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An Analytical Assessment of Critical Parameters in Subsea Pipeline Installation: Methodologies, Technical Challenges, and Strategic Solutions

Abstract

The installation and construction of subsea pipelines is a highly complex process, necessitating critical engineering calculation models. Considering that oil and gas reserves are increasingly being extracted from deeper oceanic depths, there is a growing need for new methodologies for the design and analysis of subsea pipelines. This paper investigates the pipeline installation technology in deep waters, highlighting both its advantages and limitations. During the research, international standards such as ASME and DNV were referenced. The calculations were applied to a pipeline with a diameter of 18 inches, examining the dependencies of local buckling propagation pressure, external pressure, and burst pressure for pipelines with varying wall thicknesses at different sea depths. Finally, graphical simulations and a parametric dependence table were developed to illustrate the results.

Keywords: *ovality, material resistance factor, material safety class factor, propagation buckling, external pressure*

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Sualtı boru kəməri quraşdırılmasında kritik parametrlərin analitik qiymətləndirilməsi: metodologiyalar, texniki çağırışlar və strateji həllər

Xülasə

Sualtı boru kəmərlərinin çəkilməsi və quraşdırılması əməliyyatlarının aparılması çox çətin proses olduğundan onların kritik mühəndisi hesablama modellərinə ehtiyac duyulur. Neft və qaz ehtiyatlarının gün keçdikcə dənizin daha dərinliklərindən hasil olunduğunu nəzərə alsaq, sualtı boru kəmərlərinin hesablanması üçün yeni metodologiyalara ehtiyac duyulur. Məqalədə dərin sularda boru kəmərlərinin çəkiliş texnologiyası araşdırılmış, onların müsbət və çatışmayan cəhətləri göstərilmişdir. Tədqiqat zamanı ASME və DNV kimi beynəlxalq standartlarlara istinad edilmişdir. Hesablamalar diametri 18 düymə olan boru kəməri üçün müxtəlif dəniz dərinliklərində, müxtəlif divar qalınlıqlı boru kəmərlərinin yerli bükülmənin yayılma təzyiqindən, xarici təzyiqdən və dağılma təzyiqindən asılılıqları əldə etmək üçün tətbiq edilmişdir. Sonda parametrik asılılıqları göstərmək üçün qrafiki simulyasiya və parametrik asılılıq cədvəli tərtib edilmişdir.

Açar sözlər: *ovallıq, material müqavimət amili, material təhlükəsizlik sinfi amili, bükülmənin yayılması, xarici təzyiq*

Introduction

As the population increases, the environment deteriorates, and resources become scarce, the oceans demonstrate clear advantages in terms of space, resources, environment, and strategy due to continuous advancements in ocean science and technology. Ocean resources, including fisheries, space, and energy, have become a major area with significant potential for development in the 21st century (Wang, Lu, & Yin, 2021; Peng, 2020). Currently, oil and gas reserves, the primary sources of energy, have driven countries around the world to engage in active exploration and exploitation (Cherepovitsyn, Rutenko, & Solovyova, 2021; Wang, Zhang, & Xu, 2023). The extraction, processing, storage, and transportation of offshore oil and gas reserves involve pipelines, which play a crucial role as efficient, safe, cost-effective, and reliable means that tightly integrate the entire production process of ocean resource development, ensuring the proper functioning of resource development (Koley, 2023; Zhang, 2020; Guo et al., 2022). Given these considerations, the requirements for subsea pipeline installation technologies and the development of new methods for their safe application are among the most critical issues.

There are four methods for the installation of subsea pipelines:

- S-lay method
- J-lay method
- Reel-lay method
- Tow method

This paper explores the advantages and disadvantages of these installation technologies, as well as the challenges encountered during the installation process, with an aim to optimize them. Considering the challenges faced in deepwater installations, such as the application of S and J-lay technologies and the joining of pipelines on the seabed, the article investigates undesirable occurrences and proposes various methods to prevent them. The following presents the sequence of the process, as well as the positive and negative aspects of the S-lay installation technology. The S-lay method is specifically designed for the installation of subsea pipelines in shallow to medium-depth waters (Callegari et al., 2003). The process sequence includes pipe preparation, installation of the laying vessel, pipe assembly, diagnostic testing, application of protective coating, and final pipeline installation (Figure 1) (DNV, 2005). This method has both notable advantages and certain limitations.

