

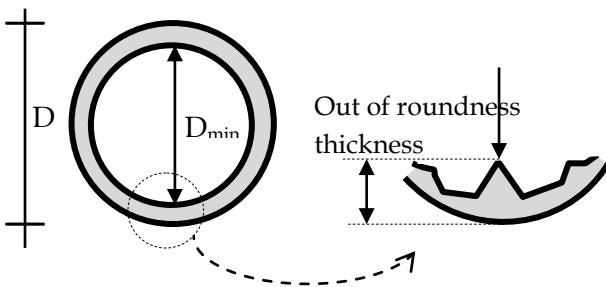
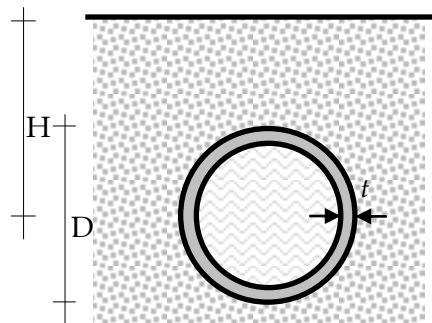
2. INPUTS

2.2 Basic Information

- (1) Location : Srinagar Seismic Zone as per Indian Seismic Code: V
 (2) Type : Gas Site-specific horizontal acceleration $Z_{SS} : 0.36g$
 (3) Importance Factor I_p

| Class of pipeline | Importance factor I_p | | | |
|--|---|-----------|----------|------------------|
| | BCD | Landslide | Faulting | Wave propagation |
| I : Pipelines which would cause major impact in case of failure or damage | 1.50 | 2.60 | 2.30 | 1.50 |
| II : Pipelines which are vital but service of those can be interrupted for minor repairs | 1.35 | 1.60 | 1.50 | 1.25 |
| III : Low pressure oil and gas pipelines and Water supply pipelines for ordinary use | 1.00 | 1.00 | 1.00 | 1.00 |
| IV : Pipelines of very little importance and impact in the event of failure | Seismic conditions need not be considered | | | |

2.2.1 Geometry



| Measurements | Units |
|---|--------------------------|
| H | = 1.200 m |
| D | = 0.600 m |
| D_{min} | = |
| t | = 0.0064 m |
| Section modulus of pipe cross section $Z = \frac{\pi}{32} [D^4 - (D - 2t)^4]$ $= \frac{\pi}{32} [0.6^4 - (0.6 - 2 \times 0.0064)^4]$ | = 0.00175 m ³ |
| Cross sectional area $A = \frac{\pi}{4} (D^2 - (D - 2t)^2)$ $= \frac{\pi}{4} (0.6^2 - (0.6 - 2 \times 0.0064)^2)$ | = 0.0119 m ² |

Figure 2.2.1: Cross-section of the pipeline

2.2.2 Material Properties

| | | | | | | |
|---|---------|------|------|------|-------|--------------------------------------|
| Grade of the pipe | | | | | | |
| Ramberg-Osgood parameters for steel pipes | | | | | | |
| Grade of pipe | Grade B | X 42 | X 52 | X 60 | X 70 | $n = 11.385$ |
| σ_y (MPa) | 227 | 310 | 358 | 413 | 517.0 | |
| n | 10 | 15 | 9 | 10 | 5.5 | $r = 81.16$ |
| r | 100 | 32 | 10 | 12 | 16.6 | |
| Yield Stress of pipe material σ_y | | | | | | = 358 MPa |
| Modulus of Elasticity E | | | | | | = 2×10^5 MPa |
| Yield Strain of the pipe material ϵ_y | | | | | | = 0.00179 |
| Failure strain of the pipe in tension ϵ_u | | | | | | = 0.150 |
| Linear coefficient of thermal expansion of steel α | | | | | | = $12 \times 10^{-6}/^\circ\text{C}$ |
| Poisson's ratio μ | | | | | | = 0.3 |
| Unit weight of steel pipe γ_{pipe} | | | | | | = 78.560 kN/m ³ |
| Unit weight of the content $\gamma_{content}$ | | | | | | = 0 kN/m ³ |

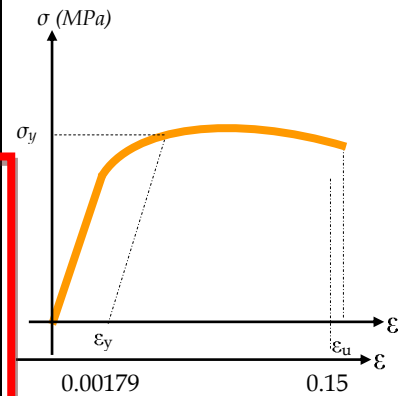


Figure 2.2.2: Ramberg-Osgood's σ - ϵ curve for steel

2.2.3 Soil Properties

| | | | |
|--|--------------|-----|------------------------|
| Velocity of shear wave V_s | | | = 150 m/s |
| Coefficient of cohesion of backfill soil c , [$c = 0$ for sandy soil] | | | = 0 kPa |
| Effective unit weight of the soil $\bar{\gamma}$ | | | = 18 kN/m ³ |
| Saturated Unit weight of soil γ_{sat} | | | = 18 kN/m ³ |
| Dry Unit weight of soil γ_d | | | = 16 kN/m ³ |
| Internal friction angle of the soil ϕ | | | = 32° |
| Friction factor for various types of pipes f | Pipe coating | f | $f = 0.7$ |
| | Concrete | 1.0 | |
| | Rough steel | 0.8 | |
| | Smooth Steel | 0.7 | |

