1. INTRODUCTION

1.1 Introduction

Buried continuous pipelines gain their post-earthquake importance for being essential lifeline structures used for transporting basic amenities, such as water, oil and gas. Many of these pipelines run over long distances and across critical fault zones. Though steel as a material possesses enough ductility, steel pipelines can fail in a sudden manner owing to (1) faulting of ground under the pipeline, (2) unstable soil underneath it, or (3) buoyancy due to liquefied soil. These can incur significant damage to the pipeline. Hence, it is necessary to assess safety of existing buried pipelines that are built without regard to the above three aspects. Considering the above deficiencies, a procedure is described below for *Rapid Assessment* of *earthquake safety* of existing buried pipelines in India.

1.2 Assumptions

The following assumptions are made in the *Rapid Evaluation of Seismic Safety of Buried Continuous Pipelines.*

(1) Safety evaluation of only iron and steel pipeline is discussed.
(2) The top soil layer is assumed to be uniform
(3) The pipelines are continuous
(4) Safety check for vertical settlement are not provided

1.3 Philosophy of the Checks

This document covers safety evaluation methods for buried pipelines for various seismic hazards such as: wave propagation, fault crossing and permanent ground deformation due to liquefaction and lateral spreading. The strain induced in the pipeline by these hazards have been estimated and checked for safety against the allowable maximum strain for the given pipe material.

1.4 Classification of Pipelines

The pipelines are classified into four groups as per functional requirement as

Class I	Pipelines which would cause major impact in case of failure or damage
Class II	Pipelines which are vital but service of those can be interrupted for minor repairs
Class III	Low pressure oil and gas pipelines and Water supply pipelines for ordinary use
Class IV	Pipelines of very little importance and has less impact in the event of failure

1.5 Classification of Soil

The soil at the site in the top 30m is classified as given in Table 1.1 according to shear wave velocities. When sufficient detail of soil is unavailable to define site, soil shall be assumed to be of Class D.

Table 1.1: 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	$760 < V_s \leq 1500$	-
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	$V_s < 180$	$N < 15$

1.5.1 Soil Properties

(a) Axial soil resistance t_u

The maximum axial soil resistance t_u per unit length of the pipe is calculated as:

$$t_u = \pi D c \alpha + \pi D H \gamma \frac{-1+K_0}{2} \tan\delta' \qquad (1)$$

where
D = Outside diameter of the pipe,
c = Coefficient of cohesion of backfill soil,
H = Depth of soil above the centre of the pipeline,
$\bar{\gamma}$ = Effective unit weight of the soil,
$\alpha = \text{Adhesion factor} = 0.608 - 0.123c - \frac{0.274}{c^2+1} + \frac{0.695}{c^3+1}$ (c is in kPa/100),
ϕ= Internal friction angle of the soil,
f = Friction factor for various types of pipes; Table 1.2 may be used,
δ' = Interface angle of friction between pipe and soil = $f\phi$, and
K_o = Coefficient of soil pressure at rest = 1- sin ϕ; alternately, Table 1.3 may be used.
For deep buried pipelines with soil properties varying between the ground surface and the pipeline depth, the equation presented above do not hold good.

Table 1.2: Friction factor f for various types of pipes

Pipe coating	*f*
Concrete	1.0
Rough steel	0.8
Smooth Steel	0.7

Table 1.3: Values of lateral pressure coefficient K_o for *soil* at rest under different soil conditions

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

(b) Lateral soil resistance P_u

The maximum lateral resistance of soil per unit length of pipe can be calculated as:

$$P_u = N_{ch} cD + N_{qh} \overline{\gamma H D} \qquad (2)$$

where
N_{ch} = Horizontal bearing capacity factor for clay, 0 for c = 0 (Table 1.4)
$= a_1 + b_1 x + \frac{c_1}{(x+1)^2} + \frac{d_1}{(x+1)^3} \le 9,$, where $x = H/D$
N_{qh} = Horizontal bearing capacity factor for sandy soil $= a_1 + b_1 x + c_1 x^2 + d_1 x^3 + e_1 x^4$

Table 1.4: Lateral bearing capacity factor of soil

Factor	ϕ	*a*	*b*	*c*	*d*	*e*
N_{ch}	0°	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}

1.6 Classification of Seismic Hazards

The seismic hazards which are directly related to pipeline failure can be classified as:

(1) Permanent Ground Deformation (PGD) related to soil failures owing to:
   (a) Longitudinal PGD; and
   (b) Transverse PGD.
(2) Buoyancy due to liquefaction
(3) Permanent Ground Deformation related to faulting (Abrupt PGD)
(4) Seismic Wave Propagation

1.7 Design Seismic Hazard

The design level of seismic safety to be provided to a pipeline depends on the importance of the pipeline and the consequence of its failure. The importance can be accounted in two ways

(1) Design the pipeline for higher seismic hazard, which is corresponding to higher return period. Table 1.5 gives the design basis earthquake fro different types of pipes; and
(2) Design the pipeline for the hazards corresponding to design basis earthquake and multiplied by an importance factor I_p;

In this procedure presented, the second approach is adopted.

The design basis earthquake ground motion in terms of acceleration and ground deformation (faulting, transverse and longitudinal PGD etc.) corresponds to class III pipeline and is estimated based on site specific hazard analysis for an earthquake of 10% probability of exceedance in 50 years (return period of 475 years). This corresponds to Peak Ground Acceleration (PGA) on soil site class B. If not then PGA value has to be multiplied by ground amplification factor (I_g) as given in Table 1.6.

Table 1.5 Recommended design levels of seismic hazard

Pipe class	*Probability of exceedance in 50 years*	*Return period (years)*
I	2%	2475
II	5%	975
III	10%	475
IV	No seismic design consideration required	

Table 1.6: Ground amplification factor I_g for the soil classes

Class of Soil	*Peak Ground Acceleration Values at site (PGA) / Peak Ground Acceleration at base rock layer (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

The amount of ground motion amplification relative to bedrock depends on the soil conditions at the site. In general, the amplification is more in softer soils (with lower shear wave velocities, *i.e.*, soil class E) than stiffer soils. The *Design Seismic Hazard* for various classes of pipelines is calculated by multiplying importance factor I_p given in Table 1.7 with the *Design Basis Seismic Hazard*.

Table 1.7: Importance factor I_p for different classes of pipelines

Class of Pipeline	Importance Factor I_p			
	PGD	*Landslide*	*Faulting*	*Wave propagation*
I	1.50	2.60	2.30	1.50
II	1.35	1.60	1.50	1.25
III	1.00	1.00	1.00	1.00
IV	Seismic conditions need not be considered			

1.7.1. Permanent Ground Acceleration (PGA) as per Seismic Zones

When the site specific ground acceleration data are not available, the expected PGA at the base rock level can be approximated as given in Table 1.8 for different seismic zones defined in IS 1893-2002 (Part I).

Table 1.8: PGA as per Seismic Zones

Seismic Zone	II	III	IV	V
PGA_r	0.1g	0.16g	0.24g	0.36g

1.7.2. Determining Permanent Ground Velocity (PGV) from PGA

When only the peak ground acceleration is available, Table 1.9 is used to estimate Peak Ground Velocity (PGV) at that site. The relationship between PGV and PGA is less certain in soft soils.

