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2D vs 3D Finite Element Analysis of Free Span Response in Subsea Pipelines

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ABSTRACT

Free-span formation in subsea pipelines, often caused by seabed irregularities, local scour, or differential settlements, poses a significant threat to pipeline integrity through the induction of vortex-induced vibrations (VIV), fatigue damage, and potential structural failure. While two-dimensional (2D) numerical models are widely used in early-stage designs due to their simplicity and computational efficiency, their ability to accurately predict the complex dynamic behavior of pipelines remains limited. In contrast, three-dimensional (3D) models provide a more realistic representation of seabed geometry, pipe-soil interaction, and hydrodynamic loading, albeit at the expense of greater computational resources. This study presents a comparative numerical analysis of subsea pipelines with free spans under both 2D and 3D finite element models using ABAQUS software. Key parameters, including deformed shapes, natural frequencies, and simulation run-times, are extracted and evaluated. The results offer valuable insight into the accuracy and applicability of simplified 2D models for preliminary design purposes, providing engineers with a practical framework for selecting appropriate modeling strategies based on project constraints and performance requirements. The study also lays the groundwork for aligning simplified numerical analyses with international design standards.

1. Introduction

A submarine pipeline is a vital component of the hydrocarbon resources from offshore fields to onshore facilities in a safe manner. There is a high level of complexity in the environmental conditions surrounding these structures. It is important to note that these conditions have a significant influence on pipeline performance and safety. As far as the environmental conditions are concerned, free spans play a substantial role in the design and operation of these pipelines. A free span affects pipeline support conditions and can lead to vortex-induced vibrations (VIV), leading to structural fatigue and reduced service life. To ensure safety and optimize design, it is therefore imperative to understand the mechanical and dynamic behavior of pipelines in the presence of free spans [1-4].

In the early stages of subsea pipeline design, structural analyses under free-span conditions were mainly based on simplified theoretical models, such as the Euler-Bernoulli beam theory, where the pipeline was assumed to act as a rigid beam resting on a rigid seabed with linear dynamic behavior [5]. While useful for preliminary assessments, these approaches lacked the capability to accurately capture the interaction between the seabed, hydrodynamic loading, and the pipeline's dynamic response. Subsequently, experimental and field-based approaches gained traction for studying the real behavior of free-spanning pipelines. Experimental studies in flow channels and water tunnels enabled direct investigation of phenomena such as VIV, hydrodynamic pressure distribution, and structural response [6]. In addition, field data obtained from in-situ monitoring systems installed on operational pipelines provided valuable insights into real-world performance [7]. Nevertheless, inherent limitations such as high costs, limited scalability, and difficulty in controlling environmental parameters restricted the broad applicability of experimental methods in

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practical design processes.

With the development of numerical methods and increased computational capacity, the finite element method (FEM) has become a standard tool in subsea pipeline design. Many early studies adopted two-dimensional modeling as a practical compromise to reduce computational cost and complexity [8]. In this approach, the pipeline is typically modeled as a cross-sectional element and analyzed under hydrodynamic loading, self-weight, and interaction with the seabed in a two-dimensional plane [9].This method enables faster simulations and supports extensive parametric studies, making it common in early design phases or projects constrained by time and resources [10]. However, 2D models exhibit inherent limitations that may result in inaccurate predictions of actual pipeline behavior. For example, they cannot accurately evaluate vibration frequency, structural displacements, or complex nonlinear interactions between the pipeline and seabed. Therefore, evaluating the accuracy and applicability of 2D models, particularly through comparison with 3D simulations, remains a critical issue in simulation-based design.

With advancements in computational tools and numerical software, three-dimensional modeling of free-spanning subsea pipelines has gained widespread attention among researchers and engineers. 3D analyses allow for a more realistic representation of complex effects such as three-directional seabed irregularities and nonlinear pipeline–seabed interaction [11]. In scenarios involving hydrodynamic phenomena, 3D modeling for obtaining reliable results is not just important, but vital. Many recent studies have employed software platforms such as ABAQUS, ANSYS, and OrcaFlex to capture nonlinear behavior, dynamic loading, and pipe seabed flow interactions. Although these models require greater computational effort, they offer superior accuracy in predicting dynamic responses, especially in VIV-related fatigue and progressive failure analyses. Consequently, 3D simulations not only provide deeper insights into pipeline behavior but also serve as reference standards for validating simplified 2D models.

