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Numerical simulation of the interference between trawl gear and offshore pipelines

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WHILE DEEPWATER SUBSEA pipelines are designed to withstand a broad range of load patterns, including large hydrostatic pressure, high internal pressure, hydrodynamic loading, and temperature induced axial stresses, the interaction between fishing gear and the pipeline is one of the most severe design cases for an offshore pipeline system.

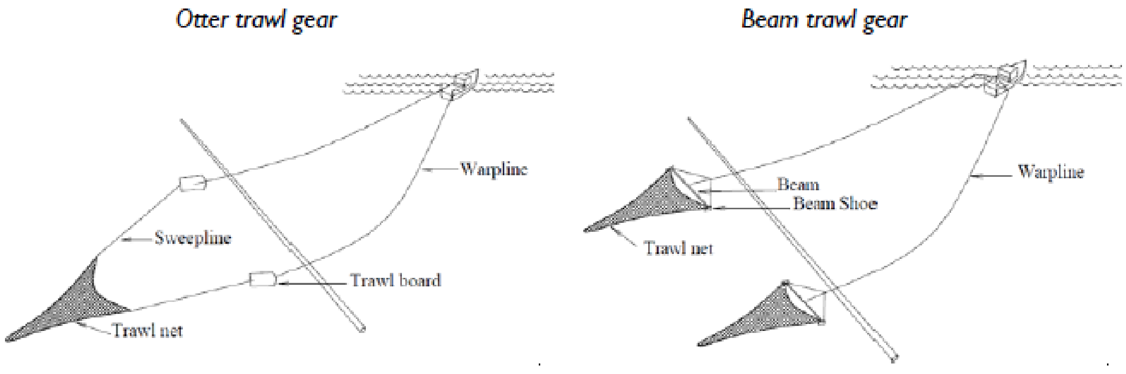
When bottom trawl gear is towed across the surface-laid pipeline, the interaction can be divided in different stages: *impact* (very short duration, high forces, local response) and subsequent *pull-over* (longer time duration, global pipeline response). In special cases, *hooking* may occur, where the trawl equipment is stuck under the pipeline.

The damage, afflicted to the pipeline, depends on the type of fishing gear (weight and velocity, beam trawl or otter trawl), and the pipeline conditions (primarily wall thickness and coating system). The most important issue with respect to the design of fishing gear resistant pipelines is the ability to provide a realistic description of the applied loads and their time history, and the response of the as-laid offshore pipeline (including potential pipeline spans).

In this paper, numerical models are presented to simulate the displacements and corresponding stresses induced during trawl gear pull-over. The finite element analyses are compared with simplified analytical approaches to investigate whether the recommended practices used in the offshore industry provide conservative predictions of impact energy dissipation and pipeline integrity.

Trawl gear interference in a historical perspective

Subsea installations like offshore pipelines attract fish – and hence fishing activity. Equipment used for bottom trawling, such as the otter and beam trawl gear schematically shown in Figure 1, can expose a surface-laid pipeline to substantial loads that may induce damage (DNV, 2010). The load is associated with the local, short duration impact (when the trawl gear hits the pipeline) and the subsequent pull-over (when the trawl gear is dragged over the pipeline). Moreover, accidental hooking may impose significant loads on the pipeline.


Otter trawl gear

Beam trawl gear

Figure 1 – Interference between trawl gear equipment and subsea pipelines (DNV, 2010).

Both the oil and gas exploration and production industry and the fishing industry have been interacting and working together to achieve safer industry practices for the benefit of both parties (Henderson, 2000).

One of the first papers addressing pipeline and fishing interaction was presented at the Offshore Technology Conference in 1972 (Brown, 1972). The paper describes some of the anchors and fishing boards commonly used in the sixties. The paper also outlines an approach to assess the risk of damage from dragging anchors or fishing boards. As the proposed risk management philosophy is based on the determination of the extent of possible impact induced damage and an evaluation of the number of occurrences, (Brown, 1972) can be read as a historical precursor for the DNV Recommended Practice RP-F111 (DNV, 2010).

In (Gjorsvik, 1975), model tests are reported for a 16" X60 pipeline with 11.1 mm wall thickness in the wave basin of the Trondheim lab. These experiments were performed on behalf of the Norwegian Deep Water Pipeline Project Committee, to evaluate the loads induced by bottom trawl gear on subsea pipelines for the North Sea and the Norwegian continental shelf. Although the OTC paper (Gjorsvik, 1975) describes in detail the model arrangement, the field test program and the instrumentation of the test pipes, the authors fail to report the test results.

