

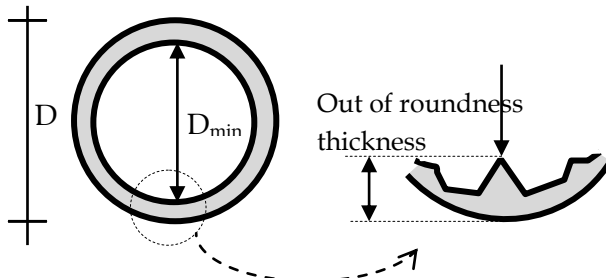
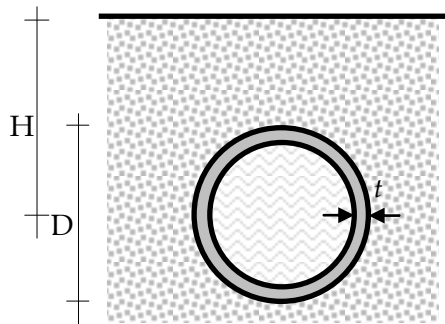
2. INPUTS

2.2 Basic Information

- (1) Location : Chandigarh Seismic Zone: IV Z = 0.24g
 (2) Type : Water
 (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	= 1.5 m
D	= 0.74 m
D_{min}	= 0.70 m
t	= 0.01 m
Section modulus of pipe cross section $Z = \frac{\pi}{32} \left[D^4 - (D - 2t)^4 \right]$ $= \frac{\pi}{32} \left[0.74^4 - (0.74 - 2 \times 0.01)^4 \right]$	= 0.00412 m ³
Cross sectional area $A = \frac{\pi}{4} (D^2 - (D - 2t)^2)$ $= \frac{\pi}{4} (0.74^2 - (0.74 - 2 \times 0.01)^2)$	= 0.0229 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						= 250 MPa
Modulus of Elasticity E						= 200000 MPa
Yield Strain of the pipe material ϵ_y						= 0.00125
Failure strain of the pipe in tension ϵ_u						= 0.15
Linear coefficient of thermal expansion of steel α_t						= $12 \times 10^{-6} / ^\circ\text{C}$
Poisson's ratio μ						= 0.3
Unit weight of steel pipe γ_{pipe}						= 78.6 kN/m ³
Unit weight of the content $\gamma_{content}$						= 10.0 kN/m ³

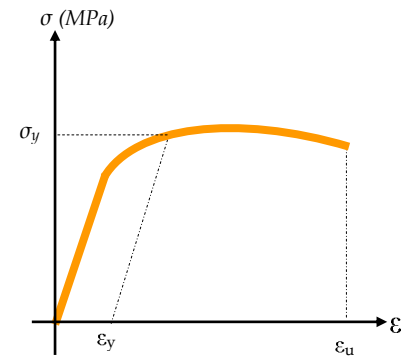


Figure 2.2.2: Ramberg-Osgood's σ - ϵ curve for steel

2.2.3 Soil Properties

Velocity of shear wave V_s			= 300 m/s
Coefficient of cohesion of backfill soil c , [$c = 0$ for sandy soil]			= 0 kPa
Effective unit weight of the soil $\bar{\gamma}$			= 16 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			= 30°
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	= 0.8 MPa
Temperature in the pipe at the time of installation T_1	= 25 °C
Temperature in the pipe at the time of operation T_2	= 5, 45 °C

(b) For Permanent Ground Deformation (PGD)

