CLSM is small, it does not provide any side support for the pipe, and the deflection must be calculated using the E′ value corresponding to the native soil.**

Note: When excavation is in rock where blasting is required, the minimum space between the pipe and rock should be at least 6 inches.
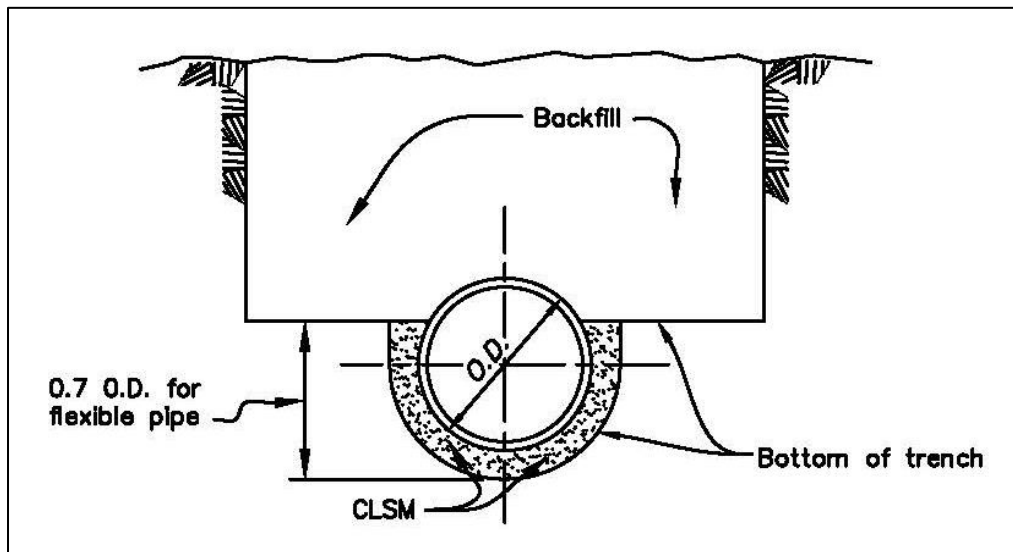

Figure 2. CLSM trench details for Material Type 1.

CLSM compressive strength for typical Reclamation designs is normally between 50 and 150 lb/in^2 at 7 days. This compressive strength is not the same as the E′. For a CLSM with a 50-lb/in^2 compressive strength, the E′ is assumed to be 4000. If the load on the pipe occurs before the CLSM has reached design strength, an E′ of 3000 can be used when the compressive strength reaches 30 lb/in^2.

As shown in figure 3, in Material Type 2, the CLSM can be used in the haunch area of the pipe, and compacted embedment material (or CLSM) can be used in the area beside the pipe from 0.25 to 0.70 of the OD of the pipe. The required trench width at springline can be determined by using the E'_b and E'_n to compute the combined E' for the given design conditions. See section 3.10.
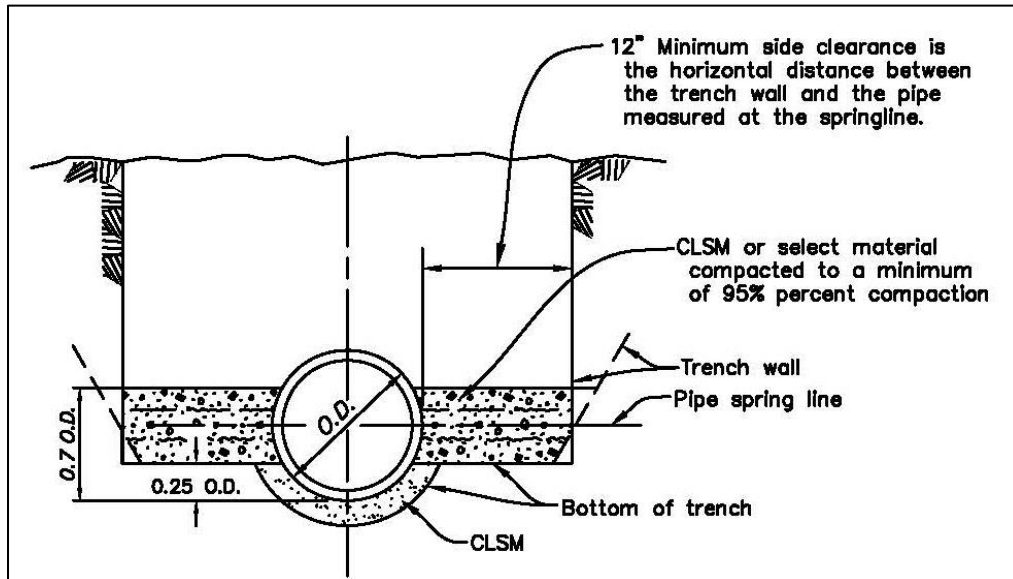

Figure 3. CLSM trench details for Material Type 2.

The CLSM installation method could be used when the native material is designated as Material Type 3, but the installation required to retain the CLSM in a swamp or peat bog, for example, could be very expensive.

CLSM can be used at road crossings to provide quick restoration of the road. If the long-term strength is higher than 150 lb/in^2, the CLSM will not be easily excavated. If CLSM is used for backfill, CLSM must also be used for the bedding and the embedment.

A 1-foot layer of CLSM over the pipe can be used to protect the pipe from road equipment blades that cause gradual degradation of the road base.

Application and practice for proper pipe installation in support of trench design assumptions can be found in Pipeline Installation 2.0 by Amster Howard [16].

6. Flexible Pipe 10 Inches in Diameter and Smaller

As shown in figure 4, the soil for flexible pipe that is 10 inches and smaller in diameter can be uncompacted beside the pipe for the following reasons:

1. Compaction of soil around small pipe is difficult.

2. The wall thickness of small diameter pipe required for handling or for internal pressure is usually so large, the pipe is quite stiff in relation to the soil; thus, the pipe stiffness influence in the deflection equation is much larger than the soil stiffness influence, and the soil stiffness does not contribute significantly to preventing excessive deflection.
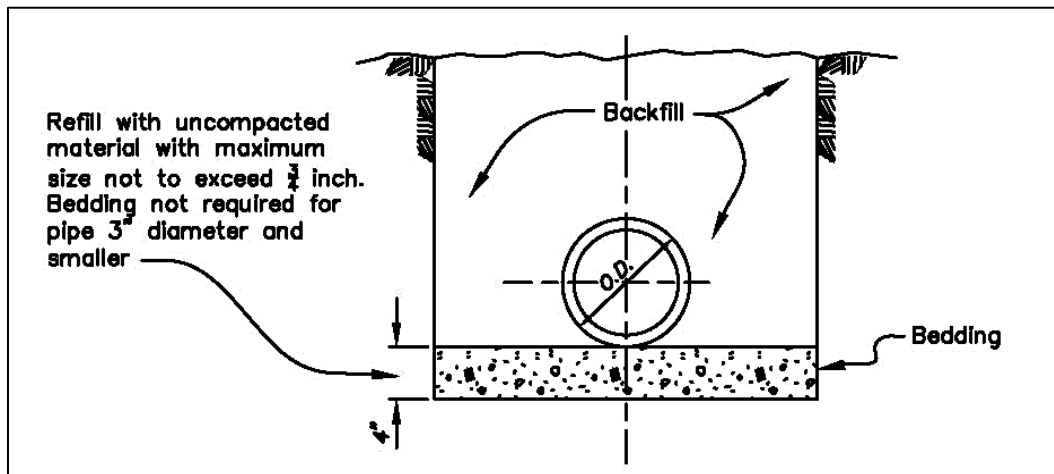

Figure 4. Flexible pipe 10 inches and smaller.

