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Mathematical modelling of sand wave migration and the interaction with pipelines

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Abstract

A new method is presented for identifying potential pipeline problems, such as hazardous exposures. This method comprises a newly developed sand wave amplitude and migration model, and an existing pipeline–seabed interaction model. The sand wave migration model is based on physical principles and tuned with field data through data assimilation techniques. Due to its physical basis, this method is trusted to be more reliable than other, mostly engineering-based methods. The model describes and predicts the dynamics of sand waves and provides the necessary bed level input for the pipeline–seabed interaction model. The method was tested by performing a hindcast on the basis of survey data for a specific submarine gas pipeline, diameter 0.4 m, on the Dutch continental shelf. Good agreement was found with the observed seabed–pipeline levels. The applicability of the method was investigated further through a number of test cases. The self-lowering of the pipeline, in response to exposures due to sand wave migration, can be predicted, both effectively and efficiently. This allows the use of the method as a tool for pipeline operation, maintenance and abandonment.

Keywords: Sand waves; Pipelines; Morphodynamics; Data assimilation; North Sea

1. Introduction

The bed of shallow seas such as the North Sea is not entirely flat. In many areas, various bed forms occur (Knaapen et al., 2001). Table 1 summarises the characteristics of several bed forms found offshore in sandy beds. One type of such bed form is the sand wave. Sand waves are offshore rhythmic features with the crests roughly perpendicular to the principal tidal direction. Sand waves are very interesting from an engineering point of view, because their migrating nature and long spatial and temporal scales may interfere with offshore activities. Analysis of geological charts (RijksGeologischeDienst, 1984) showed that their crest-to-crest distances vary from 200 to 800 m and that the heights are up to 20% of the water column (Hulscher and Van Den Brink, 2001; Bijker et al., 1998). Sand waves migrate at rates up to tens of metre per year.

These variations can interfere with pipelines and cables on the seabed (Staub and Bijker, 1990). For

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Table 1
Characteristics of offshore sand bed forms

Bed form	Related flow	$L[m]$	$A[m]$	T	c
Ripples	instant flow	~ 1	~ 0.01	h	~ 1 m/day
Mega-ripples	storm surges?	~ 10	~ 0.1	days	~ 100 m/year
Sand waves	tide	~ 500	~ 5	years	~ 10 m/year
Long bed waves	unknown	~ 1500	~ 5	unknown	unknown
Tidal sandbanks	tide	~ 5000	~ 10	century	~ 1 m/year

L denotes the wavelength, A is the amplitude, T is the times scale and c is the order of magnitude of the migration rate.
For an overview and definitions, see e.g. Dodd et al. (2003), Knaapen et al. (2001) and Hulscher (1996).

instance, migrating sand waves may cause free spans of pipelines (Németh et al., 2002). In the present paper we focus on the probability of pipeline exposure due to sand wave migration.

The diameters of pipelines on the seabed of the North Sea are typically between 0.1 and 1.5 m. and are often covered with 0.2 m (as a legal minimum for pipes smaller then 16 in. on the Dutch continental shelf) or 1–2 m to provide additional protection. The migration of sand waves results in large variations of the seabed level in time. As a result, pipelines crossing sand waves areas can become exposed or even free spans may develop, which may lead to high stresses, vibrations or fatigue, jeopardising pipeline integrity.

The self-lowering of pipelines, due to scour around the pipe, may compensate for the migration. Often this is the case, since the scour has a timescales of days (Fredsøe et al., 1992), and the self-lowering of the pipeline has an estimated timescale of months depending on the flexibility of the pipeline. However, in the case of relatively fast migrating sand waves (in the order of several metres per year) and a large rigid pipeline the self-lowering mechanism may be too slow to prevent pipeline exposures.

Until recently, literature contained no reliable method for predicting the dynamics of a pipeline embedded in an evolving seabed, especially in sand wave areas. Predicting this seabed–pipeline interaction is useful, since it provides insight in the possible exposure risks of the pipeline.

Over the years, several models have been developed to predict and understand the behaviour of sand waves. Table 2 summarises the characteristics of these models. Some of these models focused on growth, finite amplitude, migration or wavelengths of sand waves. None of the models is able to simulate both amplitude evolution and migration of sand waves.

The ‘migration’ in the model of Fredsøe and Deigaard (1992) is limited. Fredsøe and Deigaard (1992) only calculate the volume of transported sediment. This model is time-independent and is unable to predict long term sand wave evolution. Németh et al. (2002) presented a linear small-amplitude model, based on the model of Hulscher (1996). This gives an estimate for the wavelength and migration rate of sand waves, but does not account for the interaction between finite amplitude and migration. None of the models in Table 2 have been combined with pipeline–seabed interaction models.

In this paper a newly developed sand wave model is combined with a pipeline management model, which contains a pipeline–seabed interaction module. The sand wave model relates the amplitude evolution of the sand waves to their migration rate. Using a genetic algorithm, which is a global optimisation routine (Davis, 1991), the coefficients of this model are tuned to fit the actual bathymetric data of the considered site, in this study being a specific site in the Southern North Sea. After tuning the model predicts the bed changes over, e.g. 20 year. The resulting bed level development is used as input for the pipeline–seabed interaction model which then

Table 2
Characteristics of existing models for the description of sand waves

Criteria	FD92	OC92	H96	KN00	KN02	Nea02
Oscillatory flow forcing	no	yes	yes	yes	yes	yes
Predictions:						
wavelength	yes	yes	yes	yes	no	yes
initial growth	no	no	yes	yes	yes	yes
migration	yes	no	no	no	no	yes
Amplitude evolution	no	no	yes	yes	yes	no
Equilibrium situation	yes	yes	no	yes	yes	no

In this table FD92 is Fredsøe and Deigaard (1992), OC92 is O’Conner (1992), H96 is Hulscher (1996) and the improvements suggested by Komarova and Hulscher (2000) and Gerkema (2000), KN00 is Komarova and Newell (2000), KH02 is Knaapen and Hulscher (2002) and Nea02 is Németh et al. (2002).

predicts possible pipeline exposures and free span development.

