UNIVERSITY OF HOUSTON

PROSPERITAS PIPELINE DESIGN

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Introduction

The goal of this project is to design of the infield flowline system attached to the floating host facility. The water depth is in range of 7200-7800 feet. The method used in the design is Front End Engineering and Design (FEED) of the infield flowline system. The following calculation was performed in excel sheet and the result has been published in this report.

- Pipe wall thickness
- Total weight of the Pipeline
- Design of Integral Ring type Buckle arrestor for S-Lay and J-Lay Installation options
- Pipe/Soil interaction study
- On Bottom stability analysis
- Flowline expansion analysis and global buckling screening
- Top tension and residual tension installation loads analysis
- Allowable Span length analysis
  - In-line and Cross-flow VIV onset

The pipe has been modeled for the export pipeline in following Conditions:

- Installation Condition
  - Empty
  - Flooded
- Hydrotest condition
- Operation condition

Wall Thickness Calculations

The minimum wall thickness for the pipeline should satisfy the following criteria.

- Pressure containment
- Hydrostatic test Pressure
- Burst Pressure
- Hydrostatic collapse
- Buckle Propagation
- Buckling due to combined bending and external Pressure

Table 1: Input Values

Pipe Data		Unit
Outside diameter(D)	10.75	inches
Min Yield Strength (S)	65300	psi
Min Tensile Strength(U)	77600	psi
Young’s Modulus	29000000	psi
Poisson’s Ratio (v)	0.3	
Corrosion Allowance (C.A.)	0.1575	inches
Ovality	0.0075	
Design Pressure	7000	psi
Density of Sea water (ρ_w)	0.0371	pci
Density of Product (ρ_{pr})	0.01157	pci
Maximum Water Depth(h)	7800	ft
Minimum Water Depth	7000	ft

Pressure Containment:

From 49 CFR 192,

$$P_d = \frac{2*S*t*F*E*T}{D}$$

Where,

F= Design factor for submerged component = 0.72

E= Longitudinal joint factor =1.0

T= Temperature Derating factor = 1.0

t= thickness of pipe

By solving above equation, we get **t= 0.800259 inches.**

Hydrostatic Test Pressure:

In this the pipeline wall thickness will be checked to ensure that it can withstand the hydrostatic test pressure. Ensuring the pipeline can accommodate the hydrostatic test provides the Installation Contractor with as much flexibility as possible concerning installation and hydrostatic test sequence.

The hydrostatic test pressure is 1.25 x pipeline design pressure at the specified elevation or water depth. The minimum pipeline wall thickness required to withstand the riser hydrostatic test pressure will be determined as follows:

As per 30 CFR 250.1003

$t = (Pd*1.25+\rho*g*h)*D/2*S*f_{ht}$

f_{ht} = hydrostatic test design factor = 0.95

Thickness obtained is **0.762003 inches**

As hydrostatic test occurs during installation, corrosion allowance is not added to the minimum pipeline wall thickness required to withstand the pipeline hydrostatic test pressure.

Internal Pressure (Burst) Design:

Limit state design has been integrated into API 1111 to provide a uniform factor of safety with respect to burst failure as the primary design condition which is independent of the pipe diameter, wall thickness, and material strength. The hydrostatic testing pressure, design pressure, and incidental overpressure, including both internal and external pressures acting on the pipeline shall not exceed those determined by equations

As Per RPI 1111:

$P_d \leq 0.80\ P_{hyd2}$

$P_a \leq 0.90\ P_{hyd2}$

$P_{hyd2} \leq f_e * f_d * f_t * P_b$

$P_b = 0.45(S+U)*\ln(D/D_I)$

P_b = Specified minimum Burst Pressure of pipe

P_a = Incidental over pressure

P_{hyd2} = Hydrostatic test pressure
f_e = Weld joint factor = 1.0
f_d = Internal pressure burst design factor = 0.90
f_t= Temperature derating factor = 1.0
Di = Inner diameter= D-2t

Table 2: Burst Design Obtained Values

P_b	8750 psi
P_{hyd2}	9722.22 psi
Thickness nominal	0.911693 inches

Hydrostatic Collapse:

P_y =2*S*(t/D)
P_e =(2*E*(t/D)^3)/(1-v^2)
P_c = P_y * P_e/ Square root of ((P_e)^2 +(P_y ^2))
(P_o-P_i)/ f_o P_c $\leq$ 1 -------- (a)
P_y = yield pressure at collapse
P_e = elastic collapse pressure of pipe
P_c = collapse pressure of pipe
P_o = external pressure
P_i = internal design pressure
E= young's modulus of elasticity
f_o = collapse factor = 0.6

In this part thickness value is assumed and calculations are done until equation a is satisfied. It includes 3 parts installation condition, operation condition and shut down condition.

For Installation condition,

P_o = 3477.24 Psi (ρ_w *g*h= 0.0371*7800*12)
P_i = 0
When t= 0.59, condition (a) is satisfied, values obtained are:

Table 3: Hydrostatic Collapse Installation Obtained Values

P_y	6681.86 psi
P_e	10537.00639 psi
P_c	5642.92298 psi

For operation condition tnominal = 0.59+0.1575= **0.7475 Inches**

For Shutdown Condition,
P_o = 3477.5 Psi (ρ_w *g*h= 0.0371*7800*12)
P_i = 1083.33 Psi (ρ_{pr} *g*h= 0.011*7800*12)

When t= 0.47, condition (a) is satisfied, values obtained are:

Table 4: Hydrostatic Collapse Operation Obtained Values

P_y	5709.953 psi
P_e	5326.65psi
P_c	3894.97 psi

Buckle Propagation:

As per API RP 1111,
P_p = 24*S*((t/D)^2.4)
$P_p \leq (P_o-P_i)/ f_p$
t= ((P_o-P_i)/ 24*S*f_p)^2.4*D

Where
P_p =Buckle propogation pressure
f_p = Propogation Buckle design factor = 0.8

In this part a thickness value is assumed and calculations are done until equation a is satisfied. It includes 3 parts; installation condition, operation condition and shut down condition.

For Installation condition,

P_o = 3477.5 Psi (ρ_w *g*h= 0.0371*7800*12)
P_i = 0

Table 5: Buckle Propagation Installation Condition

P_p	4440.78 psi
t	0.933 inches

For operation condition tnominal = 0.933+0.1575= **1.0905 Inches**

For Shutdown Condition,

P_o = 3477.5 Psi (ρ_w *g*h= 0.0371*7800*12)
P_i = 1083.33 Psi (ρ_{pr} *g*h= 0.011*7800*12)
tnominal = **0.952 inches**

Buckling due to Combined Bending and External Pressure:

As per API RP 1111,

$e/e_b+(P_o-P_i)/ f_c * P_c \leq g(ovality)$ --------- (b)
$e \geq f_1 e_1$,
$e \geq f_2 e_2$
g(ovality)=1/1+20(ovality)
e=bending strain in pipe
e_b=buckling strain under pure bending = t/2D
e_1 = maximum installation bending strain= 3.33 for installation condition
e_2 = maximum in-place bending strain = 2.0 for operating condition
f_1 = safety factor for installation bending plus external pressure,
f_2= safety factor for in-place bending plus external pressure,
ovality= 0.0075
g(ovality)= collapse reduction factor,

t value is assumed and calculations are done till equation b is satisfied, following values are obtained

Table 6: Combined Bending and External Pressure Obtained Values

Po	3477.5 psi
Pi	7000 psi
e_b	0.0358
Thickness(for installation)	0.77 inches
Thickness(for operation)	0.9275 inches

Pipe Weight Calculations

The total weight for the infield pipeline calculation was handled by using the previous section wall thickness and the pipe material data such as carbon steel density, Seawater density and product density.