For some flexible pipe types, especially PVC and HDPE, the pipe stiffness (wall thickness) for diameters 10 inches and smaller may have to be increased over the minimum required for internal pressure to keep the deflection below the allowable amount.

Pipe types have different allowable long-term deflections based on the material type (see table 10).

Table 11 shows the pipe stiffness factor required for pipe when the pipe embedment and the trench wall native soil are assumed to provide minimal support or E′ for various allowable deflections.

Table 11. Pipe Stiffness Factor (EI/r³)

Earth cover (ft)	E'	T$_f$	F$_d$	Allowable deflection (%)				
				7.5	**6**	**5**	**4**	**3**
				Required pipe stiffness factor				
5	100	1.5	0.5	5.35	7.45	9.55	12.7	17.95
10	100	1.5	0.5	13.75	17.95	22.15	28.45	38.95
15	100	1.5	0.5	22.15	28.45	34.75	44.2	59.95
20	100	1.5	0.5	30.55	38.95	47.35	59.95	80.95

Note: Wheel loads (W_L) are assumed to be zero.

For PVC and HDPE pipe, the wall thickness changes with pipe diameter and, therefore, provides a constant DR for all diameters. Based on the allowable deflection for each pipe type, the required DR to prevent excessive deflection, without embedment support, for PVC and HDPE is summarized in table 12.

Table 12. Dimension Ratio Required for PVC and HDPE Pipe

Pipe type	Cover height (ft)			
	5	**10**	**15**	**20**
PVC	25	25	18	18
HDPE	13.5	9	7.3	–

Ductile iron and steel pipe have minimum wall thicknesses based on handling or manufacturing requirements; therefore, the wall thickness does not necessarily change with the pipe diameter. Ductile iron has minimum pipe wall thicknesses that provide sufficient stiffness, where the pipe embedment and the trench wall native soil are assumed to provide no support, to prevent excessive deflection.

The minimum steel pipe thickness suggested by pipe manufacturers for 4-inch- through 8-inch-diameter pipe is 0.1046 inch. This minimum pipe wall thickness would provide sufficient stiffness to prevent excessive deflection where the pipe embedment and the trench wall native soil are assumed to provide no support. Ten-inch-diameter pipe will require a minimum wall thickness of 0.1345 inch to prevent excessive deflection under these conditions. This includes steel pipe with or without mortar lining or coating.

Note: Bar-wrapped concrete cylinder pipe is not typically produced in diameters less than 12 inches.

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[1] LRFD = Load and Resistance Factor Design

Appendix A

Example Calculations

A-1

A pipeline has a maximum depth of cover of 10 feet, and the native soil is a sandy lean clay, CL (contains more than 30 percent coarse-grained particles), with an average in-place density of 96-percent compaction. The pipe is 90-inch-diameter steel pipe with a 1/2-inch wall thickness and a flexible coating and lining. The live load equals 0. What would be the predicted deflection for the flexible pipe if the native soil was used as the embedment material? The native material will be compacted to 90-percent compaction and will be above the water table.

Predicted Vertical Deflection

$$\Delta Y(\%) = \frac{T_f 0.07\gamma h + 10W_L}{\frac{EI}{r^3} + 0.061F_d E'} \qquad \text{Equation 3.1}$$

Using table 6,[1] $E'_n = 2500$.

Using table 5, $E'_b = 1000$.

> $T_f =$ 2. (from table 5)
> γ = 120 pounds per cubic foot (lb/ft^3) (assumed since no soil data is available)
> $E =$ 29 x 10^6 pounds per square inch (lb/in^2) (E for steel; see table 4)
> h = 10 feet

$$\frac{EI}{r^3} = \frac{E(\frac{t^3}{12})}{r^3} = \frac{(29 \times 10^6)(\frac{0.5^3}{12})}{45^3} = 3.315 \text{ lb/in}^2$$

Assume the CL material has a safe slope of 1:1. Assuming a bottom trench width for a 90-inch-diameter pipe is ID + 3 feet or 10.5 feet. This gives a trench width (B) at springline of 18 feet at springline:

> B/D = 18/7.5 =2.4
> Live load (W$_L$) = 0

---

[1] All tables referred to in this appendix appear in the main body of this report.

h $= 10$ feet
$F_d = 0.67$ (from table 5)

Using table 7 and interpolating between values:

$S_c = 1.225$

$$E' = 1.315(1000) = 1225 \qquad \text{Equation 3.6}$$

$$\Delta Y(\%) = \frac{2(0.07)120(10) + 0}{3.315 + 0.061(0.67)1225} = \frac{168}{53.38} = 3.15\%$$

The predicted deflection, 3.15% percent, is less than the allowable value of 5 percent (table 10), so the pipe design would be acceptable for deflection.

A-2

Percent Compaction Required

From example calculation A-1, the pipe stiffness (EI/r^3) is 3.315 lb/in^2 based on a minimum pipe wall thickness (0.50 inch) required for handling or internal pressure. Could the percent compaction of the embedment be reduced?

Try uncompacted embedment. From table 5, $E'_b = 200$.
$B/D = 18/7.5 = 2.4$

$$\frac{E'_n}{E'_b} = \frac{2500}{200} = 12.5$$

Using table 7 and interpolating between values:

$S_c = 1.44$

$$E' = 1.44\,(200) = 288 \qquad \text{Equation 3.6}$$

$$\Delta Y(\%) = \frac{1.5(0.07)120(10) + 0}{3.315 + 0.061(0.5)288} = \frac{126}{12.099} = 10.41\%$$

No, the predicted value is greater than the 5-percent allowable deflection.

A-3

What is the required pipe stiffness factor for 10-inch polyvinyl chloride (PVC) pipe?

Solve Equation 3.1 for pipe stiffness factor:

$$\frac{EI}{r^3} = \frac{T_f 0.07\gamma h + 10W_L}{\Delta Y(\%)} - 0.061 F_d E'$$

Assume the following:

E' = 100 lb/in^2
F_d = 0.5
T_f = 1.5
γ = 120 lb/ft^3
h = 20 feet
ΔY = 5% allowable (table 10)
W_L = 0.0 for 20 feet of cover (table 2)

$$\frac{EI}{r^3} = \frac{1.5\,(0.07)\,120\,(20) + 0}{5} - 0.061(0.5)100 = 50.4 - 3.1 = 47.3$$

PVC comes in Dimension Ratios (DR) or Standard Dimension Ratios (SDR) of 18, 21, 25, 26, and others. Using the equation:

$$\frac{EI}{r^3} = \frac{2E}{3(DR-1)^3} \qquad\qquad \text{(Equation 3.5)}$$

$$DR = \sqrt[3]{\frac{2Er^3}{3EI}} + 1$$

$$DR = \sqrt[3]{\frac{2(400{,}000)}{3(47.3)}} + 1 = 18.8$$

The equivalent DR would be 18.8. Because a pipe with a DR of 18 is stiffer than the 18.8 required, a PVC pipe with a DR of 18 should be specified.