Table 1.9: Ratio of Peak Ground Velocity to Peak Ground Acceleration ρ

Soil Type	*Moment Magnitude (M_w)*	*Ratio of PGV (cm/s) to PGA (g)*		
		Distance of Site from Source		
		0-20 (km)	*20-50 (km)*	*50-100 (km)*
Rock	6.5	66	76	86
	7.5	97	109	97
	8.5	127	140	152
Stiff Soil	6.5	94	102	109
	7.5	140	127	155
	8.5	180	188	193
Soft Soil	6.5	140	132	142
	7.5	208	165	201
	8.5	269	244	251

1.8 Strain Calculation

1.8.1. Operational Longitudinal Strain in the Pipeline

(a) Initial Stresses and Strain due to Internal Pressure in Pipeline

The longitudinal stress in pipe due to internal pressure may be calculated as:

$$S_p = \frac{PD\mu}{2t}, \tag{3}$$

where
P = Maximum internal operating pressure of the pipeline
D = Outside diameter of the pipe
μ = Poisson's ratio (generally taken as 0.3 for steel)
t = Nominal wall thickness of the pipe
The equation presented is the basic equation used for pipes subjected to internal pressure.

When the stress-strain relationship for the pipe material is not defined, it may be approximated by Ramberg-Osgood's relationship as:

$$\varepsilon_p = \frac{S_p}{E}\left[1 + \frac{n}{1+r}\left(\frac{S_p}{\sigma_y}\right)^r\right], \tag{4}$$

where
ε = Engineering strain,
σ = Stress in the pipe,
E = Initial Young's modulus,
σ_y = Yield stress of the pipe material, and
n,r = Ramberg-Osgood parameters (from Table 1.10). For 'n' and 'r' values of other pipes (Ramberg *et al*, 1943) may be referred.

Table 1.10: Ramberg-Osgood parameters for steel pipes

Grade of pipe	*Grade B*	*X 42*	*X 52*	*X 60*	*X 70*
σ_y (MPa)	227	310	358	413	517.0
n	10	15	9	10	5.5
r	100	32	10	12	16.6

(b) Initial Stresses and Strain due to Temperature Change in Pipeline

The longitudinal stress in pipe due to temperature change may be estimated by the following equation:

$$S_t = E\alpha_t(T_2 - T_1), \tag{5}$$

where
E = Modulus of elasticity,
α_t = Linear coefficient of thermal expansion of steel,
T_1 = Temperature in the pipe at the time of installation, and
T_2 = Temperature in the pipe at the time of operation.
The equation used is basic thermal equation for any material subjected to temperature variation.

Temperature strain can be found from Ramberg-Osgood's relationship given by Eq.(4). The stresses (or strains) obtained from the seismic analysis should be combined linearly with the stresses (or strains) in the pipeline during operation while making the safety checks.

1.8.2 Strain in the Pipeline due to Permanent Ground Deformation (PGD)

There are many patterns of PGD which depend on local site condition and geological settings. The pipeline may cross the PGD zone in any arbitrary direction. However, in this document the pipeline is checked for two critical situations, parallel crossing and perpendicular crossing as the pipelines are subjected to longitudinal PGD and transverse PGD.

(a) Longitudinal PGD

From the geotechnical investigations, the spatial extent, *i.e.,* length *L*, width *W* and maximum longitudinal ground displacement (δ^l) of PGD zone should be established. The design ground displacement in longitudinal direction may be taken as:

Design Longitudinal PGD $\delta^l_{design} = \delta^l I_p$ (6)

where
δ^l = Maximum longitudinal ground displacement, and
I_p = Importance factor (Table 1.3).

The pattern of longitudinal PGD may be of various types. For critical response, the block pattern, *i.e.,* the longitudinal ground movement being uniform through out the PGD zone

(Figure 1.1) of ground deformation is used and is applicable only when the pipeline is subjected to ground displacement parallel to its pipe axis.

Two types of inelastic models for buried pipelines subjected to a block pattern of longitudinal PGD are used, namely

Case I: The amount of ground movement (δ^l_{design}) is large and the pipe strain is controlled by the length *(L)* of the PGD zone.

Case-II: The length *(L)* of the PGD zone is large and the pipe strain is controlled by the amount of ground movement (δ^l_{design})

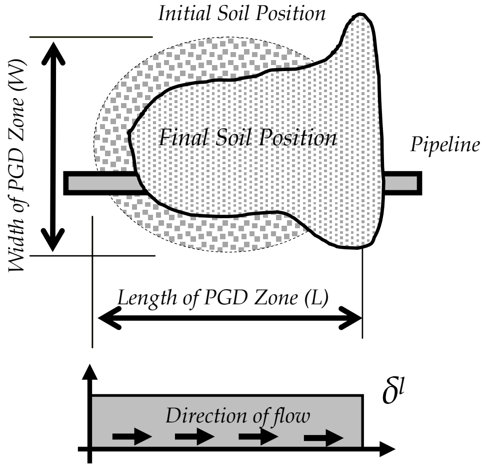


Figure 1.1: Block pattern of longitudinal ground deformation across the buried pipeline

(a) Case I :: Strain Controlled by Length of PGD region

The situation for Case-I is depicted in Figure 1.2. The friction force per unit length of pipe in the entire length of PGD zone (L) from point B to point D, acts to the right due to ground displacement δ^l. By symmetry and equilibrium, the friction force per unit length acts to the left, over a distance of L/2 before the head of the PGD zone (from point A to point B) and over a distance of L/2 beyond the toe of the PGD zone (from point D to point E). In the pipe, the maximum tensile strain occurs at point B and maximum compressive strain occurs at point D. As a result, the maximum stress (tensile or compressive) in the pipe is the stress induced due to friction force over a length of L/2. Hence, the maximum tensile/compressive stress in the pipe can be calculated as:

$$\sigma = \frac{t_u L}{2\pi D t}. \tag{7}$$

Ramberg-Osgood's stress-strain relationship give by Eq.(4) is used to find the maximum strain in the pipe from the maximum stress value. Hence, when δ^l_{design} is large the maximum axial strain in the pipe for both tension and compression is calculated as:

$$\varepsilon_a = \frac{t_u L}{2\pi D t E}\left[1 + \frac{n}{1+r}\left(\frac{t_u L}{2\pi D t \sigma_y}\right)^r\right] \tag{8}$$

where

L = Length of PGD zone,

σ_y = Yield stress of pipe material,

n,r = Ramberg-Osgood parameter (Table 1.10),

t_u = Peak friction force per unit length of pipe at soil pipe interface,

t = Thickness of pipe, and

D = Outside diameter of pipe.

