A non-touch sensor for local scour measurements

Capteur sans contact pour mesures d'érosion locale

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ABSTRACT
A diffuse light intensity photocell coupled with a fiber optic was tested as a non-touch switch sensor for bottom profiling. The device is inexpensive and robust. When mounted on a mechanical positioning carriage it allows continuous scour measurements underwater. Only the fiber optic is immersed in water; therefore the sensor is little intrusive and can be easily used in proximity of side walls. Control tests on a fixed shape showed that the accuracy of the system is appropriate for measurements of local scours. The apparatus was successfully used during mobile bed scour experiments, allowing highly detailed measurements.

RÉSUMÉ
Nous avons couplé une cellule photoélectrique mesurant l'intensité lumineuse diffuse à une fibre optique et l'avons utilisée comme capteur sans contact pour la profilométrie des fonds. L'appareil est robuste et bon marché. Lorsqu' il est monté sur un support de positionnement mécanique, il permet, sous l'eau, la mesure en continu de l'érosion; comme seule la fibre optique est immergée, le capteur est peu intrusif et peut facilement être utilisé auprès de parois latérales. Des tests effectués sur des profils connus ont montré que la précision du système est adaptée à des mesures d'érosion locale. L'appareil a pu être utilisé avec succès pour des expériences sur des lits mobiles, fournissant des mesures très détaillées.

1 – Introduction

Typically, local erosion phenomena are characterised by complex scour patterns, evolving over very long time spans (days → weeks, see for example [1]-[3]). A device for scour surveys, therefore, should operate with repeated measurements at certain locations; if the instrument is required to be dipped under the water surface, it should be as little intrusive as possible, with respect to both the flow field and the bottom grains; finally, in local scour experiments the distance between water surface and the bottom may vary up to an order of magnitude: hence, a wide measuring range is often required.

The use of manual point gauges and/or visual inspection for scour depth measurements is very simple but puts an obvious constraint to the number of measures that can be taken and to their temporal frequency; moreover such methods require a visual access to the scour hole. Therefore, automatic systems are preferable for detailed surveys.

Optical triangulation sensors may be used for accurate point distance measurements underwater [4]. Unfortunately, their measuring range is a fraction of their nominal operating distance, so that they must be coupled with a vertical positioning system which dips them into the hole as scour depths increase; in such conditions waterproofness and intrusiveness may become problematic.

Different image analysis techniques have been used for scour monitoring; such methods allow for simultaneous measurements over a section or an area, but typically either require a lateral optical access [5]-[6] or operate in the absence of free surfaces [7]. Due to the complexity of the system, it may be difficult to achieve automatically repeated measurements on different sections.

Acoustic sensors (sonars) are an obvious choice for underwater distance measurements and typically they have wide operation ranges; therefore, they are widely used for field scour monitoring (see, for example, [8]-[11]). Examples of the use of such systems in laboratory flumes seldom occur in the literature, possibly because laboratory acoustic sensors are not easily available on sale and/or they may be excessively intrusive. Reference [12] does not provide any specification of the ultrasonic sensor used for the experiments; an acoustic sensor was unsuccessfully tested in [13] for clear water scour measurements around abutments; the SedBed Monitor [14] is proposed for measurements of bedforms but it has been used also for surveying local scour holes [15].

If a vertical carriage is available, the distance sensor can be substituted with a simple switch that halts the vertical movement at a fixed distance from the bottom. While the experiment is running, bottom grains are inherently unstable so that touch devices [16] may be too intrusive; the same is true for conductivity non-touch devices [17]-[19], since their low sensitivity only allows for very small clearances between the sensor and the bed. It should also be considered that the intense sediment flux at the beginning of the scour process and/or for severe live bed conditions may damage a probe which does not operate at a safety distance from the bottom surface.

In this note we describe a simple non-touch optical switch device which can be mounted on a mechanic positioning system for continuous measurements of scours in movable bed experiments. The probe is robust and inexpensive; it has small dimensions and operates at a distance of 1÷2 cm from the bed, thus creating little disturbance to both the flow and the grains.