2.2.4 Inputs for Peak Strain Calculation

(a) For Operational Longitudinal Strain in the Pipeline

| | |
|---|-----------|
| Maximum internal operating pressure of the pipe P | = 7.5 MPa |
| Temperature in the pipe at the time of installation T_1 | = 30°C |
| Temperature in the pipe at the time of operation T_2 | = 60°C |

(b) For Permanent Ground Deformation (PGD)

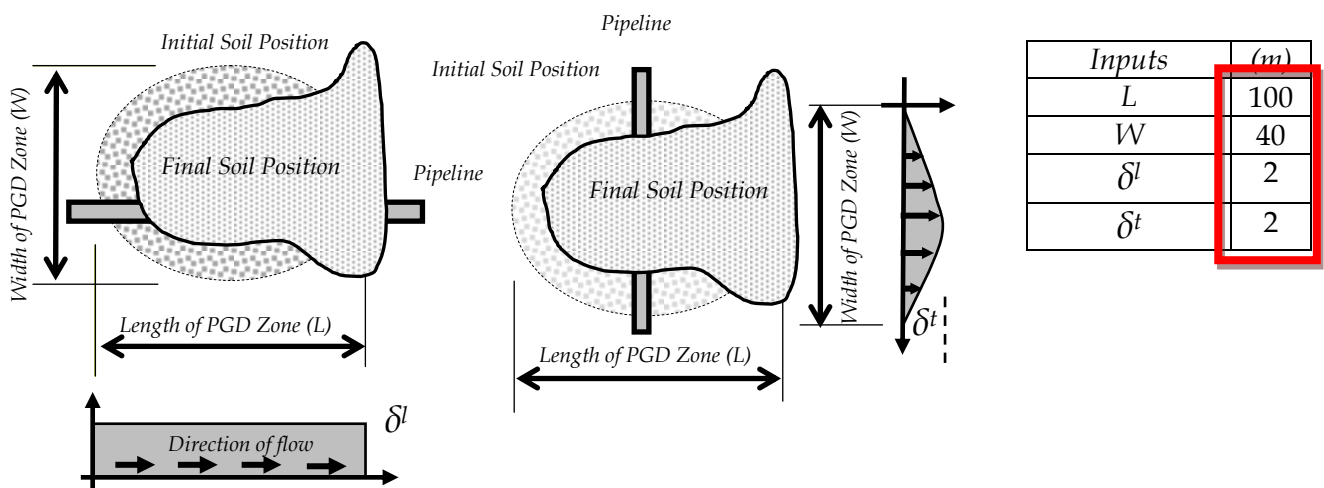
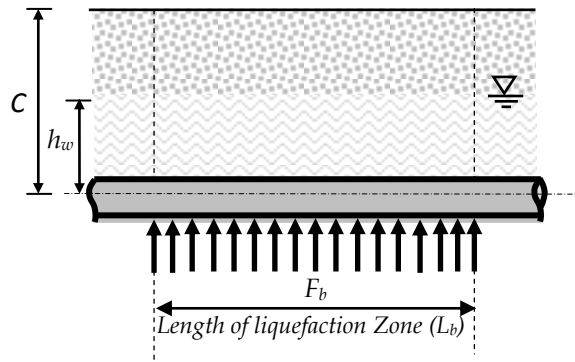


Figure 2.2.2: (a) Longitudinal PGD

(b) Transverse PGD

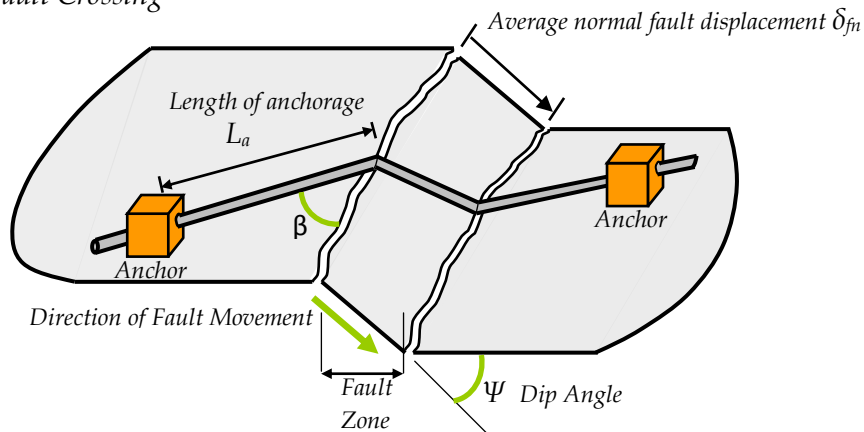
(c) For Liquefaction



| Inputs | (m) |
|--------|-----|
| L_b | 40 |
| h_w | 0 |
| C | 2 |

Figure 2.2.3: Longitudinal section of the pipeline

(d) For Fault Crossing



| Inputs | Units |
|---------------|-------|
| δ_{fn} | 2.5 m |
| Ψ | 35° |
| β | 40° |
| L_a | 100 m |