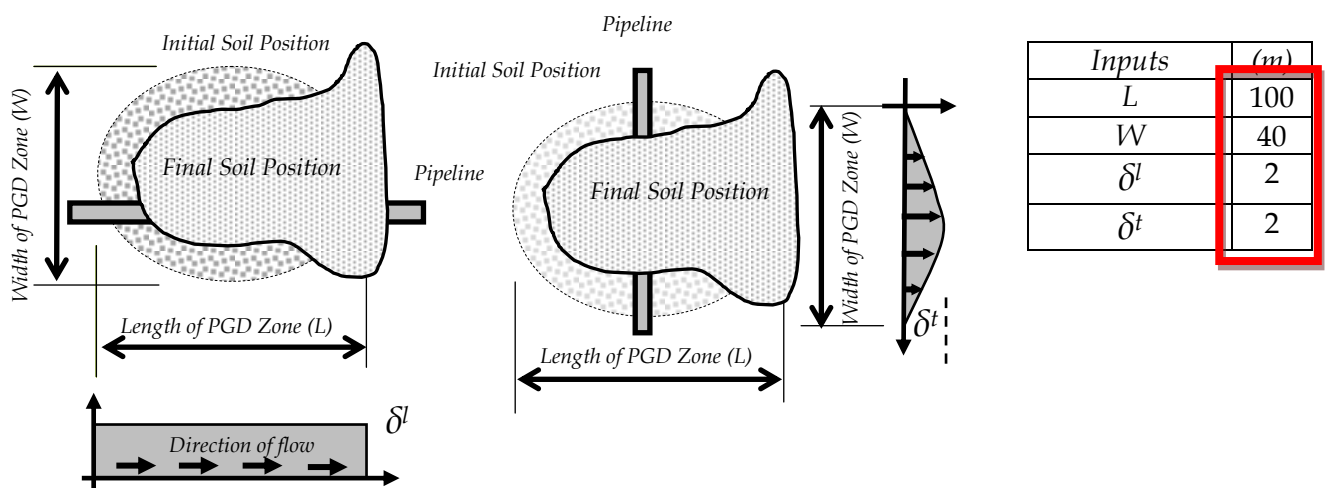
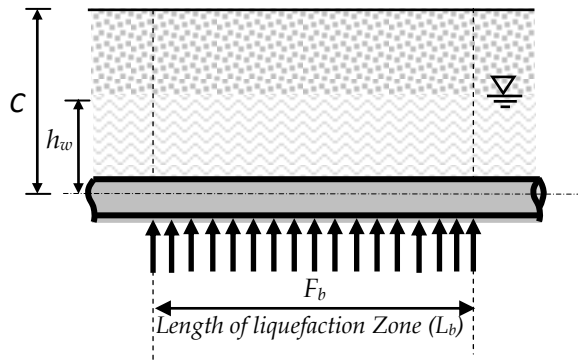


