2. INPUTS

2.2 Basic Information

(1) Location : Kwalak

(2) Type : Water

(3) Importance Factor I_p

Seismic Zone as per Indian Seismic Code: IV

Site-specific horizontal acceleration Z_{SS} : 1g

Class of pipeline	Importance factor I_p			
	PGD	*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

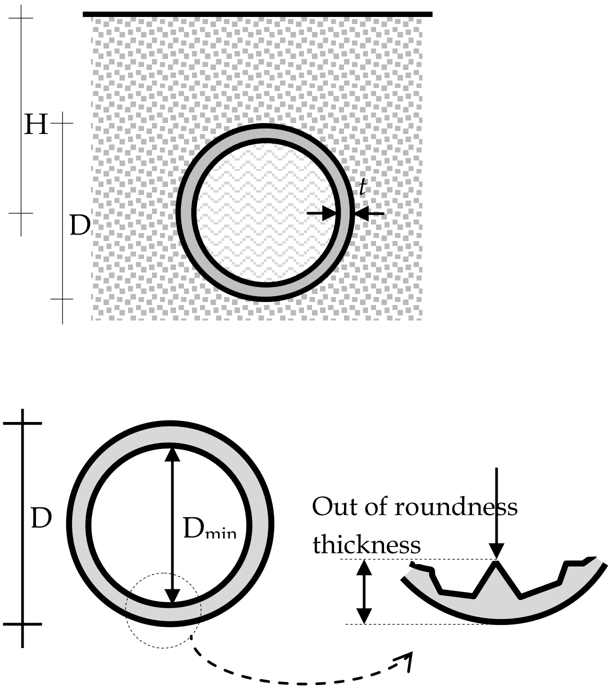


Figure 2.2.1: Cross-section of the pipeline

Measurements	*Units*
H	= 1.25 m
D	= 0.512 m
D_{min}	= 0.5 m
t	= 0.006 m
Section modulus of pipe cross section $Z = \frac{\pi}{32}\frac{\left[D^4 - (D-2t)^4\right]}{D} = \frac{\pi}{32}\frac{\left[0.512^4 - (0.512 - 2\times 0.006)^4\right]}{0.512}$	=0.00119m³
Cross sectional area $A = \frac{\pi}{4}\left(D^2 - (D-2t)^2\right) = \frac{\pi}{4}\left(0.512^2 - (0.512 - 2\times 0.006)^2\right)$	=0.00953 m²

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						**= 12×10^{-6}/°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

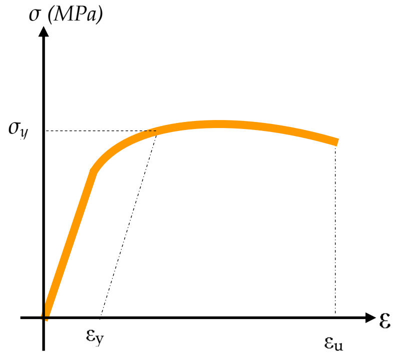


Figure 2.2.2: Ramberg-Osgood's ***σ- ε*** curve for steel

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: Concrete 1.0; Rough steel 0.8; Smooth Steel 0.7	f = 0.8

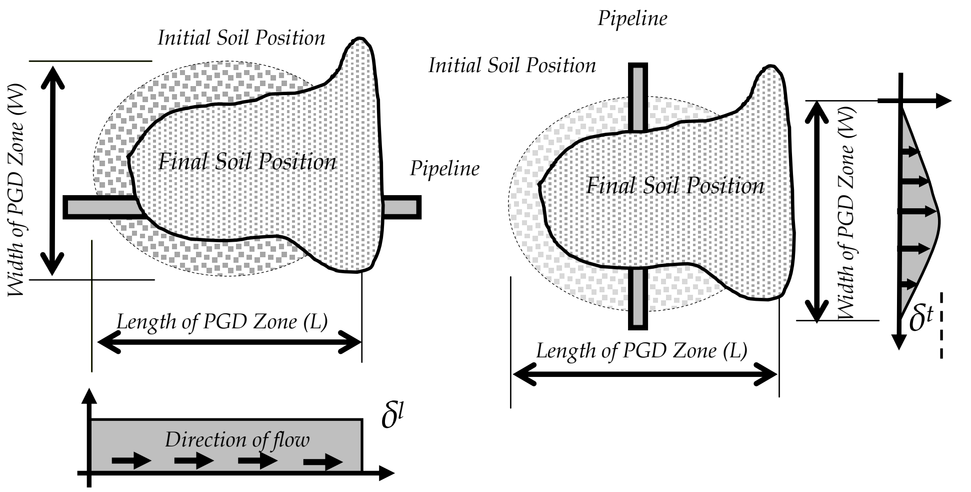
Pipe coating	f
Concrete	1.0
Rough steel	0.8
Smooth Steel	0.7

