Scour and sedimentation of submarine pipelines: closing the gap between laboratory experiments and field conditions

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ABSTRACT: Predicting changes to subsea pipeline embedment due to sediment mobility is critical to many aspects of pipeline design, including on-bottom stability, thermal management, fatigue analysis and flow assurance. Motivated by this requirement, significant advances have been made over the last few decades in understanding the mechanisms of pipeline scour and sedimentation. This has led to the development of predictive models and formulas, based predominantly on laboratory experiments. However, despite these developments uncertainties still remain in predicting scour and sedimentation in actual field conditions. One reason for this continued uncertainty is that previous laboratory experiments have often focused on idealised testing conditions, consisting of uniform sandy sediments and steady or stationary near-bed current and wave velocities. Although these idealised conditions enable systematic studies, they are not representative of the range in marine sediments and metocean conditions observed in practice; hence extrapolation is necessary. A second reason for uncertainty is that there has only been limited comparison of laboratory results with field data, and so quantitative validation is lacking. Noting these areas of uncertainty, in this paper we review a collection of recent studies completed at the University of Western Australia (UWA) which each aim to close the gap between laboratory experiments and actual field conditions, and therefore reduce uncertainty in predicting changes in scour and sedimentation in the field. These studies focus on three aspects of work: (i) the effect of variations in marine sediment properties on the rate of pipeline scour; (ii) the effect of time-varying seabed velocities on pipeline scour; and (iii) comparisons of laboratory based estimates of scour and sedimentation with field data. In each study an emphasis is placed on developing reliable predictive models and formulas that better represent field conditions, or are validated against field observations. It is argued that these models allow for improved predictions of pipeline scour and sedimentation, and may be used to form a rational design approach for subsea pipelines.

1 INTRODUCTION

Changes in the embedment of submarine pipelines due to scour, lowering and/or sedimentation can present both a potential benefit for pipeline design as well as a complication. For example, an increase in pipeline embedment due to sediment mobility can improve on-bottom stability, thereby enabling the development of lighter and potentially cheaper pipelines. Conversely, unexpected changes in pipeline embedment due to sediment mobility may reduce the reliability of thermal management plans and flow assurance, as well as potentially forming pipeline free spans that can reduce the fatigue life of the pipeline.

Because of this range in implications, design predictions of pipeline embedment accounting for sediment mobility must be based on unbiased estimates of scour and sedimentation; i.e. it is not normally possible to simply apply conservative estimates which favor negligible or significant change to embedment. As a result, the estimation of scour and sedimentation represents a difficult design challenge. This challenge is compounded by the fact that existing pipeline design guidelines, such as DNV-RP-F109 for example, note that seabed mobility should be considered in pipeline stability design but do not provide detailed guidance to predict the associated changes to pipeline embedment.

To better inform pipeline design a significant amount of research has been undertaken over the last 3-4 decades to qualitatively and quantitatively study the mechanisms of scour and sedimentation. Owing to the complexity of sediment transport phenomena, the majority of this research has focused on laboratory experiments in which pipelines are placed on a mobile seabed and subjected to currents, waves or combined waves and current conditions. An extensive review of this work has been presented by Sumer and Fredsøe (2002) and Whitehouse (1998). In more recent years numerical models have also been used to investigate scour (Sumer, 2015), however experimental modelling still remains arguably the main mode of investigation because of the computational expense of numerical models and the reliance of numerical models on empirical expressions to parameterize unresolved processes such as sediment transport.

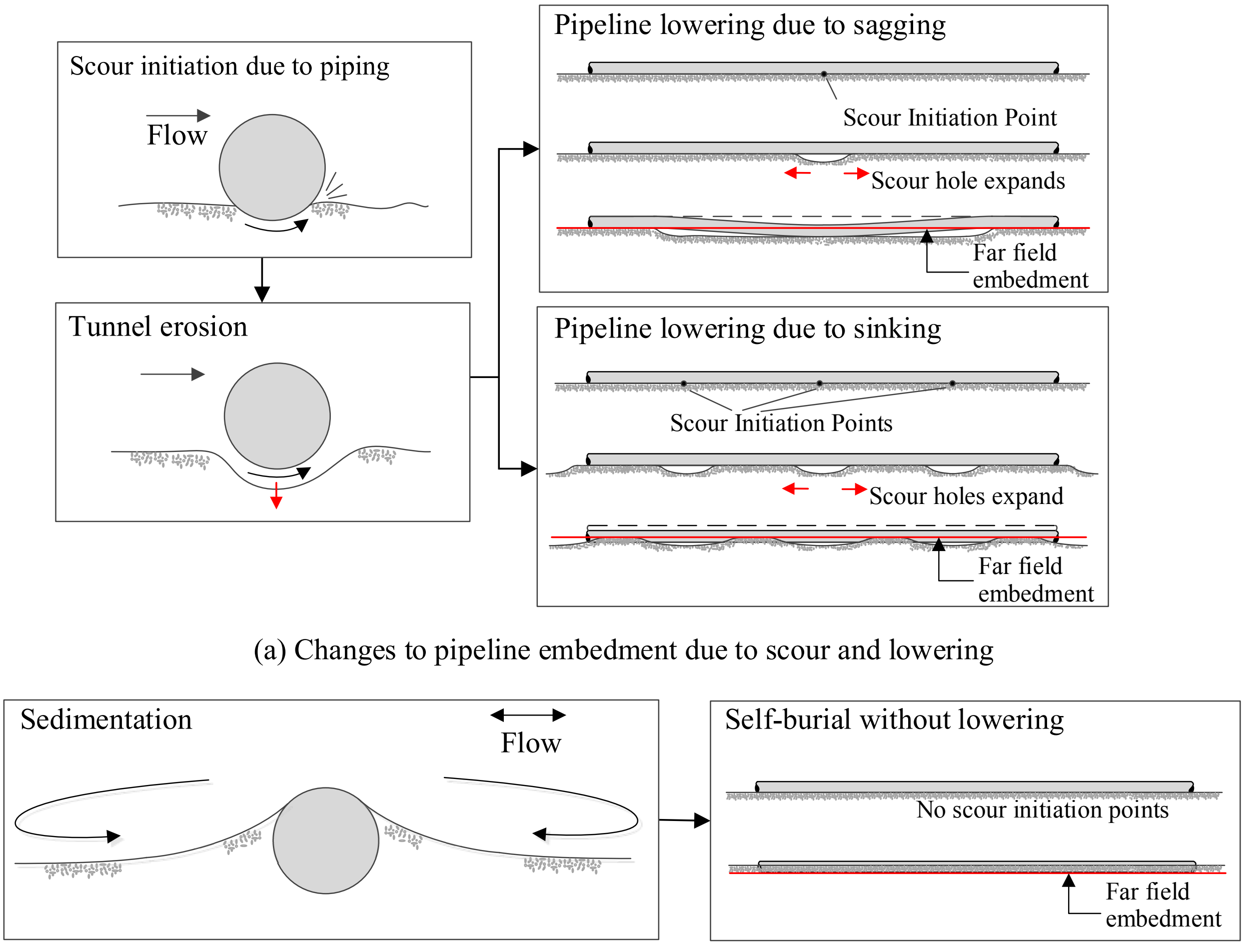
A common aim of the existing body of experimental research has been to develop models and empirical formulas to predict the rate and extent of scour and sedimentation, and a number of important contributions have been made in this direction. Nevertheless, the majority of these contributions have been based on experiments performed in idealized laboratory conditions, incorporating uniform sands and/or steady or stationary flow conditions. This restriction has been necessary to reduce the experimental problems to a tractable number of key parameters over which a systematic study of the reduced parameter space may be performed. It has therefore allowed, for example, the mechanisms of onset of pipeline scour and 3D scour along a pipeline to be investigated in detail (see, respectively, Sumer et al., 2001 and Cheng et al., 2009, 2014). Nevertheless, a consequence of this approach is that the application of the results from these experimental studies to field conditions introduces inevitable uncertainty. This is because the grain size distribution and particle shape and density of marine sediments in the field can be very different to uniform sands, and this can lead to significant (sometimes order of magnitude) differences in erosion properties and scour/sedimentation rates (as will be discussed in more detail in Section 4). Furthermore, in field conditions near bed flows can approach the pipeline from different directions and are rarely steady or stationary. Due to the inherent non-linear nature of scour this can have a significant impact on scour lowering and sedimentation (as will be described in more detail in Section 5).

A second cause for uncertainty in using laboratory derived empirical models is that only limited comparisons between the empirical models and field observations have been reported. For example, whilst recent reviews have highlighted the value of field data within offshore scour research (see, for example, Harris and Whitehouse, 2015), in the context of subsea pipelines only a few papers have reported field observations in detail (see, for example, Bruschi et al., 1997; Pinna et al., 2003; Borges-Rodreiguez et al., 2013 and Section 6). Without detailed quantitative comparison to field observations, validation of the empirical models, and the underlying experiments (including their inherent scaling and modelling assumptions), is not possible.

With these uncertainties in mind, the primary aim of this paper is to present a series of laboratory studies and field data analyses that have been undertaken recently at the University of Western Australia (UWA) to try and close the gap between traditional laboratory results and field conditions. These include (i) an experimental study to relate the erosion properties of different marine sediment to the rate of pipeline scour; (ii) an experimental study to investigate the effect of non-stationary seabed velocities on pipeline scour; and (iii) detailed comparisons between laboratory data and field observations of scour and sedimentation. The first two of these studies are focused on refining laboratory experiments to better represent field conditions. The last study is focused on validation of laboratory predictions with field observations.

Each of the three studies presented in this paper lead to predictive models and formulae that may be used predict scour and sedimentation induced changes to pipeline embedment in the field. Consequently a secondary aim of this paper is to describe how these results may be used in pipeline design to form unbiased estimates of sediment mobility induced changes to pipeline embedment. This discussion draws on a larger body of research that has been undertaken within the STABLEpipe Joint Industry Project (JIP), which has been sponsored by Woodside and Chevron, with JIP participation by UWA, Wood Group Kenny and a number of other prominent industry organisations and technical authorities. The main goal of the STABLEpipe JIP is to develop new engineering guidelines to quantify the effects of sediment mobility on pipeline design. Griffiths et al. (2010) and Fogliani et al. (2013) present a more detailed description of the JIP.

