THRUST RESTRAINT DESIGN EQUATIONS AND SOIL PARAMETERS FOR DUCTILE IRON AND PVC PIPE
Thrust Restraint Design Equations and Soil Parameters

These equations and soil parameters are an effort to provide the piping system designer with conservative techniques and parameters for the design of underground restrained joint piping systems. They utilize recognized design equations and conservative soil parameters.

The design equations in this handbook have proven useful in a wide variety of applications since 1982. The soil parameters presented include the results of an extensive study of the actual frictional performance of soils on ductile iron, ductile iron encased with polyethylene, and PVC pipe.

The theory and application of this design method are outlined in a series of “Connections” ™ bulletins [PD-01 through PD-05]. These bulletins can be obtained from EBAA Iron Sales [www.ebaa.com]. A computer program utilizing all the information provided in these bulletins and this booklet is also available from EBAA Iron Sales.

These equations and soil values have proven conservative over the years and are dependent upon accurate soil identification and classification and good installation procedures and inspection. The ultimate responsibility for the identification of soil type, the proper use of the data provided, the final design, and the inspection of the system must rest with the design engineer.
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Definition of Terms

\( A \) = Cross sectional area of the pipe, \( in^2 \)

\( A_b \) = Cross sectional area of the branch of a tee, \( in^2 \)

\( A_l \) = Cross sectional area of the large side of a reducer, \( in^2 \)

\( A_p \) = Area based on half of the pipe circumference in contact with the soil, \( \frac{ft^2}{ft} \)

\( (A_p)_b \) = Area based on full pipe circumference in contact with the soil, \( \frac{ft^2}{ft} \)

\( A_s \) = Cross sectional area of the small side of reducer, \( in^2 \)

\( c \) = Cohesion of the soil, \( \frac{lbs}{ft^2} \)

\( D \) = Outside diameter of the pipe, ft

\( f_c \) = Cohesion modifier coefficient

\( F_s \) = Frictional resistance acting on the pipeline (acting on half of the pipe diameter), \( \frac{lbs}{ft} \)

\( F_{sb} \) = Frictional resistance acting on the pipeline (acting on the full pipe diameter), \( \frac{lbs}{ft} \)

\( (F_{sb})_l \) = \( F_{sb} \) on the large side of a reducer, \( \frac{lbs}{ft} \)

\( f_{\phi} \) = Friction angle modifier coefficient

\( H_c \) = Mean depth from surface to pipe center line, ft

\( K_n \) = Trench compaction modifier

\( K_p \) = Rankin passive pressure coefficient

\( L \) = Minimum restrained length for bends, ft

\( L_b \) = Minimum restrained length for the branch of a tee, ft

\( L_l \) = Minimum restrained length for the large side of a reducer, ft

\( L_r \) = Minimum restrained length on each side of the run of a tee, ft

\( P \) = Internal pressure, \( \frac{lbs}{in^2} \)

\( R_s \) = Bearing resistance acting on the pipeline, \( \frac{lbs}{ft} \)

\( S_f \) = Safety Factor

\( s_u \) = Undrained shear strength, \( \frac{lbs}{ft^2} \)

\( T \) = Resultant thrust force, lbs

\( W \) = Normal force acting on the pipeline, \( \frac{lbs}{ft} \)

\( W_v \) = Normal force due to the vertical prism load of the soil, \( \frac{lbs}{ft} \)

\( W_p \) = Normal force due to the weight of the pipe, \( \frac{lbs}{ft} \)

\( W_w \) = Normal force due the weight of the water in the pipe, \( \frac{lbs}{ft} \)

\( \phi \) = Internal friction angle of the soil, degrees

\( \gamma \) = Soil density, \( \frac{lbs}{ft^3} \)

\( \Theta \) = Bend angle, degrees

\( \sigma_h \) = Horizontal passive soil pressure, \( \frac{lbs}{ft^2} \)
Bearing Resistance

Rankin Passive Pressure theory for soils states

\[ \sigma = \gamma H c K_p + 2c \sqrt{K_p} \]

where

\[ K_p = \tan^2 (45 + \Phi / 2) \]

Therefore, the bearing resistance along the pipeline is denoted by the term “\( R_s \)” and is represented as

\[ R_s = K_n \sigma h D \]

Frictional Resistance

The frictional resistance acting on a pipeline, “\( F_s \)”, can be determined by an adaptation of Potyondy’s equation.

\[ F_s = A_p (f_c) + W \tan(f_\phi \Phi) \]

where

\[ A_p = \pi D / 2 \]
\[ W = 2W_c + W_p + W_w \]

When analyzing the branch of a tee, reducers, or dead ends, the full pipe circumference should be taken into account since the full surface of the pipe is moving longitudinally into the soil. This modified version of the frictional force is denoted as

\[ F_{sb} = (A_{pb}) (f_c) + W \tan(f_\phi \Phi) \]

where

\[ (A_{pb}) = \pi D \]