Figure 2.2.2: (a) Longitudinal PGD

(b) Transverse PGD

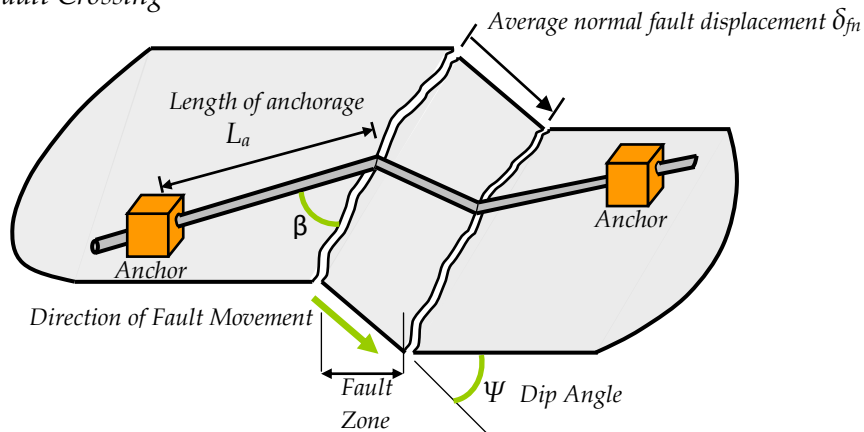
(c) For Liquefaction



Inputs	(m)
L_b	40
h_w	1
C	2

Figure 2.2.3: Longitudinal section of the pipeline

(d) For Fault Crossing



Inputs	Units
δ_{fn}	2.5 m
Ψ	15°
β	45°
L_a	250 m

Figure 2.2.4: Pipeline crossing normal slip fault

(e) For Seismic Wave Propagation

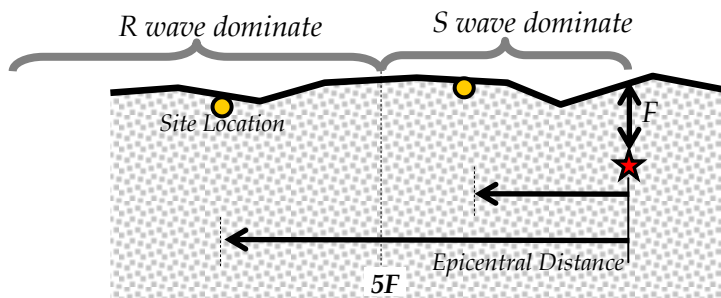


Figure 2.2.5: Considerations for S-waves and R-wave in pipeline design

Focal length F	= 15 km												
Distance of site from earthquake source	= 100 km												
Magnitude of design basis earthquake considered M_w	= 8												
Expected peak ground acceleration of the site at base rock layer PGA_r	$PGA_r = 1g$												
<table border="1"> <thead> <tr> <th>Seismic Zone</th> <th>II</th> <th>III</th> <th>IV</th> <th>V</th> <th>Site Specific</th> </tr> </thead> <tbody> <tr> <td>PGA_r</td> <td>0.1g</td> <td>0.16g</td> <td>0.24g</td> <td>0.36g</td> <td>!!</td> </tr> </tbody> </table>	Seismic Zone	II	III	IV	V	Site Specific	PGA_r	0.1g	0.16g	0.24g	0.36g	!!	
Seismic Zone	II	III	IV	V	Site Specific								
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: D
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 $K_o = 1 - \sin \phi$ $= 1 - \sin 30^\circ$ (or)		Type of soil	K_o				$K_o = 0.5$
		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 $\delta' = f\phi = 0.7 \times 30^\circ$							= 21°
Maximum axial soil force per unit length $t_u = \pi D c \alpha + \pi D H \bar{\gamma} \left(\frac{1+K_o}{2} \right) \tan \delta'$ $= 0 + \pi \times 0.74 \times 1.5 \times 16 \left(\frac{1+0.5}{2} \right) \tan 21$							= 16.06 kN/m
Factor	ϕ	a_1	b_1	c_1	d_1	e_1	
N_{ch}		6.752	0.065	-11.063	7.119	-	
N_{qh}	20	2.399	0.439	-0.03	1.059×10^{-3}	-0.175×10^{-4}	
N_{qh}	25	3.332	0.839	-0.090	5.606×10^{-3}	-1.319×10^{-4}	
N_{qh}	30	4.565	1.234	-0.089	4.275×10^{-3}	-0.916×10^{-4}	
N_{qh}	35	6.816	2.019	-0.146	7.651×10^{-3}	-1.683×10^{-4}	
N_{qh}	40	10.959	1.783	0.045	-5.425×10^{-3}	-1.153×10^{-4}	
N_{qh}	45	17.658	3.309	0.048	-6.443×10^{-3}	-1.299×10^{-4}	
Horizontal bearing capacity factor for clay $N_{ch} = a + bx + \frac{c}{(x+1)^2} + \frac{d}{(x+1)^3} \leq 9$ where $x = H/D = 1.5/0.74 = 2$; $N_{ch} = 6.752 + 0.065 \times 2 + \frac{-11.063}{(2+1)^2} + \frac{7.119}{(2+1)^3}$							= 5.911
Horizontal bearing capacity factor for sandy soil $N_{qh} = a + bx + cx^2 + dx^3 + ex^4$ $= 4.565 + 1.234 \times 2 + (-0.089)2^2 + (4.275 \times 10^{-3})2^3 + (-0.916 \times 10^{-4})2^4$							= 6.71
Maximum lateral resistance of soil per unit length of pipe $P_u = N_{ch} c D + N_{qh} \bar{\gamma} H D = 0 + 6.71 \times 16 \times 1.5 \times 0.74$							= 119 kN/m

