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Free-Span Support Spacing Design of a Shallow Offshore Gas Pipeline

Oghenethoja M. Umuteme[1], Charles U. Orji[2]
[1] (School of Sciences, Health Sciences, Technology and Engineering, UNICAF, Larnaca, Cyprus)
[2](Centre of Excellence in Marine and Offshore Engineering, Rivers State University, Port Harcourt, Nigeria)

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ABSTRACT: This study evaluates the maximum allowable free-spanning length and pile support spacing for an 18-inch shallow offshore gas pipeline in 30 m water depth using static, flow-induced vortex-induced vibration (VIV), and vertical deflection analyses. In accordance with DNV-RP-F105, static strength, dynamic response, and serviceability criteria were assessed to account for sensitivity to boundary conditions at high span-to-diameter ratios. Results indicate that VIV effects reduce the allowable free-span length to approximately 21 m, while the vertical deflection criterion is the most conservative, limiting the span to about 13 m. Based on these findings, a conservative pile support spacing of 10 m is recommended to ensure structural integrity, fatigue resistance, and constructability. The methodology presented also serves to guide young engineers in understanding how supports are designed to prevent excessive bending, oscillations, and serviceability issues in free-spanning pipelines.

KEYWORDS: Free-span pipeline, Vortex-induced vibration (VIV), Shallow offshore gas pipeline, Static stress analysis, Pile support spacing.

I. INTRODUCTION

This design evaluation provides constructability assurance for the selected pipe support spacing over the 25 m spanning section (L_{span}) of a shallow offshore gas pipeline in 30 m water depth using static and flow-induced VIV Analyses. For the 18-inch (0.4572 m) pipeline diameter (D), the resulting span-to-diameter ratio (L_{span}/D) exceeds 30. In accordance with DNV-RP-F105 (2006), such a ratio indicates that the natural frequency of the free span is highly sensitive to boundary conditions, as summarized in Table 1-1 of the recommended practice. To address this sensitivity, established methodologies reported in the literature [1], [2], [3] are applied to determine the maximum allowable free spanning length (MAFSL). The assessment incorporates both the static analysis method and cross-flow–induced vortex-induced vibration (VIV) analysis. Input parameters for the evaluation are presented in Table 1, together with pipeline specification which collectively form the technical basis of this study. The rationale for this study stems from the critical need to ensure the structural integrity and operational reliability of offshore pipelines, particularly in sections where free spans occur due to seabed irregularities or environmental conditions. Free spans are susceptible to bending stresses, excessive deflections, and flow-induced vibrations, which can compromise pipeline safety and service life if not properly assessed. By integrating static analysis, flow-induced vortex-induced vibration (VIV) analysis, and serviceability-based deflection checks, this study provides a systematic methodology to determine maximum allowable free-span lengths and appropriate pile support spacing. Furthermore, the approach presented serves as a practical guide for young engineers to understand the principles behind support design, bridging the gap between theoretical analysis and real-world constructability considerations.

The remainder of this report is organized as follows. Section II presents the methodology, while III evaluates the MAFSL for the candidate pipeline. Section IV discusses the results of the analyses, while Section V concludes the report and provides recommendations.

II. METHODOLOGY

This study adopts a systematic analytical approach to evaluate the maximum allowable free-spanning length (MAFSL) and corresponding pile support spacing for a shallow offshore gas pipeline in 30 m water depth. The methodology integrates static strength assessment, flow-induced vortex-induced vibration (VIV) analysis, and serviceability-based deflection checks to ensure compliance with applicable codes and industry best practices.

Design Basis and Input Data: The evaluation is based on pipeline geometry, material

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properties, coating configuration, operating conditions, and environmental parameters obtained from the final design report and issued pipeline specification documents. Key inputs include pipe diameter, wall thickness, steel grade, coating thickness and density, internal pressure, fluid density, seawater density, current velocity, and span gap. These parameters form the basis for all analytical calculations and are summarized in Table 1.

Governing Codes and Standards: The assessment methodology follows the recommendations of DNV-RP-F105 (2006) for free-span evaluation, supplemented by guidance from ASME B31.8 (2004) for allowable stress limits and established formulations from published literature (Mohitpour et al., 2007; Xu et al., 2010). These standards provide criteria for static stress limits, dynamic response, and span sensitivity to boundary conditions.

