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Scour below submarine pipelines under irregular wave attack

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ABSTRACT

Submarine pipelines are widely used coastal structures, and scour around them can influence their stability. In this study, scour around rigid submarine pipelines under normal-incidence irregular wave attack on horizontal and (1/10) sloping beaches is studied. This paper presents experimental results concerning scour under irregular wave attack. Multiple regression analysis is used to develop models to predict the scour depth under pipelines under the influence of irregular wave attack. The representative wave parameters that characterize the irregular sea state that causes the same scour depth as regular wave attack were determined.

1. Introduction

Liquids and gases are most frequently transported in pipelines. Fuel oil, natural gas, biofuels, water, waste water, slurry water and chemically stable substances are carried by pipelines. Pipelines installed on sandy seabeds in coastal areas are exposed to wave and current action. The interaction between submarine pipelines, erodible beds and water flow causes spanning and scour around the pipelines. When a pipeline is installed on an originally flat plane bed without any gap between the bed and the pipeline, scour develops due to the complicated flow generated around the pipeline and the seabed.

The onset of scour is related to the seepage flow in the sand beneath the pipeline, which is driven by the pressure difference between the upstream and downstream sides of the pipe. Piping occurs when this flow exceeds a critical limit, ejecting sediment and water downstream of the pipeline. Tunnel erosion follows this. During this stage, a substantial amount of water is diverted to the gap, leading to very large velocities in the gap and presumably resulting in very large shear stress on the bed just below the pipeline. The large increase in the bed shear stress below the pipe results in a tremendous increase in the sediment transport. This stage is followed by lee-wake erosion (Sumer and Fredsøe, 2002).

Flow around the pipelines in a steady current and under waves has been investigated extensively in the past few decades. Scour depth around submarine pipelines, both in steady current and waves, has been investigated by Chao and Hennesy (1972), Kjeldsen et al. (1973), Littlejons (1977), Herbich (1981), Bijker and Leeuweistein (1984), Lucassen (1984), Leeuweistein et al. (1985), Herbich et al. (1984), Bijker (1986), İbrahim and Nalluri (1986), Mao (1988), Kristiansen (1988), Kristiansen and Torum (1989), Sumer and Fredsøe (1990, 1996), Klomp et al. (1996), Çevik and Yüksel (1999) and Mousaviet et al. (2009).

Numerical methods and other computing tools have been developed to simulate scour around submarine pipelines by Yasa (2011), Liang and Cheng (2005a,b), Kambekar and Deo (2003), and Bateni et al. (2007a,b).

Myrhaug et al. (2008) provided an approach to determine the scour depth below pipelines in shoaling conditions beneath non-breaking and breaking random waves. This approach combines the scour depth formula presented by Çevik and Yüksel (1999) and the wave height distribution, including shoaling and breaking waves, presented by Mendez et al. (2004). Mendez et al. (2004) assumed a stationary Gaussian narrow-band random process. Yasa (2011) developed a model using multiple regression analysis to predict the scour depth in both live bed and clear water conditions.

Most of the experimental studies of scour around submarine pipelines to date have been conducted under conditions of regular wave attack. The purpose of this study is to model the local scour depth around a fixed and rigid submarine pipeline under normal-incidence of irregular wave attack on horizontal and sloping beaches. An experimental study was conducted, models for estimating the scour depth were developed, and comparisons were made with regular wave conditions.

2. Experimental setup and procedure

The experiments were carried out in a 1 m-deep, 1 m-wide and 20 m-long wave flume at the Hydraulic and Coastal-Harbor Engineering Laboratory of Yıldız Technical University. Both sides of the wave flume

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were made of glass 16 m long. The experiments were conducted under irregular wave conditions. The channel is equipped with an irregular/regular wave generator, and HR Wave Data software was used for data acquisition and analysis. A displacement piston-type wave maker was used to generate waves. It consists of two interconnected shapes that rotate relative to each other. The rear surface of each of the components forms part of a cylinder centered on its axis of rotation, so no back wave is formed when the structure rotates. The wave maker measures the incoming wave and corrects the paddle motion to absorb it. The resultant wave field is totally predictable even with highly reflective models. The wave maker can generate both sinusoidal and random waves (Fig. 1).

HR Wave Data is a spectral analysis program that produces the wave spectrum and associated spectral parameters. It also includes a wave counting routine that uses wave down-crossing to obtain some statistical values.

The beach was modeled with a 1/10 steel ramp with a 25 cm-sand layer on top. Sand with $d_{50} = 1.28$ mm, $d_{90} = 1.89$ mm and $\sigma = 1.57$, where σ is the standard deviation of sand, was used for live bed conditions. The standard deviation of sand is defined as follows:

$$\sigma = \frac{1}{2}\left(\frac{d_{50}}{d_{16}} + \frac{d_{84}}{d_{50}}\right) \tag{1}$$

where d_{16} is 16% of sand particles pass through, d_{50} is 50% of the sand particles pass through, d_{84} is 84% of the sand particles pass through.