Assumptions:

Parameter	Empty	Flooded	Operation
Wall Thickness	0.952	0.952	0.952
OD(in)	10.75	10.75	10.75
ID (in)	8.846	8.846	8.846
External Corrosion Coating (in)	0.024	0.024	0.024
External Corrosion Coating Density (pcf)	90	90	90
Steel Density (pcf)	490	490	490
Product Density (pcf)	20	20	20
Water Density (pcf)	64.2	64.2	64.2
Minimum Product Density (pcf)	**5**	**5**	**5**
Marine growth Thickness (in)	**0**	**0**	**0**
CRA Liner (in)	0	0	0

Figure 1: Pipe Weight Assumptions

Methodology:

There are three cases of empty condition, flooded and operation condition for the pipeline actual weight. It is important to note that the pipeline dry air is different from the pipeline submerged weight. In each condition of pipeline, the submerged weight is equal to the difference of dry air weight and buoyancy force acting on the pipe in the opposite direction of gravity. In order to calculate the dry air pipeline weight, all coatings, marine growth and CRA liner has been taken into consideration

$$W_{Submerge} = W_{Dry} - F_{Bouyancy}$$

Where,

$W_{Submerge}$: Submerged Weight
W_{Dry} : Dry air pipe Weight

W_{Dry} :
- Steel pipe

- CRA liner
– Coatings
- Marine growth
- Min. contents

$$W_{Dry} = \frac{\pi}{4}\rho_{Steel}g(D_o^2 - D_i^2) + \frac{\pi}{4}\rho_{Coating}g(D_c^2 - D_o^2) + \frac{\pi}{4}\rho_{Content}gD_i^2$$

$$F_{Bouyancy} = \frac{\pi}{4}\rho_{Water}g(D_C^2)$$

Where,

D_C : Outer diameter of corrosion coating
D_O : Outer Diameter of Pipe

D_i: Inner Diameter of Pipe

Results:

Conditon	Dry Air Weight (lb/ft)	Submerged Weight (lb/ft)
Empty	100.2220198	59.39490438
Flooded	127.6223578	86.7952424
Operation	108.7579507	67.93083522

Figure 2: Pipe Weight Results

Buckle Arrestor Design

In order to design the buckle arrestor for the J-Lay and S-lay Method the following methodology has been used to find the water depth at which the buckle arrestor is required.

Assumptions:

Table 7: Buckle Arrestor Design Assumptions

Parameters	Value	Reference
Pipe Material Data		
Pipe Outside Diameter	10.798 inch	Calculated
Wall Thickness	0.952 inch	Buckle Propagation
Minimum Yield Strength	65.3 Ksi	Assumed
Minimum Arrestor Strength	77.6 Ksi	Assumed
Poisson's Ratio	0.3	Assumed
Young Modules	29000 Ksi	Assumed
Sea Water Density	64.2 lb/ft3	Assumed

Methodology:

$$P_y = \frac{2\sigma_y t}{D} \rightarrow P_y = \frac{2 \times 65300 \times 0.952}{10.798} = 11514.2 \text{ psi}$$

$$P_e = \frac{2.2Et^3}{D^3} \rightarrow P_e = \frac{2.2 \times 29 \times 10^6 \times 0.952^3}{10.798^3} = 43722.15 \text{ psi}$$

$$P_c = \frac{P_y P_e}{\sqrt{P_y^2 + P_e^2}} \rightarrow P_c = \frac{502926221}{\sqrt{132578654 + 1907809267}} = 11133.9152 \text{ psi}$$

$$P_m = 1.35\ \gamma\ WD \rightarrow P_m = 4694.625 \text{ psi}$$

$$P_p = 24\ \sigma_y \left[\frac{t}{D}\right]^{2.4} \rightarrow P_p = 24 \times\ 65300 \times \left[\frac{0.952}{10.798}\right]^{2.4} = 4611.36 \text{ psi}$$

D = Outside diameter
t = Wall thickness

σy = Pipe material yield strength
σa = Buckle arrestor yield strength
E = Modulus of elasticity
μ = Poisson's ratio
WD = Maximum water depth
Psw = Density of seawater

Py = Pipeline yield pressure
Pe = Pipeline elastic buckling pressure
Pc = Pipeline collapse pressure
Pm = Minimum crossover pressure

$$H_a = \frac{P_p}{1.25\gamma} = \frac{4611.36*144}{1.25\times 64.2} = 8274.6 \text{ ft.}$$

$$H_a > WD$$

H**a** = Minimum arrestor depth;
P**p** = Pipeline propagation pressure;
γ = Seawater density.

Results:

Our calculations show that the minimum water depth for buckle arrestor is higher than the actual maximum water depth!

As Recommendation we do not need any buckle arrestor with the wall thickness of 0.952 inch and outer diameter of 10.75 inch.

Pipe-Soil Interaction Study

The initial pipe embedment is rarely known in practice due to the uncertain and variable influence of the laying process. Also, in tests this value is not always reported, or the immediate (undrained) embedment is not always differentiated from subsequent consolidation-induced settlement.

The pipe embedment is highly dependent on the lay process, and further research is needed to clarify the lay-induced forces, to enable a more reliable prediction of initial embedment. The approach adopted in this design is to multiply the pipe weight by a touchdown lay factor (Klay) to account for stress concentration at the touchdown point. On soft clay, this factor is typically between 2 and 3.

The friction factor for two axial and lateral load conditions has been calculated by using geotechnical and soil data. According to these data the embedment and friction factors has been estimated for three different soil shear strength.

