From Chapter 5, with minimum cover, the maximum bending moment $M = 0.022\ P_v r_s^2$. Therefore,

$$M = 0.022 P_v (73.75/2)^2 = 29.91 P_v$$

Also, $\sigma = Mc_1/I_s = 36{,}000$ psi at yield;
$I_s = t_s^3/12 = 0.3125^3/12 = 0.00254$ in.^{3};
$c_1 = t_s/2 = 0.3125/2 = 0.1563$ in.
Therefore, $M = \sigma I_s/c_1 = 36{,}000\ (0.00254)/(0.1563) = 585$ lb-in. at yield.
Equating Ms and solving for P_v,

$$29.91 P_v = 585$$

$$P_v = 19.6 \text{ psi.}$$

Also from Chapter 5, $P_v = W/(H_c + 8 \text{ in.})(H_c + 24 \text{ in.})$, where $W = 20$ kip. Therefore,

$$19.6 = 20{,}000/(H_c + 8)(H_c + 24)$$

$$H_c^2 + 32 H_c + 192 = 20{,}000/19.6$$

Solve for H_c by completing the square,

$$(H_c + 16)^2 = 20{,}000/19.6 - 192 + 256 = 1{,}084.4$$

$$H_c + 16 = 32.9$$

$$H_c = 16.9 \text{ in.}$$

Minimum cover is conservative because the longitudinal strength of pipe is neglected and a line load is assumed. Nevertheless, if $H_c = 17$ in., or about 1.5 ft, the approach of a 20-kip wheel load must be made with caution. With a safety factor, a reasonable minimum depth of cover would be 3 ft.

7.2.4 Design of Soil Column

The following is an analysis for flexible pipes only, and it assumes that the pipe has been found adequate for resistance to the ring compression loads. Referencing Fig. 7-1, the vertical load on the two flexible pipe walls at section AA is no less than $2P_v D_P/2 = P_v D_P$. In the design of the soil column, it is assumed, conservatively, that the pipe wall takes a vertical load of $P_v D_P$, which is only part of the total load. The remainder of the load must be supported by the soil. The greatest load occurs when the heavy live load W is centered above section AA—not over the top of the pipe. At this location, the live load pressure at AA is the maximum. Pipe walls carry $\gamma_t H_c D_P$ due to the dead load. Live load pressure P_l on the pipes is small enough to be neglected. Moreover, it is already supported by the ring stiffness required for minimum cover. What cannot be neglected is the live load on section AA. Vertical soil stress, σ_y, on section AA must be less than vertical soil compression strength, S'. Vertical stress is soil load divided by the cross-sectional area.

$$\sigma_y = Q'/X \leq S'/\mathrm{sf} \tag{7-2}$$

where
σ_y = vertical soil stress on section AA (psf),
$Q' = Q - \gamma_t H_c D_P$ = load supported by the soil at section AA = total load less load supported by the pipe walls (lb/ft),
Q = vertical load on section AA = $w_d + w_l$ (lb/ft),
γ_t = unit weight of soil (pcf),
H_c = height of soil cover (ft),
D_P = outside diameter of pipe (ft),
X = width of section AA between pipes (ft),
S' = vertical soil compression strength (psf),
sf = safety factor.

Per unit length, Q is the sum of the dead weight of the crosshatched soil mass w_d and that portion of w_l of the surface live load W that reaches section AA. The dead load w_d per unit length (l) of pipe is soil unit weight times the crosshatched area:

$$w_d = (l)\left[(X + D_P)(H_c + D_P/2) - \pi(D_P/2)^2/2\right]\gamma_t \tag{7-3}$$

The live load w_l is the volume under the live load pressure diagram of Fig. 7-1 at section AA. It is calculated by means of Boussinesq or Newmark, as described in Chapter 4. The pyramid–cone punch-through stress analysis does not apply because the height of cover is greater than the required minimum. From the Boussinesq method, the live load w_l per unit length is

$$w_l = 0.477WX\big/(H_c + D_P/2)^2 \tag{7-4}$$

Example 7-2: Vertical Soil Stress and Safety Factor

The pipe from Example 7-1 is installed in parallel, with a separation between pipes, X = 1 ft, and with the same trench conditions. Again, a surface wheel load of W of 20 kip is anticipated. The pipe is tape coated, resulting in $D_P \approx D_O = 73.750$ in. a. What is the vertical soil stress at section AA of Fig. 7-1? b. What is the safety factor against soil slip?

a. Vertical Load on Section AA. First, the vertical load on section AA, Q, must be found. $Q = w_d + w_l$.

