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Clear-water scour and flow field alteration around an inclined pile

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ABSTRACT

The present experimental study investigates the scour pattern and the near-wake flow field alteration around an emergent rigid cylinder, which is inclined towards the downstream direction. Three different inclination angles were tested separately, namely 14°, 30°, and 42° with respect to the wall-normal axis. The induced flow and scour patterns were assessed and compared with the well-known case of the emergent upright cylinder (inclination angle 0°). The experiments were conducted for steady flow conditions in a 26 m long recirculating flume and the flow velocity measurements were conducted with an acoustic Doppler velocimeter. For the clear-water scour experiment, a false bed with a sand-pit was installed within the flume and a laser scanner was utilized to render a detailed representation of the scoured bed. The results show how the scouring gets mitigated with increasing inclination angle. Spatial distribution of time-averaged and fluctuation velocity patterns are presented, which exhibit that the vertical mixing gets significantly enhanced behind the inclined cylinder with increasing inclination angle, while the lateral mixing gets weakened at the upper flow region. An upward flow is seen at the immediate downstream of the inclined pile close to the bed, which becomes stronger with the inclination angle. Energy spectra as well as joint frequency distributions of velocity components were analyzed together with the time series, revealing that the inclination of the pile alters the wake significantly. The results further indicate that with increasing inclination angle the pile becomes more streamlined and the vortex shedding gets suppressed.

1. Introduction

One of the most prominent problems of flow-seabed-structure interaction is the flow and scour around a circular cylinder placed normally on an erodible bed. Such a pile radically alters the flow around it (Sumer and Fredsøe, 2002). The flow decelerates at the upstream of the cylinder causing a downflow, followed with the separation of streamlines. Consecutively, a horseshoe vortex is generated close to bed, which significantly increases the bed shear stress and turbulence. The flow accelerates at the sides of cylinder where the streamlines are contracted. At the rear of the cylinder, the incoming boundary layer is separated due to adverse pressure gradient and lee-wake vortices are formed, which are convected downstream. Scour around the cylinder is a consequence of this complicated and aggressive flow picture. Furthermore, recent research indicates that a couple of counter-rotating streamwise vortices appearing at the downstream of the cylinder are also effective as a major flow feature in determination of scour and deposition pattern around such a structure (Petersen et al., 2014, 2015; Baykal et al., 2015). There is a large number of published studies that analyzed these phenomena and presented design charts and formulations for relevant structures, such as bridge piers and monopile foundations (e.g., Raudkivi and Ettema, 1983; Chiew and Melville, 1987; Whitehouse, 1998; Graf and Istiarto, 2002; Sumer and Fredsøe, 2002; Roulund et al., 2005; Unger and Hager, 2007; Sumer, 2014).

On the other hand, the cylinder is not always placed upright. In coastal and offshore engineering applications, the support structure may be placed inclined (making an angle with the bed normal) or may have more complicated forms. For instance, a tripod wind turbine foundation comprises three inclined cylinders connected by constructive beams. Likewise, a pile-supported pier can be designed with inclined piles for enhanced robustness and increased strength against lateral wave loads. Some forms of woody coastal and estuarine vegetation, such as mangroves or reeds, can also be considered as variations of this case. Inclined piles are expected to interact differently with the flow compared to their upright counterparts; the generated wake region, secondary flow structures and the loads on the cylinder would change considerably. Despite the popularity of flow and scour around piles, the research conducted on flow-inclined cylinder interaction is quite limited, even fewer of them considered the existence of the seabed.

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Earlier studies on inclined cylinders are mostly focused on the forces acting on the inclined cylinder rather than the flow around it (such as Bursnall and Loftin Jr, 1951; Norton et al., 1981). Hanson (1966) and Van Atta (1968) experimentally investigated the vortex shedding regime behind an inclined circular cylinder. Findings of Van Atta (1968) indicated that the classical Strouhal relationship was capable of representing the vortex shedding frequency up to an inclination angle of $\alpha < 30°$, but for steeper inclinations Strouhal number was seen to increase as much as 50% as the cylinder got inclined up to $\alpha = 60°$ (α is the angle between the pile axis and the bed normal). Later, the experiments of Ramberg (1983) yielded a similar result, but with only a 15% increase of the Strouhal number for $\alpha = 60°$.

In another experimental study, Kozakiewicz et al. (1995), showed that the streamlines around an inclined cylinder tend to bend and pass the cylinder perpendicularly to its axis. Thereby, the drag coefficient is expected to be independent of the angle of attack once the normal component of the velocity vector to the cylinder axis is considered for calculation. There are other studies which confirmed the so-called independence principle (Sumer and Fredsøe, 1997). Kozakiewicz et al. (1995) observed that the independence principle is no more valid beyond a certain inclination angle ($\alpha \approx 55°$) since the streamlines cannot bend and become perpendicular to the cylinder anymore. They further noted that the vortex shedding frequency of inclined cylinders could still be represented by Strouhal relationship without a significant increase, but the peak of the power spectra that represents the vortex shedding becomes less significant as the inclination increases. The 3D direct numerical simulations (DNS) of Zhao et al. (2009) confirmed the findings of Kozakiewicz et al. (1995), indicating a practically unchanged Strouhal number with increasing inclination. By quantifying the pressure and shear stress on the inclined cylinder surface, Zhao et al. (2009) also showed that inclination generally decreases the form drag, but increases the friction resistance. Most recently, Najafi et al. (2016) performed an experimental campaign with inclined cylinders ($\alpha \leq 45°$), in which they employed a particle image velocimeter (PIV) and dye flow visualization technique. They observed two distinctly different flow patterns as inclination angle changes and looked for the breakdown of the independence principle. In addition to the summarized literature on flow-inclined cylinder interaction, it is worth to mention that Vlachos and Telionis (2008) and Franzini et al. (2012) dealt with the influence of free surface presence on the problem, whereas Franzini et al. (2013) and Jain and Modarres-Sadeghi (2013) studied the vortex-induced vibrations of inclined cylinders.