1- Lower bound
2- Best estimate
3- Upper bound

Pipe Data:		Unit
Total External Diam	10.798	Inch
Water Depth	7800	ft
Wall Thickness	1.08	Inch

Figure 3: Pipe Soil Interaction Given Data

Soil Data:	
Penetration BML	0
Soil sensitivity	3
Su,B =	20
Su,L =	10
Su,U =	30
ηe =	1.5
ηm =	1.5
ηHs =	1.5
ηLs =	2
f.coat =	1
Klay =	2

Figure 4: Pipe Soil Interaction Assumptions

In each case pipe embedment and friction factor is governed by the undisturbed undrained shear strength of soil, which is defined as the ability of soil to resist the embedment of the pipe. The best embedment were calculated by using the following equation,

$$Z_B = \left(\frac{S_t D_o}{45}\right)\left(\frac{W}{D_o . S_{u,B}}\right)^2$$

where,

D_o: Pipe outside diameter including coating

S_t: Soil sensitivity

$S_{u,B}$: Best estimate undisturbed undrained shear strength of soil

W: Pipe submerged weight at given condition

Based on the best embedment there were two estimates of lower bound and upper bound calculated as follow,

$$Z_L = \frac{1}{h_e}\left(\frac{S_t D_o}{45}\right)\left(\frac{W}{D_o . S_{u,U}}\right)^2$$

$$Z_H = h_e\left(\frac{S_t D_o}{45}\right)\left(\frac{W}{D_o . S_{u,L}}\right)^2$$

Where

$S_{u,L}$: Lower bound undisturbed undrained shear strength of soil

$S_{u,U}$: Upper bound undisturbed undrained shear strength of soil

Z_H: High estimate pipe embedment

Z_L: Low estimate pipe embedment

The results for the embedment is tabled and it's necessary to note that by a higher soil shear strength we will be having lower amount of embedment and the results confirm the idea.

			Embedment (inch)		
Water Depth	Wall Thickness	Effective Submerged weight	Low	Best	High
7200-7800 Klay=2	0.952	118.7898088	2.323231654	7.840906833	47.045441
7200-7800 Klay=3	0.952	178.1847131	2.323231654	7.840906833	47.045441

Figure 5: Pipe Embedment for the Empty Case

Afterwards and by using the results from embedment the two types of axial and lateral frictional forces has been calculated. The term Axial Breakout and Lateral Breakout is used for the frictional forces since $Z_B > D_o/2$ we have

$$F_{Abo}^{B} = \pi\, S_{u,B} \frac{D_o}{2}\, f_{coat}$$

The high estimate breakout or peak axial resistance to monotonic axial displacement can be defined as:

$$F_{Abo}^{H} = \eta_H F_{Abo}^{B}$$

$$\eta_H = e^{\sqrt{\ln(\eta_m)^2 + \ln(\eta_S^H)^2}}$$

For axial resistance the model uncertainty factor, η_m, is 1.5. The shear strength uncertainty factor, η_s, is defined as:

$$\eta_S^H = \frac{F_{Ab,max}}{F_{Abo}}$$

The low estimate breakout or peak axial resistance to monotonic axial displacement is defined as:

$$F_{Abo}^{L} = \frac{F_{Abo}}{\eta_L}$$

$$\eta_L = e^{\sqrt{\ln(\eta_m)^2 + \ln(\eta_S^L)^2}}$$

$$\eta_S^L = \frac{F_{Abo}}{F_{Abo,min}}$$

The breakout or peak axial friction factor is given by,

$$f_{Abo} = \frac{F_{Abo}}{W}$$

D_o: Pipe outside diameter including coating
F_{Abo}: Axial breakout resistance
η_H: High estimate soil strength uncertainty factor
η_L: Low estimate soil strength uncertainty factor

In a same manner the lateral breakout or peak resistance can be estimated as:

$$F_{Lbo}^{B} = \frac{3\, S_{u,B} D_o}{\sqrt{G}} + 0.2W \qquad Z_B < D_o$$

$$F^B_{Lbo} = \frac{3\, S_{u,B} Z_B}{\sqrt{G}} + 0.2W \qquad Z_B > D_o$$

where,

$$G = \frac{S_{u,B}}{\acute{\gamma} D_o}$$

The breakout or peak lateral friction factor is given by

$$f_{Lbo} = \frac{F_{Lbo}}{W}$$

Where,

D_o: Pipe outside diameter including coating
F_{Lbo}: Lateral breakout resistance
γ': Submerged unit weight

The results for three pipe conditions (Empty, Flooded and Operation) are shown in the following tables:

		Axial Friction Factor			Lateral Friction Factor		
Water Depth	Effective Submerged weight	Low	Best	High	Low	Best	High
7200-7800 Klay=2	118.7898088	0.23793089	0.47586178	0.71379267	0.50452302	1.69197586	0.72744645
7200-7800 Klay=3	178.1847131	0.15862059	0.31724119	0.47586178	0.40301535	1.19465057	0.55163097

Figure 6: Axial and Lateral Friction Factors (Empty Pipe)

		Axial Friction Factor			Lateral Friction Factor		
Water Depth	Submerged weight	Low	Best	High	Low	Best	High
7200-7800 Klay=2	86.7952424	0.23793089	0.23793089	0.35689634	0.50452302	1.69197586	0.72744645
7200-7800 Klay=3	86.7952424	0.15862059	0.15862059	0.23793089	0.40301535	1.19465057	0.55163097

Figure 7: Axial and Lateral Friction Factors (Flooded)

		Axial Friction Factor			Lateral Friction Factor		
Water Depth	Submerged weight	Low	Best	High	Low	Best	High
7200-7800 Klay=2	61.52888709	0.11896545	0.23793089	0.35689634	0.50452302	1.69197586	0.72744645
7200-7800 Klay=3	61.52888709	0.0793103	0.15862059	0.23793089	0.40301535	1.19465057	0.55163097

Figure 8: Axial and Lateral Friction Factors (Operation)

On-Bottom Stability Analysis

Stability is an integral part of pipeline design .A pipeline engineer needs to evaluate the requirements to ensure that the pipeline is stable on the seabed, under the influence of extreme environmental conditions.

The main factors that influence the stability of the pipeline are:

- Hydrodynamic loads (under extreme environmental conditions)
- Resulting resistance (from seabed soil/secondary stabilization)

Hydrodynamic loads comprise of loads from:

- Waves (oscillatory) and steady currents.
- Wave spreading and directionality
- Seabed roughness(boundary layer effects)

Seabed soil resistance is given by the following factors.

- Coulomb friction
- Pipe embedment (passive soil resistance)
- History dependent (captured in 3D analysis)
- Pipe submerged weight (lowest contents density)

<u>Wave and current loading:</u>

At any given point of time there are wave and current loading on the pipeline. An engineer needs to ensure that the pipe can combat these forces and keep the pipe in its place so that there are no unnecessary stresses developed in the pipeline.

As mentioned above the major contributors to this resistance will be the submerged weight of the pipe and the soil resistance that oppose the lateral forces on the pipe.