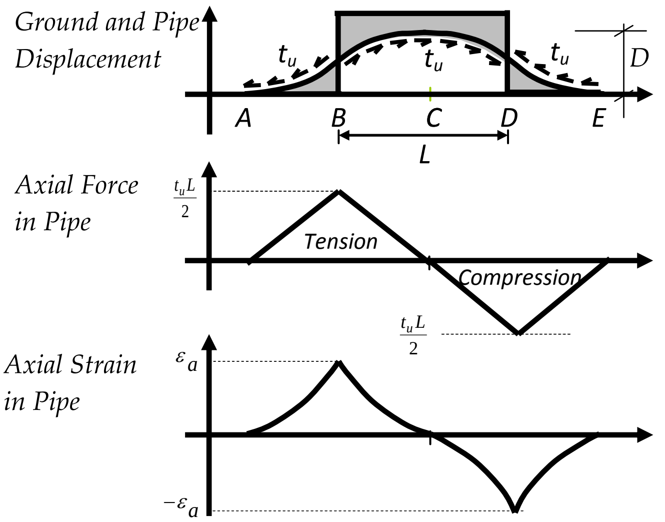


Figure 1.2: Case I: Inelastic model for longitudinal PGD

(b) Case II :: Strain Controlled by Amount of Ground Movement

The situation for Case II is depicted in Figure 1.3. Here, the friction force is acting over a length L_e on each side of the PGD zone (from point A to point B and from point E to pint F). The pipe displacement matches the ground displacement (δ^l) over a region of length $L\text{-}2L_e$ at the centre of the PGD zone. Hence in this case the maximum strain in pipe (tensile or compressive) is calculated as worked out in case-I except for the frictional force is considered to act over the length L_e instead of L/2. The axial strain generated in the pipe is obtained by:

$$\varepsilon_a = \frac{t_u L_e}{2\pi D t E}\left[1+\frac{n}{1+r}\left(\frac{t_u L_e}{2\pi D t \sigma_y}\right)^r\right] \tag{9}$$

From Figure 8.3, by symmetry, the pipe displacement at point B is $\delta^l/2$, where

$$\frac{\delta^l}{2} = \int_0^{L_e} \varepsilon_a(x)dx \tag{10}$$

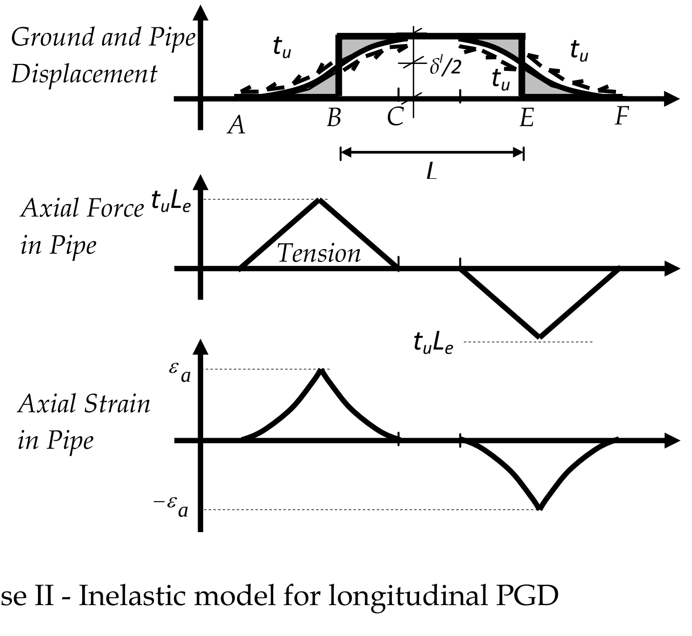


Figure 1.3: Case II - Inelastic model for longitudinal PGD

By using the peak strain of pipe in above equation, the effective length of the pipeline over which the frictional force acts *(L_e)* can be estimated as:

$$\delta^{l}_{design} = \frac{t_u L_e^{\,2}}{2\pi DtE}\left[1+\left(\frac{2}{2+r}\right)\left(\frac{n}{1+r}\right)\left(\frac{t_u L_e}{2\pi Dt\sigma_y}\right)^{r}\right] \tag{11}$$

The maximum of the pipe strain (ε_{l-pgd}) should be considered for safety check.

(c) Transverse PGD

The design ground displacement in longitudinal direction may be taken as:

Design Transverse PGD $\delta^{t}_{design} = \delta^{t} I_p$ (12)

where

δ^t = Maximum transverse ground displacement, and

I_p = Importance factor (Table 1.3).

When subjected to transverse ground deformation, a continuous pipe line will stretch and bend as it attempts to accommodate it. Like longitudinal ground displacement pattern of the transverse ground displacement can also be different types. A cosine function is assumed here to define the transverse permanent ground deformation profile as shown in Figure 8.4.

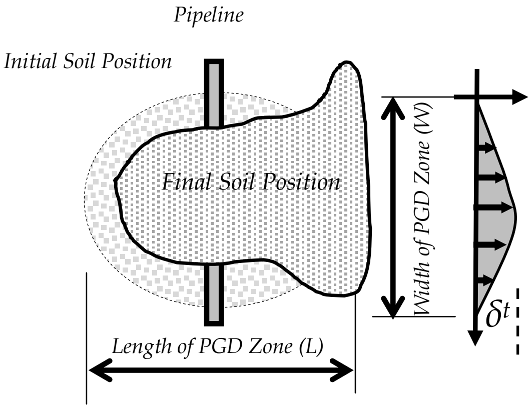


Figure 1.4: Block pattern of longitudinal ground deformation

The two conditions of PGD had been considered:

(a) Large width of permanent ground deformation zone and pipeline is assumed to be flexible, and
(b) Narrow width of permanent ground deformation zone and pipeline is assumed to be stiff.

The maximum bending strain in the pipe may be conservatively calculated as the greater of the following two expressions:

$$\varepsilon_b = \pm\frac{\pi D\delta^{t}_{design}}{W^2}, \tag{13}$$

where

D = Outside diameter of the pipe,

δ^{t}_{design} = Design transverse ground displacement,

W = Width of permanent ground deformation zone, and

t = Thickness of pipe; AND

$$\varepsilon_b = \pm\frac{P_u W^2}{3\pi EtD^2}, \tag{14}$$

where P_u is the maximum lateral resistance of soil per unit length of pipe.

1.8.3 Strain in Pipeline due to effect of Buoyancy due to Liquefaction

The net upward force per unit length of pipeline due to buoyancy may be calculated as:

$$F_b = \frac{\pi D^2}{4}\left(\gamma_{sat} - \gamma_{content}\right) - \pi D t \gamma_{pipe} + \left({h_w}\!\big/_{3} - C \right) D \gamma_d \,. \tag{15}$$

where

γ_{sat} = Saturated Unit Weight of the soil,
γ_d = Dry Unit Weight of the soil,
$\gamma_{content}$ = Unit Weight of content of the pipe,
γ_{pipe} = Unit Weight of pipe material,
C = Height of soil fill over pipeline, and
h_w = Height of water over pipeline (Figure 1.5)

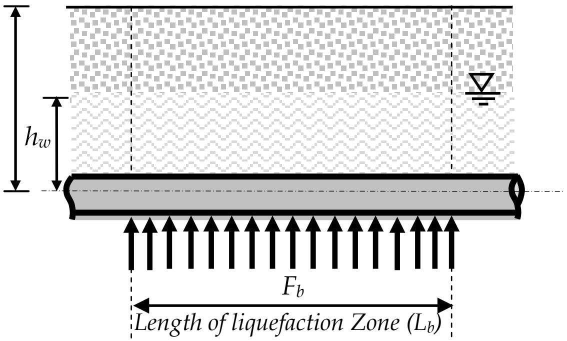


Figure 1.5: Longitudinal section of the pipeline showing the forces acting on it due to buoyancy

Bending stress induced for a relatively short section of continuous pipeline subjected to buoyancy can be calculated as:

$$\sigma_{bf} = \pm \frac{F_b L_b^{\;2}}{10Z}\,, \tag{16}$$

where

L_b = Length of pipe in buoyancy zone,
Z = Section modulus of pipe cross section, and
F_b = Buoyant force acting on pipe.

