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3D Measurement of Water and Bed Surface Shapes During the Formation of Sand Waves Using the Moving Optical Cutting Method

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ABSTRACT

This study aims to develop a three-dimensional measurement method for flume experiments involving both water- and bed-surface shapes and evaluate measurement accuracy during the formation of sand waves. An experiment on flow through a bed with an array of hemispheres and two movable bed experiments under hydraulic conditions wherein sand dunes and sandbars were formed were conducted. The measurements confirmed that water- and bed-surface shapes can be tracked at spatiotemporal high resolutions during the formation of sand waves, suggesting that the developed measurement technique is useful for investigating the mechanics of sand waves.

KEY WORDS: Moving optical cutting method; Sand waves; Photogrammetry; Water surface measurement; Bed-surface measurement

INTRODUCTION

Sand waves are three-dimensional (3D) undulations on the bottom of a river or the sea along the longitudinal and transverse directions. Such undulations often form on both bed and water surfaces; they arise and move because of interactions between water flow and sediment transport and rarely settle into position even after long time intervals. Based on these characteristics, it is necessary to obtain 3D water- and bed-surface shapes from the water flow with high spatiotemporal resolution in order to grasp the physical mechanics of sand waves.

In recent years, several types of remote sensing techniques have been developed to obtain water- and bed-surface shapes. For instance, Coleman (1997) used an acoustic bed profiler to measure submerged topography; Butler et al. (2002) validated a stereophotogrammetry technique through water measurement, and Bertin and Friedrich (2014) compared an acoustic bed profiler, a hand-held laser scanner, and a stereophotogrammetric system for obtaining water-worked gravel bed topographies. Despite these advances, there is still no technique that can simultaneously measure the fluctuations of water- and bed surfaces during the formation of sand waves.

This study aims to develop a flume experiment-based 3D measurement method that allows for the simultaneous measurement of water and bed surfaces with high spatiotemporal resolution during water flow. The current measurement method, which is called the moving optical
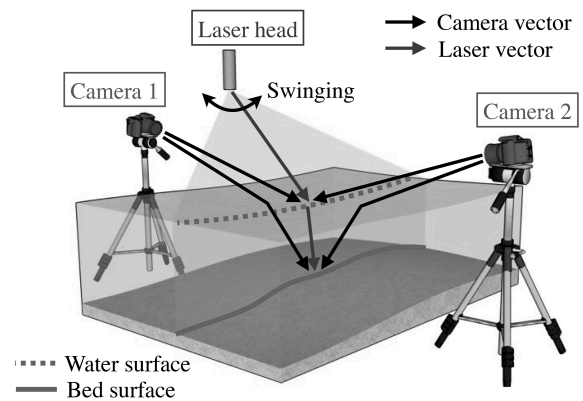

Fig. 1 MOCM Equipment Components

cutting method (MOCM), is based on photogrammetry. Using MOCM, it is possible to simultaneously measure both water- and bed-surface shapes through contactless measurement without draining or suspending the water supply. These characteristics make it possible to grasp the relationship between water- and bed-surface shapes without interference arising from drainage or contact. Our study was conducted to evaluate the accuracy of MOCM via fixed-bed flume experiments and verify the possibility of assessing the mechanics of sand waves via movable-bed flume experiments simulating the hydraulic conditions under which anti-dunes and alternate bars form.

MOVING OPTICAL CUTTING METHOD

Equipment

The equipment of the MOCM (Fig. 1) comprises a laser oscillator, a laser head, and two digital cameras. The laser head is attached to a swinging mount placed above the flume; it projects a longitudinal laser beam onto the water- and bed surfaces to visually distinguish the respective surfaces. The swinging mount swivels the laser head repeatedly and with constant angular velocity, enabling the laser beam to scan the full width of the flume at a high sweep speed. The digital cameras are placed on each side of the flume to capture consecutive photographic images without blind spots.
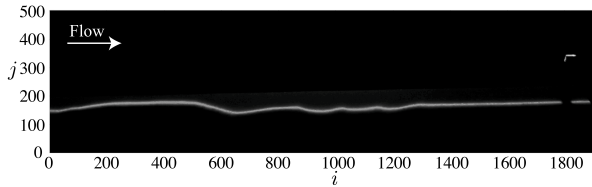
Measurement Principle

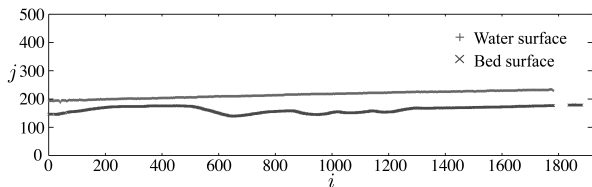Fig. 2 Bright green pixels extracted from raw picture

Fig. 3 Distinguished water- and bed-surface pixels

The MOCM principle is based on using triangulation to measure an object's surface coordinates from two known vectors and their starting point coordinates. Measurement of a water surface is based on a simple geometric relation that represents laser light and camera rays as 3D vectors and calculates the intersection point of two vectors as water surface coordinates. To measure a bed-surface profile, it is necessary to consider the refraction of the two vectors on the water surface, which involves instantaneous deformation of the vectors in open channel flow. Thus, the MOCM process uses the water-surface shapes derived as above to calculate the two refraction vectors and their intersection point as bed surface coordinates.

