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Predicting the rate of scour beneath subsea pipelines in marine sediments under steady flow conditions

H. Mohr [a,*], S. Draper [a,b], L. Cheng [b], D.J. White [c]

[a] Centre for Offshore Foundation Systems, The University of Western Australia, Crawley WA6009, Australia
[b] School of Civil, Environmental and Mining Engineering, The University of Western Australia, Crawley WA6009, Australia
[c] Shell EMI Chair of Offshore Engineering, The University of Western Australia, Crawley WA6009, Australia

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ABSTRACT

Model scale experiments of scour beneath a submarine pipeline, coupled with erosion testing, have been undertaken using two marine sediments and five artificial sediments having a wide range of grain size. The experiments reveal that for both the marine and artificial sediments the time scale of scour beneath the pipeline depends on the erosion properties of the sediment. For coarser sediments, mobilised mainly in transport along the bed, the rate of scour is found to agree well with the existing empirical formula of Fredsøe et al. (1992). In contrast, for finer sediments that are mobilised mainly through entrainment into suspension and can have relatively high erosion resistance, the rate of scour is different to that predicted using the same empirical formula. To explain this result, theoretical arguments are used to relate the rate of scour beneath a pipeline to the fundamental erosion properties of the sediment; namely the transport rate along the bed and the true erosion rate of the sediment. These arguments lead to two new empirical formulas that may be used to predict the time scale of the scour process beneath subsea pipelines. The first formula is appropriate when the sediment scours predominantly via transport of sediment along the bed, and is consistent with the empirical formula due to Fredsøe et al. (1992). The second formula is appropriate when sediment erodes mainly via entrainment into suspension, as is often the case for fine or 'cohesive' sediments. Collectively, the two formulas may be used in practice to make predictions of the rate of scour for pipelines in marine sediments and artificial sediments, provided erosion testing results are available.

1. Introduction

When a submarine pipeline is placed on a mobile seabed, local erosion of sediment (*i.e.* scour) can occur beneath the pipeline owing to the enhanced sediment transport near the pipeline. In practice, the scour process is important to the stability of the pipeline because scour can lead to self-burial. Self-burial affects the lateral stability of pipelines in storms (*e.g.* Palmer, 1996; Draper et al., 2015) and leads to variations in lateral soil resistance that can also influence the lateral buckling behaviour of pipelines (*e.g.* Borges-Rodriguez et al., 2013).

For pipelines placed on a uniform sand bed, the mechanisms of scour beneath a pipeline that lead to self-burial have been summarised in detail by Sumer and Fredsøe (2002). Empirical formulas have been developed to predict, for example, the maximum depth of scour (*e.g.* Kjeldsen et al., 1973; Sumer and Fredsøe, 2002) and the rate at which scour occurs beneath a pipeline (Fredsøe et al., 1992). These results feed directly into more complex models for scour development in three dimensions along a pipeline (Cheng et al., 2009, 2014a) and the extent and rate of pipeline lowering and self-burial (Fredsøe et al., 1988; Sumer et al., 2001). Collectively, the empirical formulas can, therefore, be used to provide predictions of scour-induced changes to pipeline embedment, which may be used in pipeline stability design and thermal management provided the seabed is representative of the sediments used to establish the empirical formulas.

In practice, however, pipeline routes cross a range of seabeds comprised of marine sediments. Real marine sediments can have different erosion properties to the uniform sands that are often used in laboratory experiments. These properties include the threshold shear stress (*i.e.* the seabed shear stress required for erosion; Mohr et al., 2013; Mohr, 2015), the volumetric transport rate (*e.g.* Roberts et al., 1998; Whitehouse et al., 2000) and the mode of sediment movement (*i.e.* transported along the bed or entrained into suspension; Roberts et al., 2003). Extrapolation of the empirical scour formulas that have been developed primarily based on experiments in uniform sand is, therefore, unlikely to be valid for all marine sediments.

This expectation is consistent with 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 with a

* Corresponding author.
E-mail address: henning.mohr@uwa.edu.au (H. Mohr).

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range of kaolin and silt percentages by mass. 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. More recently, Leckie et al. (2015) have reviewed survey data of scour and pipeline lowering of an actual pipeline on the North West Shelf (NWS) of Australia over a period of several years. In that work, soil classification and erosion testing of samples recovered from the location of the pipeline indicated that the seabed was predominantly silty sand with a threshold shear stress higher than that predicted by the empirical Shields curve. When analysing the increase in length of scour holes between the initial surveys, they found that the horizontal scour rate along the pipeline was slower than predicted using continuous metocean current velocity measurements and the empirical formulas developed by Cheng et al. (2009), which are based on scour experiments in uniform sand. Subject to the accuracy of the metocean and survey data used by Leckie et al. (2015), this result is again consistent with the expectation that empirical formulas based on experiments in uniform sands are not appropriate for all marine sediments.