The maximum bending strain corresponding to above bending stress given by Eq.(8.14) can be obtained by using Ramberg-Osgood's stress-strain relationship given by Eq.(8.2).

1.8.4. Strain in Pipeline due to effect of Fault Crossing

A fault is a crack or zone of crack between two blocks of rock. Faults allow the blocks to move relative to each other. Faults may be classified according to the direction of motion as *normal slip, strike slip,* or *reverse slip* faults. The normal, strike and reverse slip faults are formed to due to tensile, shear and compressive stresses respectively. Often the normal or reverse fault occurs in combination with the strike slip fault. This kind of faulting is referred to as oblique fault, which is formed due to the combination of stresses action both vertically and horizontally. In general, the fault displacements are three-dimensional and it depends on the magnitude of strike-slip and normal or reverse-slip. For a normal slip fault (Figure 1.8.6), the fault movement along, transverse and vertical to the pipeline may be obtained as:

Component of fault displacement in the axial direction of pipeline:

$$\delta_{fax} = \delta_{fn} \cos\psi \sin\beta\,, \tag{17}$$

Component of fault displacement in the transverse direction of pipeline:

$$\delta_{ftr} = \delta_{fn} \cos\psi \cos\beta\,, \text{ and} \tag{18}$$

Component of fault displacement in the vertical direction of pipeline:

$$\delta_{fv} = \delta_{fn} \sin\psi \tag{19}$$

where
β = Angle of pipeline crossing a fault line (Figure 1.6), and
ψ = Dip angle of the fault (Figure 1.6).

The strike slip fault is particular case of normal fault in which the Dip angle ψ, is zero and the displacement corresponds to strike slip fault. In case of reverse faults, the displacement components are evaluated in the similar way as in normal-slip fault, but, with a negative slip. For oblique faults, the strike slip displacement and normal slip (or reverse slip) displacement may be added algebraically in axial, transverse and vertical direction of the pipeline axis. Design fault displacement (δ_{design}) is evaluated by multiplying the importance factor (I_p) with the expected fault displacement.

The expression for average strain in pipeline is based on the Newmark-Hall model (Figure 1.7). A factor of 2 in the Eq. (20) is used to counterbalance the unconservatism involved in this model. The average pipe strain due to fault crossing can be calculated as:

$$\varepsilon_b = 2\left[\left(\frac{\delta_{fax-design}}{2L_e}\right) + \frac{1}{2}\left(\frac{\delta_{ftr-design}}{2L_e}\right)^2\right] \tag{20}$$

where L_e is unanchored pipe length in the faulting zone which is taken as the least of,

(a) $L_a = \dfrac{E\varepsilon_y \pi D t}{t_u}$, where ε_y is the yield strain of the pipe material and E_i, Modulus of pipe material before yield.

(b) Length of pipeline from point of anchorage to fault line is taken as effective unanchored length.

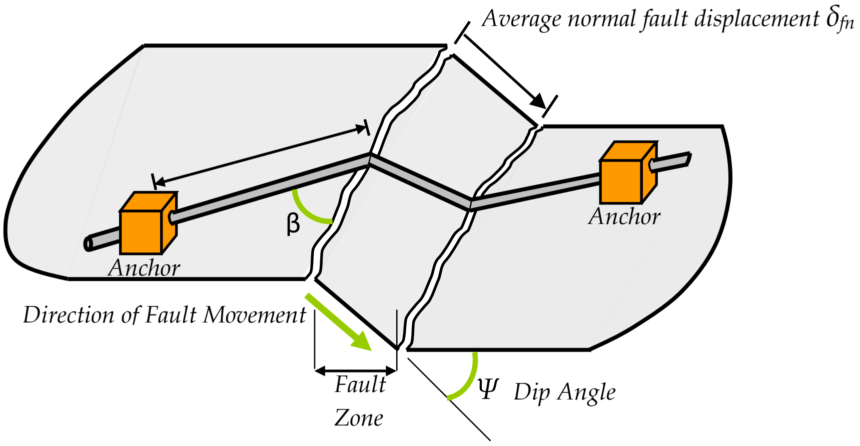
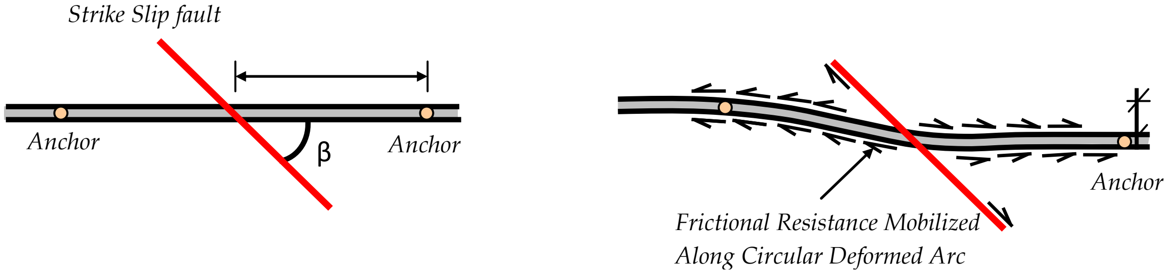


Figure 1.6: Pipeline crossing normal slip fault



(a) **(b)**

Figure 1.7: Newmark-Hall model for Fault crossing: (a) Before fault movement, and (b) After fault movement

The pipeline crossing fault line should be oriented in such a way to avoid compression in the pipeline. The ductility of pipeline should be increased in the zone of the fault-crossing to accommodate the fault movement without rupture. If longer length of pipeline is available to conform to fault movement, level of strain gets reduced. Hence, the points of anchorage should be provided away from the fault zone to the extent possible in order to lower the level of strain in the pipeline. In Indian subcontinent, the surface faulting is a relatively infrequent phenomenon. Most of the fault lines are deep below the ground level. Hence, more importance is given to the permanent ground deformation due to soil failures than surface faulting effects on pipeline.

1.8.5 Strain in the Pipeline due to the effect of Seismic Wave Propagation

The design seismic motion at a site is often characterized as the velocity of seismic wave propagation. The design wave propagation velocity is calculated as:

$$V_g = I_p \, PGV, \tag{21}$$

where
I_p = Importance factor (Table 1.3), and
PGV = Peak Ground Velocity (Table 1.5).