The dead load, w_d, is found by Eq. 7-3, with $l = 1$.

$$\begin{aligned} w_d &= (l)\left[(X + D_P)(H_c + D_P/2) - \pi(D_P/2)^2/2\right]\gamma_t \\ &= (l)\left[(1 + 73.75/12)(1.5 + 73.75/12/2) - \pi(73.75/12/2)^2/2\right]120 \\ &= 2{,}148\ \text{lb} \end{aligned}$$

The live load, w_l, is found by Eq. 7-4.

$$\begin{aligned} w_l &= 0.477WX/(H_c + D_P/2)^2 \\ &= 0.477(20{,}000)(1)/[1.5 + (73.75/12)/2]^2 \\ &= 456\ \text{lb} \end{aligned}$$

Therefore, $Q = 2{,}148 + 456 = 2{,}604$ lb

$$\begin{aligned} Q' &= Q - \gamma_t H_c D_P \\ &= 2{,}604 - 120(1.5)(73.75/12)(1) \\ &= 2{,}604 - 1{,}106 \\ &= 1{,}498\ \text{lb} \end{aligned}$$

From Eq. 7-2, the vertical soil stress, $\sigma_y = Q'/X$. Therefore, for a unit length of 1 ft,

$$\begin{aligned} \sigma_y &= 1{,}498/[(1)(1)] \\ &= 1{,}498\ \text{psf.} \end{aligned}$$

b. Safety Factor. The safety factor is $\text{sf} = P_x/\sigma_x$ (resisting stress/active stress) (Fig. 7-2). At section AA in the soil column, the granular soil slips if

$$\sigma_x/\sigma_y = (1 - \sin\Phi)/(1 + \sin\Phi)$$

For a flexible ring, $P_x = P_d = \gamma_c H_c$. Therefore, $P_x = 120(1.5) = 180$ psf.

At soil slip, the soil column widens horizontally and the pipes narrow. If the soil is lightly compacted, such that the soil friction angle is $\Phi = 30°$,

$$\sigma_x = \sigma_y(1 - \sin\Phi)/(1 + \sin\Phi) = \sigma_y/3 = 1{,}498/3 = 499\ \text{psf}$$

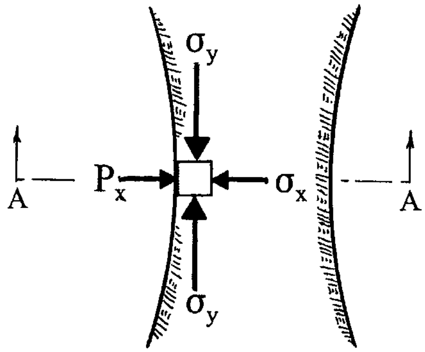

Figure 7-2. Detailed Pipe–Soil Column Between Parallel Pipes.

Therefore, the safety factor is sf = 180/499 = 0.36, which is less than 1.0, so the soil will slip. Increasing the soil friction angle to 45° only increases the safety factor to 0.7, which still results in soil slip. Other options to eliminate the potential for soil slip include increasing either X or H, placing soil cement between the pipes, or a combination of the three.

Analyses of a soil column bound between two pipes are conservative. Longitudinal resistance of the pipes and soil cover is neglected. Additionally, the arching action of the soil cover is neglected. Based on this inherent conservatism, safety factors can be small, such as less than sf = 1.5.

7.3 PARALLEL TRENCHES

Buried flexible pipes depend on embedment for stability. Compacted soil at the sides supports and stiffens the top arch. So what happens when a trench is excavated parallel to a buried flexible pipe? The fundamental questions relate to minimum separation between the newly excavated trench and pipe and the variables that relate to collapse of the trench. These issues were the objectives of research at Utah State University in 1968. To reduce the number of variables, ring stiffness was assumed to be zero. The results of the test are conservative because no pipe has zero stiffness. Most flexible steel pipes have D/t ratios of less than 300. The D/t ratio was 600 in an attempt to approach zero stiffness. The pipe shape was maintained by mandrels during placement of the backfill.

In general, if the native soil is cohesionless, the trench wall is at an angle of repose no greater than the soil friction angle, Φ. The trench slope at this angle of repose should not cut into the embedment of the buried pipe. If the native soil is cohesive, the trench wall can stand in a vertical cut, as shown in Fig. 7-3.