Despite significant progress in both 2D and 3D numerical modeling of free-spanning pipelines, challenges remain in assessing the accuracy of simplified models and their consistency with real-world conditions. In many engineering projects, the use of 2D models is inevitable due to resource or time constraints; however, their validity, particularly in predicting vibration, deformation, and dynamic responses, must be critically evaluated through comparison with 3D models. The present study aims to simulate and compare the behavior of subsea pipelines under two-dimensional and three-dimensional conditions. A validated numerical model based on the finite element method (FEM) is employed to conduct the analysis. The dynamic response of the pipeline is examined under uniform loading, with particular emphasis on the influence of a soft seabed on its structural behavior. The analysis primarily focuses on critical parameters such as the deformed shape of the pipeline, natural frequencies, and the total computation time required for the simulations. These parameters are essential for understanding the dynamic behavior and stability of subsea pipelines. Comparing them in 2D and 3D models helps assess the accuracy and reliability of each modeling approach. By emphasizing this comparison, the study seeks to identify the strengths and limitations of 2D models and assess their applicability in preliminary design scenarios. The outcomes of this study can offer practical guidance for design engineers by clarifying the capabilities and limitations of 2D analysis, supporting more informed decisions in selecting the appropriate level of modeling fidelity. Furthermore, this research contributes to efforts toward standardizing the use of simplified models in compliance with international design codes and guidelines.

2. Governing equation

Beam theory is commonly used to model free-spanning subsea pipeline structural behavior. The Euler-Bernoulli beam theory is considered an appropriate approach for estimating flexural deformation according to DNV-RP-F105 [12], particularly when the span length is large relative to the pipeline diameter. The theory ignores shear deformation and assumes that the cross-section remains as a plane perpendicular to the neutral axis after deformation. The flexural response of the beam subjected to distributed loading is formulated in Eq. 1:

$$EI\frac{d^4w(x)}{dx^4} = q(x) \tag{1}$$

where E is the Young's modulus, I is the second moment of area, $w(x)$ is the vertical deflection of the beam at position x, and $q(x)$ is the distributed load along the beam.

2.1. Two-dimensional (2D) formulation

In the 2D case, deformation is restricted to a single plane, typically involving bending about a primary axis [13]. The internal response can be characterized by the shear force $V(x)$ and bending moment $M(x)$, which are related to deflection as follows:

$$V(x) = \frac{d^3}{dx^3}\,(EI\,(x)) \tag{2}$$

$$M\,(x) = \frac{d^2}{dx^2}\,(EI\,(x)) \tag{3}$$

2.2. Three-dimensional (3D) formulation

In three-dimensional analysis, the pipeline may undergo bending about two orthogonal principal axes, and, where necessary, torsional deformation can also be considered [14]. The governing equations for flexural deformation in the y- and z-directions are as follows [15]:

$$q_y(x) = \frac{d^4 w_y(x)}{dx^4} EI_y \quad (4)$$

$$q_z(x) = \frac{d^4 w_y(x)}{dx^4} EI_y \quad (5)$$

where I_y and I_z are the second moments of area about the respective principal axes, $W_y(x)$ and $W_z(x)$ represent transverse displacements in two perpendicular directions, and $q_y(x)$ and $q_z(x)$ are the distributed loads acting in the respective directions.

3. Two-dimensional and three-dimensional simulation setup

To simulate the free-span phenomenon, a section of the pipeline path is assumed to contain loose soil. Consequently, settlements may occur due to hydrostatic pressure and the weight of both the pipeline and the supporting mattress. The simulations are performed without considering the influence of soil deformation on the settlement values. Given that the solution domain has relatively low geometric complexity and axial symmetry, computational cost can be reduced by applying static symmetry. Therefore, only half of the domain is modeled instead of the full geometry.

In both 2D and 3D models, wire elements are employed to simulate the pipeline behavior due to their simplicity and lower computational cost. Although solid elements could provide a more detailed structural representation, their use would substantially increase computational demands and add complexity to the modeling process. It is important to note that, since this study does not focus on phenomena related to the pipeline wall thickness, the use of solid elements is not considered necessary. Furthermore, while the 2D model employs shell elements for the pipeline structure, the 3D model uses solid elements for other structural components.

3.1. Model geometry

In the modeling process, span lengths of 2, 4, 6, 8, and 10 meters were considered. For an accurate simulation of the pipeline behavior in the free-span region, a relatively long pipeline segment resting on firm soil was included in the model, with an actual total length of 280 meters. To reduce computational time, only half of the geometry was modeled by exploiting static symmetry conditions. As shown in Fig. 1, all other geometrical characteristics of the model are illustrated.

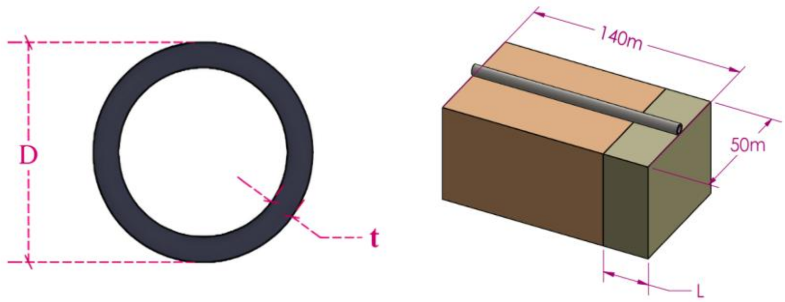

Fig. 1. The entire model and pipe section parameters.

