

# Oil and Gas Pipeline Design, Maintenance and Repair

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## Part 5: Pipeline Design

# Contents

- Introduction
  - Load Considerations
  - Stress Due To Internal Fluid Pressure
  - Steady Pressure
  - Un-steady Pressure (Water Hammer)
  - Hydrostatic Pressure
  - Stress Due To External Fluid Pressure
- Static Earth Load On Buried Pipe
    - Marston's Theory and Classification of Buried Conduits
    - Rigid Conduit in Ditch
    - Flexible Conduit in Ditch
    - Embankment Conduit
    - Tunnel Conduit

# Contents

- Live Loads On Buried Pipe
- Other Loads On Pipelines
- Performance Analysis And Design
  - High Pressure Pipes
  - Effect of Temperature Change
  - Effects of Pipe Bending
  - Seismic Design of Pipelines

- Low- Pressure Pipes
  - Soil Classification
- Rigid-pipe Analysis And Design
  - Rigid Pipe Types and Bearing Strength
  - Standard Installations
  - Design Procedure
  - Flexible-Pipe Analysis and Design

# INTRODUCTION

Pipeline design includes several general steps:

- Load determination,
- Critical performance evaluation such as determining the stress and/or deformation of the pipe,
- Comparison of performance with the limiting performance criteria established by codes and standards, and
- Final selection of the pipe and construction method based on the design

# INTRODUCTION

- Design of pipelines has evolved separately in different industries that use pipelines.
- Different industries use pipelines for different purposes, design requirements and type of pipes are different
- Petroleum industry and the natural gas industry primarily use steel pipe with welded joints
- This allows the pipeline to withstand very high pressure, often above 1000 psig and sometimes above 3000 psig.
- High pressures allow the use of long pipelines, often more than 1000 mile, with only a few booster pump or compressor stations for each pipeline

# INTRODUCTION

- Pipeline design is based on three broad categories:
  - High-pressure pipes.
  - Low-pressure pipes, and
  - Intermediate-pressure pipes
- High-pressure pipes
  - Internal pressure is so high
  - It dominates the design.
  - Most long-distance petroleum and natural gas pipelines belong to this

# INTRODUCTION

- Low-pressure pipes
  - Internal pressure is so low, or nonexistent,
  - Design is governed by external loads.
  - Most sewer pipes and culverts belong to this category.
- Intermediate-pressure pipes,
  - Internal pressure load and the external loads are of similar magnitudes
  - Both must be considered.
  - This group includes pressure sewer pipes, water pipes, and certain petroleum and natural gas pipes,

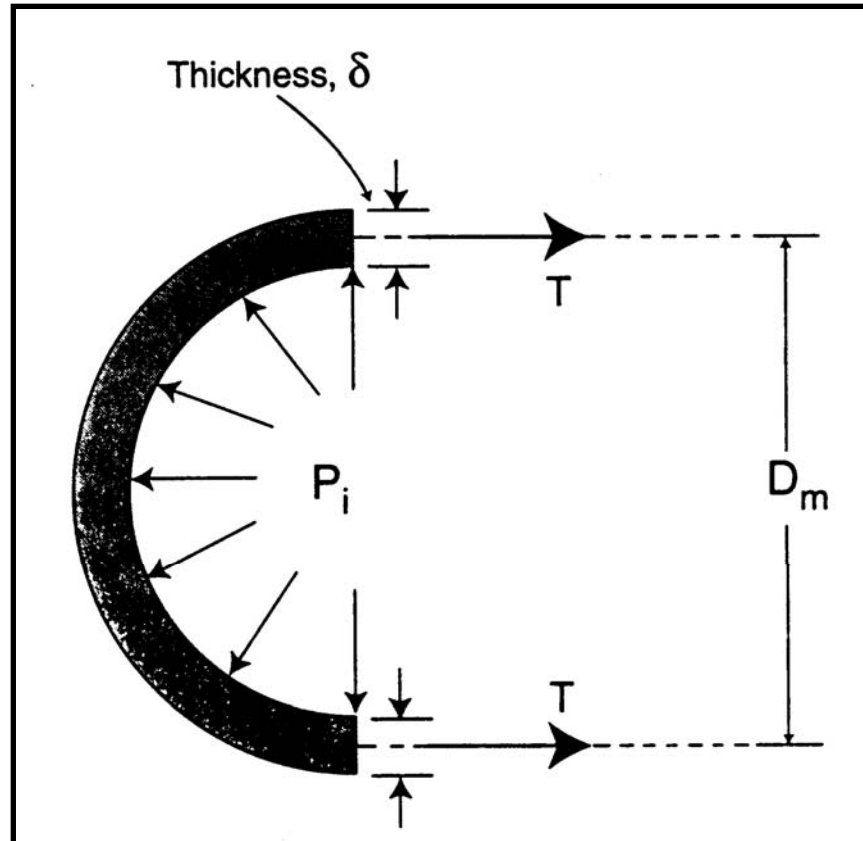
# LOAD CONSIDERATIONS

- Pipelines must be designed for many types of load, including but not limited to
- Stress due to pressure generated by the flow (internal pressure)
- External pressure by fluid if the pipe is submerged underwater
- External pressure generated by the weight of earth and by live loads on underground (buried) pipelines
- Loads due to thermal expansion, Earthquakes, etc.



# STRESS DUE TO INTERNAL FLUID PRESSURE

- Balance of forces on half of the cross section of a pipe.
- The tensile force per unit length of the pipe is
$$2T = 2\delta\sigma_t$$
- $\sigma_t$  is the hoop and  $\delta$  is the pipe thickness.
- Tensile force,  $2T$  balanced by the force in the opposite direction, caused by the internal pressure  $P_i$  as



# Analysis of Hoop Tension

$$2T = 2\delta\sigma_t = P_i D_m \quad \text{or} \quad \sigma_t = \frac{P_i D_m}{2\delta}$$

$$\sigma_{\max} = \frac{P_i (D_o^2 + D_i^2)}{(D_o^2 - D_i^2)} \quad P_i = P_1 + P_2$$

- $D_m$ , is the mean diameter of the pipe, the average of the inner diameter  $D_i$  and the outer diameter  $D_o$ ,  $D_m = (D_i + D_o)/2$ .