The response of pipeline due to wave propagation is generally described in terms of longitudinal axial strains in pipes. Flexural strains in pipes due to ground curvature are neglected since these are relatively small. In general, to evaluate the axial strain in pipe, it is assumed that the sites located closer to the Epicentral region, approximately within 5 times the focal depth are more affected by body waves (P and S waves, of which only S-waves are considered since they carry more energy and generate larger ground motion than P waves), whereas the sites at larger distance are more affected by surface waves (R and L waves, of which only R-waves are considered since they induce axial strain in the pipeline significantly higher than that of the bending strain induced by L-waves).

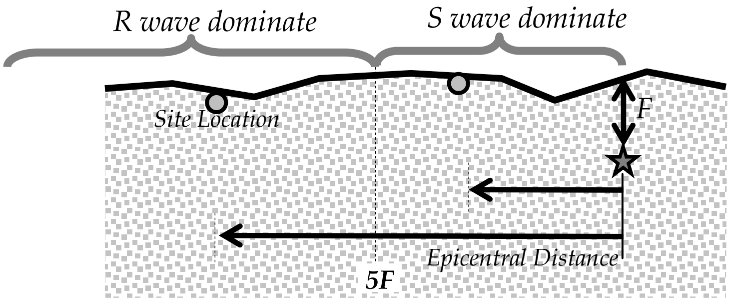


Figure 1.8: Considerations for S-waves and R-wave in pipeline design

The apparent wave propagation velocity is an important parameter in calculating the strain in pipe induced by seismic waves. The apparent wave propagation velocity of shear waves with respect to ground surface is many times higher than the shear wave velocity of the near surface material. The seismic energy originating at depth passes through increasing layers of softer materials and refraction causes a concave travel path. Hence, the net result being the body waves arriving at the ground surface with small incident angle θ with respect to vertical. Whereas in case the R-waves which travel parallel to the ground surface, the apparent propagation velocity is same as its phase velocity

The maximum longitudinal axial strain that can be induced in the pipeline due to wave propagation can be approximated as:

$$\varepsilon_{c\_wv} = \frac{V_g}{C_{apparent}} = \frac{V_g}{\alpha_{\varepsilon} C}, \tag{22}$$

where

V_g = Design Peak Ground Acceleration (given by Eq.(8.19)), and

$$C_{apparent} = \frac{C_s}{\sin\theta} \text{ (or) } C_{r\_ph}$$

in which C_s is wave propagation velocity of S-waves; θ is the angle of incidence of S-wave; and C_{r_ph} is the Phase velocity of R-wave

α_ε = Ground strain coefficient = 2.0 (for S-waves)
= 1.0 (for R-waves)

C =Velocity of seismic wave propagation = C_s for S-waves, (2.0 km/s)
= C_{r_ph} for R-waves, (0.5 km/s)

The ground strain coefficient α_ε depends on the angle of incidence and type of seismic waves. For S-waves, when there is an angle in the horizontal plane between pipe axis and the direction of apparent wave propagation, there exist a component of ground motion parallel to the pipe axis (Figure 1.9) Hence, the apparent propagation velocity in the direction of pipe axis is:

$$C_{s\_apparent} = \frac{C_s}{\sin\theta\cos\gamma}\,. \tag{23}$$

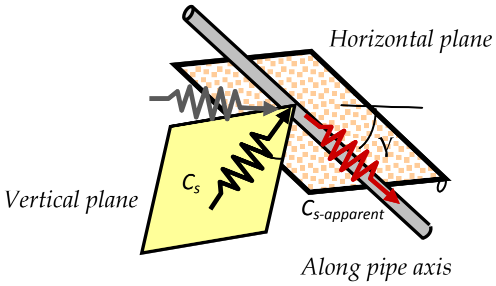


Figure 1.9: Schematic for apparent wave propagation velocity of S-wave along the pipe axis.

The ground strain is maximum for θ and γ = 45˚, *i.e.,*

$$C_{s\_apparent} = \frac{C_s}{\left(\frac{1}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)} = 2C_s$$

And hence α_ε is taken as 2 for S-waves. For R-waves, the phase velocity is considered parallel to the pipe axis, and hence the apparent propagation velocity along the pipeline axis becomes equal to its phase velocity.

Maximum strain induced in pipeline by friction at soil-pipe interface is:

$$\varepsilon_{c\_sf} = \frac{t_u\lambda}{4AE}\,, \tag{24}$$

where

t_u = Peak frictional force per unit length at soil-pipe interface given by Eq. (5.1),

λ = Apparent wavelength of seismic waves at ground surface defined as the product of apparent wave propagation velocity (V_s) and natural fundamental period of ground surface [Often taken as 1.0 km in the absence of detailed information], and

A = Cross sectional area of pipe.

1.9 Safety Checks

The maximum allowable strains in the buried continuous pipelines are specified in Table 1.11. The allowable strain given in Table 1.11 is only applicable to the pipes confirming to API standard (API, 1990). For other types of pipes, the allowable strain limit provided by the manufacturer may be used. But, API 5L Grade A and IS: 1978 YSt-210 are equivalent; API 5L Grade B and IS: 1978 YSt-240 are equivalent; and API 5L Grade X-42, X-46, X-52, X-60, X-65 and X-70 and IS: 1979 Grade YSt-290, 320, 360, 410, 450 and 480 are equivalent, respectively.

Table 1.11: 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 (0.5ε_{cr-c} to ε_{cr-c})
	Steel Pipe	3%	
Continuous water pipeline	Steel and Iron pipe	0.25 ε_u or 5%	$\varepsilon_{c-pgd} = 0.88\frac{t}{R}$
			$\varepsilon_{c-wave} = 0.75\left[0.5\frac{t}{D'} - 0.0025 + 3000\left(\frac{PD}{2Et}\right)^2\right]$ where $D' = \frac{D}{1 - \frac{3}{D}\left(D - D_{\min}\right)}$ D_{min} = Minimum inside diameter of pipe = outside diameter of pipe excluding out of roundness thickness

The design strain for continuous pipelines should be less than the allowable strain i.e.,

$$\varepsilon_{seismic} + \varepsilon_{oper} \le \varepsilon_{allowable} \tag{25}$$

where

$\varepsilon_{seismic}$ = Peak strain in pipe due to seismic hazard,

$\varepsilon_{allowable}$ = Allowable strain in pipe (Table 8.1), and

ε_{oper} = Operational strain in the pipeline which is equal $= \varepsilon_p + \varepsilon_t$; where ε_p *and* ε_t are strains in the pipe due to internal pressure and temperature respectively

References

IS:1978, (1998), *Specification for Line Pipe,* Bureau of Indian Standards, New Delhi

IS:1979, (1987), *Specification for High-Test Line Pipe,* Bureau of Indian Standards, New Delhi

IS:1893 (Part 1), (2002), *Criteria for Earthquake Resistant Design of Structures – Part 1: General Provisions and Buildings,* Bureau of Indian Standards, New Delhi

