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OUR COVER PICTURE shows a graphic of typical loading pattern for a subsea pipeline. The figure is taken from the paper on pages 273-286 which examines the issue of numerical modelling and analysis for the design, installation, and operation of subsea pipelines.
THE INCREASING demand for oil and gas, currently estimated at 135 million barrels of oil equivalent per day, keeps pushing the boundaries of offshore engineering into ever-deeper waters. For instance, in the Gulf of Mexico, exploration and production activities are performed in water depths exceeding 3000 m. Such remote locations and challenging environments call for new procedures and solutions in the design and installation of offshore pipelines.

In this paper, numerical modelling and analysis of offshore pipelines is reviewed and discussed. Finite-element techniques to assist in pipeline design are introduced, and applied to pipeline routeing optimization. Special emphasis is devoted to out-of-straightness and on-bottom stress analysis.

Contact algorithms allowing the simulation of pipelaying on an uneven seabed (using bathymetry) are reviewed, and recent developments in modelling of pipe-soil interaction are highlighted. The importance of free-span detection and evaluation is stressed. In addition, it is shown how finite-element analysis can contribute to the prediction and mitigation of both upheaval and lateral buckling of subsea pipes. At the end of this paper, pipeline walking on an inclined seabed is simulated, and the importance of seabed friction on the walking rate is demonstrated.

OIL AND GAS exploration and production is embarking into ever greater water depths. Consequently, offshore pipeline engineering is continuously pushing the boundaries, installing flowlines and export pipelines in water depths exceeding 3000 m. The availability of high-performance computing systems and dedicated software tools enable pipeline engineers to cope with the challenges associated with design of subsea completions.

In this paper, an overview is presented of numerical modelling and analysis for offshore pipeline design, installation, and operation. SAGE Profile 3D [1-3] is used to demonstrate the added value of numerical modelling as a design aid and decision tool throughout the entire life of an offshore pipeline, covering:

- preliminary pipeline design
- route selection and optimization
- offshore pipeline installation
- free-span assessment
- on-bottom stress analysis

SAGE Profile 3D uses a transient dynamic explicit integration kernel, which enables the efficient simulation of the pipelaying process and the response of the subsea pipe when subjected to hydrodynamic loading and operational conditions (time-dependent pressure and temperature profiles). In this paper, the numerical algorithms governing pipeline laydown, pipe-soil interaction, and numerical integration are briefly covered, and some examples on free-span evaluation, lateral buckling, upheaval buckling, and pipeline walking are highlighted to demonstrate the versatility of finite-element methods as a powerful support tool in offshore pipeline design.

Pipeline route selection and optimization

One of the early tasks for the pipeline engineer is to determine the preliminary route and evaluate the feasibility of the selected pipeline corridor. An informed route selection cannot be made without information on the seabed topography and geotechnical data [4].

Performing an initial desk study before embarking on an extensive (and expensive) marine survey can save a considerable amount of time and money[5]. In SAGE Profile,
of seabed elevation versus KP is updated simultaneously, which allows evaluating the on-bottom roughness of the selected route already during pre-processing, without any requirement for computing power.

At the same time, the allowable bending radii can be quickly screened. Each pipeline bend radius $R$ should be large enough to ensure that the bending stresses do not exceed the allowable stress $\sigma_a$:

$$R > \frac{E D_o}{2 \sigma_a}$$

where $E$ is the Young’s modulus of the pipeline steel and $D_o$ is the outer diameter of the pipe. Moreover, the pipeline requires sufficient frictional force to resist being dragged over the seabed by the lay barge. Hence:

$$R > \frac{T}{\mu w_s}$$

with $\mu$ the lateral friction factor, $T$ the lay tension, and $w_s$ the submerged weight per unit length. In addition to bathymetric considerations, selection of the optimum pipeline route also depends on a broad spectrum of other factors, including:

- politics and regulatory requirements
- crossing of existing pipelines or submarine cables
- iceberg plough marks, pockmarks
- areas of very soft or very hard seabed
- boulder fields, rock outcrops
- risk of anchor damage and trawling gear impact
- proximity of other subsea installations
- cost-efficiency of installation
- environmental and ecological issues