# STEADY PRESSURE

- The steady pressure  $P_1$  can be calculated by using the one-dimensional energy equation given in, Part 3.
- For a horizontal pipe, the maximum steady pressure  $P_1$  occurs immediately downstream of pumps.
- For pipelines that dip deeply into a valley, the place of maximum  $P_1$  may occur at the lowest point of the pipelines.
- In each case, the designer must use the one-dimensional energy equation to calculate the highest  $P_1$  in the line

# Example

- An 8-inch steel pipe carries water from location A to location C separated by a distance of 10 mile. The pipeline dips into a valley with the lowest elevation point B being 2 mi downstream of A. The elevations of points A, B, and C are 500 ft, 100 ft, and 520 ft, respectively. The velocity of the flow is 5 fps. Find the points of maximum pressure and design the pipe against such pressure. Assume that the maximum allowable tensile stress of the steel pipe is 20,000 psi.

# Solution

- Using the one-dimensional energy equation from point A (immediately downstream of pump) to point C (the pipe end) yields

$$R_e = \frac{5 \times 8}{12 \times 10^{-5}} = 3.33 \times 10^5,$$

$$\frac{e}{D} = \frac{0.00015 \times 12}{8} = 0.000225$$

# Solution

$$\frac{P_A}{\gamma} = (z_c - z_A) + (h_L)_{AC} = (520 - 500) + f \frac{10 \times 5280}{8/12} \times \frac{5^2}{64.4} = 20 + 30745f$$

$$\frac{P_B}{\gamma} = \frac{P_A}{\gamma} + (z_A - z_B) - (h_L)_{AB} = 527 + (500 - 100) - 101 = 826 \text{ ft}$$

Therefore,  $P_B = 51,540 \text{ psfg} = 358 \text{ psig}$

$$\delta = \frac{P_i D_m}{2S} = \frac{358 \times 8}{2 \times 20,000} = 0.0716 \text{ inches}$$

Since a standard NPS X-inch pipe has a wall thickness of 0.332 inch, a standard X-inch steel pipe is more than adequate for this pipeline.

# UNSTEADY PRESSURE (WATER HAMMER)

$$C = \frac{C_o}{\sqrt{1 + \varepsilon \frac{D E}{\delta E_p}}}$$

$$\Delta P = \rho C V$$

$$C_o = \sqrt{E / \rho}$$

$$\Delta P = \frac{2L}{CT_c} \rho C V = \frac{2L}{T_c} \rho V$$

- $E$  = bulk modulus of the fluid
- $E_p$  = Young's modulus of the pipe material
- $\varepsilon$  = constant that depends on type of pipe and pipe-support system
- $C_o$  = celerity of pressure waves in perfectly rigid pipe
- $\rho$  = fluid density, slug/ft<sup>3</sup>

# Example

- In the previous example, if a valve at the end of the pipe (location C) is closed in 10 s. what is the maximum water hammer pressure generated in this pipe?



# Solution

- In this case,  $C_o = 4720$  fps.
- $\varepsilon = 1.0$ ,  $D = 8$  inches,
- $\delta = 0.322$  inch.
- $E = 300,000$  psi and,  $E_p = 30,000,000$  psi.
- $C = 4.220$  fps.
- Therefore,  $2L/C = 25.0$  s, which is greater than  $T_c$ .
- This means that the valve closure must be regarded as rapid, yielding  $P_2 = \Delta P = 284$  psi.
- $P_B = P_1 + P_2 = 358 + 284 = 642$  psig.

# HYDROSTATIC PRESSURE

- In special cases, such as encountered in cross-mountain pipelines, a large hydrostatic pressure,  $P$ , may be developed in the low-elevation part of the pipe when the flow is stopped by closing a valve downstream.
- In such a situation,  $P$ , may be higher than the combined steady-unsteady pressure given by

$$P_0 = P_s + \gamma H_o$$

- $\gamma$  is the specific weight of the fluid, and  $H_o$  is the pump head at zero discharge

# STRESS DUE TO EXTERNAL FLUID PRESSURE

$$P_b = \frac{3E_p I_t}{(1 - \mu_p^2) r_m^3}$$

$$P_b = \frac{2E_p}{(1 - \mu_p^2) (D_m / \delta)^3}$$

- $r_m$  = mean radius of the pipe
- $\mu_p$  = Poisson's ratio
- $I_t$  = Moment of inertia of the pipe thickness, which is equal to  $\delta^3/12$
- $D_m$  = mean diameter
- $\delta$  = wall thickness