2.2.4 Inputs for Peak Strain Calculation

(a) For Operational Longitudinal Strain in the Pipeline

Maximum internal operating pressure of the pipe P	= 0.5 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	= 10, 30°C

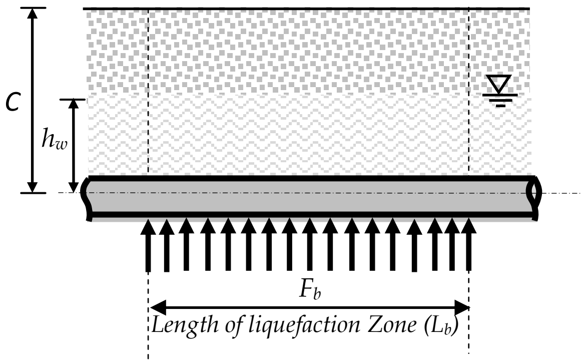
(b) For Permanent Ground Deformation (PGD)



Inputs	(m)
L	15
W	10
δ^l	2
δ^t	2

Figure 2.2.2: (a) Longitudinal PGD **(b)** Transverse PGD

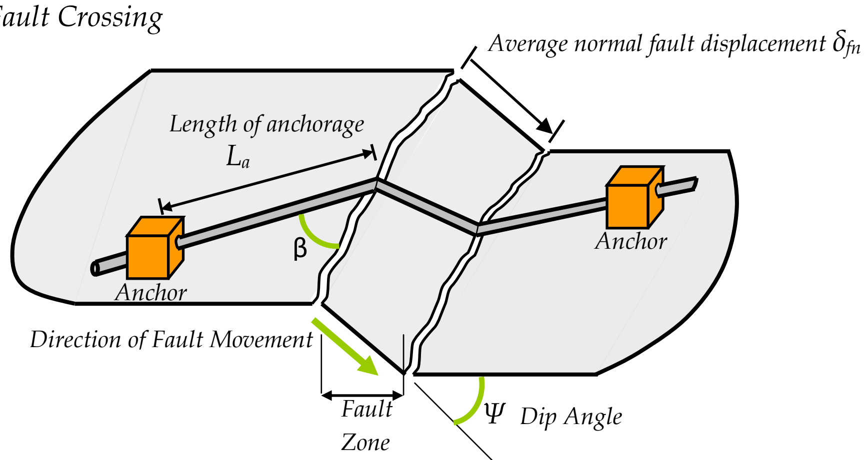
(c) For Liquefaction



Inputs	(m)
L_b	20
h_w	1
C	2

Figure 2.2.3: Longitudinal section of the pipeline

(d) For Fault Crossing



Inputs	Units
δ_{fn}	2 m
Ψ	15°
β	45°
L_a	50 m

Figure 2.2.4: Pipeline crossing normal slip fault

(e) For Seismic Wave Propagation

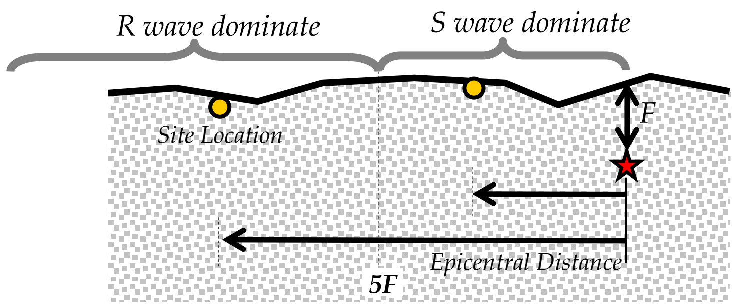


Figure 2.2.5: Considerations for S-waves and R-wave in pipeline design

Focal length *F*	= 15 km
Distance of site from earthquake source	= 80 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

