A new perspective on backfilling time scales

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ABSTRACT

Traditionally the starting point for the parameterization of the backfilling time scales for scour around a monopile or a submerged pipeline has been that it depends on the prior flow climate or scour depth. In this paper it is argued that this should not be the case within traditional two-parameter (i.e. those based on equilibrium scour depth and time scale) scour evolution models as the time scale is not a direct measure of the duration of the backfilling process, but rather the normalizing time within the asymptotic (exponential) decay towards equilibrium. Furthermore, following prior work, it is argued that the backfilling time scales should be proportional to the Shields parameter raised to the power of approximately -3/2, as this is the inverse of typical scaling in sediment transport rate formulae. Based on these arguments existing data sets for backfilling time scales are re-analyzed and novel parameterizations are suggested.

INTRODUCTION

The temporal scour evolution around a monopile or beneath a submerged pipeline can be predicted using a two-parameter scour evolution model which is based on the equilibrium scour depth and time scale, as has been done for monopiles by Nielsen & Hansen (2007), Raaijmakers & Rudolf (2008), Rudolf et al. (2008) and Harris et al. (2010). At the time of these studies no parameterizations existed for the backfilling time scales, but such parameterizations have since been proposed by Sumer et al. (2013) for monopiles or by Bayraktar et al. (2016) and Bastian et al. (2019) for pipelines. Implementing the expressions from Sumer et al. (2013) or Bastian et al. (2019) in a two-parameter scour model could be challenging, however, as the backfilling time scales in some instances are dependent on the scour depth of the previous flow condition or the so-called Keulegan-Carpenter number ($KC=U_m T_w/D$) of the previous wave climate. Here U_m is the free-stream velocity magnitude, T_w is the wave period and D is the diameter. In a situation where the wave climate and thereby scour depth is changing continuously, it is not clear which KC should be used as there is no guarantee that the scour hole in the previous wave climate would have reached equilibrium. Thereby it is similarly not clear which initial scour depth should be chosen. Using the instantaneous scour depth would e.g., result in a model which would not be able to predict properly the temporal development of constant wave climate as the time scale would not be constant. With the aid of simple thought experiments this paper aims to demonstrate that, in the absence of shape effects, the parameterization of the backfilling and scouring time scales ought not depend on the prior flow climate or scour depth. Based on this recognition backfilling time scales around monopile and pipelines are revisited.

CONVENTIONAL SCOUR MODEL

We will start by presenting the conventional two-parameter scour model, which is a model that is only dependent on two parameters, the equilibrium scour depth, S_{eq}, and time scale T (either scouring T_s or backfilling T_b). Such two-parameter model is based on the solution to the following ordinary differential equation:

$$\frac{dS(t)}{dt} = \frac{S_{eq}}{T}\left(1 - \frac{S(t)}{S_{eq}}\right), \tag{1}$$

where $S(t)$ is the instantaneous scour depth at time t. Utilizing the initial condition $S(t=t_0)=S_0$, where t_0 is an offset time, the general solution becomes

$$S(t) = S_{eq} + \left(S_0 - S_{eq}\right) \exp\left(\frac{t_0 - t}{T}\right). \tag{2}$$

For $t \to \infty, S(t) \to S_{eq}$ and T is the normalizing time within this asymptotic behavior. Both Eq. (1) and Eq. (2) can be used to describe the scour evolution for both scour and backfilling conditions. Eq. (2) has most commonly been used in the special case where $S_0=t_0=0$ and $T=T_s$, i.e.

corresponding to scouring from an initially flat bed (see e.g. Sumer & Fredsøe, 2002). In this situation the general solution given in Eq. (2) simplifies to:

$$S(t) = S_{eq}\left(1 - \exp\left(-\frac{t}{T_s}\right)\right). \tag{3}$$

This expression is well-established within the scour community and has been shown to describe observed temporal scour evolution reasonably (Sumer & Fredsøe, 2002).

