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Experimental and numerical study of wave-induced backfilling beneath submarine pipelines

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ABSTRACT

This paper presents results of complementary experimental and numerical studies involving wave-induced backfilling of current-generated scour holes beneath submarine pipelines. The laboratory experiments are conducted in a wave-plus-current flume, utilizing Laser Doppler Anemometry to measure velocities, synchronized flow visualizations using digital image technology, along with live-bed scour and backfilling measurements. Each experiment is based on a two-stage process: (1) initial scour induced by a pure current, followed by: (2) backfilling induced by pure waves (either regular or irregular). The time series of scour depths are closely monitored through video recordings. Systematic analysis of these has resulted in a closed form expression for the backfilling time scale, which is demonstrated to be a full order of magnitude greater than the well-known time scale of scour (with both governed primarily by the Shields parameter). The developed expression is strictly valid for the current-to-wave backfilling scenarios considered, while likely serving as an upper limit for more general wave-induced backfilling circumstances. The experiments are complemented by similar backfilling simulations utilizing a fully-coupled hydrodynamic and morphodynamic CFD model. The numerical simulations demonstrate the ability of the model to predict backfilling towards expected equilibrium scour depths based on the new wave climate, with time scales reasonably in line with experimental expectations.

1. Introduction

Submarine pipelines are extensively studied due to their importance in coastal and offshore engineering. They are commonly used to transport water, waste water, oil, natural gas and other hydrocarbons across marine environments. Considering the often-hazardous contents carried, the failure of a submarine pipeline may have catastrophic effects on the environment. Therefore, the integrity of the submarine pipelines is quite important. As a submarine pipeline is exposed to direct flow action, scour can develop around the pipe. This leads to suspended free spans of the pipeline which in turn increase stress and structural fatigue.

To improve the understanding of local scour developed due to current and/or waves, scour-related processes have often been studied by means of laboratory experiments (*e.g.* Fredsøe et al., 1992; Sumer and Fredsøe, 1990; Zhang et al., 2016). In addition to extensive laboratory experiments involving scour, several numerical models capable of predicting the scour evolution beneath pipelines induced by currents (*e.g.* Brørs, 1999; Larsen et al., 2016; Zanganeh et al., 2012), waves (*e.g.* Fuhrman et al., 2014; Kazeminezhad et al., 2012; Liang and Cheng, 2005), or their combination (Larsen et al., 2016) have also been developed and applied.

Most studies in the literature cover the scour process of submarine pipelines with a fixed wave or current climate, starting from a zero-scour initial bed profile (or for numerical models, a small initial scour depth). However, from an engineering point of view, it is also important to understand the scour profile development under changing wave and/or current climates. In such circumstances, the local weather and wave conditions could change over time, such as a transition from a strong wave climate to a mild wave climate or *e.g.* strong tidal currents to waves alone. While the time scales of scour processes are well-known (*e.g.* Fredsøe et al. (1992)), there is a general lack of data in the literature concerning the related time scales of backfilling processes. This presently limits the development of engineering models capable of predicting scour depth evolution beneath pipelines over long temporal durations, potentially involving changing wave, tidal current, and weather conditions. Fredsøe et al. (1992) investigated wave-induced backfilling of

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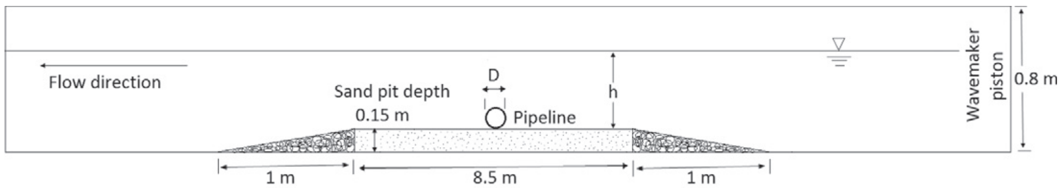
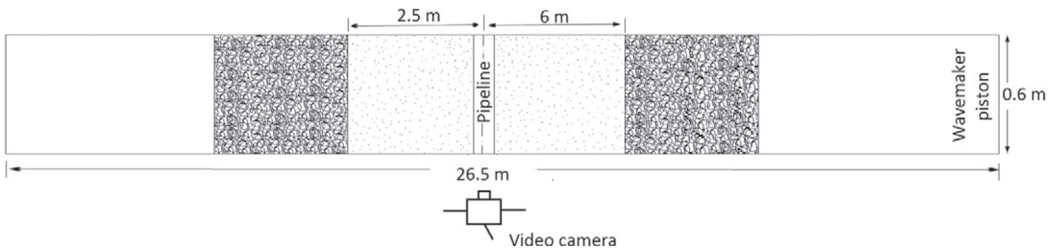