Appendix B

Pipe Deflection for Standard Installation Method

Note: This appendix is taken from the first edition of M-25, "Method for Prediction of Flexible Pipe Deflection," completed by the Bureau of Reclamation on May 1, 1997, with a revision date of March 1, 2000. It outlines past practice by Reclamation for pipe installation. Contributors to the first edition of M-25 include Amster K. Howard, Soils Specialist; Leo A. Kinney, Jr., Pipe Specialist; and Richard P. Fuerst, Pipe Specialist. **This appendix is intended for reference only.**

For the standard installation method stated in earlier Reclamation guide specifications, only one soil type and one degree of compaction of the embedment are described for flexible pipe with diameters of 12 inches and larger. This design used the trench wall material that was as firm as (or firmer than) the embedment material at E' ≥ 3000. The selected combination of soil and compaction ensures that buried flexible pipe will not deflect more than 3 percent (up to 20 feet of cover). Live loads were assumed to be zero.

The embedment soil must be clean, cohesionless, free-draining material containing 5 percent fines or less if compacted by saturation and vibration (or ≤ 12% if compacted using other methods), not more than 25% passing the No. 50 sieve, and having a maximum particle size not exceeding ¾ inch (100% passing the 3/4-inch sieve). Fines are defined as particles that would pass a No. 200 sieve. Soils meeting this description would be classified according to the Unified Soil Classification System (USCS) as Poorly Graded Sand (SP), Well Graded Sand (SW), Poorly Graded Gravel (GP), or Well Graded Gravel (GW), or any borderline soil with these symbols (e.g., GP/SP). The soil must be compacted to a minimum of 95% Compaction.

Calculation of Percent Deflection

For calculating the predicted deflection, the following values were obtained from table B-1, which was used for previous designs:

E' = 3000 pounds per square inch (lb/in^2)
T_f = 2.5 (*Previous editions of M-25 used the conservative value of 2.5*)
F_d = 1.0
W_L = 0

The value of EI/r^3 is assumed to be 0, or the worst case where pipe stiffness is negligible compared to soil stiffness.

The wet unit weight of the uncompacted backfill soil over the pipe is assumed to be 120 pounds per cubic foot (lb/ft^3).

Predicted Vertical Deflection

$$\Delta Y(\%) = \frac{T_f 0.07\gamma h + 10W_L}{\dfrac{EI}{r^3} + 0.061F_d E'} = \frac{2.5(0.07)120\,h + 0}{0 + 0.061(1.0)3000} = 0.115h$$

Where: h = height of cover, feet

For "A" pipe	H = 5 and	ΔY =	"A" pipe is pipe with 5 feet of cover or less
"B"	10	0.58%	"B" pipe >5 feet but ≤10 feet of cover, etc.
"C"	15	1.15%	
"D"	20	1.73%	
		2.30%	

The lowest maximum allowable long-term deflection for any type of pipe (except bar-wrapped concrete cylinder) is 3 percent (see Table 10, "Allowable Long-Term Deflections"). Even if the deflection is 0.5 percent higher than predicted (see Appendix D, "Design Factor (F$_d$) Variations"), the resulting deflection for 20 feet of cover is still less than the minimum allowable deflection of 3 percent.

The allowable deflection for bar-wrapped concrete cylinder pipe is "D/40" percent where D is the pipe diameter in inches. The pipe stiffness factor, EI/r^3, for bar-wrapped concrete cylinder pipe, however, is large enough that when the deflection for the most flexible bar-wrapped concrete cylinder pipe under 20 feet of cover is calculated, the resulting deflection is still less than is allowable.

These calculations are based on the premise that the appropriate trench for Trench Types 1, 2, or 3 is constructed.

The performance of flexible pipe depends on the resistance of the soil at the sides of the pipe. This side soil support results from the combination of the embedment soil and the trench wall soil. The width of the trench depends on the firmness of the embedment soil relative to the firmness of the trench wall material. If the trench walls are as firm as (or firmer than) the embedment, only a minimum amount of compacted embedment is needed between the pipe and the trench walls. If the trench walls are very soft and easily compressible, all of the side soil resistance must come from the embedment. Accordingly, three material types are specified for trenches giving the minimum distance between the pipe and the trench wall **measured at the springline of the pipe**, as shown in figure B-1.
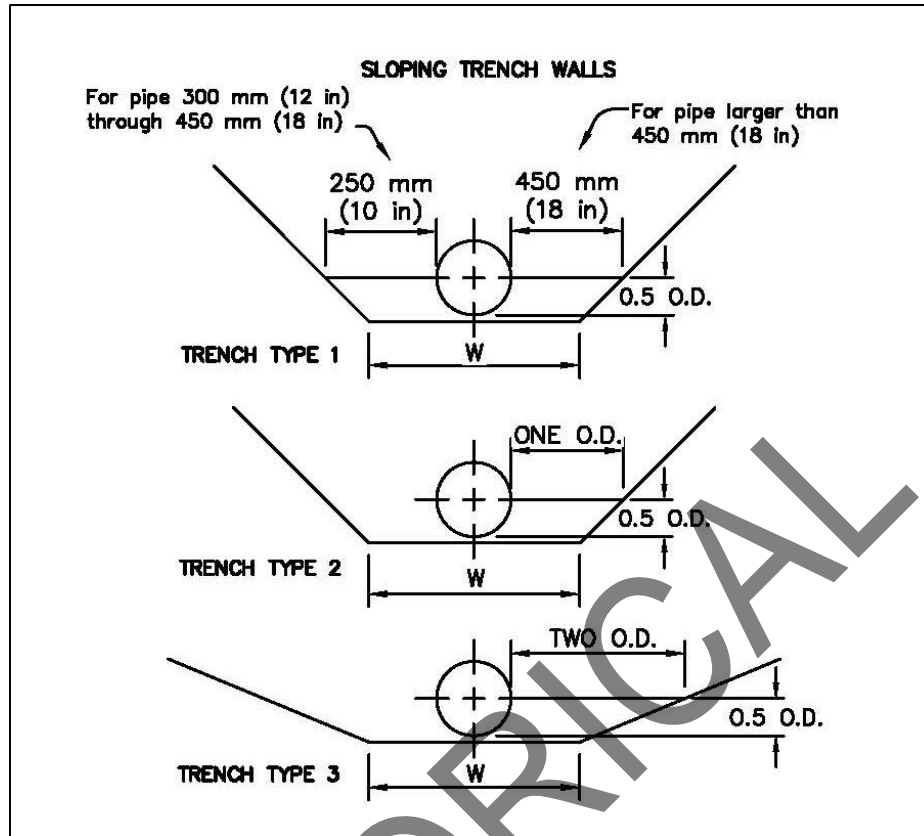
Figure B-1. Flexible pipe clearance.