# Example

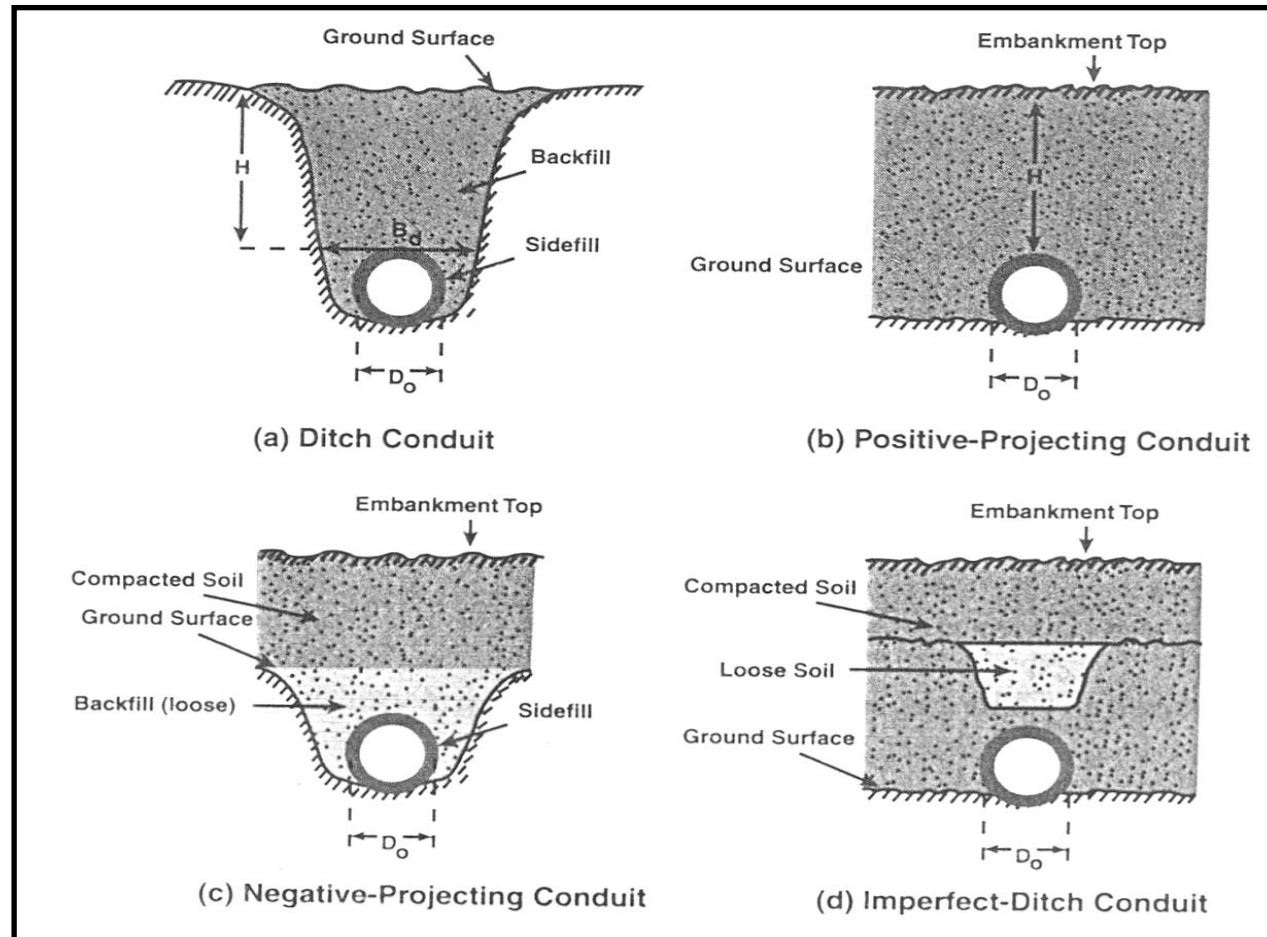
Suppose an 18-inch PVC sewer pipe is laid under a lake of 80 ft of water. Before the pipe is connected to the rest of the sewer line, its interior is filled with air at atmospheric pressure. Calculate the minimum thickness of the pipe to prevent buckling

# Solution

- PVC has a Young's modulus of  $E_p = 400,000$  psi and a Poisson's ratio of  $\mu_p = 0.38$ . The buckling pressure in this case, generated by the hydrostatic pressure of 80 ft of water is
- $P_b = 62.4 \times 80 = 4992$  psf.
- Therefore,  $D_m/\delta = 30.0$ , and  $\delta = 18/30.0 = 0.60$  inch.
- This shows that the minimum thickness of this pipe must be 0.6 inch.

# STATIC EARTH LOAD ON BURIED PIPE

## Marston's Theory



# Rigid Conduit in Ditch

$$W_e = C_d \gamma_s B_d^2$$

$$C_d = \frac{1 - e^{[-2Kn'H / B_d]}}{2Kn'}$$

$$K = \frac{\sqrt{n^2 + 1} - n}{\sqrt{n^2 + 1} + n} = \frac{1 - \sin A}{1 + \sin A}$$