2 – Surveying device

The bottom profiling system consists of a computer-controlled three-axis positioning system (maximum positioning uncertainty

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= 0.1 mm) and a proximity optical sensor (Baumer Electric FZAM 18P6460/S14) connected to a fiber optic (Baumer Electric FUE 100A1011). The fiber has a tip diameter of 3 mm and is inserted in a 100 cm long brass pipe with an external diameter of 10 mm (fig. 1). Only the pipe and the fiber are immersed in water, while the sensor is kept over the surface (fig. 2).
The photocell generates an infrared ray, which is reflected by a surface placed in front of it; the fiber conveys both the direct and the reflected light. The photocell is sensitive to the incoming light intensity, which depends on the distance between the fiber tip and the reflecting surface. As the fiber reaches the preselected sensing distance (i.e. the preselected light intensity), the sensor changes its out voltage value and halts the descending movement of the positioning system.
The nominal sensing distance (in air) for this sensor-fiber couple is 35 mm; water reduces sensing distances of approximately 50%. For the scour measurements described in this paper (in water, sediment bottom) the sensing distance was approximately 15 mm. This value can be changed with different sensor-fiber combinations.
Several tests were run to verify the features of the device. Sand grains of approximately uniform size (median size diameter d_{50} = 1.9 mm) were glued on a fixed shape. Profiles of the test shape measured in air and in water are shown in figure 3: differences between the measured values and those of the manual survey (precision point gauge), which can be considered as the reference profile, are distributed on a normal with variance σ = 1.7 mm. The uncertainty is considered to be fully acceptable if compared to the grain dimensions. The system showed full repeatability of measurements for constant operating conditions (maximum scatter ± 0.1 mm, equal to the positioning error of the carriage); no sensitivity to variation of external lighting was observed.

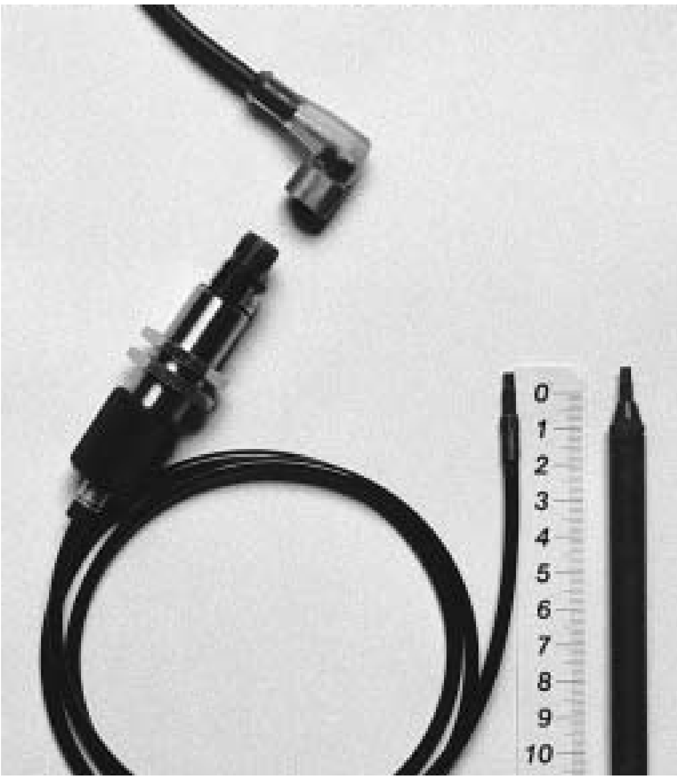

Fig. 1. Measuring device. The photocell is connected to the optic fiber; electric connection on the top. The brass pipe ending with the fiber tip is shown on the right side of the rule (scale in cm).

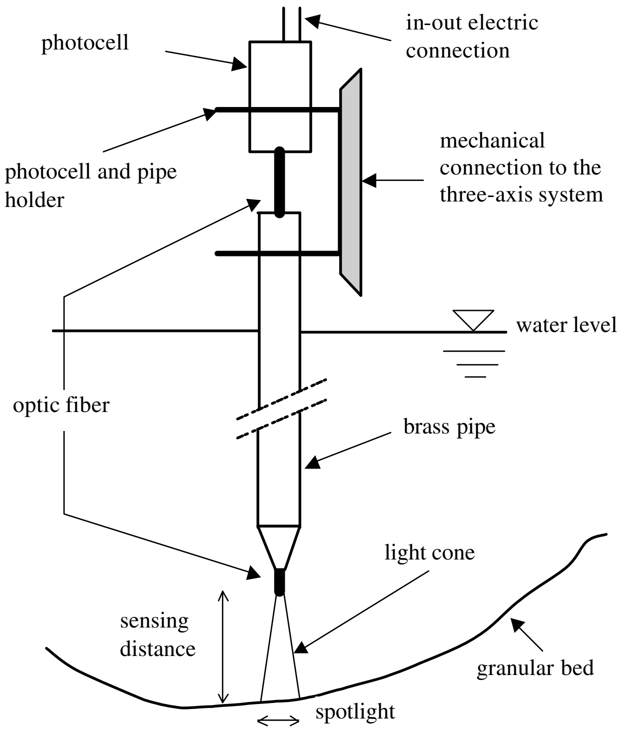

Fig. 2. Schematic diagram of the experimental device.