In none of the above studies, the interaction of the pile with the bed boundary layer is particularly considered. Majd et al. (2016) studied the flow and turbulence around a downstream-inclined pile on rigid bed. With the aid of flow visualization, they found that the upstream separation distance tends to decrease with increasing inclination, presumably leading to a weaker horseshoe vortex formation. Their findings also showed that small inclinations tend to decrease the wake turbulence compared to the upright case, but the trend reverses after a certain inclination.

Only a few studies have investigated the scour around inclined piles. Bozkus and Yildiz (2004) and Bozkus and Cesme (2010) analyzed experimentally the rate at which the maximum scour depth diminishes with increasing inclination of a bridge pier for $\alpha \leq 15°$. Vaghefi et al. (2016) conducted similar experiments for inclination angles up to $\alpha = 21°$. Euler et al. (2014) examined solid and permeable circular cylinders with larger inclination angles to simulate bended woody riparian plants under flood flows. They showed that with increasing cylinder inclination the upstream end of the scour hole shifted towards the downstream direction and after a certain inclination angle scouring occurred solely behind the cylinder. This suggests that the horseshoe vortex remains as the major scouring mechanism for low inclination angles, whereas the lee-wake vortices dominate the scour as the inclination increases. Euler et al. (2014) determined this transition to occur for inclination angles around $\alpha = 60° - 65°$.

The scope of the present experimental study is (1) to analyze the steady current induced clear-water scour and deposition patterns around a circular pile with a downstream inclination, and (2) to determine the alteration of the flow field past the pile. In order to fulfill this scope, both loose bed and rigid bed experiments were conducted, respectively. Three inclination angles are examined and compared with the upright pile case, adding up to four pile configurations. The scoured bed morphology is obtained with the aid of a laser scanner, while the flow field is analyzed by conducting instantaneous velocity measurements commencing right behind the obstacle. As such, it is aimed at getting a better understanding of the scour and flow around inclined piles.

2. Experimental setup and methodology

The experiments were conducted in the Hydraulics Laboratory of Istanbul Technical University. The utilized flume is 26 m long, 0.98 m wide, and 0.85 m deep, with plexiglass sidewalls and smooth concrete horizontal bed. A flow straightener with honeycomb pattern is placed at the flume entrance for securing smooth inlet flow conditions. For the present experiments, the water recirculation was maintained with the aid of a 25 kW external pump that elevated the water to a reservoir 7 m above the flume, from which it got gravitationally conveyed to the flume entrance, and two 5 kW pumps, which conveyed the water from the downstream end of the flume to its entrance. Two types of experiments were conducted: scour (loose bed) experiments and rigid bed experiments for velocity measurements.

2.1. Loose bed experiments

For the scour experiments a 14.5 m long and 20.5 cm high false bed made of metal sheets was installed, which covered the entire flume width as shown in Fig. 1. In the middle of the false bed, a 3.5 m long sandpit was included. Two drainage pipes buried in the sandpit facilitated the drainage of the water whenever necessary. The pit was filled with quartz sand with specific mass $\rho_s = 2.65$ ton/m^3, median diameter $d_{50} = 0.52$ mm, and geometric standard deviation $\sigma_g = \sqrt{d_{84}/d_{16}} = 1.85$. An emergent circular cylinder with a diameter of $D = 9$ cm was placed in the sandpit approximately 16 m from the flume inlet (Fig. 1), where fully developed flow conditions are attained. The inclination of the cylinder with respect to the bed normal was adjustable by means of a hinge connected to the rigid flume bottom, which stayed buried under the sand during the tests. The bottom end of the pile was tightly sleeved on the hinge and the upper end over the water surface was fixed to a metal beam crossing the flume. The rigidity of the pile together with all its connection was maintained so that no recognizable vibration was allowed. The flow depth above the false bed was set to $h = 30$ cm, while the undisturbed depth-averaged approach flow velocity (measured in the flume centerline at $10D$ upstream of the cylinder) was equal to $U_0 = 26.8$ cm/s. The resulting cylinder Reynolds number was $Re_D = U_0 D/\nu = 2 \times 10^4$, in which ν is the kinematic viscosity of water. By use of the classical bed resistance formulations, the given h and U_0 yield an undisturbed bed friction velocity of $U_f = \sqrt{\tau_0/\rho} = 1.45$ cm/s, where τ_0 is the bed shear stress and ρ is the specific mass of water. The Shields parameter, θ, and the grain Reynolds number, Re_* are defined as follows:

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

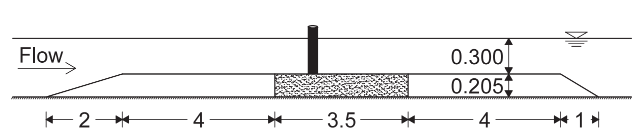

Fig. 1. The installed false bed. All dimensions are in meters and not to scale.