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In situ measurement of sediment resuspension caused by propeller wash with an underwater particle image velocimetry and an acoustic doppler velocimeter

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ABSTRACT

Flow induced by propellers of waterborne vessels can cause sediment resuspension in estuaries, bays and harbors, where sediments are usually contaminated. Bottom shear stress due to propeller wash is the key parameter that determines the initiation of sediment resuspension and the subsequent erosion. A novel self-contained underwater miniature particle image velocimetry (UWMPIV) system has been developed and deployed to study sediment resuspension under propeller wash in a US Navy harbor in San Diego, CA. Near bed profiles of mean velocity and Reynolds stresses were measured to evaluate the bottom shear stress, and to validate the shear stress measured with an acoustic Doppler velocimeter (ADV) that is simultaneously deployed with the PIV system. The critical shear stress was estimated by directly observing PIV images and identifying the moment when sediment resuspension started. PIV measurement became unfeasible as the propeller speed increased and the optical access was blocked by high level of suspended solids. However, the development of the bed erosion was able to be recorded in PIV images at several intervals when sediment concentration was relatively low and the sediment bed was visible. The observed time series of cumulative erosion depth agreed well with an erosion rate model that depends linearly on the bottom shear stress excess.

1. Introduction

Contaminated sediment is a serious environmental concern for rivers, lakes, navigation channels, estuaries, coastal bays and harbors. Many persistent contaminants from municipal, industrial and non-point sources are associated with solid particles that can accumulate in bottom sediments, creating a threat to the benthic organism. Sediments can also be resuspended at higher flow rates and pollutants can be released back into the water column to deteriorate the water quality.

In addition to natural forces such as storms and floods, propeller wash and wake of waterborne vessels have been identified to be an major cause sediment resuspension in shallow waters. A number of field studies have been conducted to investigate the propeller induced sediment resuspension in marine environments [1–4]. Most of these field studies reported field specific results that may not be extrapolated to other sites and environments. More recently, some models have been developed to predict the near bottom velocity and shear stress due to the propeller jet flow, which can be applied to various types of vessels. These models combined with field investigation on the erodibility of the sediment can be applied to estimate the total erosion under certain operation conditions. Maynord's model [5,6] is widely accepted for bottom maximum velocity estimation in a propeller wash flow. The model solves the initial exit velocity generated by a propeller and the velocity distribution at far field based on the momentum theory of a jet flow.

The bed shear stress is the most important parameter that links the flow condition to sediment transport. Estimated shear stress can be used to determine both the inception of resuspension (the critical shear stress) and the subsequent entrainment rate. Existing models for propeller wash, e.g., Maynord's model, applies an empirical drag law to estimate the bed shear stress based on the calculated velocity. This conversion is largely based on the theory of turbulent boundary layer in channel flows, usually under a uniform and steady flow condition. Most existing sediment entrainment models are obtained through laboratory flume studies with well-defined flow conditions. The flow field behind a propeller could be extremely turbulent and

Abbreviation: ADCP, acoustic Doppler current profiler; ADV, acoustic Doppler velocimeter; CCD, charge-coupled device; COV, covariance method; CW, continuous wave; DPSS, diode-pumped solid-state; FOV, field of view; PIV, particle image velocimetry; RMS, root mean square; SSC, suspended sediment concentration; TKE, turbulent kinetic energy; UWMPIV, underwater miniature particle image velocimetry

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Nomenclature

C_1	coefficient in TKE method
C_2	coefficient in modified TKE method
C_d	drag coefficient
D	cumulative erosion depth
E	mass erosion rate
E_D	depth erosion rate
k	turbulent kinetic energy
ϵ_M	erosion rate constant
ρ	density of water
ρ_b	dry bulk density of sediment
τ_0	bottom shear stress
τ_c	critical shear stress
κ	Von Karman constant
t	time
U	streamwise mean velocity
u, v, w	instantaneous streamwise, spanwise, and vertical velocity
u', v', w'	streamwise, spanwise, and vertical fluctuating velocity component
u_*	bottom friction velocity
$\overline{u'^2}$, $\overline{w'^2}$	Reynolds normal stress
$-\overline{u'w'}$	Reynolds shear stress
z	height above bottom
z_0	roughness height

unsteady, which differs significantly from that in a channel or river. The accuracy of models is still questionable as few field data is available to validate the predicted bed velocity and shear stress induced by a propeller jet in real environment.