This paper addresses two questions concerning the risks of pipeline exposure. The first question is posed by pipeline operators, who like to know if the pipeline integrity is not jeopardised due to exposures or free spans for the first 5–10 years. The second question is posed by authorities who are interested in what will happen to the pipeline after decommissioning. After decommissioning, a pipeline is normally filled with water replacing the gas. Due to the associated weight change, the pipeline may behave differently.

The paper is organised as follows. Section 2 discusses the risks of exposed pipelines due to migrating sand waves. In Section 3, the site data and the data processing are described. Section 4 describes the sand wave model, DA'SWAM, which then is coupled to the pipeline management model, PIPECAST, in Section 5. Section 6 gives the results of coupling the two models. The paper ends with the discussion and conclusions in Sections 7 and 8.

2. Risks of exposed submarine pipelines

The risks associated to pipelines crossing migrating sand waves are divided in two categories. The first category involves the risk of the release of the pipeline's hydrocarbon content due to pipeline failure, which may result in an environmental disaster. The second risk involves the physical presence of the pipeline in or on the seabed as a potential obstacle to other offshore activities. For example, fishing nets or anchors may become hooked under the pipeline, which may lead to damaged or loss of gear, or even worse.

Several factors may cause pipelines to rupture. One of these factors is mechanical failure because of design, production or installation errors. Instability may be a second potential cause of pipeline damage. A pipeline may become unstable due to extreme hydrodynamic forces. The resulting large tensions can in turn cause the pipeline to buckle (Klomp et al., 1995) or burst. This could also happen after significant local erosion around and under the pipeline. Fig. 1 explains how migration of sand waves could lead to pipeline exposure.

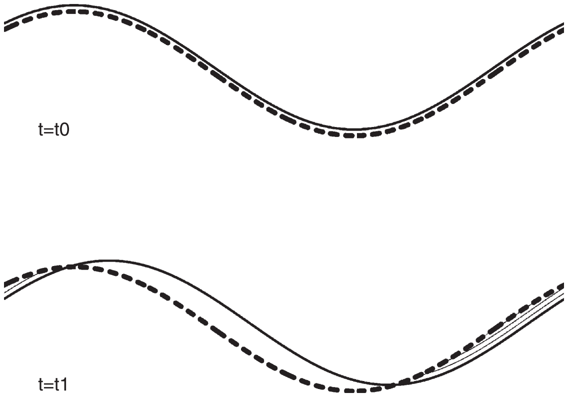

Fig. 1. Sketch explaining the exposure of a pipeline due to migration of sand waves. The dashed line represents the pipeline imbedded in the sea bed (solid line). The top figure shows the situation after embedment of the pipeline ($t=t_0$). At $t=t_1$ in the lower figure, the crests of the sand waves have migrated. This migration causes exposure of the pipeline in the dashed areas.

3. Bathymetric surveys along a pipeline in the North Sea

The data used in the research described here are extracted from pipeline alignment sheets. The bathymetric profiles along the pipeline have been digitised. Data were collected from two sections of a pipeline in the Southern North Sea, each about 9 km long, where the sand waves run almost perpendicular to the pipeline. Fig. 2 gives a rough indication about the position of these sections. For both sections, five surveys were available, carried out in 1995, 1996, 1998, 1999 and 2000.

Since the position of the pipeline is very stable, it provides a reliable reference position for bathymetric measurements. The pipeline position itself is given with only a few measuring points. The errors in the digitised data are estimated as follows. The total error of the point positioning is less then ± 10 m, with equal contributions of the error in the original positioning and in the digitisation error. The total vertical error is in the order of 0.2 m, again equally divided over measurement error and digitisation error.

3.1. Preprocessing the data

To compare the measured data with result of the sand wave model, the mean bed profile has to be

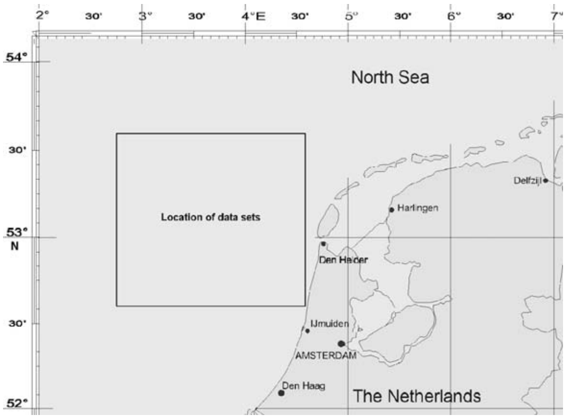

Fig. 2. Location of the pipeline data sets.

filtered out. This was done using a low-pass filter, based on a Hanning window (see e.g. Oppenheim and Schäfer, 1989). Subsequently, this mean bottom profile was subtracted from the original data to isolate the sand wave profile. Figs. 3 and 4 show the data before and after the filtering.

