Stability of Offshore Pipelines in Close Proximity to the Seabed

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ABSTRACT

In traditional offshore pipeline design, the on-bottom stability of submarine pipelines is governed by the Morrison’s equations. According to this set of equations, offshore pipelines are designed to satisfy two stability conditions: the submerged weight of the pipe has to be greater than the lift force, and the horizontal frictional force should exceed the combined drag and inertia forces.

It is common practice to used fixed hydrodynamic coefficients (drag, lift and inertia) to calculate the pipe stability, based on the assumption that the pipeline is either trenched or in contact with the seabed. However, due to uneven seabed topology and/or scouring, a gap may exist between the pipe and the seafloor. In such a case, the force coefficients not only depend on the relative gap between the pipe and the seabed. Moreover, in unsteady oscillatory flow (induced by waves), the time-dependent laminar or turbulent characteristics of the boundary layer become important.

In this paper, a computational fluid dynamics (CFD) model is presented to study on-bottom stability of offshore pipelines in close proximity to the seabed. Numerical simulations of fluid flow are performed to evaluate the lift, drag and inertia forces exerted on a subsea pipeline when subjected to both steady current (tides) and oscillatory flow (waves). The evolution of the hydrodynamic coefficients with the relative gap between the pipe and the seafloor is investigated, and the effect of boundary proximity on the stability is revealed.
1. FLOW INDUCED FORCES ON OFFSHORE PIPELINES

Offshore pipelines are subjected to wave loading and tidal flows. Currents induce time-constant water particle velocities, although they normally vary along the spatial coordinates. Current velocity as a function of depth is commonly estimated by a one-seventh power law

\[ V(z) = V_0 \left( \frac{d + z}{d} \right)^{\frac{1}{7}} (z \leq 0) \]  

(01)

where \( d \) is the water depth and \( V_0 \) is the tidal current at the still water level. In shallow water, the current induced velocity can generate a significant load on the marine pipeline. Differences in (measured) tidal height \( \delta H \) can be converted to expected current velocity \( V \) by the Voith relation

\[ V = m (\delta H)^n \]  

(02)

where \( m \) is a scaling factor and \( n \) the shape exponent. A prediction of current velocity is shown on Figure 1, indicating that the fluid flow velocity in shallow water can range between \( V = 1 \) m/s to \( V = 5 \) m/s.

![Figure 1: Fluid flow velocity induced by tidal flow](image)

A sea state consists not only of currents, but also of waves. In reality, there is always a steady current underlying waves. Based on the water depth \( d \) and the (measured) wave period \( T \), the corresponding wave length can be calculated with Airy wave theory [01] by iteratively solving the transcendent equation

\[ L = \frac{g T^2}{2\pi} \tanh \left( \frac{2\pi d}{L} \right) \]  

(03)
A wave with length $L$, height $H$ and period $T$ in a water depth $d$ induces a horizontal water particle velocity

$$u_x = \frac{\pi H}{T} \frac{\cosh \left\{ 2\pi \left( \frac{z + d}{L} \right) \right\}}{\sinh \left\{ 2\pi \frac{d}{L} \right\}} \cos \left\{ 2\pi \left( \frac{x}{L} - \frac{t}{T} \right) \right\}$$

which gives rise to a drag and a lift force, and a vertical water particle velocity

$$u_z = \frac{\pi H}{T} \frac{\cosh \left\{ 2\pi \left( \frac{z + d}{L} \right) \right\}}{\sinh \left\{ 2\pi \frac{d}{L} \right\}} \sin \left\{ 2\pi \left( \frac{x}{L} - \frac{t}{T} \right) \right\}$$

These horizontal and vertical water particle velocities at the still water level are shown for a wave with height $H = 2.5 \text{ m}$ and a period $T = 5.0 \text{ s}$.

