Catena 91 (2012) 35–46

Contents lists available at ScienceDirect

Catena

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

Controls on local scour and deposition induced by obstacles in fluvial environments

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ARTICLE INFO

Article history:
Received 6 November 2009
Received in revised form 30 August 2010
Accepted 26 November 2010

Keywords:
Complex system
Fluvial bedform
Obstacle mark
Flume experiment
Three-dimensional obstacle
Obstacle Reynolds number

ABSTRACT

Obstacles in fluvial environments cause flow separation and the emergence of three-dimensional flow fields that can lead to scour and deposition, even when no general sediment transport at the bed occurs. Resulting forms are commonly denoted as ‘fluvial obstacle marks’. The morphology and dynamics of these forms is depended on obstacle-, flow- and sediment characteristics. As no generally approved approach for analysis of these forms exists yet, a process-based method is developed that relates certain dependent morphometric variables to an adapted obstacle Reynolds number. The novel approach was applied by conducting experiments in a laboratory flume and validated against other laboratory and field data. The results of this work have shown a significant relationship between the morphometry of fluvial obstacle marks and obstacle Reynolds number, especially when morphometric variables were combined. Further validation, calibration and extension and of this approach will help to adequately asses the influence of obstacles in the fluvial environment on micro- and meso-scale processes of sediment transport.

1. Introduction

When flow is separated by an immobile obstacle at the river bed, areas of potential scour and deposition arise due to local acceleration and deceleration of the flow around the obstacle. This results in forms that typically consist of a scour hole reaching from the upstream part to the sides of an obstacle and an adjacent sediment ridge (Fig. 1). In geomorphology, these sedimentary features are better known as fluvial obstacle marks. Synonymous expressions used by earth scientists related to erosional and/or depositional sedimentary structures at obstacles include: current crescent, comet mark, obstacle shadow, obstruction-formed pool and scour mark. The unique aspect about fluvial obstacle marks is that they can develop even when the threshold for general sediment movement is not exceeded (i.e. when ‘clear-water’ conditions prevail). Hence, an obstacle exposed to a current can be the agent to initiate erosive and depositional processes.

In fluvial environments, obstacle marks can potentially develop at each obstacle that is exposed to the flow but that is immobile under the prevailing current conditions and located in an erodible channel bed (e.g. cobbles, boulders, plants, and deadwood). Examples have been documented by Karcz (1968), Russell (1993), Nakayama et al. (2002), Fay (2002); Herget (2005) and Rodrigues et al. (2007). An overview and initial classification is given by Allen (1984).

Specific obstacle mark morphologies depend on flow conditions, sediment characteristics, obstacle characteristics and duration of formative processes. In fact, three-dimensional flow fields around obstacles exposed to turbulent boundary layers are exceedingly complex. This complexity is even increased by characteristics of individual natural obstacles (such as geometry, shape, and porosity) as well as by the developing form itself, which is dynamically related to the flow field surrounding the obstacle (Kirkil et al., 2008).

Investigations related to flow around obstacles and/or the development of obstacle marks are relevant to a variety of scientific disciplines, including fluid mechanics, hydraulic engineering, oceanography, sedimentology and geomorphology. However, few studies have systematically studied the formation of obstacle marks under controlled boundary conditions. Engineering research up to now has concentrated on local scour induced by two-dimensional obstacles (i.e. $h_o > d_w$, where h_o = obstacle height in m; d_w = water depth in m) such as bridge piles (e.g. Breusers and Raudkivi, 1991; Melville and Coleman, 2000; Richardson and Davis, 2001; Sumer and Fredsoe, 2002), while investigations on processes of both scour and downstream deposition are scarce (e.g. Kirkil et al., 2008). In fact, many researchers have conducted studies on flow fields around three-dimensional obstacles (with $h_o < d_w$) as well (e.g. Okamoto et al., 1977; Hunt et al., 1978; Okamoto, 1980; Savory and Toy, 1986; Acarlar and Smith, 1987; Okamoto and Sunabashiri, 1992; Buffin-Bélanger and Roy, 1998; Leder et al., 2003; Pattenden et al., 2005; Testik et al., 2005; Tutkun et al., 2007; Said et al., 2008), but none of these were aimed at investigating the formation of sedimentary structures. Well documented experimental studies on obstacle marks have been conducted only by Werner et al. (1980), Paola et al. (1986) and Friedrichs et al. (2009) for the case of three-dimensional obstacles, by

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doi:10.1016/j.catena.2010.11.002

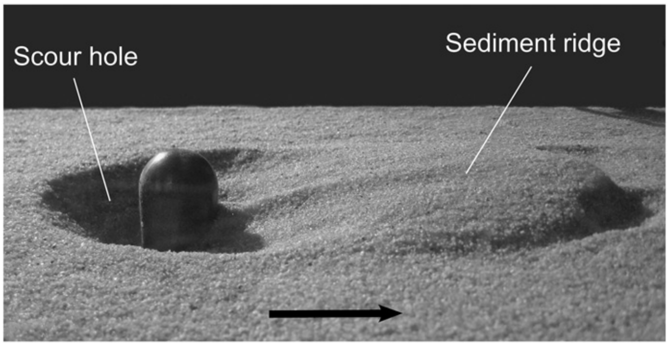

Fig. 1. Typical fluvial obstacle mark, experimentally simulated in a laboratory flume using a cylinder with hemisphere as obstacle (diameter: 3 cm). Arrow indicates flow direction.