The SAGE Profile pre-processor allows introduction of different layers of information, by importing additional information such as admiralty charts, test locations, existing pipelines, and shipwrecks. In Fig. 3, for instance, a proposed pipeline route is shown on a digital-terrain model and, in addition, an overlay plot is made to display data associated with the seabed topology can easily be created or imported from survey data, either as:

- kilometre point (KP) versus seabed elevation
- Easting-Northing-elevation (ENE) coordinates
- full 3D digital-terrain model (DTM)

In Fig. 1, two corridors imported from survey data are compared. In the northern corridor, a curved pipeline route has been drawn, whilst a straight pipeline section is proposed for the southern part.

The pipeline route can be easily imported, or constructed through a user-friendly and straightforward graphical interface. This interface will convert the constructed route automatically into a proprietary route format, with successive sections of straight lines and circle arcs. The straight sections (like the green route in Fig.1) are defined by a start and end point, whereas the circular arcs (for example, the middle section of the red route shown in Fig.1) are defined by the tangent points and the centre of the circle linking these tangent points.

As demonstrated in Fig. 2, the user interface enables an early assessment of seabed topography and on-bottom roughness. Whilst modifying the proposed pipeline route, the graph
with the pockmarks. This layered presentation of information offers the pipeline designer an intuitive dashboard with a wealth of data to select the most appropriate pipeline route. In addition to overlay plots, contour maps, and slope angles can easily be visualized, which provides additional input to assess potential geohazards.

**Simulating pipe laydown and installation**

Offshore pipeline installation is performed from a laybarge, typically in S-lay configuration. For smaller diameters, pipeline reeling can be the most cost efficient solution, whereas J-lay is the only feasible approach in (ultra-) deep water. Depending on the installation method, the pipeline is subjected to different load patterns during installation, including hydrostatic pressure, lay tension, and bending on the stinger and in the sagbend. A comprehensive overview on the mechanics of installation design can be found in [6].

The simulation of the pipelaying process is one of the most challenging tasks once the optimum route has been selected. Implementing pipeline installation in a general-purpose finite-element package can be a time-consuming and tedious job, in particular when importing vast amounts of seabed data. Most often, advanced scripting techniques are required to define the seabed profile, select the optimum pipeline route, and simulate the laydown process. In addition, the available constitutive models for pipe-soil interaction may not comply with industry standards.

Finite element tools like SAGE Profile have been tailored to assist the pipeline engineer during offshore pipeline design. Using an explicit integration algorithm, the actual pipeline-installation process can be approximated. The pipe is simulated by discretising the entire pipeline into section of finite length. These sections are represented by beam elements with 12 degrees of freedom (DOF), bounded at either side by nodes. The distributed mass of the pipe is lumped at these nodes. The finite-element kernel uses an explicit solver, which computes the dynamic motion of the pipe and is therefore ideally suited to simulate the pipelaying process.

During this pipeline installation process, new pipe elements are continuously created and the pipe is laid along the target path defined on the seabed. The lay tension $T$, applied at the barge, is used as an input and the unstressed length $L_0$ of the last element is updated such that the axial force corresponds to the applied lay tension:

$$\frac{L - L_0}{L_0} E A - F_p = T$$

with $L$ the original element length,

$$A = \frac{\pi}{4} (D_o^2 - D_i^2)$$

the cross-sectional area of a circular pipe with inner diameter $D_i$ and outer diameter $D_o$, and

$$F_p = (1 - 2\nu)(p_o A_o - p_i A_i)$$

the pressure induced axial force component, accounting for both the internal pressure $p_i$ and the (hydrostatic) external pressure $p_o$. As a result, both empty and water-filled installation can be simulated. In Equn 3, $\nu$ is the Poisson’s coefficient of the pipeline steel, where $A$ and $A_0$ are the surface areas of the interior and exterior of the pipe respectively. When the unstressed element length:

$$L_0 = \frac{L E A}{T + F_p + E A}$$
where \( \theta \) is the angle between the pipe and the target path, and \( h \) is the height of the feeding point above the seabed. Replacing the laybarge with a feeding point close to the seabed allows for a significant reduction in calculation time, without losing accuracy. Given the inherent complexity of pipeline laying, an accurate and robust steering mechanism of the feeding point is of paramount importance. In SAGE Profile, this steering mechanism is governed by a proportional-integrating-differentiating (PID) controller, providing a smooth movement of the feeding point and ensuring that the pipeline is installed on the predefined target path (shown in red in Fig.5).