The trench types are designated 1, 2, or 3 as follows:

Trench Type 1 - The trench walls are about as firm as (or firmer than) the compacted embedment soil. Minimum clearance between the pipe and the trench is all that is required. The E′ of the trench wall material should be at least 80 percent of the E′ of the embedment soil.

Trench Type 2 - The trench walls are softer than the compacted embedment. A width of one pipe diameter of compacted embedment is required between the pipe and the trench walls at the springline of the pipe (total trench width = three pipe diameters). The E′ of the trench wall material should be between 30 and 80 percent of the E′ of the embedment soil.

Trench Type 3 - The trench walls are extremely soft and are considered not able to provide any support. A width of two pipe diameters of compacted embedment is required between the pipe and the trench walls (total trench width = five pipe diameters). The E′ of the trench wall material would be less than 30 percent of the embedment soil.

To determine the trench design, the E′ of the in situ trench wall material at the level of the pipe springline must be determined. To determine the E′, the soil classification and degree of compaction (percent compaction or percent relative density) of the native material in the trench wall must be determined during investigations.

The trench design thus depends on the relative stiffness of the compacted embedment and the trench wall as indicated by the E′ value. Because the standard installation method used by Reclamation provides a compacted embedment with an E′ of 3,000 lb/in^2, the material types are evaluated in Reclamation guide specifications relative to this E′ value.

The trench types related to Reclamation's standard installation method are as follows:

Trench type	E' of the trench wall material
1	2500 lb/in^2 or greater
2	1000 to 2000 lb/in^2
3	below 1000 lb/in^2

Table B-1 shows the E′ values and the corresponding trench for different trench types for easy reference.

The designated trench type determines whether or not the controlled low strength material (CLSM) installation method can be used.

Trench Type 1 - A minimum annular space is required between the pipe and the in situ soil, and the in situ soil thus provides the soil support for the pipe.

Trench Type 2 - CLSM is used in the haunch area of the pipe, and one pipe diameter of compacted select material (or CLSM) is required between the side of the pipe and the trench wall.

Trench Type 3 – The trenches are very seldom constructed because they require a total trench width of five pipe diameters at the pipe springline, which may require an excavation or a spoil pile that may go outside the right-of-way; require scrapers instead of backhoes; or require other equipment of a size not normally used for pipe construction.

When Trench Type 3 soil conditions are identified prior to construction, design methods can be used to avoid the five-pipe-diameter-wide trench. These methods are:

1. Specify only rigid pipe.

2. Increase the pipe stiffness factor (EI/r^3) by increasing the wall thickness or increasing the thickness of mortar coatings, or both.

3. Encase the pipe in reinforced concrete.

4. Use a combined E' for other than standard Reclamation installation methods.

Table B-1. Selection of Trench Type for Compacted Embedment E' = 3000 (for reference only)

	Degree of compaction of trench walls		
	Slight	**Moderate**	**High**
Trench wall soil classification (USCS)	**< 85% P < 40% RD**	**≥ 85 to < 95% P ≥ 40 to < 70% RD**	**≥ 95% P ≥ 70% RD**
Highly compressible fine-grained soils: CH, MH, OH, OL Peat, swamps, bogs	Trench Type 3 (trench wall E' << 100)		
Fine-grained soils: Soils with medium to no plasticity and with less than 30% coarse-grained particles CL, ML (or CL-ML, CL/ML, ML/CL)	Trench Type 3 (trench wall E' = 200)	Trench Type 3 (trench wall E' = 400)	Trench Type 2 (trench wall E' = 1500)
Sandy or gravelly fine-grained soils: Soils with medium to no plasticity and with 30% or more coarse-grained particles CL, ML (or CL-ML, CL/ML, ML/CL) Coarse-grained soils with fines: Sands, gravels with more than 12% fines GC, GM, SC, SM, or any soil beginning with one of these symbols (i.e., SC/CL)	Trench Type 3 (trench wall E' = 400)	Trench Type 2 (trench wall E' = 1000)	Trench Type 1 (trench wall E' = 2500)
Clean coarse-grained soils: Sands, gravels with 12% or less fines GW, GP, SW, SP, or any soil beginning with one of these symbols (i.e., GP-GM)	Trench Type 3 (trench wall E' = 700)	Trench Type 2 (trench wall E' = 2000)	Trench Type 1 (trench wall E' = 3000)
Rock, sandstone, shale: Highly cemented soils, etc.	Trench Type 1 (trench wall E' >> 3000		

Note: % P = % Proctor, % RD = % relative density, E' = shown as lb/in^2

Appendix C

Reclamation's Deflection Equation Development

The deflection equation used by Reclamation is a variation of the modified Iowa Formula [2].[1] The significant differences are:

- Predicts vertical deflection in percent rather than horizontal deflection in inches.

- Can be used to predict deflection occurring immediately after backfilling over the pipe (initial deflection) rather than the deflection that occurs when the maximum backfill load is attained after several months.

- Relates the long-term deflection to the initial deflection by use of a time-lag factor.

- Uses a prism load on the pipe rather than the Marston load theory. The Marston load theory uses soil characteristic values that are usually not readily available. The prism load was used to develop the E′.

- Uses a design factor to reduce the E′ value to compensate for the variation between actual and predicted deflection.

- A bedding constant of 0.1 is used. The research work by Amster Howard derived the E′ values using a bedding constant of 0.1. [8]

The modified Iowa Formula [2] is given as:

$$\Delta X = \frac{D_l K\, Wr^3}{EI\, + 0.061E'\, r^3}$$

Equation C.1

Where:

ΔX = horizontal deflection of pipe (inches)
D_l = deflection lag factor, dimensionless
K = bedding constant, dimensionless
W = load per unit of pipe length (pounds per linear inch of pipe)
r = radius (inches)
E = modulus of elasticity of pipe (pounds per square inch [lb/in^2])

[1] Numbers in brackets refer to references that are contained in Section 7, "Bibliography," of the main report.

I = moment of inertia of cross section of pipe wall (inch^4 per linear inch of pipe)

E' = modulus of soil reaction (lb/in^2)

Changes can be made progressively as follows:

1. The terms are rearranged so that the pipe properties are together and substituting $W = W_E + W_L$ with the deflection lag factor only applied to the earth load.