The remainder of this paper is laid out as follows. In Section 2 the mechanisms of scour and sedimentation are briefly reviewed. Following this, the UWA O-Tube facilities are introduced in Section 3. These facilities were specifically designed to enable more detailed laboratory studies of pipe-fluid-seabed interaction and have been used exclusively for the studies discussed in this paper and the work underpinning the STABLEpipe JIP. The three different studies are then presented in turn through Sections 4, 5 and 6, and the outcomes of these studies are discussed collectively in Section 7 with a particular focus on how the results may be used to provide unbiased estimates of scour and sedimentation within a rational design approach. Concluding remarks are presented in Section 8.



(a) Changes to pipeline embedment due to scour and lowering

(b) Changes to pipeline embedment due to sedimentation

Figure 1. Mechanisms of pipeline (a) scour leading to lowering, and (b) sedimentation. Adapted from Fredsøe et al. (1988) and Leckie et al. (2015).

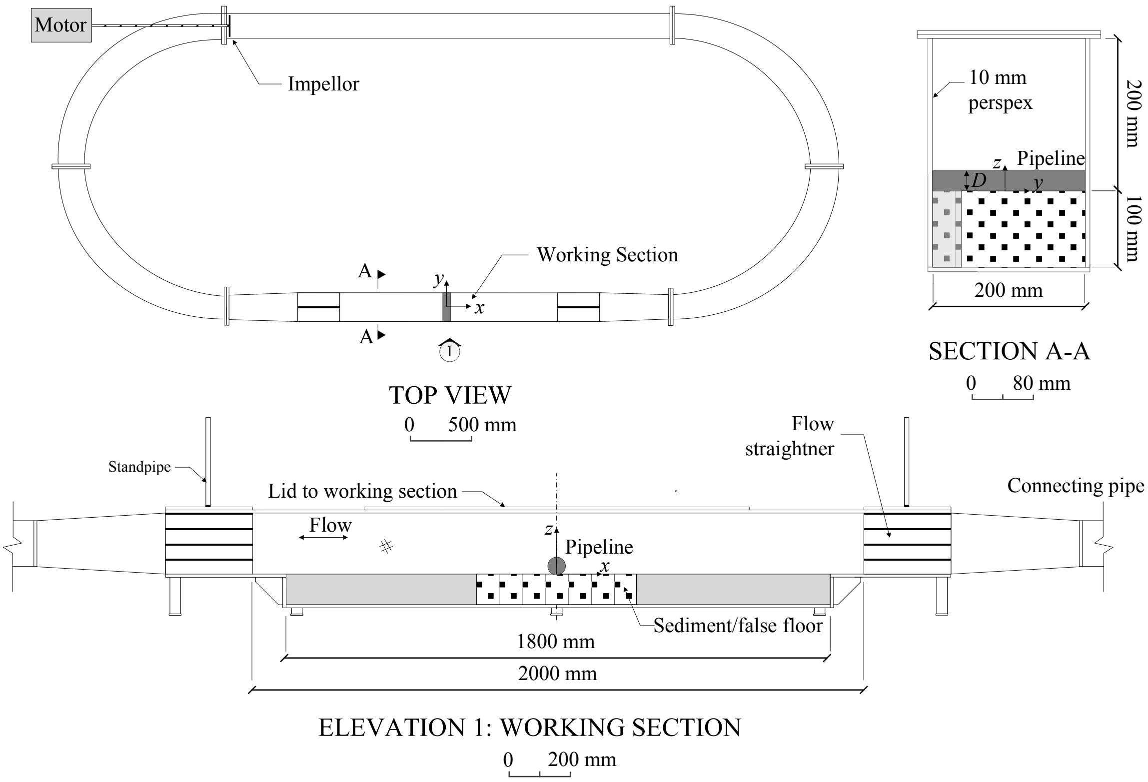


Figure 2. Schematic drawing of the mini O-tube (MOT) at UWA.

2 MECHANISMS OF PIPELINE SCOUR AND SEDIMENTATION

Figure 1 summarises the main mechanisms of pipeline scour and sedimentation that lead to changes in pipeline embedment. This figure has been split into two main subfigures; the first describing scour and lowering (Figure 1a) and the second sedimentation (Figure 1b). Field observations (see Section 6) suggest that either scour and/or sedimentation may result when a pipeline is first placed on a seabed, and both may lead to changes in pipeline embedment. For this reason we choose to distinguish between scour and sedimentation in this section, and describe both in turn.

Whether scour or sedimentation is more dominant for a pipeline immediately following lay appears to depend primarily on the initial as-laid embedment of the pipeline (i.e. the embedment of the pipeline following lay from a pipe lay barge) and the flow conditions near the seabed (Griffiths et al., 2016). For shallowly embedded pipelines, or frequently spanning pipelines, scour is expected to be more common. This is because (i) scour can commence when current and/or wave velocities near the seabed are sufficiently large to mobilize sediment due to streaming of the flow into pre-existing spans under the pipeline, and (ii) shallowly embedded pipelines require significantly lower velocities to initiate scour due to 'piping' failure of the sediment downstream of the pipeline (see Chiew, 1990 and Sumer et al., 2001) both with and without variations in sediment supply (Zhang et al., 2013). In contrast, the velocities required to initiate piping become excessive as embedment increases, such that piping is unlikely when embedment is >20% of the pipeline diameter. Hence in these cases local reworking of the sediment (i.e. sedimentation) may predominate.

2.1 *Scour and pipeline lowering*

The processes of scour and lowering have been documented in detail by Fredsøe et al. (1988) and Sumer and Fredsøe (1994, 2002). Following the initiation of scour (due to piping or flow streaming in a pre-existing gap), a process known as tunnel erosion prevails, in which a scour hole expands vertically beneath the pipe at a rate that is dependent on the near seabed velocity, the pipeline geometry, the pipeline initial embedment and the erosion properties of the seabed (see Leeuwenstein et al., 1985, Sumer and Fredsøe, 2002). The scour hole will also begin to extend along the pipeline at a rate that is dependent on these same parameters in addition to the three dimensional geometry of the scour hole and the span shoulders (see, for example, Hansen et al., 1991; Cheng et al., 2009, 2014; Wu and Chiew, 2013). Eventually this scour hole can become sufficiently long that lowering of the pipeline will occur. In principle this lowering can occur in two ways as depicted in Figure 1a. Firstly, if scour holes initiate at locations which are widely spaced along the pipeline, the pipeline can 'sag' into the hole (Fredsøe, 1988). Alternatively, if the scour holes are closely spaced, then the pipeline can 'sink' into the supporting soil between spans when they become short (Sumer and Fredsøe, 1994). For both pipelines that sag and sink into the seabed, locations where the pipeline has lowered may experience backfill. This final process of backfill leads to self-burial of the pipeline.

2.2 *Sedimentation*

Sedimentation without scour is depicted in Figure 1b and results from the accumulation of sediment near the pipeline due to the local reworking of sediment around the pipeline. The rate and extent of sedimentation are related to the local disturbance to the flow caused by the pipeline, as well as the sediment erosion properties. The build-up of sediment is only local to the pipeline, and may occur without any initial scour (as shown in Figure 1a) or following scour and lowering of the pipeline (i.e. backfill). In the former scenario, sedimentation can be distinct from the scour processes in figure 1a because the pipeline becomes partially buried by sand without lowering into the seabed at any location.

Compared with pipeline scour and pipeline lowering, dedicated laboratory studies of sedimentation have been more limited. Chiew (1990) described laboratory experiments where scour did not initiate in a unidirectional current due to deposition of sediment behind the pipe by the lee-wake vortex, whilst more recently Zhao et al. (2015) presented results from CFD analysis which provide insight into locations for local deposition of sediment. Sumer et al. (2001) have presented some experimental results on the time-scale of pipeline sinking into a scoured trench, and Fredsøe et al. (1992) presented experimental results for time-scale of wave induced backfill following initial scour. More recently, Fuhrman et al. (2014) presented numerical simulation of both scour and backfilling, in which backfill rates were found to agree reasonably well with the experiment results of Fredsøe et al. (1992). However, despite these works the types of local seabed profile caused by sedimentation and the rate (or time-scale) of sedimentation are still not well known.

3 EXPERIMENTAL FACILITIES USED

A variety of physical modelling facilities have been developed to study offshore structures, including open channel flumes, closed U-tube flumes and oscillating water tunnels driven by a piston. However, as pointed out by An et al. (2013), each of these facilities have limitations when considering experiments involving scour and sedimentation over a large range of combined wave and current flow conditions. Open channel flumes, for example, are limited to wave velocities below which wave breaking occurs. Additionally using a driven trolley in an open channel allows higher velocities to be achieved but is impractical for large regions of mobile bed. U-tubes allow higher velocities to be achieved, but with limited flexibility (due to the requirement to operate at or near resonance). Finally, piston driven water tunnels offer more flexible control but are limited by the stroke of the piston.

To overcome these limitations, an alternative flume configuration, known as an O-tube, has been developed at UWA. This flume comprises a horizontal fully enclosed recirculating water tunnel, with a rectangular test section and an impeller-type pump driven by a motor. This arrangement has the relative advantages that (i) currents can be introduced easily, and (ii) wave velocities are limited only by the pump characteristics and not by wave breaking, resonance of the water mass or the stroke of a piston. These features allow for reproduction of storm conditions, and allow experimental flow conditions that are more representative of field conditions (as discussed further in Section 5 of this paper).

Three O-tubes have been constructed at UWA: the Large O-Tube (LOT); Small O-Tube (SOT) and the Mini O-Tube (MOT). The key dimensions and performance characteristics of the flumes are given in Table 1. The different scales of O-tube are suited to different purposes. The LOT is capable of modelling small pipelines at full scale, with negligible blockage effects and potentially 1:1 scale flow conditions. The MOT and SOT require less sediment to fill and nourish the working section compared with the LOT. This allows small scale tests and sediment-specific erosion testing to be undertaken using prototype sediments gathered from the field.