Experimental results of field tests on a large diameter (36" X60, 22 mm wt) pipeline are documented in (Moshagen, 1980). This OTC paper is one of the first publications to provide a broad overview of measured pull-over forces for different pipeline diameters (16" and 36") and increasing trawling velocities (ranging from 1 to 4 m/s) for both V-shaped doors, oval doors, polyvalent trawl boards and beam trawl equipment. The results reveal that the magnitude of the pull-over load is not sensitive to the type of trawl equipment, and that the pull-over loads are up to 25% higher for free spans as compared to pipelines sitting on the seabed. The authors provide some recommendations to redesign trawl gear equipment to reduce pull-over loads when crossing subsea pipelines as well.

Guijt and Horenberg from Shell investigate the effects of bottom trawl gear crossings on submarine pipeline integrity in two accompanying OTC papers. In (Guijt, 1987), they present a purpose-designed finite difference model to predict the response of offshore pipelines subjected to trawl pull-over. The non-linear pipe response is described by two equations of motion to capture the lateral and axial pipeline displacements. The results of the simulations show the evolution of the local (dimensionless) curvature versus time, and the displaced pipe shape at the end of the pull-over load. These results are used in the paper at hand to compare the final pipeline shape predicted by SAGE Profile. The numerical simulations are complemented by a field test on an 18" interfield gas line in the Dutch sector of the Southern North Sea. Unfortunately, the test runs were deemed not representative of normal trawler operations, and the corresponding results have not been included in the paper. In (Horenberg, 1987), the same authors introduce a numerical simulator to perform transient calculations of trawl gear pull-over by deriving the dynamic equations of motion for the fishing vessel and the trawl gear, and an equilibrium equation for the warp line. For large diameters, the pipeline was assumed to be rigid and fixed. The predicted warp line forces from the numerical simulations were compared with results from a limited number of field (prototype) tests. Based on these comparisons, the authors conclude that the trawl gear – pipeline interaction is correctly captured, and the warp line peak force and duration can be predicted within 10%.

In 1991, Statoil and Marintek published a landmark paper on free spanning pipelines subjected to trawl forces (Verley, 1991). Model tests investigating trawl forces for free spans up to 6 m in height are described, and the results are presented for maximum warp force, maximum force applied to the pipeline and the shape of the force-time trace. The effects of tow velocity, span and warp flexibility and trawl door type are quantified. In addition, numerical simulations using an equivalent single degree of freedom system are presented. In our paper, the results of these simulations are used to benchmark the capability of different finite element solvers to describe transient dynamic events like trawl gear pull-over.

In (Mellem, 1996), an accurate method to determine the impact energy of a trawl board and –in particular- the impact energy absorbed by the pipe shell was proposed. This advanced impact calculation method has later been included in Appendix A of DNV-RP-F111 (DNV, 2010).

(Tornes, 1998) marks the advent of finite element analysis as an emerging tool in (pipeline) engineering. The authors (from JP Kenny, Norway) developed a 3D, non-linear transient dynamic finite element model to investigate the structural response of pipelines to pull-over loads. Their analysis was based on a full Digital Terrain Model (DTM) by importing survey data directly in the finite element model. Sensitivity analyses were presented to demonstrate the effects of effective axial force, seabed friction, seabed roughness and the presence of lateral buckles. For small diameter pipelines, the span height was found to be the governing parameter. For large diameter pipelines with low effective axial force, the span height was found to be less important. For large diameter pipes prone to buckling, it was concluded that a free span may be beneficial due to the absence of lateral soil restraint.

The DNV Recommended Practice on trawl gear interference (DNV, 2010) was first presented in (Askheim, 2006), with a separate paper on the effect of trawl clump weights (Fyrileiv, 2006). More recently, Longva has presented dynamic simulations of pull-over (Longva, 2011) and hooking (Wu, 2013).

Simulation of free span subjected to trawl pull-over

In this paper, we want to explore the potential of the SAGE Profile software suite (Wintgens, 2006) to simulate transient dynamic events like trawl gear pull-over. SAGE Profile has been tailored to assist the pipeline engineer during offshore pipeline design. The numerical tool is primarily used to predict the equilibrium response of offshore pipelines to static loading such as buoyancy, hydrostatic pressure, steady-state pressure and temperature profiles during operation, steady current velocities, ... A comprehensive overview of the added value that SAGE Profile can bring during offshore pipeline design, installation and operation is provided in (Van den Abeele, 2012).