(a) Section view of the flume



(b) Plan view of the flume

Fig. 1. A schematic view of the experimental set-up.

wave-generated scour holes experimentally for a submarine pipeline for a limited number of test cases. Numerical studies also investigating scour as well as backfilling, due to changes in wave climate have likewise been conducted by Fuhrman et al. (2014). Zhang et al. (2016) also considered several experiments involving time varying flow conditions, including two cases involving the time evolution of backfilling beneath a submarine pipeline. Leckie et al. (2016) likewise studied the times scale of sedimentation around pipelines (*i.e.* involving the accumulation of sediment adjacent to a pipeline). Also relatedly, Sumer et al. (2013) investigated the 3D backfilling of scour holes around a monopile.

Through complementary experimental and numerical efforts, the present paper aims to make a significant contribution to the overall understanding of backfilling processes beneath submarine pipelines. For this purpose, we aim to simplify the backfilling process to its most elementary form: pure-wave backfilling of current-generated scour holes (*i.e.* so-called current-to-wave backfilling scenarios). For simplicity fixed pipelines will be considered, hence any complicating effects *e.g.* of a pipeline sagging into scoured regions will not be accounted for. Through analysis of the scour depth time series, we aim to provide the first systematic quantification of the backfilling time scale, appropriate for engineering use.

The present paper is organized as follows: The experimental study is discussed in Section 2 which describes the wave-plus-current flume, details of the velocity measurements done with Laser Doppler Anemometry (LDA), test conditions, as well as systematic analysis of the results in terms of the most important governing parameters. Subsequent numerical simulations are then described in Section 3, the results of which will be directly compared with the most important experimental findings herein. Finally, conclusions are given in Section 4.

2. Experimental study

2.1. Experimental set-up

The experiments have been conducted in a wave-plus-current flume which is 26.5 m in length and 0.6 m in width, equipped with an Active Wave Absorption Control System (AWACS) and DHI Wave Synthesizer 2.40 (*e.g.* Schäffer et al. (1994)). During the generation of the desired incident waves, this system absorbs the reflected waves.

A sediment section in the form of a sand pit with two ramps at the two ends was built in the flume. The ramp was made of crushed stones. The sand pit was 0.6 m wide and 0.15 m deep and 8.5 m long. A pipeline having diameter $D = 3$ cm was mounted horizontally along the width of the flume directly on the sediment bed. The median grain size of the sediment corresponds to $d = 0.18$ mm, with the relative density of the sand being $s = 2.65$. The position of the pipeline and other details are shown in the schematic view of the experimental set-up in Fig. 1.

The water depth has been maintained constant as $h = 40$ cm at the sand pit section except for a single case (test R4, to be presented in what follows). For this special case, the water depth was $h = 35$ cm at the sand pit section in order to maintain the desired characteristics. The details of this case as well as the other test conditions are given in Tables 1 (regular waves) and 2 (irregular waves). The origin $(x, y) = (0, 0)$ is taken as the bottom of the pipeline.

The orbital velocity of the water particles at the bed has been measured using a two-component Dantec Dynamics LDA system (only the green component was used to measure horizontal particle velocities). The measurements have been conducted in forward scatter mode with a photo detector placed on the other side of the flume's glass wall. The system was equipped with a 55N10 frequency shifter and a 55N20 frequency tracker. The velocity measurements have been made in the absence of the pipeline, as they are intended to represent the far field. The vertical measurement point was taken as $y = D/2$ (corresponding to the center of the pipeline) and was at a position 30 cm from the side wall *i.e.* at the center of the tank.

2.2. Results

2.2.1. Velocity measurements

The orbital velocities measured with LDA are used to estimate Keulegan-Carpenter (KC) numbers and Shields parameters (θ), which are expected to be the main parameters governing the wave-induced backfilling process. The Keulegan-Carpenter number is defined as

$$KC = \frac{U_m T_w}{D}, \tag{1}$$