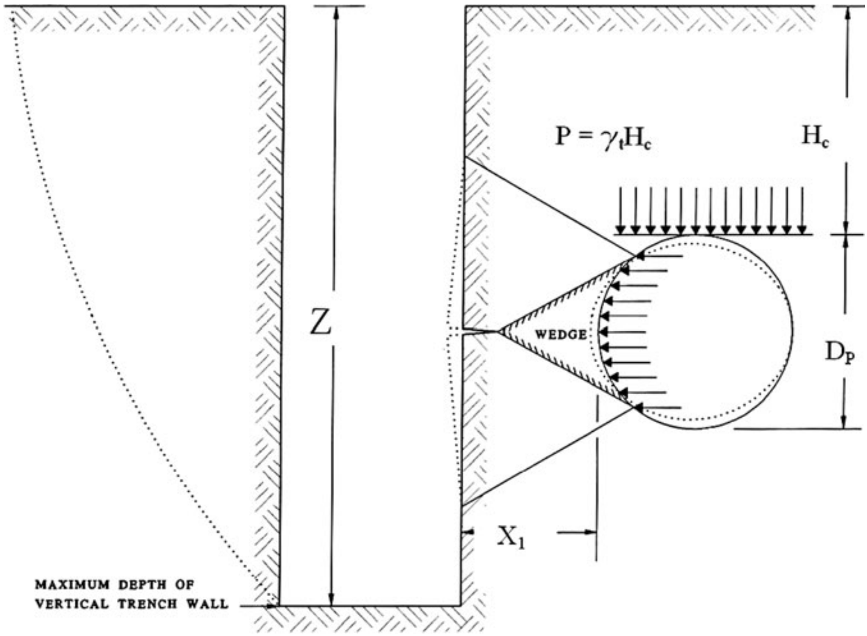

Figure 7-3. Maximum Depth of a Vertical Cut.

The primary concern when using separate parallel trenches is having sufficient separation to maintain the stability of the trench wall adjacent to the existing buried pipe. Vertical soil pressure on the buried pipe creates a horizontal pressure, which if large enough can result in punchout of the adjacent trench wall (Fig. 7-3). The ability of the adjacent trench wall to sustain the imposed load is a function of the soil properties and the height of cover and diameter of the buried pipe. From this information, the minimum distance, X_1, of undisturbed soil from the adjacent trench wall to the buried pipe can be calculated. Tests performed on moist, granular soil have shown that $X_1 = 1.4\ H_cD_P/Z$ at complete collapse of a flexible pipe under a vertical prism of soil. Applying a safety factor of approximately 2 results in $X_1 = 3H_cD_P/Z$. Z is the maximum depth of self-sustaining vertical cut, a measure of the "soil strength," the value of which is determined by excavation of a test pit, or by the equation $Z = 2c/[\gamma_t \tan(45° - \Phi/2)]$. This analysis is conservative, though, because it does not account for any support due to the ring stiffness of the pipe. Inclusion of the ring stiffness could allow for a reduction in the value X_1, but this change would need to be verified based on tests of the proposed pipe–soil system.

Z = maximum depth of trench with vertical walls, at cave-in. (ft),
X_1 = minimum separation (ft),
H_c = depth of cover (ft),
D_P = diameter of pipe (ft),
γ_t = unit weight of soil (pcf),
c = soil cohesion (lb/in.^{2}),
Φ = soil friction angle (deg).

Example 7-3: Minimum Trench Separation

Assume that a 48-in. flexible pipe is buried to a depth of cover of 5 ft in soil with cohesion c = 4 psi, a soil friction angle of Φ = 30°, and γ_t = 125 pcf. What is the minimum separation between an adjacent trench of maximum depth and the buried pipe?

First, the maximum depth of the adjacent trench must be determined. From the above,

$$\begin{aligned} Z &= 2c/[\gamma_t \tan(45° - \Phi/2)] \\ &= 2(4)(144)/[125 \tan(45° - 30°/2)] \\ &= 15.96 \text{ ft} \\ &= 16 \text{ ft} \end{aligned}$$

The minimum separation is then calculated as

$$\begin{aligned} X_1 &= 3H_cD_P/Z = 3(5)(48/12)/16 = 3.75 \text{ ft} \\ &= 3.75 \text{ ft} \end{aligned}$$

7.4 TRENCHES IN POOR SOIL

Poor soil can pose a concern for the buried flexible pipe designer. Soil strength (soil bearing capacity) can be measured by driving a 2-in.-diameter split-barrel sampling tube into the soil using a 140-lb hammer falling 30 in. The blow count is the number of blows per foot of penetration. The tube can be driven to depths below the surface. Generally, soils achieving 4 blows per foot or less are considered poor. In such conditions, the trench width may need to be increased to achieve the necessary support for the embedment material. Additionally, soil particle migration may need to be addressed as well to maintain long-term support for the pipe–embedment system.