3.2 Peak Strain Calculation

3.2.1 Operational Longitudinal Strain in the Pipeline

Longitudinal Stress due to <i>internal pressure</i> $S_p = \frac{PD\mu}{2t} = \frac{0.8 \times 0.74 \times 0.3}{2 \times 0.01}$	= 8.9 MPa
Longitudinal Stress due to <i>temperature change</i> $S_t = E\alpha_t(T_2 - T_1)$ $= 2 \times 10^5 \times 12 \times 10^{-6} \times (45 - 25)$	= 48 MPa
Longitudinal Strain due to <i>internal pressure</i> $\epsilon_p = \frac{S_p}{E} \left[1 + \frac{n}{1+r} \left(\frac{S_p}{\sigma_y} \right)^r \right]$ $n = 11.385; r = 81.16; \epsilon_p = \frac{8.9}{2 \times 10^5} \left[1 + \frac{11.385}{1+81.16} \left(\frac{8.9}{250} \right)^{81.16} \right]$	= 0.0000445
Longitudinal Strain due to <i>temperature change</i> $\epsilon_t = \frac{S_t}{E} \left[1 + \frac{n}{1+r} \left(\frac{S_t}{\sigma_y} \right)^r \right]$ $= \frac{48}{2 \times 10^5} \left[1 + \frac{11.385}{1+81.16} \left(\frac{48}{250} \right)^{81.16} \right]$	= 0.00024
Total Operational Longitudinal Strain in pipe $\epsilon_{oper} = \epsilon_p + \epsilon_t$ $= 0.0000445 + 0.00024$	0.000285

3.2.2 Effect of Permanent Ground Deformation (PGD)

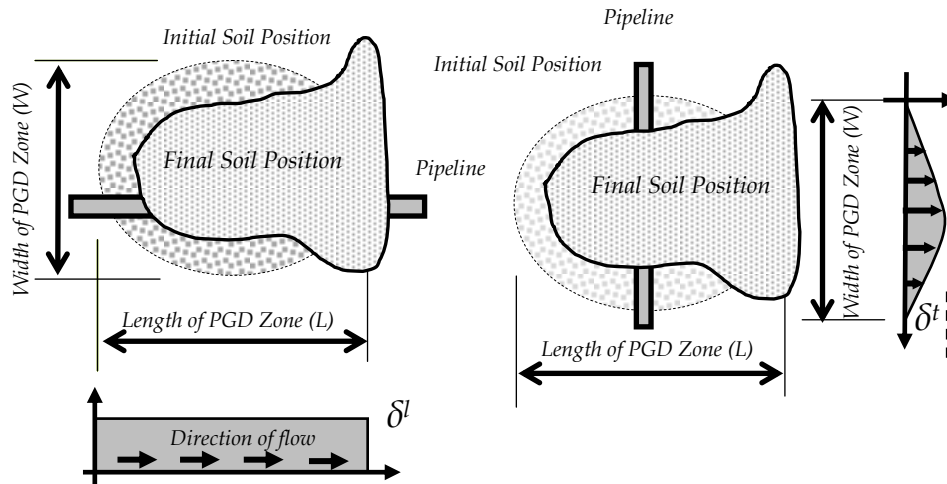


Figure 3.1.2: (a) Longitudinal PGD (b) Transverse PGD

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 $\delta_{design}^l = \frac{t_u L_e^2}{2\pi D t E} \left[1 + \left(\frac{2}{2+r} \right) \left(\frac{n}{1+r} \right) \left(\frac{t_u L_e}{2\pi D t \sigma_y} \right)^r \right]$ $t_u = 16.06 \text{ kN/m}; D = 0.74 \text{ m}; t = 0.01 \text{ m}; E = 200000 \text{ MPa}; n = 11.385; r = 81.16;$ $\delta_{design}^l = 3 \text{ m}$ Assume $L_e = 100 \text{ m}$ $\delta_{design}^l = \frac{16.06 \times 10^3 \times 100^2}{2\pi \times 0.74 \times 0.01 \times 2 \times 10^{11}} \left[1 + \left(\frac{2}{2+81.16} \right) \left(\frac{11.385}{1+81.16} \right) \left(\frac{16.06 \times 10^3 \times 100}{2\pi \times 0.74 \times 0.01 \times 250 \times 10^6} \right)^{81.16} \right]$ $= 0.01728$	$L_e = 782 \text{ m}$