Setup

The laser oscillator is a 532-nm wave length YAG laser with the swinging mount set to a 0.075 rad/s reciprocating swing and placed 193 cm above the flume bed. In this setting, the laser beam on the flume bed moves in the transverse direction at approximately 15 cm/s. This study uses a 30 cm width flume, resulting in a laser beam sweep time from the left to the right end of 2 s.

The two digital cameras have resolutions of 1,920 × 1,080 pixels each and a shutter speed 1/500 s and are set to 30 fps. The cameras' intrinsic and extrinsic parameters are calibrated using Zhang's calibration method (Zhang 1998).

The water used in the experiments is colored green by dissolving in Fluorescein sodium salt to form clearly recognizable luminescence at the intersections between the water surface and the laser light.

Procedure

Taking Consecutive Photographs

In the initial measurement process, the swinging mount rotates the laser head and the two digital cameras take consecutive images. A sample picture is shown in Fig. 2.

Image Analysis

In the following process, pixels where the laser light crosses the water- and bed surfaces are distinguished in the photographic results.

The pixel numbers where the laser light crosses the water surface (iw, jw) are distinguished by threshold values of brightness in the green gradient in the pictures. In the same manner, the pixel numbers at which the laser light crosses the bed-surface (ib, jb) are distinguished as positions of maximum green brightness. An example of distinguished pixels is shown in Fig. 3.

Calculation of a Water-Surface Shape

In the third process, water-surface coordinates are calculated based on image geometry.

In an advance preparation step, the light beam-water surface intersection points (iw, jw) and the laser head swing angle are converted to a camera vector and a laser vector that intersect a water surface. A water-surface longitudinal profile is then calculated based on the geometric relation shown in Fig. 1. Using consecutive images obtained while the laser head projects the laser beam across the full width of the flume, it is possible to obtain multiple longitudinal water-surface elevations for different sections across the flume. Combining these results makes it possible to construct a 3D water-surface profile. As this process is conducted, images are obtained by the two side cameras, producing sets of simultaneous 3D water-surface representations from each side; when merged, these produce an overall 3D water-surface that has no blind spots because the two images' measuring areas overlap their respective dead angles. Finally, the resulting data are converted into equal-interval structured data as inputs into the next process.

Calculation of a Bed-Surface Shape

In the final process, bed-surface coordinates are calculated based on a geometric relationship that considers the refraction of light on a water surface.

Each coordinate of the bed-surface is calculated based on the geometric relation shown in Fig. 1 As a preparatory step, the light beam-bed surface intersection points (ib, jb) and the laser head swing angle are converted to a camera vector and a laser vector that intersect the bed-surface. The incidence vectors from the laser head or cameras are refracted onto a water surface and the resulting reflectional vectors intersect at a bed-surface. The reflectional vectors are calculated as follows: 1) the intersection points of each vector with the water surface are calculated, and 2) using Snell's law, reflectional vectors are calculated using the water-surface shape estimated in the preceding process. Using the two reflectional vectors makes it possible to obtain longitudinal bed-surface elevation, from which a 3D bed-surface can be derived in a manner similar to that used for the calculation of a 3D water-surface shapes.

APPLICATION TO FIXED BED OPEN CHANNEL FLOW

To verify the validity of the MOCM, we conducted an experiment on flow through a bed with an array of uniform hemispheres with a topography similar to that of dunes in which we measured water-surface shapes and the channel bed form using the MOCM.
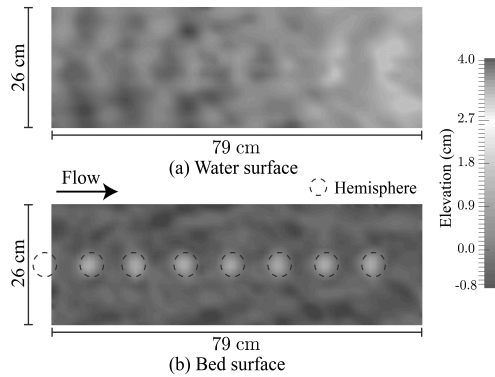
Experimental Setup
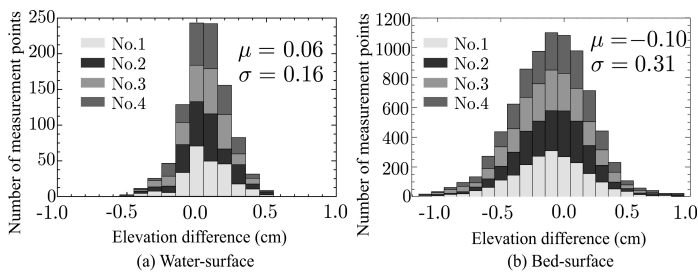