Figure 2 provides an overview of the smallest O-tube, termed the MOT. In this figure a model pipeline is included to give an indication of the typical test setup used in the pipeline experiments explained throughout the remainder of this paper. More details on the operation of the O-Tube flumes are presented in An et al. (2014), Luo et al. (2012), Cheng et al. (2014) and Mohr et al. (2016*a*).

Table 1. O-tube dimensions

Properties of working sec-	LOT	SOT	MOT
Length, L (m)	17	3.0	2.0
Width, W (m)	1.0	0.3	0.2
Height, H (m)	1.4	0.45	0.3
Maximum steady current	3	4.5	1.5
Maximum wave velocity	1–	1–3	0.5
Period, T (s)	5–13	4–10	6

4 STUDY 1: PIPELINE SCOUR IN MARINE SEDIMENTS

In practice, pipelines cross a range of different geological regions and encounter a variety of different marine sediments. Generally, these sediments will have a wide range in grain size distribution, particle shape and density. Consequently they can have very different erosion characteristics to the uniform sands often used in laboratory testing, including differences in:

(i) Threshold shear stress (i.e. the seabed shear stress required for erosion; Mohr et al., 2013),
(ii) Volumetric transport rate (e.g. Roberts et al., 1998 and Whitehouse et al., 2000) and
(iii) The mode(s) of sediment movement (i.e. they may transport along the bed or via entrainment into suspension; Roberts et al., 2003).

Because of these differences, direct extrapolation of empirical scour formulas that have been developed primarily based on experiments in uniform sand are unlikely to be valid for all marine sediments. In the context of pipelines, this has been shown to be the case via the experimental findings of Pluim-van der Velden and Bijker (1992) who conducted a series of sediment erosion tests and a series of model pipeline scour experiments on artificial sand-kaolin mixtures and natural sand-silt sediment. Their experiments indicated that with an increase in the percentage of fine material (i.e. kaolin or silt) the threshold shear stress of the sediment increased. They also reported that scour occurred much more slowly for the artificial mixtures as the percentage of kaolin increased.

In this section the recent experimental and theoretical study reported by Mohr et al. (2016*b*) is summarized. This work involved a series of erosion tests and pipeline model scale experiments on artificial and marine sediments. The aim of the work was to systematically explore how the rate of scour related to the erosion properties (and erosion rate) of the sediment. The work focused on tunnel scour in current only conditions.

4.1 *Sediments studied*

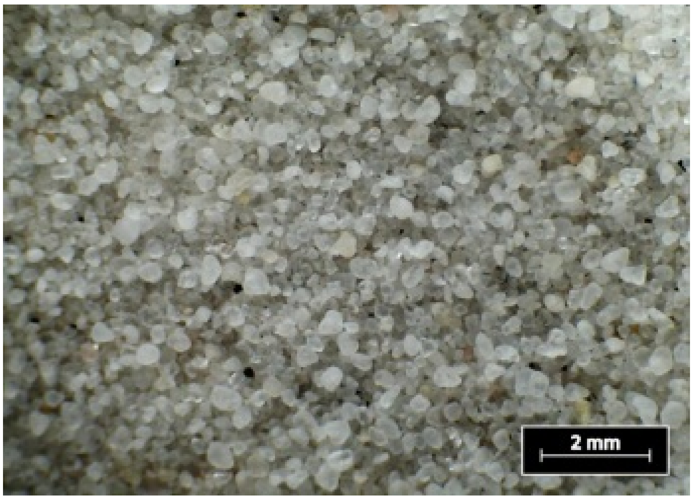
Mohr et al. (2016*b*) focused on a set of five artificial sediments (SS1, SS2, CS1, CS2, CS3), which provided a range in median grain size spanning from 15 to 540 µm, as well as two marine sediments (NWS1, NWS2) recovered from the North West Shelf of Australia. Particle Size Distribution (PSD) curves, and close range photographs for a selection of the sediments are given in Figure 3. It can be seen here that the artificial sediments are relatively uniform in grain size (especially, SS1, SS1 and CS1), whilst the marine sediments have much wider grading and a significant fraction of 'fine' sediment (defined here to be grains with diameter less than 75 μm). The shape of the marine sediment grains also vary significantly compared with the artificial sediment.

4.2 *Erosion properties*

For sediments with significant fines content, empirical methods to predict erosion properties (i.e. threshold shear stress, erosion rate and mode of erosion) are still very limited, showing significant scatter amongst different soil types (Briaud et al., 1999; Whitehouse et al., 2000). Consequently, in practice an approach that is often used to estimate erosion properties for marine sediments is to perform erosion tests either ex situ or in situ. The approach taken in Mohr et al. (2016*b*) was to perform ex situ testing in a laboratory flume following the methodology outlined in Mohr et al. (2013). Example erosion results from this testing are given in Figure 4, which plots the measured erosion rate (η) as a function of applied shear stress (τ) for the marine sediments. It can be seen that the sediments show no measurable erosion until the shear stress exceeds some threshold value, beyond which the erosion rate increases with shear stress. In general, the erosion testing results for each of the sediments tested could be explained well via the relationship

$$\eta = A(\tau - \tau_{cr})^B, \tag{1}$$

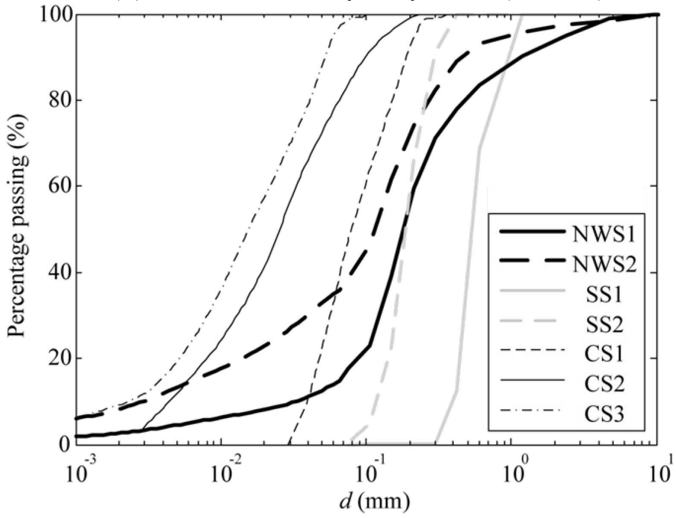
where A and B may be fitted empirically, and τ_{cr} is the critical or threshold shear stress.



(a) Silica sand (SS1)

(b) Calcareous very silty sand (NWS1)

(c) Calcareous sandy silt (NWS2)



(d) Particle size distribution curves

Figure 3. Photographs of sediments, and PSD curves. Figure adapted from Mohr et al. (2016*b*).

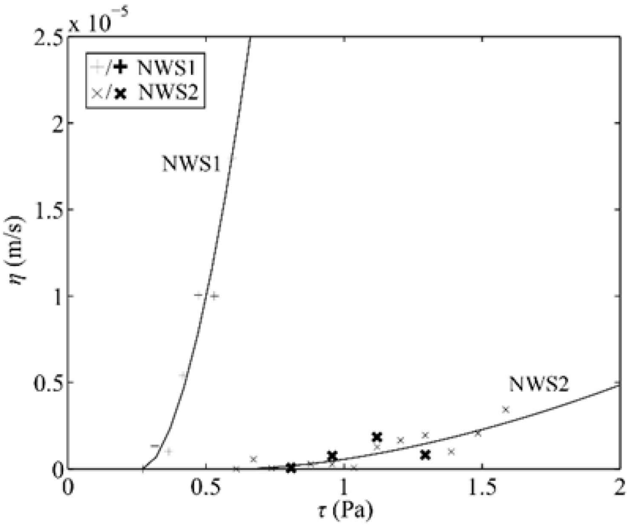


Figure 4: Example erosion rate measurement of marine sediments. Figure from Mohr et al. (2016*b*).

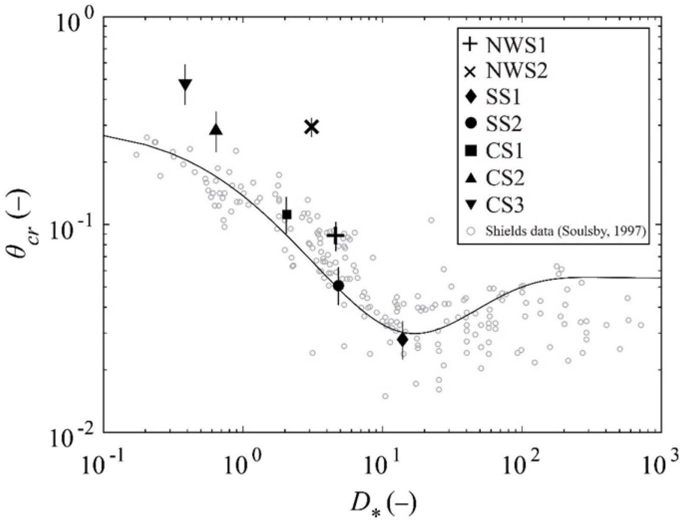


Figure 5. Measured threshold shear stress. The solid line represents a modified Shields curve fitted by Soulsby and Whitehouse (1997). Figure adapted from Mohr et al. (2016*b*).

Figure 5 plots the non-dimensional threshold shear (θ_{cr}) interpreted from the erosion testing experiments as a function of non-dimensional grain size (D_*). The artificial sediments SS1, SS2 and CS1 can be seen to agree well with the Shields curve. In contrast CS1, CS2 and the marine sediments tend to plot above the Shields curve. This increased erosion resistance is typical of 'cohesive' sediments. Detailed observations, reported in more detail in Mohr et al. (2016b), also showed that sediments CS2, CS3 and NWS2 tended to erode via entrainment into suspension. SS1, SS2 and CS1 eroded via bedload transport.

4.3 *Pipeline scour experiments*

To correlate the erosion test results with pipeline scour rate and extent, a series of 25 model pipeline experiments were performed by Mohr et al. (2016*b*) across the 5 artificial and two marine sediments, using a 40 mm model pipeline. These experiments used the test setup shown in Figure 2 and explored a range of fixed current conditions chosen to give a range of shear stress conditions for the different sediments. Care was taken in each experiment to ensure the sediments were prepared in the same way as the erosion tests.