Static Analysis Method: The static analysis method is employed to estimate the MAFSL by limiting the maximum bending stress in the free span. The pipeline is idealized as a beam subjected to uniformly distributed submerged weight, including steel, coating, internal fluid, and hydrodynamic effects. Section modulus and bending stresses are computed using closed-form expressions from the literature. Allowable bending stress is determined by accounting for internal pressure, longitudinal stress limits, combined stress interaction, and Poisson's effect. Thermal expansion stresses are neglected based on the assumption of uniform operating temperature along the span. The MAFSL is then calculated by equating the induced bending stress to the maximum allowable bending stress. A conservative design factor is applied to derive a practical pile support spacing.

***Flow-Induced VIV Analysis*:** To account for dynamic instability, flow-induced VIV analysis is conducted in accordance with DNV-RP-F105 recommendations [4]. Over extended service life, spanning pipeline sections can undergo fatigue failure due to cyclic loading from vortex-induced vibration (VIV) [5]. The vortex shedding frequency is calculated using the Strouhal relationship as a function of current velocity and pipeline diameter [4]. The natural response of the free span is evaluated by computing the critical span length that prevents resonance between vortex shedding frequency and the pipeline's natural frequency. A pipe span experiences flow-aligned oscillations when its vortex shedding frequency is about one-third of its natural frequency [4], [6]. The pipeline dynamic mass includes contributions from steel, coating, internal fluid, and added hydrodynamic mass. A partially fixed boundary condition is assumed for the free span ends, consistent with typical offshore pipeline support conditions. The critical free-span length obtained from this analysis represents the maximum span permissible to mitigate VIV risk. A safety factor is applied to account for uncertainties in flow conditions.

***Maximum Vertical Deflection Check*:** As an additional serviceability criterion, a maximum vertical deflection limit is assessed using classical beam theory. The allowable mid-span deflection is limited to 3% of the pipeline outside diameter, in accordance with industry guidance. The free span is modelled as a simply supported beam with uniform loading, and the corresponding span length is calculated. This approach provides a conservative check on excessive sagging that may affect coating integrity or seabed clearance.

***Governing Span Length and Support Spacing Selection*:** The final MAFSL is determined as the minimum span length obtained from the static analysis, VIV analysis, and deflection-based approach. The governing value is then reduced using an appropriate design factor to establish a conservative and constructable pile support spacing. This ensures adequate safety against static overstress, dynamic fatigue, and excessive deformation under the defined operating and environmental conditions.

The effect of the 30 m water depth was neglected because, at shallow depths, hydrostatic pressure and water-induced loading variations have minimal influence on the bending stress of the pipeline, VIV response, and vertical deflection for the span lengths considered. The dominant factors controlling free-span behaviour are the pipeline geometry, material properties, and span length. Including the water depth effect would not significantly alter the calculated maximum allowable free-span length or support spacing, and the simplification allows for a conservative and practical design approach. The influence of water depth on allowable free–span length is generally considered secondary to hydrodynamic loading and span geometry in free–span pipeline design. Recommended practices such as DNV-RP-F105 focus on current- and wave-induced loads and dynamic response criteria, and do not prescribe specific allowable depth effects for span calculations. A review on free-span design highlights environmental loading regimes from shallow to deep water and notes that hydrodynamic loads are the focus of assessment, rather than static water depth per se [7].

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III. MAFSL ESTIMATION

The input parameters for the calculations are defined in Table 1, below.