   In this form, the modified Iowa Formula can be represented as:

$$\Delta X = \frac{K\,(D_l W_E + W_L)}{\dfrac{EI}{r^3} + 0.061E'}$$

Where:

$$\Delta X = \frac{\text{load on the pipe}}{\text{pipe stiffness factor} + \text{soil stiffness factor}}$$

W_E = prism earth load per unit of pipe length (pounds per linear inch of pipe)
W_L = live load per unit of pipe length (pounds per linear inch of pipe)

2. The prism load is used instead of the Marston load. The prism load is the weight of a column of earth above the pipe with the width equal to the outside pipe diameter and expressed in pounds per linear inch.

$$W_E = \gamma\, hDL \text{ (conversion/linear inch)}$$

Where:

γ = unit weight of soil, pounds per cubic feet (lb/ft^3)
h = cover over pipe, feet
D = pipe diameter, inches
L = 1 linear inch

$$\text{conversion} = \frac{ft^3}{1{,}728 \text{ in}^3} \times \frac{12 \text{ in}}{ft} = \frac{1 ft^2}{144 \text{ in}^2} \text{ per linear inch}$$

$$
\begin{aligned}
W_E &= \gamma\left(\frac{lb}{ft^3}\right) h\,(ft)\,D(in)\,L(in)\,\frac{1\ ft^2}{144 \text{ in}^2} \text{ per linear inch}\\
&= \frac{\gamma\,h}{144}\left(\frac{lb}{inch}\right) D\,(in) \text{ per linear inch}
\end{aligned}
$$

The equation is rearranged to express the deflection in percent:

$$\frac{\Delta X}{D} = \frac{D_l K \left(\frac{\gamma h}{144}\right) + KW_L}{\frac{EI}{r^3} + 0.061E'}$$

3. Next, ΔY is substituted for ΔX and then divided by the pipe diameter and multiplied by 100 to express the deflection in percent:

$$\frac{\Delta Y}{D} \times 100 = \frac{\left(\frac{D_l K \gamma h}{144}\right) + KW_L}{\frac{EI}{r^3} + 0.061E'} \times 100$$

4. Time-lag factor (T_f) replaces the deflection lag factor (D_l), and the bedding constant (K) is set at 0.1:

$$\Delta Y\% = \frac{T_f\, 0.07\, \gamma h + 10W_L}{\frac{EI}{r^3} + 0.061E'}$$

5. A design factor (F_d) is included with the E' variable as described in section 3.6 and in appendix D:

$$\Delta Y\% = \frac{T_f\, 0.07\, \gamma h + 10W_L}{\frac{EI}{r^3} + 0.061F_d E'}$$

Equation C.2
(Equation 3.1)

Appendix D

Design Factor (F_d) Variations

A design factor, F_d, is included, so the equation can be used for different purposes, depending on the design requirements. The various cases are Case A, Case B, and Case C as described below. Table 5 in the main part of this report gives Case B values. Table D-1 gives the complete set of F_d values. The values of F_d vary with the soil classification and the percent compaction. Values of F_d are given for three cases, which are described below.

Case A is used for comparing actual measured deflections against calculated theoretical deflections. In this instance, F_d equals 1.0 for all soil types and degrees of compaction. The actual and theoretical deflections should compare within plus or minus 2 percentage points for the **uncompacted** condition, within plus or minus 1 percentage point for **moderate** degrees of compaction, and within plus or minus 0.5 percentage point for **high** degrees of compaction [8].[1]

Case B is used for design purposes and selected to give a predicted deflection that has a 95-percent deflection probability that the actual installed pipe average deflection will not exceed the predicted values by more than 0.5 percentage points. Case B values of F_d are used when the actual deflection can be equal to, or less than, a value representing the theoretical deflection plus 0.5 percentage point, or:

Desired actual ΔY (%) = theoretical ΔY (%) + 0.5%

Case C may also be used for design purposes. Values of F_d for Case C should be used when deflection is a critical criterion for a pipeline design. Use of Case C values should result in an actual deflection equal to, or less than, the calculated theoretical deflection.

For Bureau of Reclamation purposes, Case B is used, and these are the F_d values shown in table 5. Using these values, there is a 95-percent probability that actual average deflection will be equal to, or less than, predicted (figure 2 in reference [3]) and, if more than the predicted value, the actual deflection will never be more than 0.5 percentage point greater than the predicted value.

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[1] Numbers in brackets refer to references that are contained in Section 7, "Bibliography," of the main report.

Table D-1. Values of F_d for Use in Reclamation Equation

Soil classification of embedment (USCS)	Percent compaction of embedment		
	Uncompacted (< 85% C)	**Moderate (≥ 85 to < 95% C)**	**High (≥ 95% C)**
CRUSHED ROCK: Not more than 25% passing 3/8-inch sieve and not more than 12% fines; maximum size not to exceed 3 inches	F_d for A = 1.0 B = 0.67 C = 0.5	F_d for A = 1.0 B = 1.0 C = 0.75	
CLEAN COARSE-GRAINED SOILS: Sands, gravels with 12% or less fines GW, GP, SW, SP, or any soil beginning with one of these symbols (i.e., GP-GM)	F_d for A = 1.0 B = 0.67 C = 0.5	F_d for A = 1.0 B = 0.75 C = 0.67	F_d for A = 1.0 B = 1.0 C = 0.7
SANDY OR GRAVELLY FINE-GRAINED SOILS: Silts and clays with 30% or more coarse-grained particles CL, ML, (or CL-ML, CL/ML, ML/CL) **COARSE-GRAINED SOILS WITH FINES:** Sands, gravels with more than 12% fines GC, GM, SC, SM, or any soil beginning with one of these symbols (i.e., SC/CL)	F_d for A = 1.0 B = 0.5 C = 0.3	F_d for A = 1.0 B = 0.67 C = 0.5	F_d for A = 1.0 B = 0.75 C = 0.6
FINE-GRAINED SOILS: Silts and clays with less than 30% coarse-grained particles CL, ML (or CL-ML, ML/CL, CL/ML)	F_d for A = 1.0 B = 0.5 C = 0.3	F_d for A = 1.0 B = 0.67 C = 0.5	F_d for A = 1.0 B = 0.75 C = 0.6
HIGHLY COMPRESSIBLE FINE-GRAINED SOILS: CH, MH, OH, OL, or any soil containing one of these symbols (i.e., CL/CH)	Soils with medium to high plasticity or with significant organic content No data available **Not Recommended**		

Note: USCS = Unified Soil Classification System, % C = percent compaction.

Appendix E

Live Loads (W$_L$)

General

There are many types of live loads, but the two most common live loads used in design are highway (HS-20)[1] and railroad (E80) loads.

Highway Live Loads

Highway loads should be determined separately for the two types of roadway pavements: rigid and flexible. Rigid pavements would constitute reinforced concrete pavements, and flexible pavements would include bituminous pavements and dirt and gravel surfaces. The essential difference between the two types of pavements is how they distribute the load over the subgrade. Rigid and flexible pavements are designed to distribute the load over the subgrade; however, because the modulus of elasticity of the rigid pavement is much greater than the foundation material, a major portion of the load bearing capacity is derived from the concrete slab. Dirt or gravel surfacing provides the least amount of load distribution over the pipe; therefore, it is a worst case for design. American Association of State Highway Transportation Officials (AASHTO) considers flexible bituminous pavements as unpaved surfaces, and they should be designed as dirt or gravel roads.

Loads for pipe under rigid pavements are calculated in accordance with AASHTO's 2010 LRFD[2] Bridge Design Specifications [17] methods outlined in section 3.6.1.2.6. Loads for pipe under flexible pavements, including dirt and gravel surfacing, are calculated using the Boussinesq's theory.

Impact Factors

The range of impact factors applied to the static load will vary with the type of pavement. For rigid pavement, the impact factors are the lowest. Flexible pavements are next lowest, and dirt or gravel will produce the highest impact factors.