Following the approach by Fredsøe et al. (1992), time scales around monopiles or beneath submerged pipelines can be non-dimensionalized according to:

$$T^* = T\frac{\sqrt{g(s-1)d^3}}{D^2} \tag{4}$$

where g is the gravitational acceleration, s is the relative sand/water density, and d is the median sediment grain size. If the scour evolution is given by Eq. (1) then the time scale can be estimated from temporal integration of the scour curve

$$T = \int_{t_0}^{\infty} \frac{S_{eq} - S(t)}{S_{eq} - S(t_0)}\,dt, \tag{5}$$

or by evaluating the slope of the temporal scour curve

$$T = \frac{S_{eq} - S(t)}{dS/dt} \tag{6}$$

Traditionally the slope has always been evaluated at $t=0$ for determination of the time scale (see e.g. Fredsøe et al., 1992; Sumer et al., 2013). However, as Eq. (6) comes directly from Eq. (1), the time scales can, in principal, be estimated by evaluating Eq. (6) at any t. If the evolution of the scour depth follows Eq. (2), then Eq. (5) and Eq. (6) yield identical time scales.

THOUGHT EXPERIMENTS

We will now present two simple thought experiments. An underlying assumption in these thought experiments is that the temporal scour depth evolution can be characterized using a two-parameter model as presented above, with a fixed equilibrium scour depth and time scale for any fixed flow condition. We also neglect shape effects such that the shape of the scour hole is assumed to somehow depend uniquely on the scour depth for any scenario (waves, currents, or waves-plus-currents, including potential changes from one to another).

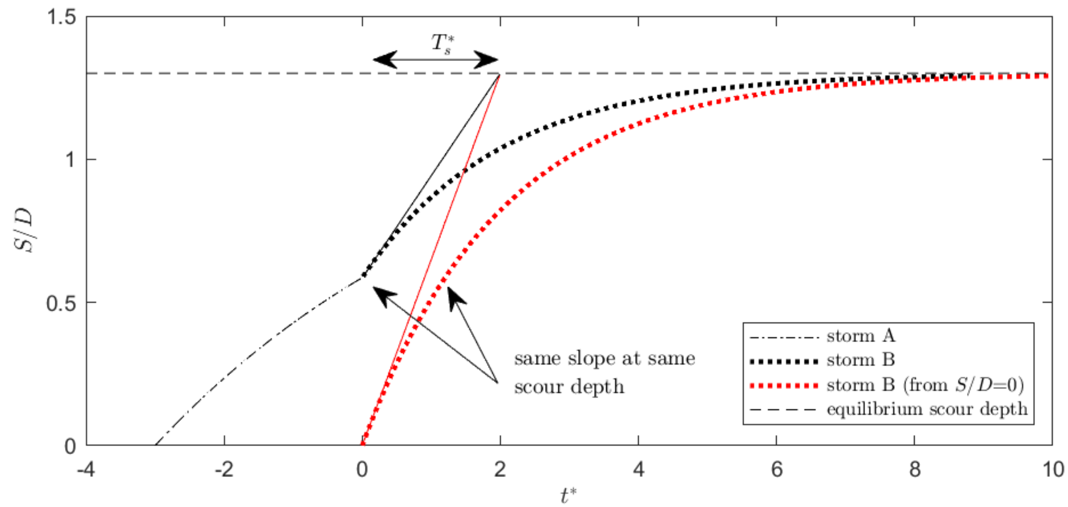

Figure 1: Thought experiment involving initial scour development due to storm A followed by a subsequent scour development due to storm B.

The first thought experiment involves a situation with an initially flat bed. A storm (storm A) hits thereby creating waves and/or currents. This initiates the scour process, and the scour depth evolves towards an equilibrium. Both S_{eq} and T_s of this process are defined by the flow conditions created by storm A. This hypothetical scour evolution is shown with dashed-dotted line in Figure 1. The duration of storm A is not long enough for the equilibrium scour depth to be reached, and after some later time (taken as at $t^*=0$, where t is non-dimensionalized as in Eq. 4) the flow climate changes, and storm B begins. The scour depth evolution caused by storm B would be expected to evolve towards a potentially new equilibrium scour depth, with S_{eq} and T_s both now governed exclusively by these new storm B conditions (black dotted line in Figure 1). It is our contention that the scour evolution of storm B following storm A ought to simply correspond to a time-shifted variation of the scour evolution induced by storm B from an initially plane bed. This is shown with the red dotted line in Figure 1. The two storm B curves also yield the same time scale as depicted by the two full lines in Figure 1, thereby visually confirming that the time scale can be found by evaluating the tangent of the scour curve at any point in time.