Transient dynamic solver and explicit integration algorithm

Although SAGE Profile is primarily used for static applications such as on-bottom roughness, span assessment, route optimization, end expansion and pipeline stress analysis, the explicit solver enables the simulation of transient dynamic load patterns including trawl gear pull-over. Indeed, to calculate the position of the pipeline over time, the transient dynamic solver uses an explicit integration method. The velocities v are obtained from the acceleration using the central difference integration scheme:

$$v\left(t+\frac{\Delta t}{2}\right) = v\left(t-\frac{\Delta t}{2}\right) + \Delta t \cdot a(t) \tag{1}$$

and a similar scheme is used to update the nodal positions p:

$$p(t+\Delta t) = p(t) + \Delta t \cdot v\left(t+\frac{\Delta t}{2}\right) \tag{2}$$

A similar integration algorithm applies for the rotational degrees of freedom. The explicit integration algorithm is conditionally stable (Bathe, 1996), provided the time increment Δt is sufficiently small. For the (dominant) axial deformation mode, the critical time step is closely connected to the acoustic velocity, and

$$\Delta t < L_0 \sqrt{\frac{\rho_{st}}{E}} \left(\sqrt{1+\xi^2} - \xi\right) \tag{3}$$

must be satisfied to avoid that information propagates over more than one element during one time increment. In (03), ρ_{st} is the density of the steel, E its modulus of elasticity, and ξ is a damping factor..

Long free span subjected to trawl pull-over load

To explore the potential of the explicit solver to simulate transient dynamic events, the case study proposed in (Verley, 1991) is used as a benchmark. In that paper, Verley considers a 24" pipeline with 17.3 mm wall thickness and a concrete weight coating of 45 mm. The initial axial tension is assumed to be 1 000 kN, and the axial soil friction factor is chosen as $\mu_{ax} = 0.2$, representing a clay soil. For the transverse behavior, the pipe-soil interaction model proposed by (Wagner, 1897) is used, which can be approximated by a Coulomb friction factor $\mu_{lat} = 0.3$.

For the simulations of a long span subjected to pull-over loads, Verley assumes an artificial seabed with a gap of 125 meter. Two trapezoidal force-time histories were employed. The maximum force applied at the midspan were 100 kN and 200 kN, for a total duration of 2s and 4s respectively. The loading and unloading duration was 0.5s in all cases.

In (Verley, 1991), an equivalent Single Degree of Freedom (SDOF) system

$$m\ddot{x} + c\dot{x} + k_p x = f(t) \tag{4}$$

was identified to predict the lateral displacements x as a function of time. In Figure 2, the lateral displacements predicted by this SDOF model are compared with results from three different solvers, i.e.

1. the static solver of Ansys,
2. the implicit dynamic solver of Abaqus, and
3. the explicit dynamic solver of SAGE Profile 3D

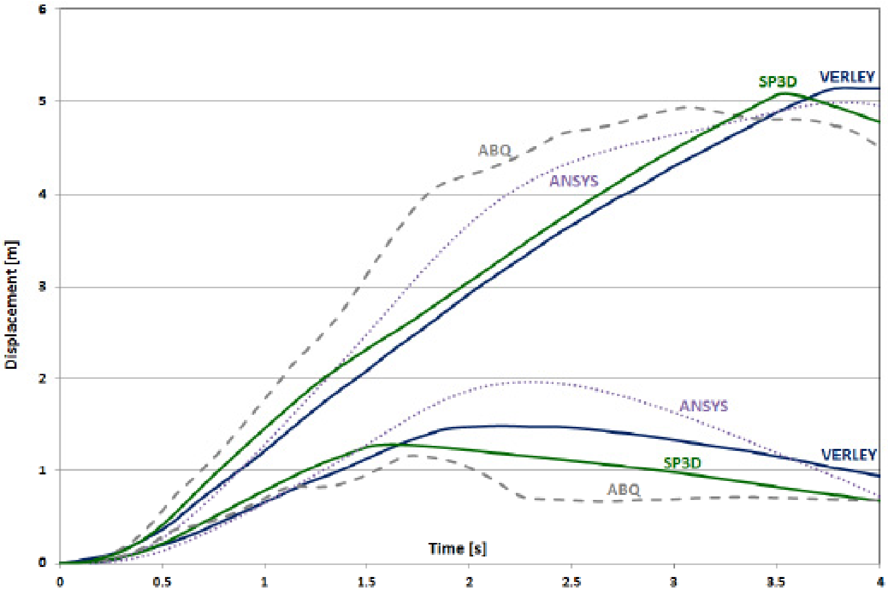


Figure 2 – Predicted displacements for a 125 m span subjected to pull-over.