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[1] AASHTO uses a HL-93 loading, which consists of the HS-20 truck loading plus a lane loading.
[2] LRFD = Load and Resistance Factor Design

Highway Live Loads on Rigid Pavement

A typical design case for a highway with rigid pavement assumes a two-lane concrete paved road with an AASHTO HS-20 truck centered in each 12-foot-wide lane (figure E-1). The diameter of pipe at a given depth will determine the actual load on the pipe (i.e., a larger pipe will be influenced by four wheels at a given depth, as opposed to a smaller pipe, which would only be affected by two wheels). Two wheels from passing trucks will give the greatest load, and this load case should be used for rigid pavement design. The pipe may be perpendicular or parallel to the direction of truck travel, or any intermediate position. Other design truck loads can be specified as required by project needs and local practice. The rigid pavement is assumed to distribute the load evenly over the tire contact area and through the soil below on the slope indicated in figures E-2 and E-1. The tire contact length can be calculated using AASHTO's 2010 LRFD [17], which yields a length of 10.0 inches and a width of 20 inches (based on a wheel load of 16,000 pounds) and an impact factor of 33 percent at the surface and dissipating to zero at 8 feet of depth.

The live load (W_L) for two passing trucks can then be calculated using the following formula:

$$W_L = \frac{P\,I_f}{144\,L_1 L_2}$$

Equation E.1

Where:

W_L = live load on pipe, pounds per square inch (lb/in^2)
P   = 32,000 pounds (HS-20 axle load)
I_f = impact factor = 1.33 at road surface
                 = 1.17 for 4.0 feet
                 = 1.00 for 8.0 feet
h   = depth of cover to top of pipe, feet ($\geq$ 2 feet)
L_1 = $AL_1 = 0.83 + 1.15\,h$
L_2 = $AL_2 = 4 + 1.67 + 1.15\,h$, for 2 feet $< h <$ 3.8 feet
L_2 = $AL_2 = 6 + 4 + 6 + 1.67 + 1.15\,h$, for h $>$ 3.8 feet

Note: This formula is only applicable for depths greater than 2 feet.

For special circumstances with depths of covers of less than 2 feet, the distance between the inside edges of the tires is 4 - 1.667 or 2.33 feet; therefore, only one wheel should be used to determine the live load. Therefore:

P = 16,000 pounds (HS-20 wheel load)
Impact factor = 1.29 for a depth of 1 foot

$$L_1 = 0.83 + 1.15h$$
$$L_2 = 1.67 + 1.15h$$

The live load can be computed independent of pipe diameter (lb/in^2) and results in live loads shown in table E-1.
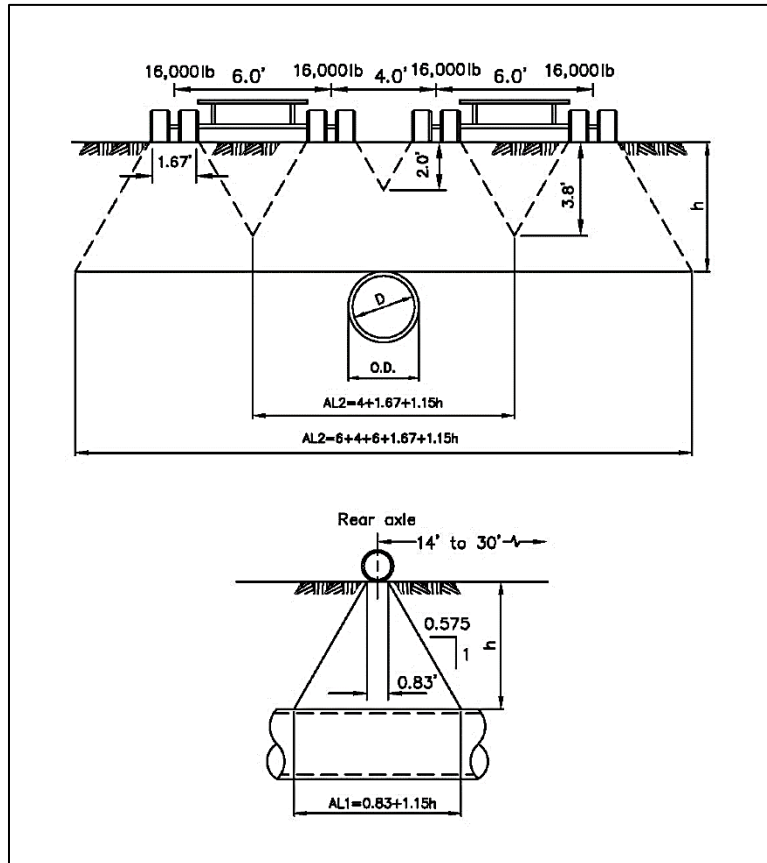

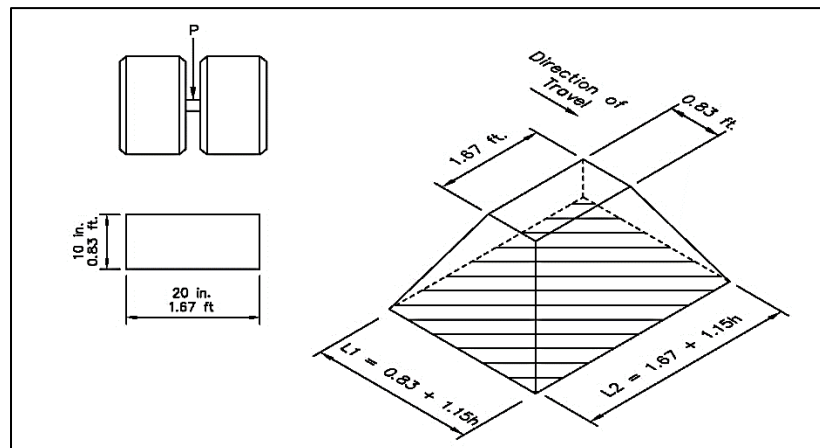
Figure E-1. Two HS-20 trucks located in adjacent lanes.

Figure E-2. Distribution of HS-20 live load through fill.

Table E-1. HS-20 Live Loads for Rigid Pavement (lb/in²)

Depth (ft)	AL₁	AL₂	I_f	P	W_L* (lb/in²)
0	0.833	1.667	1.33	16000	106.7
1	1.983	2.817	1.29	16000	25.7
2	3.133	7.967	1.25	32000	11.1
2.5	3.708	8.542	1.23	32000	8.5
3	4.283	9.117	1.21	32000	6.7
4	5.433	22.267	1.17	64000	4.3
5	6.583	23.417	1.12	64000	3.2
6	7.733	24.567	1.08	64000	2.5
7	8.883	25.717	1.04	64000	2.0
8	10.033	26.867	1.00	64000	1.6

*Per AASHTO's 2010 LFRD [17] for granular fill, assume load spread angle of 1.15 h.

Note: The Bureau of Reclamation requires a minimum of 5 feet of cover over pipelines under roads.