<p>Assume $L_e = 500 \text{ m}$; $\delta_{design}^l = 0.432 \text{ m} < 3\text{m}$, so increase L_e when $L_e = 800 \text{ m}$; $\delta_{design}^l = 14.1 \text{ m} > 3\text{m}$, now decrease L_e , so that it is close to δ_{design}^l $L_e = 700 \text{ m}$; $\delta_{design}^l = 0.847 \text{ m} < 3\text{m}$ $L_e = 750 \text{ m}$; $\delta_{design}^l = 1.032 \text{ m} < 3\text{m}$ $L_e = 780 \text{ m}$; $\delta_{design}^l = 2.63 \text{ m} < 3\text{m}$ $L_e = 785 \text{ m}$; $\delta_{design}^l = 3.756 \text{ m} > 3\text{m}$; so $780 < L_e < 785 \text{ m}$ So, when $L_e = 781 \text{ m}$; $\delta_{design}^l = 2.813 \text{ m}$ $L_e = 782 \text{ m}$; $\delta_{design}^l = 3.014 \text{ m} \approx \delta_{design}^l$ Hence $L_e = 782 \text{ m}$</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>$t_u = 16.06 \text{ kN/m}$; $D = 0.74\text{m}$; $t = 0.01\text{m}$; $E = 200000 \text{ MPa}$; $n = 11.385$; $r = 81.16$; $L = 100 \text{ m}$; $L_e = 782\text{m}$</p> $\varepsilon_l = \text{Max} \left[\frac{16.06 \times 10^3 \times 100}{2\pi \times 0.74 \times 0.01 \times 2 \times 10^{11}} \left[1 + \frac{11.385}{1 + 81.16} \left(\frac{16.06 \times 10^3 \times 100}{2\pi \times 0.74 \times 0.01 \times 250 \times 10^6} \right)^{81.16} \right]; \frac{16.06 \times 10^3 \times 782}{2\pi \times 0.74 \times 0.01 \times 2 \times 10^{11}} \left[1 + \frac{11.385}{1 + 81.16} \left(\frac{16.06 \times 10^3 \times 782}{2\pi \times 0.74 \times 0.01 \times 250 \times 10^6} \right)^{81.16} \right] \right]$		<p>$\varepsilon_l = \text{Max}[0.000173, 0.1054]$ $= 0.1054$</p>
Total strain in the pipe	Tensile $\varepsilon_{l-pgd} = \varepsilon_l + \varepsilon_{oper} = 0.1054 + 0.000285$	=0.105685
	Compressive $\varepsilon_{l-pgd} = \varepsilon_l - \varepsilon_{oper} = 0.1054 - 0.000285$	=0.105115
(ii) Transverse PGD		
<p>Maximum normal strain due to bending of pipe is</p> $\varepsilon_t = \pm \text{Max} \left[\frac{\pi D \delta_{design}^t}{W^2}; \frac{P_u W^2}{3\pi E t D^2} \right] = \pm \text{Max} \left[\frac{\pi \times 0.74 \times 3}{40^2}; \frac{119 \times 10^3 \times 40^2}{3\pi \times 2 \times 10^{11} \times 0.01 \times 0.74^2} \right]$		=0.0043;0.0185 =0.0185
Total strain in the pipe	Tensile $\varepsilon_{t-pgd} = \varepsilon_t + \varepsilon_{oper} = 0.0185 + 0.000285$	= 0.018785
	Compressive $\varepsilon_{t-pgd} = \varepsilon_t - \varepsilon_{oper} = 0.0185 - 0.000285$	= 0.018215