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	*Soil Type*	*Velocity of shear wave (V_s) m/s*	*Uncorrected Standard Penetration Resistance (N)*
A	Hard Rock	$V_s > 1500$	-
B	Rock	$760 < V_s \le 1500$	-
C	Very Dense and Soft Rock	$360 < V_s \le 760$	$N > 50$
D	Dense/Stiff Soil	$180 < V_s \le 360$	$15 \le N \le 50$
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

Soil Class: D

Coefficient of soil pressure at rest

$$K_o = 1 - \sin\varphi \qquad \text{(or)}$$
$$= 1 - \sin 30^\circ$$

Type of soil	K_o
Loose soil	0.5-0.6
Dense soil	0.3-0.5
Clay(drained)	0.5-0.6
Clay (undrained)	0.8-1.1
Over consolidated soil	1.0-1.3

$K_o = 0.5$

Adhesion factor $\alpha = 0.608 - 0.123c - \dfrac{0.274}{c^2+1} + \dfrac{0.695}{c^3+1}$ (c is in kPa/100)

$$= 0.608 - 0.274 + 0.695$$

$= 1.029$

Interface angle of friction between soil and pipe $\delta' = f\phi = 0.8 \times 30°$ $= 24°$

Maximum axial soil force per unit length $t_u = \pi D c \alpha + \pi D H \bar{\gamma}\left(\dfrac{1+K_o}{2}\right)\tan\delta'$

$$= 0 + \pi \times 0.512 \times 1.25 \times 16\left(\frac{1+0.5}{2}\right)\tan 24$$

$= 10.74\ \text{kN/ m}$

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}

Factor	$\phi = 30^\circ$	
	N_{ch}	N_{qh}
a_1	6.752	4.565
b_1	0.065	1.234
c_1	-11.063	-0.089
d_1	7.119	4.275×10^{-3}
e_1	-	-0.916×10^{-4}

Horizontal bearing capacity factor for clay $N_{ch} = a + bx + \dfrac{c}{(x+1)^2} + \dfrac{d}{(x+1)^3} \le 9$

where $x = H/D = 1.25/0.512 = 2.44$;

$$N_{ch} = 6.752 + 0.065 \times 2.44 + \frac{-11.063}{(2.44+1)^2} + \frac{7.119}{(2.44+1)^3}$$

$= 6.15$

Horizontal bearing capacity factor for sandy soil

$$N_{qh} = a + bx + cx^2 + dx^3 + ex^4$$
$$= 4.565 + 1.234 \times 2.44 + (-0.089)2.44^2 + (4.275\times10^{-3})2.44^3 + (-0.916\times10^{-4})2.44^4$$

$= 7.10$

Maximum lateral resistance of soil per unit length of pipe

$$P_u = N_{ch} c D + N_{qh} \bar{\gamma} H D = 0 + 7.1 \times 16 \times 1.25 \times 0.512$$

$= 72.70\ \text{kN/m}$

3.2 Peak Strain Calculation

3.2.1 Operational Longitudinal Strain in the Pipeline

Longitudinal Stress due to *internal pressure* $S_p = \dfrac{PD\mu}{2t} = \dfrac{0.5\times 0.512\times 0.3}{2\times 0.006}$	= 6.4 MPa
Longitudinal Stress due to *temperature change* $S_t = E\alpha_t(T_2 - T_1)$ $= 2\times10^5 \times 12\times10^{-6}\times(30-10)$	= 48 MPa
Longitudinal Strain due to *internal pressure* $\varepsilon_p = \dfrac{S_p}{E}\left[1+\dfrac{n}{1+r}\left(\dfrac{S_p}{\sigma_y}\right)^r\right]$ n = **11.385**; r = **81. 16 ;** $\varepsilon_p = \dfrac{6.4}{2\times10^5}\left[1+\dfrac{11.385}{1+81.16}\left(\dfrac{6.4}{250}\right)^{81.16}\right]$	= 0.000032
Longitudinal Strain due to *temperature change* $\varepsilon_t = \dfrac{S_t}{E}\left[1+\dfrac{n}{1+r}\left(\dfrac{S_t}{\sigma_y}\right)^r\right]$ $= \dfrac{48}{2\times10^5}\left[1+\dfrac{11.385}{1+81.16}\left(\dfrac{48}{250}\right)^{81.16}\right]$	= 0.00024
Total Operational Longitudinal Strain in pipe $\varepsilon_{oper} = \varepsilon_p + \varepsilon_t$ = 0.000032 + 0.00024	**0.000272**