For the 200 kN pull-over load (with a total duration of 4s and a loading and unloading flank of 0.5s), all three solvers predict a final displacement in line with the SDOF model, although the general purpose FEA solvers (Abaqus and Ansys) predict an initial response which is stiffer than the solution obtained with SAGE Profile or the SDOF model.

For the 100 kN pull-over load (with a total duration of 2s and a loading and unloading flank of 0.5s), Ansys appears to overestimate the lateral displacements during the trawl gear pull-over, whereas Abaqus underestimates the displacements. However, all three solvers reach the exact same final displacement.

Short free span subjected to trawl pull-over load

The simulations have been repeated for a shorter (75 m) span, with the same pull-over load traces. The results are compared in Figure 3. For the 200 kN pull-over load, SAGE Profile 3D compares well with the SDOF model, whereas Ansys slightly underestimates the displacements. For the 100 kN pull-over load, both SAGE Profile 3D and Ansys are in line with the SDOF model. The Abaqus implicit dynamics solver, however, cannot accurately capture the transient behavior of the short span subjected to trawl gear pull-over: for the high pull-over loads, the initial response is too stiff, for the low pull-over loads, Abaqus even seems to predict a vibrating span.

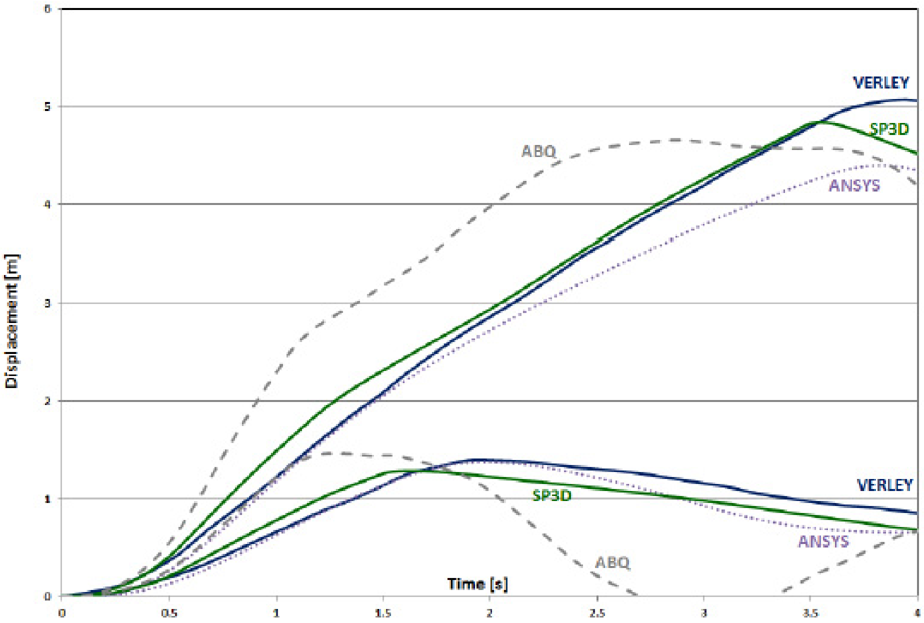


Figure 2 – Predicted displacements for a 125 m span subjected to pull-over.

Although the transient responses are (significantly) different for the static (Ansys), implicit dynamic (Abaqus) and explicit (SAGE Profile 3D) solvers, they do predict almost the same final state for all cases, like summarized in Table 1:

Table 1 – Final value of predicted lateral displacement [m] for each solver.

Span Length [m]	**Pull-Over Load [kN]**	**solver**			
		SDOF	SP3D	Abaqus	Ansys
125	200	5.146	4.805	4.530	4.958
	100	0.944	0.682	0.683	0.719
75	200	5.056	4.516	4.220	4.345
	100	0.854	0.687	0.665	0.658

Discussion on damping

The benchmark, presented here, shows that –although the final predicted state is similar- the transient response of the pipe is different when simulated with a static, an implicit dynamic or an explicit dynamic finite element solver. This can be attributed to the numerical architecture, where the implementation of damping is of particular importance. The explicit solver of SAGE Profile 3D introduces three types of damping:

Material damping

The material damping reflects the viscoelastic behavior of the pipeline steel, which reduces the velocity content of a node by adding an axial damping force

$$F_d = \xi_{ax} \frac{EA}{L_0} (v_{i+1} - v_i) \qquad (6)$$

where the axial damping coefficient is computed as

$$\xi_{ax} = \xi_c \sqrt{\frac{2\, m_l\, L^2}{EA}} \tag{7}$$

with m_l the element mass per unit length, and ξ_c the critical damping fraction. Similar equations hold for bending and torsion. For pipeline steels, the Kelvin-Voigt type damping forces are very low, and only influence the constitutive law connecting strains to stresses. Hence, the material damping has only very limited influence on the simulated global pipe displacements.