Fig. 4 Measurement results (No.1)

Fig. 5 Histogram of the measurement results

Results

Fig. 4 shows the measured water- and bed-surface shapes at a resolution of 1 cm × 1 cm. Fig. 5(a) shows a histogram of the differences between the point gauge and MOCM measurements in terms of water-surface elevation, and Fig. 5(b) shows the differences between the actual and MOCM-measured bed-surface elevations. For the water-surface measurement, the average elevation difference (μ) and variance (σ) were 0.06 and 0.16 cm, respectively; for the bed-surface measurement, these figures were −0.10 and 0.31 cm, respectively. The bed-surface measurement has lower accuracy than the water-surface measurement because it uses the water-surface measurement as an input, thereby adding a propagating factor to the latter's error. However, the presence of the hemispheres was reflected in the measured water-surface shape and the artificial undulations were precisely measured, indicating that the proposed measurement setup can measure both types of 3D surface during the formation of sand waves with adequate accuracy.

APPLICATION TO MOVABLE BED OPEN CHANNEL FLOW

(a) Water surface (b) Bed surface

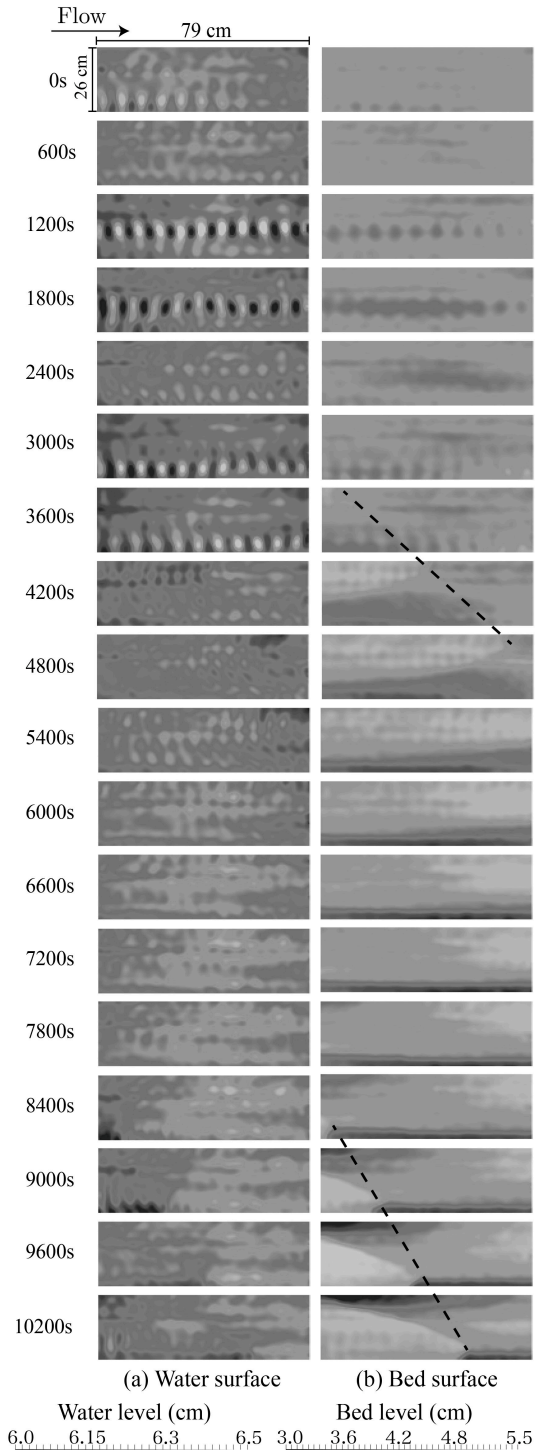Water level (cm)   Bed level (cm)

Fig. 6 Measurement results (Run1)

Experimental Setup

In this experiment, we set two types of hydraulic condition in terms of

water discharge and sediment supply quantity to create sand waves at different scales. In Run1, the water discharge was set to 1.3 l/s and the sediment supply quantity was 1.92 g/s. In Run2, these factors were 4.0 l/s and 2.95 g/s, respectively. The flume condition was the same as that in the preceding chapter, except that the bed gradient was 1/200. The sediments had an average width of 0.76 mm and were spread onto the flume bed at a thickness 5.0 cm. The total experiment times were 10,200 s (Run1) and 2,040 s (Run2), and the measuring interval was 2 s.