![Figure 2: Horizontal and vertical water particle velocity at the still water level](image)

In addition, the corresponding (horizontal) acceleration

$$a_x = \frac{2\pi^2 H}{T^2} \frac{\cosh \left\{ 2\pi \left( \frac{z + d}{L} \right) \right\}}{\sinh \left\{ 2\pi \frac{d}{L} \right\}} \sin \left\{ 2\pi \left( \frac{x}{L} - \frac{t}{T} \right) \right\}$$

will induce an inertia force. The magnitude of the velocities (04) – (05) decays exponentially with water depth, and is negligible in deep water conditions. For shallow water conditions, the water depth is generally (much) smaller than the wave length:

$$d < \frac{L}{20}$$
and the wave length \(03\) can be approximated by

\[ L \approx T \sqrt{g d} \quad (08) \]

The simplified equations for the velocity \(04\) and the acceleration \(06\) in shallow water read

\[ \begin{align*}
    u_x & \approx \frac{\pi H}{k d T} \cos \theta \\
    a_x & \approx \frac{2\pi^2 H}{k d T^2} \sin \theta
\end{align*} \quad (09) \]

with \( k = 2\pi/L \) the wave number and \( \theta = 2\pi \left( \frac{x}{L} - \frac{t}{T} \right) \) the phase angle.

2. MORRISON’S EQUATIONS AND STABILITY CONDITIONS

Subsea pipelines are installed on the seabed, and they are expected to stay in their installed position throughout their operational life. As already indicated in the previous section, a subsea pipeline is subjected to environmental forces due to waves and currents, which may move the pipe and hence cause damage to its coatings or even overstressing the structure in case of excessive displacements. To ensure long term safe operation, pipelines are designed to be stable under worst case conditions, and a concrete coating is applied to satisfy the stability conditions.

When assuming shallow water conditions, expressed by \(07\), the horizontal water particle velocity and corresponding acceleration, induced by wave loading, is given by \(09\). Moreover, a steady current can give rise to an additional fluid flow velocity \(01\). Assuming that the waves are approaching the pipeline at an angle \(\alpha\) and the current flow direction is at an angle \(\beta\), the flow velocity will impose a lift force \(02\)

\[ F_L = \frac{1}{2} C_L \rho D_o \left( u_x \cos \alpha + V \cos \beta \right)^2 \quad (10) \]

and a drag force

\[ F_D = \frac{1}{2} C_D \rho D_o \left( u_x \cos \alpha + V \cos \beta \right) \left| u_x \cos \alpha + V \cos \beta \right| \quad (11) \]

where \(C_L\) and \(C_D\) are the lift and drag coefficients respectively, and \(D_o\) is the outer diameter of the pipe, including corrosion allowance, coating thickness and marine fouling. On top of that, the wave induced acceleration \(06\) gives rise to an inertia force

\[ F_I = C_I \rho \frac{\pi D_o^2}{4} a_x \cos \alpha \quad (12) \]

with \(C_I\) the inertia coefficient.
The empirical relations (10) – (12) are known as the Morison equations [03], relating the hydrodynamic forces (lift, drag and inertia) to the pipe diameter. On Figure 3, these forces are shown as a function of the phase angle $\theta$, for a unit length of a pipeline with diameter $D_o = 1$ meter, subjected to a wave of height $H = 10$ meter and period $T = 10$ s and a steady current with velocity $V = 0.5$ m/s.

The Morison’s equations show that the drag and lift forces are proportional to the square of the fluid particle velocity, and that the inertia force is directly proportional to the fluid particle acceleration. The drag force acts in a direction parallel to the fluid flow, while the lift force is vertically upwards (i.e. normal to the seabed). The inertia force acts in the direction of the flow or against it, depending on whether the flow is accelerating or decelerating.

The Morison’s equations are used to determine the appropriate thickness of a concrete weight coating to ensure offshore pipeline stability. The pipeline stability condition is considered to be satisfied when the forces that resist the pipeline displacement are greater than the forces that tend to displace it. As a result, the pipeline is stable when the submerged weight of the pipe $w_p$ is greater than the lift force in vertical direction:

$$w_p = W - F_B \geq \lambda F_L$$

with $W$ the weight of the pipe, coatings and contents, and $F_B$ the buoyancy forces acting on the pipe. At the same time, the horizontal friction force has to remain greater than the combined drag and inertia forces:

$$\mu(W - F_B - F_L) \geq \lambda(F_D + F_I)$$
where $\mu$ is the coefficient of friction between the pipe and the seabed. In the stability conditions (13) - (14), $\lambda = 1.1$ is a safety factor. Self-weight of the pipe (and its contents) is generally not sufficient to satisfy these criteria. In order to achieve stability, subsea pipelines are coated on the outside with high density concrete. The required thickness of the concrete coating is determined by an iterative procedure [04] such that the above criteria are satisfied for the most severe load combination, and for every value of the phase angle $\theta$.