Table 1. Input Parameters

S/N	Input Parameter	Value	Description
1	D_o	0.4572m	Pipe outside diameter
2	D_i	0.4368m	Pipe inner diameter
3	D_c	0.4632m	Overall diameter including polythene coating
4	t	10.21mm	Pipe wall thickness
5	t_{cpe}	3mm	3 layer of polythene coating thickness
6	ρ_c	965 kgm^{-3}	Density of polythene coating
7	ρ_s	7850 kgm^{-3}	Density of steel
8	ρgas	0.9 kgm^{-3}	Density of pipeline content (gas)
9	ρ_w	1250kgm^{-3}	Density of water
10	E	207×10^3 MPa	Young's Modulus
11	SMYS	413.8 MPa	Specified minimum yield strength of the pipe
12	P_{MAOP}	10.4 MPa	Maximum allowable operating pressure
13	e	2.35m	Gap between pipeline and seafloor

MAFSL Estimation Using the Static Analysis Method

The static analysis method is employed to determine the MAFSL by calculating the maximum bending moment. Thus, the maximum allowable span length, (L, m), can be calculated using the relationship in the literature [3]:

$$L=\sqrt{\frac{10z\sigma_b}{w}} \tag{1}$$

where z is the pipeline section modulus, w is the submerged weight of the pipeline per meter, and $\sigma_b$maximum allowable bending stress (N/m^2).

$$w_s=\frac{\pi}{4}[({D_o}^2-{D_i}^2)\rho_s+({D_{Cpe}}^2-{D_o}^2)\rho_{Cpe} + {D_i}^2\rho_{gas}-{D_{cpe}}^2\rho_w]g \tag{2}$$

$$z=\frac{\pi}{32}\,({D_o}^4-{D_i}^4)\Big/D_0 \tag{3}$$

The maximum allowable bending stress is determined as detailed in Table 2 from the literature [3], below:

Table 2. Maximum Allowable Bending Stress [3]

Stress	Maximum allowable stress(es)
Hoop stress σ_h	$\sigma_H=\frac{P_{MAOP}D_o}{2t}$
	$\sigma_{L\max}=f_l(SMYS)$
Longitudinal stress σ_l	$\sigma_{L1,L2}=\frac{1}{2}\left[\sigma_H\pm\sqrt{(-\sigma_H)^2-4\left(\sigma_H^2-\sigma_{C\max}^2\right)}\right]$
Poisson's effect σ_p	$\sigma_P=-v_0\sigma_H$
Combined stress σ_c	$\sigma_{C\max}=f_{\text{combined}}(SMYS)$
	$\sigma_{b1}=\min\left(\lvert\sigma_{L\max}-\sigma_P\rvert,\lvert-\sigma_{L\max}-\sigma_P\rvert\right)$
Bending stress σ_b	$\sigma_{b2}=\min\left(\lvert\sigma_{L1}-\sigma_P\rvert,\lvert\sigma_{L2}-\sigma_P\rvert\right)$
	$\sigma_b=\min(\sigma_{b1},\sigma_{b2})$

The longitudinal stress factor (f_l), is taken as 0.8 and the combined stress ($f_{combined}$), as 0.9 as per the code [8]. The Poisson's ratio (v_0), for carbon steel is taken as 0.3 [2]. For API 5L X60, the SMYS is 413.80 MPa. The longitudinal stress due to thermal expansion has been neglected because it is assumed that the temperature of the fluid remains constant along the 25 m span length. Thus, the outcomes of the calculations are as follows:

$$w_s=\frac{3.142}{4}[(0.4572^2-0.4368^2)7850 + (0.4632^2-0.4572^2)965 + \left(0.4368^2(0.9)\right)]9.81$$

$= \mathbf{1.15\ KN/m}$ (without buoyancy effect since the pipe is already restrained).

Since the buoyancy effect will create a negative self-weight load, an added weight equivalent to the buoyancy effect is included. For the spanning section, the additional weight ($\boldsymbol{w_h}$) is:

$$w_h=\rho_w g A_{cs}$$

$$A_{cs}=\frac{\pi {Dcpe}^2}{4}=\frac{3.142\times0.4632^2}{4}=0.169\ \text{m}^2$$

Therefore, $w_h=\rho_w g A_{cs}=1025\times9.81\times\ 0.169$ = 1.70 KN/m

Maximum weight acting at full deformation at 30 m depth; $w=w_s+w_h$ = 1145.73+1700.00 =**2.9 KN/m**

$$z=\frac{3.142}{32}(0.4572^4-0.4368^4)\Big/0.4572=\mathbf{0.0016}$$

$$\sigma_H=\frac{P_{MAOP}D}{2t}=\frac{10{,}344{,}828\times0.4572}{2\times0.01021}=\mathbf{231.62\ MN/m^2}$$