The migration of the sand waves was assessed by a comparison of successive data sets. The sand waves appear to migrate in a northerly direction (to the left in Figs. 3 and 4. This is in accordance with the northward direction of the residual current in the Southern North Sea (Dronkers et al., 1990).

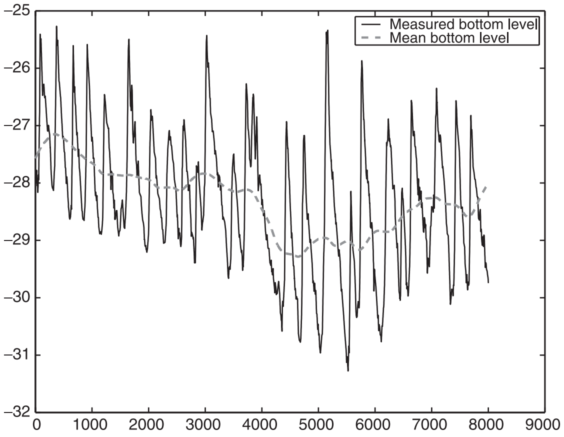

Fig. 3. The original data (dark line) and the mean bottom profile (light line) found using the low pass filter. Bed level on the vertical axis and position along the pipeline on the horizontal axis are in metre. On large sand waves, short bed level undulations can be seen for example at the sand wave at 1750 m. These undulations are mega-ripples superimposed on the sand waves (see Table 1). Mega-ripples fall outside the scope of this paper.

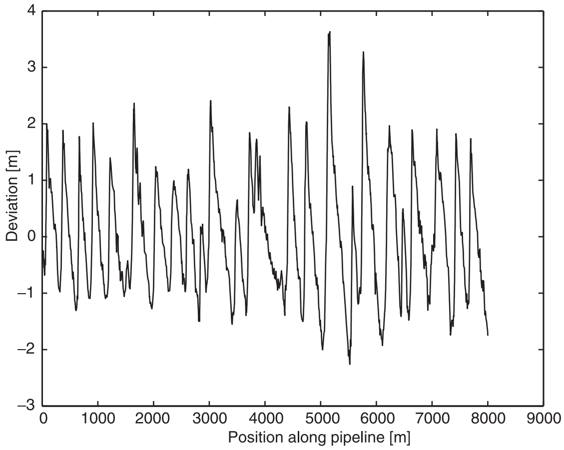

Fig. 4. Resulting sand waves after subtraction of the mean bottom profile. The deviation from the mean depth on the vertical and the position along the pipeline on the horizontal axis are in metre.

As mentioned before, the position of the pipeline on the maps was given in few points only. Consequently, the vertical position of the pipeline is not known accurately in some sections and reliable conclusions about the future locations of pipeline exposure cannot be drawn from the calculations. The mapped locations of pipeline exposures, however, were accurately known. For practical reasons, we selected pipeline locations whose position were known relatively accurately and were suitable for this research.

4. Mathematical sand wave model

The underlying physical assumption of DA'SWAM (Data Assimilated Sand Wave Amplitude Migration model) is that sand waves are free unstable modes within the coupled tidal current–seabed–topography system. Hulscher and Van Den Brink (2001) showed that a stability type model indeed predicts the occurrence of sand waves in the North Sea well.

Komarova and Newell (2000) came up with a model that describes the amplitude evolution of sand waves. It includes the existence of a longer bed pattern, called the soft mode. In our area such a long pattern (which could be the pattern observed by Knaapen et al., 2001) does not occur. Therefore, this mode is neglected by taking the amplitude of the so-called soft mode equal to 0. For reasons of simplicity, the sand wave amplitude is assumed constant in space. Extension to spatial variations in amplitude and wavelength will be part of future research. Now the complex Landau equation describes the amplitude A of the sand waves, changing over the long time scale ($\tau=t/T$, $T \gg 1$):

$$\frac{\partial A}{\partial \tau} = (c_n + ic_i)A(\tau) - (d_r + id_i)\,|A(\tau)|^2 A(\tau), \qquad (1)$$

in which c and d are complex coefficients. The initial growth rate is taken into account by c, the nonlinear coefficient d describes the decrease in growth rate due to nonlinear effects. Eventually this will result in a dynamic equilibrium of a slowly varying amplitude.

The sand waves in the Southern North Sea are often asymmetric. If a model is to have any practical application in this region, it should incorporate this asymmetry. Furthermore, within the scope of the present study, modelling the migration and evolution of sand waves is crucial to be able to describe the pipeline–seabed interaction. In fact the amplitude of the sand waves might affect their migration. Therefore a model is needed that is able to simulate the migration and growth of finite-amplitude, asymmetrically shaped sand waves.