3. WALL PROXIMITY EFFECTS FOR SUBSEA PIPELINES

When the pipeline is sitting on the seabed, the hydrodynamic coefficients are frequently fixed to $C_D = 0.7$, $C_L = 0.9$ and $C_I = 3.29$. However, the hydrodynamic coefficients depend on both the Keulegan-Carpentar number [05]

$$KC = \frac{VT}{D_o}$$

and the Reynolds number

$$Re = \frac{VD_o}{\nu}$$

which expresses the ratio of inertia to viscous forces, with the kinematic viscosity $\nu = \mu/\rho$ as the ratio of the dynamic viscosity $\mu$ with the density $\rho$. In addition, the value for $C_D$, $C_L$ and $C_I$ is dependent on the position of the pipe.

If the pipeline is sitting on the seabed - which is always intended by design - the hydrodynamic coefficients will be significantly different from those for pipeline spans with a gap between the pipe and the seabed or for partially buried pipes. When the pipeline is trenched, the pipe weight must be higher than the lift forces induced by the waves and currents in order to remain buried. As shown on Figure 4, the side slope will contribute to the horizontal stability.

![Stability conditions for a trenched offshore pipeline](image)

**Figure 4: Stability conditions for a trenched offshore pipeline**
The effect of the slope angle on the apparent pipe weight can be written as

$$\frac{W_t}{W_o} = \frac{1}{\cos \varphi + \mu \frac{\sin \varphi}{\mu}}$$  \hspace{1cm} (17)$$

where $W_t$ is the weight in the trench, and $W_o$ is the weight outside the trench. According to [05], the fluid flow velocity in the trench can be estimated as

$$\frac{V_t}{V_o} = 1 - 0.305 d_i$$  \hspace{1cm} (18)$$

with $d_i$ the depth below the undisturbed seabed.

![Figure 5: Fluid flow patterns for different pipe positions](image)
A distinct difference between the flow patterns [06] of a pipe sitting on the seabed, an unsupported pipeline span and a partially buried subsea pipe is seen on Figure 5. Sarpkaya has performed experimental research [07-08] to study the hydrodynamics of a cylinder near a plane boundary. He measured the in-line and transverse forces on cylinders placed at various distances from the bottom of a U-shaped water tunnel. The main conclusions from these investigations read

- The hydrodynamic coefficients are functions of the Reynolds number Re (16), the Keulegan-Carpenter number $K$ (15), the gap $e$ between the pipe and the seabed and the depth of penetration $\delta$ of the viscous wave or the boundary layer thickness:

$$ \{ C_D, C_L, C_I \} = \varphi(Re, K, e/D_o, \delta/D_o) $$

- The effect of the boundary layer or the penetration depth of the viscous wave is small, provided that the boundary layer remains laminar. Boundary layer effects are ignored for $e/D_o > 0.1$. For turbulent oscillatory boundary layers, the characteristics of the wall jet and separation over the cylinder may be significantly affected.

- The drag and inertia coefficients for the in-line force acting on the cylinder are increased by the presence of the wall. This increase is most evident in the range of $e/D_o < 0.5$.

- The proximity of the wall helps to decouple the frequency of oscillations in the top and bottom shear layers. This decoupling effect prevents the occurrence of regular vortex shedding for small values of $e/D_o$.

- The transverse force towards the wall is relatively small and fairly independent of $e/D_o$. The transverse force away from the wall is quite large and dependent on $e/D_o$, particularly in the range $0 < e/D_o < 0.5$.

- The use of the Morison’s equations to decompose the in-line force into two components is a sound approach. The lumping of the entire in-line force into a single coefficient is not justified, and obscures the flow mechanics.