Figure 2.2.4: Pipeline crossing normal slip fault

(e) For Seismic Wave Propagation

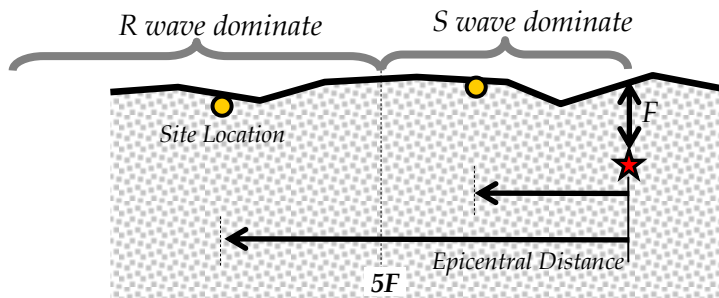


Figure 2.2.5: Considerations for S-waves and R-wave in pipeline design

| | | | | | |
|--|------|-------|-------|-------|-----------------|
| Focal length F | | | | | = 3 km |
| Distance of site from earthquake source | | | | | = 20 km |
| Magnitude of design basis earthquake considered M_w | | | | | = 6.5 |
| Expected peak ground acceleration of the site at base rock layer PGA_r | | | | | $PGA_r = 0.36g$ |
| Seismic Zone | II | III | IV | V | |
| PGA_r | 0.1g | 0.16g | 0.24g | 0.36g | !! |

Rapid Assessment of Seismic Safety of
Buried Continuous Pipelines

3. BASIC SAFETY CHECKS

3.1 Soil Properties

| | | | | | | | | | |
|--|--------------------------|--------|--------------------------------------|---|-------------------------|-------------------------|----------------|-------------------|-------------------------|
| Classification of soil at site | | | | | | | Soil Class: E | | |
| Soil Class | Soil Type | | Velocity of shear wave (V_s) m/s | Uncorrected Standard Penetration Resistance (N) | | | | | |
| A | Hard Rock | | $V_s > 1500$ | - | | | | | |
| B | Rock | | $760 < V_s \leq 1500$ | - | | | | | |
| C | Very Dense and Soft Rock | | $360 < V_s \leq 760$ | $N > 50$ | | | | | |
| D | Dense/Stiff Soil | | $180 < V_s \leq 360$ | $15 \leq N \leq 50$ | | | | | |
| E | Loose/Soft Soil | | $V_s < 180$ | $N < 15$ | | | | | |
| When sufficient detail of soil is unavailable to define site, soil shall be assumed to be of Class D | | | | | | | | | |
| Coefficient of soil pressure at rest $K_o = 1 - \sin \phi = 1 - \sin 32^\circ$ (or) | Type of soil | | K _o | | K _o = 0.47 | | | | |
| | Loose soil | | 0.5-0.6 | | | | | | |
| | Dense soil | | 0.3-0.5 | | | | | | |
| | Clay(draind) | | 0.5-0.6 | | | | | | |
| | Clay (undraind) | | 0.8-1.1 | | | | | | |
| | Over consolidated soil | | 1.0-1.3 | | | | | | |
| Adhesion factor $\alpha = 0.608 - 0.123c - \frac{0.274}{c^2 + 1} + \frac{0.695}{c^3 + 1}$ (c is in kPa/100) $= 0.608 - 0.274 + 0.695$ | | | | | | | = 1.029 | | |
| Interface angle of friction between soil and pipe $\delta' = f\phi = 0.7 \times 32^\circ$ | | | | | | | = 22.40° | | |
| Maximum axial soil force per unit length $t_u = \pi D c \alpha + \pi D H \gamma \left(\frac{1+K_o}{2} \right) \tan \delta'$ $= 0 + \pi \times 0.600 \times 1.20 \times 18 \left(\frac{1+0.47}{2} \right) \tan 22.4^\circ$ | | | | | | | = 12.33 kN/ m | | |
| Factor | ϕ | a_1 | b_1 | c_1 | d_1 | e_1 | Factor | $\phi = 32^\circ$ | |
| N_{ch} | | 6.752 | 0.065 | -11.063 | 7.119 | - | N_{ch} | 6.752 | 5.465 |
| N_{qh} | 20 | 2.399 | 0.439 | -0.03 | 1.059×10^{-3} | -0.175×10^{-4} | N_{qh} | | |
| N_{qh} | 25 | 3.332 | 0.839 | -0.090 | 5.606×10^{-3} | -1.319×10^{-4} | a_1 | 6.752 | 5.465 |
| N_{qh} | 30 | 4.565 | 1.234 | -0.089 | 4.275×10^{-3} | -0.916×10^{-4} | b_1 | 0.065 | 1.548 |
| N_{qh} | 35 | 6.816 | 2.019 | -0.146 | 7.651×10^{-3} | -1.683×10^{-4} | c_1 | -11.063 | -0.112 |
| N_{qh} | 40 | 10.959 | 1.783 | 0.045 | -5.425×10^{-3} | -1.153×10^{-4} | d_1 | 7.119 | 5.625×10^{-3} |
| N_{qh} | 45 | 17.658 | 3.309 | 0.048 | -6.443×10^{-3} | -1.299×10^{-4} | e_1 | - | -1.223×10^{-4} |
| Horizontal bearing capacity factor for clay $N_{ch} = a_1 + b_1x + \frac{c_1}{(x+1)^2} + \frac{d_1}{(x+1)^3} \leq 9$ | | | | | | | = 5.916 | | |
| where $x = H/D = 1.2/0.6 = 2$; $N_{ch} = 6.752 + 0.065 \times 2 + \frac{-11.063}{(2+1)^2} + \frac{7.119}{(2+1)^3}$ | | | | | | | | | |
| Horizontal bearing capacity factor for sandy soil $N_{qh} = a_1 + b_1x + c_1x^2 + d_1x^3 + e_1x^4$ $= 5.465 + 1.548 \times 2 + (-0.112)2^2 + (5.625 \times 10^{-3})2^3 + (-1.223 \times 10^{-4})2^4$ | | | | | | | = 8.156 | | |
| Maximum lateral resistance of soil per unit length of pipe $P_u = N_{ch}cD + N_{qh}\bar{\gamma}HD = 0 + 8.156 \times 18 \times 1.2 \times 0.6$ | | | | | | | = 105.702 kN/m | | |