IITK-GSDMA, (2007), *IITK-GSDMA Guidelines for Seismic Design of Buried Pipelines*, National Information Centre of Earthquake Engineering *(NICEE),* Indian Institute of Technology Kanpur

Rapid Assessment of Seismic Safety of
Buried Continuous Pipelines

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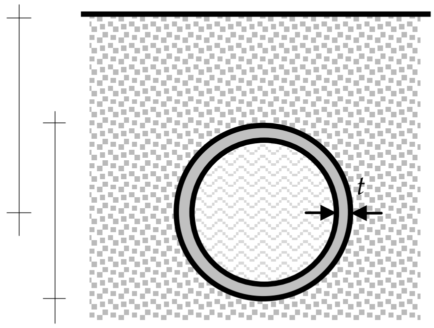
2. INPUTS

2.2 Basic Information

(1) Location : Srinagar Seismic Zone: Z =
(2) Type : Water/Oil/Gas
(3) Importance Factor I_p

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



Measurements	*Units*
H	= m
D	= m
D_{min}	= m
t	= m
Section modulus of pipe cross section $Z = \frac{\pi}{32} \frac{\left[D^4 - (D-2t)^4\right]}{D}$	= m^3
Cross sectional area $A = \frac{\pi}{4}\left(D^2 - (D-2t)^2\right)$	= m^2

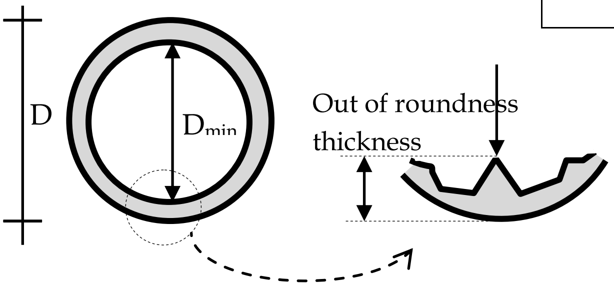


Figure 2.2.1: Cross-section of the pipeline

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* =
σ_y (MPa)	227	310	358	413	517.0	
n	10	15	9	10	5.5	*r* =
r	100	32	10	12	16.6	
Yield Stress of pipe material σ_y						= MPa
Yield Strain of the pipe material ε_y						=
Failure strain of the pipe in tension ε_u						=
Linear coefficient of thermal expansion of steel α_t						= /˚C
Poisson's ratio μ						=
Modulus of Elasticity E						= MPa
Unit weight of steel pipe γ_{pipe}						= kN/m³
Unit weight of the content $\gamma_{content}$						= kN/m³

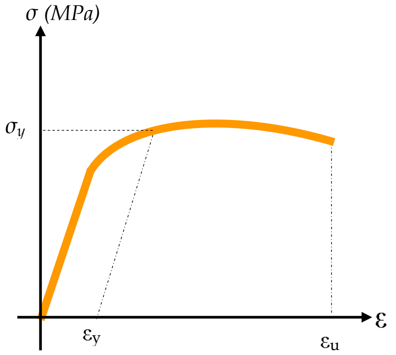


Figure 2.2.2: Ramberg-Osgood's **σ- ε** curve for steel

2.2.3 Soil Properties

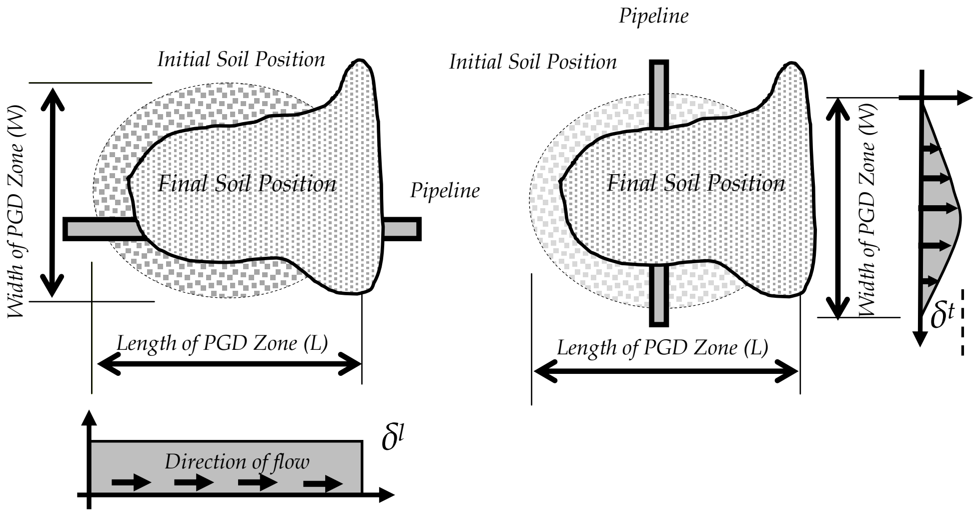
Velocity of shear wave V_s			=	m/s
Coefficient of cohesion of backfill soil *c, [c = 0 for sandy soil]*			=	kPa
Effective unit weight of the soil $\overline{\gamma}$			=	kN/m³
Saturated Unit weight of soil γ_{sat}			=	kN/m³
Dry Unit weight of soil γ_{sat}			=	kN/m³
Internal friction angle of the soil ϕ			=	
Friction factor for various types of pipes *f*	*Pipe coating*	*f*	*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*	=	MPa
Temperature in the pipe at the time of installation T_1	=	˚C
Temperature in the pipe at the time of operation T_2	=	˚C

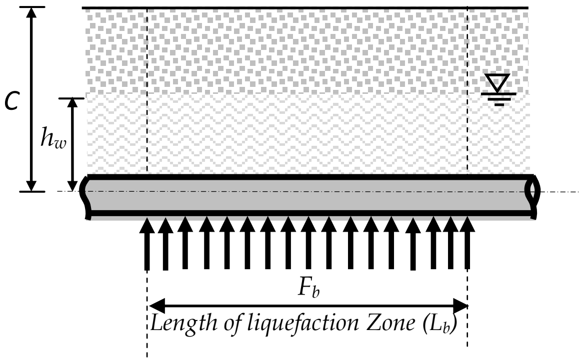
(b) For Permanent Ground Deformation (PGD)