The frictional values for the soil should always be based on the soil that is in contact with the pipe. The pipe friction tests also indicated that ductile iron pipe encased with polyethylene (PE) film slips inside of the polyethylene encasement. This lends itself to conventional friction theory where the coefficient of friction of polyethylene on a ductile iron pipe surface was determined to be the tangent of 14 degrees. Therefore, for PE encased ductile iron pipe, \( F_s = F_{sb} = W \tan 14 = 0.249W \)

Table lists the properties for most soils. Figure 1 lists the soils classifications from ASTM D2487

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>( f_c ) (psf)</th>
<th>( c ) (psf)</th>
<th>( f_\phi ) (pvc)</th>
<th>( \Phi ) (deg)</th>
<th>( \gamma ) (pcf)</th>
<th>( K_n ) Trench Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW, SW</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>0.7</td>
<td>36</td>
</tr>
<tr>
<td>GP, SP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>0.7</td>
<td>31</td>
</tr>
<tr>
<td>GM, SM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>0.7</td>
<td>30</td>
</tr>
<tr>
<td>GC, SC</td>
<td>0.4</td>
<td>0.2</td>
<td>225</td>
<td>1.0</td>
<td>0.6</td>
<td>25</td>
</tr>
<tr>
<td>CL</td>
<td>0.5</td>
<td>0.3</td>
<td>250</td>
<td>1.0</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>ML</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>0.6</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 1. Properties of Soils used for Bedding to Calculate \( F_s \) and \( F_{sb} \)
<table>
<thead>
<tr>
<th>Major Divisions</th>
<th>Group Symbols</th>
<th>Typical Names</th>
<th>Classification Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>COARSE-GRAINED SOILS</td>
<td>GW</td>
<td>Well-graded gravels and gravel-sand mixtures, little or no fines</td>
<td>$C_z = \frac{D_{30}}{D_{60}}$ Greater than 4</td>
</tr>
<tr>
<td></td>
<td>GP</td>
<td>Poorly graded gravels and gravel-sand mixtures, little or no fines</td>
<td>$C_z = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3</td>
</tr>
<tr>
<td></td>
<td>GM</td>
<td>Silty gravels, gravel-sand-silt mixtures</td>
<td>Not meeting both criteria for GW</td>
</tr>
<tr>
<td></td>
<td>GC</td>
<td>Clayey gravels, gravel-sand-clay mixtures</td>
<td>Atterberg limits plot below “A” line or plasticity index less than 4.</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>Well-graded sands and gravelly sands, little or no fines</td>
<td>Atterberg limits plot above “A” line and plasticity index greater than 7.</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>Poorly graded sands and gravelly sands, little or no fines</td>
<td>Atterberg limits plot below “A” line or plasticity index less than 4.</td>
</tr>
<tr>
<td></td>
<td>SM</td>
<td>Silty sands, sand-silt mixtures</td>
<td>Atterberg limits plot above “A” line and plasticity index greater than 7.</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>Clayey sands, sand-clay mixtures</td>
<td>Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.</td>
</tr>
<tr>
<td>FINE-GRAINED SOILS</td>
<td>ML</td>
<td>Inorganic silts, very fine sands, rock flour, silty or clayey fine sands</td>
<td>$C_z = \frac{D_{30}}{D_{60}}$ Greater than 6</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays</td>
<td>$C_z = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3</td>
</tr>
<tr>
<td></td>
<td>OL</td>
<td>Organic silts and organic silty clays of low plasticity</td>
<td>Not meeting both criteria for SW</td>
</tr>
<tr>
<td></td>
<td>MH</td>
<td>Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts</td>
<td>Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.</td>
</tr>
<tr>
<td></td>
<td>CH</td>
<td>Inorganic clays of high plasticity, fat clays</td>
<td>Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.</td>
</tr>
<tr>
<td></td>
<td>OH</td>
<td>Organic clays of medium to high plasticity</td>
<td>Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.</td>
</tr>
</tbody>
</table>

**PLASTICITY CHART**

For classification of fine-grained soils and fine fraction or coarse-grained soils.

Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.

Equation of A-line:

$$PI = 0.73 \times (LL - 20)$$

*Based on a material passing the 3-in. (75-mm) sieve.*

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Figure 1. The Unified Soil Classification System
- ASTM D2487 (Reprinted With Permission)
Special Soil Conditions

The values in Tables 2 and 3 are for near saturated, undisturbed soils, type CL, ML, CH, and MH with pipe surrounded with sand or gravel having a minimum Standard Proctor Density of 80% or greater. While these values are conservative for most situations, a competent soils engineer should be contacted for pipelines in wetlands, river bottoms, etc.