3.2.2 Effect of Permanent Ground Deformation (PGD)

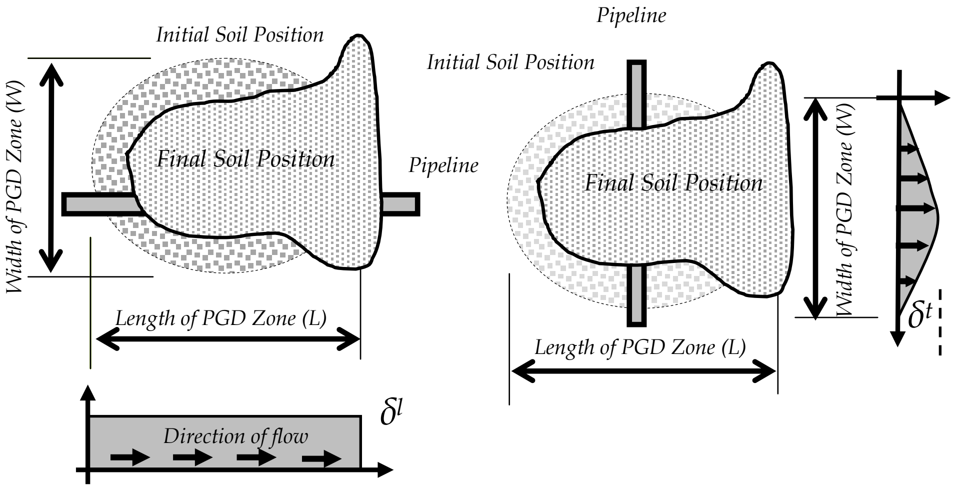


Figure 3.1.2: (a) Longitudinal PGD **(b)** Transverse PGD

Design Longitudinal PGD $\delta^l_{design} = \delta^l I_p = 2\times1.5$	= 3m
Design Longitudinal PGD $\delta^t_{design} = \delta^t I_p = 2\times1.5$	= 3m
(i) Longitudinal PGD	
Effective length L_e of the pipeline over which the friction force t_u acts is obtained from $$\delta^l_{design} = \frac{t_u L_e^2}{2\pi DtE}\left[1+\left(\frac{2}{2+r}\right)\left(\frac{n}{1+r}\right)\left(\frac{t_u L_e}{2\pi Dt\sigma_y}\right)^r\right]$$ t_u = **10.74** kN/m ; D = **0.512**m ; t= **0.006**m ; E= **200000** MPa; n =**11.385** ; r=**81.16;** δ^l_{design} **= 3**m Assume L_e = 100 m	L_e = 489.5m

<table>
<tr><td>

$$\delta^l_{design} = \frac{10.74\times10^3\times100^2}{2\pi\times0.512\times0.006\times2\times10^{11}}\left[1+\left(\frac{2}{2+81.16}\right)\left(\frac{11.385}{1+81.16}\right)\left(\frac{10.74\times10^3\times100}{2\pi\times0.512\times0.006\times250\times10^6}\right)^{81.16}\right]$$
$$= 0.0278$$

Assume L_e = 100 m ; δ^l_{design} = 0.0278 m < 3m , so increase L_e

when L_e = 500 m ; δ^l_{design} = 14.9 m > 3m , now decrease L_e , so that it is close to δ^l_{design}