In the next section, a computational fluid dynamics (CFD) model is introduced to study the stability of offshore pipelines close to the seabed. The numerical simulations shed a brighter light on the effects of boundary proximity, and enable a more profound understanding of the experimental insights developed by Sarpkaya.
4. EVOLUTION OF HYDRODYNAMIC COEFFICIENTS WITH PIPELINE POSITION

To study the influence of boundary proximity on the evolution of the hydrodynamic coefficients, a computational fluid dynamics (CFD) model was constructed. A fixed pipeline with diameter $D_o$ exhibiting a gap $e$ with the seabed was subjected to a fluid flow velocity $V$. By changing the velocity (and hence the Reynolds number (16)) and the gap $e$, the experimentally observed relations (19) can be calculated.

The CFD solver uses a generalized version of the Navier-Stokes equations, solving for the velocity field $\bar{u} = (u, v)$ and the pressure $p$:

$$
-\nabla \cdot \left[-p I + \eta \left(\nabla \bar{u} + (\nabla \bar{u})^T\right)\right] + \rho_w \frac{\partial \bar{u}}{\partial t} + \rho_w (\bar{u} \cdot \nabla) u = F
$$

whilst

$$
\nabla \cdot \bar{u} = 0
$$

Where $I$ is the unit diagonal matrix, $\rho_w$ is the density of seawater and $F$ is the volume force affecting the fluid.

On Figure 6, the CFD model was used to predict the variation of the drag coefficient $C_D$ as a function of seabed proximity $e/D_o$. As can be seen, the drag coefficient for a specific Reynolds number will change from a relatively high value when the pipe is close to the seabed ($e/D_o << 1$) to the free stream value when $e/D_o \approx 1$. 
Figure 7: Flow patterns for increasing distance to the seabed
In Figure 7, streamlines of the flow and contour plots of the pressure are plotted for a Reynolds number $Re = 2.0 \times 10^5$. In these plots, it is clear that the flow behind the pipe changes from primarily a blunt body on the seabed ($e/D_o = 0.1$) to a free stream cylinder with increasing distance $e$ from the seabed. The shape of the wake behind the pipe changes accordingly, which in turn strongly influences the drag (and drag coefficient) of the pipe.

The distinct advantage of computational fluid dynamics over experimental testing is that a huge amount of flow data is available to analyze the physical phenomena that are taking place. In addition, it is straightforward to assess the effect of modifications, and hence quickly optimize the solution.

5. CONCLUSION: CFD SIMULATIONS CONTRIBUTE TO PIPELINE STABILITY

In this paper, a computation fluid dynamics (CFD) model was presented to study on-bottom stability of offshore pipelines in close proximity to the seabed. The evolution of the hydrodynamic coefficients with the relative gap between the pipe and the seabed was investigated, and the effect of boundary proximity was revealed. The major conclusions read:

- The Morison’s equations are empirical relations, relating the hydrodynamic forces (lift, drag and inertia) to the pipe diameter. These equations show that the drag and lift forces are proportional to the square of the fluid particle velocity, and that the inertia force is directly proportional to the fluid particle acceleration.

- In traditional offshore pipeline design, the Morison’s equations are used to determine the appropriate thickness of a concrete weight coating to ensure pipeline stability. The pipe is stable when the submerged weight is greater than the lift force and, at the same time, the frictional force exceeds the combined drag and inertia forces.

- When the pipeline is sitting on the seabed, the hydrodynamic coefficients are usually fixed to $C_D = 0.7$, $C_L = 0.9$ and $C_I = 3.29$. However, in oscillatory flow, the hydrodynamic coefficients depend on both the Keulegan-Carpenter number, the Reynolds number and the position of the pipe.

- The drag and inertia coefficients for the in-line force acting on the pipe are increased by the presence of the wall. This increased is most evident in the range of $e/D_o < 0.5$.

- For a given Reynolds number, the drag coefficient changes from a relatively high value (close to the seabed) to the free stream value ($e/D_o > 1$). The flow in the wake of the pipe changes from primarily a blunt body on the seabed to a free stream cylinder with increasing distance to the seabed.

- Computational fluid dynamics provides a powerful means of evaluating flow mechanics and optimizing the conditions in order to ensure pipeline stability.
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