A higher-order Fourier approximation was chosen to describe the asymmetric shape of migrating sand waves in shallow shelf seas (Eq. (2)):

$$\begin{aligned} z(x,t) = {} & \epsilon(D_{\mathrm{mean}} + D'(x))A(\tau) \\ & \times \sum_{n=1}^{N} \frac{\gamma \sin[(2n-1)(kx-\omega t)]}{(2n-1)} \\ & - \frac{\sin[(2n)(kx-\omega t)]}{(2n)} + \text{c.c.}, \end{aligned} \qquad (2)$$

in which, z is the bed level at place x and time t, relative to the spatial and temporal mean water depth D_{mean} locally corrected by $D'(x)$ to include gradients in the mean profile. The height of the sand waves is determined by the complex valued amplitude $A(\tau)$. Furthermore, ϵ is a small valued constant linking the two time scales ($\tau=\epsilon^2 t$) and $k=2\pi/L$ is the wave number related to the wavelength L and ω is the complex valued wave frequency (parameter for migration rate). The direction of the asymmetry is deter-

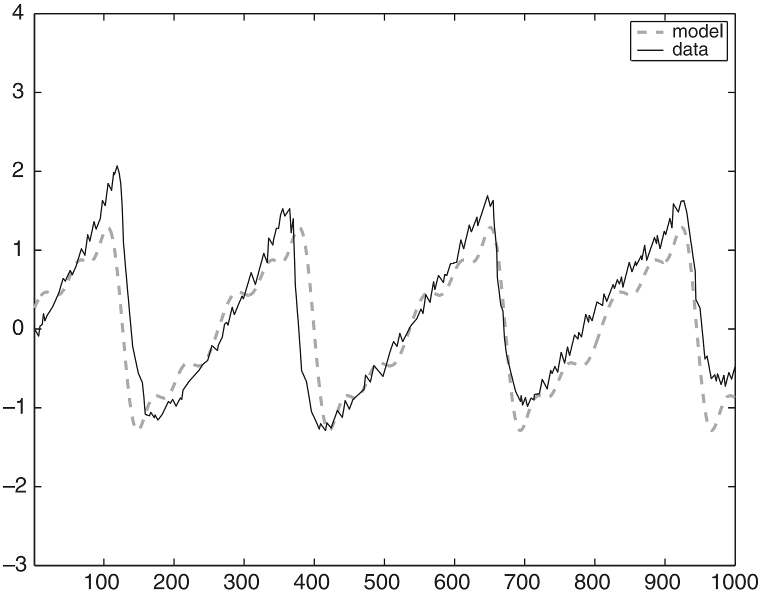

Fig. 5. Comparison of the bed profile from the data (dark noisy line) and computed with the higher-order model (light smooth line) with $N=3$ after tuning and with the correction on the mean depth (year 2000). The deviation from the mean depth on the vertical and the position along the pipeline on the horizontal axis are in metre.

mined by the constant γ. Finally c.c. denotes the complex conjugates of the summation.

The model parameters c, d, ϵ, γ, k and ω, as well as the number of approximating terms N, are all determined using a genetic algorithm, a global optimisation routine (Davis, 1991; Knaapen and Hulscher, 2002). Here, the genetic algorithm is used to find those parameters that give the smallest root-mean-square error between the model estimates and a few of the measured bed profiles (Fig. 5).

Tuning the model showed that it is sufficiently accurate and convenient to use $N=3$ (6 terms in total) in Eq. (2), since the root-mean-square error does not decrease significantly for larger n-values. Furthermore, the computational time required to tune the model increases significantly with increasing values of N.

Although the overall error for $N=2$ and $N=1$ is smaller than the error for $N=3$ (see Table 3), the latter should be used. With $N<3$ the model is unable to reproduce the distinct crests and troughs of the sand waves. Consequently, it may predict pipeline exposure at these points, whereas in reality this will, most likely, not occur. Fig. 6 shows the approximation with $N=1$. Such a significant conservatism in pipeline risk assessment is undesirable.

For that reason, the errors in the peaks and troughs of the model are taken into account. Here the peaks and troughs are defined as the upper and lower 10% of the sand waves (crests and troughs) (Table 3). Then, $N=3$ is the lowest choice for the model to give acceptable errors.

Table 3
Root-mean-square errors (RMSE) of the model for different values of N

N	Overall RMSE (m)	RMSE in crests and troughs (m)
1	~ 2.10	10.32
2	~ 2.08	7.42
3	~ 2.14	6.31
4	~ 2.25	6.19
5	~ 2.22	6.07
6	~ 2.23	5.87
7	~ 2.30	6.02

On the left the RMSE for the complete profile. On the right the RMSE of the crests (upper 10% of the profile) and troughs (lower 10% of the profile). The lowest choice with acceptable errors in $N=3$.

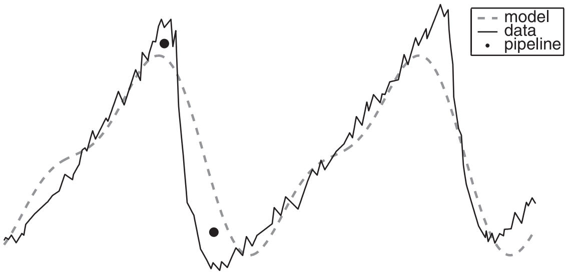

Fig. 6. In the case a low-order approximation ($N=1$) is used, the model (smooth light line) predicts pipeline (dots) exposure both in the trough and at the crest, while the data (noisy dark line) shows no exposure.

Tuning of the model with the field data showed that the migration rate of the sand waves is in the order of 10 m/year and differs spatially as the amplitude of the sand waves changes. The larger waves (in the sections from 0 and 1 km and between 7 and 8 km) migrate about 10 m/year, whereas the smaller ones (between 2 and 3 km) migrate approximately twice as fast, 20 m/year.

Now that the sand waves are described with sufficient accuracy, DA'SWAM gives a good indication of the covered and exposed sections of the pipeline. Moreover, since the sand waves are fully grown, the shape of the sand waves will not change significantly in time. Consequently, the migration rate of the bed forms can be assumed fairly constant as well. Therefore, DA'SWAM is assumed to predict the future migration with sufficient accuracy.