We do not believe that the thought experiment presented just above is controversial or presents any novel perspective on scour processes, but rather is in line with what we believe to be standard engineering practice. Similar temporal scour development as in the thought experiment above has been presented experimentally by Zhang et al. (2016). The above thought experiment was presented as a natural predecessor to a similar thought experiment involving backfilling, which will be presented in what follows.

In a second thought experiment, two otherwise-identical monopiles or pipelines are initially subjected to two different storms (storms 1 and 2), yielding different predicted time scales and equilibrium scour depths. The storms continue until equilibrium scour is reached. Storms 1 and 2 are shown as dashed-dotted lines in Figure 2. Both structures are then hit by a relatively milder

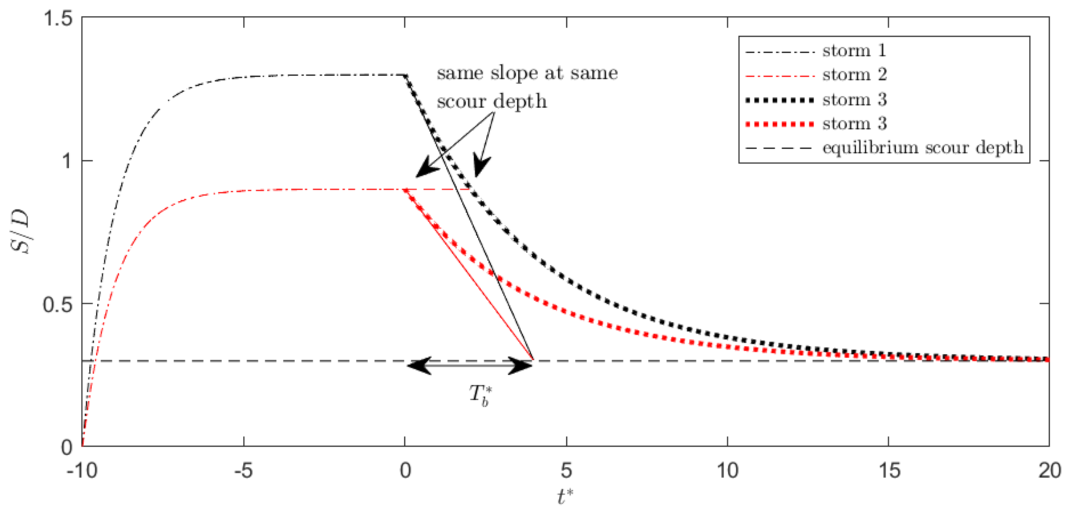

Figure 2: Thought experiment involving backfilling induced by the same storm from two different initial conditions.

storm (storm 3) and backfilling starts and continues towards a new equilibrium. This process is shown with dotted lines in Figure 2. Similar to the prior thought experiment, the equilibrium backfilling scour depth is governed by storm 3 alone. This again not controversial and has been demonstrated experimentally and numerically (Fredsøe et al., 1992; Sumer et al., 2013; Fuhrman et al., 2014). Analogous to thought experiment 1, we postulate that the two cases ought to share a common backfilling time scale T_b, governed only by the new (storm 3) backfilling climate. If the backfilling time scale is not only governed by storm 3 the two scenarios would not share the same slope at identical scour depths. Therefore, the pre-existing scour depth or previous flow conditions, should not govern the backfilling time scale (again for a common scenario, i.e. waves, currents, or waves-plus-currents); Indeed, as the scour depth is changing, the initial scour depth ought not govern the time scale more than the depth at any other time in the scour process. If the backfilling time scale was somehow dependent on the prior scour depth, then the time scale could not be assumed constant and would be changing throughout the process. This conclusion is contrary to conventional wisdom and practice, which typically include prior flow conditions or scour depth in the parameterization of the backfilling time scales (even following common initial scouring scenarios). This practice seems to stem from Fredsøe et al. (1992), who proposed that the backfilling time scale for pipelines could be a function of the initial, KC_i, as well as the present KC and Shields parameter, Θ. Similar functional dependency has since been suggested for both monopiles (Sumer et al., 2013) and pipelines (Bayraktar et al., 2016, Bastian et al., 2019). It is emphasized that the latter two studies involve the first and third authors.