In this study, three different pipeline configurations have been employed. The geometric specifications corresponding to each scenario are summarized in Table 1.

Table 1. Geometry properties.

No.1		No.2		No.3	
***t*(m)**	***D*(m)**	***t*(m)**	***D*(m)**	***t*(m)**	***D*(m)**
0.02	1	0.035	1	0.035	2

3.2. Material

The materials used in this study are classified into three main groups. The first group relates to the mechanical properties of steel pipelines and includes both elastic and plastic characteristics. To model the nonlinear plastic behavior of steel, a bilinear stress-strain model has been employed, with its parameters presented in Table 2. For the plasticity modeling of steel, an isotropic hardening law is used, and the Von Mises yield criterion governs the onset of yielding. The second and third groups relate to the geotechnical properties of the subsoil. The second group represents zones with high settlement potential, modeled using soils with low stiffness. In contrast, the third group corresponds to areas with adequate stiffness and higher resistance, where significant settlement is not expected. To define the plastic behavior of the soil materials, the Mohr-Coulomb failure criterion has been applied. The parameters used in this model are provided in Table 3.

Table 2. Mechanical properties of pipe.

Apparent density (kg/m²)	**5000**	
Elastic	**Young's modulus (GPa)**	**Poisson's ratio**
	210	0.3
Plastic	**Young's modulus (GPa)**	**Poisson's ratio**
	455	0.3

Table 3. Mechanical properties of soils.

Apparent density (kg/m²)	**Stiff soil**		**Soft soil**	
Elastic	**Young's modulus (MPa)**	**Poisson's ratio**	**Young's modulus (MPa)**	**Poisson's ratio**
	100	0.25	1	0.25
Moher coulomb plasticity	**Friction angle**	**Dilation angle**	**Friction angle**	**Dilation angle**
	35	15	25	8

3.3. Load and boundary conditions

To define the boundary conditions in the Abaqus model and in accordance with the requirements of geometric and loading symmetry, a Cartesian coordinate system is adopted. In this system, the *xx*-axis is aligned with the longitudinal direction of the pipeline, the *yy*-axis is defined as vertical and perpendicular to the *xx*-axis, and the *zz*-axis is horizontal and orthogonal to both *xx* and *yy* axes. Based on this coordinate system, roller supports are assigned at both ends of the pipeline along the *yy*-axis, allowing vertical displacement while constraining motion in all other directions. The interaction between the pipeline and the surrounding soil is modeled using a surface-to-surface contact definition. In this contact formulation, frictional forces are considered in both the normal and tangential directions. In the tangential direction, the coefficient of friction between the pipe and the soil is assumed to be 0.2, following the recommendations of the DNV-ST-F101 [16] standard for soft soils. This standard suggests a typical friction coefficient in the range of 0.2 to 0.3 under such conditions. A Hard Contact condition is applied in the normal direction to prevent unrealistic penetration between the pipe and the soil, thereby ensuring a more accurate simulation of their physical interaction. This contact formulation allows for proper transfer of normal forces and effectively eliminates numerical interpenetration between the contacting surfaces.

To accurately represent the plane strain conditions inherent to the actual problem, additional constraints have been applied in the three-dimensional analysis to eliminate any out-of-plane deformations. Within the scope of this study, the following loads are considered:

- Internal pressure applied to the inner wall of the pipe, resulting from the fluid flow within it;
- The external pressure is the hydrostatic pressure created by the pipe's location 50 meters below sea level;
- The weight of the pipeline, applied in the model using gravitational acceleration;
- The weight of the mattress, modeled as a line load.

It is noteworthy that the internal pressure, external pressure, and self-weight of the pipelines are gradually applied during the first-time stage (stage 1). Subsequently, in the second time stage (stage 2), the load induced by the mattress is introduced, while the previously applied loads remain active. This two-stage loading approach is designed to more accurately simulate real-world conditions and to minimize the effects of sudden load application. Moreover, this method enables the individual assessment of each loading component, allowing for a clearer evaluation of their respective significance. The loading values are specified in Table 4.

Table 4. Load values.