The pipeline was placed approximately 3 mm above the initial seabed level in all experiments so as to ensure scour would initiate. To provide an indication of the scour process, Figure 6 provides example scour profiles at several times for three different sediments. These figures show how the scour hole expands beneath the pipeline. It is common to summarise the growth in terms of the scour depth (S) directly below the pipeline, as shown in Figure 7. This time variation in scour depth may be parameterized, respectively, via one of the following simple expressions due to Fredsøe et al. (1992) and Briaud et al. (1999):

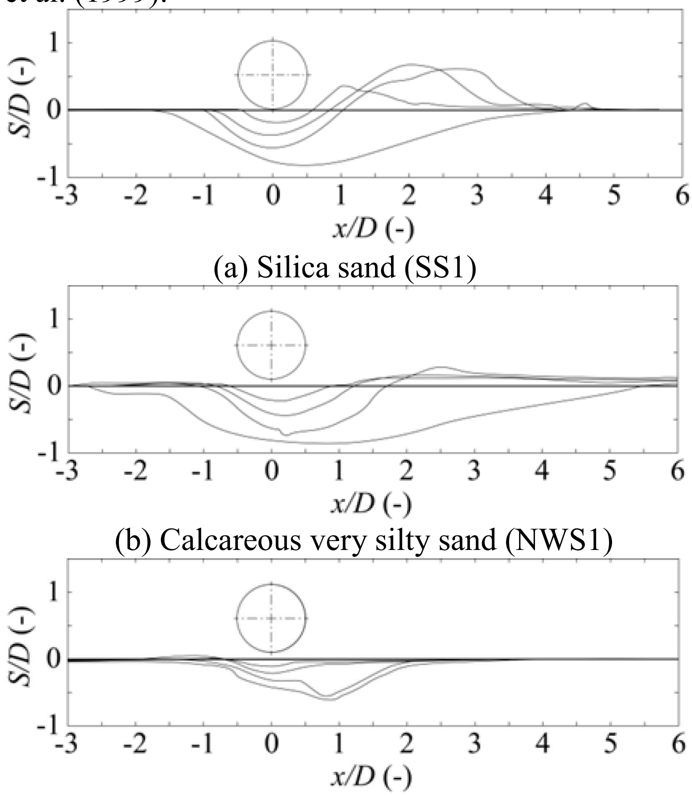


Figure 6. Scour profiles at various times during the scour process. Flow is from left to right. Figure adapted from Mohr et al. (2016b).

$$S(t) = S_e\left(1 - \exp\left(-\frac{t}{T}\right)\right), \tag{2}$$

and

$$S(t) = S_e\left(\frac{t}{t+T}\right), \tag{3}$$

where in both expressions t is time, S_e is the equilibrium scour depth and T defines the time-scale of the scour process. The equilibrium scour depth is generally in the order of 0.6-0.8 times the pipeline diameter and is mostly dependent on flow velocity (Sumer and Fredsøe, 2002). The time scale of the scour process, in contrast, is expected to be highly dependent on the flow velocity and the erosion properties of the sediment.

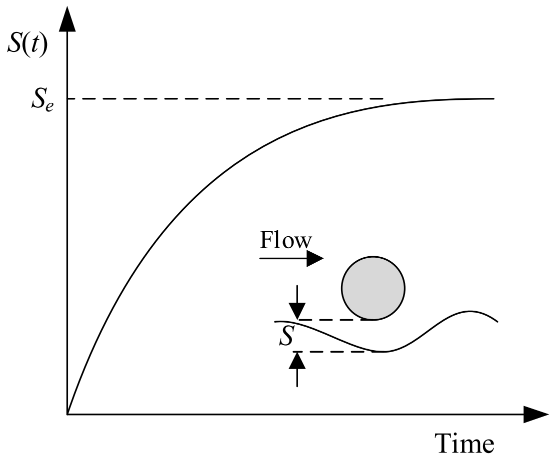


Figure 7: Time development of scour directly under the pipeline.

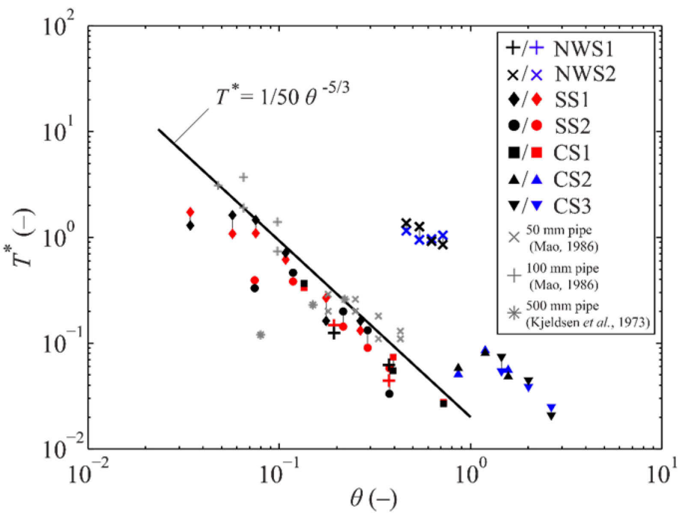


Figure 8. Time scales calculated from experimental results. Solid line is prediction due to Fredsøe et al. (1992). Figure adapted from Mohr et al. (2016*b*).

Figure 8 plots the measured time-scale for each of the model scale pipeline experiments performed. Also shown in this figure is a predictive formula given by Fredsøe et al. (1992) based on experiments in mostly sandy sediments. It can be seen in this figure that the uniform artificial sediments tend to agree well with the empirical formula, but for the finer sediments NWS2, CS2 and CS3, which appear to be 'cohesive' (see Figure 5) the time-scale of scour is up to an order of magnitude larger than the empirical formula. This result is not unexpected, since these fine sediments have relatively higher erosion resistance compared with sandy sediments.

4.4 *Predicting the rate of scour in marine sediments*

Using simple control volume arguments Mohr et al. (2016*b*) were able to write the time-scale as a function of the maximum erosion rate at the start of the scour process for sediments that erode either via transport along the bed or via entrainment into suspension. This led to two expressions to predict the time-scale in terms of the maximum erosion rate; one for sediment eroding in bedload and one for sediment eroding in suspended load. These expressions are given, respectively, by

$$T = 2.8 \frac{S_e}{\eta_{max}} \frac{D}{L}, \tag{4}$$

and

$$T = \frac{S_e}{\eta_{max}}, \tag{5}$$

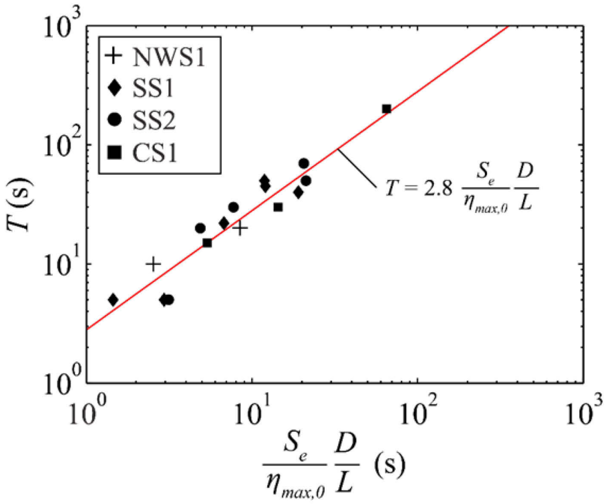
where η_{max} is the maximum erosion rate (i.e. the erosion rate experienced at the start of the scour process under the pipeline; equal to the erosion rate evaluated at the amplified shear stress under the pipeline at the initiation of scour), L is the length of the erosion sample used in the erosion testing, and (as described above) D is pipeline diameter and S_e is the equilibrium scour depth. Figure 9 illustrates the agreement between Equations (4) and (5) with the experimental measurements.

The results in Figure (9) suggest that Equation (4) and (5) may be used to estimate scour rate in marine sediments. Importantly the expressions given in (4) and (5) are a function of the measured erosion properties, and so they naturally account for the potentially 'cohesive' nature of marine sediments. To use either Equation (4) or (5) in practice only requires that the erosion rate curve $\eta(\tau)$ may be achieved via erosion testing leading to the empirical expression in (1).

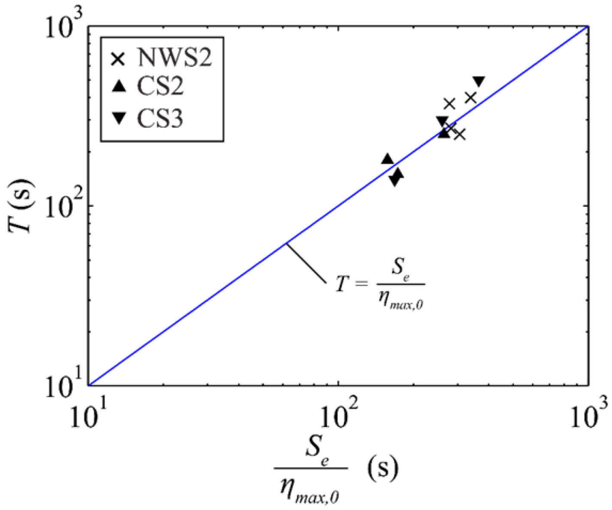
5 STUDY 2: PIPELINE SCOUR IN TIME-VARYING FLOW CONDITIONS

Scour and pipeline lowering are cumulative processes, occurring in time at a rate that can be slower than the rate at which near-bed velocities are changing. Incorporating predictions of scour and pipeline lowering into stability design, therefore, requires that the cumulative effects of scour can be estimated for all velocity conditions contributing to sediment mobility prior to the time at which stability is to be analysed. In a storm for example, this requires that scour associated with the storm velocities leading up to peak conditions are included in the analysis.

In this section we present a summary of recent results presented in Draper et al. (2015) which focus on the scour process during time-varying flow conditions. Two different scenarios are investigated in Draper et al. (2015): (i) sagging pipelines, and (ii) sinking pipelines (see Figure 1a). Here we will focus on sagging pipelines for brevity and focus on how the scour profile varies with changes in velocity and pipeline sagging; since both of these variations are possible in the field.



(a) Sediments mobilized along the seabed.



