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Clear water scour around a finite array of cylinders

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ABSTRACT

This experimental study presents clear-water scour and deposition patterns around hexagonal arrays of circular cylinders in steady flow conditions. Understanding the scour processes around such configurations could facilitate the design of several hydraulic and marine engineering structures, such as bridge piers and piles. The flow alteration caused by the examined porous obstacles depends on the solid volume fraction of the obstacles and on the angle of attack of the incoming flow, due to the limited number of cylinders constituting the array. Flume experiments with erodible bed were carried out for four array densities (solid volume fractions: 0.14, 0.20, 0.32 and 0.56) under three different orientations (regular, angled and staggered configurations). The scour/deposition characteristics were obtained by means of laser scanner and the results were compared to solid cylinders of equal circumambient diameter. Different angles of attack of the incoming flow lead to different blockage ratios, which have direct impact on the scour characteristics and deposition patterns. The arrays with the higher solid volume fraction generated scour/deposition patterns similar to solid cylinder, while in the arrays with the lower solid volume fractions, local scour around the individual small cylinders became evident. Finally, considering that the load bearing capacity of a pier basically depends on the area of its cross-section, a comparison of the maximum induced scour depth and volume by the cylinder arrays and the solid cylinder with equal solid cross-sectional area is presented, in order to introduce an alternative pier configuration that induces less scour. The results showed that the array of cylinders could generate 27% less scour volume and 22% less scour depth compared to its single solid cylinder counterpart.

1. Introduction

Bottom-mounted piles are commonly applied in the field of coastal/offshore and river engineering to construct safe and feasible infrastructure systems; such as piled breakwaters, offshore wind turbine foundations, oil/gas platforms and bridge piers. Particularly, in recent years with the increasing environmental awareness pile-supported emerged structures gained a special importance [1–4] since those structures can be classified as environmental-friendly coastal structures due to their mitigated impacts on coastal zone [5]. The design of a typical pile foundation in marine or riverine environment requires the consideration of not only the structural and geotechnical, but also the hydrodynamic and scour perspectives. The presence of a cylinder in the flow field increases turbulence and generates some secondary flow structures (downflow, surface roller, horseshoe vortex, lee wake vortices, streamline contraction) in its vicinity [6]. Even in cases where the undisturbed flow is weak and cannot entrain bed sediment, scour around the cylinder is likely to be triggered by the local flow accelerations and the horseshoe vortex intensity. This phenomenon is called clear-water scour. Numerous experimental studies (e.g., [7–10]) investigated the scour patterns around a slender circular pile, the simplest form of supporting piles, for clear-water scour as well as for live-bed scour, where general bed-load transport is observed. The gained knowledge from this simple problem has constituted a benchmark case, which assists in better understanding the scour around more-complex structures, such as pile groups, jacket and tripod foundations [11–13].

The hydrodynamics of isolated riparian vegetation, which acts as a permeable obstacle against the flow in a riverine system, has been examined at the individual plant scale [14,15] due to its morphological [16,17], ecological [18] and fluvial [19] consequences. A distinguishing characteristic of permeable obstacles, like vegetation or an array of cylinders, is the bleed-flow through the obstacle.

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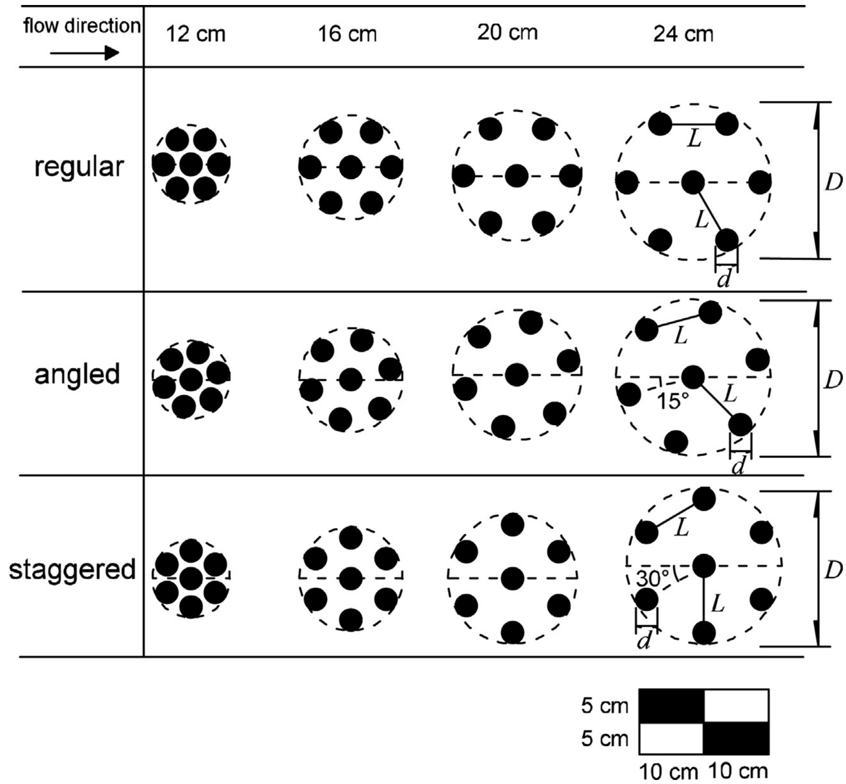