In addition to the concept of a feeding point, an efficient element-killing procedure has been implemented to control the computational effort during pipeline laydown. Indeed, it would be too expensive to simulate the entire length of the pipe from its starting point up to the feeding point. In order to reduce the required calculation time, elements that are already lying on the seabed and are no longer moving will be removed from the simulation. If the magnitude of the velocity vector for a node is lower than a predefined threshold, the associated element has little or no contribution to the simulation results and can be killed without losing accuracy. In Fig.5, the elements that have been killed are also shown.

**Evaluation of free-spanning pipelines**

Accurate prediction of free spans (location, length, and height) is an important prerequisite in offshore pipeline design. Indeed, free-span lengths should be maintained within an allowable range [7], which is determined during the design phase. Pipelines installed on a very rough seabed can cause a high number of free spans that can be difficult to rectify. A judicious assessment of free spans can dramatically reduce the costs associated with seabed intervention (trenching, rock dumping, and span supports).

Figure 6 demonstrates that finite-element analyses enable the simulation of pipeline installation on an uneven seabed, and allow detection of free spans. The colour code on Fig.6 reflects the local span height, i.e. the gap between the pipeline and the seabed. After the pipelay simulation has been completed, SAGE Profile automatically detects the spans over the entire pipeline route, and plots the span location, length and height in comprehensive and easy-to-read design charts, as shown in Fig.7.

Once a free span that is longer than the allowable span length occurs, the span may suffer from vortex-induced vibrations (VIV) which can induce fatigue damage in the pipe. It was only recently that the commonly used pipeline design codes allow free vibrating spans, as long as the structural integrity of the pipeline system remains assured [8].

Span checks can be performed to assess whether an installed pipe is compliant with the guidelines recommended in...
DNV-RP-F105 [9]. For each detected span, SAGE Profile will calculate the associated reduced velocity:

\[ V_R = \frac{U_c + U_w}{f_1 D_o} \]  

(8)

where \( U_c \) is the mean current velocity (normal to the pipe), \( U_w \) the significant wave-induced flow velocity, and \( f_1 \) an approximation [9] for the lowest natural frequency given by:

\[ f_1 \approx \sqrt{1 + CSF} \left( \frac{E I}{m_e L_e^2} \left[ 1 + \frac{F_e}{P_{cr}} + C_3 \left( \frac{\delta}{D_o} \right)^2 \right] \right) \]  

(9)

with SCF the stiffening effect of the concrete coating, \( L_e \) the effective span length [10], \( m_e \) the effective mass, \( F_e \) the effective axial force, \( \delta \) the static deflection and \( C_3 \) the end boundary coefficient. The moment of inertia for the hollow circular pipe is given by

\[ I = \frac{\pi}{64} (D_0^2 - D_e^2) \]  

(10)

and the critical buckling load can be calculated as

\[ P_{cr} = (1 + SCF) \frac{C_2 \pi}{L_e^2} \frac{E I}{\rho_w D_o^2} \]  

(11)

where \( C_2 \) is an end boundary coefficient as well.

In addition to the reduced velocity (Eqn 8), the software calculates the stability parameter:

\[ K_s = 4 \pi \frac{m_e \xi_T}{\rho_w D_o^2} \]  

(12)

for each span, where \( \xi_T \) is the total modal damping ratio, comprising structural damping, hydrodynamic damping and soil damping. Based on the values of the reduced velocity from Eqn 8 and the corresponding stability parameter from Eqn 12, the software will check whether the conditions for the onset of in-line or cross-flow VIV are met in full compliance with DNV-RP-F105. This powerful capability provides a quick and easy tool to evaluate the severity of free spans for a given pipeline route, and hence can save a tremendous amount of time and money associated with seabed rectification.

In the next sections, some operational analyses are presented to evaluate the susceptibility of high-temperature subsea pipelines for buckling and walking. First, some details and recent developments on numerical modelling of pipe-soil interaction are reviewed.