The forces acting on the pipeline when installed on the seabed, both hydrodynamic and restraining:

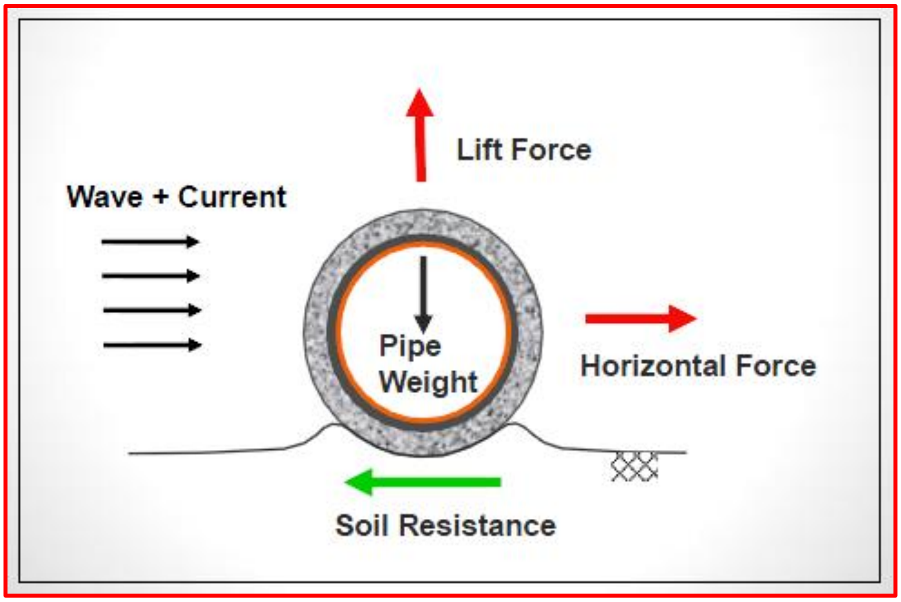

Figure 9: Submerged Pipe External Forces

Design of Pipeline for on bottom stability:

The most important factor that needs to be considered for On Bottom Stability is the minimum submerged weight of the pipe. Submerged weight can be increased by increasing the thickness of the pipe. But just increasing the pipe material is not recommended as this may lead to exponential increase in the cost of the pipeline. This may not augur well with the customer for whom the design is being done.

The alternative to increasing the pipe material is to increase the stability of the pipe by adding extra material onto the pipe in terms of Concrete coating and liner coating.

The more economical of these two would be to put a concrete layer on to the pipe which would increase the weight of the pipe and provide the required stability.

ASSUMPTIONS:

Nomenclature:

Pipe outer diameter = D

Wall Thickness = t

Significant Wave Height = H_s

Wave Spectral Peak Period = T_p

Current Speed = U_r

Current Reference Height = Z_r

Dynamic viscosity = v

Low estimate of lateral frictional factor = f_{LBO}

Water depth = d

Reduction factor = R

Parameter = T_n

Mean zero-up crossing period = T_u

Current velocity perpendicular to the pipe = U_d

Significant velocity perpendicular to the pipe = U_s

Significant velocity perpendicular to the pipe without reduction factor = U_S*

Mean grain size = d_{50}

Calibration factor = F_w

Bottom roughness parameter = z_o

Reference height above seabed = z_r

Acceleration due to gravity = g

Significant acceleration = A_s

Keulegan - Carpenter number = K

Current to wave velocity ratio = M

Drag Coefficient = C_D = 0.7 or 1.2

Lift Coefficient = C_L = 0.9

Inertia Coefficient = C_M = 3.29

Drag Force = F_D

Lift Force = F_L

Inertial Force = F_I

Reynolds' number = Re

Minimum submerged weight = $W_{s,min}$

Critical phase angle = θ_c

Minimum Product density = ρ (**which is equal to 5pcf in this check**)

Density of water = ρ_w

Jonswap spectrum γ=3.3

There are several cases to be considered for on bottom stability:

<u>Case 1</u>: Wave dominated loading in operational condition with low estimate of lateral frictional factor at start of life of the pipeline.

As this is a wave dominated case, longer time span of wave loading is considered and shorter time span of current data is considered. For operational case 100 year data of wave loading is considered and 10 year current data is considered.

For start of life the thickness is considered with corrosion allowance, which is 0.952 inches. The lateral frictional factor for low estimate of lateral frictional factor is used, which is 0.5. The values for embedment and thickness are obtained from calculations done earlier in the project.

Pipe Given Data		Unit	Hydrodynamics Data		unit
H_s	42.8	ft	C_L	0.9	
T_p	14.5	s	C_D	1.2	
d	7800	ft	C_M	3.29	
U_r	1.57	ft/s	ρ_W	64.2	lb/ft3
z_o	0.00000521	m	f_{LBO}	0.5	
d_{50}	0.0625	mm			
F_w	1				
D	10.798	in			
v	0.0000126	ft2/s			
z_r	3	m			

Figure 10: Case 1 Given Data

<u>Case 2</u>: Current dominated loading in operational condition with low estimate of lateral frictional factor at start of life of the pipeline.

As this is a wave dominated case, longer time span of current loading is considered and shorter time span of wave data is considered. For operational case 100 year data of current loading is considered and 10 year wave data is considered.

For start of life the thickness is considered with corrosion allowance, which is 0.952 inches. The lateral frictional factor for low estimate of lateral frictional factor is used, which is 0.5. The values for embedment and thickness are obtained from calculations done earlier in the project.

Pipe Given Data		Unit
H_s	27.2	ft
T_p	12.6	s
d	7800	ft
U_r	1.85	ft/s
z_o	0.00000521	m
d_{50}	0.0625	mm
F_w	1	
D	10.798	in
v	0.0000126	ft2/s
z_r	3	m

Hydrodynamics Data		unit
C_L	0.9	
C_D	1.2	
C_M	3.29	
ρ_W	64.2	lb/ft3
f_{LBO}	0.5	

Figure 11: Case 2 Given Data

<u>Case 3</u>: In the installation case, wave dominated loading means we need to consider wave loading data for 10 years and current data for 1 year. Since 1 year data is not given, we consider both loadings for 10 years. Hence wave dominated loading is same as the current dominated loading and it is given in this case.

For start of life the thickness is considered with corrosion allowance, which is 0.952 inches. The lateral frictional factor for low estimate of lateral frictional factor is used, which is 0.5. The values for embedment and thickness are obtained from calculations done earlier in the project.

Pipe Given Data		Unit	Hydrodynamics Data		unit
H_s	27.2	ft	C_L	0.9	
T_p	12.6	s	C_D	1.2	
d	7800	ft	C_M	3.29	
U_r	1.57	ft/s	ρ_W	64.2	lb/ft3
z_o	0.00000521	m	f_{LBO}	0.5	
d_{50}	0.0625	mm			
F_w	1				
D	10.798	in			
v	0.0000126	ft2/s			
z_r	3	m			

Figure 12: Case 3 Given Data

<u>Case 4</u>: Wave dominated loading in operational condition with low estimate of lateral frictional factor at end of life of the pipeline.

As this is a wave dominated case, longer time span of current loading is considered and shorter time span of wave data is considered. For operational case 100 year data of current loading is considered and 10 year wave data is considered.

For end of life the thickness is considered without corrosion allowance, which is 0.7945 inches. The lateral frictional factor for low estimate of lateral frictional factor is used, which is 0.5. The values for embedment and thickness are obtained from calculations done earlier in the project.

All the other inputs are same as in case 1.

<u>Case 5</u>: Current dominated loading in operational condition with low estimate of lateral frictional factor at end of life of the pipeline.

As this is a wave dominated case, longer time span of current loading is considered and shorter time span of wave data is considered. For operational case 100 year data of current loading is considered and 10 year wave data is considered.

