14

Buried Pipe

14.1 TO BURY OR NOT TO BURY

The decision to bury a pipe or place it above ground depends on several factors: on one hand, a buried pipe (a) reduces plant congestion, (b) allows for the shortest route (fewer bends) from point to point, (c) avoids existing above ground obstructions, (d) is protected from ambient temperature changes, (e) is protected from wind loads, and (f) if buried deeply, is protected from surface traffic and activities. In certain cases, burying the pipe may be the only viable alternative.

On the other hand, a buried pipe (a) has unique corrosion challenges that may dictate the use of coating and cathodic protection, (b) requires more elaborate repairs, with the need to locate the pipe, locate the leak, open the trench or resort to specialized trenchless repair techniques, (c) can be accidentally damaged by digging, (d) may leak for some time before the leak is detected, (e) requires careful trenching and backfill to avoid excessive soil settlement, and (f) has to be designed for soil and surface loads, which requires a good understanding of the soil condition and properties. In certain plant yard applications, burying the pipe has proven to be a costly decision, and it is not uncommon, after years of corrosion and leakage, to see buried plant piping abandoned in place, and replaced by above ground systems.

Buried pipes (either buried underground or covered by an embankment) can experience a broad range of loads that must be accounted for in design. Normal service loads include internal pressure, constrained expansion or contraction due to changes in fluid temperature, soil weight, surface traffic, and normal soil settlement. Abnormal (accidental) loads include large pressure transients (such as waterhammer), large soil settlement (soil failure), and seismic forces.
14.2 INTERNAL PRESSURE

The design of buried pipe for internal pressure consists in selecting the minimum required wall thickness, given the material, diameter, design pressure, and corrosion allowance. The equations for pressure design are given in the applicable ASME B31 code for pressure piping, or AWWA for water works systems. The wall thickness sizing equation for buried pipe is the same as if the pipe was placed above ground (Chapter 4). No credit is taken for the external bearing pressure applied by the soil to counter the internal pressure, no matter how well compacted. Internal pressure will also cause a thrust force in bell and spigot construction. This thrust force must be restrained through tie rods bridging the joint or thrust blocks at changes in direction [DIPRA].

14.3 SOIL LOADS

The study of the effect of soil loads on buried pipe dates back to the early 1900's, a time when the first large scale irrigation projects were developed, relying on underground clay tiles to carry and distribute water to fields. In a pioneering study published in 1913, Professor A. Marston presented the experimentally based "Theory of Loads on Pipes in Ditches" and the formula for predicting soil loads on buried pipes [Marston]. More recent publications in this field have confirmed the wisdom of Marston's theory [Moser, Watkins]. Design equations for soil loads can be found in AWWA manuals and standards [AWWA C150, AWWA C900, AWWA M11, AWWA M23]. The simplest design rule for pipes installed in a trench with backfill, is to apply the prism formula, which states that the earth load on the pipe is equal to the weight of the soil prism right above the pipe, as shown in Figure 14-1

\[ P_v = \gamma H \]

- \( P_v \) = earth load pressure on buried pipe, psi
- \( \gamma \) = unit weight of backfill, lb/in\(^3\)
- \( H \) = burial depth, in

If the pipe is below the water table, then the soil pressure is reduced by buoyancy and increased by the weight of water

\[ P_v = \gamma H - 0.33 \frac{h}{H} \gamma H + \gamma_w h \]

- \( h \) = height of water above pipe, in
- \( \gamma_w \) = unit weight of water, lb/in\(^3\)
If, instead of being placed in a ditch with backfill, the pipe is tunneled through undisturbed soil, the earth pressure is lower by a factor $2c (H/D)$ where $c$ is the soil cohesion [Moser]. Whether in a ditch or tunneled into place, the soil load on steel pressure piping is small. For example, under 10 ft of dry soil ($\gamma = 0.07 \text{ lb/in}^3$) the pressure on the pipe is $0.07 \times 120 = 8.4 \text{ psi}$. Soil loads become important for large diameter thin pipes (large diameter / thickness ratio) as encountered in waterworks (water conduits made of corrugated sheet metal) and for materials with limited ductility, prone to fracture under external loads (concrete, cast iron).