The reason why researchers have previously attempted to include preceding conditions (or scour depth) in the parameterizations of T_b^* is seemingy based on the intuitive expectation that backfilling from initially larger scour caused by storm 1 to storm 3 would take longer than backfilling from storm 2 to storm 3. However, this is already accounted for by the difference

$\left(S_0 - S_{eq}\right)$ in Eq. (2). It should therefore not be doubly-accounted for within the parameterization of T_b^*.

In light of the discussion above, we will therefore re-visit selected formulations for backfilling time scales, and re-parameterize any which includes prior scour or flow conditions. As we are aware that shape effects cannot be completely absent in practice, we will allow for different formulations for different backfilling scenarios, i.e., wave-induced scouring followed by wave-induced backfilling can have a different backfilling time scale than current-induced scouring followed by wave-induced backfilling.

SCALING

Before attempting to re-parameterize the backfilling time scales we will present some scaling considerations which ought to be taken into account when parametrizing both scouring and backfilling time scales.

Larsen et al. (2017) argued that the time scale of the scour process for monopiles should be proportional to the volume of the scour hole ($V \propto D^3$) divided by the product of the sediment transport rate q_T and the width of the scour hole ($\propto D$):

$$T_s \propto \frac{V}{q_T D} \propto \frac{D^3}{q_T D} = \frac{D^2}{q_T}. \tag{7}$$

As the non-dimensional sediment transport rate $\Phi_T = q_T/\sqrt{g(s-1)d^3}$ typically scales as $\Phi_T \propto \theta^{3/2}$ (see e.g Fredsøe & Deigaard, 1992). The non-dimensional scour time scale can be expected to scale as $T_s^* \propto \theta^{-3/2}$. Note that Zhang et al. (2017) have made similar arguments regarding the scaling of the scour time scale for pipelines. Using the same arguments, the backfilling time scale may be expected to scale as $T_b^* \propto \theta^{-3/2}$.

MONOPILES

Parameterizations of backfilling time scales around monopiles for different scenarios have been suggested by Sumer et al. (2013). Upon inspection of their parameterizations it is clear that only their expression of wave-induced scour followed by wave-induced backfilling involves parameters from the previous flow climate. For this scenario Sumer et al. (2013) suggested:

$$T_b^* = \left(70\frac{KC}{KC_i}\theta^2\right)^{-1.45} \quad (8)$$

which can be seen to involve the previous (scouring) wave climate and a strong Shields number scaling $T_b^* \propto \theta^{-2.9}$. In what follows we will therefore re-analyze the data for the backfilling time scale around monopoile for this scenario, with the goal of formulating predictive equations that are consistent with the thought experiments and the scaling considerations regarding the Shields parameter presented above.

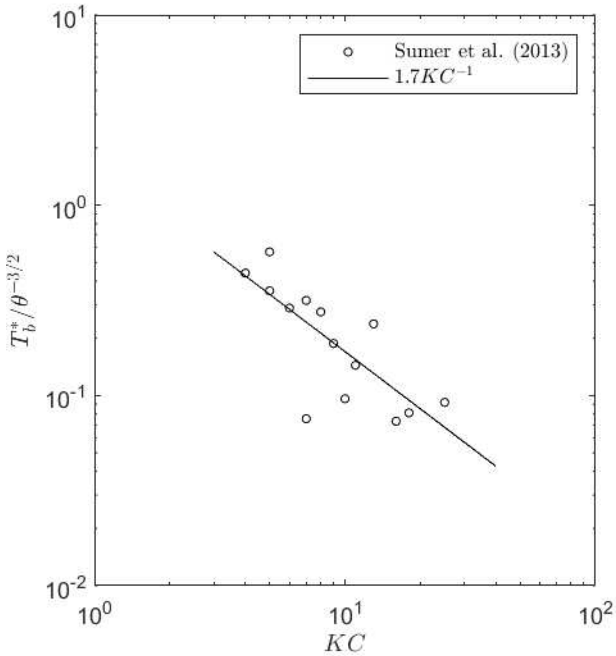

Figure 3: $T_b^*/\theta^{-3/2}$ vs. *KC* for backfilling in waves to waves

Figure 3 shows measured $T_b^*/\theta^{-3/2}$ from Sumer et al. (2013) as a function of *KC*. As can be seen the data clusters nicely around a line proportional to $\propto KC^{-1}$and the corresponding backfilling time scale may be approximated by:

$$T_b^* = 1.7KC^{-1}\theta^{-3/2}, \quad KC > 4 \text{ and } D/L \lesssim 0.05 \quad (9)$$

where *L* is the wave length. The limits for *KC* and *D/L* are included as we do not believe the expression to be valid in the so-called large monopile regime, where diffraction effects become important.