5. Combining sand wave modelling with local pipeline impact

The objective is to develop a tool to predict the long-term behaviour of (decommissioned) offshore pipelines. This means that a description for the processes near the pipeline is needed. For that purpose a three-dimensional model is used, simulating self-lowering and free span development of a pipeline on the seabed (see Bijker et al., 1991; Hansen et al., 1995; Klomp et al., 1995; Chen and Bijker, 2001). This model is also known as PIPESIN.

The model is based on the detailed flow dynamics near the pipeline. The exposed pipeline acts as a body in the water, forcing the flow to go around. The resulting higher flow velocities will cause erosion at both sides of the pipe. This causes a scour hole, eventually resulting in a free span. If the free span is wide enough for the pipeline to bend, gravity will pull the pipeline down into the hole. The pipeline no longer effects the flow, and the scour hole will be filled due sedimentation. In this situation, the gravitational lowering will compete with the exposure due to sand wave migration and scour effects.

As described in Bijker and Chen (2001) the model has been further developed into a management tool, using as input the actual survey data of an existing pipeline as well as simultaneous field data on waves and currents. Thus allowing model calibration (hindcasting) in order to improve the reliability of the prediction of the future pipeline behaviour (forecasting). This model is called PIPECAST and has been used in this study.

The initial pipeline and seabed levels have to be specified in the model. Surveys provide such input. The seabed profile along the pipeline is allowed to vary in time. This may be caused by migration of sand waves or other large-scale morphological variations. These seabed variations have to be specified separately. At this moment this can be done at maximal three points in time.

The model then simulates the dynamic behaviour of the pipeline as the result of the morphodynamic interaction with the seabed, such as the migration of sand waves. The simulation can start at any time during pipeline operation. For example, the model can simulate how an existing free span will develop and thus assist in assessing the need for corrective actions. Typically, a pipeline section with a length of 500–1000 m is simulated.

Input wave and current fields are translated into effects on the seabed, after which the resulting sediment transport is calculated. Onset of scour is determined based on the wave and current conditions and pipeline embedment. The model calculates the generation of tunnel erosion, leeside erosion and the development of free spans, and finally backfilling, if conditions allow. Pipeline deflections are calculated for a variety of combinations of seabed configurations and pipeline mechanics.

To predict the global seabed variations for the next 5–20 years, we used DA'SWAM (see Section 4). This model accounts for interactions between amplitude growth and migration rate, which is not accounted for if, e.g. only data extrapolation is used.

6. Evaluation of the models in a test case

The morphodynamic changes and the consequences for a segment of the pipeline have been evaluated by the application of both DA'SWAM and PIPECAST. In the present version of DA'SWAM, no variation of the wavelengths and amplitudes are

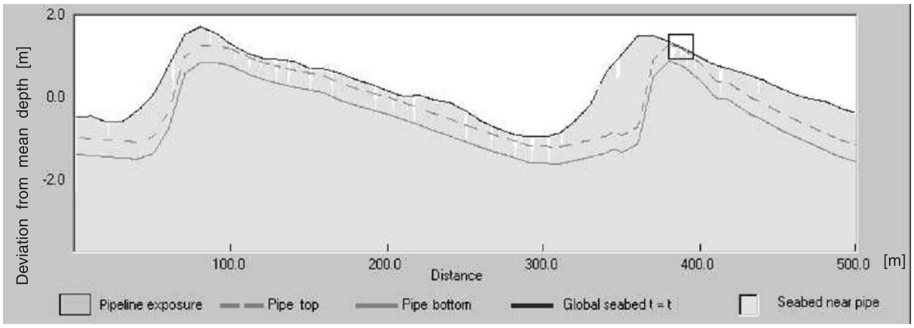

Fig. 7. Pipe and seabed levels according to the actual data for the bed profile. The snapshot is made at the same point in time as Fig. 8. The dashed line and the solid line indicate the top and bottom of the pipeline, while the square indicates the stretch of pipeline exposure.

included yet. Therefore, it is applied in situations where several sand waves are located with a fairly uniform wavelength and amplitude (variations not exceeding 10%). In the data, this is only the case over short segments. The second reason to keep test sections short is to limit the computational time of PIPECAST. In this study, the model is applied on sections of 500 m, covering almost two sand waves.

Four different scenarios have been evaluated. First, the bed profile computed by DA'SWAM is compared with the measured bathymetric data. Second, this bed profile is used as input for PIPECAST to predict the effect of the morphodynamic changes on the pipeline. The pipeline levels resulting from the pipeline model are compared with the measured pipeline positions. This comparison focuses on the locations of exposure, since these locations are known accurately, unlike the covered parts of the pipeline. Third, the differences between gas-filled and water-filled pipelines are examined. Finally, the effect of a dredging or retrenching operation is modelled.

6.1. Verification: comparison of bed levels

In this subsection, the results of PIPECAST calculations with bathymetric input from the DA'SWAM model are compared to the results using the field data as bathymetric input. Fig. 7 shows the pipe and seabed levels calculated using the field data. Fig. 8 shows the same levels at the same date according to the calculations using input from the dynamic sand wave model. The parameter values used in this simulation are given in Table 4.

Table 4
Parameter values of DA'SWAM after tuning to the data

Parameter	ϵ [−]	ω [s^{-1}]	k [m^{-1}]	A_0 [−]	γ [−]	Correction [m]
Value	0.22	− 0.095	0.023	$0.031 + i * 0.056$	2.4	0.14

Values for c and d are excluded from this list as they are not tuned accurately due to the absence of sand wave growth in the data. Consequently, the initial amplitude A0 determines the height completely (see Eq. (2)).