### 14.4 SURFACE LOADS

Buried pipes crossing highways, runways, railroad tracks, construction sites, are exposed to loads due to the passage of heavy surface traffic. The pressure transmitted to the buried pipe by a surface load is [ALA, Moser, WRC]

$$P_s = 0.48 \frac{P_s}{H^2 \left[1 + (d/H)^2\right]^{3/2}}$$

$P_s =$ surface load, lb
$d =$ offset distance from surface load to buried pipe, in

For example, an 180,000 lb surface load right above a pipe ($d = 0$) will cause a pressure of 6 psi if the pipe is buried 10 ft below ground. Under the effect
of soil and external loads, the buried pipe will tend to ovalize, causing through-wall bending stresses, with [ALA]

\[
\sigma_t = 4E \frac{\Delta A}{D^2 D} \\
\Delta = 0.15P + 0.06 \frac{E}{R^3} + 0.061E'
\]

\( \sigma_t \) = through-wall bending stress, psi  
\( E \) = modulus of elasticity of pipe, psi  
\( \Delta \) = change in pipe diameter due to ovalization, in  
\( D \) = pipe diameter, in  
\( t \) = pipe wall thickness, in  
\( E_\text{I} \) = pipe wall stiffness, in-lb  
\( E' \) = modulus of soil reaction, psi [AWWA C150]

For example, a downward pressure of 6 psi on a carbon steel pipe buried in poorly compacted soil will cause it to ovalize 0.8%, with a through-wall bending stress of 14.5 ksi. Where the surface load is both significant and repetitive, fatigue considerations may dictate a deeper soil cover. This subject has been extensively investigated for steel pipelines crossing highways and railroad tracks, and techniques have been developed to predict fatigue life and minimum depth of cover in this case [API 1102].

14.5 THERMAL EXPANSION AND CONTRACTION

When the fluid temperature conveyed in a buried pipe differs from the soil temperature, the pipe will tend to contract or expand. In a straight pipe, fully restrained by the surrounding soil, unable to expand or contract, the temperature change will cause an axial stress \([B31.4, B31.8, ALA]\)

\[
\sigma_A = E \alpha (T_f - T_i) - \frac{P D}{2t}
\]

\( \sigma_A \) = axial stress in a pipe fully constrained by the surrounding soil, psi  
\( E \) = modulus of elasticity of pipe material, psi  
\( \alpha \) = coefficient of thermal expansion of pipe \(1/\text{°F}\)  
\( T_f \) = fluid temperature, °F  
\( T_i \) = burial installation temperature, °F  
\( v \) = Poisson ratio of pipe material  
\( P \) = internal pressure, psi
D = pipe diameter, in
\( t = \text{pipe wall thickness, in} \)

The situation is different if the buried pipe contains a bend, and is not assumed to be fully restrained by an infinitely stiff soil at the bend. In this case, the pipe will tend to flex around the bend, with the surrounding soil exerting a restraining force. The pipe acts as a beam on elastic foundation, as illustrated in Figure 14-2. The hand calculation of stresses is only possible in the simplest of configurations [ASME B31.1, ALA, WRC 425].

In most cases, it will be necessary to analyze the expansion or contraction around the bend using a pipe stress analysis program, with the soil modeled as spring elements around the pipe. The stiffness and spacing of soil springs depends on the soil and compaction properties [ALA, WRC 425, ASCE]. The bending stresses in the pipe are calculated and compared to an allowable stress, such as defined in Appendix VII of ASME B31.1.

\[
N = \sigma A_{\text{pipe}} = [E \alpha(T_2 - T_1) - v \frac{PD}{2t}] \pi Dt
\]

The critical compressive buckling force in a perfectly straight pipeline is [Friedman, WRC 425]
\[ N_{\text{critical,perfect}} = 2\sqrt{EI}k_e \]

\( N_{\text{critical,perfect}} \) = compressive buckling force for a perfectly straight buried pipe, lb

\( E \) = pipe material Young modulus, psi

\( I \) = pipe cross section moment of inertia, in\(^4\)

\( k_e \) = stiffness of soil cover, lb/in

The critical compressive buckling force in a real pipeline with an initial curvature is a fraction of

\[ N_{\text{critical,actual}} = \lambda N_{\text{critical,perfect}} \]

\( N_{\text{critical,actual}} \) = compressive buckling force for an initially deformed pipeline, lb

\( \lambda \) = fraction that depends on initial curvature of the pipeline

The uplift resistance of the soil can also be expressed in terms of force per linear foot of pipeline. In a cohesionless soil [Schaminée]

\[ P = \gamma HD(1 + f_d \frac{H}{D}) \]

\( \gamma \) = soil density, lb/in\(^3\)

\( H \) = burial depth, in

\( D \) = pipeline diameter, in

\( f_d \) = load factor 0.6 for gravel or rock dump, down to 0.15 for very loose soil

For cohesive soils

\[ P = D C_s (1 + f_c \frac{H}{D}) \leq 5.14 D C_s \]