(b) Sediment mobilized through entrainment.

Figure 9. Comparison of predictive formulas with measurements. Figure adapted from Mohr et al. (2016*b*).

5.1 *Scour beneath a sagging pipeline*

For widely spaced scour holes (see Figure 1a) a pipeline can sag into the center of the scour hole as it grows along the pipeline. At any time the amount of sagging is related to the length of the scour hole, the flexural rigidity of the pipeline and the submerged weight of the pipeline. Assuming that at both ends of the scour hole the constraint on the pipeline is somewhere between a fixed and pinned connection, Fredsøe et al. (1988) suggested that the vertical deflection of the pipeline can be given by:

$$z_p = \frac{3}{384}\frac{w' l_s^4}{EI}, \tag{6}$$

where w' is the submerged weight of the pipeline, l_s is the length of the scour hole and EI is the flexural rigidity of the pipeline.

In turn the length of the scour hole will vary in time according to:

$$\frac{dl_s}{dt} = v_h, \tag{7}$$

where v_h is the rate of scour along the pipeline and t is time. The rate v_h has been investigated in detail by Cheng et al. (2009, 2014) and has been shown to vary with velocity, sediment properties and pipeline embedment.

Combining (6) and (7) allows one to calculate the vertical deflection (or sag) of a pipeline into the scour hole as a function of time. These equations were used in Draper et al. (2015) to determine the rate at which three different pipelines lowered into a scour hole during a velocity time-series with a constant acceleration of 2×10^{-3} m^2/s. This acceleration was found to be an upper bound estimate of the rate at which current velocities increase in storms (and, although not noted in Draper et al. (2015), it is also similar to the upper end of what would be expected in a soliton current).

The calculated deflections were used as an input into experiments in the Large O-Tube facility in which a short section of 200 mm diameter pipeline was modelled to represent the central section of a spanning pipeline. A scour hole was allowed to develop under the short section of pipe, and the pipe was moved vertically downwards to mimic sagging of the pipeline (see Figure 10). Three different experiments were conducted, with input deflections computed assuming $EI/w' = 10$, 10^4 and 10^6 m^3, and a horizontal scour rate calculated using the formulas outlined in Cheng et al. (2014).

It should be noted that this experimental setup is similar to that used by Fredsøe et al. (1988) to explore sagging under constant currents, for a pipeline that was lowered at a fixed rate (rather than that due to the relationship implied by equation (6) and (7), which varies in time).

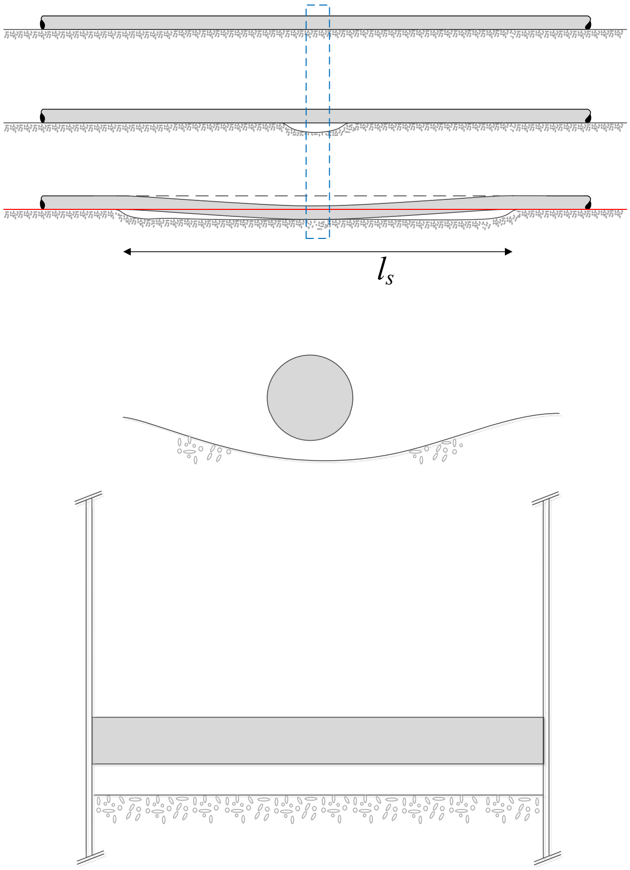


Figure 10: Section of pipeline modelled in the O-Tube indicated by the square rectangle in the top figure. Bottom figures indicate test setup within the O-tube.

Figure 11 presents the vertical deflection of the pipeline for each of the three experiments, together with the velocity time-series and the measured scour depth beneath the pipeline. Also shown is a predicted scour depth, which is described in more detail in the following subsection. The point in time when the vertical deflection matches the scour hole depth in Figure 11 indicates when the pipeline has 'touched down' into the scour hole. At this point no further vertical movement of the pipeline was simulated and the experiment was terminated soon afterwards.

Comparing across the experiments in Figure 11 it is clear that the final touch down depth differs significantly. For example, the most flexible pipeline drops fastest into the scour hole, but only reaches a depth of $0.58D$. In contrast the stiff pipeline drops later and over a longer period of time, leading to a final depth of $1.28D$. The reason for this difference in final lowered depth is due to the fact that the vertical position of the pipeline has an effect on scour locally beneath the pipeline. This interaction is clear in Figure 12 which presents the scour profile around the pipeline as it moves vertically into the scour hole; as the pipeline drops (but has not yet touched the bottom of the hole) the scour hole increases in depth and the side slopes become steeper and more symmetric. This increase in scour hole depth does, however, take a finite time to occur. Consequently the stiffer pipeline, which drops more slowly into the hole (allowing sufficient time for additional scour), can lower to a greater depth.

A second observation on Figure 11 is that it can be seen that before the pipelines begin to deflect the scour depth grows almost linearly with time. This is different to that observed in Section 4 (see Equation (2) and (3) and Figure 7) for a pipeline subjected to a current with constant velocity. This trend is a result of the linearly increasing velocity and provides a clear example of how non-stationary (or time-varying flow conditions) can alter the scour development in time. A similar conclusion has also been observed by Zhang et al. (2016) for a larger variety of flow conditions. Accounting for these differences in scour development due to time-varying flow conditions is essential for accurate predictions of scour in the field.

5.2 *Predicting scour for a sagging pipeline*

The different touchdown depths in Figure 11 imply that the amount of lowering (and ultimately the pipeline stability) are dependent on the weight and flexural properties of the pipeline. From a design perspective it is, therefore, valuable to be able to predict the scour depth in time as the current velocity varies and the pipeline sags. Draper et al. (2015) showed that a reasonable prediction could be developed by noting, from equation (2), that

$$\frac{dS}{dt} = \frac{S_e(z_p, u(t)) - S}{T(z_p, u(t))}, \tag{8}$$

where it has been acknowledged that, in general, the equilibrium scour depth and time-scale are dependent on the velocity (denoted here as u) and the position of the pipeline.

Based on supplementary experiments in steady current conditions Draper et al. (2015) found that, in reasonable agreement with Hansen et al. (1986), the equilibrium scour depth in live bed conditions was given by

$$\frac{S_e}{D} = 0.86 \times \exp\left(\frac{0.6 z_p}{D}\right), \tag{9}$$

over the range in pipeline deflections modelled. In contrast the time-scale was almost independent of the pipe position, but depended on velocity such that

$$T(\theta) = 0.65 \times \frac{D^2 \theta^{-5/3}}{50\left(g(s-1){d_{50}}^3\right)^{1/2}}, \tag{10}$$

where θ is the dimensionless shear stress due to the current, s is the relative density of the sediment, g is acceleration due to gravity and d_{50} is the median grain size of the sediment.