3.2 Peak Strain Calculation

3.2.1 Operational Longitudinal Strain in the Pipeline

| | |
|--|------------------|
| Longitudinal Stress due to <i>internal pressure</i> $S_p = \frac{PD\mu}{2t} = \frac{7.5 \times 0.6 \times 0.3}{2 \times 0.0064}$ | = 105.5 MPa |
| Longitudinal Stress due to <i>temperature change</i> $S_t = E\alpha_t(T_2 - T_1)$ $= 2 \times 10^5 \times 12 \times 10^{-6} \times (60 - 30)$ | = 72 MPa |
| Longitudinal Strain due to <i>internal pressure</i> $\epsilon_p = \frac{S_p}{E} \left[1 + \frac{n}{1+r} \left(\frac{S_p}{\sigma_y} \right)^r \right]$ $n = 9; r = 10;$ $= \frac{105.5}{2 \times 10^5} \left[1 + \frac{9}{1+10} \left(\frac{105.5}{358} \right)^{10} \right]$ | = 0.00053 |
| Longitudinal Strain due to <i>temperature change</i> $\epsilon_t = \frac{S_t}{E} \left[1 + \frac{n}{1+r} \left(\frac{S_t}{\sigma_y} \right)^r \right]$ $= \frac{72}{2 \times 10^5} \left[1 + \frac{9}{1+10} \left(\frac{72}{358} \right)^{10} \right]$ | = 0.00036 |
| Total Operational Longitudinal Strain in pipe $\epsilon_{oper} = \epsilon_p + \epsilon_t$ $= 0.00053 + 0.00036$ | = 0.00089 |

3.2.2 Effect of Permanent Ground Deformation (PGD)

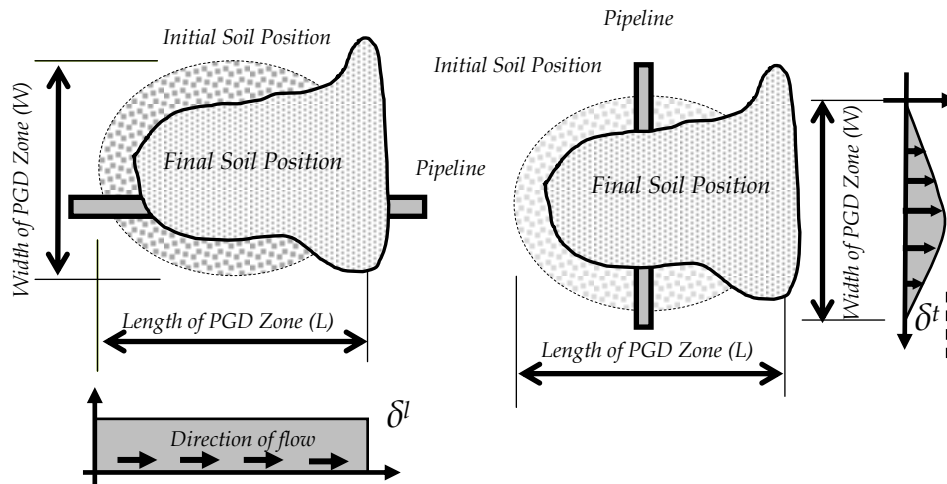


Figure 3.1.2: (a) Longitudinal PGD (b) Transverse PGD

| | |
|---|-----------------------|
| Design Longitudinal PGD $\delta_{design}^l = \delta^l I_p = 2 \times 1.5$ | = 3m |
| Design Longitudinal PGD $\delta_{design}^t = \delta^t I_p = 2 \times 1.5$ | = 3m |
| (i) Longitudinal PGD | |
| Effective length L_e of the pipeline over which the friction force t_u acts is obtained from $\delta_{design}^l = \frac{t_u L_e^2}{2\pi D t E} \left[1 + \left(\frac{2}{2+r} \right) \left(\frac{n}{1+r} \right) \left(\frac{t_u L_e}{2\pi D t \sigma_y} \right)^r \right]$ $t_u = 12.33 \text{ kN/m}; D = 0.600\text{m}; t = 0.0064\text{m}; E = 200000 \text{ MPa}; n = 9; r = 10;$ $\delta_{design}^l = 3\text{m}$ Assume $L_e = 100 \text{ m}$ $\delta_{design}^l = \frac{12.33 \times 10^3 \times 100^2}{2\pi \times 0.6 \times 0.0064 \times 2 \times 10^{11}} \left[1 + \left(\frac{2}{2+10} \right) \left(\frac{9}{1+10} \right) \left(\frac{12.33 \times 10^3 \times 100}{2\pi \times 0.6 \times 0.0064 \times 358 \times 10^6} \right)^{10} \right]$ $= 0.0255$ | $L_e = 827 \text{ m}$ |