7.4.1 Minimum Trench Width

If the trench walls are of poor quality soil, the trench width may need to be up to twice the diameter of the pipe, and a trench box should be used for excavation. Figure 7-4 shows how vertical pressure, *P*, on a flexible pipe is transferred horizontally to the trench wall, where it can be supported by roughly half of the pressure on the pipe. This trench width analysis is conservative. In fact, theoretically, the trench wall could be mud, but in this unlikely case, the pipe would need to be designed for external fluid pressure. Generally, if the trench wall can stand in vertical cut, it has sufficient strength to provide horizontal support for the pipe in a trench of width equal to 2*DP*.

7.4.2 Soil Particle Migration

Soil particle migration is generally a function of either groundwater flow that washes trench wall fines into the voids in a coarser embedment or wheel loads and earth tremors that shove or shake coarser particles from the embedment into the finer soil of the trench wall. If fines migrate from the trench wall into the embedment, the trench wall may settle, but the pipe is unaffected. If the embedment particles migrate into the trench

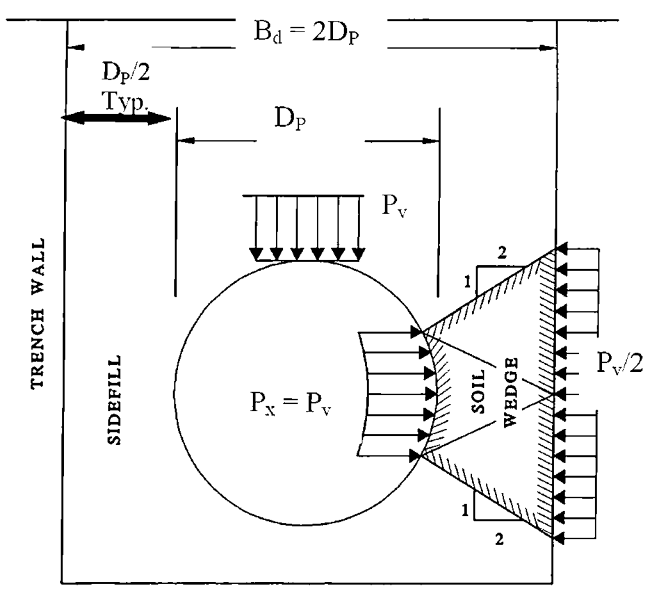

Figure 7-4. Soil Wedge at Incipient Slip of Sidefill in the Trench Width B_d = $2D_P$.

wall, the shift in sidefill support may allow a slight ring deflection. This migration could occur only if the trench wall soil is loose enough or plastic enough that the embedment particles can be shoved into it. The conditions for soil particle migration are unusual. Nevertheless, they must be considered. Remedies for soil particle migration include embedment with enough fines in it to filter out migrating particles in groundwater flow and trench liners. Geotextile trench liners may be specified in severe cases.

7.5 FLOWABLE FILL

Some installations are subject to extremely narrow trenches where placement and compaction of embedment is impractical. In other situations, the process for compacting the embedment to its desired density may be impractical. For these and other select instances, the use of a free-flowing material, called flowable fill, for bedding and embedment is beneficial. Pipe is typically placed on small soil berms or sand bags for support and vertical alignment in the trench, which also allows the material to flow under and around the pipe. The supports should be of a material that is less rigid than the proposed fill to avoid the possibility of introducing localized stress risers in the pipe. The benefits and desired characteristics of flowable fill are discussed in the next sections.

7.5.1 What Is Flowable Fill and What Are Its Benefits?

Common practice is to specify select, imported soil for bedding and embedment. An alternative to imported materials is recycling the native soil as flowable fill, also referred to as controlled low-strength material. Flowable fill is granular soil, usually composed of native materials with enough fines and cementitious material to result in a slurry. It is a full-contact bedding and can also be used as a sidefill, or even as embedment over the top of the pipe. Flowable fill reduces or eliminates problems such as uneven bedding, voids under the haunches, and excessive ring deflection. The objectives of flowable fill are to recycle native soil and to place bedding and embedment in fewer steps, in a narrower trench, and with improved quality assurance. If flowable fill is used properly, the trench width may be reduced. Care should be exercised to prevent flotation of the pipe.

7.5.2 Desired Characteristics

The slurry must be fluid enough to flow under and maintain full contact with the pipe but be structurally sound after curing. The slurry must include cementitious material but may also include silt and some clay. Many native soils containing fines can be used for flowable fill, provided the clay content is not over two-thirds of the fines. Large rocks must be screened out of flowable fill.

