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Effect of limited sediment supply on sedimentation and the onset of tunnel scour below subsea pipelines

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ABSTRACT

This paper summarises the results of a series of experiments performed to investigate the onset of tunnel scour below subsea pipelines in steady currents. The experiments were performed on a model seabed that extended different lengths upstream of the pipeline to assess the effects of sediment supply on sedimentation around the pipeline and the potential for onset of tunnel scour. In each experiment, the flow velocity and pipeline embedment were recorded continuously from inside and outside of the model pipe. In general, the results show that following evolution of the seabed profile around the pipeline due to sedimentation and changes in sediment supply, the onset of tunnel scour may still occur even when the initial embedment is larger than the critical value obtained by an existing empirical formula according to Sumer et al. (2001). This result suggests the potential for tunnel scour beneath deeply embedded pipelines in the field where the sediment supply may be interrupted by, for example, rock outcrops or upward-sloping seabed on the upstream side of the pipe. It also demonstrates that onset of tunnel scour is possible for a pipeline on a seabed that is not flat on either side of the pipe, provided that the flow conditions are sufficient to promote piping. To complement the experiments, a series of numerical simulations have been conducted to investigate the seepage flow and dynamic pressure difference upstream and downstream of the pipeline prior to the onset of tunnel scour. The numerical results show that despite significant alteration of the surrounding seabed topography due to local scour for a deeply embedded pipe with limited sediment supply, the pressure gradient across the pipe is still sufficient to cause piping compared with the flat seabed case, and the maximum pressure gradient at the downstream side of the pipeline is consistent with the breakthrough point observed in the physical experiments.

1. Introduction and motivation

Interaction between a submarine pipeline and an erodible seabed has attracted much attention because of its importance in offshore engineering. Of particular interest is the 'onset of tunnel scour', which defines the point at which sediment is washed away beneath a pipeline. Onset of tunnel scour results in the development of a scour hole below a pipeline, followed by spanning of the pipeline and possibly subsequent self-burial (Sumer and Fredsøe, 2002) or pipeline breakout. Prediction of the onset of tunnel scour is therefore important in understanding and predicting the stability of a subsea pipeline.

For the case of a pipeline partially embedded in a flat seabed, a number of investigations have been reported regarding the onset of tunnel scour. Chiew (1990), for example, conducted a series of physical experiments and found that piping (backwards erosion of sediment) leads to the onset of tunnel scour. Sumer et al. (2001) investigated this mechanism in more detail and presented an empirical expression to predict the onset of tunnel scour in steady currents for a pipeline partially buried in a flat seabed. This expression is given as

$$\frac{U_{cr}^2}{gD(1-n)(s-1)} = 0.025\exp\left[9\left(\frac{e}{D}\right)^{0.5}\right]. \tag{1}$$

where U_{cr} is a 'critical' undisturbed steady current velocity (measured at the level of the top of the pipeline), above which the onset of tunnel scour due to piping will occur; g is the acceleration due to gravity; D is the pipe diameter; n is the porosity of the sediment; s is the specific gravity of sediment grains; and e is the burial depth of the pipeline.

Numerical studies on the onset of tunnel scour below subsea pipelines have also been reported in the literature. Liang and Cheng (2005), for instance, were the first to establish a numerical model of the onset of tunnel scour below subsea pipelines subject to steady currents. In that work, the pressure gradient that governs the seepage flow below the pipeline was determined by solving the two-dimensional Reynolds-averaged continuity and Navier–Strokes equations with the standard $k-\varepsilon$ turbulence closure. The seepage flow was calculated

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Notation

ADV	Acoustic Doppler velocimeter
C_p	Pressure coefficient
D	Diameter of pipe
d_{50}	Average grain size
e	Burial depth of pipeline
F_s	Seepage force
g	Acceleration due to gravity
k_s	Nikuradse equivalent sand grain roughness
n	Porosity of the sediment
p	Local pressure
p_∞	Pressure at far field
$q_{flyover}$	Volumetric transport rate over the pipe
q_{lee}	Volumetric transport rate due to the lee wake vortex
q_{luff}	Volumetric transport rate due to the luff vortex
q_{in}	Volumetric transport rate from the far field flow
q_{out}	Volumetric transport rate leaving the pipe
RE	Reynold's number for the near-bed wave-orbital motion
Re_c	Pipe Reynolds number in current
s	Specific gravity of sediment grains
SP	Distance of seepage flow path
U_c	Velocity induced by current component at the height of D
U_{cr}	Critical undisturbed steady current velocity
u_{*c}	Friction velocity based on grain roughness in current
V_{up}	Volume sediment transport for the upstream side of the pipe
V_{down}	Volume sediment transport for the downstream side of the pipe
W	Submerged weight of the soil element
X	Seepage flow path
z_0	Bed roughness length
α	Soil permeability
γ	Specific weight of water
ε	Void fraction, porosity
θ_c	Current Shields parameter
k	Von Karman's constant (=0.41)
ρ	Fluid density
τ_c	Current shear stress
ν	Kinematic viscosity of water