| | | |
|--|---|--|
| <p>Assuming $L_e = 100 \text{ m}$; $\delta_{design}^l = 0.0255 \text{ m} < 3\text{m}$, so increase L_e when $L_e = 1000 \text{ m}$; $\delta_{design}^l = 14.9 \text{ m} > 3\text{m}$, decrease L_e, so that it is close to δ_{design}^l $L_e = 900 \text{ m}$; $\delta_{design}^l = 5.54 \text{ m} > 3\text{m}$ $L_e = 800 \text{ m}$; $\delta_{design}^l = 2.48 \text{ m} < 3\text{m}$ $L_e = 810 \text{ m}$; $\delta_{design}^l = 2.65 \text{ m} < 3\text{m}$ $L_e = 820 \text{ m}$; $\delta_{design}^l = 2.85 \text{ m} < 3\text{m}$ $L_e = 830 \text{ m}$; $\delta_{design}^l = 3.07 \text{ m} > 3\text{m}$ so $830 < L_e < 820 \text{ m}$ So, when $L_e = 825 \text{ m}$; $\delta_{design}^l = 2.96 \text{ m} < 3\text{m}$ $L_e = 827 \text{ m}$; $\delta_{design}^l = 3.01\text{m} \approx \delta_{design}^l$ Hence $L_e = 827 \text{ m}$</p> | | |
| <p>Peak pipe strain (Tensile/Compressive)</p> $\varepsilon_l = \text{Max} \left[\frac{t_u L}{2\pi D t E} \left\{ 1 + \frac{n}{1+r} \left(\frac{t_u L}{2\pi D t \sigma_y} \right)^r \right\}; \frac{t_u L_e}{2\pi D t E} \left[1 + \frac{n}{1+r} \left(\frac{t_u L_e}{2\pi D t \sigma_y} \right)^r \right] \right]$ <p>$t_u = 12.33 \text{ kN/m}$; $D = 0.6\text{m}$; $t = 0.0064\text{m}$; $E = 200000 \text{ MPa}$; $n = 9$; $r = 10$; $L = 100 \text{ m}$; $L_e = 827 \text{ m}$</p> $\varepsilon_l = \text{Max} \left[\frac{12.33 \times 10^3 \times 100}{2\pi \times 0.6 \times 0.0064 \times 2 \times 10^{11}} \left[1 + \frac{9}{1+10} \left(\frac{12.33 \times 10^3 \times 100}{2\pi \times 0.6 \times 0.0064 \times 358 \times 10^6} \right)^{10} \right]; \frac{12.33 \times 10^3 \times 827}{2\pi \times 0.6 \times 0.0064 \times 2 \times 10^{11}} \left[1 + \frac{9}{1+10} \left(\frac{12.33 \times 10^3 \times 827}{2\pi \times 0.6 \times 0.0064 \times 358 \times 10^6} \right)^{10} \right] \right]$ | | <p>$\varepsilon_l = \text{Max}[0.0003, 0.0112]$ $= 0.0112$</p> |
| Total strain in the pipe | Tensile $\varepsilon_{l-pgd} = \varepsilon_l + \varepsilon_{oper} = 0.0112 + 0.00089$ | = 0.0121 |
| | Compressive $\varepsilon_{l-pgd} = \varepsilon_l - \varepsilon_{oper} = 0.0112 - 0.00089$ | = 0.0103 |
| (ii) Transverse PGD | | |
| <p>Maximum normal strain due to bending of pipe is</p> $\varepsilon_t = \pm \text{Max} \left[\frac{\pi D \delta_{design}^t}{W^2}; \frac{P_u W^2}{3\pi E t D^2} \right] = \pm \text{Max} \left[\frac{\pi \times 0.6 \times 3}{40^2}; \frac{105.7 \times 10^3 \times 10^2}{3\pi \times 2 \times 10^{11} \times 0.0064 \times 0.6^2} \right]$ | | <p>$\text{max}[0.0035, 0.0039]$ $= 0.0039$</p> |
| Total strain in the pipe | Tensile $\varepsilon_{t-pgd} = \varepsilon_t + \varepsilon_{oper} = 0.0039 + 0.00089$ | = 0.0048 |
| | Compressive $\varepsilon_{t-pgd} = \varepsilon_t - \varepsilon_{oper} = 0.0039 - 0.00089$ | = 0.0030 |