An univocal definition of the spatial resolution of the optical device is not straightforward. The light cone exiting from the fiber has a very small angle, so that the spotlight has a diameter of approximately 3÷4 mm for an operating distance of 10÷20 mm from the surface. Specific tests, however, showed that the device is sensitive to indirect reflections over a larger area, whose size depends on the nature of the surface. While measuring sediment surfaces, this area was estimated to have a radius smaller than 10 mm for the worst conditions (vertical reflecting surface beside the fiber). As a matter of fact, the system was able to correctly identify the limits of the 45° slope of the test shape in figure 3. Higher spatial resolution may be achieved by reducing the sensing distance.

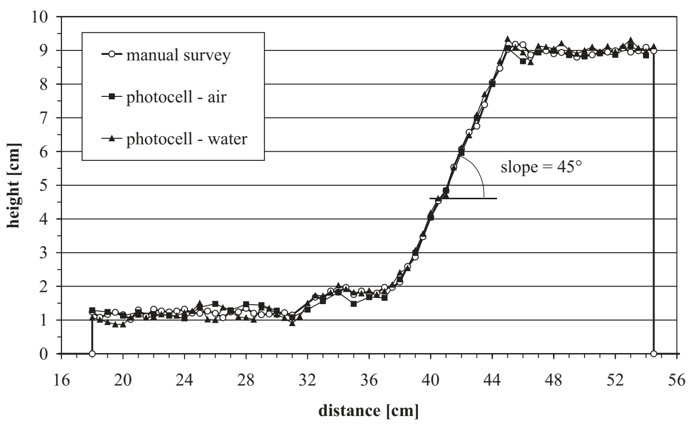

Fig. 3. Comparison of profiles of a fix shape covered with sediments.

The intensity of the reflected light which enters the photocell depends on the measuring distance but also on the surface characteristics (reflectance); this may limit the use of intensity optical devices as proximity sensors. The system was tested over smooth surfaces with decreasing reflectance; as the surface colour was progressively varied from white to black, the sensing distance diminished of about 5 cm. This problem was automatically overcome when operating over sediments: in spite of the colour variation of the grains (randomly spread from white to black, with some percentage of yellow-brown), the profiles in fig. 3 do not show any particular dispersion and/or irregularity. The reflected light entering the fiber comes in fact from a sufficiently large number of grains, thus resulting in a stable median colour; such an averaging effect may be enhanced by the diffusive effects of the rough surface.
The only limitation experienced while using this device was a malfunctioning in completely still water, due to the formation of small air bubbles on the optical fiber tip; the phenomenon does not take place in flowing water.

3 – An application: scour at bridge abutments

The device was tested for scour measures around a bridge abutment model (fig. 4). The experiment was run in a 15 m long and 1.93 m wide channel, bottom slope S = 0.13 %, normal water depth h = 0.099 m, flow rate Q = 0.089 m^3/s. The obstacle was placed at the half-length of the channel; its dimensions in the transverse and streamwise directions were 0.20 m and 0.10 m respectively. Rounded sediments of almost uniform size were used (density ρ_s = 2.61 kN/m^3, mean diameter d_{50} = 1.9 mm, uniformity coefficient $\sigma = (d_{84}/d_{16})^{0.5} = 1.22$).
The experimental conditions corresponded to incipient motion for the undisturbed current (Shields number $\phi = (hS)/(\Delta d_{50}) = 0.041$ where $\Delta = (\rho_s - \rho)/\rho$ and ρ is the density of water).
The surveying system allowed detailed measurements of the scour hole, both in time and in space. Figure 5 shows the temporal evolution of maximum scour values at the abutment, which are always located in front of the obstacle, along section 1 (bottom profiles in fig. 6). Erosion develops at a decreasing rate: after a short transient, depths increase almost linearly in a logarithmic scale for time; no asymptotic scour value could be recognised

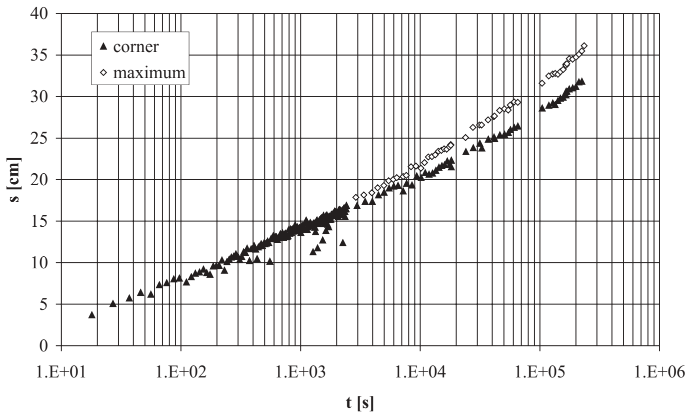

Fig. 5. Time development of scour in front of the obstacle (section 1).