Hydrodynamic damping

The hydrodynamic damping accounts for the fact that the offshore pipeline is moving (with a velocity v_n normal to the pipe) in still standing water rather than air or vacuum. According to the generalized Morison's equations (Morison, 1950), the moving pipe will experience a hydrodynamic drag force

$$F_D = \frac{1}{2}\, \rho_{sw}\, C_D\, D_{tot}\, |v_n|\, v_n \tag{8}$$

which is proportional to the seawater density ρ_{sw}, the total outer diameter D_{tot} and an empirical drag coefficient C_D. In (Verley, 1991), the drag coefficient has been selected as $C_D = 1.0$.

Artificial (viscous) damping.

The artificial damping is a general nodal force that is applied to avoid instabilities in (highly) dynamic load scenarios like anchor impact or trawl gear interference. The magnitude of the artificial damping force is proportional to the velocity

$$F_{ad} = c\, v_i \tag{9}$$

which renders it a viscous damping force.

In (Verley, 1991), the damping factor was calibrated as $c = 117$ kNs/m for the 200 kN load case, and as $c = 100$ kNs/m for the 100 kN load case.

To evaluate the influence of these damping factors on the predicted pipe response, a sensitivity analysis was performed for the 125m span under 200 kN pull-over load, where the lateral displacements are most pronounced.

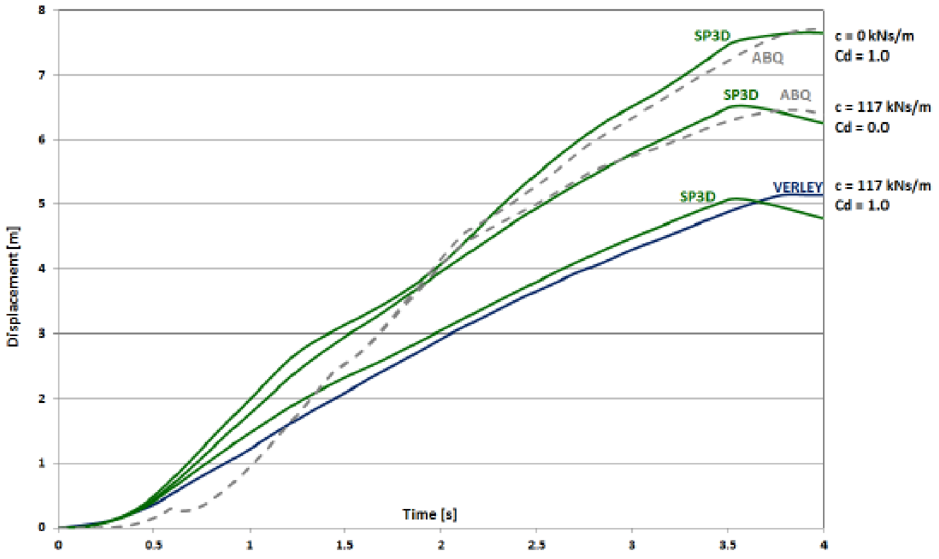


Figure 3 – Influence of damping on predicted lateral displacements.

The results, shown on Figure 3, indicate that the artificial damping factor has a more pronounced influence than the drag coefficient. In this analysis, the SAGE Profile 3D results are compared with simulations from the Dynamic Explicit solver of Abaqus, showing very good agreement.
As the hydrodynamic drag is a physical phenomenon, and the selection of drag coefficients is well documented, there is little incentive to challenge the selection of $C_D = 1.0$. On the other hand, Figure 3 clearly indicates that value for the artificial damping must be judiciously chosen to avoid unconservative predictions. In the analysis, presented here, the simulations with $C_D = 1.0$ and $c = 0$ kNm/s lead to a maximum lateral displacement u_{max} = 7.7 m, which can be interpreted as a conservative upper bound value for design purposes.

Pipeline on the seabed subjected to trawl pull-over

The (Verley, 1991) benchmark allows the comparison of the evolution of lateral displacement versus time during trawl gear pull-over. However, the paper does not provide information on the final pipeline shape. To evaluate the potential of SAGE Profile 3D to accurately predict the pipeline shape after trawl gear crossing, the case study presented in (Guijt, 1987) is used.