To compare the two results, Fig. 9 shows the embedment of the pipeline for both calculations. The differences between the embedment, as calculated by the dynamic sand wave model, and the embedment following from the field data are small. No exposures have been missed and no exposure has been predicted incorrectly. Thus, it can be concluded that the dynamic sand wave model reproduces the bathymetry sufficiently accurate.

6.2. Pipeline embedment predictions

Pipeline operators want to know what will happen to their pipeline during operation, which may cover significant periods. For this purpose, PIPECAST was set to evaluate the development over a period of eleven years. The available data from the first 5 years (1995–2000) have been used to hindcast the measured development. This hindcast is the basis for the prediction for the next 6 years (2000–2006).

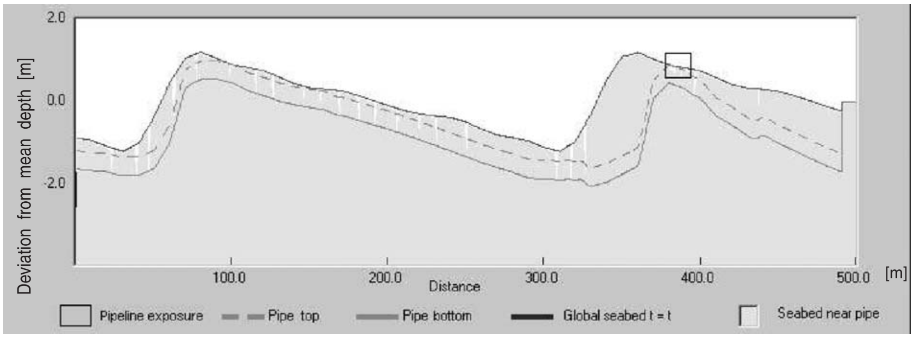

Fig. 8. Pipe and hindcasted seabed levels using the dynamic sand wave model DA'SWAM. The snapshot is made at the same point in time as Fig. 7. The dashed line and the solid line indicate the top and bottom of the pipeline, while the square indicates the stretch of pipeline exposure.

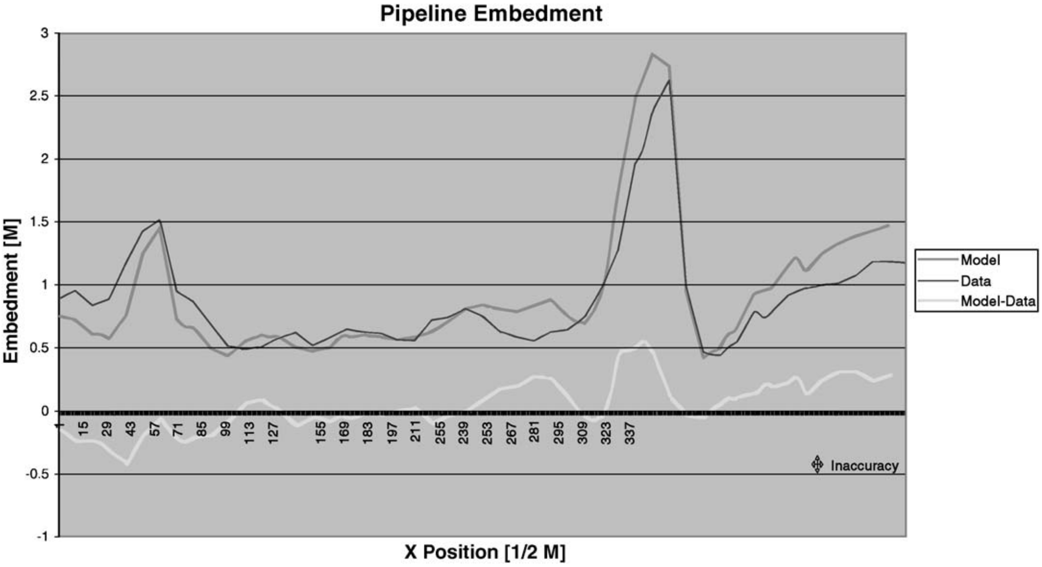

Fig. 9. Comparison of pipeline embedment relative to the bottom of the pipeline calculated with the pipeline model (PIPECAST) (thin line) using the actual data for the bed profile (see Fig. 7) and (thick line) using the dynamic sand wave model (see Fig. 8).

Based on these calculations it is concluded that the pipeline indeed is subject to self-lowering. This process keeps up with sand wave migration, exposures occur only over a few short sections that cause no danger to the pipeline. Free spans do not occur in this period.