The specific weight of the sand was $\gamma = 2650$ N/m^3. Beach profiles were measured using an HR Wallingford Touch-Sensitive Two-Dimensional Beach Profiler.

Rigid steel model pipes with diameters D = 32.3, 49, 77 and 114 mm were placed 1 mm from the channel sides. To avoid wall effects, all measurements were made in the middle of the cylinder axis. The pipes were rigidly fixed to prevent sagging.

The test cylinders were placed at various positions in the shoaling zone at depths of $d_1 = 35$ cm on the horizontal seabed and $d_2 = 31$ cm and $d_3 = 23$ cm on the 1/10 sloping bed (Table 1). The effect of water depth on scour may be important when the water depth becomes comparatively small because of the blockage effect. Significant blockage effect was not observed in these test conditions (Moncada-M and Aguirre-Pe, 1999). The pipelines were exposed to normal-incidence waves.

The waves were measured at 4 different locations along the channel. The first wave probe is in front of the wave generator at location 1, the second is at the horizontal bed, and the two others are at the beach where the pipeline is located. Eight different random wave series were generated for each location and for each of the four different pipe diameters. The experimental ranges are summarized in Table 2. The deep water wave heights (Table 2 in column 3) were obtained from the measured wave heights at location 1 in front of the wave generator by using Goda (2000) equations given for the wave height estimation within the surf zone for irregular wave heights. A total of 96 tests were conducted. The incident wave spectrum used in the experiments was the Bretschneider spectrum model given below:

Table 1
Measurement locations and depths.

Measurement Locations	4	3	2	1
Depths (d_i, mm)	230	310	350	600
Probe Locations	×	×	×	×
Pipe Locations	×	×	×	

$$S(f) = \frac{5m_0}{f_p}\left(\frac{f_p}{f}\right)^5 e^{-1.25(f_p/f)^4} \tag{2}$$

where m_0 is the variance of the free surface elevation and f_p is the peak spectral frequency.

The target wave heights and periods are given in Table 2. H_{s0} is the average of the highest third of deep water wave heights in the record and T_m is the spectral mean wave period which corresponds to $\sqrt{m_0/m_2}$, where m_2 is the second moment of the spectrum. Each test was continued until the equilibrium scour depth was reached. Equilibrium scour depths (S) were obtained by taking the difference of undisturbed bed elevation in the absence of the pipe and after the scour developed with the pipe.

Irregular waves exibit a wide spatial spread in the region of breaking; some waves break far from shore, some at an intermediate distance and others approach quite near the shoreline before they break. In coastal areas wave breaking takes place in a relatively wide zone of variable water depth. However the surf similarity parameter was calculated for the experimental conditions with deep water significant wave height and peak period in Table 2, where the surf similarity parameter is defined by $\xi = s/\sqrt{H_{s0}/L_{p0}}$. All the breaking types were plunging and the significant breaking depths were less than 14 cm and after the pipe.

Before the scour experiments were started, the shore-normal evolution of the beach profiles was examined, because the study area is in a shoaling region. The profiles were recorded for all irregular wave storms, defined in terms of their deep-water significant wave heights, as shown in Table 2, when they reached dynamic equilibrium during the storms. The beach profiles before and after the storms were plotted together to determine the profile types. All of the profiles developed were summer-type profiles with a step at the shoreline. Some examples of the profiles are shown in Fig. 2.

3. Scour in regular waves

Sumer and Fredsøe (1990) demonstrated that the relative scour depth, S/D, is remarkably well correlated with the Keulegan–Carpenter

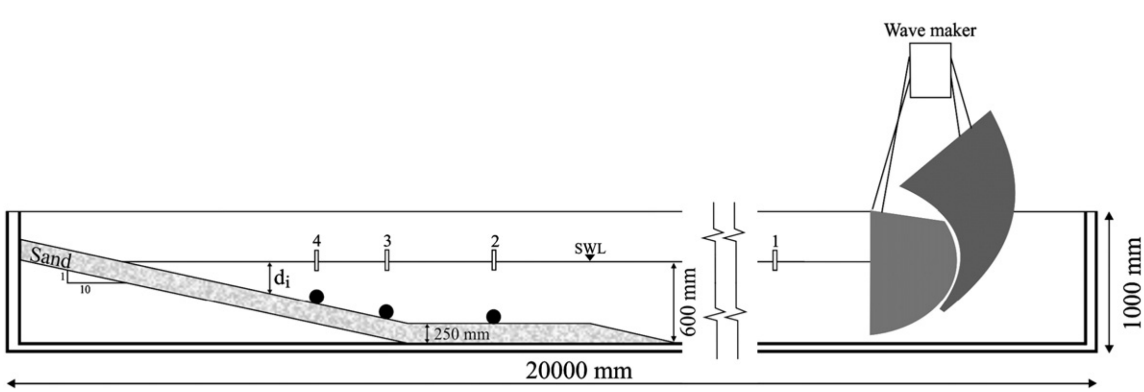

Fig. 1. Schematic representation of experimental setup.