Guijt et. al. present simulations for an 18" pipeline with 12.7 mm wall thickness and a concrete weight coating of 65 mm. The 9.35 km pipeline is located in the Dutch sector of the Southern North Sea, in 30 to 30 m water depths. The seabed conditions are reported to be sandy soils, with lateral friction factors $0.7 \leq \mu_{lat} \leq 1.0$ and axial friction factors $0.5 \leq \mu_{lat} \leq 0.7$. The pipeline steel grade is not disclosed in (Guijt, 1987).

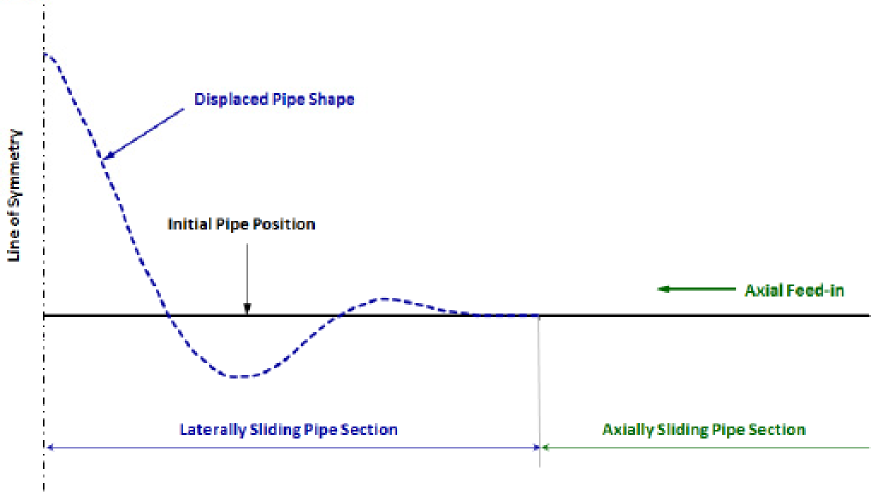


Figure 4 – Two dimensional model to predict pipeline response during pull-over.

A non-linear dynamic model is presented, where the lateral response of the pipe is described by the equation of motion

$$m_{lat}\frac{\partial^2 y}{\partial t^2} = -\frac{dM}{d\kappa}\frac{\partial^4 y}{\partial x^4} - \frac{d^2 M}{d\kappa^2}\left(\frac{\partial^3 y}{\partial x^3}\right)^2 + F_e\frac{\partial^2 y}{\partial x^2} + Q_{lat} \tag{10}$$

with Q_{lat} the pull-over force, which was estimated to have a triangular shape with a total duration of 1s, reaching the maximum force of 300 kN after 0.75s. The axial displacements are found as the root of

$$m_{ax}\frac{\partial^2 u}{\partial t^2} = \frac{\partial F_e}{\partial x} - \frac{dM}{d\kappa}\left(\frac{\partial^3 y}{\partial x^3}\right)\frac{\partial^2 y}{\partial x^2} + Q_{ax} \tag{11}$$

where the external axial load is assumed to be $Q_{ax} = 0$. The pipe is installed on the seafloor, hydrotested at 150 bar and subsequently subjected to maximum operating conditions (internal pressure of 100 bar at a temperature differential of $\Delta T = 35°C$.