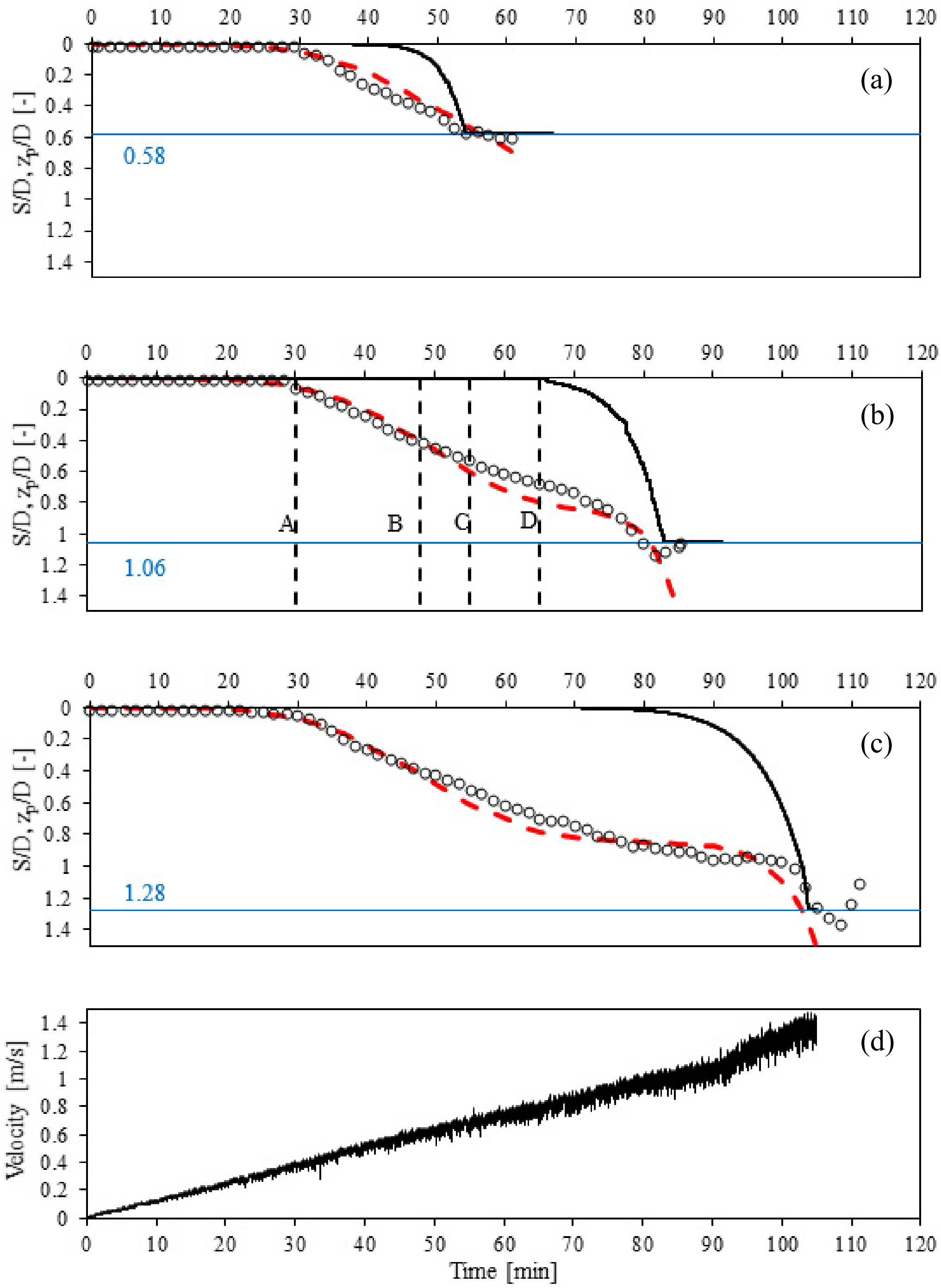


Figure 11: Scour depth and pipeline lowering in time for three different pipelines; from top to bottom, first three figures represent 200 mm diameter pipelines with EI/w' =10, 10^4 and 10^6 m^3, respectively. Bottom figure is the velocity time history. Figure adapted from Draper et al. (2015).

Adopting (9) and (10), the scour depth under the pipeline was then recovered following the time stepping approach introduced by Whitehouse (1998). More specifically, the scour was computed according to

$$S(t) = \int_0^t \left(\frac{S_e\left(\frac{z_p}{D}\right) - S}{T} \right) dt. \qquad (11)$$

Predictions based on (11) are shown in Figure 11 as red dashed lines. It is apparent that the model gives reasonable predictions of the scour depth observed in the experiments both prior to any pipeline vertical displacement and during vertical displacement of the pipeline. More importantly, the final lowered depth agrees to within 10-20% of the touchdown depth.

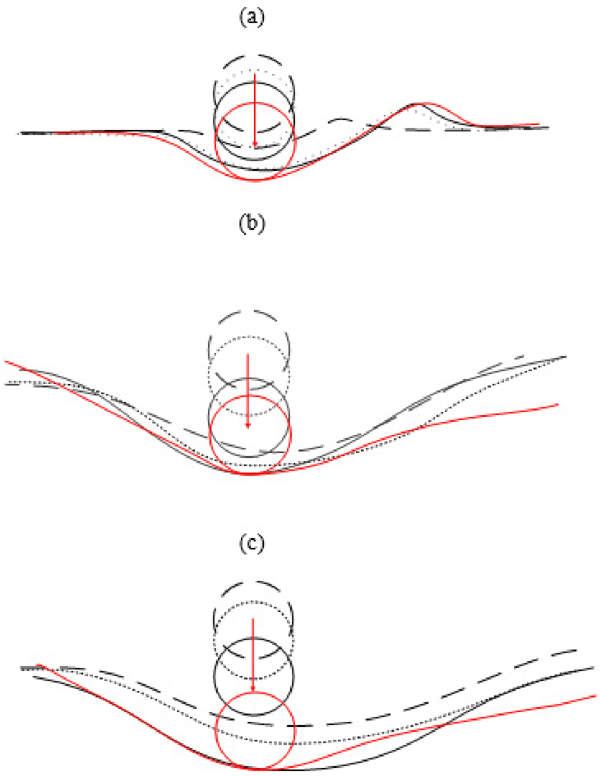


Figure 12: Sections indicating the scour development as the pipeline sags into a scour hole. (a), (b) and (c) correspond to the same subfigures in Figure 11. Figure adapted from Draper et al. (2015).

6 STUDY 3: LEARNINGS FROM FIELD DATA

As mentioned in the Introduction there is only a limited amount of published comparisons between observations of scour, pipeline lowering and sedimentation in the field and predictions based on laboratory experiments. Of the literature that is available, Bruschi et al. (1997) reviewed the theory relating to scour, sediment transport and stability design, and noted based on field observations that "natural lowering occurs for pipelines characterised by a high submerged weight which lay on an erodible seabed affected by strong environmental conditions".

More recently Pinna et al. (2003) reported observations of scour induced pipeline self-burial and spanning over a period of 9 years for the Goodwyn Interfield Pipeline, located on the North West Shelf. This analysis provided some insight into span geometry and evolution over time, but did not give specific profiles of scour along the pipeline. Following on from Pinna et al. (2003), Borges-Rodriguez et al. (2013) examined changes in pipeline embedment due to scour for a range of pipelines on the North West Shelf. They focused on the consequences of scour for both pipeline stability and thermal expansion management. For the pipelines they analysed it was noted that scour, spanning and lowering were evident until the pipeline had lowered to 70 to 90 % of the pipeline diameter.

In the following two subsections we describe results from two comparative studies of laboratory data and field data that have previously been undertaken. The former (Leckie et al., 2015) focuses on scour and lowering, whilst the latter (Leckie et al., 2016*b*) focuses on sedimentation. An emphasis is placed on comparing expectations of scour and sedimentation from the laboratory experiments with field observations.

6.1 *Field observations: Scour and lowering*

The first comparative study focused on seven years of annual field survey measurements of a subsea pipeline on the North West Shelf of Australia. As reported by Leckie et al. (2015) the pipeline has a diameter of 12 inches and measures 22.9 km in length. It is orientated approximately perpendicular to the predominant tidal and soliton currents. Figure 13 presents raw video and sonar data for this pipeline. Together with metocean data, soil samples and span reports the data in Figure 13 was analysed at all locations along the pipeline. For convenience, an image analysis routine was written to convert the sonar image in the bottom left of Figure 13 into (x,y,z) data (see Leckie et al., 2016*b* for more details on the analysis routine).

Analysis of the field data revealed significant scour and lowering within 2 years following lay of the pipeline. The majority of the scour (based on a comparison of near-bed velocity measurements to the erosion properties of the seabed sediment) appeared to have resulted from sustained ambient currents as opposed to larger storms. The lowering of the pipeline was found to result in an increase in (far-field) pipeline embedment of up to 0.7 times the pipe diameter (where far-field is referenced at a distance ±8 diameters from the pipeline). At many locations along the pipeline this increase in far-field embedment was uniform and follows after the formation of many, closely spaced scour holes. This suggests the pipeline lowered mainly through sinking into the seabed at span shoulders at these locations (see Figure 1a; sinking). At other locations there is evidence of pipeline sagging and a beam bending analysis indicated that this sagging can be up to 0.5 pipeline diameters at the time of surveying.

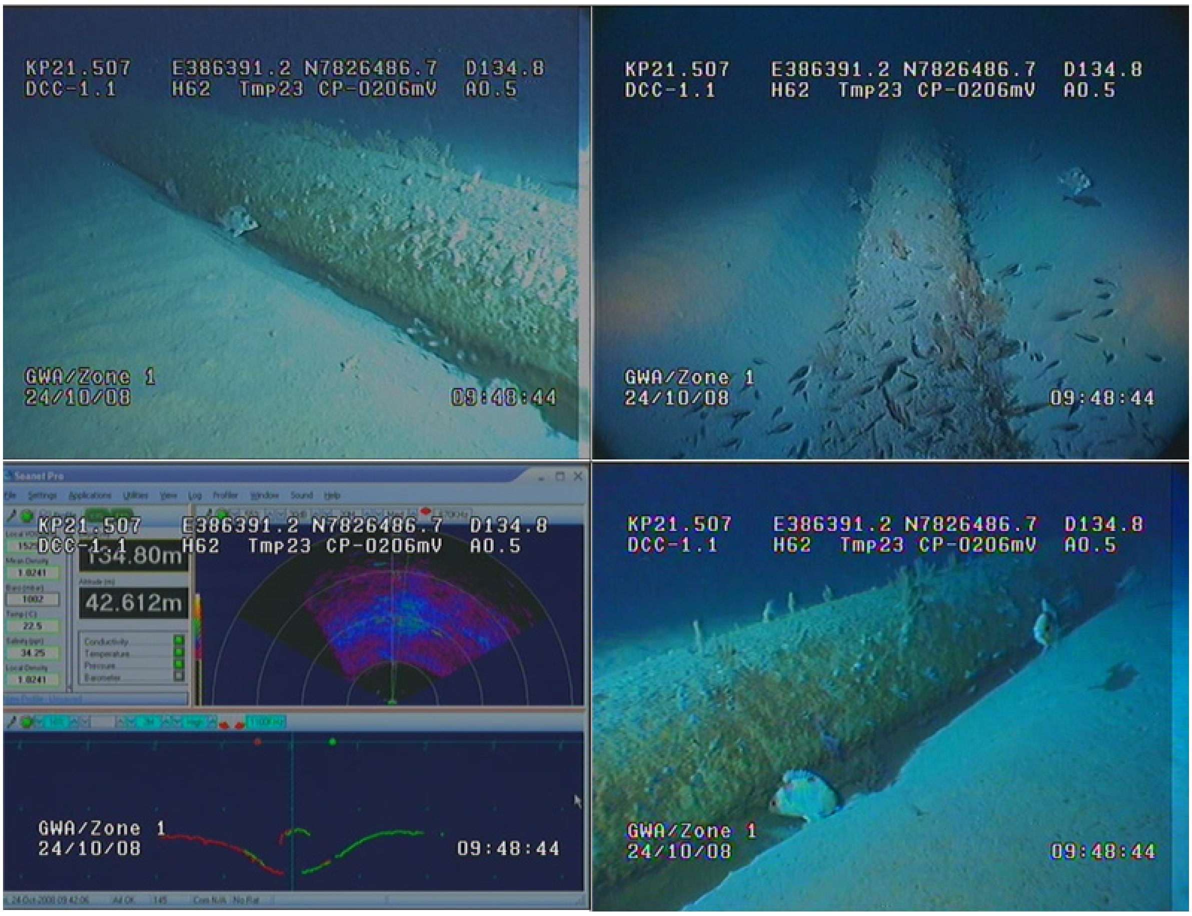


Figure 13: Still image of the raw video and sonar data analysed (Leckie et al. 2015)