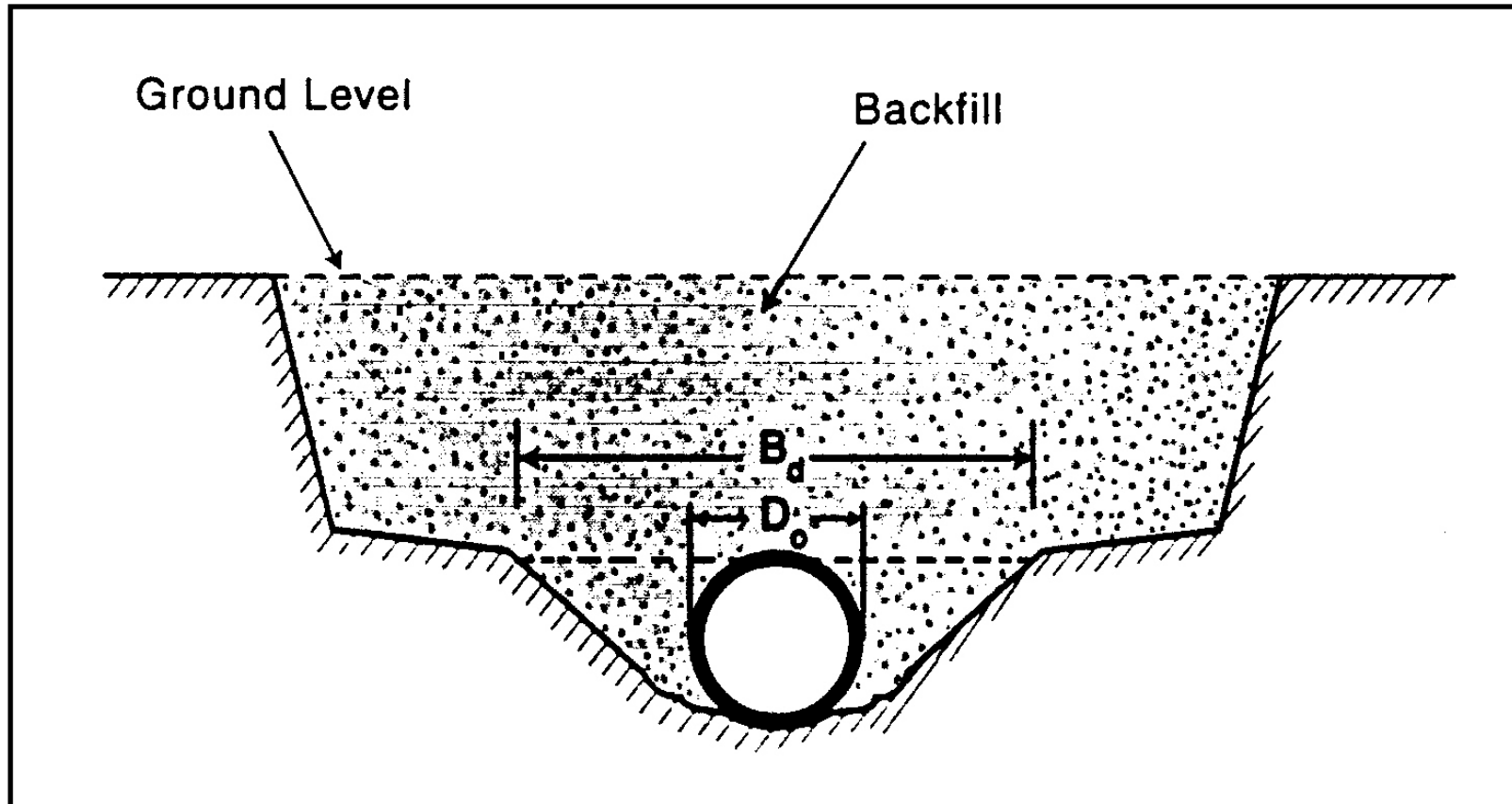
- $\gamma_s$  = specific weight of the soil above the pipe
- $B_d$  = width of the ditch
- $K$  = ratio of active lateral pressure to vertical pressure
- $H$  = height of fill above the top of the conduit
- $n'$  = coefficient of friction between fill material and sides of ditch
- $n$  = coefficient of internal friction of fill material
- $A$  = angle of response of material.

# Values of $K_n'$ for Various Types of Backfill Soil

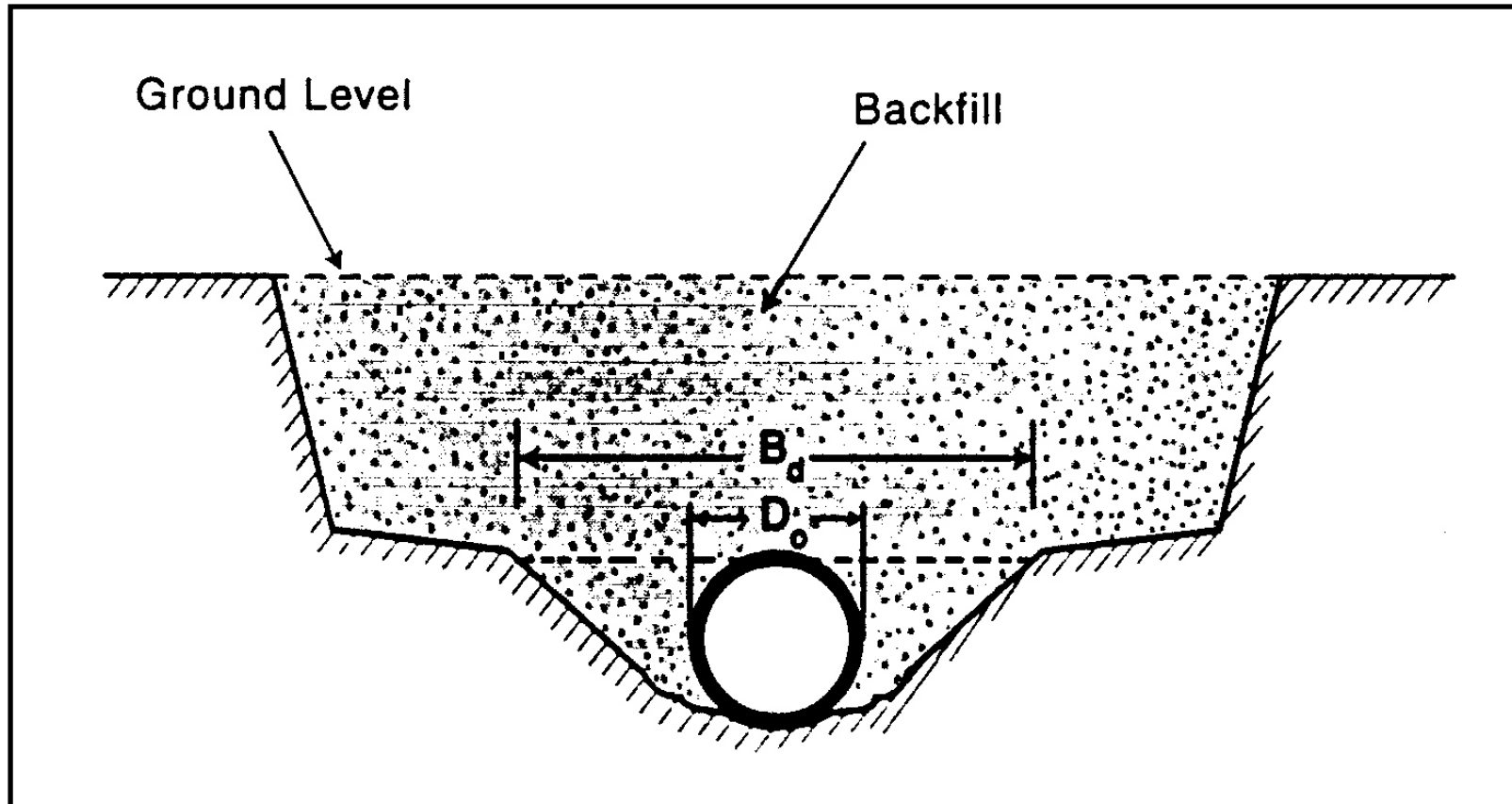
Type of Soil	Value of $K_n'$
Granular materials without cohesion	0.1924
Maximum for sand and gravel	0.165
Maximum for saturated topsoil	0.150
Ordinary maximum for clay	0.130
Maximum for saturated clay	0.110