L_e = 490 m ; δ^l_{design} = 3.31 m > 3m

L_e = 480 m ; δ^l_{design} = 1.17 m <3 m so 490 < L_e < 480 m

So, when L_e = 489 m ; δ^l_{design} = 2.89 m < 3m

L_e = 489.5 m ; δ^l_{design} = 3.09m ≈ δ^l_{design}

Hence **L_e = 489.5 m**
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Peak pipe strain (Tensile/Compressive)

$$\varepsilon_l = Max\left[\frac{t_u L}{2\pi DtE}\left\{1+\frac{n}{1+r}\left(\frac{t_u L}{2\pi Dt\sigma_y}\right)^r\right\};\frac{t_u L_e}{2\pi DtE}\left[1+\frac{n}{1+r}\left(\frac{t_u L_e}{2\pi Dt\sigma_y}\right)^r\right]\right],$$

t_u = **10.74** kN/m ; D = **0.512**m ; t= **0.006**m ; E= **200000** MPa; n =**11.385** ; r=**81.16;** L =**15** m; L_e = **489.5**m

$$\varepsilon_l = Max\begin{bmatrix}\frac{10.74\times10^3\times15}{2\pi\times0.512\times0.006\times2\times10^{11}}\left[1+\frac{11.385}{1+81.16}\left(\frac{10.74\times10^3\times15}{2\pi\times0.512\times0.006\times250\times10^6}\right)^{81.16}\right]\\ \frac{10.74\times10^3\times489.5}{2\pi\times0.512\times0.006\times2\times10^{11}}\left[1+\frac{11.385}{1+81.16}\left(\frac{16.06\times10^3\times489.5}{2\pi\times0.512\times0.006\times250\times10^6}\right)^{81.16}\right]\end{bmatrix}$$
</td><td>

ε_l =
Max[0.000417,
0.2075]

= 0.2075
</td></tr>
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<table>
<tr><td rowspan="2">Total strain in the pipe</td><td>Tensile $\varepsilon_{l-pgd} = \varepsilon_l + \varepsilon_{oper} = 0.2075 + 0.000272$</td><td>=0.207772</td></tr>
<tr><td>Compressive $\varepsilon_{l-pgd} = \varepsilon_l - \varepsilon_{oper} = 0.2075 - 0.000272$</td><td>=0.207228</td></tr>
<tr><td colspan="3">(ii) Transverse PGD</td></tr>
<tr><td colspan="2">Maximum normal strain due to bending of pipe is

$$\varepsilon_t = \pm Max\left[\frac{\pi D\delta^t_{design}}{W^2};\frac{P_u W^2}{3\pi EtD^2}\right] = \pm Max\left[\frac{\pi\times0.512\times3}{10^2};\frac{72.7\times10^3\times10^2}{3\pi\times2\times10^{11}\times0.006\times0.512^2}\right]$$
</td><td>=0.0482;0.0025

=0.0482</td></tr>
<tr><td rowspan="2">Total strain in the pipe</td><td>Tensile $\varepsilon_{t-pgd} = \varepsilon_t + \varepsilon_{oper}$ = 0.0482 + 0.000272</td><td>= 0.048472</td></tr>
<tr><td>Compressive $\varepsilon_{t-pgd} = \varepsilon_t - \varepsilon_{oper}$ = 0.0482 - 0.000272</td><td>= 0.047928</td></tr>
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3.2.3 Effect of Buoyancy due to Liquefaction

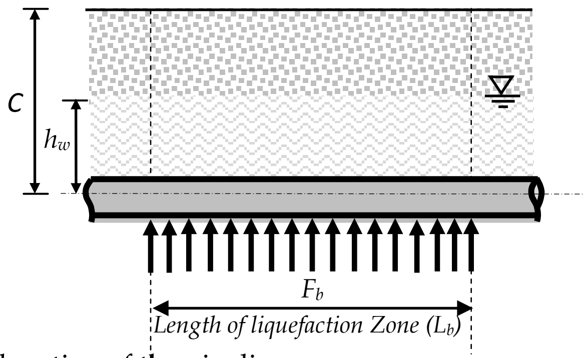

Figure 3.2.2: Longitudinal section of the pipeline

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(Net upward force per unit length of pipe

$$F_b = \frac{\pi D^2}{4}(\gamma_{sat} - \gamma_{content}) - \pi Dt\gamma_{pipe} + \left(h_w/3 - C\right)D\gamma_d$$
</td><td>= -12.76 kN/m</td></tr>
</table>