**Numerical modelling of pipe-soil interaction**

The key to a successful simulation of offshore pipeline installation and operation is a profound understanding of the pipe-soil interaction, which is the most important parameter governing the design. The elastoplastic constitutive behaviour of the pipeline steel can be described by the Ramberg-Osgood equation [11-12], connecting pipe
Ramberg-Osgood formulation in SAGE Profile takes into account the combined effects of plasticity, ovalization [14-15], axial force, and hydrostatic pressure ([15-16]).

The pipe is assumed to be in contact with the seabed when the difference between the z-coordinate of a pipe node and the corresponding seabed elevation at this (x,y) location is less than the external pipe radius $R_e$. Once contact has been detected, a soil response will be exerted depending on the type of seabed soil. The soil response is captured by a combination of vertical, axial, and lateral springs.

The bearing capacity $Q_u$ is reflected by the vertical soil reaction. For sands, DNV-RP-F105 recommends:

$$Q_u(z_p) = \left( \gamma_s N_q + \gamma_s z_p N_a \right) B(z_p)$$

where $\gamma_s$ is the submerged unit weight,

$$N_q = \exp(\pi \tan \varphi) \tan^2 \left( \frac{\pi}{4} + \frac{\varphi}{2} \right)$$

with $\varphi$ the friction angle, and

$$N_f = \frac{3}{2} (N_q - 1) \tan \varphi$$

The bearing width $B$ depends on the pipe penetration $z_p$, as is schematically shown in Fig.8, and can be calculated as:

$$B(z_p) = \begin{cases} \sqrt{z_p (D_o - z_p)} & 0 \leq z_p \leq D_o/2 \\ D_o & \text{otherwise} \end{cases}$$

For clays, DNV-RP-F105 recommends:

$$Q_u(z_p) = 5.14 C_u + \gamma_s z_p B(z_p)$$

where $C_u$ is the undrained shear strength. Figure 9 compares the vertical soil-spring reaction forces for a medium-dense sand (with a friction angle $\varphi = 33^\circ$ and a submerged unit weight $\gamma_s = 8.5 \text{kN/m}^3$) with the soil reaction of a soft clay (with undrained shear strength $C_u = 30 \text{kPa}$ and a submerged unit weight $\gamma_s = 7.5 \text{kN/m}^3$).

In addition to the vertical soil springs recommended by DNV-RP-F105 [9], other soil models for both cohesive and cohesionless materials are described in DNV-CN30.4 [17-18]. For very soft clays ($C_u \leq 20 \text{kPa}$), a buoyancy formulation could be used, assuming that the soil behaves like a liquid and that the soil-induced buoyancy of the pipeline is equal to the vertical soil reaction:

$$Q_u(z_p) = \frac{z_p}{6 B(z_p)} \left( 3 z_p^2 + 4B^2(z_p) \right) \gamma_s$$
The combination of a vertical, axial and lateral soil spring fully defines the pipe-soil interaction. In addition to the commonly used soil-spring models, presented here, SAGE Profile offers dedicated and more enhanced soil models to describe complex soil behaviour such as berm formation, buried pipes, and trenching operations [19]. Moreover, an application programming interface (API) can be used to access an advanced soil library based on the incremental plasticity approach described by Zhang [20-21]. In this approach, the load-displacement relationship for an elastoplastic soil model is expressed in its incremental form:

\[
\{dU\} = [C] \{dF\}
\]  

(24)

where the vector of incremental loads \{dF\} is connected to the resulting displacements \{dU\} by the compliance matrix [C]. In addition to an extensive library of predefined soil models, user-defined constitutive laws can be implemented as well to construct the compliance matrix.

Accurate pipe-soil interaction is a key requirement for the reliable prediction of the on-bottom behaviour of offshore pipelines. Significant development efforts are being conducted to continuously improve the predictive capability of the pipe-soil interaction parameters [22]. Recently, much R&D effort has been devoted to the development of coupled soil springs to comply with the guidelines of the SAFEBUCK JIP [23-24].

In the next sections, some case studies on pipeline instability (lateral buckling, upheaval buckling, and pipeline walking) are presented to demonstrate the importance of pipe-soil interaction in finite-element simulations. First, the numerical architecture of the transient dynamic solver is briefly explained.