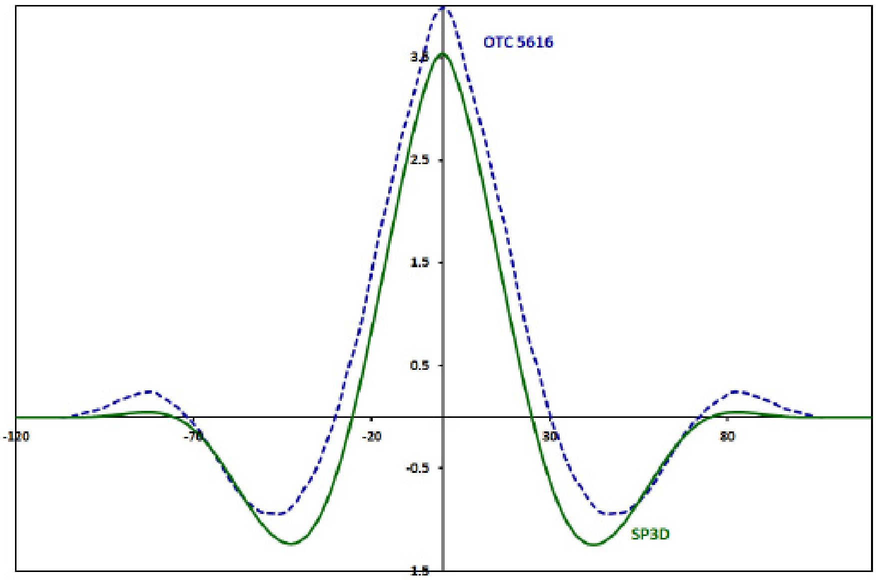


Figure 5 – Predicted pipeline shape after trawl gear pull-over.

In Figure 5, the final pipeline shape predicted by (Guijt, 1987) is compared with SAGE Profile 3D simulations. The results show a good agreement, acknowledging that detailed information on selection of friction factors and steel properties has been obscured in (Guijt, 1987).

Pipeline subjected to subsequent pull-over loads

As a final case study, the example provided in Appendix B of the DNV Recommended Practice on Trawl Gear Interference (DNV, 2010) was investigated using SAGE Profile. This example covers a 13 km X65 pipeline with a diameter of 14", a wall thickness of 16 mm and a corrosion allowance of 3 mm. The water depth is assumed constant at 300 m, and the soil conditions are described as sand with a friction angle ϕ = 35°, and axial friction coefficient μ_{ax}= 0.4 and a lateral friction coefficient μ_{lat} = 0.6.

To focus on the pipeline response from the pull-over load only, the pipeline is considered to have released the residual forces by global buckling close to the pull-over location. Hence, the laydown simulation in SAGE Profile 3D has been performed with a very low value for the residual on-bottom lay tension. The pipeline on the seabed has negligible compressive forces due to thermal and internal pressure effects, and the analyses are based on zero operational pressure and ambient (seawater) temperature.

A polyvalent trawl board with height $h = 2B = 3.5$ m is considered, and the warp line stiffness can be estimated as

$$k_w = \frac{3.5 \cdot 10^7}{L_w} \tag{12}$$

where the length of the warpline L_w can be approximated as three times the water depth. The maximum pull-over force is given by

$$F_p = C_F V \sqrt{m_t \, k_w} \tag{13}$$

with $V = 2.8$ m/s the trawl velocity, $m_t = 4000$ kg the trawl board steel mass, and the empirical force coefficient

$$C_F = 8.0\left(1 - \exp\left(-0.8\,\overline{H}\right)\right) \tag{14}$$

Where

$$\overline{H} = \frac{H_{sp} + D_{tot}/2 + 0.2}{B} \tag{15}$$

is a dimensionless height, where $H_{sp} = 0$ for a pipeline sitting on the seabed, and B is half the trawl board height, which leads to $F_p = 48.6$ kN. The corresponding maximum downward acting force becomes

$$F_z = F_p\left(0.2 + 0.8\exp\left(-2.5\,\overline{H}\right)\right) = 31.1\ \text{kN} \tag{16}$$

The total pull-over duration is estimated according to DNV-RP-F111 to be

$$T_p = C_T\,C_F\,\sqrt{\frac{m_t}{k_w}} + \frac{\delta_p}{V} \tag{17}$$

with $C_T = 2.0$, $C_F = 1.39$ and δ_p the displacement of the pipe at the point of trawl gear impact. Since this value is obviously unknown prior to performing the impact response simulations, the total pull-over duration (17) has to be determined using an iterative approach. However, the response is rather insensitive to realistic values of δ_p, and DNV recommends to approximate the total response time as

$$T_p \approx 1.1\left(C_T\,C_F\,\sqrt{\frac{m_t}{k_w}}\right) \approx 1\,\text{s} \qquad (17)$$

For the polyvalent board in this example, this leads to a triangular force-time history with a total duration of 1s and a ramping time of 0.4s. The simulated displacements for four subsequent trawl pull-over loads are compared to the DNV-RP-F111 results in Figure 6, showing that SAGE Profile predicts a similar trend: the lateral displacement increases for each pull-over, but the pipeline material still behaves linear elastically.