# Determination of $B_d$ for Trench of An Arbitrary Cross-sectional Shape



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# Determination of $B_d$ for Trench of An Arbitrary Cross-sectional Shape

- values of  $K$  and  $n'$  can be determined from laboratory tests of soil samples, in practice they are determined simply by classification of soil type as given in Table
- When the characteristics of the soil is uncertain, it is usually assumed that  $\gamma_s = 120 \text{ lbs/ft}^3$  and  $Kn' = 0.150$ .

# Example

- A concrete pipe of 3-ft outer diameter is laid in a rectangular ditch of 5-ft width. The top of the ditch is 6-ft above the top of the pipe. The backfill material is saturated topsoil having a specific weight of 120 lb/ft<sup>3</sup>. What is the earth load on the pipe?

# Solution

- For saturated topsoil, Table gives the maximum value of  $K_n'$  as 0.150. But,  $H/B_d = 6/5 = 1.2$ , and  $\gamma_s = 120 \text{ lb/ft}^3$ .
- So, from Equation 5.11,  $C_d = 1.008$ .
- Substituting these values into Equation 5.10 yields  $W_c = 3024 \text{ lb/ft}$ .

# Flexible Conduit in Ditch

$$W_c = C_d \gamma_s D_o B_d$$

- Moser reported, flexible ditch conduits, the simple soil prism formula yields good conservative projections of the loads

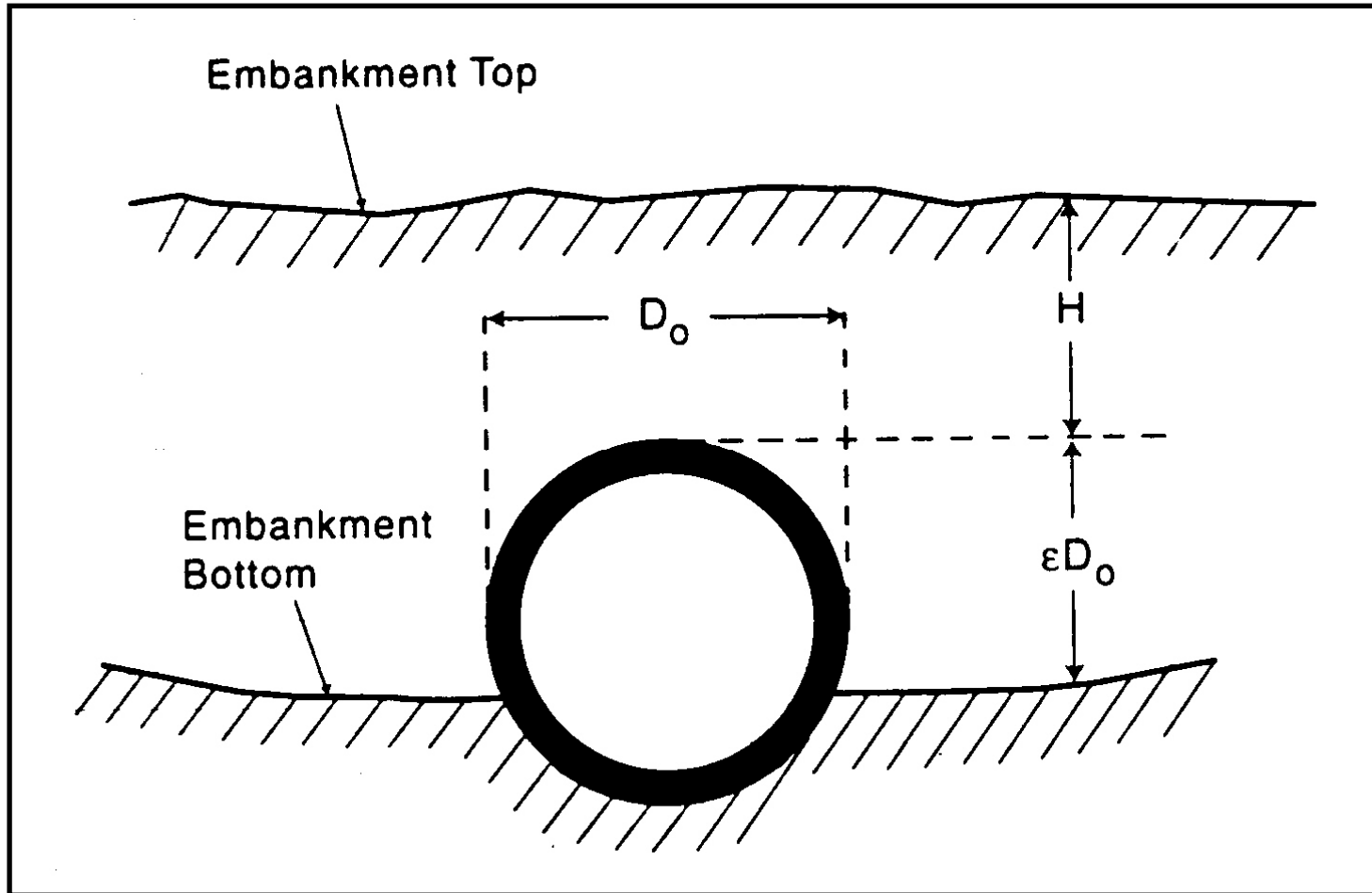
$$W_c = \gamma_s H D_o$$

# Embankment Conduit

$$W_c = C_e \gamma_s D_o^2$$

- $D_o$  = outer diameter of the pipe
- $C_e$  = load coefficient for embankment conduits. which is a function  $H/D_o$ ,
- $n$  = coefficient of friction of the soil
- $\epsilon r_s$  = product where  $\epsilon$  is the projection ratio of the pipe

# Determination of settlement ratio $\epsilon$ , of embankment conduits





# Example

- A corrugated steel pipe of 2-m diameter is used as a culvert to drain water across a highway. Suppose that the top of the highway is 6 m above the top of the pipe, and the bottom is laid 1 m below the foundation (ground level) so the projection ratio  $\varepsilon$  of the pipe is 0.5. The soil above the pipe has a density of  $1925 \text{ kg/m}^3$ . The sidefills on the two sides of the pipe are well compacted to receive loads from above. Find the load on this pipe.