	Value
Pipe external pressure (N/m²)	502762
Pipe internal pressure (N/m²)	1E07
Acceleration of gravity(g) (m/s²)	9.81
Weight of mattress (N/m)	100000

3.4. Model validation

To validate the numerical model developed in this study, a benchmark problem was simulated numerically, consisting of a pipe with an outer diameter of 1 meter and a wall thickness of 2 cm under specified boundary conditions. In this model, one end of the pipe was fixed (clamped), and an axial load of 100,000 N was applied to the free end. The objective of this analysis was to evaluate the axial displacement resulting from the applied axial load on the pipe structure. The numerical results obtained using the Abaqus software were compared with the corresponding analytical solution derived based on linear elasticity theory and classical Euler beam equations. In the analytical solution, the axial displacement due to the applied load was calculated using Eq. 6, which relates the axial load, geometric and mechanical properties of the pipe, and the resulting displacement within the elastic deformation framework:

$$\delta = \frac{PL^3}{3EI} \tag{6}$$

Each parameter employed in Eq. 6 corresponds to the values specified in Table 5.

Table 5. Analytical parameters.

P **(N)**	100000
L **(m)**	10
E **(GPa)**	210

A comparison of the vertical and in-plane displacements at the free end of the pipeline, derived from the numerical simulation and analytical solution, is provided in Table 6, and the in-plane deformation of the pipe section is shown in Fig. 2.

Table 6. Comparison of numerical and analytical results.

Numerical Solution	Analytical Solution	Percentage Error (%)
0.0214728	0.021464	0.04

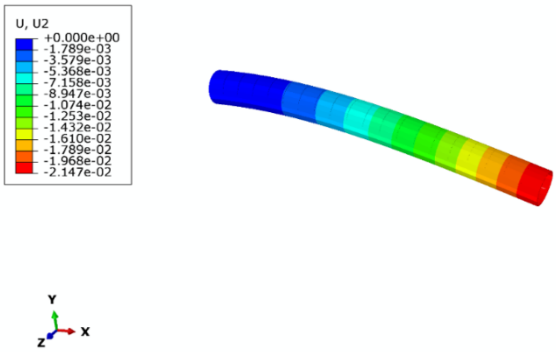

Fig. 2. In-plane deformation of the pipe-section beam.

The results obtained from the numerical and analytical analyses exhibited a satisfactory level of agreement, with the deviations falling within an acceptable range. This comparison verifies the reliability of the numerical model and confirms the appropriateness of the applied boundary conditions and loading scenarios in the simulation process. Therefore, it can be concluded that the numerical modeling approach employed in this study possesses sufficient accuracy and validity for analyzing the intended physical behavior.

4. Results and discussion

4.1. Parametric study of model geometry

The effects of varying the free span length on pipeline deformation are examined for different geometric configurations, including variations in the outer diameter and wall thickness of the pipe, as illustrated in Figs. 3 to 5.

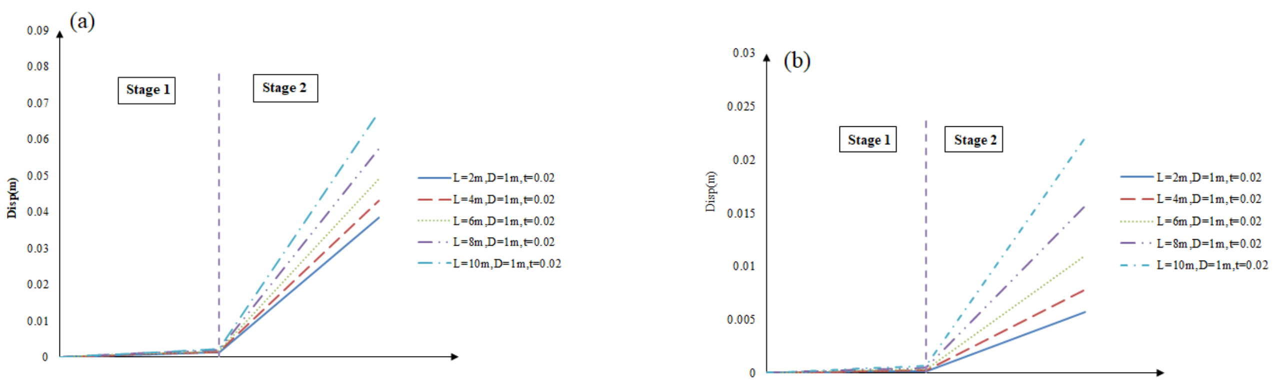

Fig. 3. Max displacement of model: D = 1 m, t = 0.02 m, in the vertical direction within the plane; a) 2D modeling, b) 3D modeling.