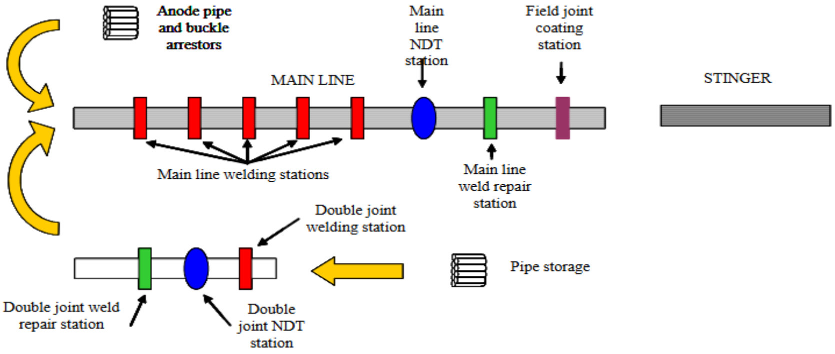


Figure 1. Schematic description of S-lay technology

Advantages of the method: high productivity, efficiency, versatility.

Disadvantages of the method: deck space, depth limitations.

The sequence of steps, along with the positive and negative aspects of the J-lay method, are as follows:

Process steps: Pipe preparation, mobilization of the pipelayer vessel, pipe assembly, diagnostic testing, application of protective coating, pipeline installation (Figure 2) (Springmann & Hebert, 1994).

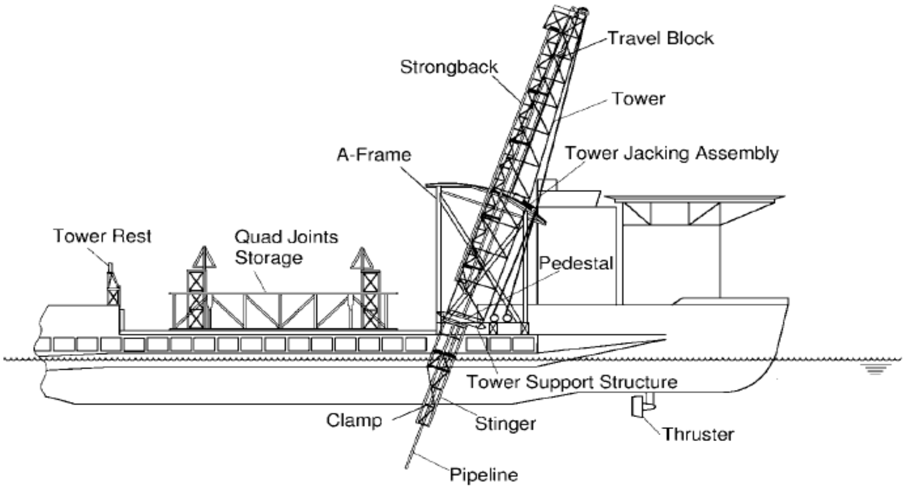


Figure 2. Schematic drawing of the DP 50 and its J-lay tower

Advantages of the method: precise control over pipe laying, high-quality welding, operational capacity.

Disadvantages of the method: lower installation rates, need for specialized vessels.

Problem setting

- In the initial stages of design, DNV-OS-F101 [11] outlines preliminary criteria for assessing both overbend and sagbend conditions. Specifically, overbend static strains are to be calculated in accordance with "Criterion 1" as outlined in Table 1, which accounts for strains induced by axial forces, bending loads, and localized roller loads. Effects due to varying stiffness are considered negligible under this criterion. Conversely, "Criterion 2" in table 1 addresses combined static and dynamic loading conditions, encompassing all relevant effects, including those related to stiffness variation.

Table 1

Criterion	X70	X65	X60	X52
1	0.270%	0.250%	0.230%	0.205%
2	0.325%	0.305%	0.290%	0.260%

For combined static and dynamic loads, the equivalent stress at the stinger end and sagbend region should not exceed the prescribed limits [11].

$$\sigma_{eq} < 0.87 \cdot f_y \qquad (1)$$

f_y - yield stress;

σ_{eq} - equivalent stress.

The selection of material types and properties is influenced by factors including external pressure, internal pressure, fluid characteristics, mechanical requirements, weight constraints, and cost considerations. According to DNV-OS-F101, the following material characteristics are essential for submarine pipelines:

- Weldability, mechanical properties, corrosion resistance, fatigue resistance, hardness, fracture toughness

These properties must be rigorously evaluated to ensure the pipeline's structural integrity and operational reliability under diverse environmental and loading conditions. Pipeline wall thickness must have a minimum wall thickness to avoid the following three failures:

- Collapse due to external pressure only (local buckling).
- Propagation buckling for external pressure only.
- Bursting (containment of internal pressure).