Authorities, at the other hand, are most interested in the long-term effects of sand wave migration on the pipeline. Normally when a pipeline is decommissioned, it is filled with water replacing the gas. With PIPECAST we calculated the long-term effects over 20 years. Although the submerged weight of the pipeline increased from 1.2 to 2 kN/m, the differences in self-lowering are minimal (see Section 6.3). Fig. 10 shows the predicted situation for 2020. In this figure, one can clearly see that the sand waves have migrated significantly compared to the situation in Fig. 8. The figure also shows that the evaluated section of the pipeline buried itself to such extent that the water-filled pipeline remains covered, except

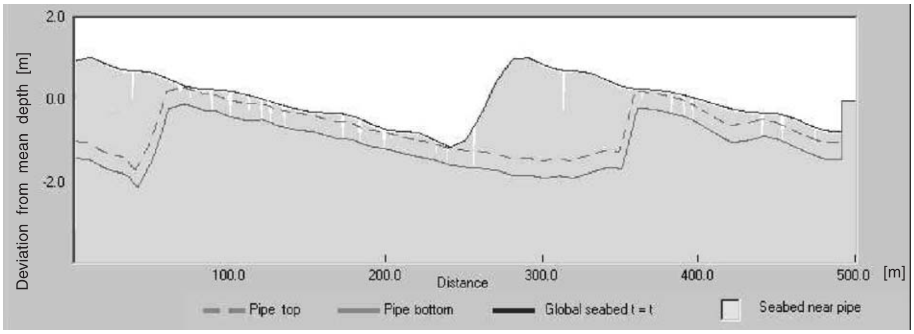

Fig. 10. Predicted pipe and seabed levels for 2020. The pipeline's self-lowering appears to have kept up with the migration of the sand waves in this test section. The dashed line and the solid line indicate the top and bottom of the pipeline, no exposure of the pipeline can been detected. The narrow vertical spikes in the seabed are the result of numerical errors.

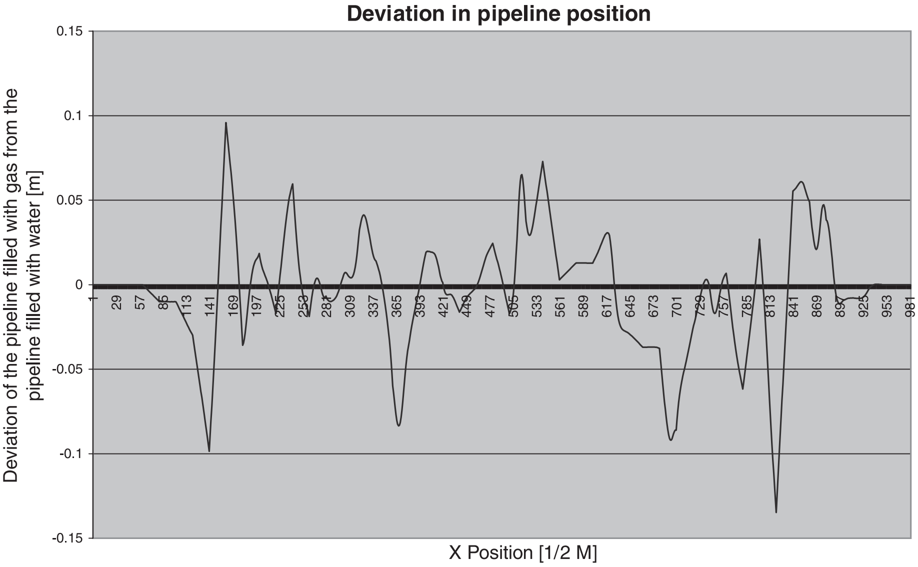

Fig. 11. Differences in pipeline location between a pipeline filled with water and a pipeline filled with gas after 25 years.

for some partial exposure short sections that cause no danger to the pipeline. Free spans of the pipeline do not occur at all.

6.3. Differences between a pipeline containing water one containing gas

To estimate the differences in self-lowering between a gas-filled pipeline and a water-filled pipeline, we computed two scenarios of 25 years. In these scenarios, all conditions are the same, except for the pipeline's content. The effect to the self-lowering mechanism is small. The calculations show that the vertical positions for the two scenarios differs less then 0.1 m. These differences can be positive in one part and negative in another (see Fig. 11).

Apparently, the effect of the additional weight is limited in this case of a pipe with a diameter of 0.4 m. This may have two reasons. First of all, it is possible that the pipeline is never exposed far enough to cause pipeline lowering. The second reason might be that the weight difference between gas and water is limited. Due to the size of the pipeline, the weight of the contents might be small compared to the weight

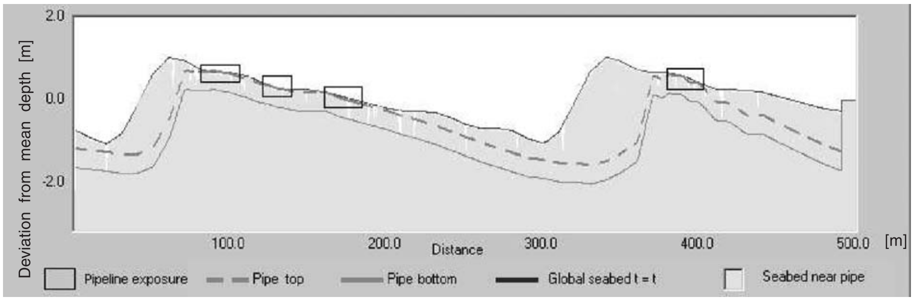

Fig. 12. Predicted pipe and seabed levels in 2006, directly after dredging. The dashed line and the solid line indicate the top and bottom of the pipeline, while the square indicates the stretch of pipeline exposure. The narrow vertical spikes in the seabed are the result of numerical errors.