3.2.3 Effect of Buoyancy due to Liquefaction

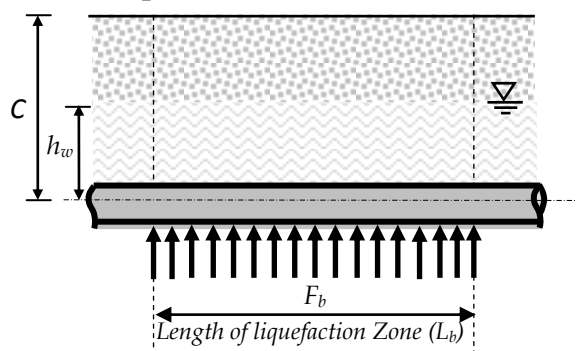


Figure 3.2.2: Longitudinal section of the pipeline

<p>(Net upward force per unit length of pipe)</p> $F_b = \frac{\pi D^2}{4} (\gamma_{sat} - \gamma_{content}) - \pi D t \gamma_{pipe} + \left(\frac{h_w}{3} - C \right) D \gamma_d$	
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$= \frac{\pi \times 0.74^2}{4} (18 - 10) - \pi \times 0.74 \times 0.01 \times 78.6 + \left(\frac{1}{3} - 2\right) 0.74 \times 16$		= -18.12 kN/m
Bending stress in pipe due to uplift force $\sigma_{bf} = \pm \frac{F_b L_b^2}{10Z} = \pm \frac{18.12 \times 10^3 \times 40^2}{10 \times 0.00412}$		= 703.7 MPa > 250 MPa UNSAFE!!
Bending strain in pipe due to bending stress $\varepsilon_a = \frac{\sigma_{bf}}{E} \left[1 + \frac{n}{1+r} \left(\frac{\sigma_{bf}}{\sigma_y} \right)^r \right]$ $= \frac{703.7}{2 \times 10^5} \left[1 + \frac{11.385}{1+81.16} \left(\frac{703.7}{250} \right)^{81.16} \right]$		= 1.46×10^{33}
Total strain in the pipe	Tensile $\varepsilon_{bf} = \varepsilon_a + \varepsilon_{oper} = 1.46 \times 10^{33} + 0.000285$	= 1.46×10^{33}
	Compressive $\varepsilon_{bf} = \varepsilon_a - \varepsilon_{oper} = 1.46 \times 10^{33} - 0.000285$	= 1.46×10^{33}

3.2.4 Effect of Fault Crossing

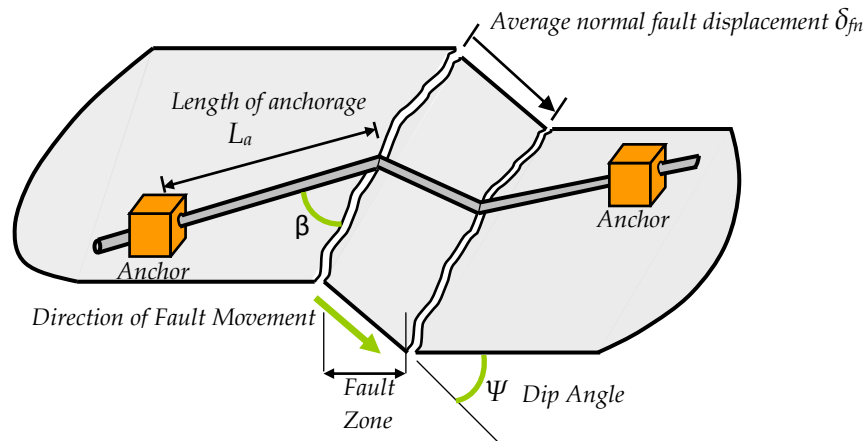
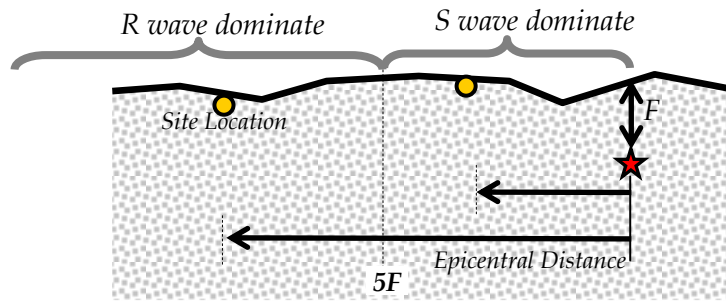