# Solution

- The most conservative value of  $r_s$  for flexible pipe with well-compacted sidefills is -0.2.
- The projection ratio is  $\varepsilon = 0.5$ ,
- hence,  $\varepsilon r_s = -0.1$ .
- Because  $H/D_o = 6.0/2.0 = 3.0$ ,
- Table 5.2 yields  $C_e = 2.51$ .
- Then, from Equation 15,
- $We = 2.51 \times 1925 \times 22$   
= 19,330 kg/m  
= 189,600 N/m.

# Tunnel Conduit

$$W_e = C_d B_t (\gamma_s B_t - 2C)$$

- $W_e$  = earth load on unit length of the conduit
- $C_d$  = same as determined from Equation 5.11
- $B_t$  = maximum width of the tunnel ( $B_t = D_o$  for pipe jacking)
- $C$  = cohesion coefficient, varies considerably with different types of soil.
- The U.S. Water Pollution Control Federation recommends approximate values for  $C$ : 0, 40, 100, 250, 300, and 1000 (lb/ft<sup>2</sup>) for loose dry sand, very soft clay, silty sand, medium clay, dense sand, and hard clay, respectively.
- values of  $C$  should never be greater than  $\gamma_s B_t / 2$ ; otherwise, Equation 5.16 is not applicable.

# LIVE LOADS ON BURIED PIPE

Live Loads Transferred to Pipe, psi				Live Loads Transferred to Pipe, psi			
Height of Cover, ft	Highway	Railway	Airport	Height of Cover, ft	Highway	Railway	Airport
1	12.5	-	-	16	NG	3.47	3.06
2	5.56	26.39	13.14	18	NG	2.78	2.29
3	4.17	23.61	12.28	20	NG	2.08	1.91
4	2.78	18.40	11.27	22	NG	1.91	1.53
5	1.74	16.67	10.09	24	NG	1.74	1.14
6	1.39	15.63	8.79	26	NG	1.39	1.05
7	1.22	12.15	7.85	28	NG	1.04	NG
8	0.69	11.11	6.93	30	NG	0.69	NG
10	NG	7.64	6.09	35	NG	NG	NG
12	NG	5.56	4.76	40	NG	NG	NG
14	NG	4.17	4.17				

# OTHER LOADS ON PIPELINES

- Pipeline through an earthquake zone, the loads induced by potential earthquakes and their effects must be considered to achieve an earthquake-resistant design
- Pipeline above ground, the effect of high winds on the pipe, both static and dynamic effects, must be considered and analyzed.
- Pipeline undersea, loads due to ocean current and large forces during construction of the pipe, including those caused by the pipe's own weight while the pipe is being laid from a lay barge, must be carefully analyzed
- Pipeline buried in an area of high ground water elevation, the load generated by groundwater table fluctuations must be considered

# PERFORMANCE ANALYSIS AND DESIGN

- Structural design involves
  - Calculation of loads
  - Calculation of maximum stresses, strains, and deformations of the structure
  - Comparing the limiting states of allowable stresses, strains, and deformations to prevent structural failure such as rupture, buckling, crushing, or excessive deformation.
- Design aspects for both high-pressure and low-pressure pipes considered

# High Pressure Pipes

- Analysis and design focused on the stress, deformation, and failure caused by high internal pressure.
- Determination of hoop tension and failure caused by high pressure was presented earlier in this chapter.
- If water hammer: highest pressure generated by water hammer, dynamic effects of the water hammer, vibration and material fatigue, carefully analyzed.
- Many critical external loads, such as earthquake (in earthquake region), high winds (for elevated pipes), ocean current (for submarine pipes), thermal stresses (for pipes welded in hot weather), to be considered.
- Pressure due to earth load in this case is much lower

# Effect of Temperature Change

$$\Delta L = \alpha \Delta T L$$

$$\sigma_T = E_p \frac{\Delta L}{L} = E_p \alpha \Delta T$$

- $\alpha$  = thermal expansion coefficient of pipe



# Effects of Pipe Bending

$$(\sigma_f)_{\max} = \frac{M_{\max} D_o}{2I_p} = \frac{4M_{\max}}{\pi\delta D_o^2} \quad (\sigma_f)_{\max} = \frac{E_p}{(1-\mu_p^2)} \left( \frac{\delta}{D_m} \right)^2$$

$$R_b = \frac{D_n^2}{1.12\delta}$$

- $(\sigma_f)_{\max}$  = maximum bending stress
- $M_{\max}$  = maximum moment
- $\delta$  = wall thickness
- $I_p$  = moment of inertia of the pipe
- $R_b$  = highest radius for buckling

# Effects of Pipe Bending

- Whenever a pipe bends, pipe cross section deforms, changing from a circular to an elliptic shape
- Major axis of the ellipse is perpendicular to the plane of bending
- Pipe diameter increases by an amount equal to  $\Delta M$  along the major axis, and it decreases by an amount equal to  $\Delta Y$  along the minor axis.
- For small deformation,  $\Delta X = \Delta Y$ .

$$\frac{\Delta X}{D} = \frac{1}{16} \left( \frac{D}{\delta} \right)^2 \left( \frac{D}{R_b} \right)^2$$

# Seismic Design of Pipelines

- To be safe, the spacing between supports,  $L$ , must be within the following limit:

$$L = \left( \frac{\pi}{2f} \right)^{1/2} \left( \frac{gE_p I_p}{w} \right)^{1/4} \quad \text{where } f \gg f_n$$

- $f$  = design frequency of the pipe in hertz (cycles per second):

# Seismic Design of Pipelines

- Seismic stress generated due to vibration

$$\sigma_e = 0.000488iwGD_0L^2 / I_p$$

- $i$  = stress intensification factor,
- $G$  = seismic acceleration in  $g_s$ , dimensionless
- $w$  = weight of the pipe (including the fluid in it) per unit length

# LOW- PRESSURE PIPES

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- Analysis and design are focused on
  - Soil properties
  - Soil-pipe interaction
  - Installation (bedding) method
  - Rigidity of the pipes.