Two distinct characterizations of wall thickness, denoted as t_1 and t_2, are employed within the design criteria to address different failure scenarios. Thickness t_1 is applied in contexts where failure is anticipated due to low structural capacity, often influenced by system effects. Conversely, thickness t_2 is utilized for conditions where failure is expected under extreme load effects at locations with average wall thickness. The specific definitions and applicable values for t_1 and t_2 are detailed in table 2.

Table 2

Characteristic wall thickness		
	Prior to operation	operation
t_1	$t-t_{fab}$	$t-t_{fab}-t_{cor}$
t_2	t	$t-t_{cor}$

t_{fab} - fabrication thickness tolerance;

t_{corr} - corrosion allowance.

According to DNV, all points along the pipeline must meet the following criteria:

$$Pe-Pmin\leq P_C(t_1)/\gamma_m\gamma_{SC} \quad (2)$$

The resistance to external pressure (Pc) (bursting) should be calculated as follows:

$$\left(P_c(t)-P_{el}(t)\right)*\left(P_c(t)^2-P_{el}(t)^2\right)=P_c(t)*P_{el}(t)*P_p(t)*f_0*\frac{D}{t} \quad (3)$$

Wall thickness tolerances are defined by DNV-OS-F101 to be in accordance with table 3 for the different pipeline types.

Table 3

Tolerance for wall thickness			
Type of pipe	Wall thickness	Frequency of inspection	Tolerances
SMLS	t<4.0	100%	+ 0.6 mm - 0.5 mm
	4.0≤t<10.0		+ 0.15 t - 0.125 t
	10.0≤t<25.0		± 0.125 t
	t≥25.0		+ 0.1 t or + 3.7 mm, whichever is greater - 0.1 t or - 3.0 mm, whichever is greater
HFW, EBW, LBW and MWP	t≤6.0		± 0.4 mm
	6.0<t≤15.0		± 0.7 mm
	t>15.0		± 1.0 mm
SAW	t≤6.0		± 0.5 mm
	6.0<t≤10.0		± 0.7 mm
	10.0<t≤20.0		± 1.0 mm
	t>20.0		+ 1.5 mm - 1.0 mm

t = Nominal wall thickness;

SMLS = Seamless Pipe;

HFW = High Frequency Welding;

EBW = Electronic Beam Welded;

LBW = Laser Beam Welded;

MWP = Multiple Welding Process;
SAW = Submerged Arc-Welding.

The likelihood of local buckling occurring over long distances in pipelines can be reduced by installing buckle arrestors. To ensure protection of the pipeline against local buckling, the following conditions must be satisfied:

$$P_e < \frac{P_{PR}}{\gamma_m \gamma_{SC}} \qquad (4)$$

Pe – external pressure;
γ_m- material resustance factor;
γ_{SC} – material safety class factor;
P_{PR} – the pressure for propagation buckling, and determine the following equation:

$$P_{PR} = 35 f_y \alpha_{fab} \left(\frac{t_2}{D}\right)^{2.5}; \qquad \frac{D}{t_2} < 45 \qquad (5)$$

f_y – yield stress;
α_{fab} – fabrication factor;
t_2 – pipe wall thickness;
D – pipe diameter.

The initial parameters required for the calculation of collapse pressure, propagation pressure, and burst pressure in an underwater pipeline are provided in the table below (Table 4).

Table 4

Initial parameters	**Corresponding values**
Pipe material	steel
Material grade	X65
Pipe diameter	457.20 mm
Steel density	7850 kq/m^3
Young's modulus	2.07*10^{-7}
Poison ratio	0.3
SMYS	448*10^6 Pa
SMTS	531*10^6 Pa
Corrosion thickness	3 mm
Sea density	1025 kq/m^3
Sea depth	{100-500} m
Empty pipe	Weather
Ovality	1.5 %
Material resistance factor	1.15
Material safety class factor	0.96
Fabrication factor	1 mm
Pipe wall thickness	{7.92; 9.53; 9.53; 12.7} [12]
Gravity	9.81 m/s^2
Corrosion coating	20 mm
Material stength factor	0.96
Maximum fabrication factor	0.93 for *UO & TRB & ERW*
Functional load effect factor	1.2
Condition load effect factor	1.07
Enviromental load effect factor	0.7

Conclusion

For each sea depth and wall thickness, check whether $P_{external} > P_{collapse}$ and $P_{propagation}$ or $P_{ex} > P_{burst}$.

Observations:

- **Collapse pressure** is constant for a given wall thickness, as it depends only on material properties and dimensions.
- **Propagation pressure** and **burst pressure** are significantly higher than environmental pressures at all sea depths, ensuring safety for internal and external loads.
- **Environmental pressure** increases linearly with sea depth, posing a greater challenge to pipeline integrity at higher depths.

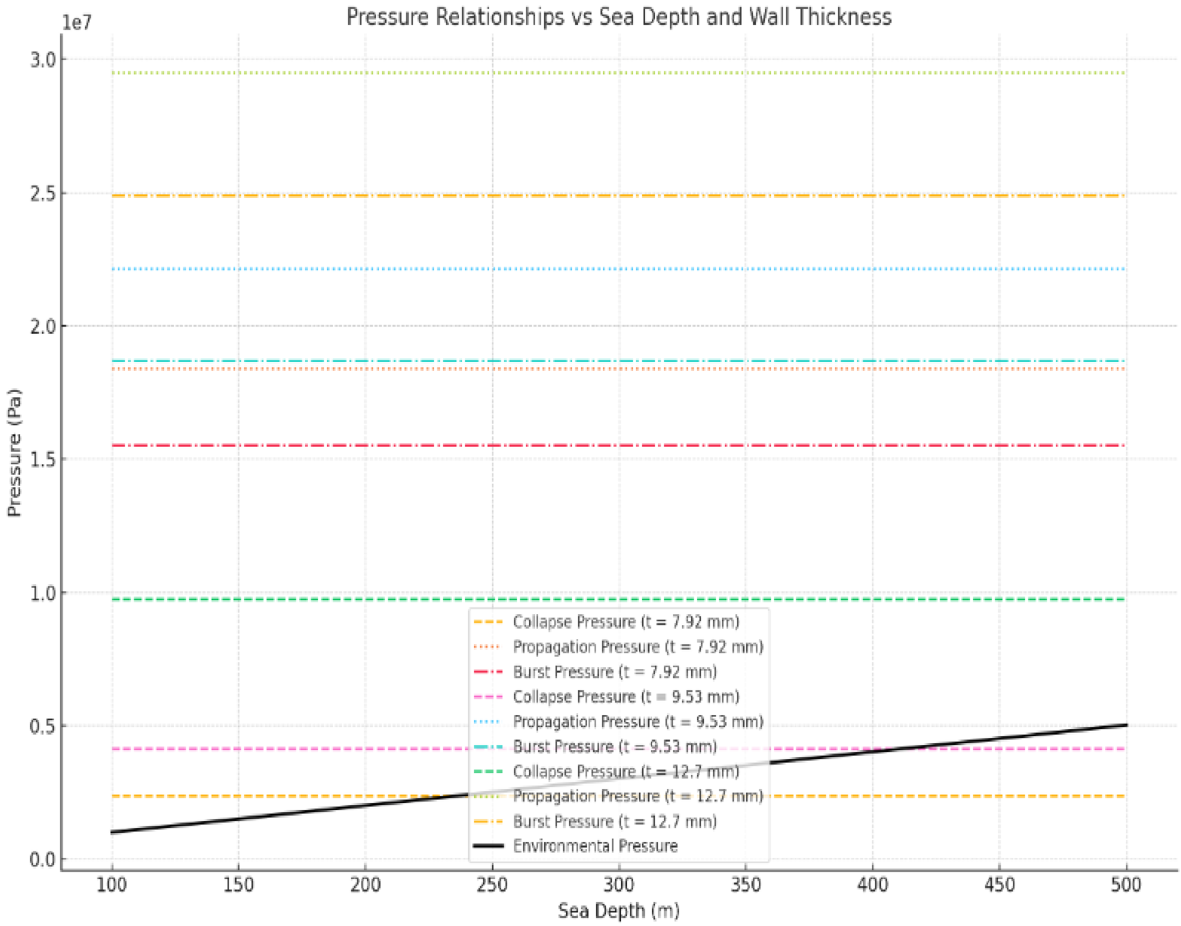
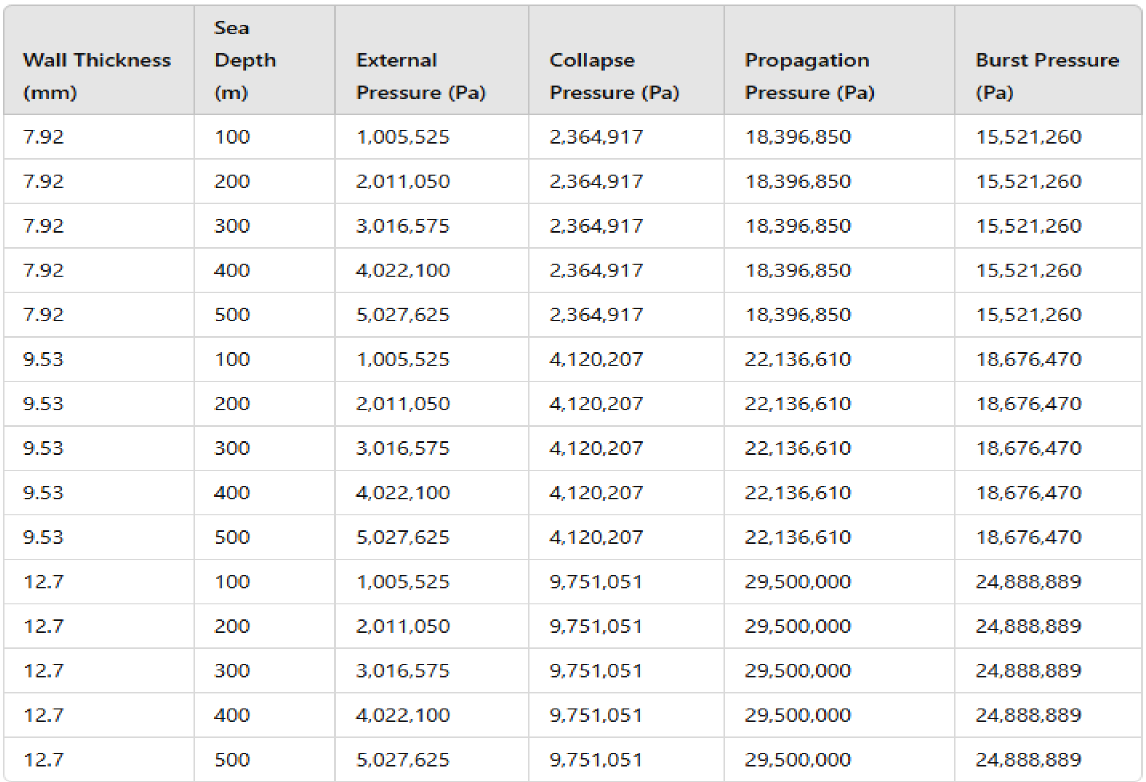


Figure 3. Pipe wall thickness and collapse pressure, propagation pressure and burst pressure relationships

Table 5



Wall Thickness (mm)	Sea Depth (m)	External Pressure (Pa)	Collapse Pressure (Pa)	Propagation Pressure (Pa)	Burst Pressure (Pa)
7.92	100	1,005,525	2,364,917	18,396,850	15,521,260
7.92	200	2,011,050	2,364,917	18,396,850	15,521,260
7.92	300	3,016,575	2,364,917	18,396,850	15,521,260
7.92	400	4,022,100	2,364,917	18,396,850	15,521,260
7.92	500	5,027,625	2,364,917	18,396,850	15,521,260
9.53	100	1,005,525	4,120,207	22,136,610	18,676,470
9.53	200	2,011,050	4,120,207	22,136,610	18,676,470
9.53	300	3,016,575	4,120,207	22,136,610	18,676,470
9.53	400	4,022,100	4,120,207	22,136,610	18,676,470
9.53	500	5,027,625	4,120,207	22,136,610	18,676,470
12.7	100	1,005,525	9,751,051	29,500,000	24,888,889
12.7	200	2,011,050	9,751,051	29,500,000	24,888,889
12.7	300	3,016,575	9,751,051	29,500,000	24,888,889
12.7	400	4,022,100	9,751,051	29,500,000	24,888,889
12.7	500	5,027,625	9,751,051	29,500,000	24,888,889

Failure modes (Table 5) and (Figure 3): At a depth of **500 meters**, pipes with a thickness of **7.92 mm** fail due to collapse because the external pressure exceeds the collapse pressure. **9.53 mm** and **12.7 mm** thickness pipes remain safe at 500 m.

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