$=\frac{\pi\times0.512^2}{4}(18-10)-\pi\times0.512\times0.006\times78.6+\left(\frac{1}{3}-2\right)0.512\times16$		
Bending stress in pipe due to uplift force $\sigma_{bf}=\pm\frac{F_b L_b^{\,2}}{10Z}=\pm\frac{12.76\times10^3\times40^2}{10\times0.00119}$		= 429 MPa > 250 MPa **UNSAFE!!**
Bending strain in pipe due to bending stress $\varepsilon_a=\frac{\sigma_{bf}}{E}\left[1+\frac{n}{1+r}\left(\frac{\sigma_{bf}}{\sigma_y}\right)^r\right]$ $=\frac{429}{2\times10^5}\left[1+\frac{11.385}{1+81.16}\left(\frac{429}{250}\right)^{81.16}\right]$		$=3.2\times10^{15}$
Total strain in the pipe	Tensile $\varepsilon_{bf}=\varepsilon_a+\varepsilon_{oper}=3.2\times10^{15}+0.000272$	$=3.2\times10^{15}$
	Compressive $\varepsilon_{bf}=\varepsilon_a-\varepsilon_{oper}=3.2\times10^{15}-0.000272$	$=3.2\times10^{15}$

3.2.4 Effect of Fault Crossing

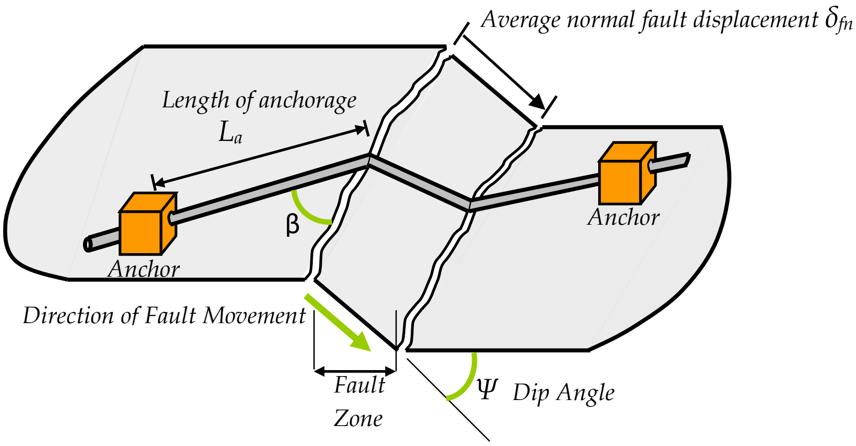
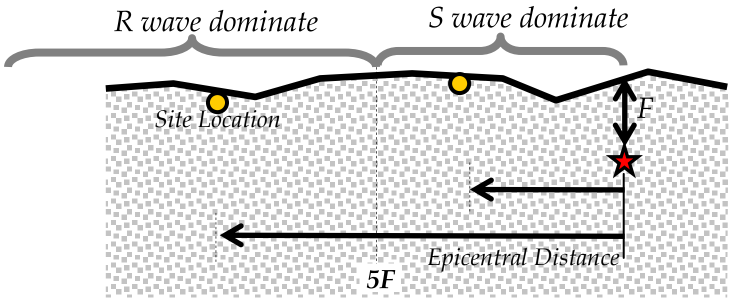


Figure 3.2.3: Pipeline crossing normal slip fault

Component of fault displacement of pipe	Axial direction $\delta_{fax}=\delta_{fn}\cos\psi\sin\beta$ $\delta_{fax}=2\times\cos15\sin45$	= 1.36m
	Transverse direction $\delta_{ftr}=\delta_{fn}\cos\psi\cos\beta$ $\delta_{ftr}=2\times\cos15\cos45$	= 1.36 m
Design fault displacement of pipe	Axial direction $\delta_{fax-design}=\delta_{fax}I_p=1.36\times2.3$	= 3.13 m
	Transverse direction $\delta_{ftr-design}=\delta_{ftr}I_p=1.36\times2.3$	= 3.13 m
Effective anchored length of pipe in fault zone $L_e=Min\left[\frac{E\varepsilon_y\pi Dt}{t_u};L_a\right]$ $L_e=Min\left[\frac{2\times10^{11}\times0.00125\times0.512\times0.006}{10.74\times10^3};50\right]$ t_u=**16.06** kN/m; E =**2×10^{11}** N/m^2; L_a=250m		= 71.5,50 m = 50 m
Average pipe strain due to fault movement in axial direction $\varepsilon_b=2\left[\left(\frac{\delta_{fax-design}}{2L_e}\right)+\frac{1}{2}\left(\frac{\delta_{ftr-design}}{2L_e}\right)^2\right]=2\left[\left(\frac{3.13}{2\times50}\right)+\frac{1}{2}\left(\frac{3.13}{2\times50}\right)^2\right]$		= 0.0636
Total Tensile strain in the pipe $\varepsilon_{fc}=\varepsilon_b+\varepsilon_{oper}=0.0636+0.000272$		= 0.0639