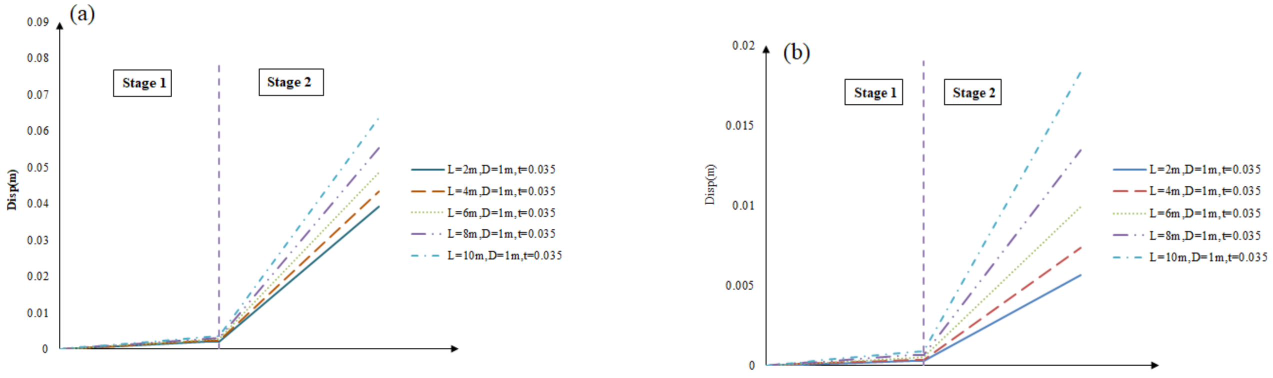

Fig. 4. Max displacement of model: D = 1 m, t = 0.035 m, in the vertical direction within the plane; a) 2D modeling, b) 3D modeling.

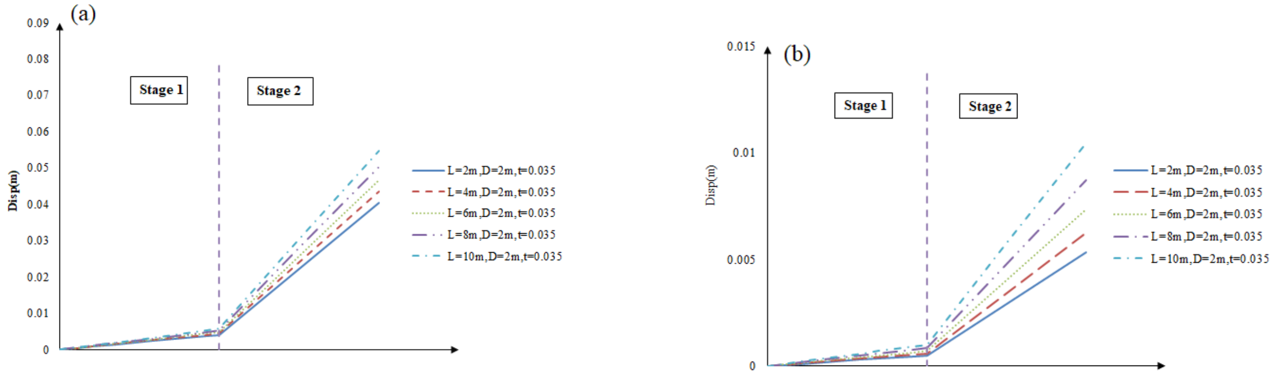

Fig. 5. Max displacement of model: D = 1 m, t = 0.035 m, in the vertical direction within the plane; a) 2D modeling, b) 3D modeling.

According to the Figs. 3 to 5, there is a pronounced and progressive increase in structural displacement with an increase in the length of the free span from 2 m to 10 m. The results obtained from the three sets of numerical displacement diagrams reveal a clear and consistent trend regarding the deformation behavior of subsea pipelines with varying geometric configurations. Specifically, pipelines with an outer diameter of 1 meter exhibit significantly larger free span displacements compared to those with a 2 m diameter. This variation can be attributed to the fundamental influence of geometric properties on flexural resistance. While the cross-sectional area and consequently the self-weight increase proportionally with the square of the radius, the moment of inertia, a key parameter governing flexural stiffness, increases with the fourth power of the radius. Therefore, assuming constant wall thickness, an increase in pipe diameter results in a substantial increase in flexural rigidity, leading to a notable reduction in deformation.

Furthermore, the comparison between 2D and 3D finite element models demonstrates considerable differences in the predicted displacement magnitudes. According to the illustrated results, the maximum displacement in the 2D model ranges from 0.03 to 0.06 meters, whereas the 3D model shows considerably lower values between 0.005 and 0.02 meters. Similar trends are observed in the other sets of diagrams, clearly indicating that 3D modeling predicts lower deformations under identical loading conditions. This distinction originates from fundamental differences in geometric representation and loading application: the 3D model incorporates the full spatial geometry of the pipe and allows for the simultaneous evaluation of bending and torsional effects, along with a more realistic load distribution and stress propagation across the structure. These factors collectively enhance the model's effective stiffness and reduce its predicted displacement. In contrast, the 2D model, based on plane strain or plane stress assumptions, is limited to simulating in-plane bending responses and fails to capture torsional resistance or out-of-plane deformation mechanisms. As a result, the 2D model generally overestimates displacement when compared to a more comprehensive 3D analysis.