$\sigma_{Lmax}=f_l(SMYS)=0.8(413{,}793{,}103)$ =**331,04 MN/m^2**

$\sigma_{cmax}=f_{combined}(SMYS)=0.9(413{,}793{,}103)=$ **372.41 MN/m^2**

$\sigma_p=-v_o\sigma_H=-0.3(231{,}618{,}773.83)$ = **-69.5 MN/m^2**

$$\sigma_{L1,L2}=\frac{1}{2}[\sigma_H\pm\sqrt{(-\sigma_H)^2-4({\sigma_H}^2-{\sigma_{cmax}}^2)}]$$

$$=\frac{1}{2}[231{,}618{,}773.83\pm\sqrt{(-231{,}618{,}773.83)^2-4(231{,}618{,}773.83^2-372{,}413{,}792.70^2)}]$$

$\boldsymbol{\sigma_{L1}}$**=430 MN/m^2;** $\boldsymbol{\sigma_{L2}}$**= −198 MN/m^2**

$$\sigma_{b1}=\min(\lvert331{,}034{,}482.75-(-69{,}485{,}632.15)\rvert,\lvert-331{,}034{,}482.75-(-69{,}485{,}632.15)\rvert)$$

$= \min(400{,}520{,}114.90,-261{,}548{,}850.57)$; minimum = **$-261.55$ MN/m^2**

$$\sigma_{b2}=\min(\lvert429{,}587{,}319.06-(-69{,}485{,}632.15)\rvert,\lvert-197{,}968{,}545.23-(-69{,}485{,}632.15)\rvert)$$

$= \min(499{,}072{,}951.21,-128{,}482{,}913.08)$; minimum = **$-128.48$ MN/m^2**

Since, the bending stress due to the combined stress limit, σ_{b2}, is minimum of both, the maximum allowable bending stress (N/m^2), σ_b is estimated as **128.48 MN/m^2**. Therefore, from Equation 1 above, the MAFSL using the static analysis method is estimated as:

$$Lmax = \sqrt{\frac{10(0.0016)(128{,}482{,}913.08)}{2799}} = \mathbf{27m}$$

The pipe specification suggests an API 5L X60 pipeline hence a 27 m maximum span length is recommended based on the static analysis method. Applying a 0.5 design factor results in about 13 m spacing between supports. However, this outcome will be compared with the outcome from flow induced VIV analysis.

MAFSL Estimation Using Flow Induced VIV Analysis

Vortex-induced vibrations arise from the periodic shedding of vortices from the pipeline. Resonance occurs in the free-span when the shedding frequency of the vortices aligns with the natural frequency of the pipe. The critical length of the span to prevent vibration is given in the literature [3] as:

$$L_c < \left[\frac{0.5C}{f_s}\sqrt{\frac{EI}{M}}\right]^{0.5} \quad (4)$$

where C is the free span end fixity constant, which is generally taken as 2.52, because usually the free span ends will be partially fixed. f_s is the vortex shedding frequency which is calculated using the Strouhal Number (S_t). M is the pipeline dynamic mass (taken as total weight, w). E is the modulus of elasticity of steel (E =207 GPa). I is the pipe moment of inertia.

$$S_t = 0.27 - 0.03\frac{e}{D_{cpe}} \quad (5)$$

$$f_s = \frac{S_t U}{D_{cpe}} \quad (6)$$

Where U is the current velocity at the pipeline span which is given as 3.5 m/s, e is the gap between the spanning pipeline section and the river bed (2 m), D_{cpe} is the outer diameter due to 3-layer PE coating. The pipeline dynamic mass is computed as follows:

$$M = \frac{\pi}{4}[(D_o{}^2 - D_i{}^2)\rho_s + (D_{Cpe}{}^2 - D_o{}^2)\rho_{Cpe} + D_i{}^2\rho_{gas} + D_{cpe}{}^2\rho_w] \quad (7)$$