3.2.5 Effect of Seismic Wave Propagation



5F = 75 < 80 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 αε = 2.0 (for S-waves) = 1.0 (for R-waves)	= 2.0
Velocity of seismic wave propagation C = Cs for S-waves, (2.0 km/s) = Cr_ph for R-waves, (0.5 km/s)	= 2.0 km/s
Ground amplification factor I_g for soil classes	$\frac{PGA}{PGAr} = 1.0$

Class of Soil	PGA/ 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 $PGA = PGA_r I_g$	= 1g
Ratio of Peak Ground Velocity to Peak Ground Acceleration ρ	ρ = 174

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)*
	6.5	66	76	86
Rock	7.5	97	109	97
	8.5	127	140	152
	6.5	94	102	109
Stiff Soil	7.5	140	127	155
	8.5	180	188	193
	6.5	140	132	142
Soft Soil	7.5	208	165	201
	8.5	269	244	251

Peak Ground Velocity $PGV = \rho PGA$	= 1.74 m/s
Design peak ground velocity $V_g = I_p\, PGV$	= 2.55 m/s
Maximum axial strain in the pipe due to wave velocity $\varepsilon_{c\_wv} = \frac{V_g}{\alpha_\varepsilon C} = \frac{2.55}{1 \times 2 \times 1000}$	= 0.0013
Apparent wavelength of seismic waves at ground surface λ = 1.0 km (in the absence of detailed information)	
Maximum axial strain that can be transmitted by soil friction $\varepsilon_{c\_sf} = \frac{t_u \lambda}{4AE}$ $= \frac{10.74 \times 10^3 \times 1 \times 10^3}{4 \times 0.00953 \times 2 \times 10^{11}}$	= 0.00141
Total Tensile strain in pipe $\varepsilon_{swp} = Max[\varepsilon_{c\_wv}, \varepsilon_{c\_sf}] + \varepsilon_{oper}$ $= Max[0.0013, 0.00141] + 0.000272$	= 0.00168

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 $\varepsilon_{cr-c} = 0.175\frac{t}{R}$ *For wave propagation*: 50% to 100% of onset of wrinkling ($0.5\varepsilon_{cr-c}$ 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%	$\varepsilon_{c-pgd} = 0.88\frac{t}{R} = 0.88\frac{0.006}{0.512/2}$	= 0.0206
				$\varepsilon_{c-wave} = 0.75\left[0.5\frac{t}{D'} - 0.0025 + 3000\left(\frac{PD}{2Et}\right)^2\right]$ where $D' = \frac{D}{1-\frac{3}{D}\left(D-D_{min}\right)} = \frac{0.512}{1-\frac{3}{0.512}(0.512-0.50)}$ = 0.55m $\varepsilon_{c-wave} = 0.75\left[0.5\frac{0.006}{0.55} - 0.0025 + 3000\left(\frac{0.5\times0.512}{2\times2\times10^5\times0.006}\right)^2\right]$	= 0.00224

3.4 Check for Safety

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

Case		*Maximum strain in pipe*		*Allowable strain in pipe*		*Safe/Unsafe*
		Tension	*Compression*	*Tension*	*Compression*	
(1) PGD	*Longitudinal*	0.2078	0.2072	0.0375	0.0206	Unsafe
	Transverse	0.0485	0.0479	0.0375	0.0206	Safe
(2) Liquefaction		3.2×10[15]	3.2×10[15]	0.0375	0.0206	Unsafe
(3) Fault Crossing		0.0639	-	0.0375	0.0022	Unsafe
(4) Seismic Wave Propagation		0.0017	-	0.0375	0.0022	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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