Example

Assume: h = 5 feet

$\quad\quad$ I_f = 1.12

$\quad\quad$ Tire width = 20 inches

$\quad\quad$ Tire length = 10 inches

1. Compute L_1, load width (feet) parallel to direction of travel (see figure E-2).

$\quad$ AL₁ = 0.83 + 1.15 h
$\quad$ AL₁ = 0.83 + 1.15 (5) = 6.58 feet

2. Compute L_2, load width (feet) perpendicular to direction of travel (see figure E-2).

$\quad$ h ≥ 2 feet

Therefore: AL₂= ((6 + 4 + 6+ 1.67) + 1.15 h)
$\quad$ AL₂ = (17.67 + 1.15 h)
$\quad$ AL₂ = (17.67 + 1.15 (5)) = 23.42 feet

$$W_L = \frac{P\, I_f}{144\, L_1 L_2} \quad\quad\quad\quad \text{(Equation E.1)}$$

3. Compute W$_L$:

Substituting:

$$W_L = 64000 \ (1.12 \ / \ (144 \ (6.58) \ (23.42)) = 3.2 \ lb/in^2$$

Highway Live Loads on Flexible Pavement

The following method for finding the pressure acting on a pipe at a given depth directly below a surface load is based on the Boussinesq's equation (see figure E-3). Please note that this method is valid for any roadway or any construction equipment wheel load calculation. More complex loading situations can be analyzed using the more general Boussinesq procedure.
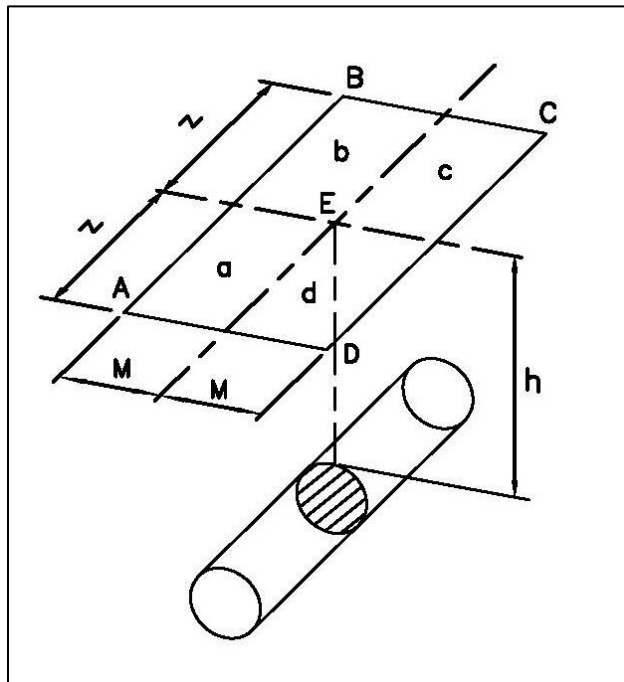
Figure E-3. Distributed load over pipe.

The point pressure on the pipe is found by dividing the rectangular wheel load area (ABCD) into four subarea rectangles (abcd) which have a common corner, E, in the surcharge area, and over the pipe. The live load pressure at the surface is determined when the live load is divided over the four subareas. Each subarea pressure at depth is calculated by multiplying an influence coefficient, I, from table E-2, by the live load:

Method for Prediction of Flexible Pipe Deflection

$$4\,P_s = P_a + P_b + P_c + P_d$$

$$W_L = 4\,I\,P_s$$

(Equation E.2)

Where:

W_L = live load pressure at point on pipe, lb/in^2
I = influence coefficient from table E-2
P_s = distributed live load pressure acting over ground surface, lb/in^2 or
     wheel load/load area or $16{,}000 / (10 \times 20) = 80\ lb/in^2$

Table E-2. HS-20 Live Loads for Flexible Pavement (lb/in^2)

Depth (ft)	I_f	I	P	W_L (lb/in^2)
2	1.5	0.035	16,000	16.8
2.5	1.5	0.024	16,000	11.5
3	1.4	0.017	16,000	7.6
4	1.3	0.010	16,000	4.2
5	1.2	.0064	16,000	2.5
6	1.1	.0046	16,000	1.6
7	1.0	.0034	16,000	1.1
8	1.0	.0027	16,000	0.9

Note: Reclamation requires a minimum of 5 feet of cover over pipelines under roads and other surfaces that will have vehicular travel, such as service yards or parking lots.

Newmark Influence Coefficient

The Newmark influence coefficient is dependent on the dimensions of the rectangular area and the depth to the top of pipe. Table E-2 gives influence coefficients in terms relating to figure E-3:

Where:

h = vertical distance from surface to the pipe crown, feet
M = horizontal distance, normal to pipe centerline, from the center of the load
     to the load edge, feet
N = horizontal distance, parallel to pipe centerline, from the center of the
     load to the load edge, feet

The total load can then be computed by applying an appropriate impact factor.

$$W_L = 4\,I\,P_s\,I_f$$

(Equation E.3)

The impact factor [13][3] will vary with depth:

$$I_f \;=\; \text{impact factor} \;=\; 1.50 \text{ for } 2.0 \text{ feet} < h < 3.0 \text{ feet}$$
$$= 1.40 \text{ for } 3.0 \text{ feet} < h < 4.0 \text{ feet}$$
$$= 1.30 \text{ for } 4.0 \text{ feet} < h < 5.0 \text{ feet}$$
$$= 1.20 \text{ for } 5.0 \text{ feet} < h < 6.0 \text{ feet}$$
$$= 1.10 \text{ for } 6.0 \text{ feet} < h < 7.0 \text{ feet}$$
$$= 1.00 \text{ for } \geq 7.0 \text{ feet}$$

For depths less than 2.0 feet, the impact factor should be increased significantly and will depend on surface material and roughness.

If the footprint of the tire is assumed to be 10 inches by 20 inches, the influence coefficients (I) can be calculated (see table E-2).

The live load (W$_L$) can be computed independent of pipe diameter (lb/in^2) and results in live loads shown in table E-2.

Example

Determine external load W$_L$ (lb/in^2) for h= 2 feet on a dirt road:

$$W_L = 4 \, I \, P_s \, I_f \qquad\qquad \text{(Equation E.3)}$$

Solution of W$_L$ requires determining: P$_s$, I, and I$_f$:

For an HS-20 load, a typical tire width is 10 inches by 20 inches.
Therefore, M = 0.42 and N = 0.83.

P$_s$ = 16000 / (10) (20) = 80 lb/in^2
For h = 2 feet. I$_f$ = 1.50

M/h = 0.42/2 = .21 N/h = 0.83/2 = .42

From table E-3: I = .035

Compute W$_L$:

$$W_L = 4 \, (.035) \, (80) \, (1.50) = 16.8 \text{ lb/in}^2$$

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[3] Numbers in brackets refer to references that are contained in Section 7, "Bibliography," of the main report.