# Soil Classification

- **Class I:** manufactured angular granular materials. 0.5 to 1.5 inches (6 to 40 mm) size
- **Class II:** Coarse sands and gravels with maximum particle size of 1.5 inches (40 mm), little or no fines, with more than 95% materials retained on a clean no. 200 sieve: Four subgroups. GW. GP. SW. and SP
- **Class III:** Fine sands and clay (clay-filled) gravels, with more than 50% materials retained on a number 200-sieve: Four subgroups, GM, GC, SM, and SC.
- **Class IV:** Silt, silty clays, and clays, including inorganic clays and silts of low to high plasticity and liquid limits, with less than 50% materials retained on a no. 200 sieve: Four subgroups, ML, CL, MH, and CH.
- **Class V:** Organic silts, organic silty clays, organic clays, peat, muck, and other highly organic materials: Three subgroups, OL, OH, and PT

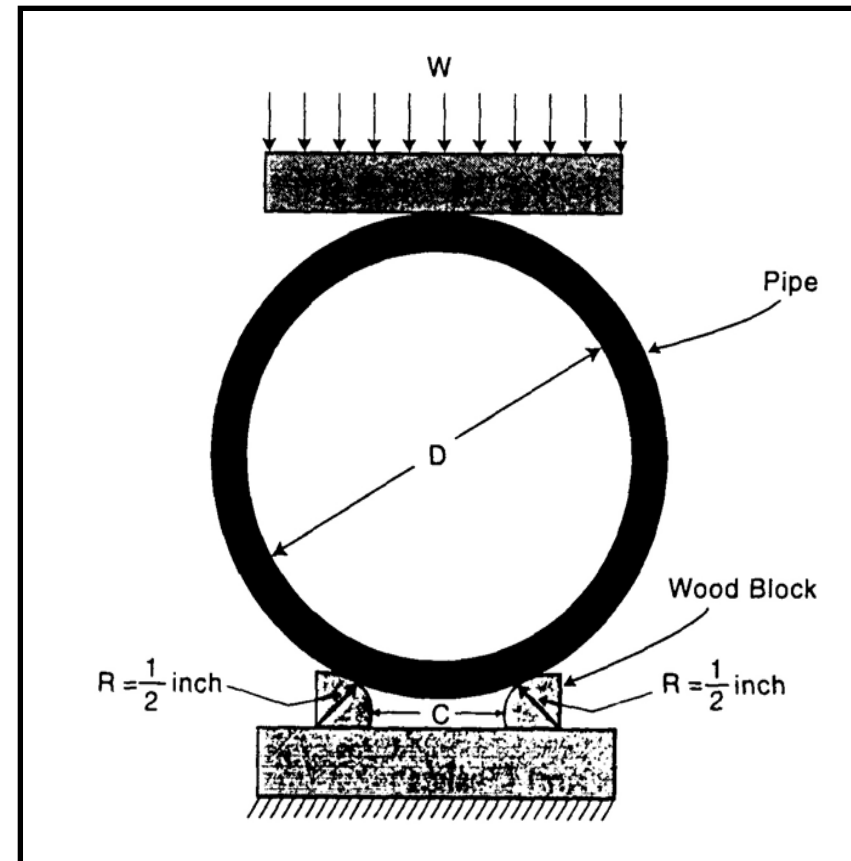
# Soil-Pipe Interaction

- Highly complicated by the fact that the system is structurally indeterminate.
- Forces and stresses between the soil and the pipe cannot be determined from using only static and dynamics (Newton's laws).
- The stiffness properties of the pipe and of the soil must also be included in the analysis
- Recent advancement in high-speed digital computers made it possible to solve some complex soil-pipe interaction problems numerically by using the finite element method (FEM)

# RIGID-PIPE ANALYSIS AND DESIGN

## Rigid Pipe Types and Bearing Strength

- Three-edge test have to be conducted using the system shown in which involves a test specimen
- Load gradually increased until the pipe fails or develops severe cracks.
- failure load gives the 3-edge bearing strength of the pipe, in the units of lb/ft, kips/ft (kilo pounds per foot), kg/m, or N/m.
- The 3-edge bearing strength divided by the pipe diameter gives the D-load of the pipe
- Has units of psi, psf., kg/m<sup>2</sup>, or N/m<sup>2</sup>.





# Design Procedures

The design procedure for the rigid pipe systems:

- Determine the earth load by using Marston's theory  
Determine the live load by using empirical data such as provided in Table 5.3;
- Combine the earth load with the live load. By adding them together;
- Select the type of construction according to the WPCF classification A. B. C. And D. And determine the corresponding bedding factor;
- Determine the safety factor from standards or codes (if no standards exist on safety factor, use a minimum of 1.5);
- Select the piping strength by using the following formuals:

# Design Procedures

$$W_3 = \frac{W_t N_s}{B}$$

$W_3$  = required three-edge strength

$W_t$  = total combined load on the pipe which is the sum of the earth load  $W_e$  and the live load WL

$N_s$  = safety factor

$B$  = the bedding factor.