3.2.3 Effect of Buoyancy due to Liquefaction

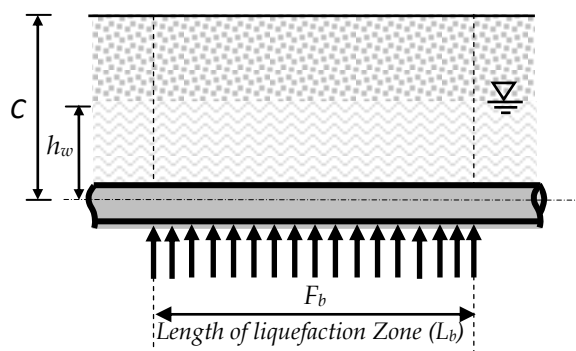


Figure 3.2.2: Longitudinal section of the pipeline

| | | |
|--|---|---|
| Net upward force per unit length of pipe $F_b = \frac{\pi D^2}{4} (\gamma_{sat} - \gamma_{content}) - \pi D t \gamma_{pipe}$ | | = 4.13 kN/m |
| $= \frac{\pi \times 0.6^2}{4} (18 - 0) - \pi \times 0.6 \times 0.0064 \times 78.6$ | | |
| Bending stress in pipe due to uplift force $\sigma_{bf} = \pm \frac{F_b L_b^2}{10Z}$ | $= \pm \frac{4.14 \times 10^3 \times 40^2}{10 \times 0.00175}$ | = 378 MPa > 358 MPa UNSAFE!! |
| Bending strain in pipe due to bending stress $\epsilon_a = \frac{\sigma_{bf}}{E} \left[1 + \frac{n}{1+r} \left(\frac{\sigma_{bf}}{\sigma_y} \right)^r \right]$ | $= \frac{378}{2 \times 10^5} \left[1 + \frac{9}{1+10} \left(\frac{378}{358} \right)^{10} \right]$ | = 0.00455 |
| Total strain in the pipe | Tensile $\epsilon_{bf} = \epsilon_a + \epsilon_{oper} = 0.00455 + 0.00089$ | = 0.0054 |
| | Compressive $\epsilon_{bf} = \epsilon_a - \epsilon_{oper} = 0.00455 - 0.00089$ | = 0.0036 |

3.2.4 Effect of Fault Crossing

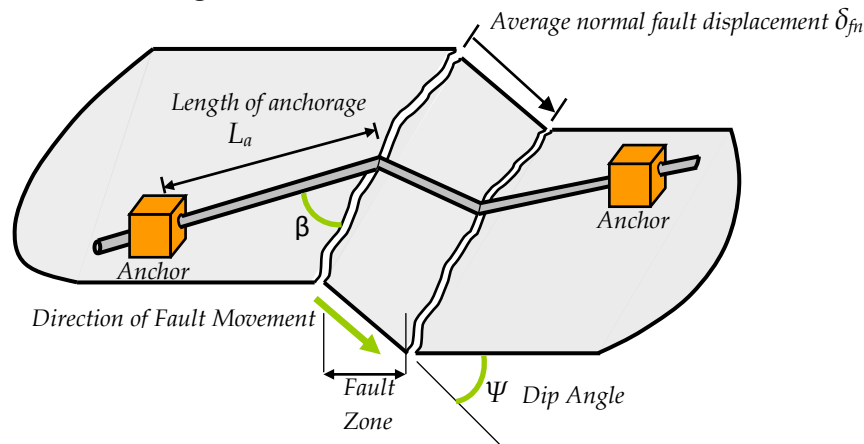
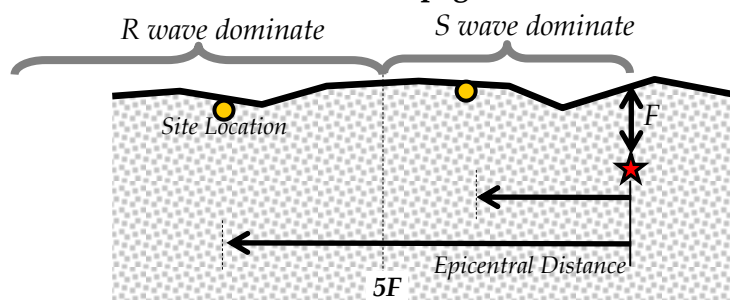


Figure 3.2.3: Pipeline crossing normal slip fault

| | | |
|---|--|--------------------------|
| Component of fault displacement of pipe | Axial direction $\delta_{fax} = \delta_{fn} \cos \psi \sin \beta$ | = 1.316 m |
| | $\delta_{fax} = 2 \times \cos 15 \sin 45$ | |
| Design fault displacement of pipe | Transverse direction $\delta_{ftr} = \delta_{fn} \cos \psi \cos \beta$ | = 1.569 m |
| | $\delta_{ftr} = 2 \times \cos 15 \cos 45$ | |
| Design fault displacement of pipe | Axial direction $\delta_{fax-design} = \delta_{fax} I_p = 1.36 \times 2.3$ | = 3.027 m |
| | Transverse direction $\delta_{ftr-design} = \delta_{ftr} I_p = 1.36 \times 2.3$ | = 3.609 m |
| Effective anchored length of pipe in fault zone $L_e = \text{Min} \left[\frac{E \epsilon_y \pi D t}{t_u}; L_a \right]$ | $L_e = \text{Min} \left[\frac{2 \times 10^{11} \times 0.00125 \times 0.6 \times 0.0064}{12.33 \times 10^3}; 100 \right]$ | min [350,100] = 100 m |
| $t_u = 12.33 \text{ kN/m}; E = 2 \times 10^{11} \text{ N/m}^2; L_a = 100 \text{ m}$ | | |
| Average pipe strain due to fault movement in axial direction | $\epsilon_b = 2 \left[\left(\frac{\delta_{fax-design}}{2L_e} \right) + \frac{1}{2} \left(\frac{\delta_{ftr-design}}{2L_e} \right)^2 \right] = 2 \left[\left(\frac{3.027}{2 \times 100} \right) + \frac{1}{2} \left(\frac{3.609}{2 \times 100} \right)^2 \right]$ | = 0.031 |
| Total Tensile strain in the pipe $\epsilon_{fc} = \epsilon_b + \epsilon_{oper} = 0.031 + 0.00089$ | | = 0.032 |

