Appendix B

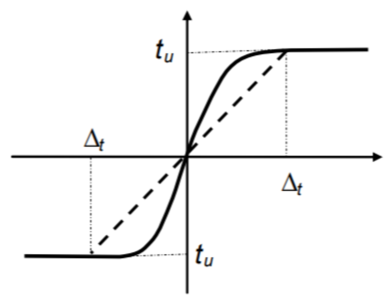
Soil Spring / PGD Procedure

Appendix B – Soil Spring Calculations

B.1.1 Axial Soil Spring

The axial soil spring represents soil resistance over the pipe surface along its length. The properties of axial soil springs are estimated considering the soil properties of the backfill material used in the trench if known, or the predominant soil type based on boring logs.

Figure B1: Soil Springs used to Represent Axial Force on Pipe and Bi-linear Idealization



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

$$t_u = \pi D c \alpha + \pi D H \bar{\gamma} \left(\frac{1 + K_O}{2} \right) tan\delta$$

Where:

D = Outside diameter of pipe

c = Coefficient of cohesion of backfill soil

H = Depth of soil above the center of the pipeline

$\bar{\gamma}$ = Effective unit weight of soil

α = Adhesion factor

δ = Interface angle of friction between pipe and soil. δ= f φ (See Table B1)

φ = Internal friction angle of the soil

f = Friction factor for various types of pipes

K_o = Coefficient of soil pressure at rest. K_o= 1-sin(φ)

Table B1: Friction Factor for Various Types of Pipes

Pipe Coating	*f*
Concrete	1.0
Coal Tar	0.9
Rough Steel	0.8
Smooth Steel	0.7
Fusion Bonded Epoxy	0.6
Polyethylene	0.6

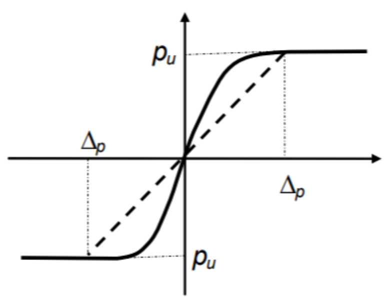
The maximum soil force along the pipe axial direction is t_u and the critical relative displacement reaching t_u is Δ_t. The maximum mobilizing displacement of soil (Δ_t) in axial direction of pipe can be taken as:

- 0.1 in for dense sand
- 0.2 in for loose sand
- 0.3 in for stiff clay
- 0.4 in for soft clay

B.1.2 Lateral Soil Spring

The lateral spring represents the lateral resistance of soil to the pipe movement. The properties of axial soil springs are estimated considering the soil properties of the native soil at the site.

Figure B2: Soil Springs used to Represent Lateral Force on Pipe and Bi-linear Idealization



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

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

Where:

N_{ch} = Horizontal bearing capacity factor for clay, (0 for c = 0)

N_{qh} = Horizontal bearing capacity factor for sandy soil, (0 for φ = 0)

The equations below are closed form fits to published empirical relations:

$$N_{ch} = a + bx + \frac{c}{(x+1)^2} + \frac{d}{(x+1)^3} \leq 9$$

$$N_{qh} = a + bx + cx^2 + dx^3 + ex^4$$

Where $x = H/D$

Table B2: Lateral Soil Spring Coefficients

Factor	ϕ	*x*	*a*	*b*	*c*	*d*	*e*
N_{ch}	0°	*H/D*	6.752	0.065	-11.063	7.119	--
N_{qh}	20°	*H/D*	2.399	0.439	-0.03	$1.059(10)^{-3}$	$-1.754(10)^{-5}$
N_{qh}	25°	*H/D*	3.332	0.839	-0.090	$5.606(10)^{-3}$	$-1.319(10)^{-4}$
N_{qh}	30°	*H/D*	4.565	1.234	-0.089	$4.275(10)^{-3}$	$-9.159(10)^{-5}$
N_{qh}	35°	*H/D*	6.816	2.019	-0.146	$7.651(10)^{-3}$	$-1.683(10)^{-4}$
N_{qh}	40°	*H/D*	10.959	1.783	0.045	$-5.425(10)^{-3}$	$-1.153(10)^{-4}$
N_{qh}	45°	*H/D*	17.658	3.309	0.048	$-6.443(10)^{-3}$	$-1.299(10)^{-4}$

