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Experimental investigation of the equilibrium scour depth below submerged pipes both in live-bed and clear-water regimes under the wave effect

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ABSTRACT

Pipelines are the key structures to carry fluids such as oil, petroleum, gas and water; any inadequate design induces bottom stability problems causing unintended consequences. In the present study, the equilibrium scour depth below submerged pipes due to regular waves was investigated experimentally. During the experiments various pipe diameters, bed material grain sizes and wave characteristics were used. The novelty of the study is that the experiments were performed both in live-bed and clear-water regime conditions. The analysis of the experimental data showed that the equilibrium scour was correlated with Shields parameter as well as Keulegan-Carpenter number, especially for live-bed scour condition. However, in the case of clear-water scour, the Keulegan-Carpenter number was found as a unique non-dimensional parameter that dominates the scour phenomenon. New empirical relations were also proposed for clear-water and live-bed scour separately.

1. Introduction

It is important to understand the scour process which affects the design of the pipeline. There are lots of study investigated scour processes induced by current [1–7]. However, recent studies pertaining to scour around pipelines under the wave effect are quite limited.

Sumer and Fredsoe [8] investigated experimentally scour below pipelines subjected to waves. According to their results, it was revealed that the Keulegan-Carpenter number was the main parameter that governs the equilibrium scour depth. In addition to this, it was also found that the surface roughness does not affect the scour process. Cevik and Yuksel [9] investigated scour depth variation with respect to water depth using regular waves. Based on the experimental data they proposed a new equation for calculating the maximum equilibrium scour depth in live bed conditions without gap between seabed and pipe. They demonstrated that the modified Ursell number has a key role in determining the equilibrium scour depth. The onset of scour and self-burial of pipelines in currents and waves were investigated by Sumer et al. [10]. During the experiments pressure was measured on the surface of the buried pipe at upstream and downstream sides of the pipe. They found that the excessive seepage flow and the resulting piping were the major factors to cause the onset of the scour below the pipeline. Kumar et al. [11] investigated wave-induced pressures and uplift forces on a submarine pipeline in clayey soil of different consistency index both in regular and random waves. They also studied experimentally the scour under the pipeline resting on the clayey bed. The equilibrium scour depth was estimated as 42% of the pipe diameter for consistency index of 0.17 and as 34% of the pipe diameter for consistency index of 0.23. Cataño-Lopera and García [12] developed new empirical predictor for estimating the equilibrium burial of short cylinders under combined flows. The equation is based on the combination of Shields parameter, Keulegan-Carpenter number and the ratio of current velocity to the effective wave plus current velocity. The coupling effects between pipeline vibration and sand scour were investigated experimentally by Gao et al. [13]. After the experimental studies, they found that there exist two phases in the process of sand scouring around the pipeline with an initial embedment. The first phase is the scour beneath pipe without vortex-induced vibrations and the second is the scour with vortex-induced vibrations of pipe. Kiziloz et al. [14] investigated the scour around rigid submarine pipelines under irregular wave attack on horizontal and sloping beaches. A new model was developed to predict the scour depth under pipelines under the influence of irregular wave attack.

In the present study, the equilibrium scour depth under submerged pipes was investigated experimentally in different scour regimes. The first scour regime is the clear-water condition that means the Shields parameter is less than the threshold value determined according to the grain Reynolds number. In this case, the approach flow generated by

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the waves does not contain sediment. So the sediment motion occurs only around the pipe. However, in live-bed condition the Shields parameter is larger than the threshold value so the sediment motion occurs far from the pipe as well as close to pipe. This means, the approach flow generated by the waves transports sediment into the scour hole. Both clear-water and live-bed scour experiments were realized by using relatively coarse sediment. Thus, new empirical relations were proposed with regard to scour regime effect.

2. Mathematical background

Sumer and Fredsoe [8] proposed Eq. (1) and Cevik and Yuksel [9] suggested Eq. (2) to estimate equilibrium scour depth (S), below a pipeline located at an elevation equal to the far-field seabed elevation, with non-cohesive bed materials under the wave effect for live-bed scour conditions, respectively.

$$\frac{S}{D} = 0.1\sqrt{KC} \tag{1}$$

$$\frac{S}{D} = 0.11\,KC^{0.45} \tag{2}$$

where, D and KC are the pipe diameter and Keulegan-Carpenter number, respectively. In Sumer and Fredsoe [8] study, the used bed materials had median grain sizes of $d_{50} = 0.18$ and 0.58 mm. This parameter was 1.28 mm in the study of Cevik and Yuksel [9]. Keulegan-Carpenter number can be expressed as follows:

$$KC = \frac{U_m\,T_w}{D} \tag{3}$$

In this relation, U_m is the maximum value of the horizontal component of the water particle velocity and T_w is the wave period.

Although Eqs. (1) and (2) do not include Shields parameter, it is a highly important dimensionless parameter affecting the relative equilibrium scour depth. Shields parameter (θ) which allows the determination of the inception motion point of the bottom sediment can be calculated from Eq. (4).

$$\theta = \frac{U_{fm}^2}{g\,(s-1)\,d_{50}} \tag{4}$$

in which, g denotes the gravitational acceleration, s is the specific gravity of sandy sediment and d_{50} is the median size of sand grains. The sketch of the wave scour around submarine pipe is given in Fig. 1.