For end of life the thickness is considered without corrosion allowance, which is 0.7954 inches. The lateral frictional factor for low estimate of lateral frictional factor is used, which is 0.5. The values for embedment and thickness are obtained from calculations done earlier in the project.

All the other inputs are same as in case 2.

<u>Case 6</u>: Wave dominated loading in operational condition with best estimate of lateral frictional factor at start of life of the pipeline.

As this is a wave dominated case, longer time span of wave loading is considered and shorter time span of current data is considered. For operational case 100 year data of wave loading is considered and 10 year current data is considered.

For start of life the thickness is considered with corrosion allowance, which is 0.952 inches. The lateral frictional factor for best estimate of lateral frictional factor is used, which is 1.6. The values for embedment and thickness are obtained from calculations done earlier in the project.

All the other data is same as in case 1.

<u>Case 7</u>: Current dominated loading in operational condition with low estimate of lateral frictional factor at start of life of the pipeline.

As this is a wave dominated case, longer time span of current loading is considered and shorter time span of wave data is considered. For operational case 100 year data of current loading is considered and 10 year wave data is considered.

For start of life the thickness is considered with corrosion allowance, which is 0.952 inches. The lateral frictional factor for best estimate of lateral frictional factor is used, which is 1.6. The values for embedment and thickness are obtained from calculations done earlier in the project.

All the other data is same as in case 2.

<u>Case 8</u>: In the installation case, wave dominated loading means we need to consider wave loading data for 10 years and current data for 1 year. Since 1 year data is not given, we consider both loadings for 10 years. Hence wave dominated loading is same as the current dominated loading and it is given in this case.

For start of life the thickness is considered with corrosion allowance, which is 0.952 inches. The lateral frictional factor for best estimate of lateral frictional factor is used, which is 1.6. The values for embedment and thickness are obtained from calculations done earlier in the project.

All the other data is same as in case 3.

<u>Case 9</u>: Wave dominated loading in operational condition with best estimate of lateral frictional factor at end of life of the pipeline.

As this is a wave dominated case, longer time span of current loading is considered and shorter time span of wave data is considered. For operational case 100 year data of current loading is considered and 10 year wave data is considered.

For end of life the thickness is considered without corrosion allowance, which is 0.7945 inches. The lateral frictional factor for best estimate of lateral frictional factor is used, which is 1.6. The values for embedment and thickness are obtained from calculations done earlier in the project.

All the other inputs are same as in case 1.

<u>Case 10</u>: Current dominated loading in operational condition with best estimate of lateral frictional factor at end of life of the pipeline.

As this is a wave dominated case, longer time span of current loading is considered and shorter time span of wave data is considered. For operational case 100 year data of current loading is considered and 10 year wave data is considered.

For end of life the thickness is considered without corrosion allowance, which is 0.7954 inches. The lateral frictional factor for best estimate of lateral frictional factor is used, which is 1.6. The values for embedment and thickness are obtained from calculations done earlier in the project.

All the other inputs are same as in case 2.

The conditions for different cases are taken as per the standards and the required weight of the pipeline for stability is calculated. The calculations are done best and low estimates of lateral friction factor as these two conditions give the worst cases which are required to consider by any engineer performing on bottom stability check.

METHODOLOGY

We calculate wave induced velocity using RP E305 using the Jonswap spectrum. This is done by firstly calculating T_n.

Where T_n is called a parameter.

$$\mathrm{Tn} = \sqrt{d/g}$$

d = water depth

g= acceleration due to gravity.

There is plot in RP E305 with T_n/T_p on the X axis and $U_s{}^*T_n/H_s$ on the y axis. By using this plot we can deduce $U_s{}^*$.

And we have, $U_s{}^* = U_s x R$, Where R=1. Hence we find the significant wave velocity.

This velocity is very small as the impact of wave loading is small as we move into deeper water depths.

The values of z_o and d_{50} are given in RP E305 and we have the velocity from the given inputs.

The current velocity is found using the boundary layer equation, which is:

$$U_D = \frac{U_r}{\ln(\frac{z_r}{z_o}+1)}\left[\left(1+\frac{z_o}{D}\right) * \ln\left(\frac{D}{z_o}+1\right) - 1\right]$$

We need to find the reynolds' number, Keulegan - Carpenter number and Current to wave velocity ratio.

$$Re = UD/\nu$$

$$M = \frac{U_D}{U_s}$$

$$K = \frac{U *_s * T_p}{D}$$

Using the above values we find the Calibration factor F_w, which is got as1.

The submerged weight of the pipeline needs to be calculated. This has already been done in the project, but the submerged weight for this check varies as the minimum product density is considered. This is considered because we need to check the stability of the pipe at the worst condition which is in case of a product in the pipe with very low densities

The submerged weights for empty, flooded and installation conditions with marine growth thickness of 0 and a corrosion allowance to the outer diameter of the pipe of 24mils, is considered.

This is again taken for start of life and end of life.

Thickness with corrosion allowance is:

	Submerged Weight (lb/ft)
Empty	59.39490438
Flooded	86.7952424
Operation	61.52888709

Figure 13: Submerged Weights for Start of Life

Thickness without corrosion allowance is:

	Submerged Weight (lb/ft)
Empty	44.23574842
Flooded	73.62224525
Operation	46.5244164

Figure 14: Submerged Weights for End of Life

The specific gravity of the pipe is calculated which should be greater than 1.2.

$$Specific\ gravity = \frac{\rho_{Pipe}}{\rho_w}$$

The hydrodynamic forces on the pipe which are in lb/ft are calculated by usin the below given formulas:

$$F_L = \frac{1}{2}\rho_w * D * C_L * (U_S\,Cos(\theta) + U_D)^2$$

$$F_D = \frac{1}{2}\rho_w * D * C_D * (|U_S\, Cos(\theta) + U_D|)(U_S\, Cos(\theta) + U_D)$$

$$F_I = \frac{\pi}{4} * D^2 * \rho_w * C_M * A_S * \sin\theta$$

After the hydrodynamic forces are calculated the minimum weight required to sustain these forces needs to be calculated.

We have,

$\mathbf{f_{LBO}(W_s - F_L) \geq F_w(F_D + F_I)}$

From the above equation the minimum submerged weight is calculated. We have a submerged weight already from our weight calculations.

As we can see the values for hydrodynamic forces are driven by an angle θ, which is the angle with which the flow attacks the pipe called the phase angle. Iterations are done to find the maximum weight obtained at different phase angles. This phase angle is the critical phase angle θ_c and the weight obtained is the minimum weight required for the stability of the pipe.

This would give us the worst case.

We compare the submerged weight from the weight calculations (W_s) with the minimum weight required to resist the hydrodynamic forces ($W_{s,min}$).

We then perform 3 checks to determine if our design is O.K.

Check 1: Unity check:

UC= Required submerged weight/actual submerged weight.

For the design to be stable this ratio must always be less than 1.

Check 2: Vertical Stability Check

S_{vert}=Actual submerged weight / F_L.

As the weight must withstand the lift force the actual weight must be greater than the lift force, which means that this ratio must always be greater than 1.