**Loading patterns and explicit integration**

Offshore pipelines are subjected to hydrodynamic loading (combined actions of currents and waves), internal and external pressure, operational loads (temperature and pressure), and external loads. As is schematically shown in Fig.11, these loads can be either defined directly (for example, lay tension,
and a drag force:

\[ F_D = \frac{1}{2} C_D \rho_w D_o (u \cos \alpha + V \cos \beta) (u \cos \alpha + V \cos \beta) \]

are imposed based on the Morison’s equations [25], where \( C_L \) and \( C_D \) are the lift and drag coefficients respectively. On top of that, the wave induced acceleration gives rise to an inertia force:

\[ F_I = C_I \rho_w \frac{\pi D_o^2}{4} a \cos \alpha \]

with \( C_I \) the inertia coefficient. For combined wave and current action, the hydrodynamic coefficients \( \{C_L, C_D, C_I\} \) can be selected [26] based on the surface roughness on the pipe, the Reynolds number \( Re \), the Keulegan-Carpenter number \( K \), and the gap between the pipe and the seabed [27]. Current and wave velocity and incidence angle can be supplied directly by the user. The wave parameters can also be calculated based on the JONSWAP spectrum [28]. In this modification of the Pierson-Moskowitz spectrum [29] for a developing sea state in a fetch-limited situation, the significant flow velocity amplitude and the mean zero-up crossing period are calculated based on linear Airy wave theory [30].

Finally, the pipeline loading history, which is fundamental for the realistic simulation of its response, is tracked by defining successive load cases. Loading sequences such as shut-down cycles, can be modelled using restart capabilities, which allows a load case to start from the final configuration of a previous condition.

All of the load patterns described above are converted to nodal forces. The forces acting upon each node are summed, resulting in an out-of-balance force \( F(t) \). According to Newton’s law, this force implies an acceleration:

\[ a(t) = \frac{F(t)}{m} \]

with \( m \) the total mass lumped at this node.

To calculate the position of the pipeline over time, a transient dynamic solver uses an explicit integration method. Indeed, the velocities \( v \) are obtained from the acceleration using the central difference integration scheme:

\[ v \left( t + \frac{\Delta t}{2} \right) = v \left( t - \frac{\Delta t}{2} \right) + \Delta t \cdot a(t) \]

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

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

A similar scheme applies for the rotational degrees of freedom. The explicit integration algorithm is conditionally operational pressure and temperature) or modelled using either uniformly distributed loads (such as to model buried pipe sections), point loads (such as to reflect the additional mass of sacrificial anodes), or pre-described displacements (such as the pipeline being lifted by the plough grabs during trenching operations).

Internal and external pipe pressure are modelled by taking into account the water depth at each node. Temperature profiles can vary with KP, reflecting the temperature gradient between the hot end (close to the wellhead or manifold) and the cold end (riser tie-in). Pressure and temperature variations (as well as the residual bottom tension after lay-down) contribute to the nodal forces. Assuming that waves are approaching the pipeline with a velocity \( u \) and at an angle \( \alpha \), and the current with steady velocity \( V \) is approaching at an angle \( \beta \), both a lift force:

\[ F_L = \frac{1}{2} C_L \rho_w D_o (u \cos \alpha + V \cos \beta)^2 \]

Fig.12. Introduction of quasi-static loading.

Fig.13. SAGE Profile simulation of lateral buckling.
In Fig. 13, the plan view of an operational pipeline is shown when subjected to increasing temperatures. The simulation has been performed with SAGE Profile, using the vertical soil spring for medium dense sand (shown in Fig. 9), and lateral and axial friction factors equal to $\mu = 0.7$. The pipeline path deviates from its original route, and a lateral buckle develops. In post-buckling behaviour, the effective axial force in the buckle zone (which reached the critical value to trigger instability) drops because of the additional length that feeds into the buckle. Simulations have shown [37] that the length of the buckle, its maximum amplitude, and the effective axial force mainly depend on the mechanical material properties, the pipeline geometry and weight, and the pipe-soil interaction.