Maximum value of the bed shear velocity is denoted by $U_{f\,m}$ and it can be determined by Eq. (5). Friction coefficient of wave boundary-layer flow (f_w) can be calculated by means of the relation given by Eq. (6) assuming that the bed is a rough boundary, as this is the case in the study of Fredsoe and Deigaard [15].

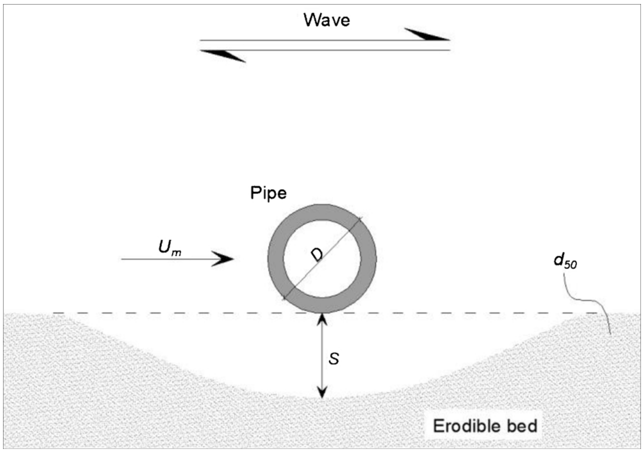

Fig. 1. Sketch of the wave scour process around submarine pipe.

$$U_{fm} = \sqrt{\frac{f_w}{2}}\,U_m \tag{5}$$

$$\begin{aligned} f_w &= 0.04\left(\frac{a}{k_b}\right)^{-1/4} \quad if \quad \frac{a}{k_b} > 50\\ f_w &= 0.40\left(\frac{a}{k_b}\right)^{-3/4} \quad if \quad \frac{a}{k_b} \le 50 \end{aligned} \tag{6}$$

In these expressions, a corresponds to the amplitude of horizontal corresponds to the amplitude of horizontal component of orbital motion of water particles and bed roughness height k_b can be taken as $2.5\cdot d_{50}$, as suggested in the study of Sumer and Fredsoe [16]. In the sinusoidal wave case, that is, when small amplitude wave theory is valid, a can be calculated from Eq. (7).

$$a = \frac{H}{2}\,\frac{1}{\sinh(2\pi h/L)} \tag{7}$$

where, H is the wave height, h is the mean water depth and L is the wave length.

3. Experimental set-up, measurement devices and method

The scheme of the experimental set-up used in the scope of this study is given in Fig. 2. The channel was 33 m long, 3.6 m wide and 1.2 m high. The wave generator producing regular waves with different heights and periods was located on the offshore side of the channel. A wave absorption system has been built up on the onshore side of the channel in order to prevent the reflection.

The bed material was uniform sand with a relative specific weight of s = 2.65. The test pipe was fixed on the mobile bed. After each experiment the bed material was readjusted to get a horizontal surface. The duration of the experiments were designated as 75 min to generate minimum 1000 individual waves. For the maximum wave period of 4.3 s in this study more than 1000 individual waves were generated during the experiments. This value is much more for the shorter wave periods. The time-dependent scour measurements supported the view that this value was sufficient for scour to reach equilibrium.

The horizontal component of the water particle velocity (U_m) was measured by means of UVP (Ultrasonic Velocity Profiler) transducer (shown as UVP-T2 in Fig. 3). The temporal variation of the scour depths was determined by using UVP transducer shown as UVP-T1 in Fig. 3. The details of such measurements were given in the study of Guney et al. [17]. The time-dependent water levels were measured by using two USSs (Ultra Sound Sensor) belong to ULS (Ultra Level System). The locations of the sensors are also shown in Fig. 3. The wave length and wave height were determined from water level measurements. For better comprehending of the settlement of the UVP transducers and pipe fixers, Fig. 4 is also given.

In Fig. 5, two example photos taken at the end of the individual experiments were shown. The observation windows located on the both sides of the channel allow us to take these pictures.

To test statistically the empirical equations obtained from regression analysis, the determination coefficient (R^2) is one of the major parameters and it can be computed by Eq. (8). In this equation, SSE is the sum of squares due to errors (Eq. (9)) and SSR is the sum of squares due to regression (Eq. (10)).

$$R^2 = \frac{SSR}{SSR + SSE} \tag{8}$$

$$SSE = \sum\nolimits_{i=1}^{n} (Y_i - \hat{Y}_i)^2 \tag{9}$$

$$SSR = \sum\nolimits_{i=1}^{n} (\hat{Y}_i - \overline{Y})^2 \tag{10}$$

Here, n denotes the number of data and Y_i represents the experimental values. $\hat{Y}_i$ and $\overline{Y}$ are the values estimated by the regression equation and the mean value of the experimental data, respectively. In performing the regression analysis, the root mean square errors ($RMSE$) given by