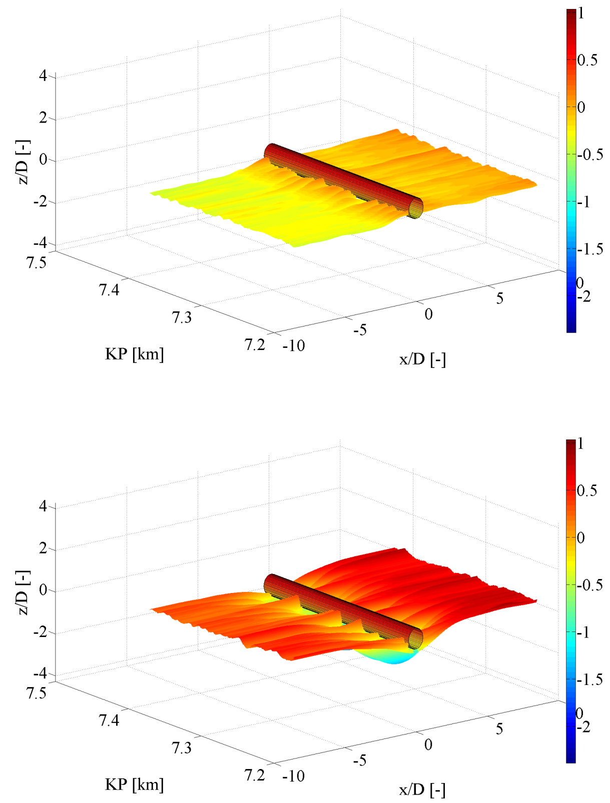


Figure 14: Example seabed profiles for a 200 m long section of pipeline. (Top) profile in 2002, (Bottom) profile in 2006. (Adapted from Leckie et al. 2015).

Figure 14 indicates the local seabed profile around the pipeline for an example 200 m long section of pipe in 2002 (just after lay) and later in 2006. For this example section, lowering of the pipeline through sinking is very apparent; providing arguably the first clear evidence of this mechanism of lowering in practice.

To explore the profile along the pipeline further, Figure 15 presents a section through the same length of pipeline as that shown in Figure 14. This figure helps to illustrate the scour holes and their evolution along the pipeline over time. Importantly, the dimensions of these holes (i.e. their maximum length and depth) were shown by Leckie et al. (2015) to be in good agreement with predictions based on existing literature, especially in 2002. The rate of growth along the pipeline of the scour holes was found to be slower than that predicted by the formula derived by Cheng et al. (2009) based on laboratory experiments on clean sands. This was attributed to the increased erosion resistance of the sandy SILT and silty SAND along the pipeline route and is consistent with trends outlined in Section 4 for vertical scour beneath a pipeline.

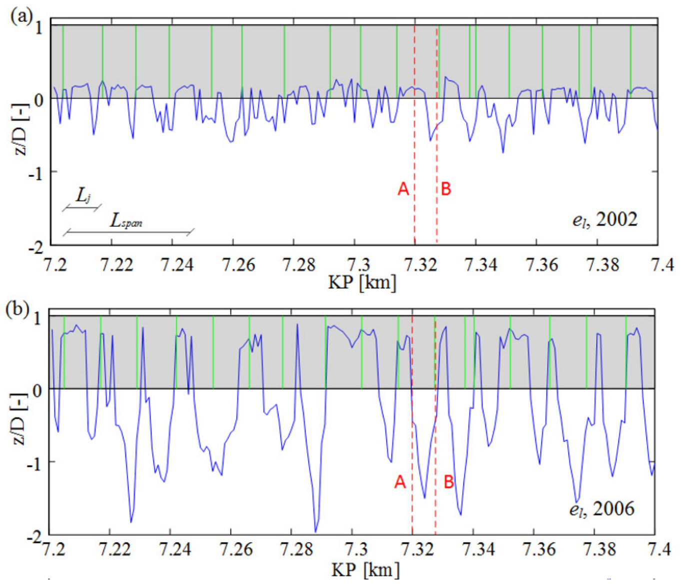


Figure 15: Variation in embedment the pipeline section shown in Figure 14. (a) profile in 2002, (b) profile in 2006. (Adapted from Leckie et al. 2015).

Aside from providing direct measurements to compare with existing predictions of scour, the pipeline observations also present new insight. In particular, it was observed that in contrast to the traditional conception of pipeline scour which conceives of pipeline burial as an endpoint, the observed lowering approaches a mature state that consists of a pseudo-static profile along the pipeline of alternating spanning and embedded sections, which occur at regular intervals. This pseudo-static profile is believed to have resulted in the field for this pipeline because the scour processes appear to have been almost entirely in the clear water regime; hence sediment has not been supplied to the pipeline to backfill the scour holes following lowering of the pipeline.

In summary the results from this first study therefore provide some reassurance that the expectations of scour and lowering (as depicted for sinking pipelines in Figure 1a) do occur in the field. Furthermore the occurrence of scour and the scour hole dimensions also agree reasonably well with expectations at the start of the scour process (i.e. in 2002 especially). Later in the project life the observed scour did not agree with the classical expectation of self-burial, but this difference is enlightening and appears to be explainable in terms of arguments concerning sediment supply.

6.2 *Field observations: Sedimentation*

The second comparative study focuses on three 26 km long sections of subsea pipeline reported in Leckie et al. (2016*b*). The pipelines all run parallel to each other in close proximity, and traverse a range of metocean conditions, water depths and soil conditions (varying from sand through to fine silt). Two of the pipes have diameters of 0.64 m and one has a diameter 0.1 m.

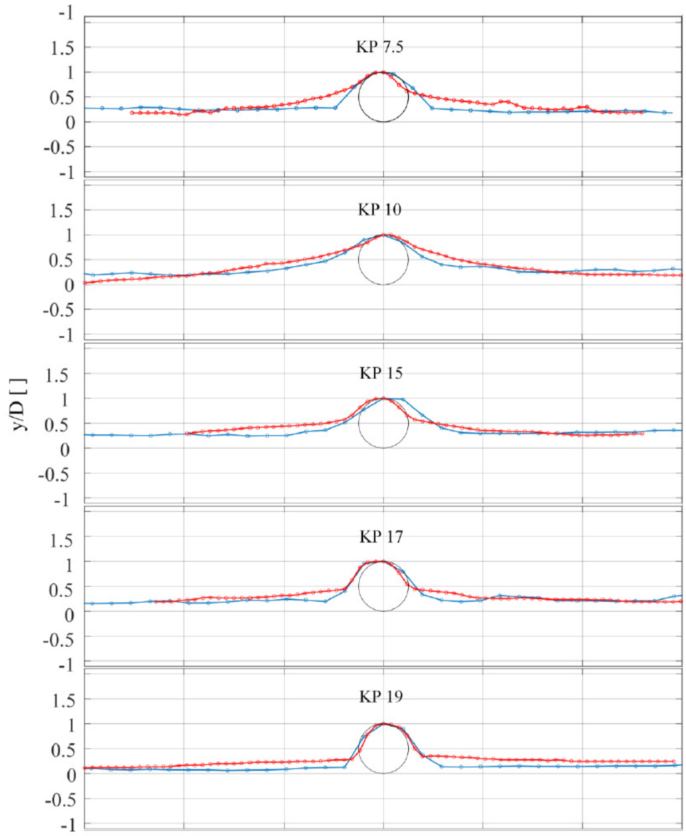


Figure 16: Embedment local to the pipeline observed in survey footage. Blue line corresponds to 2009 within 7-9 months of lay) and red line is 2013 data. Figure adapted from Leckie et al. (2016*b*).

The most significant observation from this second study was that the two larger pipelines did not appear to have experienced significant scour or scour induced lowering. Instead it was apparent that the seabed had built up local to the pipeline, leading to an increase in local embedment without lowering of the pipeline. To illustrate these changes in embedment Figure 16 presents cross-sections of the local embedment at various locations. The increase in embedment was found to mainly occur through the middle section of the pipelines (i.e. KP 4.5 to KP 20). This section of pipeline was not in the shallowest water conditions, but did coincide with locations where perpendicular near-bed soliton currents were largest (see Leckie et al. 2016*b*).

To better understand the observed changes in embedment, a series of model scale experiments were undertaken in the Small and Large O-Tube flumes. In each of the experiments the initial pipeline embedment, soil conditions and the near-bed time varying flow conditions were selected to try and mimic the observations in the field. The key dimensionless parameters that were explored in the experiments included the relative shear stress (given by the ratio of maximum to critical Shields parameter) and the relative duration of the flow conditions (chosen to replicate short duration soliton current events, which attacked the pipe from both perpendicular directions). This duration was captured through a *KC* number given by

$$KC = \frac{2U_{max}T_D}{D}, \qquad (12)$$

where U_{max} represented the peak soliton current, D is the pipeline diameter and T_D is the duration of the near-bed current event.

Figure 17 presents example results from one of these experiments. It can be seen that for the initial embedment modelled in the experiment, onset of scour was not observed. Instead sediment began to pile up either side of the pipeline in a similar way to the sedimentation mechanism described in Figure 1b.