Check 2: Lateral Stability Check:

S_{lat}= [(Ws/F_W)-F_L].[f_{LBO}/(F_D+F_I)].

For the sake of stability S_{lat} should be greater than 1.

RESULTS:

The results obtained for each case are as follows:

Case 1:

Here, the critical phase angle is in radians. When converted into degrees the critical phase angle is **58 degrees**. This was obtained by iterations for angles 0 to 90 and it is consistent for all the 10 cases.

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	2.74995E-06	1.168486452	1.1096E-06	424912.2757	4.43129E-05	83447.86186
7000	14.74419562	2.90284E-06	1.168486452	1.23641E-06	402532.5427	4.67766E-05	83447.86186

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.102306066	1.469741422	0.00012619	4.042076963	1.01
Min	1.10230622	1.469741626	0.000140612	4.042110907	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	61.52888709	4.042076963	0.065693972	55.81833301	27.40916651
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 15: Case 1 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	1.74763E-06	1.376878941	7.05163E-07	787854.8611	2.44714E-05	98330.28309
7000	14.74419562	1.84479E-06	1.376878941	7.85754E-07	746359.2809	2.58319E-05	98330.28309

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.530544104	2.040725471	8.01955E-05	5.612177219	1.01
Min	1.530544219	2.040725625	8.93607E-05	5.612198805	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	61.52888709	5.612177219	0.091212071	40.20066259	19.60033129
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 16: Case 2 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	1.74763E-06	1.168486452	7.05163E-07	668611.9632	2.44714E-05	83447.86186
7000	14.74419562	1.84479E-06	1.168486452	7.85754E-07	633396.7952	2.58319E-05	83447.86186

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.10230506	1.469740081	8.01955E-05	4.041968284	1.01
Min	1.102305158	1.469740211	8.93607E-05	4.041989855	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	61.52888709	4.041968284	0.065692205	55.81838394	27.40919197
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 17: Case 3 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	2.74995E-06	1.168486452	1.1096E-06	424912.2757	4.43129E-05	83447.86186
7000	14.74419562	2.90284E-06	1.168486452	1.23641E-06	402532.5427	4.67766E-05	83447.86186

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.102306066	1.469741422	0.00012619	4.042076963	1.01
Min	1.10230622	1.469741626	0.000140612	4.042110907	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	46.5244164	4.042076963	0.086880767	42.20644141	20.6032207
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 18: Case 4 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	1.74763E-06	1.376878941	7.05163E-07	787854.8611	2.44714E-05	98330.28309
7000	14.74419562	1.84479E-06	1.376878941	7.85754E-07	746359.2809	2.58319E-05	98330.28309

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.530544104	2.040725471	8.01955E-05	5.612177219	1.01
Min	1.530544219	2.040725625	8.93607E-05	5.612198805	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	46.5244164	5.612177219	0.120628643	30.39730531	14.69865265
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 19: Case 5 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	2.74995E-06	1.168486452	1.1096E-06	424912.2757	4.43129E-05	83447.86186
7000	14.74419562	2.90284E-06	1.168486452	1.23641E-06	402532.5427	4.67766E-05	83447.86186

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.102306066	1.469741422	0.00012619	2.020982999	1.01
Min	1.10230622	1.469741626	0.000140612	2.020993631	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	61.52888709	2.020982999	0.032846084	55.81833301	87.70933282
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 20: Case 6 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	1.74763E-06	1.376878941	7.05163E-07	787854.8611	2.44714E-05	98330.28309
7000	14.74419562	1.84479E-06	1.376878941	7.85754E-07	746359.2809	2.58319E-05	98330.28309

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.530544104	2.040725471	8.01955E-05	2.80605335	1.01
Min	1.530544219	2.040725625	8.93607E-05	2.806060113	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	61.52888709	2.80605335	0.045605462	40.20066259	62.72106014
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 21: Case 7 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	1.74763E-06	1.168486452	7.05163E-07	668611.9632	2.44714E-05	83447.86186
7000	14.74419562	1.84479E-06	1.168486452	7.85754E-07	633396.7952	2.58319E-05	83447.86186

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.102306066	1.469741422	0.00012619	2.020982999	1.01
Min	1.10230622	1.469741626	0.000140612	2.020993631	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	61.52888709	2.020948882	0.03284553	55.81838394	87.70941431
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 22: Case 8 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	2.74995E-06	1.168486452	1.1096E-06	424912.2757	4.43129E-05	83447.86186
7000	14.74419562	2.90284E-06	1.168486452	1.23641E-06	402532.5427	4.67766E-05	83447.86186

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.10230506	1.469740081	8.01955E-05	2.020948882	1.01
Min	1.102305158	1.469740211	8.93607E-05	2.020955638	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	46.5244164	2.020982999	0.043439191	42.20644141	65.93030626
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 23: Case 9 Results

Water Depth	T_n	U_s	U_D	A_s	M	K	Re
7800	15.56393346	1.74763E-06	1.376878941	7.05163E-07	787854.8611	2.44714E-05	98330.28309
7000	14.74419562	1.84479E-06	1.376878941	7.85754E-07	746359.2809	2.58319E-05	98330.28309

Water Depth	F_L	F_D	F_I	$W_{s,max}$	Critical Phase angle
Max	1.530544104	2.040725471	8.01955E-05	2.80605335	1.01
Min	1.530544219	2.040725625	8.93607E-05	2.806060113	1.01

Concrete Thickness	Actual Submerged Weight	Required Submerged Weight	Unity Check	S(vertical)	S(lateral)
0	46.5244164	2.80605335	0.060313564	30.39730531	47.03568849
			Unity check2	Vertical Check	Lateral Check
			OK	OK	OK

Figure 24: Case 10 Results

As the submerged weight is higher than the required weight for stability, a concrete coating is not required for Prosperitas pipeline design.

Flowline Expansion Analysis and Global Buckling Screening

Installation Loads

Two load cases will be considered while determining the installation loads; the empty submerged pipe and a flooded submerged pipe. The top tension, residual tension and the touch down point (TDP) will be calculated using catenary equations. It is important to note that this is a static analysis and does not account for any vessel motion due to wave, wind or current motion.

The catenary equations provide a rather quick way of determining the top tension, the on bottom tension, the distance between the stinger or vessel and the touch down point as well as the appropriate departure angle. An excel spread sheet was used for the calculations and the input criteria can be seen below in Figure X. The pipe weight, water depth and the sag-bend length are necessary and the main components of the installation loads.