Figure 3.2.3: Pipeline crossing normal slip fault

Component of fault displacement of pipe	Axial direction $\delta_{fax} = \delta_{fn} \cos \psi \sin \beta$ $\delta_{fax} = 2.5 \times \cos 15 \sin 45$	= 1.7 m
	Transverse direction $\delta_{ftr} = \delta_{fn} \cos \psi \cos \beta$ $\delta_{ftr} = 2.5 \times \cos 15 \cos 45$	= 1.7 m
Design fault displacement of pipe	Axial direction $\delta_{fax-design} = \delta_{fax} I_p = 1.7 \times 2.3$	= 3.91 m
	Transverse direction $\delta_{ftr-design} = \delta_{ftr} I_p = 1.7 \times 2.3$	= 3.91 m
Effective anchored length of pipe in fault zone $L_e = \text{Min} \left[\frac{E \varepsilon_y \pi D t}{t_u}; L_a \right]$ $L_e = \text{Min} \left[\frac{2 \times 10^{11} \times 0.00125 \times 0.74 \times 0.01}{16.06 \times 10^3}; 250 \right]$ $t_u = 16.06 \text{ kN/m}; E = 2 \times 10^{11} \text{ N/m}^2; L_a = 250 \text{ m}$		= 115.2, 250 m = 115.2 m
Average pipe strain due to fault movement in axial direction $\varepsilon_b = 2 \left[\left(\frac{\delta_{fax-design}}{2L_e} \right) + \frac{1}{2} \left(\frac{\delta_{ftr-design}}{2L_e} \right)^2 \right] = 2 \left[\left(\frac{3.91}{2 \times 115.2} \right) + \frac{1}{2} \left(\frac{3.91}{2 \times 115.2} \right)^2 \right]$		= 0.0342
Total Tensile strain in the pipe $\varepsilon_{fc} = \varepsilon_b + \varepsilon_{oper} = 0.0342 + 0.000285$		= 0.0345