Inputs	*(m)*
L	
W	
δ^l	
δ^t	

Figure 2.2.3: (a) Longitudinal PGD **(b)** Transverse PGD

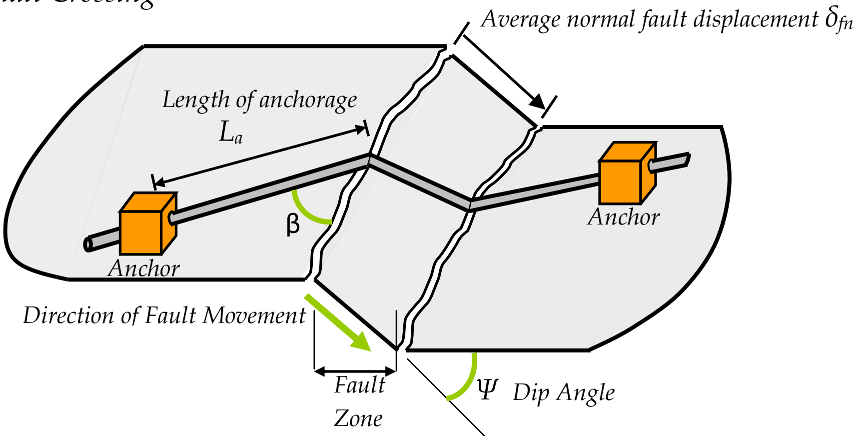
(c) For Liquefaction



Inputs	*(m)*
L_b	
h_w	
C	

Figure 2.2.4: Longitudinal section of the pipeline

(d) For Fault Crossing



Inputs	*Units*
δ_{fn}	m
Ψ	
β	
L_a	m

Figure 2.2.5: Pipeline crossing normal slip fault

(e) For Seismic Wave Propagation

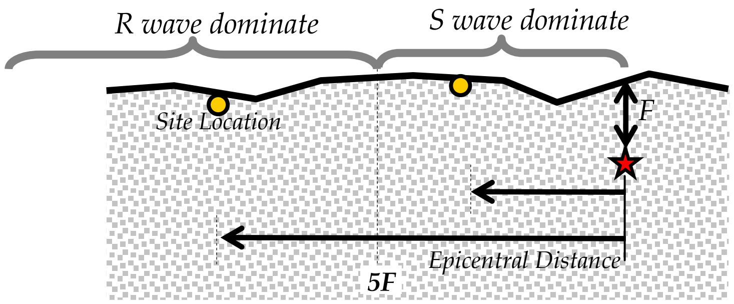


Figure 2.2.6: Considerations for S-waves and R-wave in pipeline design

Focal length F	=	km
Distance of site from earthquake source	=	km
Magnitude of design basis earthquake considered M_w	=	
Expected peak ground acceleration of the site at base rock layer PGA_r	PGA_r =	

Seismic Zone	II	III	IV	V	Site Specific
PGA_r	0.1g	0.16g	0.24g	0.36g	!!

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	$760 < V_s \leq 1500$	-
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

Soil Class:

Coefficient of soil pressure at rest

$K_o = 1 - \sin\phi$ (or)

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 =

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

=

Interface angle of friction between soil and pipe $\delta' = f\phi$

=

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

= kN/m

Factor	ϕ	a_1	b_1	c_1	d_1	e_1
N_{ch}	0	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	$\phi = 32^\circ$	
	N_{ch}	N_{qh}
a_1		
b_1		
c_1		
d_1		
e_1		

Horizontal bearing capacity factor for

clay $N_{ch} = a_1 + b_1 x + \frac{c_1}{(x+1)^2} + \frac{d_1}{(x+1)^3} \leq 9$

where $x = H/D$

=

Horizontal bearing capacity factor for sandy soil

$N_{qh} = a_1 + b_1 x + c_1 x^2 + d_1 x^3 + e_1 x^4$

=

Maximum lateral resistance of soil per unit length of pipe

$P_u = N_{ch} c D + N_{qh} \bar{\gamma} H D$

= kN/m

3.2 Peak Strain Calculation

3.2.1 Operational Longitudinal Strain in the Pipeline

Longitudinal Stress due to *internal pressure* $S_p = \dfrac{PD\mu}{2t}$	= MPa
Longitudinal Stress due to *temperature change* $S_t = E\alpha_t(T_2 - T_1)$	= MPa
Longitudinal Strain due to *internal pressure* $\varepsilon_p = \dfrac{S_p}{E}\left[1+\dfrac{n}{1+r}\left(\dfrac{S_p}{\sigma_y}\right)^r\right]$	=
Longitudinal Strain due to *temperature change* $\varepsilon_t = \dfrac{S_t}{E}\left[1+\dfrac{n}{1+r}\left(\dfrac{S_t}{\sigma_y}\right)^r\right]$	=
Total Operational Longitudinal Strain in pipe $\varepsilon_{oper} = \varepsilon_p + \varepsilon_t$	=

3.2.2 Effect of Permanent Ground Deformation (PGD)

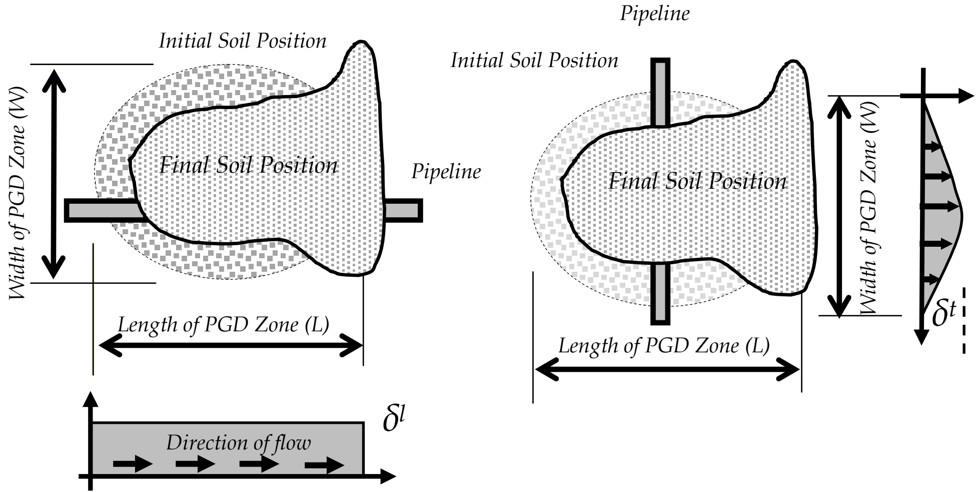


Figure 3.1.2: (a) Longitudinal PGD **(b)** Transverse PGD

Design Longitudinal PGD $\delta^l_{design} = \delta^l I_p$		= m
Design Longitudinal PGD $\delta^t_{design} = \delta^t I_p$		= m
(i) Longitudinal PGD		
Effective length L_e of the pipeline over which the friction force t_u acts is obtained from, $\delta^l_{design} = \dfrac{t_u L_e^2}{2\pi DtE}\left[1+\left(\dfrac{2}{2+r}\right)\left(\dfrac{n}{1+r}\right)\left(\dfrac{t_u L_e}{2\pi Dt\sigma_y}\right)^r\right]$		= m
Peak pipe strain (Tensile/Compressive) $\varepsilon_l = Max\left[\dfrac{t_u L}{2\pi DtE}\left\{1+\dfrac{n}{1+r}\left(\dfrac{t_u L}{2\pi Dt\sigma_y}\right)^r\right\};\dfrac{t_u L_e}{2\pi DtE}\left[1+\dfrac{n}{1+r}\left(\dfrac{t_u L_e}{2\pi Dt\sigma_y}\right)^r\right]\right]$		=
Total strain in the pipe	Tensile $\varepsilon_{l-pgd} = \varepsilon_l + \varepsilon_{oper}$	=
	Compressive $\varepsilon_{l-pgd} = \varepsilon_l - \varepsilon_{oper}$	=
(ii) Transverse PGD		
Maximum normal strain due to bending of pipe is $\varepsilon_t = \pm Max\left[\dfrac{\pi D\delta^t_{design}}{W^2};\dfrac{P_u W^2}{3\pi EtD^2}\right]$		=
Total strain in the pipe	Tensile $\varepsilon_{t-pgd} = \varepsilon_t + \varepsilon_{oper}$	=
	Compressive $\varepsilon_{t-pgd} = \varepsilon_t - \varepsilon_{oper}$	=