3.2.5 Effect of Seismic Wave Propagation



5F = 15 < 20 km
 If 5F < Site distance from source
 Dominant Wave : S-wave
 If 5F > Site distance from source
 Dominant Wave : R-wave

Figure 3.2.4: Considerations for S-waves and R-wave in pipeline design

| Ground strain coefficient $\alpha\epsilon = 2.0$ (for S-waves) = 1.0 (for R-waves) | = 2.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|--------------|----------------------------|--|----------------|----------------|-------------------------|--|--|-------------------|----------------|----------------|----------------|-------------------|----|-----|-----|-----|-----|-----|-----|-----|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Velocity of seismic wave propagation $C = C_s$ for S-waves, (2.0 km/s) = C_{r_ph} for R-waves, (0.5 km/s) | = 2.0 km/s | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ground amplification factor I_g for soil classes | = 1.05 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="background-color: #d9ead3;">Class of Soil</th> <th colspan="5" style="background-color: #d9ead3;">PGA_r/PGA_r</th> </tr> <tr> <th style="background-color: #d9ead3;"></th> <th style="background-color: #d9ead3;">$PGA_r \leq 0.1g$</th> <th style="background-color: #d9ead3;">$PGA_r = 0.2g$</th> <th style="background-color: #d9ead3;">$PGA_r = 0.3g$</th> <th style="background-color: #d9ead3;">$PGA_r = 0.4g$</th> <th style="background-color: #d9ead3;">$PGA_r \geq 0.5g$</th> </tr> </thead> <tbody> <tr> <td style="text-align: center;">A</td> <td style="text-align: center;">0.8</td> <td style="text-align: center;">0.8</td> <td style="text-align: center;">0.8</td> <td style="text-align: center;">0.8</td> <td style="text-align: center;">0.8</td> </tr> <tr> <td style="text-align: center;">B</td> <td style="text-align: center;">1.0</td> <td style="text-align: center;">1.0</td> <td style="text-align: center;">1.0</td> <td style="text-align: center;">1.0</td> <td style="text-align: center;">1.0</td> </tr> <tr> <td style="text-align: center;">C</td> <td style="text-align: center;">1.2</td> <td style="text-align: center;">1.2</td> <td style="text-align: center;">1.1</td> <td style="text-align: center;">1.0</td> <td style="text-align: center;">1.0</td> </tr> <tr> <td style="text-align: center;">D</td> <td style="text-align: center;">1.6</td> <td style="text-align: center;">1.4</td> <td style="text-align: center;">1.2</td> <td style="text-align: center;">1.1</td> <td style="text-align: center;">1.0</td> </tr> <tr> <td style="text-align: center;">E</td> <td style="text-align: center;">2.5</td> <td style="text-align: center;">1.7</td> <td style="text-align: center;">1.2</td> <td style="text-align: center;">0.9</td> <td style="text-align: center;">0.9</td> </tr> </tbody> </table> | | Class of Soil | PGA_r/PGA_r | | | | | | $PGA_r \leq 0.1g$ | $PGA_r = 0.2g$ | $PGA_r = 0.3g$ | $PGA_r = 0.4g$ | $PGA_r \geq 0.5g$ | A | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | B | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | C | 1.2 | 1.2 | 1.1 | 1.0 | 1.0 | D | 1.6 | 1.4 | 1.2 | 1.1 | 1.0 | E | 2.5 | 1.7 | 1.2 | 0.9 | 0.9 |
| Class of Soil | | PGA_r/PGA_r | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | $PGA_r \leq 0.1g$ | $PGA_r = 0.2g$ | $PGA_r = 0.3g$ | $PGA_r = 0.4g$ | $PGA_r \geq 0.5g$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C | 1.2 | 1.2 | 1.1 | 1.0 | 1.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| D | 1.6 | 1.4 | 1.2 | 1.1 | 1.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| E | 2.5 | 1.7 | 1.2 | 0.9 | 0.9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Peak Ground Acceleration at ground $PGA = PGA_r I_g = 0.36 \times 1.05$ | = 0.38g | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ratio of Peak Ground Velocity to Peak Ground Acceleration ρ | $\rho = 140$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th rowspan="3" style="background-color: #d9ead3;">Moment Magnitude (M_w)</th> <th colspan="3" style="background-color: #d9ead3;">Ratio of Peak Ground Velocity (cm/s) to Peak Ground Acceleration (g)</th> </tr> <tr> <th colspan="3" style="background-color: #d9ead3;">Source-to-Site Distance</th> </tr> <tr> <th style="background-color: #d9ead3;">0-20 (km)</th> <th style="background-color: #d9ead3;">20-50 (km)</th> <th style="background-color: #d9ead3;">50-100 (km)</th> </tr> </thead> <tbody> <tr> <td rowspan="3" style="text-align: center;">Rock</td> <td style="text-align: center;">6.5</td> <td style="text-align: center;">66</td> <td style="text-align: center;">76</td> </tr> <tr> <td style="text-align: center;">7.5</td> <td style="text-align: center;">97</td> <td style="text-align: center;">109</td> </tr> <tr> <td style="text-align: center;">8.5</td> <td style="text-align: center;">127</td> <td style="text-align: center;">140</td> </tr> <tr> <td rowspan="3" style="text-align: center;">Stiff Soil</td> <td style="text-align: center;">6.5</td> <td style="text-align: center;">94</td> <td style="text-align: center;">102</td> </tr> <tr> <td style="text-align: center;">7.5</td> <td style="text-align: center;">140</td> <td style="text-align: center;">127</td> </tr> <tr> <td style="text-align: center;">8.5</td> <td style="text-align: center;">180</td> <td style="text-align: center;">188</td> </tr> <tr> <td rowspan="3" style="text-align: center;">Soft Soil</td> <td style="text-align: center;">6.5</td> <td style="text-align: center;">140</td> <td style="text-align: center;">132</td> </tr> <tr> <td style="text-align: center;">7.5</td> <td style="text-align: center;">208</td> <td style="text-align: center;">165</td> </tr> <tr> <td style="text-align: center;">8.5</td> <td style="text-align: center;">269</td> <td style="text-align: center;">244</td> </tr> </tbody> </table> | | Moment Magnitude (M_w) | Ratio of Peak Ground Velocity (cm/s) to Peak Ground Acceleration (g) | | | Source-to-Site Distance | | | 0-20 (km) | 20-50 (km) | 50-100 (km) | Rock | 6.5 | 66 | 76 | 7.5 | 97 | 109 | 8.5 | 127 | 140 | Stiff Soil | 6.5 | 94 | 102 | 7.5 | 140 | 127 | 8.5 | 180 | 188 | Soft Soil | 6.5 | 140 | 132 | 7.5 | 208 | 165 | 8.5 | 269 | 244 | | |
| Moment Magnitude (M_w) | | | Ratio of Peak Ground Velocity (cm/s) to Peak Ground Acceleration (g) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | Source-to-Site Distance | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | 0-20 (km) | 20-50 (km) | 50-100 (km) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Rock | 6.5 | 66 | 76 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 7.5 | 97 | 109 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 8.5 | 127 | 140 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| | 8.5 | 269 | 244 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Peak Ground Velocity $PGV = \rho PGA = \frac{140}{100} \times 0.38$ | = 0.532 m/s | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Design peak ground velocity $V_g = I_p PGV = 1.05 \times 0.532$ | = 0.56 m/s | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Maximum axial strain in the pipe due to wave velocity $\epsilon_{c_wv} = \frac{V_g}{\alpha_\epsilon C} = \frac{0.56}{1 \times 2 \times 1000}$ | = 0.0003 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Apparent wavelength of seismic waves at ground surface $\lambda = 1.0$ km (in the absence of detailed information) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Maximum axial strain that can be transmitted by soil friction $\epsilon_{c_sf} = \frac{t_u \lambda}{4AE}$ $= \frac{12.33 \times 10^3 \times 1 \times 10^3}{4 \times 0.0119 \times 2 \times 10^{11}}$ | = 0.0013 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Total Tensile strain in pipe $\epsilon_{swp} = \text{Max}[\epsilon_{c_wv}, \epsilon_{c_sf}] + \epsilon_{oper}$ $= \text{Max}[0.0003, 0.0013] + 0.00089$ | = 0.00219 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