Susceptibility to upheaval buckling

Buried pipelines subjected to a large temperature increase and axial restraint are prone to upheaval buckling. As a benchmark, a straight 100-m long pipeline, pinned at both ends, was simulated on a rigid frictionless soil. An initial imperfection was introduced at mid-length to invoke upheaval buckling. The SAGE Profile simulation results, shown in Fig. 14, show excellent agreement with the Abaqus simulations for both the onset of buckling and the post-buckling behaviour.

By introducing the concept of damping, the explicit (and hence inherently dynamic) approach can also be used to obtain solutions to (quasi-)static problems. Quasi-static load cases are phased in over a period of time, called the ramping time. Once the ramping time is reached, the load reaches its full extent, and the pipe is given time to settle down and reach equilibrium. This quasi-static load introduction is explained on Fig. 12.

The total sum of the kinetic energy over all nodes:

$$E_{\text{kin}} = \sum_{i=1}^{N} m_i \frac{1}{2} v_i^2(t)$$

(32)

is a scalar value that indicates the energy content of the entire pipeline as a function of time. As shown in Fig. 12, the simulation is assumed to have reached equilibrium when the kinetic energy drops below a pre-defined threshold value $E_{\text{th}}$, or when the equilibrium time is reached.

**Numerical prediction of lateral buckling**

Pipelines operating at high temperature are susceptible to global buckling. The basics of buckling were first developed by Euler [32], who established the critical load for long, slender, structures under compression. In pipeline engineering, Hobbs [33-34] was one of the first to develop a semi-empirical method to calculate buckling. His approach was based on solving the linear differential equation for the deflected shape of a spring-supported beam-column under axial load. The most important limitations of this method are the assumptions on linear-elastic material and small rotations, and the idealized straight pipeline.

It is recognized [35] that lateral-buckling modes tend to occur at lower compressive forces than the vertical (upheaval) buckling mode. Hence, unless horizontal displacements are restrained (like for buried pipelines) or a prevailing vertical imperfection is present, pipelines tend to buckle laterally. It has even been argued to use lateral buckling as a design tool [36-37] to relieve and control axial compression in the pipeline.

Numerical prediction of lateral buckling
with \( w_p \) and \( w_c \) the submerged weight of the pipe and the backfill cover respectively.

The download \( w_d \) can then be converted to the rock dump volume \( V_d \) shown on Fig.16:

\[
V_d = a \left( Z_d + D_0 \right) + \frac{(Z_d + D_0)^2}{\tan \beta}
\]  

(38)

with \( a \) the width, \( \beta \) the slope angle and \( Z_d \) the required rock dump cover depth above the pipe. Note that this approach remains valid for a pipeline sitting on the seabed, with:

\[
Z = 0 = w_c
\]  

(39)

Numerical tools can be used to evaluate the influence of seabed modifications, such as the installation of sleepers to promote buckling, rectifying a rough seabed, or finite-element simulation of trenching operations. The post-trench soil behaviour can be reflected by intelligent backfill soil springs as shown in Fig.17, which account for the combined effects of pipe mobilization, cover download, and backfill shear resistance. Such tools allow optimizing rock dumping and controlling the costs associated with seabed interventions.

**Pipeline walking simulation**

Observations and analysis [41] have shown that short subsea flowlines operating at high temperatures can exhibit pipeline walking [42] and axial creeping [43]. A recent, comprehensive overview on pipeline walking is presented in [44]. Here, SAGE Profile is used to demonstrate the importance of pipe-soil interaction (and in particular seabed friction) on the likelihood of pipeline walking.

As explained in [44], pipeline walking can cause cumulative axial displacement of an entire pipeline, which can induce damage at termination units, expansion spools and riser tie-ins. The rate of walking depends not only on the temperature profiles, but also on the magnitude of axial resistance, the mobilization distance and the seabed topography.