3.2.3 Effect of Buoyancy due to Liquefaction

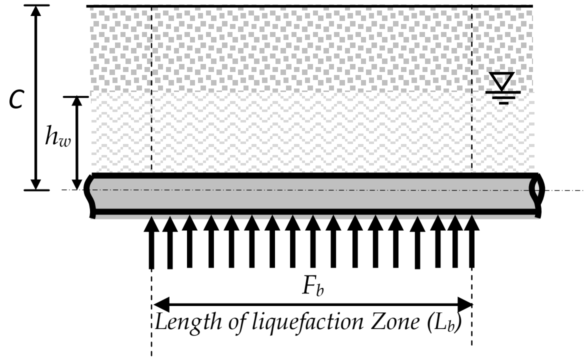


Figure 3.2.2: Longitudinal section of the pipeline

(Net upward force per unit length of pipe $F_b = \frac{\pi D^2}{4}\left(\gamma_{sat} - \gamma_{content}\right) - \pi D t \gamma_{pipe} + \left({h_w}/{3} - C \right) D \gamma_d$		= N/m
Bending stress in pipe due to uplift force $\sigma_{bf} = \pm \frac{F_b L_b^2}{10Z}$		= MPa
Bending strain in pipe due to bending stress $\varepsilon_a = \frac{\sigma_{bf}}{E}\left[1 + \frac{n}{1+r}\left(\frac{\sigma_{bf}}{\sigma_y}\right)^r\right]$		=
Total strain in the pipe	Tensile $\varepsilon_{bf} = \varepsilon_a + \varepsilon_{oper}$	=
	Compressive $\varepsilon_{bf} = \varepsilon_a - \varepsilon_{oper}$	=

3.2.4 Effect of Fault Crossing

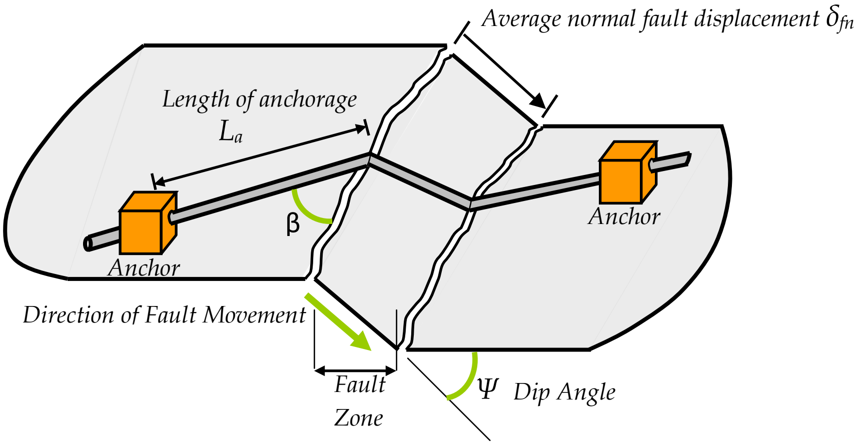
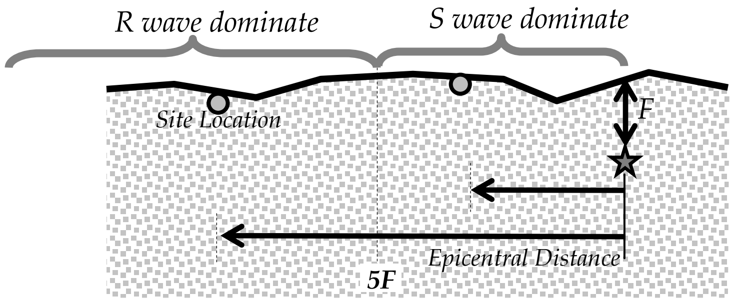


Figure 3.2.3: Pipeline crossing normal slip fault

Component of fault displacement of pipe	Axial direction $\delta_{fax} = \delta_{fn} \cos\psi \sin\beta$	=	m
	Transverse direction $\delta_{ftr} = \delta_{fn} \cos\psi \cos\beta$	=	m
Design fault displacement of pipe	Axial direction $\delta_{fax-design} = \delta_{fax} I_p$	=	m
	Transverse direction $\delta_{ftr-design} = \delta_{ftr} I_p$	=	m
Effective anchored length of pipe in fault zone $L_e = Min\left[\frac{E\varepsilon_y \pi D t}{t_u}; L_a\right]$		=	m
Average pipe strain due to fault movement in axial direction $\varepsilon_b = 2\left[\left(\frac{\delta_{fax-design}}{2L_e}\right) + \frac{1}{2}\left(\frac{\delta_{ftr-design}}{2L_e}\right)^2\right]$		=	
Total Tensile strain in the pipe $\varepsilon_{fc} = \varepsilon_b + \varepsilon_{oper}$		=	

3.2.5 Effect of Seismic Wave Propagation



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

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$_g$*	=
Ratio of Peak Ground Velocity to Peak Ground Acceleration ρ	ρ =

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

Peak Ground Velocity $PGV = \rho PGA$	= m/s
Design peak ground velocity $V_g = I_p\ PGV$	= m/s
Maximum axial strain in the pipe due to wave velocity $\varepsilon_{c\_wv} = \frac{V_g}{\alpha_\varepsilon C}$	=
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 $\varepsilon_{c\_sf} = \frac{t_u \lambda}{4AE}$	=
Total Tensile strain in pipe $\varepsilon_{swp} = Max[\varepsilon_{c\_wv}, \varepsilon_{c\_sf}] + \varepsilon_{oper}$	=

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 $\varepsilon_{cr-c} = 0.175\frac{t}{R}$	=
	Steel Pipe	3%	=	*For wave propagation*: 50% to 100% of onset of wrinkling ($0.5\varepsilon_{cr-c}$ to ε_{cr-c})	=
Continuous water pipeline	Steel and Iron pipe	$0.25\ \varepsilon_u$ or 5%	=	$\varepsilon_{c-pgd} = 0.88\frac{t}{R}$	=
				$\varepsilon_{c-wave} = 0.75\left[0.5\frac{t}{D'} - 0.0025 + 3000\left(\frac{PD}{2Et}\right)^2\right]$ where $D' = \frac{D}{1 - \frac{3}{D}\left(D - D_{\min}\right)}$	=

3.4 Check for Safety

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

Case		*Maximum strain in pipe*		*Allowable strain in pipe*		*Safe/Unsafe*
		Tension	*Compression*	*Tension*	*Compression*	
(1) PGD	*Longitudinal*					
	Transverse					
(2) Liquefaction						
(3) Fault Crossing						
(4) Seismic Wave Propagation						

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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