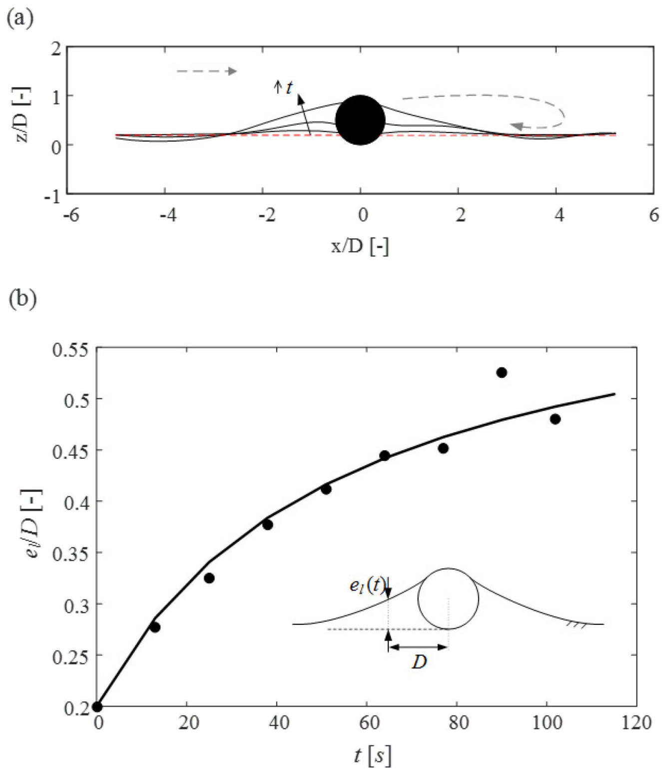


Figure 17: Example experiment conducted in the O-tube with sedimentation. (a) Profiles at various times; (b) time evolution at one location close to pipe. Figure adapted from Leckie et al. (2016*b*).

It can also be seen that the sedimentation leads to an equilibrium profile over a time-scale.

Further testing at different shear stress and KC number revealed that the equilibrium scour profile is not very sensitive to these underlying parameters. In contrast the time-scale of the sedimentation process is sensitive to these parameters, as shown Figure 18. Importantly, it can be observed in Figure 18 that the time-scale of the sedimentation process is much slower than that associated with tunnel scour (indicated as the grey line in Figure 18). At a KC = 500, for example, the time-scale is almost one order of magnitude larger than that associated with tunnel scour at the same shear stress.

As reported in more detail by Leckie et al. (2016*b*), comparisons of the sedimentation equilibrium profiles were in very good agreement with the field observations (see Figure 19). This is a very important result because it implies that the processes that occurred in the field were similar to those observed in laboratory. Furthermore, Leckie et al. (2016*b*) found that the time-scale of the sedimentation process was also consistent with the observations. This results suggests that the time-scales indicated in Figure 18 may be useful in predicting sedimentation rates for other pipelines which are not expected to experience scour and lowering initially (i.e. for pipelines without gaps following lay, or for pipelines with sufficiently larger as-laid embedment to suppress piping).

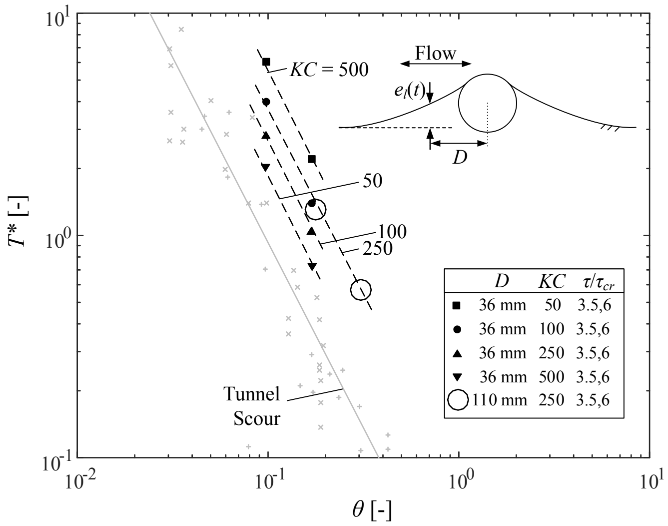
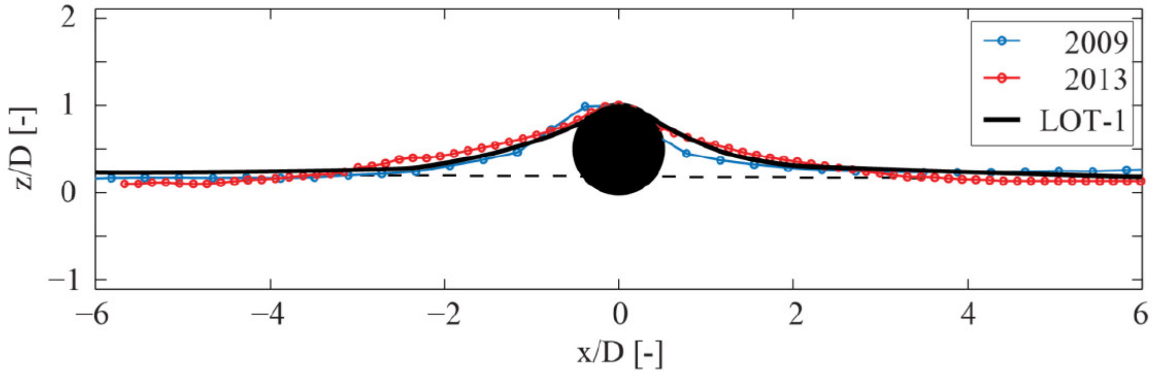


Figure 18: Time scale of the sedimentation process. Figure adapted from Leckie et al. (2016).

7 DISCUSSION

Each of the example studies presented in this paper have led to outcomes that enable improved predictions of different aspects of scour and sedimentation. In Section 4, for example, new predictive formulas were developed to predict the vertical rate of scour in marine sediments, whilst in Section 5 a time stepping model to simulate scour development beneath a sagging pipeline in time-varying flow conditions was verified. Lastly, in Section 6 the concept of pipeline sinking due to scour was verified, together with the new empirical results concerning the equilibrium profile resulting from sedimentation and the rate of sedimentation.



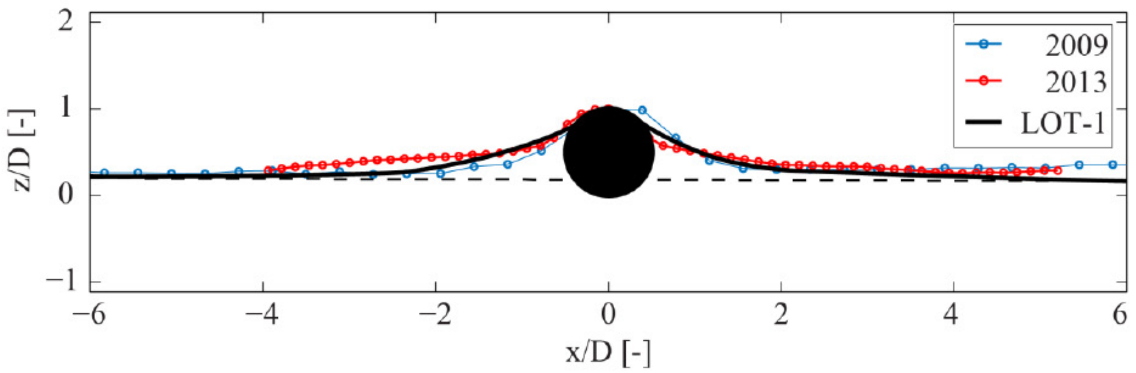


Figure 19: Overlay of local embedment profiles observed in the field with experimental results. At location (Top) *KP*=10 and (Bottom) *KP*=15. 'LOT-1' refer to the experimental profiles. Figure adapted from Leckie et al. (2015).

Individually, each of these results can be used to assess different mechanisms illustrated in Figure 1. However, to realize the full potential of these empirical results requires that they are eventually embedded in an overarching general model that can simulate all of the mechanisms in Figure 1 and can, therefore, predict changes to pipeline embedment due to sediment mobility. This type of model should ideally include four distinct steps:

1. Assessment of whether or not scour will occur along a pipeline (due to streaming at gaps identified in a bottom lay analysis or due to piping) and the locations of scour initiation points.
2. Simulation of the rate of scour development vertically beneath the pipeline and along the pipeline (in the case of scour) or sedimentation.
3. Simulation of the lowering of the pipeline into scour holes via sagging, sinking or a combination of both (accounting for the effects of pipeline lowering on scour development).
4. Simulation of backfill of sediment into scour holes following lowering of the pipeline

Research being undertaken within the STABLEpipe JIP is working towards developing guidelines to enable the effects of sediment mobility to be accounted for in pipeline design. In this sense it is aiming to facilitate the development of overarching models that are capable of undertaking the four steps listed above. The results presented in Sections 4, 5 and 6 of this paper feed into aspects of steps 1, 2 and 3, and are, therefore, part of the building blocks of a more overarching model. However, further work is required to extend the results in this paper to realize an overarching model to perform each of the four steps listed above.

As a final remark it is useful to acknowledge that the development of an overarching model capable of undertaking the four steps listed above is not expected to be able to provide deterministic predictions of scour, sedimentation and embedment. This is because (i) the underlying predictive formulas/models in each step will contain some inevitable uncertainty (even if, as is the aim of this paper, the main empirical results have been validated through comparison with field observations and/or are derived from experiments aimed to best match field conditions to minimise uncertainty), and (ii) the input parameters (such as soil properties, metocean conditions, etc.) which feed into the predictions at each step will also have uncertainty. The expectation is, therefore, that an overarching model will be able to treat uncertainty consistently and in an unbiased way using a probabilistic approach. The treatment of uncertainty in this way using probabilistic models is becoming increasingly common in scour and erosion design. For example, Tom et al. (2016) have recently presented a probabilistic approach to quantify uncertainty in the assessment of scour around subsea structures.

8 CONCLUSIONS

In this paper a series of recent studies have been summarized, which have the common theme of trying to close the gap between laboratory conditions and the field, so as to remove uncertainty in sediment mobility induced changes to pipeline embedment. In each case new predictive models/formulas have been derived which enable realistic characteristics, such as sediment erosion properties and changing flow conditions, to be accounted for directly in design. In this way the studies extend on earlier research which has tended to focus on idealised testing conditions (i.e. uniform sediments and stationary flow conditions).

Nevertheless, whilst these studies each provide new outcomes, further work is required to improve predictions of scour and sedimentation in design so as to provide a more complete set of predictive results for the range of mechanisms expected in field conditions and listed in Figure 1. Collectively the aim of this additional work should be to provide unbiased (or best estimate) predictions of scour, lowering and sedimentation. In this way the work may be used to feed into an overarching model of pipeline scour and sedimentation that may be used in different aspects of pipeline design, including on-bottom stability design, thermal management, fatigue analysis and flow assurance.

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