The trend observed as the free span length increases from 2 to 10 meters further illustrates this distinction: according to Fig.3, the displacement increases by approximately 43% in the 2D simulations, while the same parameter shows a more pronounced 74% increase in the 3D model. This sharper gradient in the 3D case is attributed to the activation of additional deformation mechanisms such as torsion, lateral bending, and full 3D stress redistribution, which are inherently absent in 2D simulations. Moreover, in Fig.4, increasing the wall thickness leads to an approximate 5% reduction in displacement growth rate in both modeling approaches. Meanwhile, in Fig. 5, increasing the pipe diameter from 1 meter to 2 meters results in an average displacement reduction of about 20%.

Collectively, these findings highlight the critical role of geometric parameters—especially radius and cross-sectional area—in governing the flexural response of subsea pipelines through their influence on the moment of inertia. The notable differences between 2D and 3D modeling outputs strongly emphasize the necessity of full three-dimensional simulations for accurate prediction of structural behavior in free-span pipeline segments, particularly under conditions involving long spans and significant torsional interactions. While 2D models offer computational simplicity and efficiency, they may overpredict displacement magnitudes due to their inherent simplifications and limited physical representation. Moreover, the final results of the analysis clearly show that, across all three modeling scenarios (No1, No2, No3), the minimum displacement corresponds to the 2-meter span, whereas the maximum displacement is observed in the 10-meter span. This observation highlights the fact that longer spans reduce the system's flexural rigidity and enhance its susceptibility to applied loads. This behavior is in agreement with the theoretical foundations of beam mechanics and emphasizes the critical role of span length control and the consideration of time-dependent cumulative loading effects in the design of free-spanning pipelines, particularly in subsea environments, to reduce displacement and maintain structural integrity. Fig. 6 presents the overall deformation patterns of the pipeline as obtained from both two-dimensional and three-dimensional modeling approaches.