using the Laplace equation, and the free water surface was tracked in the model. The critical incoming flow velocity for the onset of tunnel scour was then calculated, and the results were found to compare well with experimental data. Zang et al. (2009) also developed a numerical model for the onset of tunnel scour by solving the flow field with the $k-\omega$ turbulence model. The average pressure gradient along the buried pipe surface was employed in the evaluation of the onset condition with a calibration coefficient. Zang et al. (2009) also studied the influence of flow parameters, including water depth, embedment depth, boundary layer thickness, Reynolds number (Re), and Keuleagan–Carpenter (*KC*) number, on the pressure variation across the pipeline. Gao and Luo (2010) proposed a flow–pipe–seepage sequential coupling finite element method (FEM) model to simulate the coupling between the water flow field and soil seepage field. They indicated that the dimensionless critical flow velocity changes approximately linearly with the soil internal friction angle for a submarine pipeline partially embedded in a sandy seabed.

Collectively, this body of experimental and numerical work provides a clear description of the onset of tunnel scour for a pipeline in a flat seabed, and Eq. (1) provides a particularly valuable predictive formula. It suggests that the onset of tunnel scour is unlikely in weak ambient field conditions (smaller than the critical velocity U_{cr}) for pipelines on most soils if they are embedded to a certain level. Field survey data for subsea pipelines, however, have suggested that even if the initial (as-laid) pipeline embedment is relatively large (Westgate, 2013) or the ambient flow is relatively weak, the onset of tunnel scour may still occur. This implies that other mechanisms may contribute to the onset of tunnel scour. Moreover, in practise, it is unlikely that the seabed will remain flat prior to the onset of tunnel scour. This is because currents less than the critical velocity for piping can lead to local sedimentation, thereby altering the local seabed morphology.

In this paper, the onset of tunnel scour below subsea pipelines was revisited by conducting a series of experiments and subsequent numerical analysis in steady currents. In the physical experiments, specific attention is paid to the effect of upstream sediment supply on local sediment morphology and the potential for the onset of tunnel scour following changes to the local seabed morphology. This work is applicable for better understanding of the potential for scour of pipelines in the field, particularity where changes in seabed erosion properties or surrounding rocky outcrops and sloping seabeds may limit the upstream sediment supply. It is also applicable to understanding the potential for onset of tunnel scour following variations in the surrounding seabed profile and thus the potential for de-burial of submarine pipelines. The numerical simulations where conducted to improve the understanding of the pressure distribution around a pipeline on a seabed that is not flat.

2. Physical experiments

2.1. Experiment setup

The physical experiments were conducted in a recirculating flume (Mini O-tube) at the University of Western Australia. The Mini O-tube (MOT) test facility comprises a motor–impeller system, unplasticised polyvinyl chloride (uPVC) tube sections, two honeycomb transitions at each end of the test section, and one straight test section; the main components are indicated in Fig. 1a. The propeller in the MOT is driven by a 5.5 KW three-phase induction motor with rated speed 2885 RPM (revolutions per minute). The rotational speed of the motor is controlled by the Danfoss VLT 2800 frequency converter, which is managed in the LABVIEW software application on a local computer. The diameter of the uPVC tube is 0.17 m, and there is a tapered section measuring 0.4 m in length to connect the circular uPVC tube to each end of the rectangular test section. The test cross-section of the MOT is 0.2 by 0.3 m and has a length of 1.8 m. The bottom 0.1 m of the working section can be filled with sediment or a false floor. To reduce the length scale of turbulent structures introduced into the test section, the length of the honeycomb is 0.2 m and is composed of 81 PVC tubes in the form of a 9×9 array.

In the experiments, a smooth PVC model pipe 50 mm in diameter was fixed in the middle of the test section (see Fig. 1a). Whitehouse (1998) mentioned that artificially high blockage in a laboratory model can be avoided if the rate of flume cross-sectional area to model cross-sectional area is no less than 6. However, Mao (1986) stated that the blockage effect of the pipe on the flow is very limited, provided that the ratio is less than 3.5. In this study, the ratio of O-tube cross-sectional area to model pipe cross-sectional area is approximately 4, and the results of validation tests (as will be shown later) are consistent with previous investigations (Sumer et al., 2001).

Three types of siliceous sediment were used in the present study. Soil properties, together with critical shear stress τ_{cr} for incipient motion in steady current conditions, were measured at the beginning of the study. Relevant data are listed in Table 1, and the particle size distributions are shown in Fig. 2.

The physical experiments were conducted with different sediment, pipeline embedment and lengths of seabed upstream of the pipeline. For convenience, the experiments have been divided into two