Client (73 characters)	= UH
Project/Pipeline (73 characters)	= Prosperitas
Project Number (73 characters)	=
Engineer (73 characters)	= J Anderson

Pipe Definition		
Outside Diameter (in)	=	10.750
Wall Thickness (in)	=	1.080
API-5L Yield Strength (ksi)	=	65.30
Ultimate Tensile Strength (ksi)	=	77.60
Modulus of Elasticity (ksi)	=	29000.00
Post-Yield Slope (ksi)	=	147.50
Poisson's Ratio (-)	=	0.30

Pipe Design Factors		
Ovality, d=(OD-ODmin)/OD (%)	=	0.750
Corrosion Allowance Thickness (in)	=	0.158
Average Joint Length (ft)	=	40.00

P/L Installation Loading		
Max. Eff. Axial Tension (kips)	=	50.000

Pipe Coatings Definitions		
Corrosion Coating Thickness (in)	=	0.024
Corrosion Coating Density (kcf)	=	0.090
Concrete Coating Thickness (in)	=	0.000
Concrete Coating Density (kcf)	=	0.190

Field Joint Coating Definitions		
Corrosion Coating Cutback (in)	=	6.00
Concrete Coating Cutback (in)	=	0.00
Field Joint Filler Density (kcf)	=	0.090

Miscellaneous Input		
Water Depth (ft)	=	7800.00
Water Density (kcf)	=	0.064
Product Density (kcf)	=	0.020
Concrete Ultimate Water Absorption (%)	=	3.00

Figure 25: Catenary Input Criteria

The first installation case to consider will be the empty pipe case. The weight of the empty pipe is the void dry weight minus the weight of the displaced seawater or:

$$= 0.071 kips/ft$$

Having the maximum installation bending strain allows us to run a goal-seek analysis to determine the residual (or bottom) tension. By setting the strain cell equal to the given value of 0.0015, we can determine the arc length of the pipeline bend and in conjunction with the pipe weight we are able to determine the residual tension. The sagbend is necessary to determine the top tension and is a factor of the pipe weight, the water depth and the residual tension. The equation for the top tension is:

$$= 2683.3\ kips$$

The residual tension is correctly lower than the top tension due to the friction factor associated with the pipe soil interaction. The appropriate lay angle is a function of:

$$\cos\left(\frac{Residual\ Tension}{Top\ Tension}\right).$$

Similarly, the flooded installation load case takes in to account the same factors and methodology with one minor exception. The submerged weight of the flooded pipeline will be greater than the empty submerged case by the weight of the contained fluid. Or:

$$Flooded\ weight = Submerged\ weight +\ \rho * \pi(OD - ID)^2$$

The remainder of the flooded pipeline procedure is the same as the empty condition.

Table 8: Resulting Installation Loads

	Empty	Flooded	Units
Water Depth	7800	7800	feet
Pipe Weight	0.071	0.097	Kips/ft
Arc length	29821.606	29929.5	feet
Sagbend	22935.934	22972.6	feet
Departure Angle	37.6	37.5	degrees
Top Tension	2683.3	3665.9	kips
Residual Tension	2127	2908	kips

Allowable Span Length

Inline and Crossflow VIV onset:

Freespan and Vortex induced vibrations play an important role in determining the stability and failure point of a pipeline. Freespans refers to unsupported weight of pipeline section under the action of dynamic loads of waves and currents. High freespan lengths results in failure of pipeline due to hanging weight which results in yielding and fatigue due to vortex induced vibrations. Flow over a pipe generally results in vortex formations in the wake region behind the cylinder. The vortices are formed in the opposite directions and each time the vortices form, the local pressure distribution alters resulting in varying lift values. This varying lift induces vibrations in the pipeline. The frequency of vibrations when gets closer to natural frequency of the pipe, it results in catastrophic failure. The Pipeline span has to be selected in such a way that it resists the vibrations induced by currents.

Pipeline oscillations are characterized into types based on the direction of the flow with respect to the pipe. Inline oscillations occur at lower velocities than the velocity at which crossflow oscillations occur. The velocity at which oscillations are produced is known as ***'Reduced Velocity'*** and this varies with stream velocity and direction of the flow. Inline oscillations occur at lower velocities between 1 and 2.2. To mitigate this effect, stability parameter (K_s) is larger than 1.8. '*Crossflow oscillations'* occur at higher reduced velocities compared to inline oscillations and the stability factor is ensured to be less than 16.

Design Criteria:

Currents and waves act as significant parameters to be considered while deciding the span lengths. The more the span length is, more is the probability of VIV formation. VIVs are formed when, vibration frequency is equal to natural frequency of the pipe. so the lenghth has to be selected insuch a way that the natural frequency gets higher than the vortex shedding frequency.

Vortex shedding Frequency is given by :

$$f_s = \frac{SU_c}{D} \quad \text{.........} (1)$$

Where S = Strouhals Number
Uc = flow velocity
D = Outer diameter of the pipe

Natural Frequency of the pipe is given by

$$f_n = \frac{C_e}{2\pi}\sqrt{\frac{EI}{M_e L_s^4}} \quad \text{.........}(2)$$

Where C_e = End condition constant
E = Youngs Modulus
I = Moment of Inertia
Me = Effective unit mass (varies with working condition)

Design Procedure:

Pipeline span has to be calculated for 3 cases.

*****Installation
*****Hydrostatic
*****Operation

The effective mass of the pipe has been calculated in each case:

1. *Installation Condition:*

In this case, the pipeline weight alone has to be considered to decide the span length. The effective mass in this case is given by

$$M_e = M_{pipe} + M_{corrosion\ coating} + M_{concrete\ coating} + M_{added}$$

2. *Hydrostatic Condition:*

In this case the pipeline is hydrotested with water as internal fluid. So the pipeline mass includes: Pipeline mass, corrosion coating mass, concrete thickness mass.

$$M_e = M_{pipe} + M_{corrosion\ coating} + M_{concrete\ coating} + M_{added} + M_{water}$$

3. *Operation Condition:*

The pipeline has to be tested for operating condition, so hydrotest fluid is replaced with operating fluid and mass of the pipe is considered along with te mass of corrosion coating, concrete thickness and mass of operating fluid.

$$M_e = M_{pipe} + M_{corrosion\ coating} + M_{concrete\ coating} + M_{added} + M_{Operating\ fluid}$$

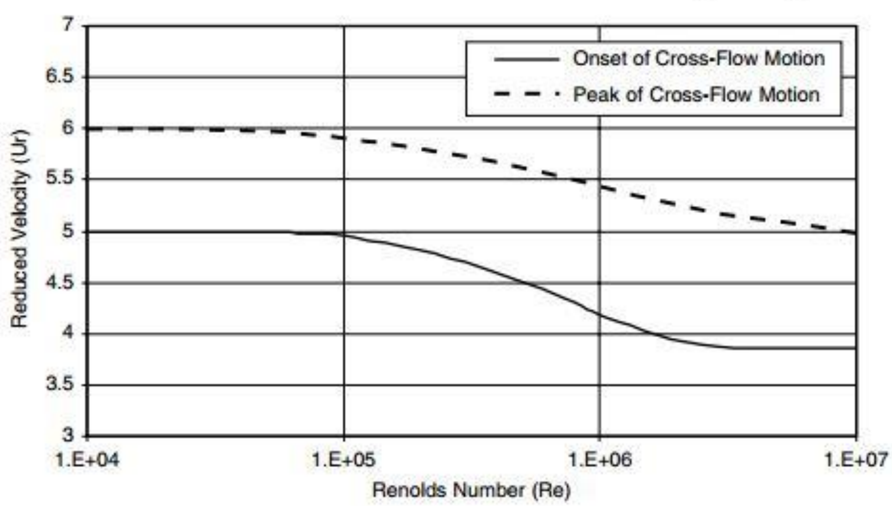

Figure 26: Ur Vs Reynolds number (Value of Reduced Velocity for Crossflow Oscillations)

