Rapid Profiling of an Evolving Bed Form Using Planar Laser Sheet Illumination

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Abstract: Traditional methods of measuring the profile of a scour hole or bed form have poor temporal resolution and may require the temporary cessation of the flow in order to be executed. These are undesirable characteristics since many hydraulic flows have unsteady water-sediment interfaces that can display considerable differences between their “dynamic” (flow on) and “static” (flow off) states. The present technical note discusses the application of planar laser sheet illumination to the erosion of a cohesionless granular bed due to a planar turbulent wall jet. The measurements allow for the quantitative study of the evolution of the bed in its earliest stages. In some cases an ephemeral bed form is observed to form prior to the development of the main bed form. Additionally, the measurements illustrate the oscillatory nature of the bed form under certain conditions. The experiments therefore demonstrate the great potential of this experimental technique for gaining previously inaccessible information on scour processes.

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Introduction

Hydraulic scour affects many natural and engineered open channel environments. From a design and management point of view, an understanding of the relationship between scour characteristics, such as bed form shape, size, and rate of growth, and the flow and sediment characteristics is desirable.

The particular case of scour due to horizontal wall jets is a relatively mature field of research. In this configuration, a bed form consisting of a trough, or scour hole, and a crest, or dune, is created just downstream of the jet nozzle. Rajaratnam (1981), Ali and Lim (1986), Ali and Neyshaboury (1991), Chatterjee et al. (1994), Balachandar et al. (2000), Kells et al. (2001), Dey and Sarkar (2006), and Hill and Younkin (2006) all presented data and, in some cases, empirical predictive equations related to various bed form characteristics, such as length, height, scoured volume, etc.

Regarding the rate of growth, several of the above studies have demonstrated that very long times may be required for a bed form to eventually attain an equilibrium state. At mid- to late stages of growth, the rate of change is very slow, permitting the use of “manual” bathymetric surveying methods such as point gauges (e.g., Ali and Lim 1986) or sidewall tracing (e.g., Chatterjee et al. 1994; Dey and Sarkar 2006).

Obtaining bathymetric information during the very early stages of growth poses a greater challenge. The present and previous studies demonstrate that a bed form can attain a substantial fraction (>50%) of its equilibrium size in a very short time [O(0.01–0.1 %) of the time required to reach that equilibrium]. Additionally, several studies (Johnston 1990; Balachandar and Kells 1997; Balachandar et al. 2000; Bey et al. 2007) have demonstrated that the bed form profile can be highly “dynamic,” or unsteady, oscillating between the so-called digging and filling phases. Finally, Balachandar and Kells (1998) performed an important study in which they used video imaging of the sidewall of their experimental flume to capture the evolution of the bed form.

The present Technical Note reports on the use of planar laser illumination in the determination of bed form geometry during the earliest stages of jet scour. This method provides for nonintrusive measurements with high spatial and temporal resolution. From a scour perspective, the present study distinguishes itself from Balachandar and Kells (1998) in that the measurements are on the flume centerline and therefore unaffected by sidewall effects. Additionally, the reported results are more continuous in time, yielding a more complete look at the developing bed form.

Variants of this experimental method have been used previously for applications ranging from pier scour in steady open channel flow (Roulund et al. 2005) and oscillatory flows (Faraci et al. 2000; Baglio 2003) to ripple generation beneath progressive surface waves (Nichols and Foster 2007) to mine burial applications (Voropayev et al. 2003). In most of these studies, however, the method was used on a fairly coarse time scale, or simply to obtain a “before” and “after” look at a sediment bed profile. The work of Soares-Frazao et al. (2007) was particularly notable both for the improved temporal resolution and for the complexity of the flow, which was that of a dam break eroding a sediment bank. From an experimental methods perspective, the present study distinguishes itself from the above studies in that it more fully demonstrates the utility of the method. The obtained results have a finer temporal resolution and, as a result, are able to capture transient features that would otherwise go unnoticed.
Methods

Facilities

The experiments were carried out in the horizontal flume illustrated in Fig. 1. Note that both a photograph and a schematic of the experimental facility are provided. A pump (not shown) recirculated water through a planar nozzle aligned with and flush with the upstream edge of a sediment bed. The nozzle had a smooth taper and a variety of flow straighteners in an effort to ensure a laterally uniform exit velocity. The maximum Reynolds number of the flow, based upon the nozzle gap height of 1 cm, was approximately 8,000. In all experiments the free surface was 25 cm above the nozzle exit. The sediment bed was 1 m long, 10 cm high, and spanned the full width of the flume. Glass beads (Ballotini Impact Beads, Potters Industries, Malvern, PA) were used in order to obtain a nearly uniform grain size distribution. The specific gravity of the glass beads was 2.5 and two different diameters (0.200 and 0.725 mm) were studied.

Imaging of the sediment bed was accomplished using a four megapixel, 12-bit digital camera (PowerView 630149G) and a 120 mJ pulse−1 Nd:YAG laser. A synchronizer was used to facilitate timing of the laser pulse and image acquisition and images were acquired and stored using Insight software (TSI, Inc., v.3.53, Shoreview, MN). Standard optics were used to form and direct the laser light sheet vertically from above the flume to the sediment bed. The light sheet was coincident with the lateral center plane of the flume and a shallow glass “pan,” which was held level and rigidly in place, was used to prevent refraction of the laser sheet by ripples on the free surface of the water. Due to the high reflectivity of the glass beads, a relatively narrow camera aperture was required in order to avoid the saturation of the camera pixels. Limited tests with natural sand revealed that adequate illumination could be attained with a wider aperture and/or greater laser power.