The pipe moment of inertia is computed as follows:

$$I = \frac{\pi}{64}(D_o{}^4 - D_i{}^4) \quad (8)$$

The computations are as follows:

$$M = \frac{3.142}{4}[(0.4572^2 - 0.4368^2)7850 + (0.4632^2 - 0.4572^2)965 + (0.4318^2(0.9)) + (0.4632^2(1025))] = \mathbf{289.54kg/m}$$

$$I = \frac{\pi}{64}(0.4572^4 - 0.4368^4) = \mathbf{0.00036}$$

$S_t = 0.27 - 0.03\frac{2.35}{0.4632} = \mathbf{0.12}$ (since this value is <0.2 for subcritical flow, 0.2 is assumed)

$f_s = \frac{0.2 \times 3.5}{0.4632} = 1.5$ Hz (vortex shedding frequency)

$$L_c < \left[\frac{0.5\times2.52}{1.5}\sqrt{\frac{2.07\times10^{11}\times0.00036}{289.54}}\right]^{0.5}; L_c < \mathbf{20.64m}$$

$L_c <$ 20.64 m (the effect of VIV reduced the allowable spanning length to <20 m), which becomes the adopted spanning length since it is the minimum between the static analysis method and the VIV analysis method. By applying a factor of 0.5 to enhance safety on the outcome of the VIV method, the spacing between support pipes is estimated as **10 m**. Therefore, spacings <10 m is appropriate for safety.

Maximum Vertical Deflection Approach

The literature [2] suggests a maximum vertical deflection of 3% times the outside diameter of the pipeline. Using the beam theory for simply-supported beam carrying a uniformly distributed load, the spanning pipeline is treated as a beam of uniform flexural stiffness EI and span L is simply-supported at its ends. The following equation applies for the MAFSL, as obtained from the literature [9].

$$L = \left[\frac{384\delta EI}{5w}\right]^{\frac{1}{4}} \quad (9)$$

Substituting the values for the parameters yields:

$$L = \left[\frac{384(0.03\times0.4572)\times2.07\times10^{11}\times0.00036}{5\times2900}\right]^{0.25} = \mathbf{12.80\ m}$$

The beam theory, based on the maximum deflection of 3% times the outer diameter of the pipeline suggests a span length of 12.72m, hence the above computation is in order. Multiplying 12.80 by a conservative factor of 0.5 yields a support spacing of 6.40 m.

IV. SUMMARY OF RESULTS AND DISCUSSION

This study evaluated the maximum allowable free-spanning length (MAFSL) and corresponding pile support spacing for an 18-inch shallow offshore gas pipeline in 30 m water depth using static analysis, flow-induced vortex-induced vibration (VIV) analysis, and a maximum vertical deflection criterion. The assessment was conducted in accordance with DNV-RP-F105 (2006) and established literature, recognizing that the span-to-diameter ratio exceeds 30 and therefore renders the pipeline response highly sensitive to boundary conditions.

The static analysis method, based on limiting allowable bending stress under combined loading, yielded a maximum allowable free-span length of approximately 27 m. Applying a conservative design factor of 0.5 to account for uncertainties in loading, material behaviour, and boundary conditions resulted in a recommended support spacing of approximately 13 m. While this outcome satisfies static strength requirements, it does not explicitly address dynamic instability mechanisms.

The flow-induced VIV analysis demonstrated a more restrictive limitation. Based on vortex shedding frequency and dynamic response considerations, the critical free-span length was estimated to be less than 20.64 m. This reduction highlights the significance of hydrodynamic excitation and resonance effects for long free spans in shallow offshore environments. When a conservative factor of 0.5 was applied to enhance design robustness, the resulting recommended support spacing was approximately 10 m. Given that VIV governs fatigue performance and long-term structural integrity, this result was identified as the controlling design criterion.

In addition, the maximum vertical deflection approach, which limits mid-span deflection to 3% of the pipeline outside diameter, produced the most conservative outcome. This method resulted in an allowable free-span length of approximately 13 m, and when further reduced by a safety factor of 0.5, indicated a support spacing of about 6.50 m. While conservative, this criterion provides an additional serviceability-based check and is particularly relevant where excessive sagging may compromise coating integrity or seabed clearance requirements. The overall, comparison of the three approaches is presented in Table 3.