3.3 Limiting Strain Calculation

Allowable strain criteria for buried continuous pipelines

| Strain component | Pipe category | Allowable Strain | | | |
|---------------------------------|------------------------|-------------------------|------------------------------------|---|-----------|
| | | Tension | | Compression | |
| Continuous Oil and Gas pipeline | Ductile Cast Iron Pipe | 2% | | For PGD: Onset of wrinkling $\epsilon_{cr-c} = 0.175 \frac{t}{R}$ $= 0.175 \times \frac{0.0064}{0.6/2}$ $= 0.00373$ | = 0.00373 |
| | Steel Pipe | 3% | = 0.03 | | |
| Continuous water pipeline | Steel and Iron pipe | 0.25 ϵ_u or 5% | $= 0.25 \times 0.15$ $= 3.75\%$ | $\epsilon_{c-pgd} = 0.88 \frac{t}{R}$ | |
| | | | | $\epsilon_{c-wave} = 0.75 \left[0.5 \frac{t}{D'} - 0.0025 + 3000 \left(\frac{PD}{2Et} \right)^2 \right]$ where $D' = \frac{D}{1 - \frac{3}{D}(D - D_{min})}$ | |

3.4 Check for Safety

Total strain for continuous pipelines should be less than allowable strain, $\epsilon_{seismic} + \epsilon_{oper} \leq \epsilon_{allowable}$

| Case | | Maximum strain in pipe | | Allowable strain in pipe | | Safe/Unsafe |
|------------------------------|--------------|------------------------|-------------|--------------------------|-------------|-------------|
| | | Tension | Compression | Tension | Compression | |
| (1) PGD | Longitudinal | 0.0121 | 0.0103 | 0.03 | 0.0037 | Unsafe |
| | Transverse | 0.0048 | 0.0030 | 0.03 | 0.0037 | Safe |
| (2) Liquefaction | | 0.0054 | 0.0036 | 0.03 | 0.0037 | Safe |
| (3) Fault Crossing | | 0.0320 | - | 0.03 | 0.0037 | Unsafe |
| (4) Seismic Wave Propagation | | 0.0022 | - | 0.03 | 0.0037 | Safe |

The pipeline is considered safe only when all the strain levels are within the allowable strain limits and appropriate retrofitting might to done to ensure safety.

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