The camera was aligned so that the optical axis was perpendicular to the flume sidewall and the camera field of view (FOV), also referred to as the object plane, covered a region about 20 cm × 20 cm. This yielded a spatial resolution of 0.1 mm pixel−1. The FOV was aligned to capture the region immediately downstream of the nozzle and the vertical centerline of the FOV was elevated slightly above the initial bed surface in order to allow a clear line of sight to the middle of the flume.

Procedures

Before beginning an experiment, a calibration image was taken to allow for the relation, or mapping, between the image coordinates of the image plane (camera pixel array) and the world coordinates of the object plane (FOV). In studies (e.g., Soares-Frazao et al., 2007) where the camera optical axis is at an angle to the flume wall, significant distortion is encountered and must be corrected for. In the present study, where this axis is perpendicular, this distortion is minimal. As discussed by Soloff et al. (1997), in the particular context of particle image velocimetry (PIV), perspective distortion is small either if the imaging is paraxial or if the “out of plane” displacements are small. In the present study, the first of these conditions is weakly satisfied and the second is fully satisfied. Therefore, a simple calibration, where a scaled rule was used to determine the world coordinate origin and the constant magnification, sufficed.

For a given experiment, the pump was then turned on and images were obtained, at a rate of 0.67 Hz, for approximately the first five minutes of the scouring process. Results for the longer-term behavior of the bed form are given by Hill and Younkin (2006). The data from the first 5 min yielded ~200 images per trial. A sample raw image is provided in Fig. 2. Note that the bright line indicating the location of the water-sediment interface was consistently 10–20 pixels thick. Postprocessing included converting the images to world coordinates and then locating the water-sediment interface. Profiles of pixel intensity along vertical lines revealed that the distribution of intensity through the region corresponding to the water-sediment interface was roughly Gaussian. The vertical location of the peak intensity was then taken as the location of the bed surface. Finally, a 1-cm sliding average filter was applied in the horizontal direction in order to smooth the derived profile.

Experiments were carried out for the two sediment sizes described above and for several flow rates. A summary of the experimental matrix, including calculated values of the nozzle Reynolds number and the densimetric Froude number is given in Table 1. The Reynolds number is given by

\[ Re = \frac{V h}{\nu} \]

where \( V \) = nozzle exit velocity; \( h \) = nozzle gap height; and \( \nu \) = kinematic viscosity of water, and the densimetric Froude number is given by

Fig. 1. (a) Photograph; (b) schematic representation of experimental flume

Fig. 2. Sample raw image showing the intersection of the sediment bed and the laser sheet
\[ F_o = \frac{V}{\sqrt{g \frac{\Delta \rho}{\rho} d}} \]  

(2)

where \( \rho \) = fluid density; \( \Delta \rho \) = density difference between the fluid and the sediment; and \( d \) = grain diameter.

**Experimental Uncertainty and Limitations**

For most experimental trials the uncertainty of the measurements was comparable to other recent studies. The scattering of the laser light from the rough bed yielded a line on the order of 1–2 mm in width. Similar values have been reported by Faraci et al. (2000) and Baglio (2003). Traditional bed surveys with manual point gauges are more accurate than this submillimeter precision but are far more time consuming. Trials with high values of \( F_o \) (in excess of approximately 10) were characterized by significant amounts of suspended sediment. In these trials, the suspended sediment resulted in significant shadowing of the sediment bed. This in turn led to unsatisfactory imaging of the bed, highlighting the suitability of the present experimental method to predominantly bedload transport applications.

**Results**

Figs. 3–5 show sample experimental results in the form of plan and perspective views of “carpet” plots of the evolving bed form. For each trial the individual two-dimensional profiles on the flume centerline have been combined to show the temporal evolution of the bed form. The three-dimensional perspective view is useful in showing the vertical relief of the scour hole and dune geometry.

Fig. 6 shows, for the particular case of Trial 4, the time history of the distance from the nozzle orifice to the dune crest and the per-unit-width volume of sand removed from the scour hole. The present data (closed symbols) have been combined with later stage data (open symbols) obtained with the manual tracing of profiles on the flume sidewall.

**Discussion**

Fig. 3 shows the temporal evolution of the bed form profile for the lowest \( F_o \) case. In addition, the streamwise location of the point of maximum elevation has been tracked and is shown by a thick black line. One item of interest is that, prior to the development of the main crest, a short-lived transient crest evolves in the first few seconds of the experiment. This ephemeral crest soon propagates out of the field of view and subsequently decays. This occurs at about \( t=70 \) s and corresponds to the sharp discontinuity in the black line. Fig. 5, showing results from one of the fine sediment experiments, more clearly shows the development of this initial and short-lived morphological feature. In this case, the initial crest propagates out of the field of view at about \( t=100 \) s.

A second item of interest is that the main face of the bed form (the sloping region between trough and dune) may begin to oscillate with a regular period, depending upon the experimental conditions.
Concluding Remarks

The present Technical Note amplifies the value of planar laser sheet imaging when it comes to studying rapidly developing and highly unsteady bed forms. The specific goal of the present study is to image the scour due to a planar wall jet. The high temporal resolution of the method reveals transient features that can not be detected with traditional methods of profiling a bed. Additionally, the measurements are made while the flow is on, allowing for the “dynamic” profile to be captured. The experiments suggest that the use of rapid laser sheet imaging is presently limited to flows with minimal suspended load. The method has considerable flexibility in that the laser sheet and the camera, with proper calibration, can be positioned in a variety of configurations. This flexibility overcomes many constraints of optical access and broadens the applicability of the method to numerous scouring applications.

References