Figure 4a shows the measured versus predicted T_b^* values using Eq. (9) and Figure 4b similarly compares these using the original expression from Sumer et al. (2013), corresponding to Eq. (8).

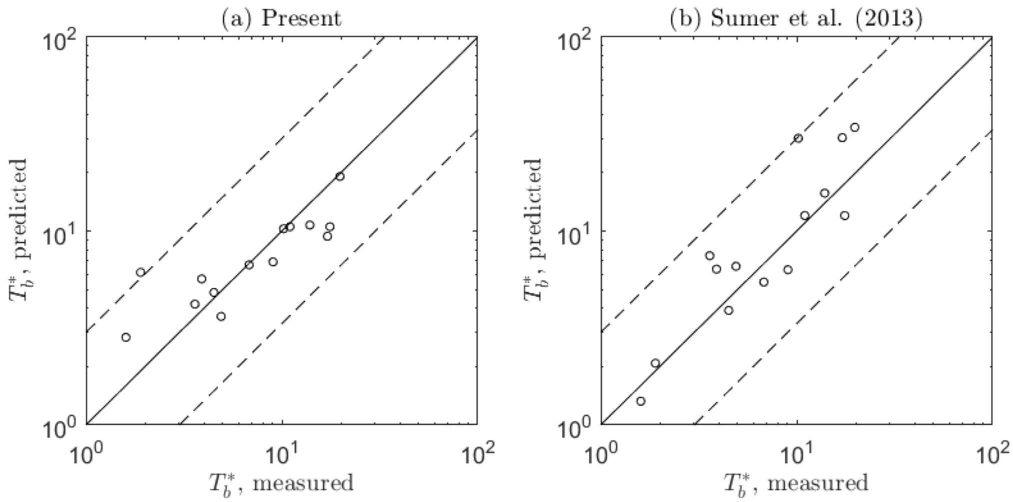

Figure 4: Comparison of measured (Sumer et al., 2013) and predicted T_b^* using (a) the present approach Eq. (9) and (b) the expression from Sumer et al. (2013) Eq. (8). The full line indicates perfect agreement, and dashed lines indicate plus and minus a factor three.

As can be seen both the present and the original formulation cluster around the line of perfect agreement (full lines) and only a single value is of by more than a factor three (dashed lines), which is a level of uncertainty expected due to the estimation procedure of T_b^* alone (see Fredsøe et al., 1992). The present formulation, Eq. (9) importantly achieves similar clustering using only information from the present wave climate, and again maintains expected scaling in terms of the Shields parameter, such that it is hopefully more reliable when extrapolated to field scales where significantly higher Shields parameters than those used in the experiments may be present.

Some of the parameterizations proposed by Sumer et al. (2013) for T_b^* of the remaining scenarios similarly have the Shields parameters raised to a high power. These will however not be investigated here, but will be left as a topic for future research.

PIPELINES

The backfilling time scales for pipelines have been investigated experimentally by Bayraktar et al. (2016) for current-induced scour followed by wave-induced backfilling and Bastian et al. (2019) for wave-induced scour followed by wave-induced backfilling. Their final formulations did not involve the prior wave climate or scour depth and are therefore not problematic in relation to the thought experiments presented herein. The starting point of their analysis was similar to that of Fredsøe et al. (1992), however, as they assumed that the backfilling time scales were potentially dependent on either the initial scour depth or *KC*. As the initial scour depths did not change much in either study, they were fortuitously eliminated during the subsequent analysis. Both the expression from Bayraktar et al. (2016) and Bastian et al. (2019) have $T_b^* \propto \theta^{-5/3}$ which is close enough to our proposed scaling that we do not feel that the backfilling time scales merit re-analysis with regards to this issue.

