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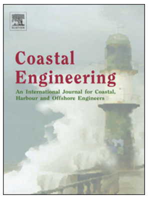

Sedimentation-induced burial of subsea pipelines: Observations from field data and laboratory experiments

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ABSTRACT

Sediment transport-induced changes to the embedment of three 26 km long sections of subsea pipeline are analysed and subsequently explained using model scale experiments. Rather than the scour and scour-induced sinking and sagging traditionally thought to dominate post-lay pipeline spanning and embedment change, the change for these pipelines is shown to be caused by sedimentation. The pipelines traverse a range of metocean and soil conditions; the variation in embedment correlates well with the variation in metocean conditions, with most change occurring in an area where multidirectional high-velocity short-duration flows associated with internal waves propagate at near-perpendicular angles to the pipeline. To understand the mechanism driving these changes, a series of model scale tests in O-tube flumes have been completed under flow conditions mimicking those recorded in the field. Good agreement is found between the field and laboratory results, both in terms of the process timescale and the post-sedimentation profile. The consistency of the embedment changes between the pipelines, their correlation with metocean conditions, and the ability to replicate these changes in model scale tests suggests that such changes can be accounted for in more effective pipeline design. Spans are relatively rare along the pipelines but where they do occur fish rather than scour are shown to be the principal agent of span formation.

1. Introduction and motivation

1.1. Motivation for this work

The inability of traditional pipeline design — particularly on-bottom stability design — to incorporate the influence of seabed mobility has been well-documented (see for instance Palmer, 1996). Hydrodynamic loading from waves and currents apply forces to both the pipeline and the sediment around it. Present design guidelines (such as RP-F109, DNV, 2010) do not provide guidance on how the effects of sediment mobility can be taken into account in the stability analysis. This is an important omission because sediment mobility can result in both scour and sedimentation, which can lead to significant changes in pipeline embedment, both local to the pipeline and in the far-field. Changes in embedment may, in turn, improve on bottom stability of the pipeline due to a reduction in pipeline hydrodynamic drag and an increase in the lateral soil resistance available to the pipeline (Tom et al., 2015). Additionally, the change in lateral soil resistance (and to a lesser extent the axial resistance) will also influence the thermal expansion design (Bransby et al., 2014), and the increase in pipeline insulation provided by the soil will change the temperature profile along the pipeline, with implications for various aspects of flow assurance including top of line corrosion (White et al., 2015). Consequently, sediment mobility can introduce benefits and risks for pipeline response and integrity; this motivates the need for improved predictions of pipeline embedment resulting from scour and/or sedimentation.

The mechanics of scour are well summarised in Sumer and Fredsøe (2002). The general understanding is that in waves and/or currents the presence of the pipeline on the seabed leads to a pressure difference across the pipeline, which (along with other sources) can initiate scour through piping (Sumer et al., 2001). Once a flow path is established beneath the pipeline, the amplification of the bed shear stress under the pipeline then leads to the removal of sediment through a process referred to as tunnel scour (Sumer and Fredsøe, 2002). With time this scour spreads along the pipeline allowing the pipeline to lower into the resulting scour hole and sink into the shoulders of the span (Fredsøe et al., 1992; Sumer and Fredsøe, 1994). Upon lowering, the pipeline is sheltered from the flow, and sediment may be deposited around the pipeline.

Each of these scour processes have been explored extensively in the laboratory and in numerical work over the last 3–4 decades. To complement this work, detailed studies comparing laboratory results to conditions encountered in the field are also now beginning to emerge (see,

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for example, Pinna et al., 2003 and Leckie et al., 2015). Generally good agreement is found, although it is important to note that almost all of the existing laboratory testing and field comparisons focus on the influence of flows occurring predominantly perpendicular to the pipeline.

Compared to scour and pipeline lowering, much less work has been completed on direct sedimentation around pipelines (i.e. the accumulation of sediment adjacent to the pipeline), and no detailed reports of sedimentation in the field have been published. Of the studies available, 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. Zhao et al. (2015) have presented results from CFD analysis which point to the presence of a shear stress 'shadow' (i.e. zones of low shear stress) in the vicinity of the pipeline. In these areas, the shear stress amplification can fall below 1, allowing for deposition of sediment carried in from the far-field or for local reworking of the scour profile.

In terms of timescale, Sumer et al. (2001) 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 and current induced scour. More recently, Fuhrman et al. (2014) presented numerical simulations of both scour and backfilling, in which backfill rates were found to agree reasonably well with the experiment results of Fredsøe et al. (1992).