3.2.5 Effect of Seismic Wave Propagation



5F = 75 > 100 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 $\alpha\varepsilon = 2.0$ (for S-waves) = 1.0 (for R-waves)	= 1.0																																									
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)	= 0.5 km/s																																									
Ground amplification factor I_g for soil classes	$\frac{PGA}{PGA_r} = 1.0$																																									
<table border="1"> <thead> <tr> <th rowspan="2">Class of Soil</th> <th colspan="5">PGA/PGA_r</th> </tr> <tr> <th>PGA_r ≤ 0.1g</th> <th>PGA_r = 0.2g</th> <th>PGA_r = 0.3g</th> <th>PGA_r = 0.4g</th> <th>PGA_r ≥ 0.5g</th> </tr> </thead> <tbody> <tr> <td>A</td> <td>0.8</td> <td>0.8</td> <td>0.8</td> <td>0.8</td> <td>0.8</td> </tr> <tr> <td>B</td> <td>1.0</td> <td>1.0</td> <td>1.0</td> <td>1.0</td> <td>1.0</td> </tr> <tr> <td>C</td> <td>1.2</td> <td>1.2</td> <td>1.1</td> <td>1.0</td> <td>1.0</td> </tr> <tr> <td>D</td> <td>1.6</td> <td>1.4</td> <td>1.2</td> <td>1.1</td> <td>1.0</td> </tr> <tr> <td>E</td> <td>2.5</td> <td>1.7</td> <td>1.2</td> <td>0.9</td> <td>0.9</td> </tr> </tbody> </table>		Class of Soil	PGA/PGA _r					PGA _r ≤ 0.1g	PGA _r = 0.2g	PGA _r = 0.3g	PGA _r = 0.4g	PGA _r ≥ 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/PGA _r																																							
		PGA _r ≤ 0.1g	PGA _r = 0.2g	PGA _r = 0.3g	PGA _r = 0.4g	PGA _r ≥ 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 $PGA = PGA_r I_g$	= 1g																																									
Ratio of Peak Ground Velocity to Peak Ground Acceleration ρ	$\rho = 174$																																									
<table border="1"> <thead> <tr> <th rowspan="3">Moment Magnitude (M_w)</th> <th colspan="3">Ratio of Peak Ground Velocity (cm/s) to Peak Ground Acceleration (g)</th> </tr> <tr> <th colspan="3">Source-to-Site Distance</th> </tr> <tr> <th>0-20 (km)</th> <th>20-50 (km)</th> <th>50-100 (km)</th> </tr> </thead> <tbody> <tr> <td rowspan="3">Rock</td> <td>6.5</td> <td>66</td> <td>76</td> </tr> <tr> <td>7.5</td> <td>97</td> <td>109</td> </tr> <tr> <td>8.5</td> <td>127</td> <td>140</td> </tr> <tr> <td rowspan="3">Stiff Soil</td> <td>6.5</td> <td>94</td> <td>102</td> </tr> <tr> <td>7.5</td> <td>140</td> <td>127</td> </tr> <tr> <td>8.5</td> <td>180</td> <td>188</td> </tr> <tr> <td rowspan="3">Soft Soil</td> <td>6.5</td> <td>140</td> <td>132</td> </tr> <tr> <td>7.5</td> <td>208</td> <td>165</td> </tr> <tr> <td>8.5</td> <td>269</td> <td>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	
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Design peak ground velocity $V_g = I_p PGV$	= 2.55 m/s																																									
Maximum axial strain in the pipe due to wave velocity $\varepsilon_{c_wv} = \frac{V_g}{\alpha_\varepsilon C} = \frac{2.55}{1 \times 0.5 \times 1000}$	= 0.0051																																									
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 $\varepsilon_{c_sf} = \frac{t_u \lambda}{4AE}$ $= \frac{16.06 \times 10^3 \times 1 \times 10^3}{4 \times 0.0129 \times 2 \times 10^{11}}$	= 0.00155																																									
Total Tensile strain in pipe $\varepsilon_{swp} = \text{Max}[\varepsilon_{c_wv}, \varepsilon_{c_sf}] + \varepsilon_{oper}$ = $\text{Max}[0.0051, 0.00155] + 0.000285$	= 0.005385																																									

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 $\epsilon_{cr-c} = 0.175 \frac{t}{R}$ For wave propagation: 50% to 100% of onset of wrinkling ($0.5\epsilon_{cr-c}$ to ϵ_{cr-c})	
	Steel Pipe	3%			
Continuous water pipeline	Steel and Iron pipe	0.25 ϵ_u or 5%	=0.25×0.15 =3.75%	$\epsilon_{c-pgd} = 0.88 \frac{t}{R} = 0.88 \frac{0.01}{0.74/2} = 0.0237$	
				$\epsilon_{c-wave} = 0.75 \left[0.5 \frac{t}{D'} - 0.0025 + 3000 \left(\frac{PD}{2Et} \right)^2 \right]$ where $D' = \frac{D}{1 - \frac{3}{D} (D - D_{min})} = \frac{0.74}{1 - \frac{3}{0.74} (0.74 - 0.70)} = 0.88m$ $\epsilon_{c-wave} = 0.75 \left[0.5 \frac{0.01}{0.88} - 0.0025 + 3000 \left(\frac{0.8 \times 0.74}{2 \times 2 \times 10^5 \times 0.01} \right)^2 \right] = 0.00244$	

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	0.1057	0.1051	0.0375	0.0237	Unsafe
	Transverse	0.0189	0.0182	0.0375	0.0237	Safe
(2) Liquefaction		1.46×10^{33}	1.46×10^{33}	0.0375	0.0237	Unsafe
(3) Fault Crossing		0.0345	-	0.0375	0.0024	Safe
(4) Seismic Wave Propagation		0.0054	-	0.0375	0.0024	Safe

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

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