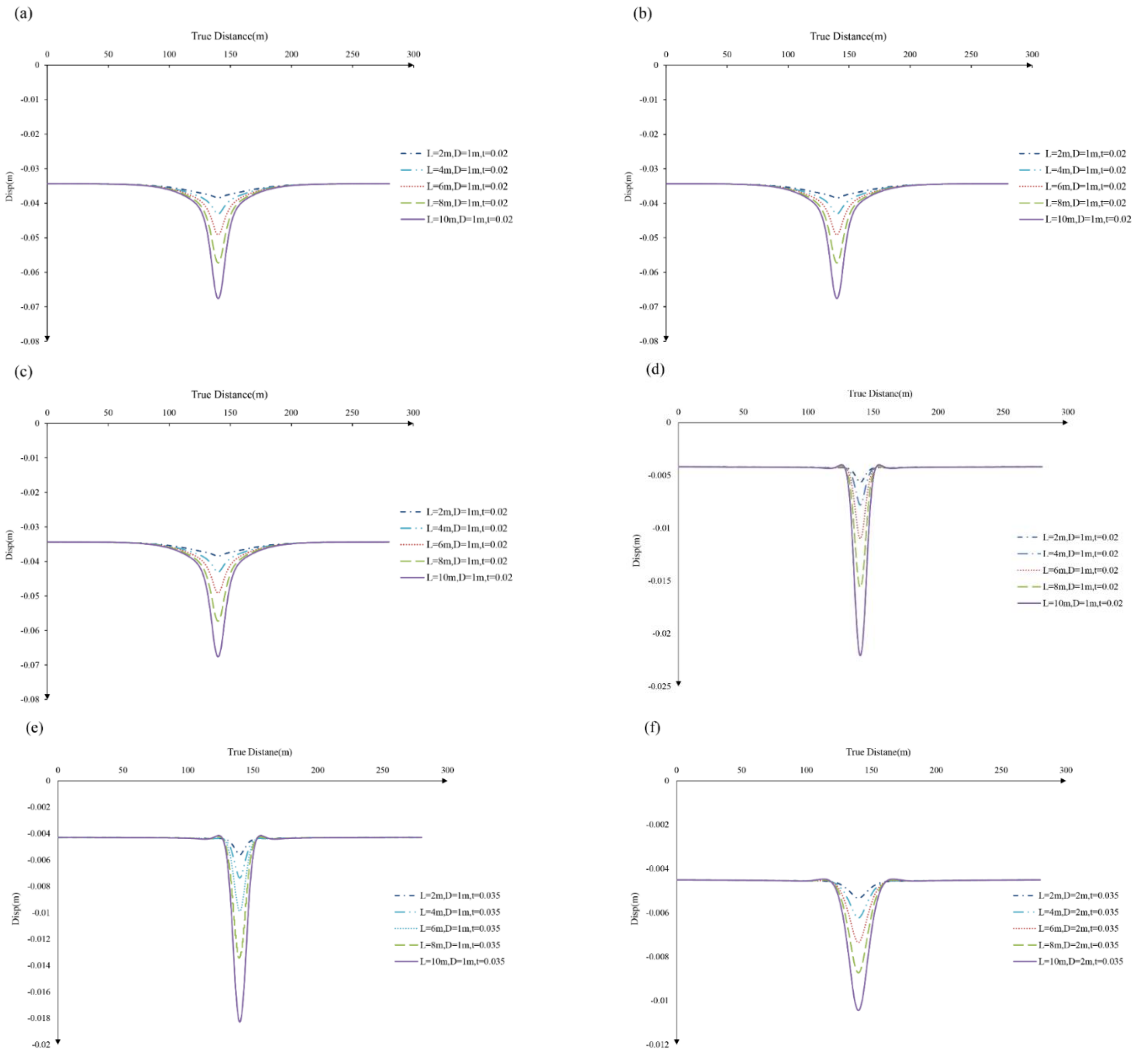

Fig. 6. Realistic pipeline deformation in all models; a,b,c) 2D modeling, d,e,f) 3D modeling.

4.2. Comparison of natural frequencies created in models

One of the additional parameters examined in both the two-dimensional and three-dimensional models is the natural frequency associated with various natural modes. The comparative evaluation of these frequencies by the 2D and 3D models is presented in Fig. 7.

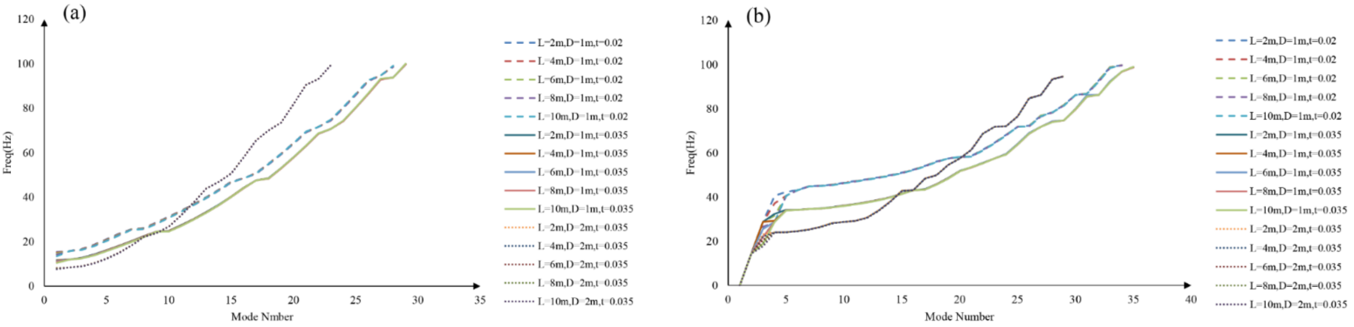

Fig. 7. Natural frequency of model: D = 1 m, t = 0.02 m; a) 2D modeling, b) 3D modeling.

Based on Fig. 7, several outcomes can be deduced from the results. First, when comparing the two-dimensional and three-dimensional models, in the lower natural modes, the frequencies obtained from the two-dimensional model are lower than the corresponding values predicted by the three-dimensional analysis. However, this trend reverses in the higher modes. The aforementioned finding is not the sole outcome derivable from this comparison. Regarding the influence of geometrical variations on natural frequencies, it is observed that changes in free span length result in only minor variations in the lower modes. The relatively minor variations in the free span length of subsea pipelines, ranging from two to ten meters in the present work, do not significantly affect the natural vibration frequency of the pipeline due to several factors. Firstly, the total length of the pipeline is substantially greater than these local variations, rendering their impact on the overall dynamic behavior negligible. Secondly, the natural frequency is primarily governed by the effective length, boundary conditions, and material properties of the entire system, which remain largely unchanged by small local length fluctuations. Thirdly, the localized nature of these variations limits their influence, as the vibrational modes are distributed throughout the entire structure rather than confined to small segments. Lastly, the inherent bending stiffness and structural rigidity of the pipeline are sufficiently high, making minor changes in free span length insufficient to produce notable shifts in the natural frequency.

In terms of diameter variation, models with smaller diameters exhibit higher natural frequencies in the initial modes, whereas in the higher modes, the trend is reversed. Variations in the external diameter of subsea pipelines have a pronounced impact on their natural vibration frequency due to the direct influence of diameter on the bending stiffness and mass per unit length of the pipeline. Specifically, the bending stiffness is proportional to the fourth power of the external diameter, as the moment of inertia of the cross-section scales approximately with D^4, where D represents the external diameter. This means that even small changes in diameter result in substantial changes in stiffness. Although the mass per unit length also increases with diameter roughly proportional to D^2, the effect of increased bending stiffness dominates in determining the natural frequency. Since the natural frequency of a vibrating system is approximately proportional to the square root of the stiffness-to-mass ratio ($\sqrt{(k/m)}$), the net effect of increasing diameter is a significant increase in natural frequency. Therefore, unlike minor variations in free span length, changes in the external diameter produce considerable shifts in the vibrational characteristics of subsea pipelines. This behavior is observed consistently in both 2D and 3D models.