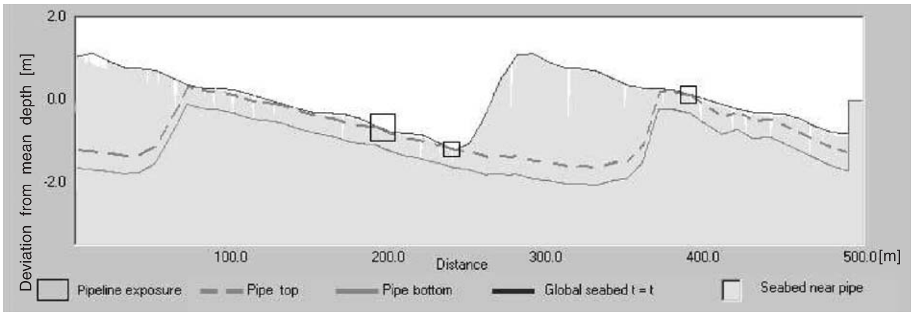

Fig. 13. Predicted pipe and seabed levels in 2020, when the sand waves have almost regained their equilibrium height. The dashed line and the solid line indicate the top and bottom of the pipeline, while the square indicates the stretch of pipeline exposure. The narrow vertical spikes in the seabed are the result of numerical errors.

of the pipe itself. In both cases, the additional weight of the contents does not make a significant difference.

6.4. A dredging scenario

The combination of DA'SWAM and PIPECAST has also been applied in a more complex scenario, involving dredging or retrenching the pipeline. The pipeline–seabed interaction is calculated after the sand wave amplitude was reduced to 25% (about 0.4 m) to simulate a retrenching operation. According to Katoh et al. (1998) and Knaapen and Hulscher (2002), the sand waves will in these conditions, regenerate to their equilibrium height within approximately 10 years. Although the pipeline is exposed over several sections of about 10 m (see Fig. 12) due to the dredging or retrenching, free spans do not occur.

The simulation shows relatively quick lowering and burial, which is the combined effect of self-lowering and backfilling. The exposures almost disappeared (see Fig. 13). This process is accelerated by the regeneration of sand waves (amplification of the amplitude). After dredging the self-lowering mechanism results in a decrease of the length of the exposed sections. Consequently, dredging does not necessarily lead to large exposures.

With this example, it is shown that the combination of the dynamic sand wave model and the model for the pipeline–seabed interaction can also be used for the planning of sand extraction in offshore areas with pipelines. The impact of subsidence on existing pipelines can be assessed as well.

7. Discussion

In its present state, the dynamic sand wave model generates uniform sand waves, with the same amplitude, wavelength and identical asymmetry. In reality such uniformity does not exist. Due to computational restrains, the present model can only effectively be used on short sections. It would take many separate model runs to evaluate a complete pipeline. Therefore, the model has to be extended to incorporate variation of the sand wave shapes. This requires the extension of the Landau equation (Eq. (2)) to the Ginzburg–Landau equation, or even to the complete model of Komarova and Newell (2000). However, this is a topic for future research, since the physical causes of variations in amplitude and wavelength are not fully understood yet.

Although the hindcasted pipeline exposures agree well with the model, the results have to be used with care. The vertical position of the buried pipeline is not always known accurately. This may have an effect on the predictions of the pipeline exposures because of a less reliable hindcast.

The results show that the self-lowering mechanism compensates for the exposure due to sand wave migration. These results are, however, strongly related to the diameter of the pipeline which in this study was small (0.4 m).

Large diameter pipes will behave differently, due to the different characteristics (more stiff and heavy). Further research in the effect of pipe diameter is recommended. However, the authors expected that research on self-lowering of pipelines as a function of the diameter will merely be an extension of existing knowledge. Consequently, the model will perform equally well for larger pipes.

8. Conclusions

In this paper a new method is presented to identify and assess potential pipeline problems. The method comprises a newly developed dynamic sand wave model and an existing pipeline–seabed interaction model. The sand wave migration model is based on physical principles and tuned to field data, using data assimilation techniques.

The sand wave model DA'SWAM has been tuned to measured profiles along a pipeline in the North Sea. This tuning, using a genetic algorithm, showed that these sand waves migrate between 10 and 20 m/year and that smaller sand waves migrate faster than larger sand waves.

This dynamic sand wave model is suitable to be combined with the local pipeline–seabed interaction model PIPECAST. The case study on the pipeline in the North Sea showed that this pipeline, with a diameter of 0.4 m, is subject to self-lowering. As a result neither long sections of exposed pipelines nor free spans occur. The pipeline showed some small exposures, mostly at the initial locations of the crests of the sand waves (in 1995).

After decommissioning, when the pipeline is filled with water replacing gas, the self-lowering mechanism will also keep up with the exposure due to the migrating sand waves. The calculations on the test section showed no dangerous exposure over a period of 20 years. The length of the exposed sections over 20 years (in the period from 2001 to 2020) do not significantly change in comparison to the length of the exposed sections after 5 years (in 2000).

The rate of the self-lowering process of a pipeline does not change substantially when the pipeline contains water instead of gas. The two calculations show only small differences (less then 0.1 m). In some sections the gas filled pipe is buried deeper, whereas in other sections the water filled pipe is buried deeper. So far, no explanation for this (lack of) difference has been found.

When the amplitude of the sand waves is decreased 25% by dredging or retrenching, the pipeline will initially become exposed over long sections. However, the model simulations show that the pipeline buries itself relatively quick and the exposures disappear. The regeneration of the sand wave enhances pipeline burial.

The quality of the results of the application of the combination of the dynamic sand wave model and the pipeline–seabed interaction model, obviously depends on the quality of the available survey data. Provided accurate and reliable pipeline and seabed data, the described method proves to be a valuable tool for pipeline operation, maintenance and decommissioning.

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