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. It is also relatively unknown how the direction of near bed currents, relative to the pipeline, may affect the sedimentation process. Motivated by the need for improved predictions of changes to pipeline embedment caused by sediment mobility, the aim of this study is to review in detail the spanning and embedment history of three pipelines located on the North West Shelf, offshore Australia. These pipelines are of particular interest as they offer an opportunity to observe changes in pipeline embedment due to sedimentation as opposed to scour (as will become clear later) and they provide insight into local sediment mobility due to near bed velocities that are not directed perpendicular to the pipeline. Furthermore, given their location these pipelines also allow for a study into the influence of; (i) varying metocean conditions through a range of water depths, (ii) pipeline diameter and structural characteristics, and (iii) soil grain size, on sediment mobility induced changes to pipeline embedment. Lastly, because the pipelines are laid parallel to each other, the natural consistency of the scour and sedimentation processes can be investigated.

1.2. The dataset

The study has been performed using pipeline survey data from three surveys, performed in 2009 (7–9 months after lay), 2012 and 2013. The analysed data consists of video and multibeam bathymetry captured from a remotely operated underwater vehicle (ROV). The ROV video and the derived pipeline-span reports cover three pipelines; Pipeline A (PA) and Pipeline B (PB) which are two flowlines with an external diameter of 0.64 m, and Pipeline C (PC) which is a mono-ethylene glycol (MEG) supply pipeline with an external diameter of 0.1 m.

The video typically consisted of port, starboard and centre camera footage, and is principally of interest in ascertaining span locations and lengths, visual confirmation of local embedment, and information on small scale bed features such as ripples. The base bathymetric dataset consisted of Easting, Northing and depth to seabed information at ~0.1–0.2 m centres, in a swathe which varied in width from ~7–16 m depending on the location and year of the survey. From the base dataset a series of two to three (depending on the year) checked longsections were available either side of the pipeline. These were offset from the pipeline centre by distances ranging from 1 diameter (D) to 12.5D. To enable comparison between years, the longsections were interpolated across short distances on to a uniform grid of points located 1D, 3D and (for the first survey) 12.5D either side of the pipe, at spacings of 1 m along the pipeline.

Due to the small diameter of PC, it was found that the multibeam bathymetry did not produce a sufficiently accurate profile of the embedment variation along this pipeline. Specifically, the accuracy of the data appears to be in the order of 0.5 to 1D for much of the length. As-laid embedment was also not available for PC. As a result, the spanning behaviour (which is visually confirmed) along PC is included in the paper, but no as-laid embedment data, or changes to the post-lay embedment are included. Thus when discussing pipeline embedment, 'the pipelines' refers to PA and PB only, elsewhere it refers to all three lines.

2. Pipeline setting

2.1. Location and bathymetry

The pipeline location is shown in Fig. 1 and the depth profile in Fig. 2. The start of the pipelines, defined as Kilometre Point (KP) 0, is in 830 m of water. The pipelines then run up the continental slope (typical slope 1V:10H) until they reach KP 5 where they arrive at the outer continental shelf. Beyond this point they progress gradually up the shelf (1V:200H) until KP 20, where they enter a series of sandwaves which have crests that run perpendicular to the pipeline. After the sandwave field, there is a brief area of flat seabed area until KP 26 where the pipelines cross the first of several reefs with cemented calcareous rock outcrops. The analysis presented herein stops at KP 26, with the scope of the study excluding the influence of rock layers on scour, pipeline lowering and sedimentation.

In terms of bathymetry, over the section of interest the pipelines can be divided into 3 main zones:

1. Zone A; the continental slope; KP 0 to KP 4.5.
2. Zone B; the continental shelf, flat section; KP 4.5 to KP 20.
3. Zone C; the continental shelf, sandwave field; KP 20 to KP 26.

The pipelines typically run perpendicular to the bathymetric slope along almost all of their length. Through Zone B the pipelines are at a slight (<20°) angle to a line perpendicular to the contour, but the gentle slopes across this area mean that the angle is not noticeable in terms of having a different seabed elevation either side of the pipelines. Slight cross-slope pipeline orientations also occur along certain subsections of the continental slope (Zone A), and through the sandwave field (Zone C). In these areas the effect of the cross-slope on apparent embedment is more noticeable and has been corrected for by rotating (in cross-section) the bathymetric data, based on the difference between the port and starboard far-field embedment in the 2009 survey. Definitions of span length and pipeline embedment used herein are shown in Fig. 3.

2.2. Pipeline properties

The mechanical properties for the pipelines are set out in Table 1. A variety of subsea infrastructure is present along the pipeline route. Along the flowlines (PA and PB), displacement initiators (sleepers) are present from KP 0 to KP 18.75 at variable spacings of ~1 to 2.5 km. The pipeline immediately either side of these structures shows signs of lateral and vertical displacement, particularly over the low KP range. Some additional signs of thermal expansion-induced movement have been observed at locations remote from the sleepers over the range of KP 0 to KP 5. Elsewhere, rock-dump areas, crossings, tie-ins, mattresses and areas where the pipeline appears to have formed a trench during lay (perhaps due to a period of delay during laying) are present. The sections of pipeline 75 m either side of all of these features have been removed from the dataset to avoid the influence they have on embedment and spanning. The interaction of sediment transport and lateral displacement within buckling sections is an important phenomenon in its own right, but beyond the scope of the current study.