Experimental Thermal and Fluid Science 97 (2018) 444–457

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Influence of turbulent horseshoe vortex and associated bed shear stress on sediment transport in front of a cylinder

Jinzhao Li[a,d], Meilan Qi[a,b,*], David R. Fuhrman[c], Qigang Chen[a]

[a] Beijing Jiaotong University, School of Civil Engineering, Beijing 100044, China
[b] Beijing' s Key Laboratory of Structural Wind Engineering and Urban Wind Environment, Beijing 100044, China
[c] Technical University of Denmark, Department of Mechanical Engineering, Section of Fluid Mechanics, Coastal and Maritime Engineering, DK-2800 Kgs. Lyngby, Denmark
[d] National Engineering Laboratory of Port Hydraulic Construction Technology, Tianjin Research Institute of Water Transport Engineering, Tianjin 300456, China

ARTICLE INFO

Keywords:
Turbulent horseshoe vortex
Bed shear stress
Sediment transport
Particle image velocimetry
Cylinder scour

ABSTRACT

This study concerns the flow and associated sediment transport in front of a cylinder in steady currents. The study comprises (i) flow characteristics induced by the turbulent horseshoe vortex (THV), (ii) bed shear stress within the THV region, and (iii) predicted sediment transport rates. The velocity fields in front of a wall-mounted circular cylinder were measured using time-resolved particle image velocimetry (PIV). The flow characteristics show that two time-averaged THVs are formed, and the dynamics of instantaneous THVs exhibit a quasi-periodic process from generation to death. Both the mean and fluctuations of bed shear stress within the THV region are significantly amplified, and their values are comparable. The probability density function of the instantaneous bed shear stress exhibits a double-peaked distribution and cannot be represented by the normally-used log-normal distribution for uniform channel-open flows. The comparisons of sediment transport rates where turbulent fluctuations in the bed shear stress are, or are not, taken into account show that the sediment transport rates calculated by the mean bed shear stress are under-predicted. Furthermore, a new sediment transport model incorporating the influence of bed shear stress fluctuations is proposed and validated by comparing the initial scour rate in front of the cylinder.

1. Introduction

When the approach flow encounters a cylinder, the incoming boundary layer separates from the upstream bed due to an adverse pressure gradient imposed by the obstacle, resulting in a so-called turbulent horseshoe vortex (THV) formed in front of the cylinder. The THV is highly relevant to many applications in hydrodynamics and aerodynamics. For example, the THV plays an important role in driving sediment transport and scour around bridge piers in river sand beds, which is a primary reason for bridge failure [1–4]. The flow field around a cylinder becomes complex and interacts strongly with a bottom sand bed, which results in local scour at the cylinder or pier. Therefore, a full understanding of the dynamics of the THV is essential for revealing the underlying mechanisms of sediment transport around piers and preventing unexpected situations in practical applications.

A number of related studies of THV have focused on the time-averaged geometrical characteristics [5–8], the dynamics of THV utilizing particle image velocimetry (PIV) [9–14], eddy-resolving large eddy simulation (LES) [15–17], or detached eddy simulation (DES) [18]. These studies mainly focus on the flow field induced by the THV, however, little literature reports on the relevant influence and relationship of the THV on sediment transport and erosion, which is essential to identify the mechanisms of pier scour and to further improve the prediction accuracy of scour depth. Escauriaza and Sotiropoulos [19] and Link et al. [20] simulated the sediment transport around a cylinder using Lagrangian particle model and found that the interaction of the THV with the wall is the fundamental mechanism for the particle motion and the increase of instantaneous bed shear stress.

Most computations of scour around the cylinder are based on Reynolds-averaged Navier-Stokes (RANS) equation models [21–30]. However, RANS modeling results are, by nature, time ensemble averaged, and are incapable of accurately capturing the intense turbulence and detailed vortex structures. For instance, Khosronejad et al. [31] pointed out that RANS models cannot resolve the energetic horseshoe vortex system at the cylinder and bed junction and thus significantly under-predict scour depth in front of the cylinder. Chang et al. [32] also noted that the sediment transport flux calculated by the mean flow field is under-predicted by 2–3 times, when compared with that predicted more correctly by the instantaneous flow fields. Recently, Kim et al. [33,34] utilized LES modeling that improves the prediction of scour

* Corresponding author at: Beijing Jiaotong University, School of Civil Engineering, Beijing 100044, China.
E-mail address: mlqi@bjtu.edu.cn (M. Qi).

https://doi.org/10.1016/j.expthermflusci.2018.05.008
Received 27 December 2017; Received in revised form 10 April 2018; Accepted 11 May 2018
Available online 14 May 2018
0894-1777/

Nomenclature

Fr	Froude number (–)
Re	Reynolds number (–)
Re_D	cylinder Reynolds number (–)
I	relative bed shear stress fluctuation (–)
τ	instantaneous bed shear stress (kg m^{-1} s^{-2})
τ_m	mean bed shear stress (kg m^{-1} s^{-2})
τ_{rms}	RMS of bed shear stress (kg m^{-1} s^{-2})
ν	kinematic viscosity (m^2 s^{-1})
ν_T	turbulent eddy viscosity (m^2 s^{-1})
ϕ	dimensionless instantaneous sediment transport rate (–)
ϕ_m	dimensionless mean sediment transport rate (–)
r	scour rate (m s^{-1})
ρ	water density (kg m^{-3})

around cylinders, though such LES modeling requires large computational resources, particularly for scour computations, which hinders its application in practice [35].