The main driving mechanisms for pipeline walking are:

- tension, associated with a steel catenary riser
- global seabed slope along the pipeline length
- thermal transients during start-up and shut-down

Although the origin may be different, the walking mechanism for each of these three cases is governed by the effective axial force profile of the pipeline. For a fully restrained, closed-ended pipeline, the effective axial force \( F_e \) is the sum of the forces due to axial elongation, internal and external pressure (including end effects), and the temperature gradient \( \Delta T \):

\[
F_e = \frac{L - L_0}{L_0} EA + (1 - 2v)(p_e A_e - p_i A_i) - EA a \Delta T
\]  

(40)
Generally, the slope of the force profile is defined by the axial friction 
\[ f = \mu w_p \]
. On an inclined seabed, the pipe weight promotes expansion in downhill direction, but counteracts the uphill expansion. This is similar to modifying the friction coefficient:

\[ \mu = \mu \pm \alpha \Delta T \]

which causes an asymmetric force profile envelope [44]. This situation gives rise to a rigid body displacement: the pipe starts to walk down-hill. Figure 19 clearly demonstrates that both pipeline ends move the same amount at the end of each cycle. The walking rate \( \Delta \theta \) can be approximated by [44]:

\[ \Delta \theta = \frac{(\Delta F + w_p L \sin \theta) - w_p L \mu \cos \theta}{EA \mu} \]

when the friction factor (or the pipeline length) is increased, the fully constrained force is still sufficient to overcome friction on first load, but not enough to mobilize the pipe during cool-down, as schematically shown in Fig. 20. Indeed, the axial friction during cool-down is enough for a certain section of the pipeline to reach fully constrained conditions.
When increasing the friction until:

$$\mu_0 > \frac{2 \Delta F}{W_p L}$$

(44)

the pipeline becomes fully constrained. As shown in Fig.22, the pipeline is anchored over a certain length during both cool-down and heat-up. Since the anchored lengths during both phases overlap, the pipeline cannot walk. This is clearly demonstrated by the vanishing axial displacements, shown in Fig.23.

Thanks to the plastic soil springs with memory component (Fig.10), modelling pipeline walking is feasible with SAGE Profile. The results for pipeline walking on an inclined seabed, presented here, are in excellent agreement with the theory [44, 45].

**Conclusions**

In this paper, recent developments in numerical modelling and analysis of offshore pipelines were reviewed and discussed. Finite-element techniques to assist in pipeline design were introduced, and the SAGE Profile software suite for offshore pipeline analysis was used to evaluate free-spanning pipelines, simulate lateral and upheaval buckling, and address pipeline walking. The main conclusions from these case studies are:

- Simulation of the pipelaying process is one of the most challenging tasks. An incremental solution was presented, where new elements are fed-in from an anchor point close to the seabed. This elegant approach allows simulating the actual installation process from a laybarge in an efficient fashion, and enables a quick and straightforward assessment of the on-bottom roughness.

- Finite-element simulations of pipelaying can contribute to route optimization, and the assessment of free-spanning pipelines can save a significant amount of time and money associated with seabed rectification.

- The key to a successful simulation of offshore pipeline installation and operation, is a profound understanding of pipe-soil interaction. The pipeline steel can be modelled by a Ramberg-Osgood material model, whereas the soil response is captured by a combination of vertical, axial, and lateral springs. The correct calibration of the pipe-soil interaction parameters is of paramount importance to reach reliable solutions.

- Transient dynamic solvers are based on an explicit integration algorithm. The central differences' scheme is conditionally stable, provided the time increment is sufficiently small. By introducing the concept of damping, the explicit (dynamic) approach can also be used to obtain quasi-static equilibrium.

- SAGE Profile can predict the occurrence of lateral and upheaval buckling. In addition to these predictive
capabilities, the software offers tools to prevent or mitigate the problems associated with buckling. Smart backfill soil springs can account for the combined effects of pipe mobilization, cover download, and backfill shear resistance, and calculation of the required download to prevent upheaval buckling contributes to rock-dump optimization.

- Pipeline walking due to seabed slope has been modelled, and the results show excellent agreement with the theory; migration only occurs when the effective axial forces along the entire pipeline remain below the fully restrained conditions during both heat-up and cool-down. Again, the influence of seabed friction on the simulation results was stressed.

- Finite-element tools, such as that described in this paper, provide added value as a design aid and a decision tool throughout the entire life of an offshore pipeline, covering (among other aspects) preliminary design, route optimization, pipelaying, span assessment, and on-bottom stress analysis.

References