It is difficult to quantify the bottom shear stress and its relation to sediment transport, particularly in complex flow fields where flow is highly three dimensional and transient, such as that in a propeller wash flow. Although methods exist to directly measure bottom shear stress with appropriate sensors, such as a shear plate [7,8], these methods are rarely applied in field experiments due to technical difficulties. In situ measurement of bottom shear stress usually relies on indirect estimation based on flow velocity measurements [9]. These methods have been well documented by Biron et al. [10], and they are summarized below. Here the bottom shear stress is denoted as τ_0, or represented by the equivalent frictional velocity $u_* \equiv \sqrt{\tau_0/\rho}$, ρ is the water density.

1. *"Law of Wall" or the "Log law"*: The shear velocity u_* is obtained by fitting the measured velocity profile by $u(z) = (u_*/\kappa)\ln(z/z_0)$, where $\kappa = 0.41$, the von Karman constant, and z_0 is the roughness height. This method requires an instrument that can measure the profile of velocities, such as a series of ADVs or and ADCP. One advantage is that it can obtain the bottom roughness along with the bed shear. However, the result is sensitive to the estimation of height z above the reference level $z=0$.
2. *Quadratic stress law*: $\tau_0 = \rho C_d U^2$, where C_d is the drag coefficient. This method is simple as it requires measurement of mean velocity at one spatial point. It is highly empirical as there is no general rule to accurately estimate the drag coefficient, which generally varies with the Reynolds number and depends on the geometry of the bottom roughness. There is also no general rule on the height of the flow measurement above the bed.
3. *Direct covariance method (COV)*: $\tau_0 = -\rho\overline{u'w'}$, where u' and w' are fluctuating velocity components in the streamwise and vertical directions, and the overline represents ensemble averaging. It directly measures the Reynolds shear stress as an estimate of bottom shear with least assumptions and there is no need to specify the bottom roughness. This method can be easily implemented with a point-wise velocimeter, such as an ADV probe. However, there are no general rules on the height of the measurement point above the bed, and the result can be biased due to sensor tilt.
4. *Turbulent kinetic energy (TKE)* method: $\tau_0 = C_1\rho k$, where $k \equiv \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$, the TKE, and the coefficient $C_1 = 0.19$. Similar to the COV method, the TKE method can be applied with an ADV and does not require the estimate of bottom roughness. The estimation of coefficient is C_1 is from the known ratio between TKE and the Reynolds shear stress observed in typical wall turbulent flow, but its value may vary in different environment.
5. *Modified TKE method*: $\tau_0 = C_2\rho\overline{w'^2}$, where $C_2 = 0.9$. The modified TKE method could be more reliable than the TKE method for an ADV probe, which usually measures the vertical component (along the direction of emitting ultrasound wave beam) with higher accuracy and lower noise.

It should be noted that all these methods are indirect. The instantaneous bottom shear stress is itself a random variable. It is related to the near bottom turbulence in a statistical sense, which depends on the temporal and spatial scales. We suppose that statistical values obtained over a longer period will produce a better estimation on the mean shear stress, but will also miss peak values which are significant for the prediction of sediment entrainment and erosion rate. For unsteady flows, such as the propeller jet induced current, longer sampling time may include the transient processes into the calculation of Reynolds stresses.

The critical shear stress and the subsequent erosion rate are largely determined by the physical and chemical properties of the sediment bed, such as the grain size, sorting, bulking density, pH, and the organic content. They are also significantly affected by the local aquatic environment. It is always necessary to conduct in situ field experiment for the best estimation of sediment erodibility. In situ flumes with artificially induced flows have been widely applied to estimate the bed stress and erosion rate [11–13]. Usually, measurements of suspended sediment concentration (SSC) is required along with the velocity measurement to determine the inception of sediment motion and the subsequent erosion rate.

In this paper, we present the application of a novel self-contained underwater PIV system that measures sediment resuspension under different propeller wash conditions. As an imaging-based instrument, PIV images enabled us to visualize the resuspension and erosion processes along with detailed near-bed flow and turbulence measurements. An ADV probe was also deployed along with the PIV system for comparison, and to provide flow data when PIV measurements were not available due to blurred images caused by high level of resuspension.

2. Apparatus and experiment setup

During past decades, many attempts were made to introduce the PIV technique into field applications. Several self-contained, fully or partially submersible in situ PIV systems were developed and applied in natural aquatic environments [14,15]. We have recently developed a battery-powered, self-contained under water miniature PIV (UWM-PIV) system which has been successfully applied to measure small-scale hydrodynamics in the bottom boundary layer and surface