The bed shear stress, a crucial quantity determining the sediment transport, can be regarded as a key factor bridging the flow characteristics (e.g., THV), sediment transport, and scour. The presence of a THV in front of a cylinder induces an increase of the mean bed shear stress and thus causes sediment transport [36]. Additionally, the instantaneous evolution of a THV directly results in large fluctuations of the instantaneous bed shear stress. Schanderl and Manhart [37] pointed out that the instantaneous bed shear stresses can reach a maximum amplification factor relative to the far field of up to ten in front of a cylinder, indicating the magnitude of these fluctuations. Regarding the influence of bed shear stress fluctuation, Cheng et al. [38] found that the probability density function of the bed shear stress can be described by the log-normal function, which is helpful to establish the relationship between the fluctuating quantity and sediment transport.

Previous investigations imply that the strong turbulence effects (induced by THV) of the flow around a cylinder on sediment transport cannot be neglected when conducting scour computations, which means that the relationship between the turbulent quantities and the sediment transport rate should be established. The results from Cheng et al. [39] show that the sediment transport rate enhanced by turbulence can be expressed as an exponential function of the relative bed shear stress fluctuation. Sumer et al. [40] proposed an empirical equation representing the influence of turbulence on sediment transport based on extensive laboratory experiments. They mainly focus on uniform and unidirectional flows, however, for the rapidly varied flows with reversal vortices in front of a cylinder, little literature reports on the influence of turbulence effects induced by THV on sediment transport.

The objective of this work is to explore the relationship between the THV and associated bed shear stress in front of a circular cylinder, with the primary aim of elucidating the underlying mechanisms responsible for sediment transport and scour, as well as establishing the link between the THV-induced bed shear stress fluctuation and sediment transport. We focus on the region influenced by the THV in front of the cylinder. The case of a turbulent flow field in front of a circular cylinder mounted on a flat rigid bed is studied experimentally using the PIV technique. Our experiments do not seek to predict the dynamic deformation of the bed and the development of the scour hole but rather to elucidate the THV-induced fluctuation effect and quantify this effect on sediment transport during the initiation of the scouring process when the bed can be assumed to be flat. As for the later stage of scour development, it is hard to measure the flow field in the scour hole by PIV because the camera view is always blocked by the sediment bed [41]. Alternatively, the flow field in the scour hole is normally experimentally studied by using ADV [7], but this is beyond the scope of this study.

The paper is organized as follows: Section 2 presents details on the experimental setup and flow conditions. In Section 3 we discuss the flow characteristics induced by THV, involving the time-averaged flow field and dynamics of THV. In Section 4 the bed shear stress within the THV region is comprehensively analyzed in terms of its instantaneous variation and statistical quantities, as well as the probability density function of the fluctuations. Section 5 emphasizes the influence of bed shear stress fluctuations on sediment transport by comparing different sediment transport rates, and further proposes a new model of sediment transport rate that incorporates this influence. This new model is also validated by comparing the initial scour rate in front of the cylinder. Finally, conclusions are drawn in Section 6.

2. Experimental setup

The experiments were performed in a tilting, water-recirculating, and glass-walled flume, 6 m long, 0.25 m wide and 0.25 m deep, at Bejing Jiaotong University. Flow straighteners were used at the entrance to calm the turbulence water, and a tailgate, positioned at the downstream end of the flume, was used to control the water depth. To

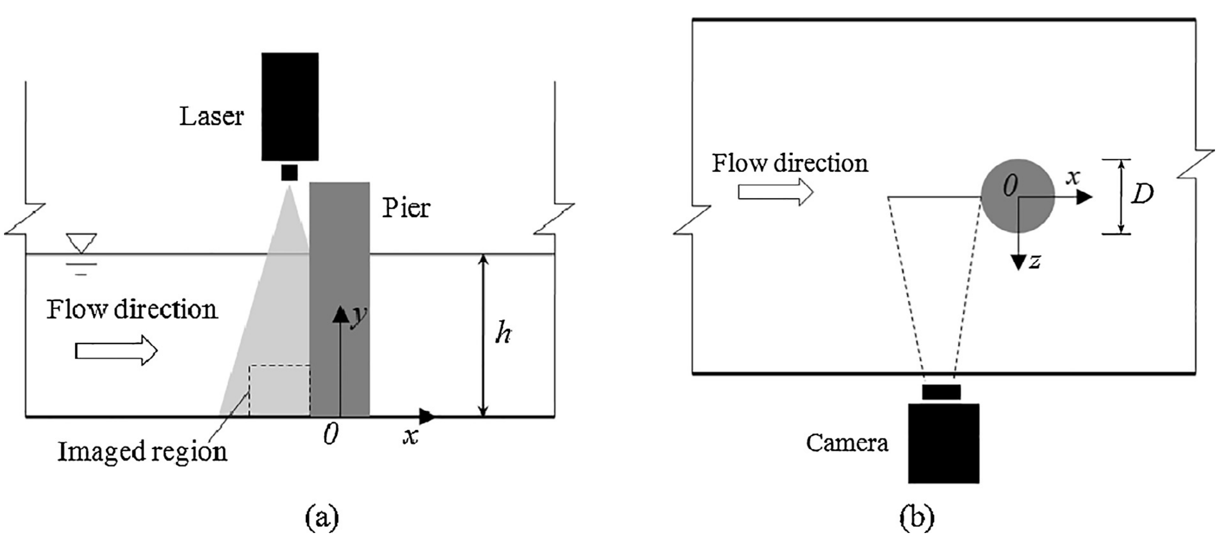

Fig. 1. Schematics of the experimental setup: (a) side view; (b) top view.