In an attempt to generalize the prediction of the backfilling time scales for both ``current to waves" and ``waves to waves" backfilling scenarios Bastian et al. (2019), however, suggested an expression involving the initial scour depth. In light of the thought experiments presented within this work, we consider this an attempt to take into account scenario-dependent differences (i.e. whether the initial scour hole was generated by a current or waves). In light of this we recommend the initial formulations by Bayraktar et al. (2016) and Bastian et al. (2019) to be used for the pipeline backfilling time scales. Both are of the form:

$$T_b^* = \alpha\, \theta^{-5/3} \tag{10}$$

where α=0.3 and 0.2 for current-to-wave and wave-to-wave backfilling scenarios, respectively.

CONCLUSION

Based on simple thought experiments, it has been proposed that for a given scenario, the time scales of both scour and backfilling should be governed solely by the present flow conditions, and not based on prior flow conditions or scour depths. This in contrast to standard practice in estimating backfilling time scales. Following arguments by Larsen et al. (2017) and Zhang et al. (2017) it is further argued that scour and backfilling time scales ought to scale roughly as $T^* \propto \theta^{-3/2}$. Following these arguments, the backfilling time scales for the "wave to wave" scenario for monopiles have been re-parameterized. The novel parameterization maintains similar scatter as the existing one, but is simpler and consistent with the thought experiments and proposed scaling.

The parameterization for the backfilling time scales for pipelines is likewise discussed, and it is argued that the existing formulations can be used without modification, as they scale reasonably and do not involve information about the prior scour depth or flow conditions.

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REFERENCES

Bastian, K., Carstensen, S., Sui, T., Fuhrman, D. R., 2019. Generalized time scale for wave-induced backfilling beneath submarine pipelines. Coast. Eng. 143, 113–122.

Bayraktar, D., Ahmad, J., Larsen, B. E., Carstensen, S., Fuhrman, D. R., 2016. Experimental and numerical study of wave-induced backfilling beneath submarine pipelines. Coast. Eng. 118, 63–75.

Fredsøe, J., Deigaard, R., 1992. Mechanics of Coastal Sediment Transport. World Scientific, Singapore.

Fredsøe, J., Sumer, B. M., Arnskov, M. M., 1992. Time scale for wave/current scour below pipelines. Int. J. Offshore Polar Eng. 2, 13–17.

Fuhrman, D. R., Baykal, C., Sumer, B. M., Jacobsen, N. G., Fredsøe, J., 2014. Numerical simulation of wave-induced scour and backfilling processes beneath submarine pipelines. Coast. Eng. 94, 10–22.

Harris, J. M., Whitehouse, R. J., Benson, T., 2010. The time evolution of scour around offshore structures. Proceedings of the Institution of Civil Engineers: Maritime Engineering 163 (1), 3–17.

Larsen, B. E., Fuhrman, D. R., Baykal, C., Sumer, B. M., 2017. Tsunami-induced scour around monopile foundations. Coast. Eng. 129, 36–49.

Nielsen, A. W., Hansen, E. A., 2007. Time-varying wave and current-induced scour around offshore wind turbines. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - Omae 5, 399–408

Raaijmakers, T., Rudolph, D., 2008. Time dependent scour development under combined current and wave conditions - laboratory experiments with online monitoring technique. In: Proc. 4th Conf. Int. Conf. Scour and Erosion. pp. 152–169.

Rudolph, D., Raaijmakers, T., Stam, C.-J., 2008. Time dependent scour development under combined current and wave conditions - hindcast of field measurements. In: Proc. 4th Conf. Int. Conf. Scour and Erosion. pp. 340– 347.

Sumer, B. M., Fredsøe, J., 2002. The Mechanics of Scour in the Marine Environment. World Scientific, Singapore.

Sumer, B. M., Petersen, T. U., Locatelli, L., Fredsøe, J., Musumeci, R. E., Foti, E., 2013. Backfilling of a scour hole around a pile in waves and currents. J. Waterw. Port C-ASCE 139, 9–23.

Zhang, Q., Draper, S., Cheng, L., Ai, H., 2017. Time scale of local scour around pipelines in current, waves, and combined waves and current. J. Hydraul. Eng. 143, article no. 04016093.

Zhang, Q., Draper, S., Cheng, L., An, H., 2016. Scour below a subsea pipeline in time varying flow conditions. App. Ocean Res. 55, 151–162.