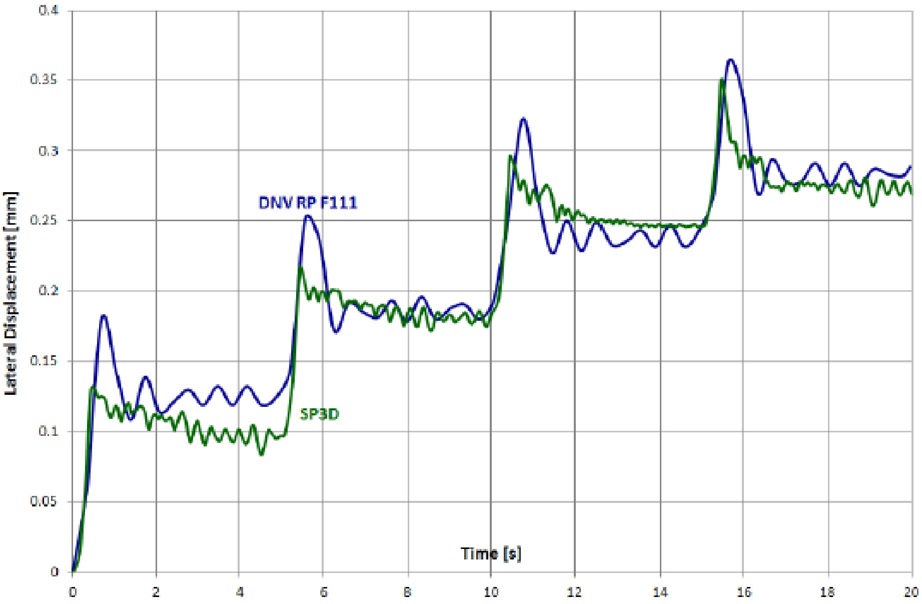


Figure 6 – Pipeline response to subsequent trawl gear pull-over loads.

The DNV-RP-F111 considers four subsequent pull-overs at the same location and in the same direction to provide a conservative estimate. The bending moments, predicted by SAGE Profile (see Figure 7) , show a maximum value of 143 kNm, which is close to the 148 kNm mentioned in (DNV, 2010). The corresponding utilisation factor (local buckling) is 0.46, implying that this pipe can indeed withstand multiple trawl gear crossings.

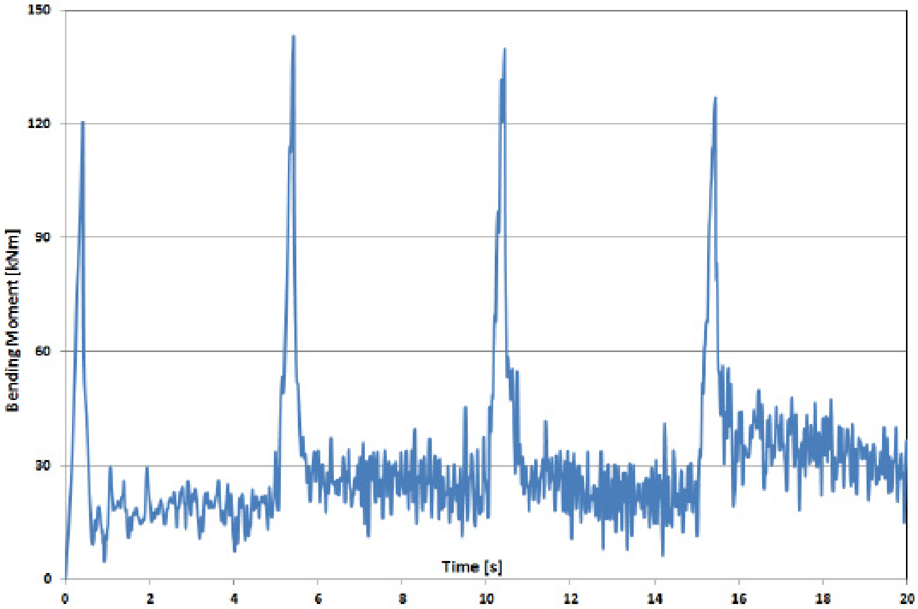


Figure 7 – Maximum bending moments during subsequent trawl gear pull-over loads.

Conclusions

In this paper, numerical models were presented to simulate the displacements and corresponding stresses induced during trawl gear pull-over. The finite element analyses were compared with simplified analytical approaches and results published in DNV-RP-F111. The results, presented here, indicate that the SAGE Profile software suite for offshore pipeline analysis can indeed predict the transient dynamic response of surface-laid subsea pipes subjected to trawl gear pull-over loading – provided the damping factors are judiciously chosen.

Based on these observations, Fugro GeoConsulting Belgium shall submit SAGE Profile for full dynamic certification and is keen on developing trawl gear pull-over (as per DNV-RP-F111) as a standard loading pattern in forthcoming versions of SAGE Profile.

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