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>$c = S_u$ (psf)</th>
<th>$\gamma$ (pcf)</th>
<th>$K_n$ 3</th>
<th>$K_n$ 4</th>
<th>$K_n$ 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>450</td>
<td>100</td>
<td>0.60</td>
<td>0.85</td>
<td>1.00</td>
</tr>
<tr>
<td>CH</td>
<td>400</td>
<td>100</td>
<td>0.40</td>
<td>0.60</td>
<td>0.85</td>
</tr>
<tr>
<td>ML</td>
<td>300</td>
<td>100</td>
<td>0.60</td>
<td>0.85</td>
<td>1.00</td>
</tr>
<tr>
<td>MH</td>
<td>250</td>
<td>100</td>
<td>0.40</td>
<td>0.60</td>
<td>0.85</td>
</tr>
</tbody>
</table>

(Note: The above values are for undisturbed soil)

Table 2. In Situ Values of Soil Properties for $R_s$

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>$f_c$</th>
<th>$c$</th>
<th>$f_\Phi$</th>
<th>$\Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP &amp; SP</td>
<td>0</td>
<td>0</td>
<td>1.00</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 3. Bedding Soil Properties for $F_s$

Bends

The resultant thrust force for bends is

$$T = 2PA \sin (\Theta / 2)$$

Horizontal Bend

$$L = SPA \tan (\Theta / 2) / (F_s + 1 / 2 R_s)$$

Vertical Down Bend

$$L = SPA \tan (\Theta / 2) / F_s$$

For vertical offsets use the equation for the vertical down bend for the upper bend and the equation for the horizontal bend for the lower bend.

Tees

$$L_b = Sf(PA_b - R_s L_r) / F_{sb}$$
**Reducers**

Restrained length on the large side.

\[ L_1 = S_f P (A_1 - A_2) / (F_{sb} \lambda) \]

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**Dead Ends**

\[ L = S_f P A / F_{sb} \]

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**References**


ASTM D 2487; “Classification of Soils for Engineering Purposes.”

Uni-Bell Plastic Pipe Association; *Handbook of PVC Pipe, Design, and Construction*, Dallas, Texas.
Type 3
Pipe bedded in 4 inches minimum loose soil.
Backfill lightly consolidated to top of the pipe.

Type 4
Pipe bedded in sand, gravel, or crushed stone to depth of \( \frac{1}{8} \) pipe diameter, 4 inch minimum.
Backfill compacted to top of pipe. (Approximately 80 percent standard Proctor, AASHTO T-99)

Type 5
Pipe bedded in compacted granular material to the center line of pipe, 4 inches minimum under pipe. Compacted granular or select material to top of pipe. (Approximately 90 percent standard Proctor, AASHTO T-99)

“Loose Soil” or “Select Material” is defined as native soil excavated from the trench, free of rocks, foreign material, and frozen earth.

Figure 7. ANSI/AWWA C150/A21.50 Trench Conditions

Table 4. Nominal Dimensions and Weights

<table>
<thead>
<tr>
<th>Nominal Pipe Size</th>
<th>Outside Diameter (feet)</th>
<th>Cross Sectional Area (sq. in.)</th>
<th>( W_p + W_w )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DI PVC</td>
<td></td>
<td>DI PVC</td>
</tr>
<tr>
<td>3</td>
<td>0.33 0.40</td>
<td>12.32 18.10</td>
<td>14.0 19.0</td>
</tr>
<tr>
<td>4</td>
<td>0.58 0.40</td>
<td>37.39 50.0</td>
<td>32.0 29.5</td>
</tr>
<tr>
<td>6</td>
<td>0.75 0.75</td>
<td>64.33 71.0</td>
<td>50.0 44.3</td>
</tr>
<tr>
<td>8</td>
<td>0.93 0.93</td>
<td>96.77 71.0</td>
<td>71.0 29.5</td>
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<tr>
<td>10</td>
<td>1.10 1.10</td>
<td>136.85 126.0</td>
<td>96.0 44.3</td>
</tr>
<tr>
<td>12</td>
<td>1.28 1.28</td>
<td>183.85 126.0</td>
<td>126.0 84.2</td>
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<tr>
<td>14</td>
<td>1.45 1.45</td>
<td>237.79 158.0</td>
<td>158.0 108.9</td>
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<td>1.63 1.63</td>
<td>298.65 192.0</td>
<td>192.0 136.8</td>
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<tr>
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<td>230.0 167.9</td>
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<td>317.0 239.5</td>
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<td>804.25 466.0</td>
<td>466.0 368.5</td>
</tr>
<tr>
<td>30</td>
<td>3.19 3.19</td>
<td>1152.09 653.0</td>
<td>653.0 527.8</td>
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<td>3.71 3.71</td>
<td>1555.28 868.0</td>
<td>868.0</td>
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<tr>
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<td>4.23 4.23</td>
<td>2026.83 1118.0</td>
<td>1118.0</td>
</tr>
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<td>48</td>
<td>4.76 4.76</td>
<td>2560.72 1407.0</td>
<td>1407.0</td>
</tr>
<tr>
<td>54</td>
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</table>