As shown earlier, the ring deflection of a buried pipe is approximately equal to the vertical compression of the sidefill soil. Therefore, if the flowable fill is placed as a sidefill, its vertical compression and shrinkage must be within the defined limits for the deflection of the pipe. Flowable fill must also have enough bearing capacity to support the backfill and hold the pipe in shape without excessive deflection.

High strength is not a primary requirement, but some cement is recommended so the material flows properly. Compressive strength should be kept low—a minimum of 40 psi—but no greater than the pipe's internal pressure. Tests show that flowable fill embedment can be of good quality with as little as one sack of cement per cubic yard of native soil. Flowable fill with excessive strength creates two problems:

- Embedment cannot be easily excavated in case the pipe must be uncovered at some future time.
- If high-strength embedment cracks due to soil movement, high stresses can be concentrated on the pipe.

7.6 LONGITUDINAL FORCES

Stresses develop in buried pipe as a result of longitudinal forces at special sections (e.g, valves, tees, elbows, wyes) caused by pressure, temperature change, beam action, and relative longitudinal pipe–soil movement. A general understanding must be reached regarding the applicable stresses involved: the interaction of thrust force stresses, the longitudinal stresses resulting from internal pressure (Poisson's effect stress), and stresses resulting from a thermal gradient. Longitudinal performance and performance limits can be analyzed by fundamentals of engineering mechanics and mechanics of materials.

Typically, a pipeline is welded to a special section to restrain that section from longitudinal movement due to thrust forces. The thrust could be due to the effect of internal pressure on an appurtenance, such as an elbow, reducer, bulkhead or valve, or it could result from thermal stresses, all of which result in a longitudinal force of some magnitude being imparted to the pipe. The frictional resistance between the pipe and the surrounding backfill material achieves restraint of that force. General analysis assumes that maximum thrust is present at the appurtenance, and, with uniform soil cover, a linear reduction of the thrust force from the appurtenance to the free end of the pipe by resistance of the soil

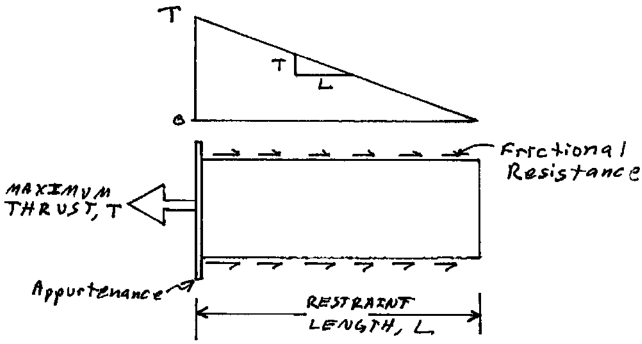

Figure 7-5. Linear Decrease of Thrust Force in Restraint Length.

embedment as the pipe shortens or lengthens. A more detailed analysis is offered in Section 7.6.3. Figure 7-5 is an example of longitudinal force, F. A section of buried pipe is attached to an appurtenance at the fixed end but is free to shorten or expand from the free end (at a coupling or gasketed joint). The pipe shortens when the temperature drops or when the pipe is pressurized. The shortening generates frictional resistance of the soil embedment, which accumulates from the free end to maximum thrust T at the appurtenance. Thrust T must not cause the stress in the pipe wall to exceed yield. If both ends of the pipe are restrained, soil friction is eliminated, but the pipe feels the thrust caused by temperature decrease and internal pressure. If the pipe is bent, longitudinal stresses can be analyzed by bending moment analysis.

The pipe connected to the appurtenance is subject to the total applied thrust at the appurtenance, which is equal to the frictional resistance of the soil for some distance, as the pipe shortens. With this shortening comes a longitudinal strain, and in turn a longitudinal stress. If the pipe could not shorten, then the thrust force would be resisted by a bearing force of the embedment material and not translated as longitudinal stress in the pipe. The total applied thrust as referenced here does not necessarily depict a maximum thrust value of PA acting on a pipe of diameter D, where P is pressure in the pipe and A is the pipe cross-sectional area = $\pi D^2/4$, but rather the full value of the thrust generated by the special section in question. For instance, pipe adjacent to a closed valve or bulkhead would be subject to a full thrust force equal to PA, whereas pipe adjacent to a reducer would be subject to a full thrust force equal to $P(A_1 - A_2)$, where A_1 and A_2 are the cross-sectional areas of the adjoining pipes. As will be shown below, stress due to thrust is the primary influence in the analysis of longitudinal forces. However, fundamentally the longitudinal stress created by a thrust force can never be greater than 50% of the