Fig. 1. The different examined array configurations in scaled form. *D* is the outer diameter of the arrays, *d* is the diameter of each cylinder constituting the array, and *L* is the gap between neighboring cylinders edges. The dashed circumferences show the fictional perimeters of the arrays.

The flow penetrating through an array of cylinders diminishes the flow diversion/contraction around the array and lessens its acceleration and the exerted bed shear stress. In addition, the flow exiting the array from its rear side inhibits the interaction of the shear layers that develop at the two sides of the wake, leading to the delay of the onset of the von Karman vortex street, compared to the wake structure behind a solid cylinder [20]. Zong and Nepf [21] referred to this flow region as the steady wake region and noted that flow velocity and turbulence intensity diminish within this region. The bleed-flow intensity defines the required distance at which the developed shear layers at the edges of the wake will be sufficiently grown to interact with each other as well as the distance behind the obstacle where the flow will recover due to lateral momentum flux [21–23].

Tafarojnoruz et al. [24] comparatively investigated some potential flow-altering countermeasures, which are common in the river engineering literature, such as submerged vanes, bed sill, sacrificial piles, collar, threading and pier slot. In their extensive experimental study, they reported that all of the tested flow-altering countermeasures exhibited low efficiencies in terms of scour depth reduction or serious practical problems. Their findings explicitly revealed that a single flow-altering countermeasure may constitute an inadequate protection. Moreover, such countermeasures usually require extra cost, labor and sophisticated construction equipment. Hence they have limited applicability and are not commonly preferable in practice.

From the structural perspective, one can expect that as long as the cross-sectional area of a pier is kept constant, the bearing capacity of the pile would basically remain the same in terms of axial loading. Based on this fundamental fact, a porous structure comprising an array of cylinders could lead to less scour compared to a single solid cylinder with equal cross-sectional solid area. Such an approach was adopted previously by Vittal et al. [25] who tested a group of three cylindrical piles angularly spaced at 120° as an alternative to a single pile. However, Vittal et al. [25] did not compare the scour efficiency of a group of piles with the corresponding solid cylinder of equal cross-sectional area. Using a group or array of cylinders as an alternative supporting structure could offer the following advantages compared to a single pier of equal solid cross-sectional area.

- Scour reduction: Due to the porous nature of the pile, certain amount of flow, i.e., bleed flow, penetrates through the permeable obstacle [20]. Graf and Istiarto [26] stated that the strength of the horseshoe vortex, which is the major responsible mechanism for the scour, depends to a great extent on the downflow strength. Also, recently the experimental data by Kitsikoudis et al. [27] clearly revealed that the presence of bleed flow decreases the strength of downflow considerably. When these pieces are put together, it is concluded that the local bed shear stress and scour around an array of cylinders are expected to be reduced due to the presence of bleed flow, decreased downflow and, eventually, mitigated horseshoe vortex strength.
- Decreased stagnation: When a solid cylinder is exposed to flow, stagnation occurs at the upstream of the pile. This stagnation correlates with the square of the velocity in accordance with the energy equation. Based on the discussion given in the preceding item, one can expect that the presence of the bleed flow reduces the stagnation at the upstream of the pile.
- Applicability: Large piles require much more aggressive, difficult and noisy driving practices compared to small diameter piles [28] as well as large piling templates which need to be fixed by sophisticated means prior to pile driving. An array of smaller cylinders facilitates the construction procedure in the field. It requires less sophisticated and more accessible construction equipment since driving smaller cylinders deep into the bed is relatively easier compared to a solid cylinder with an equal cross-sectional area. This implies the reduction of overall cost.