# Example

- A sewer made of a 24-inch (O.D.) concrete pipe is used at a large airport to drain storm water. The pipe crosses runways and taxiways at a depth of 10ft below ground. The soil above the pipe is saturated topsoil, and the specific weight of the soil is  $124 \text{ lb/ft}^3$ . Select a pipe of appropriate 3-edge strength and define the installation method used.

# Solution

- **Determination of earth load**
  - $Kn' = 0.150$ ,  $H = 10$  ft,  $B_d = 3.0$  [t (selected ditch width according to WPCF specification)]
  - $H/B_d = 10/3 = 3.333$ .
  - From Equation 5.11,  $C_d = 2.11$ .
  - Then, from Equation 5.10,  $W_c = 2.11 \times 124 \times 32 = 2355$  lb/ft
- **Determination of live load**
  - From Table 5.3, the live load in terms of pressure at 10ft below airport runways and taxiways is 6.09 psi.
  - Since a linear foot (12 inches) of the 24-inch-diameter pipe covers a load area of  $12 \times 24 = 288$  in<sup>2</sup>, the resultant live load per linear foot is  $W_t = 6.09 \times 288 = 1754$  lb/ft.

# Solution

- **Determination of total combined load –**
  - The combined total load is  $W_t = W_c + W_L = 2355 + 1754 = 4109$  lb/ft.
- **Selection of installation type and determination of bedding factor**
  - Somewhat arbitrary, WPCF Class A installation with concrete bottom is used. For this type of installation, the bedding factor is 2.8, as given previously.
- **The American Concrete Pipe Association (ACPA)**
  - recommends a safety factor N (1.25 -1.50 for concrete pipes.
  - To be conservative, the value of 1.5 is used
- **Finally**
  - From Equation 25,  $W_3 = 4109 \times 1.5/2.8 = 2201$  lb/ft.
  - Therefore, the pipe selected must have a 3-edge strength of 2201 lb/ft or greater.

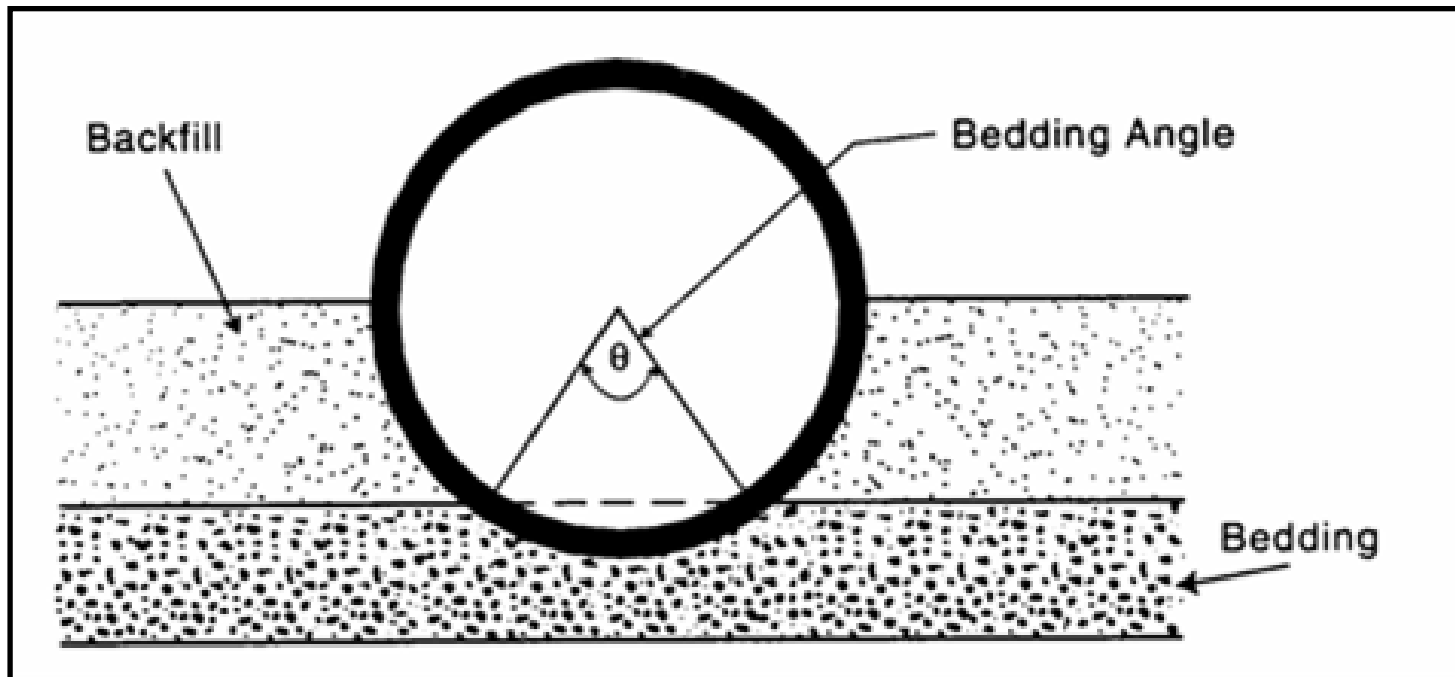
# Flexible-Pipe Analysis and Design

- As a pipe of circular cross section with a diameter  $D$  is under earth load from above, the pipe deforms into an elliptical shape with a horizontal diameter increase of  $\Delta X$  and a vertical diameter decrease of  $\Delta Y$

$$\Delta X = \frac{KD_L W_c r_m^3}{E_p I_t + 0.061E_s r_m^3}$$

- Derived by Spangler in a slightly different form, and later modified by Watkins into the above form

# Bedding angle



# Modified Iowa Formula

$$\Delta X = \frac{1.64W_c}{E_s}$$

- average value of 0.1 0 for K
- Different pipes can tolerate different amounts of ring deflection,  $\Delta X/D$ .
- For instance, PVC pipes will not collapse into a reversal of curvature



# Reversal Of Pipe Curvature Due To Over-deflection