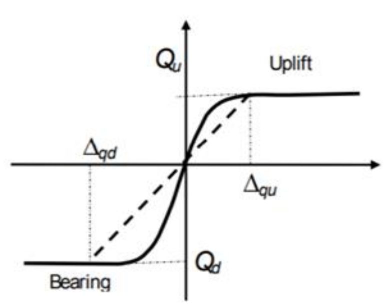
For the lateral direction to the pipe in the horizontal plane, the maximum soil force is p_u and the critical relative displacement is Δ_p. The mobilizing displacement Δ_p at p_u is taken as:

$$\Delta_p = 0.04\left(H + \frac{D}{2}\right) \leq 0.01D \ to \ 0.02D$$

B.1.3 Vertical Soil Springs

The soil spring properties are different for uplift and vertical cases. The vertical bearing spring represents the vertical resistance of soil at the bottom of the pipe while the vertical uplift spring represents the resistance at the top of the pipe. For bearing soil spring, the properties of native soil at the site may be used. However, for uplift soil spring, the properties of backfill soil are to be considered.

Figure B3: Soil springs used to represent vertical force on pipe and bi-linear idealization



For the lateral direction in the vertical plane, the soil forces are Q_u and Q_d to resist the uplifting and downward movement of the pipe respectively. The critical relative displacements are Δ_{qu} and Δ_{qd} respectively.

B.1.4 Vertical Uplift:

The maximum soil resistance per unit length of pipe can be calculate as follows:

$$Q_u = N_{cv} cD + N_{qv} \bar{\gamma} HD$$

Where:

N_{cv} = Vertical uplift factor for clay (0 for c = 0),

N_{qv}= Vertical uplift factor for sand (0 for φ = 0)

$$N_{cv} = 2\left(\frac{H}{D}\right) \leq 10 \text{ , applicable for } \frac{H}{D} \leq 10$$

$$N_{qv} = \left(\frac{\phi H}{44D}\right) \leq N_q$$

The mobilizing displacement Δ_{qu} at Q_u can be taken as:

- 0.01H to 0.02H for dense to loose sands < 0.1D, and
- 0.1H to 0.2H for stiff to soft clay < 0.2D.

B.1.5 Vertical Bearing

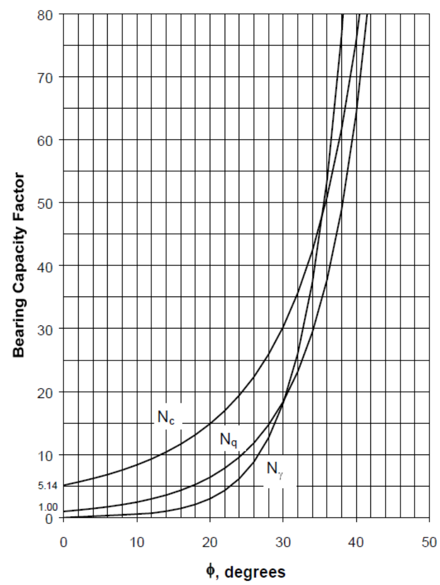
The maximum soil resistance per unit length of pipe can be calculate as follows:

$$Q_d = N_c cD + N_q \bar{\gamma} HD + N_\gamma \gamma \frac{D^2}{2}$$

Where

N_c, N_q and N_γ are bearing capacity factors from the figure below:

Figure B4: Bearing Capacity Factors



The mobilizing soil displacement Δ_{qd} at Q_d can be taken as:

- 0.1D for granular soils, and
- 0.2D for cohesive soils.

B.2.1 Longitudinal Ground Displacement

Two cases of models are used for buried pipelines as suggested by O'Rourke et al. (1995):

Case I: The amount of ground deformation is large enough and the pipe strain is controlled by the length (L) or width (W) of the permanent ground displacement (PGD) zone.

Case II: The length (L) or width (W) of the PGD zone is large and the pipe strain is controlled by the amount of ground displacement δ.

When assessing the geotechnical stability of a slope it is difficult to come up with the amount of displacement in the failing soil mass whereas determining the spatial extent of permanent deformation can be more straightforward. The methodology presented below is based on the assumption that Case 1 is more relevant to slope failure of the banks studied by the WCP.