\( C_s \) = shear strength of soil, psi

14.6 GROUND MOVEMENT

Ground movement (either a gradual settlement or spread, or a sudden failure due for example to a landslide, an earthquake or mining operations) could cause a buried pipe to fail by plastic tension or by compressive buckling. The assessment of ground movement consists of two parts: first, the prediction of the deformed pipe profile; second, the resulting stresses or strains in the deformed pipe. The first part, predicting the pipe profile, is not a simple proposition. The civil engineer must estimate the magnitude of movement and the distance over which it will take
place. Given the soil deformation profile, the stresses or strains in the pipe can be estimated by computer analysis or hand calculation. A computer analysis will generally consist of an elastic-plastic model of the pipe, restrained by non-linear soil springs, with the ground movement imposed at the base of the soil springs [ALA, ASCE]. The stresses are obtained directly as output. An elastic analysis, in which the total stress in the pipe is kept below a fraction $F_D$ of the material yield stress, can be accomplished by hand calculations. A pipe settlement $X$ would be judged acceptable if it occurs over a distance at least equal to $L$, where [API 1117]

$$L = \frac{3.87 \times 10^7 D X + 7.74 \times 10^5 X^2}{F_p S_Y - S_{el}}$$

$L$ = minimum required length ($L = 2L_1$ in Figure 14-3), ft
$D$ = outside pipe diameter, in
$X$ = mid-span deflection, ft
$F_p$ = design factor
$S_Y$ = minimum yield stress of pipe material, psi
$S_{el}$ = longitudinal stress in pipe prior to ground movement, psi

![Figure 14-3 Mid-Span Deflection](image)

The profile, along the pipe should be at least as gradual as that given by [API 1117]

$$X_a = \frac{16a^2X(L - a)^2}{L^4}$$

$X_a$ = vertical deflection, at a distance $a$, ft
$a$ = distance along the trench from origin of deflection, ft
In addition to limiting the stress to $F_S$, the strain on the compressive side of the bent pipe should be less than the buckling strain \([WRC 425]\)

$$\varepsilon_b = \frac{4AD}{L^2} = \frac{D\kappa}{2} < 2.42 \left( \frac{t}{D} \right)^{1/6}$$

$\varepsilon_b =$ maximum compressive strain in bent pipe  
$\Delta =$ maximum bow at mid-span, in  
$D =$ pipe outside diameter, in  
$L =$ length of pipe segment, in  
$\kappa =$ curvature of bent pipe ($1/R$ where $R$ is the radius of curvature), 1/in

### 14.7 SEISMIC

Earthquakes can fail buried pipes in one of two ways: (1) a large ground movement that fails the pipe by tension (particularly at corroded sections, poor weld joints and mechanical joints) or by compressive buckling, and (2) a large cyclic movement caused by the passage of the seismic wave. The effect of ground movement can be analyzed following the rules of Section 14.6. It has been argued that wave passage alone could not fail modern (arc welded), well constructed (fabrication, NDE and hydrotest per ASME B31 code), and well maintained (little corrosion) steel pipe. Where wave passage must be analyzed, the upper bound of the strain in the pipe can be obtained by assuming that it is equal to the soil strain caused by wave passage \([ALA, ASCE]\)

$$\varepsilon_s = \frac{V_g}{\alpha C_s}$$

$\varepsilon_s =$ soil strain  
$V_g =$ peak ground velocity due to wave passage, ft/sec  
$\alpha =$ factor 2 for shear waves, 1 for other seismic waves  
$C_s =$ apparent propagation velocity for seismic waves, 6560 ft/sec

### 14.8 REFERENCES

ALA, American Lifelines Alliance, Guidelines for the Design of Buried Steel Pipe, American Society of Civil Engineers, Reston, VA.

API 1102, Steel Pipelines Crossing Railroads and Highways, American Petroleum Institute, Washington, D.C.
API 1117, Movement of In-Service Pipelines, American Petroleum Institute, Washington, D.C.

ASCE Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, American Society of Civil Engineers, Reston, VA.


ASME B31.4, Pipeline Transportation Systems for Liquid Hydrocarbon and Other Liquids, American Society of Mechanical Engineers, New York.


AWWA C150, Thickness Design of Ductile-Iron Pipe, American Water Works Association, Denver, CO.

AWWA C900, PVC Pressure Pipe 4-in Through 12-in for Water Distribution, American Water Works Association, Denver, CO.

AWWA M11, Steel Pipe, American Water Works Association, Denver, CO.

AWWA M23, PVC Pipe - Design and Installation, American Water Works Association, Denver, CO.

DIPRA, Thrust Restraint Design for Ductile Iron Pipe, Ductile Iron Pipe Research Association, Birmingham, AL.