Table E-3. Influence Coefficient, I, for Distributed Loads Over a Pipe for Any Tire Footprint

M/h	N/h						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.1	0.005	0.009	0.013	0.017	0.020	0.022	0.024
0.2	0.009	0.018	0.026	0.033	0.039	0.043	0.047
0.3	0.013	0.026	0.037	0.047	0.056	0.063	0.069
0.4	0.017	0.033	0.047	0.060	0.071	0.080	0.087
0.5	0.020	0.039	0.056	0.071	0.084	0.095	0.103
0.6	0.022	0.043	0.063	0.080	0.095	0.107	0.117
0.7	0.024	0.047	0.069	0.087	0.103	0.117	0.128
0.8	0.026	0.050	0.073	0.093	0.110	0.125	0.137
0.9	0.027	0.053	0.077	0.098	0.116	0.131	0.144
1	0.028	0.055	0.079	0.101	0.120	0.136	0.149
1.2	0.029	0.057	0.083	0.106	0.126	0.143	0.157
1.5	0.030	0.060	0.086	0.110	0.131	0.149	0.164
2	0.031	0.061	0.089	0.113	0.135	0.153	0.169
∞	0.032	0.062	0.090	0.115	0.137	0.156	0.172

M/h	N/h						
	0.8	0.9	1	1.2	1.5	2	∞
0.1	0.026	0.027	0.028	0.029	0.030	0.031	0.032
0.2	0.050	0.053	0.055	0.057	0.060	0.061	0.062
0.3	0.073	0.077	0.079	0.083	0.086	0.089	0.090
0.4	0.093	0.098	0.101	0.106	0.110	0.113	0.115
0.5	0.110	0.116	0.120	0.126	0.131	0.135	0.137
0.6	0.125	0.131	0.136	0.143	0.149	0.153	0.156
0.7	0.137	0.144	0.149	0.157	0.164	0.169	0.172
0.8	0.146	0.154	0.160	0.168	0.176	0.181	0.185
0.9	0.154	0.162	0.168	0.178	0.186	0.192	0.196
1	0.160	0.168	0.175	0.185	0.194	0.200	0.205
1.2	0.168	0.178	0.185	0.196	0.205	0.209	0.212
1.5	0.176	0.186	0.194	0.205	0.211	0.216	0.223
2	0.181	0.192	0.200	0.209	0.216	0.232	0.240
∞	0.185	0.196	0.205	0.212	0.223	0.240	0.250

Railroad Live Loads

The loading configuration for an E-80 Cooper railroad loading is a uniformly loaded rectangle with dimensions 8 feet by 20 feet (figure E-4). The source of these dimensions is the width of the railroad ties (8 feet) and the spacing between the drive wheels on the locomotive. Loading is based on the axle weight exerted on the track by two locomotives and their tenders coupled together in a doubleheader fashion (figure E-5). For an E-80 loading, the axle load is 80,000 pounds, and there are four drive axles. The entire load is presumed to be uniformly distributed on the rectangle.
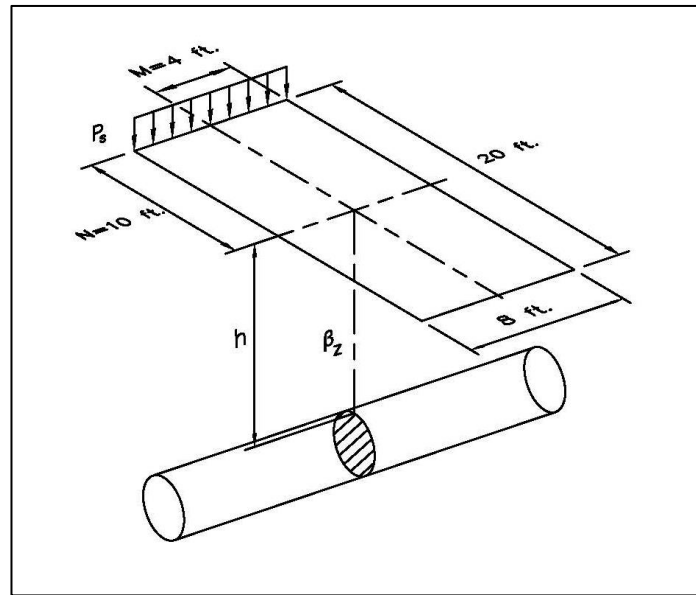

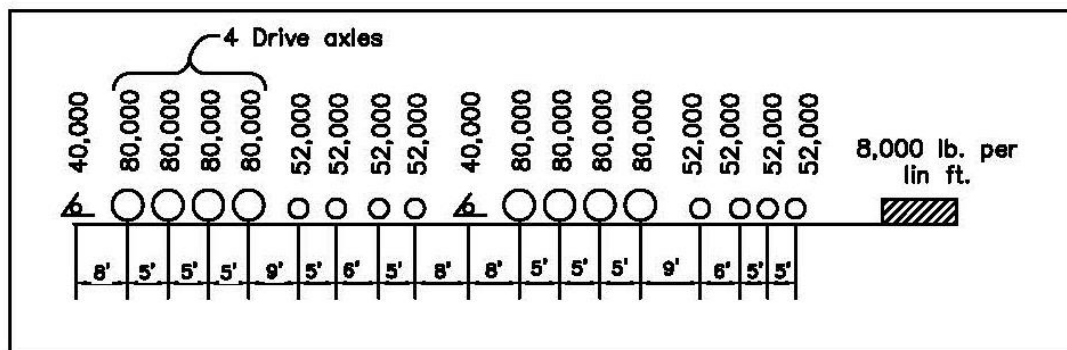**Figure E- 4. Railroad crossing load design.**

Figure E-5. Railroad loading for Cooper E-80 locomotives.

The impact factors for railroads vary differently than for highway loads. The American Railway Engineering and Maintenance of Way Association recommends a linearly variable impact factor that is 40 percent at the bottom of the railroad ties and zero at 10 feet of cover over the ties [18]. Reclamation requires a minimum cover of 5 feet between the bottom of the railroad ties and the top of the pipe at railroad crossings.

The total load can then be computed by applying an appropriate impact factor.

$$W_L = 4 \, I \, P_s \, I_f \qquad\qquad \text{(Equation E.3)}$$

Where:

I_f = impact factor
P_s = load = 13.9 lb/in^2
I = influence coefficient, from table E-3

This equation is not valid for depths less than 2.5 feet because a minimum cover is required. Because the footprint of a train is assumed to be the same for all standard gauge trains, the influence coefficients (I) can be tabulated as shown in table E-4.

The live load can be computed independent of pipe diameter (lb/in^2) and results in live loads shown in table E-4.

Table E-4. Railroad Live Loads (lb/in^2)

Depth (ft)	I_f	I	P	W_L (lb/in^2)
2.5	1.3	0.231	320,000	16.7
3	1.28	0.222	320,000	15.8
4	1.24	0.202	320,000	13.9
5	1.20	0.181	320,000	12.1
6	1.16	0.161	320,000	10.4
7	1.12	0.142	320,000	8.8
8	1.08	0.127	320,000	7.6
9	1.04	0.112	320,000	6.5
10	1	0.101	320,000	5.6
20	1	0.039	320,000	2.2

Note: Reclamation requires a minimum of 5 feet of cover over pipelines under railroads.

Example

Determine external load W_L (lb/in^2) for H= 6 feet beneath a railroad:

$$W_L = 4\ I\ P_s\ I_f \qquad\qquad \text{(Equation E.3)}$$

Solution of W_L requires determining P, I, and I_f :

From table E-4, I= 0.161

$P_s = 4(80000) / (96)\ (240) = 13.9$ lb/in^2
$I_f = 1.16$

Compute W_L:

$W_L = 4\ (.161)\ (13.9)\ (1.16) = 10.4$ lb/in^2