Fig. 7 Measurement results (Run2)

Results

Run 1(Discharge: 1.3 l/s)

Figure 6 shows the measurement results for Run1. Up to 3,600 s, the amplitudes of the water- and sand-waves were 0.5 and 0.4 cm, respectively; anti-dunes with a 7.5 cm wavelength were formed, but no

alternate bars formed during this initial period. After 3,600 s, a sandbar with an accumulated 0.4 cm was formed on the left side of the flume. This change in measurement result over times could be used to determine the wave velocity of sand waves; the dotted line in Fig. 6 shows that the sandbar moved downstream at 0.051 cm/s. After 8,400 s, a sandbar formed on the right side of the flume and began to move downstream at 0.028 cm/s. The formation of periodic undulations on the sandbars may mean that alternate bars formed simultaneously with dunes.

Run 2(Discharge: 4.0 l/s)

Fig. 7 shows the measurement results for Run2 between 1,928 and 2,032 s at intervals of 8 s. During this time span, periodic undulations formed on both the water and bed surfaces. These undulations can be considered anti-dunes because both periodic waves were in phase. The undulations on the water surface amplified or reduced repeatedly with a maximum wave amplitude of 1.6 cm and a growth and reduction period of approximately 25 s. The dotted line in Fig. 7 shows a growing water-wave moving downstream at 2 cm/s. Thus, the results obtained by the MOCM are useful in showing rapid fluctuations such as those occurring in this experiment.

CONCLUSION

We developed a new method for the 3D measurement of water- and bed-surface shapes to better understand the physical characteristics of sand waves. We evaluated the accuracy and effectiveness of the proposed measurement method by applying it in three flume experiments.

In the first assessment, the accuracy of the MOCM was evaluated during the formation of sand waves. We conducted an experiment on the flow through a bed with an array of uniform hemispheres with a topography similar to those of dunes in order to measure the water-surface shape and channel bed formation using the MOCM. The measured results agreed with the water- and bed-surface shapes, confirming that the MOCM can be used to measure water- and bed-surface shapes during the formation of sand waves.

Next, the effectiveness of the proposed method in measuring sand waves was confirmed via two movable bed flume experiments conducted under hydraulic conditions wherein sand dunes and sandbars formed. The measurements confirmed that water- and bed-surface shapes can be spatiotemporally tracked at high resolutions during the formation of sand waves. This suggests that the MOCM is a useful technique for investigating the mechanics of sand waves and confirming the validity of physical models.

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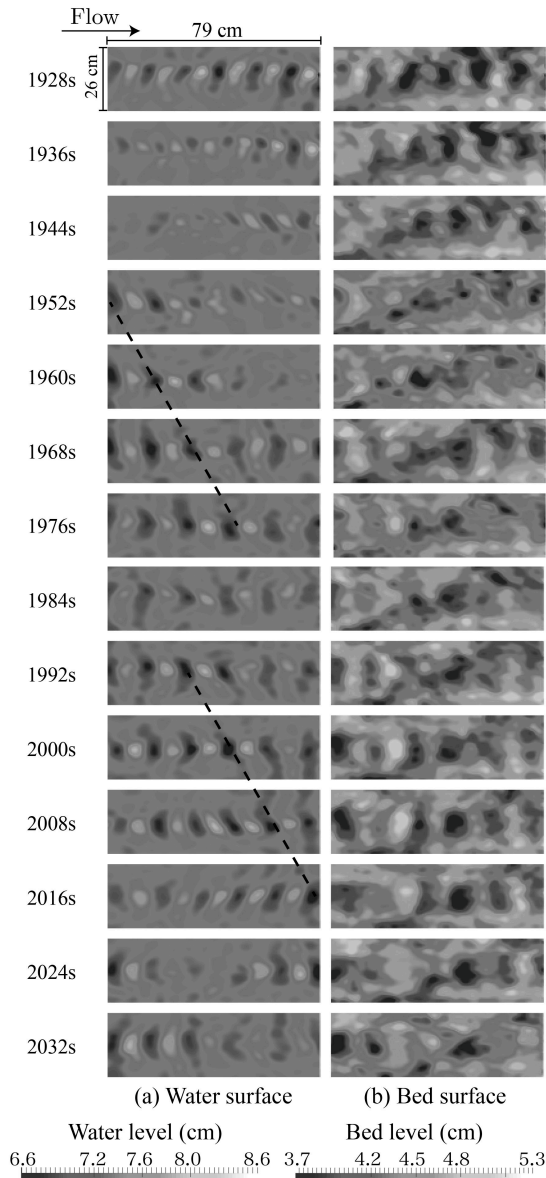Zhang, Z. (1998). A flexible new technique for camera calibration. IEEE T. Pattern Anal., 22(11), 1330-1334.