Motivated by these earlier findings, the primary aim of this paper is to investigate scour beneath subsea pipelines in marine sediments (which may or may not have similar erosion properties to uniform sand), with a particular emphasis placed on predicting the rate at which scour develops underneath a pipeline in steady currents. This is an important first step towards understanding the more complete scour and self-burial process for marine sediments. To work towards this primary aim, model scale experiments of scour beneath a fixed pipeline in steady currents have been performed using two reconstituted marine sediments sourced from the NWS of Australia and five artificial sediments, which have been sieved to provide relatively uniform grain size distribution. Collectively, the artificial sediments cover a range of grain sizes. The two marine sediments are very different in particle size composition and particle shape to the uniform sands that have commonly been used in previous pipeline scour studies.

To supplement the model pipeline experiments, a separate set of erosion tests have also been undertaken and analysed to assess the erosion properties of the two reconstituted marine sediments and the artificial sediments. This testing has been performed both to aid interpretation of the model scour tests and to investigate how erosion testing results may be used in practice to predict the scour rate beneath pipelines.

2. Sediments used in experiments

2.1. Description

The grading characteristics and physical properties of the marine and artificial sediments used in this study are listed in Table 1 and the

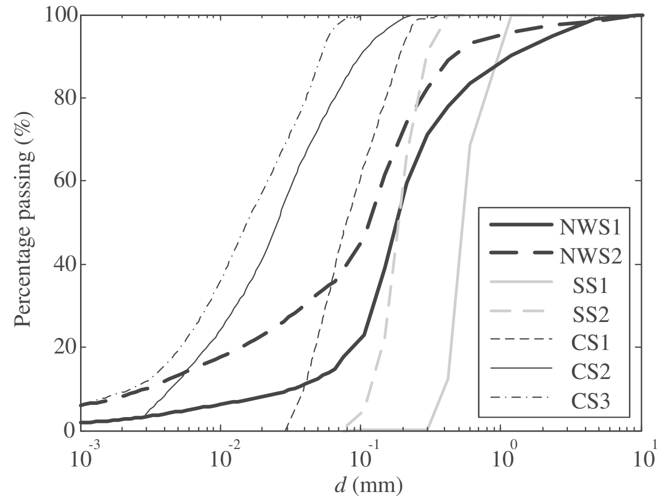

Fig. 1. Particle size distribution of sediments used in analysis.

Particle Size Distribution (PSD) curves are shown in Fig. 1. The two marine sediments in Table 1 and shown in Fig. 2, referred to as NWS1 and NWS2, are representative of very silty SAND and sandy SILT, respectively, and are both composed of small shell fragments and residue from marine fauna. The individual grains for both of the two sediments are typically angular and brittle. The artificial sediments in Table 1 consist of two subtypes: (i) silica sands SS1 and SS2, and (ii) carbonate sediments CS1, CS2 and CS3. It can be seen that the silica sands SS1 and SS2 have almost uniform particle size with no fines content (see Fig. 1), whilst the carbonate sediments are similar or slightly less uniform than the silica sands, which is in contrast to the well graded marine sediments. Collectively, the artificial sediments cover a range in median grain size of 15 to 540 μm. The silica sands (SS1 and SS2) and the coarsest carbonate sediment (CS1) are similar in grain size composition to the sediments that have been used to derive the existing empirical formula for the rate of scour beneath a pipeline given by Fredsøe et al. (1992).

2.2. Sample preparation

Throughout the testing program care was taken to ensure that samples were prepared consistently in both pipeline scour experiments and erosion tests. For the silica sands traditional wet pluviation (see Donahue et al., 2008) was used to prepare the samples, to mimic marine deposition. The sediment was mixed with water to form a thin slurry which was poured into an erosion sample container on the bottom of the flume used for the model pipeline testing. In contrast to the silica

Table 1
Properties of sediments used in the analysis.

Sediment	Median grain size, d_{50} (mm)	Fines content, f (% < 75 μm)	Clay content, c (% < 2 μm)	Uniformity index, $C_u = d_{60}/d_{10}$ (−)	Specific gravity, G_s (−)	Symbol used in figures
Marine sediments						
NWS1	0.18	17.7	2.7	8	2.74	✚
NWS2	0.12	38.9	8.2	112	2.76	✖
Artificial sediments						
SS1	0.54	0	0	1	2.75	◆
SS2	0.19	0	0	2	2.67	●
CS1	0.08	46.9	0	2	2.71	■
CS2	0.025	83.5	0	7	2.73	▲
CS3	0.015	98.6	9.2	11	2.71	▼