The *Reynolds number* is a function of current velocity, Diameter of the pipe and Kinematic viscosity and is a deciding factor of '*Reduced velocity' (VIV onset velocity).* From Fig -1 the value of Reduced velocity is determined and the value of U_r for VIV onset is considered for deciding the span length. The stability factor (K_S) is given by

$$K_s = \frac{2M_e\delta_s}{\rho D^2} \quad \text{............ (3)}$$

Where M_e = Effective Unit mass
δ_S= logarithmic decrement of structural damping (0.125)
ρ = Density of sea water
D = Diameter of the pipe

The Reduced velocity for inline motion is calculated from fig 2. The graph presents variation of reduced velocity with stability parameter for inline motion. However, reduced velocity for inline motion varies with stability parameter for three conditions (Installation, Hydrotest and Operation)

Critical Span Length:

The critical span length is the minimum length at which VIV onset occurs and is dependent on natural frequency of unsupported pipe. Span length for VIV is given by

$$L_c = \sqrt{\frac{C_e U_r D}{2\pi U_c}\sqrt{\frac{EI}{M_e}}} \quad \text{……….. (4)}$$

Where C_e = pipeline end condition
U_r = Reduced Velocity
U_c = Current Velocity
E = Youngs Modulus of pipe material
I = Moment of Inertia
M_e = Effective Mass

Equation (4) gives Critical span length for ***crossflow*** oscillations. As Me increases, the required spanlength decreases. Critical span length for inline flow oscillations is given by equation (5) and varies for each case as Me varies.

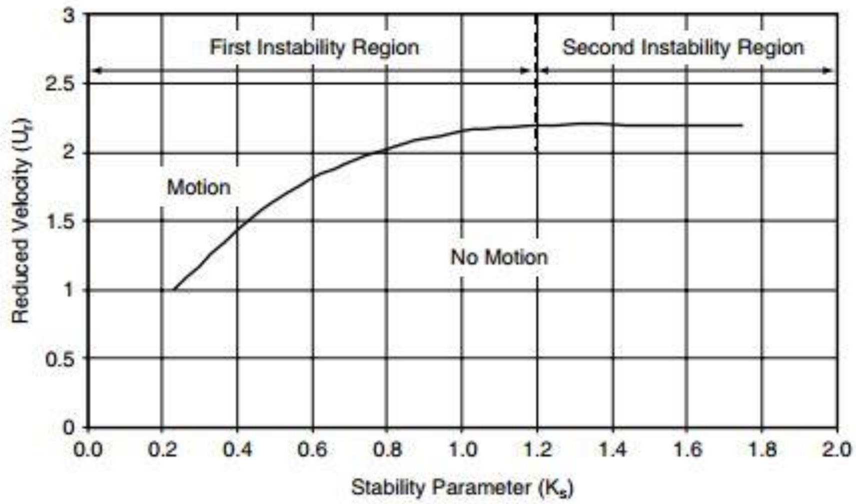

Figure 27: Reduced Velocity (Ur) vs Stability Parameter (Ks)

Critical span length for Inline motion is a function of natural frequency and Me.

$$L_c = \sqrt{\frac{C_e f_n}{2\pi}\sqrt{\frac{EI}{M_e}}}$$ …………..(5)

Where, fn= Natural frequency of pipe
E = Youngs Modulus
I = moment of Inertia

End Condition Selection:

The end condition is selection also decides Critical span length value. End condition values for each case are as follows:

Pinned – pinned: used when the ends of the pipe are free and allowed to rotate (9.87).

Clamped- Clamped: used when the ends are to be fixed

Pinned- Clamped: Used when the pipe doesn't comes under any of the cases

The change of end condition can vary the final critical value by as much as 50%. In the present case, the pipeline is considered to be pinned at both ends.

Calculations:

Effective Unit mass:

Buoyancy:

60.77 kg

Installation Condition:

Effective Mass = $M_{pipe} + M_{corrosion\ coating} + M_{concrete\ coating} + M_{added}$-Buoyancy

Unit Mass of pipe: 148.1686 Kg
Unit mass of Corrosion Coating: 0.7527 Kg
Unit mass of concrete coating: 0 Kg
Added Unit mass: 60.77 kg

Effective Unit mass: 149.20 Kg

Hydrotest Condition:

Unit mass of pipe: 148.1686 Kg
Unit mass of Corrosion Coating : 0.7527 Kg
Unit mass of Concrete coating: 0 kg
Unit mass of hydrotest fluid: 40.79 Kg
Added Unit mass: 60.77 Kg

Effective Unit mass: 189.99 Kg

Operation Condition:

Unit mass of pipe: 148.1686 Kg
Unit mass of Corrosion coating: 0.7527 Kg
unit mass of operating fluid: 40.79 Kg
added Unit mass: 60.77 Kg

Effective Unit mass: 161.91 Kg

Stability Parameter:

$$K_s = \frac{2M_e\delta_s}{\rho D^2}$$

K_S varies with effective Unit mass.

Table 9: Stability Parameters

Stability parameters (K_S)	
Installation	0.48
Hydrotest	0.61
Operating	0.52

*Reynolds number = (Current Velocity) * (Total diameter of the pipe) / (Kinematic Viscosity)*

= *132181.2*

Reduced Velocity (Cross Flow):

From Fig (1), Reynolds number gives the value of corresponding Reduced velocity of Cross flow motion which is 4.95 m/sec.

Reduced Velocity (Inline flow):

From Fig (2), The stability parameter gives the corresposnding reduced velocities of inline motion

Table 10: Reduced Velocity for Inline Flow

Reduced Velocity (Inline Flow)	m/sec
Installation	1.5
Hydrotest	1.7
Operating	1.6

Natural Frequency:

The natural frequency of an oscillating pipe is a function of current velocity, diameter of the pipe and corresponding reduced velocity.

Natural Frequency = (Current Velocity) / (Outer Diameter of pipe Reduced Velocity))*

Table 11: Natural Frequency of Pipe

Natural Frequency of Pipe	
Installation	1.37
Hydrotest	1.20
Operating	1.28

End condition selection:

Out of the 3 end conditions, C_e value is lowest for pinned pinned condition. So the end condition of the pipeline is assumed so that the least required critical length is obtained.

Ce = 9.87

Critical Length Calculation:

Critical length for crossflow and inline conditions are given by Equations (4) and (5) and the values are as follows.

Table 12: Critical Length

Critical Length	Inline flow	Crossflow motion
Installation	29.61	39.24
Hydrotest	26.18	36.94
Operation	28.09	38.45

Among the critical length values from the above table, the minimum required critical length value is set to 26.18 (operation condition in Inlineflow motion).

Recommendation/Conclusion

References: