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Pipeline Wall Thickness Assessment of Various Material Grades and Water Depths Using American and Norwegian Standards

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ABSTRACT

Two standards that are widely used by many countries in designing offshore gas transmission pipelines are American Standard – ASME B31.8, Gas Transmission and Distribution Piping Systems and Norwegian Standard – DNVGL-ST-F101, Submarine Pipeline System. A thorough understanding of these standards is vital in determining optimal pipeline design to ensure pipeline integrity for safe and sustainable operations, as well as striving for economic efficiency. This study aims to evaluate the wall thickness required for pipeline designs using American and Norwegian pipeline standards under different steel grades and water depth conditions. Pipeline costs are then compared for both standards at each water depth condition for commercial evaluation. Through this, the optimal pipeline standard for wall thickness design can be determined. Mathcad software was used for data analysis in accordance with the standards mentioned and all design requirements including pressure containment, collapse, and propagation buckling. Ultimately, the American Standards was able to provide a total cost that was 2.5% lower than the Norwegian Standard for a pipeline project with a combination of shallow, medium, and deepwater depths along its route. However, a combination of Norwegian Standards for medium and deepwater depths and American Standard for shallow water depth can further reduce total costs to 2% compared to only using the American Standard. This study highlights the importance of considering several design standards for a pipeline project instead of strictly adhering to a single standard for better technical and commercial benefit.

Keywords: Pipeline Engineering; wall thickness design; deepwater

INTRODUCTION

Pipeline is a primary method used for the transportation of processed and unprocessed oil and gas from offshore fields. It is usually made of low carbon steel pipes which are buried or laid on the seabed. Compared with other forms of transportation such as tanker, pipelines provide more continuous, stable, and high capacity supply to the users regardless of the weather condition (Dianita & Dmitrieva 2016; Lee 2008; Timerbaev 2019). Globally, an estimated 2,034,065km total length of pipelines has been constructed with start years up to 2023 (Energy 2019). Natural gas has become the primary product focus to be transported by these pipelines due to environmental reasons and cleaner energy demand, followed by petroleum and crude oil (Borraz-s 2010; Hopkins 2007; Owowo 2016).

Rigid, steel pipes are the simplest and least expensive manufacturing method with proven reliability for long-term service and high internal pressure (Kaiser 2016; Langhelle 2011). The main consideration during pipeline design, in addition to sizing, is the optimal wall thickness and steel grade of the pipeline (Dianita & Dmitrieva 2016; Hassanin & Jukes 2018). While greater internal pressure may lead to pipeline burst, problems of high external pressure will result in pipeline failure such as system collapse and propagation buckling (M. N. Junaidi & Koto 2016). As such, the calculation and selection of pipeline wall thickness and steel grade are key areas in the detailed design stage of a pipeline project. Failure in selecting a suitable wall thickness may negatively impact the pipeline's ability to withstand high internal and external pressure, as well as other loads acting on it during pipeline installation and operation.

Pipeline design philosophy is usually implemented through a set of criteria given in codes, standards, and regulations (Peletiri et al. 2018). ASME B31.8 (ASME B31.8 2016) is the American Standard that is based on the traditional Allowable Stress Design (ASD), in which design stresses are compared to factorized yielding stress level for pressure containment. Despite simpler calculation, not all capabilities of the pipeline are fully explored which may lead to conservative design (Dianita & Dmitrieva 2016). For other wall thickness design aspects (i.e. collapse and buckling), no clear explanation has been given and assessments are mostly done using the API RP111 code (API RP 1111 2015), which is the American Standard using Limit State Design (LSD). Worldwide pipeline development guided by oil production demands has given room for applying the Load Factor and Resistance Design (LRFD) method on the Norwegian Standard (DNVGL-ST-F101 2017) which provides factorization for load and material strength which covers the whole applicable design aspect. However, there is still a lack of comparison, on both international standards, in terms of technical and commercial aspects for pipeline wall thickness design, especially for application in Malaysian waters.

As the demand for oil and gas increases, followed by maturing field output declination, exploration parties have started to divert their attention towards deeper seawater regions. In Malaysia, undiscovered resources amount to ten billion barrels of oil, of which 65% are deepwater discoveries (Jaswar 2016). Thus, more often than before, pipelines are required to be installed in increasingly harsher environments, by which the external pressure is often the primary load parameter (Dàngelo et al. 2016; Fyrileiv et al. 2013; Ortega & Saad 2010). In addition, there are still pipeline replacements that need to be done for old pipelines exceeding their design life especially in shallow water. Some offshore fields may also include a combination of shallow and deepwater throughout the pipeline route. Thus, understanding the standards which will provide minimal wall thickness along different water depth conditions is crucial for optimal pipeline design. Previous studies have been done comparing the optimal pipeline standards, yet most of them involved constant water depth conditions (Dàngelo et al. 2016; Dianita & Dmitrieva 2016).

Pipe material and grade are among the key factors that affect pipeline wall thickness requirements. Thickness has a reverse relationship to specific minimum yield strength (SMYS), thus increasing the SMYS will decrease the required thickness of the pipe due to increasing strength (A. K. Junaidi & Koto 2014). However, according to API Spec 5L, higher SMYS is related to higher steel grade. This may increase fabrication costs due to the raw materials alongside difficulties in pipeline welding (Bai & Bai 2005). According to Investor (2015), deepwater opportunities in Malaysia is highly promising as long as challenges regarding cost cutting measures are adequately managed. Therefore, it is motivating to understand which standard will provide minimum required wall thickness alongside the lowest material grade acceptance for the economic or commercial benefit of the pipeline project, while still ensuring pipeline integrity for a safe and sustainable operation.

Based on the stated problems, the overall purpose of this study is thus to conduct a wall thickness design assessment comparing American and Norwegian pipeline standards under different water depths and steel grades. The study determines the optimal pipeline standard in terms of technical and commercial aspects especially for Malaysia's water condition. The analysis is carried out using a commercial Mathcad software application. All design calculations are in accordance with standards and must satisfy all design requirements including pressure containment, collapse and propagation buckling.

METHODOLOGY

The calculation methods have been carried out in accordance with the requirements of two main standards used in the industry: (1) American Standard (ASME B31.8 supplemented by API RP 1111) which is used in the US and South East Asia including Malaysia; and (2) Norwegian Standard (DNV under DNVGL ST F101) which is used in Europe. A case study of subsea pipeline and riser wall thickness assessment in shallow, medium, and deepwater conditions have been conducted. The primary objective is to investigate the most applicable pipeline standards at various water depth conditions both technical and commercial aspects.

DESIGN PARAMETERS

Three offshore field case studies with different maximum water depth conditions have been used for comparison. Based on data availability for the pacific region, these cases include: (1) shallow water, Andalas (66.7m); (2) medium deep, Malikai (575m); and (3) deepwater, Liwan (1350m). Except for the water depth, all design and environmental data used in the analysis have been based on actual data from the Malikai offshore field (2). This is due the needs to ensure consistency for other parameters which may influence the wall thickness assessment such as design pressure, pipe size and product density. In addition, Malikai offshore field is located in Malaysia water region which suit with the current study. The design and operating data for the pipeline and riser are presented in Table 1.

TABLE 1. Design and operating data

Description		Unit	Offshore Field		
			(1)	(2)	(3)
Nominal Pipe Size[(1)]		Inch (mm)	20 (508)	8 (219.1)	12.75 (323.9)
Service		-	Full Well Stream	Gas	Gas
Design Pressure		barg	70	100	294
Hydrotest Pressure[(2)]	Zone 1 (Pipeline)	barg	87.5	125	367.5
	Zone 2 (Riser)	barg	105	150	441
Maximum Operating Pressure		barg	51.8	100	294
Design Temperature		ºC	120	65	102
Content Density	Max	kg/m^3	70.8	102.6	300
	Min	kg/m^3	40.1	70.92	-
Corrosion Allowance[(3)]		mm	11.0	3.0	4.0
Design Life		years	15	20	20

Note:

1. Pipe Size is from Pipeline Hydraulic Study and as per listed in ASME B36.10M – Welded and Seamless Wrought Steel Pipe.

2. Hydrotest pressure for offshore pipeline systems is based on pressure test philosophy of 1.25 x D.P for pipeline and 1.5 x D.P for riser in accordance to ASME B31.8.

3. Corrosion allowance is from Corrosion Study. Andalas field is identified as a sour gas service (highly corrosive) thus requiring higher allowance.

TABLE 2. presents the seawater properties and water depth used in the analysis.

Properties		Unit	Offshore Field		
			(1)	(2)	(3)
Water Depth (along pipeline route)	Maximum	m	66.7	575.0	1350.0
	Minimum	m	63.0	444.0	1150.0
Seawater Density		kg/m^3	1020.4		
Kinematic Viscosity		m^2/s	1.65x10^{-6}		
Seawater Resistivity		Ω.m	0.35		

The tidal, storm surge, and wave data used in the analysis are shown in Table 3.

TABLE 3. Tidal, storm surge and wave data

Properties[(1)]	Unit	Offshore Field		
		(1)	(2)	(3)
Highest Astronomical Tide (HAT)	m	1.06	3.3	0.89
Mean Sea Level (MSL)	m	0	0	0
Lowest Astronomical Tide (LAT)	m	-1.13	-1.1	-0.75
Storm Surge (100 year)	m	0.6	0.6	1.65
Maximum Wave Height (100 year)	m	10.2	13.0	28.0

Notes:

1. Data presented is in reference to Mean Sea Level (MSL).

ASSESSMENT USING AMERICAN STANDARDS

The approach used to calculate the required wall thickness of the pipeline systems are as per ASME B31.8 as the primary design code and supplemented by API RP 1111. The minimum required wall thickness has been analysed based on the following criteria:

1. Pressure containment.
2. Collapse due to external pressure.
3. Propagation buckling.

Pressure containment calculations have been performed in accordance with the requirements of ASME B31.8. Hoop stress formula has been used to determine the minimum required wall thickness. It was evaluated based on net internal design pressure, outer pipe diameter, pipe SMYS, design factor per zone, temperature de-rating factor, and corrosion allowance. The minimum required wall thickness has been calculated through Equation (1):

$$t_{min} = \frac{(P_i - P_o) \cdot D}{2 \cdot S \cdot F \cdot T} \tag{1}$$

Where:

P_i = Internal pressure

P_o = External pressure

D = Outer diameter

S = Specified Minimum Yield Strength (SMYS)

F = Allowable Stress Factor, 0.72 for pipeline and 0.5 for riser

T = Temperature De-rating Factor, 1.0 for temperature 120 ºC

Collapse due to external overpressure check has been performed in accordance with API RP 1111. During installation and operation, the pipeline may be subjected to conditions where the external pressure exceeds the internal pressure. The collapse pressure shall exceed the net external pressure anywhere along the pipeline as per Equation (2):

$$f_o \cdot P_c \geq P_o - P_i \tag{2}$$

Where:

f_o = Collapse factor; 0.7 for seamless and ERW pipe

P_c = Collapse pressure

P_o = External pressure

P_i = Internal pressure

Collapse pressure is divided into critical collapse pressure, pure plastic collapse pressure, and pure elastic collapse pressure. The equations are given respectively:

$$P_c(t) = \frac{P_y(t) \cdot P_{ec}(t)}{\sqrt{P_y(t)^2 + P_{ec}(t)^2}} \tag{3}$$

$$P_y(t) = 2 \cdot SMYS \cdot \left(\frac{t}{D}\right) \tag{4}$$

$$P_{ec}(t) = 2 \cdot E \cdot \frac{\left(\frac{t}{D}\right)^3}{1 - v^2} \tag{5}$$

Where:

$P_c(t)$ = Critical collapse pressure

$P_y(t)$ = Plastic collapse pressure

$P_{ec}(t)$ = Elastic collapse pressure

t = Minimum calculated wall thickness

D = Outer diameter pipe

v = Poisson's ratio

A buckle resulting from excessive bending or a high impact load may propagate along the pipe. The pipeline can fail by a propagating buckling due to the hydrostatic pressure of seawater acting on the pipe. For a given wall thickness, there exists a transition water depth below which a pipeline buckle will propagate. This water depth is translated as buckle propagation pressure given by Equation (6) as per API RP 1111:

$$P_{prop}(t) = 24 \cdot SMYS \cdot \left(\frac{t}{D}\right)^2 \tag{6}$$

Where:

$P_{prop}(t)$ = Pressure required to propagate buckle

t = Minimum required wall thickness

D = Outer diameter pipe

$SMYS$ = Specified Minimum Yield Strength

Buckle arrestors shall be installed under the following conditions given by Equation (7):

$$(P_o - P_i) \geq f_p \cdot P_{prop}(t) \tag{7}$$

Where f_p is the propagating buckle design factor which is 0.80. Buckle arrestor spacing shall be based on the installation and repair costs assessment. However, it may be more economical to increase the wall thickness especially for short pipelines. The design factors considered in wall thickness assessment using ASME and API standards have been summarized as per Table 4. It is the margin adopted to ensure that stresses due to the load acting on the pipeline do not exceed the strength limit of the pipeline material (Monsalve 2014).

TABLE 4. Design Factors

Parameter		Design Factor
Hoop Stress Design Factor	Pipeline (Zone 1)	0.72
	Riser (Zone 2)	0.5
Temperature De-rating Factor		1.0
Collapse Factor		0.7
Bending Safety Factor (installation bending and external pressure)		2
Bending Safety Factor (in-place bending and external pressure)		2
Propagating Buckling Design Factor		0.8

ASSESSMENT USING NORWEGIAN STANDARDS

The approach used to calculate the required wall thickness of the pipeline systems as per DNV is described. The minimum required wall thickness has been analysed based on similar criteria as per American Standard.

In DNV standards, the design criteria calculation uses the location and safety classes to classify the pipeline design. Near platform area with riser section extended to 500m horizontal distance and shore approach i.e. 500m from landfall towards offshore is classified as Location Class 2. The pipeline section outside Location Class 2 shall be considered as Location Class 1. Table 5 shows the safety class categorization inclusive of location class.

TABLE 5. Safety Class

Phase	Location Class 1	Location Class 2
Installation / Hydrotest(1)	Low	Low
Shut-down(2)	Medium	High
Operational	Medium	High

Note:

1. Installation until pre-commissioning (temporary phase) will normally be classified as safety class low i.e applicable for installation and hydrotest design conditions.

2. For safety classification of temporary phases after commissioning, special consideration is made to the consequences of failure i.e giving a higher safety class than Low.

Pressure containment check is carried out for the yield limit and bursting limit of the operation and hydrotest cases. The criteria for pressure containment (LRFD) calculations is given as follows:

$$P_{li} - P_e \leq Min\left(\frac{P_b(t_1)}{\gamma_m \cdot \gamma_{sc}}; \frac{P_{lt}}{\alpha_{spt}} - P_e; \frac{P_h \cdot \alpha_U}{\alpha_{mpt}}\right) \quad (8)$$

$$P_{lt} - P_e \leq Min\left(\frac{P_b(t_1)}{\gamma_m \cdot \gamma_{sc}}; P_h\right) \quad (9)$$

Where:

P_{li} = Local incidental pressure
P_{lt} = Local system test pressure
P_h = Mill test pressure
α_{spt} = System pressure test factor
α_{mpt} = Mill pressure test factor
P_e = External pressure correspond to minimum water depth
$P_b\,(t_1)$ = Pressure Containment resistant
γ_m = Material resistant factor
γ_{sc} = Safety class resistant factor
min = Minimum elevation = 0.5*Hmax,100yr
α_u = Material strength factor

$$P_{li} = P_{inc} + \rho_{cont} \cdot g \cdot (h_{ref} - h_1) \quad (10)$$

$$P_{lt} = P_t + \rho_t \cdot g \cdot (h_{ref} - h_1) \quad (11)$$

Where:

P_{inc} = Incidental reference pressure at the reference elevation
P_{cont} = Density of the relevant content of the pipeline
h_{ref} = Elevation of the reference point (positive upwards)
h_1 = Elevation of the local pressure point (positive upwards)
g = Acceleration due to gravity
p_t = Test reference pressure at the reference elevation
ρ_t = Density of the relevant test medium of the pipeline

Calculations for pressure containment resistance, P_b (t_1), which is given by the minimum, is as follows:

$$P_b(t_1) = \frac{2t_1}{D - t_1} \cdot f_{cb} \cdot \frac{2}{\sqrt{3}} \quad (12)$$

$$f_{cb} = Min\left[f_y; \frac{f_u}{1.15}\right] \quad (13)$$

Where:

t_1 = Effective pipe wall thickness
= t – tfab (during installation / hydrotest)
= t – tfab – tcorr (during operation)
tfab = Negative wall thickness tolerance (12.5% t for seamless pipe)
tcorr = Corrosion allowance
D = Outside steel diameter pipe
f_y = Characteristic yield strength (SMYS - fy,-temp)
f_u = Characteristic tensile strength (SMTS – fu,temp)
SMTS = Specified Minimum Tensile Stress
fy,temp = De-rating values due to temperature of the yield stress
fu,temp = De-rating values due to temperature of tensile strength

The limiting external collapse pressure depends on the ratio of pipe wall thickness to outside diameter and ovality of the pipe. The characteristic resistance of the pipe wall against external collapse is calculated by considering the pipe as empty for installation and operation conditions and is obtained as follows:

$$(P_c - P_{el})(P_c{}^2 - P_p{}^2) = P_c \cdot P_{el} \cdot P_p \cdot f_0 \cdot \left(\frac{D}{t}\right) \quad (14)$$

$$f_0 = \frac{D_{max} - D_{min}}{D} \quad (15)$$

Elastic collapse pressure:

$$P_{el} = \frac{2E \cdot \left(\frac{t}{D}\right)^3}{1 - v^2} \quad (16)$$

Plastic collapse pressure:

$$P_p = 2 \cdot f_y \cdot \alpha_{fab} \cdot \left(\frac{t}{D}\right) \quad (17)$$

Where:

P_c = Characteristic collapse pressure
D_{max} = Greatest measured inside or outside diameter
D_{min} = Smallest measured inside or outside diameter
P_e = Maximum external pressure
= Max.elevation)
d_{max} = Maximum water depth along the route

Max.elevation = MSL + HAT + storm surge + 0.65*Hmax,100yr

Hmax,100yr = Maximum wave height 100 yr return period

γ = Specific weight of sea water

E = Modulus elasticity of steel

t = Wall thickness, shall be replaced by for external collapse check

t_1 = t – tfab (during installation)

= t – tfab - tcorr (during shutdown)

D = Outside steel diameter of pipe

To have adequate resistance against external collapse, the external pressure at any point along the route shall satisfy the following criteria:

$$P_e - P_{min} \leq \frac{P_c(t_1)}{\gamma_m \cdot \gamma_{sc}} \tag{18}$$

Where, *Pmin* is the minimum internal pressure that can be sustained. This is normally taken as zero for installation and shut down conditions. Subsea bends shall also be checked for collapse with three times external overpressure.

Once buckle is initiated, the buckle will be driven by the hydrostatic head until it reduces in a shallower water depth called buckle propagation depth. This so called buckle initiation pressure, Pin, will be higher than the buckle propagation pressure. The propagation buckling pressure occurs during the installation condition and calculations for it are as follows:

$$P_e - P_{min} \leq \frac{P_{pr}}{\gamma_m \cdot \gamma_{sc}} \tag{19}$$

$$P_{pr} = 35 f_y \cdot \alpha_{fab} \left(\frac{t_2}{D}\right)^{2.5} \qquad 15 < \frac{D}{t_2} < 45 \tag{20}$$

Where:

P_{pr} = Propagation buckling pressure

P_e = Maximum external pressure

P_{min} = Minimum internal pressure that can be sustained

α_{fab} = Fabrication factor

γ_{sc} = Safety class resistance factor

γ_m = Material resistance factor

t_2 = Effective pipe wall thickness

= t (during installation)

= t – tcorr (during shutdown)

t_{corr} = Corrosion allowance

D = Outside steel diameter of pipe

Material Grade Selection

Carbon steel pipe material properties are presented in Table 6. These properties are applicable for all the offshore field cases studied.

TABLE 6. Pipeline data

Description	Unit	Properties		
Pipe Material Specification[1]	-	API 5L PSL2		
Pipeline Grade	-	X60	X65	X70
SMYS	MPa	415	450	485
SMTS	MPa	520	535	570
Steel Density	kg/m^3	7850		
Elastic Young's Modulus	GPa	207		
Poisson's Ratio	-	0.3		
Thermal Expansion Coefficient	/ ºC	11.7 x 10^{-6}		

Notes:
1. Material grade and strength used in the study is listed in material grade selection section.

The selection of material grade is based on material strength and material cost. The most cost-effective material grades are determined based on the provided cost per metric ton as per vendor information and is shown in Table 7. Higher material grades consisting of X60, X65, and X70 have been considered in the study as they can provide better mechanical properties compared to lower material grades especially in deepwater conditions.

TABLE 7. Material cost

Material Grade	Material Cost (MYR / mt)[1]
X60	3600
X65	3800
X70	4000

Notes:
1. The cost is general for seamless pipe fabrication and may vary depending on wall thickness requirement

MATHCAD ANALYSIS

The pipeline wall thickness is commonly solved using analytical methods. Mathcad is a software application that is vastly used to solve various analytical pipeline design problems including wall thickness. It is a computer software tool for the verification, validation, documentation, and re-use of mathematical calculations. Mathcad enables users to solve complex problem by setting the mathematical notation and automatically computing the solution (Mathcad, 2020). Compared to other full programming languages such as MATLAB or Phyton, Mathcad is more suited for symbolic or numerical analyses to replace engineering graphs or calculation sheets. It is very much useful to derive symbolic expressions and data visualization which is a typical requirement in engineering problems.

In this study, the Mathcad spreadsheet contains built in design formulae that will be used to analyse and solve calculations for pipeline wall thickness using American and Norwegian standards. The spreadsheet used has been verified through manual calculation to confirm accuracy of the formula. In the beginning, data related to the pipeline design, operations, and environmental factors needed for the analysis is supplied under the input section. The input data will then be linked to the formulae written under the calculations section. The analytical process is then automatically done by Mathcad through backend calculations using the given formulae. Assuming no error was detected, the required wall thickness results will then be displayed in the output section.

Table 8 shows the overall list of pipeline wall thickness analysis. In total, 18 analyses of various pipeline grades, water depths, and standards have been conducted in this study.

TABLE 8. List of analysis for wall thickness assessment

Item	Material Grade	Water Depth (m)	Standards
1	X60	66.7	American
2	X60	575.0	American
3	X60	1350.0	American
4	X65	66.7	American
5	X65	575.0	American
6	X65	1350.0	American
7	X70	66.7	American
8	X70	575.0	American
9	X70	1350.0	American
10	X60	66.7	Norwegian
11	X60	575.0	Norwegian
12	X60	1350.0	Norwegian
13	X65	66.7	Norwegian
14	X65	575.0	Norwegian
15	X65	1350.0	Norwegian
16	X70	66.7	Norwegian
17	X70	575.0	Norwegian
18	X70	1350.0	Norwegian

RESULTS AND DISCUSSION

WALL THICKNESS RESULT USING AMERICAN STANDARDS

Table 9 presents the result of the calculated wall thickness for Zone 1 (pipeline) and Zone 2 (riser) based on different pipe material grades and water depth condition respectively. The number with asterisk symbol (*) represent the governing wall thickness selected for a safe pipeline design under this standard.

TABLE 9. Wall thickness result summary based on material grade and water depth condition under American Standards (Case 1 – Case 9)

Case	Pipe Grade	Water Depth	Zone	Calculated WT (mm) + CA(1)		
				Cri. 1	Cri. 2	Cri. 3
1	X60	Shallow	1	6.49*	5.69	4.15
			2	8.02*	5.69	4.15
2	X60	Medium	1	5.23	8.86	10.69*
			2	6.21	8.86	10.69*
3	X60	Deep	1	2.90	11.25	15.31*
			2	2.86	11.25	15.31*
4	X65	Shallow	1	6.22*	5.69	4.01
			2	7.63*	5.69	4.02
5	X65	Medium	1	5.06	8.84	10.34*
			2	5.96	8.84	10.34*
6	X65	Deep	1	2.91	11.15	14.81*
			2	2.87	11.15	14.81*
7	X70	Shallow	1	5.99*	5.69	3.89
			2	7.30*	5.69	3.89
8	X70	Medium	1	4.91	8.82	10.02*
			2	5.75	8.82	10.02*
9	X70	Deep	1	2.92	11.07	14.35*
			2	2.88	11.07	14.35*

Note:
1. The selected wall thickness value are in accordance with standard API Spec 5L.

Based on Table 9, it can be deduced that regardless of pipe grade used, pressure containment (Criteria 1) governs the wall thickness value for shallow water depth, while propagation buckling (Criteria 3) governs the wall thickness value for medium and deepwater depths. According to pass literature, external pressure becomes more dominant as water depth increases. This condition causes a shift in the wall thickness governing criteria from pressure containment (bursting) to buckling due to external over pressure (Fyrileiv et al., 2013)at least for the coming decades, the world has to rely on oil and gas to address this need. Most of the easiest accessible offshore petroleum reservoirs have been discovered and a great part developed over the last six decades. Thus, development of new oil and gas fields faces a lot of challenges as most of them are in remote areas, in deep waters and/or in areas with extreme environments like the Arctic region. One of the major trends in the offshore petroleum industry points towards deeper waters (e.g. outside West Africa, the Brazilian Pre-Salt developments and in the Gulf of Mexico. From this result, the highest wall thickness required is 15.31mm from Case 3 (X60 grade and deepwater condition) while the lowest is 5.99mm from Case 7 (X70 grade and shallow water condition).

In regards to the material grades, it was found that under the same water depth conditions, wall thickness reduces as the material grade increases. Increasing the pipe grade from

X60 to X70 will increase its material tensile strength from 520 MPa to 570 MPa. This improvement in mechanical strength increases the resistance of the pipeline to failure, resulting in lower wall thickness requirement (A. K. Junaidi & Koto, 2014. Figures 1 to 3 show the reduction trend in wall thickness requirement as material grade increases for shallow, medium, and deepwater conditions respectively.

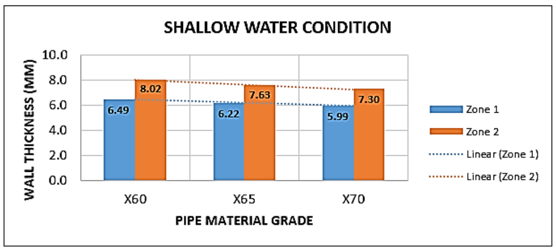

FIGURE 1. Wall thickness against material grade for shallow water depth condition (American Standards)

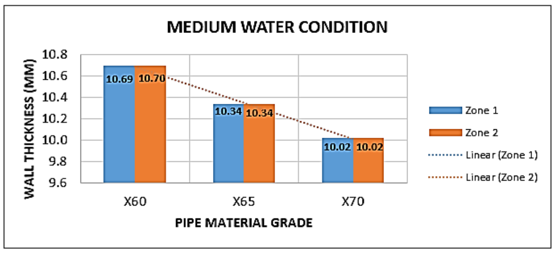

FIGURE 2. Wall thickness against material grade for medium water depth condition (American Standards)

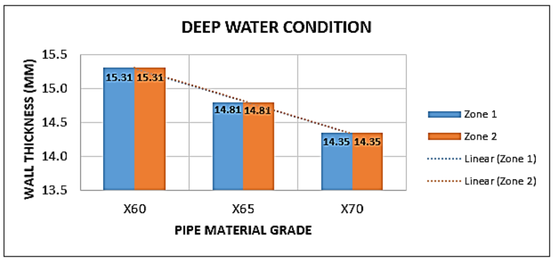

FIGURE 3. Wall thickness against material grade for deepwater depth condition (American Standards)

Overall, from Figures 1 to 3, the selected wall thickness shows a consistent reduction trend from X60 grade up to X70 grade. The highest reduction percentage occurred in shallow water condition at 8.96%. Medium water and deepwater conditions follow with a tie at 6.3% reduction. Apart from less reduction in percentage, the medium and deepwater conditions also show no apparent difference in wall thickness between zone 1 (pipeline) and zone 2 (riser). This is due to the same design factors used for both zones when propagating buckling criteria governs the wall thickness requirement as compared to pressure containment criteria.

These findings from American Standards illustrate that material grade selection has more influence on the wall thickness requirement for shallow water as compared to medium and deepwater. The higher-grade strength is found to be more advantageous when pressure containment is the governing criteria. However, with reduction range of around 6% - 9% overall, increasing the pipe's material grade is still highly beneficial for wall thickness reduction across all water depth conditions.

WALL THICKNESS RESULT USING NORWEGIAN STANDARDS

Table 10 presents the result of the calculated wall thickness for Zone 1 (pipeline) and Zone 2 (riser) based on different pipe material grades and water depth conditions respectively. The number with asterisk symbol (*) represent the governing wall thickness which is required to be selected for a safe pipeline design under this standard.

TABLE 10. Wall thickness result summary based on material grade and water depth condition under Norwegian Standard (Case 10 – Case 18)

Case	Pipe Grade	Water Depth	Zone	Calculated WT (mm) + CA[1]		
				Cri. 1	Cri. 2	Cri. 3
10	X60	Shallow	1	8.00*	6.39	4.73
			2	8.49*	6.89	4.73
11	X60	Medium	1	7.60	8.91	10.55*
			2	7.60	8.91	10.55*
12	X60	Deep	1	4.32	13.11	14.75*
			2	4.28	13.11	14.75*
13	X65	Shallow	1	7.73*	6.11	4.58
			2	8.18*	6.58	4.58
14	X65	Medium	1	7.43	8.56	10.20*
			2	7.43	8.56	10.20*
15	X65	Deep	1	4.35	12.66	14.30*
			2	4.31	12.66	14.30*
16	X70	Shallow	1	7.50*	5.88	4.45
			2	7.92*	6.30	4.45
17	X70	Medium	1	7.28	8.26	9.90*
			2	7.28	8.26	9.90*
18	X70	Deep	1	4.37	12.22	13.86*
			2	4.43	12.22	13.86*

Note:
1. The selected wall thickness values are in accordance with standard API Spec 5L.

Based on Table 10, pressure containment (Criteria 1) governs the wall thickness value for shallow water depth, while propagation buckling (Criteria 3) governs the wall thickness value for medium and deepwater depths. The highest wall thickness required is 14.75mm from Case 12 (X60 grade and deepwater condition) while the lowest is 7.50mm from Case 16 (X70 grade and shallow water condition).

This result trend is similar to previous findings under the American Standard in which the propagation buckling criteria governs medium and deepwater conditions while pressure containment governs shallow water conditions (Table 9). The Norwegian Standard provides a higher wall thickness (8.00mm) than the American Standard (6.49mm) for shallow water depth (Case 1 and Case 10) at zone 1. However, in deepwater (Case 9 and 18), the wall thickness is higher in the American Standard (14.35mm) as compared to the Norwegian Standard (13.86mm).

This difference in result is mainly due to the design factors used for both standards. Norwegian Standards implements LRFD which allows more factors as an input in the design equation compared to a more stringent requirement of American Standards with ASD. (Ragupathy & Sriskandarajah 2014). For example, the pressure containment criteria for Norwegian Standards must consider factors such as material temperature de-rating (Eq. 13). This reduces the material strength and results in more wall thickness requirement especially in shallow water (Dàngelo et al., 2016).

Meanwhile, the introduction of various factors including fabrication factor, safety class, and material resistance factor in the propagating buckling criteria of Norwegian Standard allow for less wall thickness requirement in deepwater condition compared to the single design factor used in American Standards.

For material grades, a similar trend is found between both standards. Under the same water depth condition, wall thickness reduces as the material grade increases. Figures 4 to 6 show the reduction trend in wall thickness requirement as material grade increases for shallow, medium, and deepwater respectively.

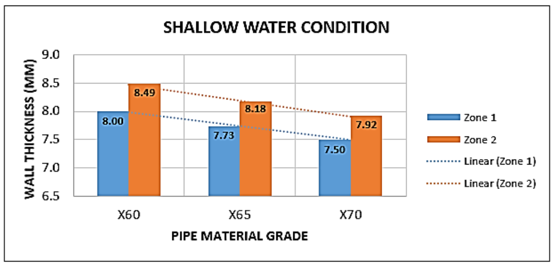

FIGURE 4. Wall thickness against material grade for shallow water depth condition (Norwegian Standards)

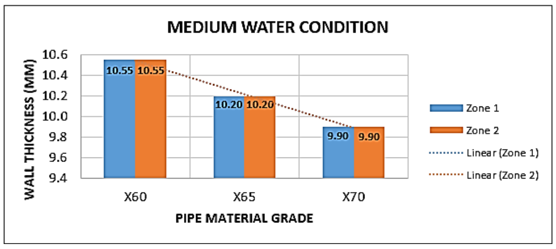

FIGURE 5. Wall thickness against material grade for medium water depth condition (Norwegian Standards)

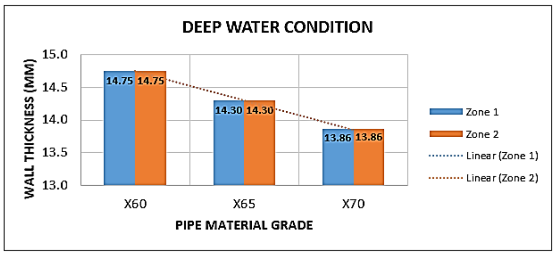

FIGURE 6. Wall thickness against material grade for deepwater depth condition (Norwegian Standards)

Based on Figures 4 to 6, the highest reduction percentage occurred in shallow water condition at 6.71%, followed by medium and deepwater condition at 6.16%, and 6.03%, respectively. This indicates that wall thickness reduction lessens as the water depth increases.

Nevertheless, the reduction percentage is still in the close range of 6 – 7%, showing the important impact of material strength on wall thickness requirement. Wall thickness between zone 1 (pipeline) and zone 2 (riser) for medium and deepwater conditions also shows no apparent difference in wall thickness requirement compared to the shallow water condition due to the influence of different governing criteria at deeper water depths.

COMMERCIAL RESULT

Table 11, 12, and 13 respectively show the commercial comparison of the wall thickness under shallow, medium, and deepwater depth conditions based on American and Norwegian Standards.

TABLE 11. Commercial comparison for shallow water depth condition

Item	Zone	Pipe Material Grade					
		American Standard (ASME & API)			Norwegian Standard (DNV)		
		X60	X65	X70	X60	X65	X70
Selected WT (mm)[1]	1	6.491	6.220	5.987	8.000	7.730	7.500
	2	8.021	7.631	7.302	8.490	8.180	7.920
Unit Cost (MYR/tonne) [2]	1	3600	3800	4000	3600	3800	4000
	2						
Unit Weight (tonne/m)	1	0.0340	0.0327	0.0315	0.0418	0.0404	0.0392
	2	0.0417	0.0398	0.0381	0.0443	0.0428	0.0414
Pipe Length[3] (m)	1	10000					
	2	250					
Total Cost[4] (MYR)	1	1,225,382.27	1,241,036.86	1,258,795.06	1,499,534.83	1,531,377.55	1,565,715.16
	2	37,583.04	37,811.82	38,145.17	39,692.19	40,426.91	41,252.84
	1 + 2	1,262,965.31*	1,278,848.68*	1,296,940.23*	1,539,227.02	1,571,804.46	1,606,968.00

Note:
1. The selected wall thickness values are in accordance with standard API Spec 5L.
2. The cost values is general for seamless pipe fabrication and will vary depending on wall thickness requirements.
3. Total length is assumed for a total 10km pipeline route and total 250m riser (both sides).
4. Asterisk symbols (*) shows the value with the lowest cost for each wall thickness grade.

TABLE 12. Commercial comparison for medium water depth condition

Item	Zone	Pipe Material Grade					
		American Standard (ASME & API)			Norwegian Standard (DNV)		
		X60	X65	X70	X60	X65	X70
Selected WT (mm)[1]	1	10.694	10.339	10.021	10.550	10.200	9.900
	2	10.695	10.340	10.021	10.550	10.200	9.900
Unit Cost (MYR/tonne) [2]	1	3600	3800	4000	3600	3800	4000
	2						
Unit Weight (tonne/m)	1	0.0550	0.0532	0.0517	0.0543	0.0526	0.0511
	2	0.0550	0.0532	0.0517	0.0543	0.0526	0.0511
Pipe Length[3] (m)	1	10000					
	2	250					
Total Cost[4] (MYR)	1	1,978,922.27	2,022,960.20	2,067,080.10	1,953,624.05	1,997,091.88	2,043,302.68
	2	49,477.45	50,578.65	51,677.00	48,840.60	49,927.30	51,082.57
	1 + 2	2,028,399.72	2,073,538.85	2,115,920.70	2,002,464.65*	2,047,019.18*	2,094,385.25*

Note:
1. The selected wall thickness values are in accordance with standard API Spec 5L.
2. The cost values is general for seamless pipe fabrication and will vary depending on wall thickness requirements.
3. Total length is assumed for a total 10km pipeline route and total 250m riser (both sides).
4. Asterisk symbols (*) shows the value with the lowest cost for each wall thickness grade.

TABLE 13. Commercial comparison for deepwater depth condition

Item	Zone	Pipe Material Grade					
		American Standard (ASME & API)			Norwegian Standard (DNV)		
		X60	X65	X70	X60	X65	X70
Selected WT (mm)[1]	1	15.313	14.805	14.350	14.750	14.300	13.860
	2	15.314	14.806	14.350	14.750	14.300	13.860
Unit Cost (MYR/tonne)[2]	1	3600	3800	4000	3600	3800	4000
	2						
Unit Weight (tonne/m)	1	0.0770	0.0746	0.0725	0.0743	0.0722	0.0702
	2	0.0770	0.0746	0.0725	0.0743	0.0722	0.0702
Pipe Length[3] (m)	1	10000					
	2	250					
Total Cost[4] (MYR)	1	2,770,863.28	2,834,820.62	2,898.755.86	2,676,362.90	2,744,893,03	2,806,474.27
	2	69,271.58	70,870.52	72,468.90	66,909,07	68,622.33	70,161.86
	1 + 2	2,840,131.86	2,905,691.14	2,971,224.76	2,743,271.97*	2,813,515.36*	2,876,636.13*

Note:
1. The selected wall thickness values are in accordance with standard API Spec 5L.
2. The cost values is general for seamless pipe fabrication and will vary depending on wall thickness requirements.
3. Total length is assumed for a total 10km pipeline route and total 250m riser (both sides).
4. Asterisk symbols (*) shows the value with the lowest cost for each wall thickness grade.

Under the shallow water depth condition, although higher grades resulted in lower wall thickness requirement and less unit weight per meter as per Table 11, the increased unit cost resulted in a higher total cost. Overall, the lowest cost was at MYR 1,262,965.31, which is pipe grade X60 based on the American Standard. Meanwhile, the highest cost was MYR 1,606,968.00 which is pipe grade X70 based on the Norwegian Standard.

Material grades comparison show a price difference between 18% - 24% for both standards, in which the American Standard costs are lower for all grades. These findings indicate that the American Standard is a more favourable option than the Norwegian Standard at shallow water condition.

For the medium water depth condition, the lowest overall cost as per Table 12 was MYR 2,002,464.65 which is pipe grade X60 based on the Norwegian Standard. Meanwhile the highest cost was at MYR 2,115,920.70 which is pipe grade X70 based on the American Standard. This result is opposite to the previous shallow water condition. As the water deepens, the transition of the governing criteria from pressure containment to buckling has benefited Norwegian Standards through its more detailed safety and resistance factors to obtain a much lower cost (Dianita & Dmitrieva, 2016).

Meanwhile, the material grades comparison shows a price difference of between 1% - 1.3% for both standards, in which the Norwegian Standard costs are lower for all grades. These findings thus indicate that the Norwegian Standard is a more favourable option than the American Standard at the medium water depth condition. Although the price difference is low in percentage, the margins in term of actual cost are bound to increase along with project requirements that may involve the usage of a larger pipe diameter and longer pipelines.

Table 13 shows the commercial comparison of wall thickness using American Standard and Norwegian Standard under deepwater depth condition. A similar result can be seen as per medium water depth condition, in which the lowest cost was pipe grade X60 based on the Norwegian Standard, which was at MYR 2,743,271.97, while the highest cost was at MYR 2,971,224.76 which was pipe grade X70 based on the American Standard.

The material grades comparison shows a price difference of between 3.2% - 3.4% for both standards in which the Norwegian Standard cost is lower for all grades. These findings indicate that the Norwegian Standard is a more favourable option than the American Standard at deepwater depth condition. In addition, grade X65 from the

Norwegian Standard (MYR 2,813,515.36) still cost relatively lower than grade X60 from the American Standard (MYR 2,840,131.86). Thus, engineers or end users have an option to upgrade their pipe strength at a relatively low cost when using the Norwegian Standards in deepwater condition. Previous studies have also shown the benefit of using this standard in deepwater which resulted in a minimum wall thickness requirement that translated to lower cost (Dàngelo et al., 2016; Langhelle, 2011).

OPTIMAL STANDARD FINDINGS

Figure 7 shows the overall commercial comparison chart between both standards showing the lowest pipeline cost incurred under shallow, medium, and deepwater conditions respectively. Based on the analysis and findings from current studies, the American Standard is the favourable option to be used in shallow water condition. At the same time, the Norwegian Standard governs for the medium and deepwater conditions.

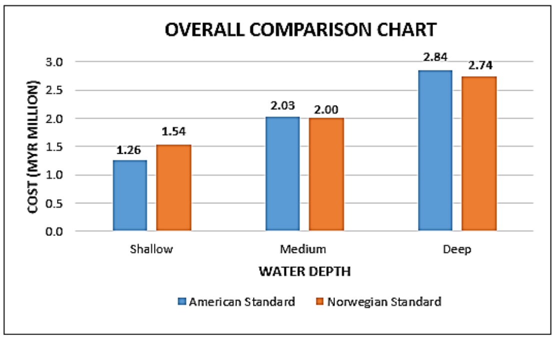

FIGURE 7. Pipeline cost against water depth for both American and Norwegian Standard

Assuming a pipeline route project consisted of shallow, medium, and deepwater conditions with 30km total length, the total cost if using only the American Standard is MYR 6,131,496.89 while for the Norwegian Standard is MYR 6,284,963.64. Though it is a small difference of around 2.5%, the lower cost obtained from the American Standard may be favourable if the project only allows for one specific design standard to be used due to a constant wall thickness requirement. However, in the case where different design standards are allowed, a combination of American Standards for shallow water and Norwegian Standards for medium and deepwater is optimal, with a total cost of MYR 6,008,701.93 which is much lower than the previous cost calculated.

CONCLUSION

There are three main objectives of this study. The first one is to evaluate the wall thickness required using American and Norwegian pipeline standards under different steel grade and water depth condition. Next is to compare the pipeline cost for both standards at each water depth condition for commercial evaluation. Finally at the end of the study, the optimal pipeline standards to be used for wall thickness design is determined. In conclusion, the conducted study has managed to achieve the required objectives as listed below:

1. The comparison in shallow water at zone 1 shows the Norwegian Standard providing higher wall thickness than American Standards. However, in deepwater it shows the American Standard providing higher wall thickness than the Norwegian Standard. The difference in result is mainly due to the type of design factor used for both standards. Norwegian Standards which implement LRFD have allowed for more factors as an input to the design equation compared to a more stringent requirement of American Standards with ASD.
2. The commercial assessment categorized by material grade for both standards shows a price difference between 18% - 24% for shallow water depth, 1% - 1.3% for medium water depth, and 3.2% - 3.4% for deepwater. American Standards have governed the lowest cost for shallow water condition using pipe grade X60, while Norwegian Standards have governed the lowest cost for medium and deepwater, both respectively for pipe grade X60. Moreover, at deepwater condition, grade X65 from the Norwegian Standard has been found to cost relatively less than grade X60 from the American Standard. Hence, this gives engineers an option to upgrade pipe strength while maintaining a reasonably lower cost when using the Norwegian Standard at deepwater condition.
3. Considering a pipeline project which consists of a combination of shallow, medium, and deepwater conditions along its route, the total cost if only using the American Standards is comparatively lower than using only Norwegian Standards, with a difference of 2.5%. Thus, the American Standard is favourable if the project only allows for one specific design standard due to constant wall thickness requirement. However, in a case whereby multiple design standards are allowed, a combination of American Standards for shallow water and Norwegian Standards for medium and deepwater is optimal, in which the total cost of the pipeline will be 2% additionally lower than using only the American Standard.

Current studies involve only a limited variety of factors such as water depth and material grade as the key focus. Other design conditions such as pipe size, transported product, product density, temperature, and corrosion allowance is controlled. In actuality, these parameters will vary as well according to project requirement. Thus, including more varied factors in the analysis will contribute to a better understanding on the influence of other design conditions towards wall thickness selection, and provide a more extensive database for a pipeline standards comparison study in the future.

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DECLARATION OF COMPETING INTEREST

None

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