Finally, with respect to wall thickness, it is evident that models with reduced thickness exhibit lower natural frequencies across all modes, a trend that holds true for both modeling approaches. The wall thickness of a subsea pipeline significantly influences its natural vibration frequency by directly affecting the cross-sectional moment of inertia and bending stiffness. An increase in wall thickness leads to a higher moment of inertia, thereby enhancing the bending stiffness of the pipeline. While greater thickness also increases the mass per unit length, the resulting increase in stiffness typically outweighs the added mass. Consequently, the ratio of stiffness to mass (k/m) increases, leading to an elevation in the natural frequency of vibration. Therefore, thicker pipeline walls contribute to higher natural frequencies, improving the pipeline's resistance to vibrational excitations.

4.3. Comparison of computational cost between 2D and 3D modeling

Despite the high level of accuracy offered by three-dimensional (3D) modeling in evaluating structural responses, this approach presents a significant challenge compared to its two-dimensional (2D) counterpart: the considerable computational effort required. The computational cost associated with 3D modeling is substantially greater than that of 2D simulations. This observation is confirmed by the simulations introduced in the previous sections. In the 2D models, the minimum and maximum run times were 19 and 40 seconds, respectively, with an average runtime of 22 seconds using a standard laptop equipped with a quad-core processor and 8 GB of RAM. In contrast, the 3D models exhibited a minimum runtime of 318 seconds and a maximum of 1996 seconds, with an average of 748 seconds on the same hardware. This represents an approximate 14-fold increase in computational time. Such a significant increase not only validates the aforementioned claim but also highlights the importance of considering computational efficiency when choosing between 2D and 3D modeling strategies, particularly in large-scale parametric studies or real-time applications where time and resources are constrained.

5. Conclusions

This study presented a detailed comparative investigation of two-dimensional (2D) and three-dimensional (3D) finite element models for the structural analysis of free-span subsea pipelines. Key parameters such as vertical deflection, natural frequencies, and computational cost were evaluated to assess the performance and applicability of each modeling approach.

The results revealed that while 2D models offer notable computational efficiency and can be effectively used in early-stage assessments, they exhibit limitations in capturing higher-mode vibrational behavior and complex dynamic responses. In contrast, 3D models demonstrated superior accuracy in representing realistic boundary conditions and deformation patterns, particularly in the presence of nonlinear interactions and complex loading scenarios, albeit at a significantly higher computational cost. Furthermore, it was observed that increasing the free span length substantially amplifies pipeline deflection, while larger diameters and thicker walls contribute to enhanced flexural rigidity and reduced displacement. The behavior of natural frequencies under varying geometric and boundary conditions was also examined, showing consistent trends across both modeling approaches. These findings underscore the critical importance of selecting appropriate modeling fidelity based on the objectives and phase of the design process. While 2D models may suffice for preliminary evaluations and parametric studies, 3D modeling remains essential for detailed structural analysis, final design validation, and integrity assessment. Overall, the insights gained from this study can inform more effective pipeline design strategies and support best practices per industry standards for free-span integrity management in subsea environments.

Despite the contributions of this study, several limitations remain, which open avenues for future research. One of the fundamental challenges in this study lies in the multiplicity of influential parameters, which necessitates extensive and diverse modeling efforts for comprehensive investigation. This complexity complicates the analysis and makes it difficult to attain a holistic understanding of the system's behavior. Therefore, it is recommended that future studies systematically evaluate the effects of various parameters by employing advanced numerical analysis methods and dimension reduction or sensitivity analysis techniques to achieve a more precise understanding of the phenomenon under investigation.

For future research, it is also suggested to examine the effects of heat transfer as a significant factor influencing system behavior. Additionally, analyzing the problem under conditions with longer free spans could provide deeper insights into the structural response under more realistic scenarios. These considerations may serve as a valuable pathway for further development and enhancement of the findings presented in this study.

Statements & Declarations

Author contributions

Meisam Qorbani Fouladi: Conceptualization, Investigation, Formal analysis, Resources, Writing - Review & Editing, Project administration, writing—original draft preparation.

Hamed Shirazi: Conceptualization, Investigation, Software, Validation.

Maryam Taghizadeh: Investigation, Methodology, Formal analysis, Writing - Review & Editing, Supervision, writing—Original draft preparation.

Giacomo Viccione: Investigation, Formal analysis, Writing - Review & Editing.

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Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interes.

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