Table 3. Summary of Results

Analysis Type	Result	Safety Factor	Final Critical Span/Support Spacing	Additional Notes
Static Static Analysis	Maximum Allowable Free Span Length (MAFSL) = 27 m	0.5 (applied to calculated MAFSL for safety)	13 m	Aligns with structural integrity limits, API 5L X60 material, submerged weight, and stress criteria.
VIV (Vortex-Induced Vibration) Analysis	Critical Span Length = 20.64 m (governed by resonance)	0.5 (applied to calculated MAFSL for safety)	10 m	Ensures safety by mitigating VIV-induced structural failure.
Maximum Vertical Deflection Approach	Span Length = 12.80 m	0.5 (applied to calculated MAFSL for safety)	6.4 m	Based on beam theory for maximum vertical deflection.

V. CONCLUSIONS

The design evaluation study comprehensively assessed the constructability and safety of the selected pipe spacing configurations using static analysis and vortex-induced vibration (VIV) analysis. The key findings confirms that dynamic effects associated with flow-induced VIV govern the allowable free-span length for the pipeline under the given site conditions. Static strength considerations alone would overestimate the permissible span length and may lead to unacceptable fatigue risk. Consequently, for the pipeline spacing section considered, a pile support spacing not exceeding 10 m is recommended as a balanced and technically justified solution, providing adequate safety against both static overstress and dynamic instability while remaining constructable for the project conditions. The approach provided in this paper can enable young engineers to understand how supports are designed and provided to prevent excessive bending, dynamic oscillations, and serviceability issues in free-spanning offshore pipelines. It also demonstrates the integration of static and dynamic analysis methods in a practical engineering workflow, bridging theoretical knowledge and constructability considerations.

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NOMENCLATURE

Abbreviation	Description
DNV-RP	Det Norske Veritas Recommended Practice.
MAFSL	Maximum Allowable Free-Spanning Length
VIV	Vortex Induced Vibration

REFERENCES

[1] DNV-RP-F105, "Free spanning Pipelines," 2006. Accessed: Dec. 17, 2025. [Online]. Available: www.dnv.com
[2] M. Mohitpour, H. Golshan, and A. Murray, *Pipeline Design & Construction: A Practical Approach, Third Edition*, 3rd ed.

New York: ASME Press, 2007. doi: 10.1115/1.802574.

[3] J. Xu, G. Li, J. J. Horrillo, R. Yang, and L. Cao, “Calculation of maximum allowable free span length and safety assessment of the DF1-1 submarine pipeline,” *Journal of Ocean University of China*, vol. 9, no. 1, pp. 1–10, Mar. 2010, doi: 10.1007/s11802-010-0001-4.

[4] H. S. Choi, “Free spanning analysis of offshore pipelines,” *Ocean Engineering*, vol. 28, no. 10, pp. 1325–1338, Oct. 2001, doi: 10.1016/S0029-8018(00)00071-8.

[5] Q. Song, J. Liu, and F. Gao, “Very High Cycle Fatigue Life of Free-Spanning Subsea Pipeline Subjected to Vortex-Induced Vibrations,” *J Mar Sci Eng*, vol. 12, no. 9, p. 1556, Sep. 2024, doi: 10.3390/jmse12091556.

[6] H. Marcollo, M. Behan, and C. Dillon-Gibbons, “Universal Screening Criteria for VIV of Free Spans, V*,” *J Mar Sci Eng*, vol. 13, no. 8, p. 1501, Aug. 2025, doi: 10.3390/jmse13081501.

[7] M. Drago, M. Mattioli, R. Bruschi, and L. Vitali, “Insights on the design of free-spanning pipelines,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 373, no. 2033, p. 20140111, Jan. 2015, doi: 10.1098/rsta.2014.0111.

[8] American Society of Mechanical Engineers, “Gas transmission and distribution piping systems (ASME B31.8-2004),” New York, 2004. Accessed: Dec. 17, 2025. [Online]. Available: ASME Press

[9] J. Case, Lord Chilver, and C. T. F. Ross, *Strength of Materials and Structures*, 4th ed. Butterworth-Heinemann, 1999. doi: 10.1016/B978-0-340-71920-6.X5000-6.