The maximum axial strain in the pipe for both tension and compression can be calculated as:

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

The first term inside the bracket accounts for elastic strain (prior to yield). The second term in the bracket accounts for elastic strain (after yielding). To remain within operating codes, the pipe should not experience yielding.

Where:

L = Length of permanent ground deformation zone

σ_y = Yield stress of pipe material

n,r = Ramberg-Osgood parameter

Table B3: Ramberg-Osgood Parameters

Pipe Grade	Yield Stress (psi)	n	r
Grade B	35,000	10	100
X-42	42,000	15	32
X-52	52,000	9	10
X-60	60,000	10	12
X-70	70,000	5.5	16.6

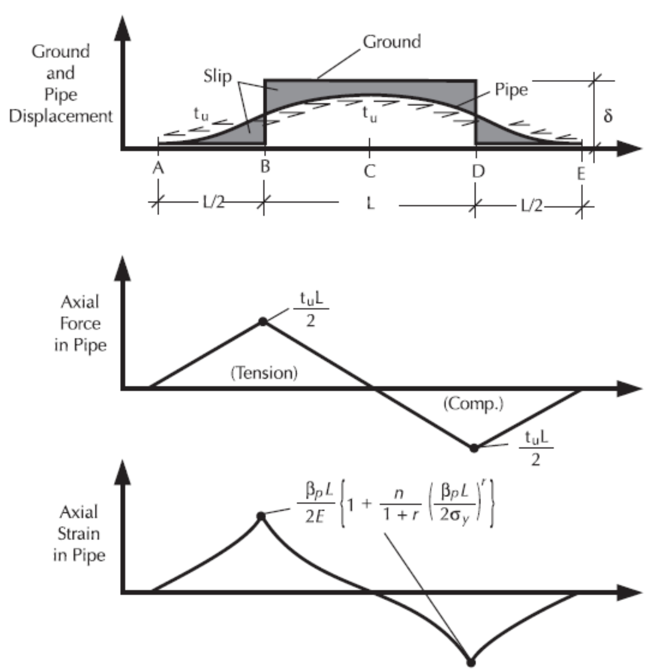
E = Modulus of elasticity of pipe material

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

D = Outside diameter of pipe

t = Wall thickness of pipe

Figure B5: Distribution of Pipe Axial Displacement, Case I (O'Rourke 1995)



B.2.2 Transverse Ground Displacement

When subjected to transverse ground displacement a pipeline will stretch and bend as it attempts to accommodate it. The analytical expression used is based on O'Rourke's simplified model of pipeline response to transverse permanent ground deformation with the conditions that a) the zone of ground deformation is relatively narrow and b) the pipe is assumed stiff.

The maximum bending strain in the pipe may be calculated as:

$$\varepsilon_b = \pm \frac{P_u W^2}{3\pi E t D^2}$$

Where:

P_u = Maximum lateral resistance of soil per unit length of pipe

W = Width of permanent ground deformation zone

E = Modulus of elasticity of pipe material

t = Wall thickness of pipe

D = Outside diameter of pipe design

B.3 Automated Excel Work Book Calculations

An Excel Workbook template has been created to perform the calculations of longitudinal and transverse PGD induced stresses on a pipeline. A Water Crossing Engineer (WCE) uses the workbook to evaluate the threat of a pipeline rupture due to slope instability. The PGD and soil profile can be determined using the SLOPE/W analysis model schematics. If a SLOPE/W model isn't available, soil strength parameters must be conservatively assumed or derived from subsurface investigation data. Soil strength parameters should represent the soil layer surrounding the pipe. Pipe properties including diameter, wall thickness, coating, and operation pressure are required as input. An average depth of cover (DOC) should be estimated based on its survey. Data necessary for the calculations are shown in Table B4.

Table B4: Work Book Input Data

Pipe Properties	Soil Properties
Pipe OD (in)	Soil Friction Angle (φ degrees)
Pipe Wall Thickness (in)	Soil Cohesion (c, psf)
Pipe Specified Minimum Yield Strength (SMYS, psi)	Soil Effective Unit Weight (γ', psf)
Pipe DOC (ft)	PGD Path (perpendicular/parallel to pipe)
Length of Pipe in PGD (ft)	
Pipe Coating	
Internal Pressure (psi)	

Once the required data is entered into the proper cells on the Excel sheet, the following are calculated to determine the values of the variables needed for the pipe bending stress calculation. Calculations are based on the equations presented in this document.

- Axial soil force on pipeline
- Lateral soil force on pipeline
- Vertical bearing soil force on pipeline
- Vertical uplift soil force on pipeline

Results of the force calculations are used to determine transverse and longitudinal strain and stress on the pipeline. The stress values are compared to allowable stress and noted as PASS or FAIL for transverse and longitudinal PGDs. The subject mater expert interprets the results and decides whether the pipeline is likely to rupture.

An example calculation performed in the Excel Workbook template is provided on the following pages.

Pipe Properties	
Pipe OD (in):	12.50
Pipe wt (in):	0.375
Pipe SMYS (psi):	X-52
Pipe DOC (ft):	6.56
Length of Pipe in PGD (ft):	473.0
Pipe Coating	Rough Steel
Internal Pressure (psi):	573

Soil Properties	
Soil Friction Angle (ϕ degrees):	27.0
Soil Cohesion (c, psf):	104.5
Soil Effective Unit Weight (γ', psf):	135.0
PGD Path (perpendicular/parallel to pipe):	Parallel

Color	Name	Unit Weight (kN/m³)	Cohesion' (kPa)
	Clay with Sand	19	5
	Sandy Clay Till	21	10
	Shale Bedrock	25	10
	Upper Fill	20	0

Conversions		
Cohesion: kpa		psf
	5	104.45
Unit weight: kn/m2		psf
	19	122.03917

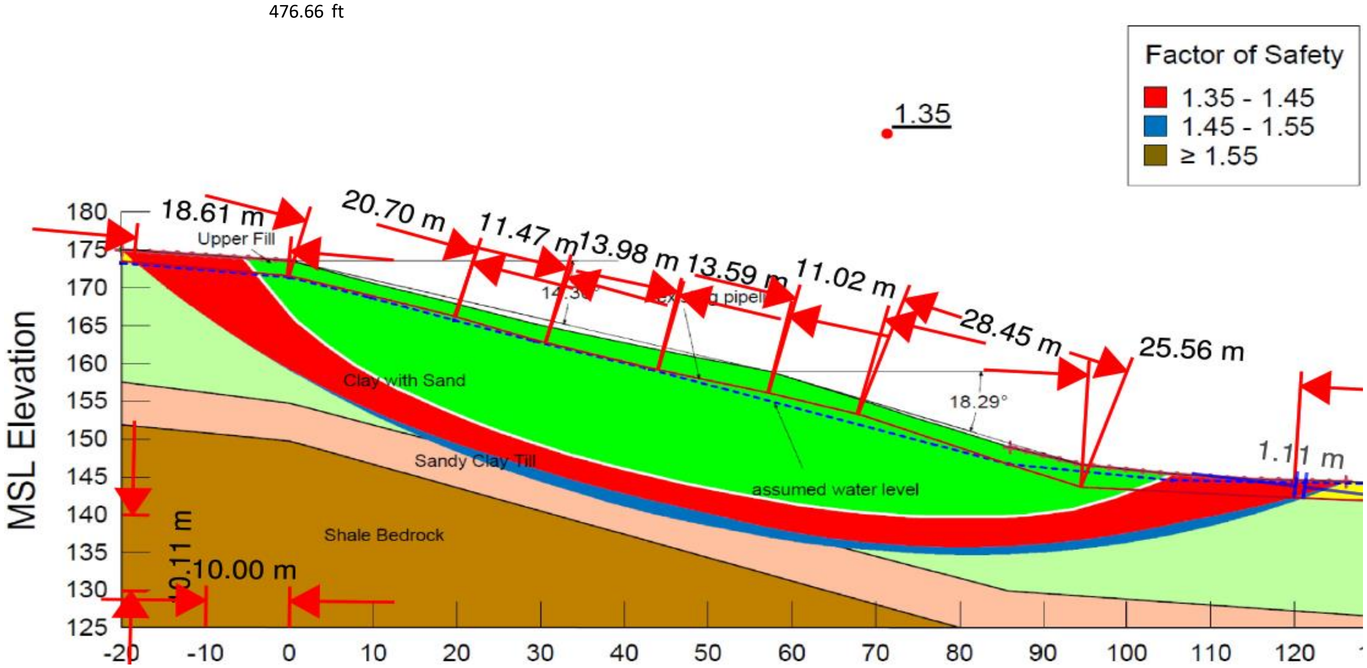
Upper Fill	
Soil Friction Angle (ϕ degrees):	30
Soil Cohesion (c, psf):	0
Soil Effective Unit Weight (γ', psf):	
Allowable length (ft)	

Color	Name	Unit Weight (kN/m³)	Cohesion' (kPa)
	Clay with Sand	19	5
	Sandy Clay Till	21	10
	Shale Bedrock	25	10
	Upper Fill	20	0

Summary Output	
Longitudinal Force (lb/ft)	1,307.5
Axial Stress (psi)	20,986.5
Remaining Allowable Stress (psi)	23,307.5
Allowable Pipe Length in PGD (ft):	525.3
Exceeds Allowable:	Does Not Exceed

Clay with Sand	
Soil Friction Angle (ϕ degrees):	27
Soil Cohesion (c, psf):	104.45
Soil Effective Unit Weight (γ', psf):	
Allowable length (ft)	

Pipeline Length: FOS 1.35-1.45		Red
	143.38	m
	144.1707767	m (measurement cor
	473.0012359	ft
Pipeline Length: FOS 1.35-1.55		Red + Blue
	144.49	m
	145.29	m (measurement correction)
	476.66	ft



Axial Forces

Pipe outside diameter	OD	12.5	inches
Pipe Coating Dependent Factor (f)	Rough Steel	0.8	
Depth of cover	DOC	6.56	ft
Depth to pipe centerline	H	7.08	
Soil cohesion	c	104.5	psf
Internal friction angle for soil	ϕ	27.0	degrees
Effective unit weight of soil	γ	135.0	lb/ft3
Coefficient of pressure at rest	K_o	0.546	
Adhesion factor	α	1.02	
Interface angle for pipe-soil	δ	21.6	degrees
Tan of interface angle	tanδ	0.396	
Axial soil force	Tu	1307.5	lbs/ft
		1.31	kips/ft

Coating dependent factor

Concrete	*1*
Coal Tar	*0.9*
Rough Steel	*0.8*
Smooth steel	*0.7*
Fusion Bonded Epoxy	*0.6*
Polyethylene	*0.6*

Lateral Forces

Pipe outside diameter	OD	12.5	inches
Depth of cover	DOC	6.56167979	ft
Depth to pipe centerline	H	7.08	
Effective unit weight of soil	γ	135	lb/ft3
Soil cohesion	c	104.45	psf
Internal friction angle for soil	ϕ	27	degrees
Horizontal bearing capacity factor for clay	N_{ch}	3.795	
Horizontal bearing capacity factor for sand	N_{qh}	3.872	
a		3.825	
b		0.997	
c		-0.090	
d		0.005	
e		0.000	
H/D		0.047	

Lateral soil force	Pu	4269.4	lbs/ft
		4.27	kips/ft

Lateral Bearing Capacity Factor of Soil

	ϕ (degrees)	a	b	c	d	e
Nch	0	6.752	0.065	-11.063	7.119	
Nqh	20	2.399	0.439	-0.03	1.06E-03	-1.75E-05
	25	3.332	0.839	-0.09	5.61E-03	-1.32E-04
	30	4.565	1.234	-0.089	4.28E-03	-9.16E-05
	35	6.816	2.019	-0.146	7.65E-03	-1.68E-04
	40	10.959	1.783	0.045	-5.43E-03	-1.15E-04
	45	17.658	3.309	0.048	-6.44E-03	-1.30E-04

Vertical Forces

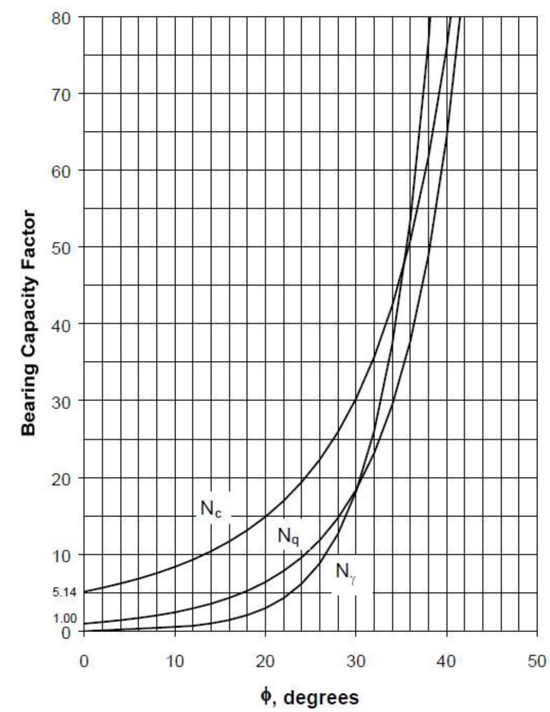
Pipe outside diameter	OD	12.5	inches
Depth of cover	DOC	6.56167979	ft
Depth to pipe centerline	H	7.08	
Effective unit weight of soil	ɣ	135	lb/ft3
Total unit weight of soil	γ	135	
Soil cohesion	c	104.45	psf
Internal friction angle for soil	ϕ	27	degrees
Vertical bearing capacity factor	N_c	23.94	
Vertical bearing capacity factor	N_q	13.20	
Vertical bearing capacity factor	Nγ	10.59	

Vertical Bearing Soil Force	Q_d	16526.9	lbs/ft
		16.53	kips/ft

Vertical bearing capacity factor	N_{cv}	0.094	<10 ok
Vertical bearing capacity factor	N_{qv}	4.172244094	<Nq ok

Vertical Uplift Soil Force	Q_u	4165.74	lbs/ft
		4.17	kips/ft

Bearing Capacity Factor of Soil



Longitudinal PGD Stress

Pipe outside diameter	OD	12.5	inches
Wall thickness of pipe	t	0.37519685	inches
Pipe Grade / SMYS	X-52	52000	
Modulus of elasticity	E	29,000,000	psi
Length of PGD zone/Length of pipe in slide	L	473.0012359	ft
Axial soil force	Tu	1307.46	lbs/ft
Elastic strain	ε_{el}	0.072%	
Plastic strain	ε_{pl}	0.000%	
Total strain	ε_{tot}	0.072%	

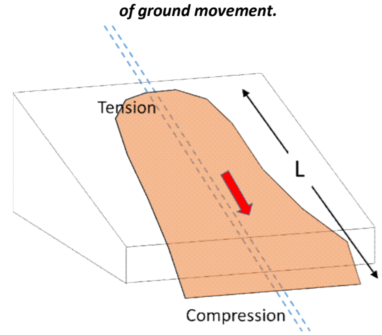
5%

Bending Stress on pipe	σ_{axial}	**20,986.5**	psi	**PASS**

Design Factor		0.54	
Pipe Internal Diameter	ID	11.7496063	in.
Maximum Operating Pressure	MOP	573	psi
Allowable Stress		28080	psi
Internal pressure stress		4772.49	psi
Remaining Stress Available		23307.51	psi

Allowable length of Longitudinal PGD		525.31	ft

Pipeline crossing permanent ground deformation zone in the direction of ground movement.



Pipe Grade	Yield stress (psi)	n	r
Grade B	35000	10	100
X-42	42000	15	32
X-52	52000	9	10
X-60	60000	10	12
X-70	70000	5.5	16.6
		9	10

Transverse PGD Stress

Pipe outside diameter	OD	12.50	inches
Wall thickness of pipe	t	0.37519685	inches
Pipe Grade	X-52	52000	
Modulus of elasticity	E	29,000,000	psi
Width of PGD zone/Length of pipe in slide	L	473.0012359	ft
Lateral soil force	Pu	4269.41	lbs/ft
Elastic strain	ε_{el}	71.536%	

Bending stress on pipe	σ_{axial}	**20,745,456.8**	psi	**FAIL**

Design Factor		0.54	
Pipe Internal Diameter	ID	11.7496063	in.
Maximum Operating Pressure	MOP	711	psi
Allowable Stress		28080	psi
Internal pressure stress		5921.89	psi
Remaining Stress Available		22158.11	psi

Allowable length of Longitudinal PGD		15.46	ft

Pipeline crossing permanent ground deformation zone transverse to the direction of ground movement.