after almost three days of run. The erosion process began at the abutment inner corner, the sediments being continuously displaced by the main flow, forming a thin cloud around the obstacle. After the first hour of run, however, the maximum sediment activity progressively moved to the channel side, while movements were less continuous; finally the erosion process became mainly impulsive, and the grains were clearly forced upstream and laterally by a vortical flow with a transverse horizontal axis (front region of a horseshoe vortex). Scour measurements at the corner of the obstacle in fig. 5 are consistent with the characteristics of the grains motion: most values lay on a unique growing trend; the few lower values recorded during the first hour of run are due to the occasional presence of grains in suspension over the bottom. As the scour process develops, this scatter is no longer present since the grains roll over the surface without being suspended. The distinction between corner values and maximum scour values (fig. 5, $t \geq 3000$ s) required the survey of several points along the section, so that the temporal acquisition frequency was reduced. Notice that the maximum temporal frequency is mainly connected to the characteristics of the mechanical system and its control software, since the reaction time of the photocell is extremely small.
As the scour depth increased, a higher concentration of dark sediments was observed at the bottom of the scour hole (fig. 6). This phenomenon was interpreted as a 'densimetric armouring' due to

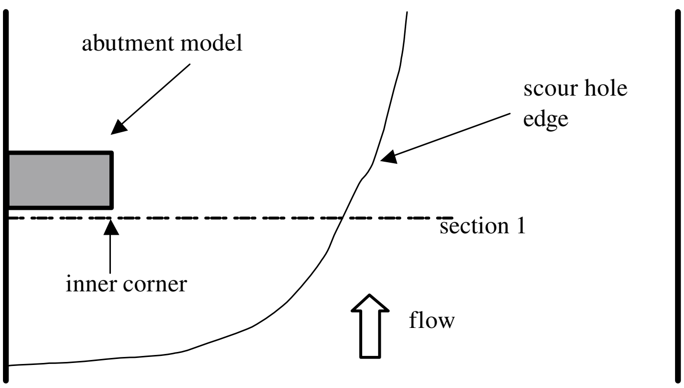

Fig. 4. Bridge abutment experimental model – definition sketch. Section 1 is placed 2 cm ahead of the abutment.

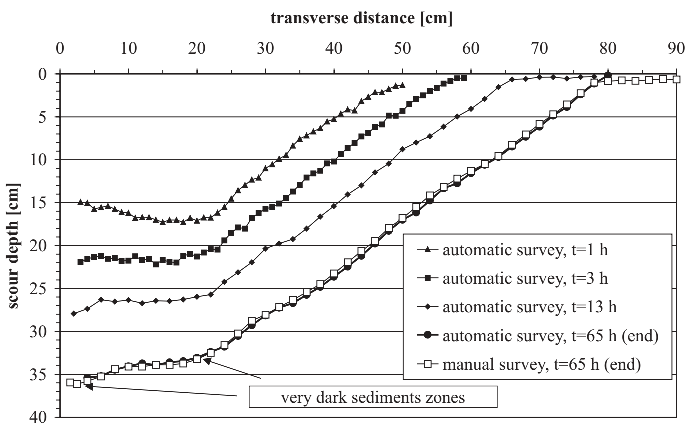

Fig. 6. Surveys of section 1 during the erosion test. Comparison with manual survey at the end of the experiment.

the higher density of the dark sediments compared to the mean value. The inhomogeneous colour of the bottom may, in principle, affect the survey accuracy because of the variation of reflectance along the surface. The comparison of measurements with a manual survey shows that the distortion due to the colour effect is negligible.

4 – Conclusions

A new non-touch device for bed profiling was successfully tested. The system is simple, robust and inexpensive; it works underwater with negligible disturbance to both the flow and the bottom grains; when coupled with a mechanical positioning system it is particularly indicated for automatic continuous survey in local scour experiments.

The functioning principle of the device is based on the intensity of diffuse reflected light; potential problems of sensitivity of the system to the surface reflectance (colour, smoothness, …) were shown to be non-critical for the survey of natural sediment flume beds.

The characteristics of the system were controlled on a fixed shape and subsequently tested in an application example: the regularity and consistency of the time series of local scour values and the comparison with a manual survey show the suitability of the device for the study of scour phenomena.

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