Boyer and Roy (1991) for the case of two-dimensional obstacles and by Shamloo et al. (2001), Dey et al. (2008), Sadeque et al. (2008) and Sadeque et al. (2009) for both cases.

The aims of this study are to identify variables as well as thresholds controlling different obstacle mark morphometries and to incorporate these into a simple statistical model. To achieve this, available field and laboratory studies on that topic are reviewed first. Secondly, the results of our own laboratory flume experiments are analysed and compared with other available laboratory and field data. The focus of this study is on formative processes around three-dimensional, submerged obstacles, as appropriate data and coherent methods for analysis are mostly lacking here.

2. Background

2.1. Natural obstacle marks

Fluvial obstacle marks at three-dimensional obstacles described on the basis of field studies typically consist of a frontal crescent-shaped scour hole with a streamline shaped adjacent sediment ridge beyond (Karcz, 1968; Nakayama et al., 2002; Rodrigues et al., 2007). If the obstacle is strongly inclined towards the downstream direction (e.g. as riparian trees often do), maximum scour depth shifts from the frontal to the lateral zones around the obstacle (Nakayama et al., 2002). Fig. 2 shows a very symmetric obstacle mark resulting from a flash flood that has developed around a boulder in the *Anapodaris River gorge* in Crete (Greece).

In some cases more than one sediment ridge behind the same obstacle is found, which can be explained by changing directions of flow during the passing flood wave (Nakayama et al., 2002). Grain sizes of sediment ridges are in general finer than those of the surrounding stream bed (Russell, 1993; Rodrigues et al., 2007; Thompson, 2008). During waning flood stages, ridges are draped by layers of fine material (silt, clay, and organic debris), deposited under low-flow conditions as reported by Rodrigues et al. (2007). Other examples of obstacle marks reported by Karcz (1968) include types where the crescent shaped scour hole progresses as single or multiple furrows in the downstream direction. Multiple furrows are then separated by scour-remnant ridges. Furrows can be arranged either in a diverging, converging or parallel fashion. A common feature of natural obstacle marks is a layer of coarse particles located at the base of the scour hole. Such armour layers develop when coarse particles are deposited that cannot be transported out of the scour hole by prevailing local currents in the scour hole. As they increase the sediment-porosity at the base of the scour hole, non-uniform particle size distributions thus have a reductive effect on scour depth (Karcz, 1968; Breusers and Raudkivi, 1991; Dey and Raikar, 2007b).

Fig. 2. Obstacle mark at a boulder of the Anapodaris River gorge in south central Crete. Flow direction is indicated by the black arrow. The dashed black line shows the rim of the scour hole, the white dashed line shows the location of the sediment ridge. Person is for scale. (Photo by J. Herget).

The investigation of natural obstacle marks can be problematic in that morphometric measurements are best conducted during dry periods when the obstacle mark is drained (cf. Fig. 2), such that morphometric measurements made during their formation are often not available. Borg et al. (2007) provided indirect measurements of eroded and filled material in scour holes over a very long period using pressure sensors, but could not detect any significant relation between local scour patterns and discharge. Hence, linking the morphology of a drained obstacle mark to specific (formative) flow conditions remains difficult. An obstacle can be three-dimensional under high water stages as well as two-dimensional under low water stages in the course of a single flood event. Due to these limitations costly field studies with multi-data sampling devices would be needed to provide sufficient data during formation. In contrast, laboratory flume experiments can provide important insights into processes of obstacle mark generation and dynamics as well, having the advantage of high feasibility.

2.2. Formative processes

2.2.1. Horseshoe vortex system

When a current approaches an immobile obstacle, the flow separates at the frontal surface. Due to adverse pressure gradients, a major part of the current is subsequently transferred downward to the base of the obstacle, where it starts to circulate clockwise. At the sides of the obstacle lateral pressures and the incoming flow stretch the circulating current, resulting in a horseshoe shaped vortex (schematically illustrated in Fig. 3).

Beneath the horseshoe vortex local bed shear stresses are increased so that sediment can be eroded, even when there is no general sediment movement over the surrounding stream bed. The horseshoe vortex is the most important agent for erosion at obstacles. Detailed investigations on the development, structure and erosivity of

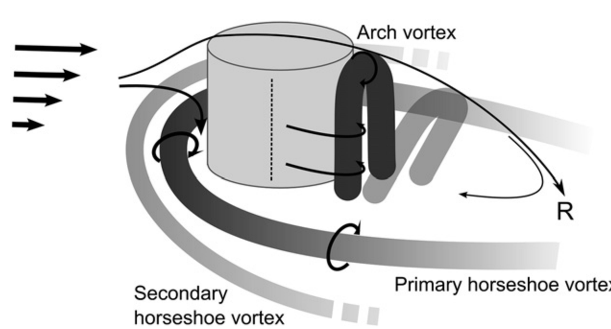

Fig. 3. Idealised flow patterns around a three-dimensional cylinder under flat bed conditions. R marks the area of current reattachment and thus the downstream end of the recirculation zone. The arch vortex is compound of two lateral vortices, originating from the laterally detached shear layers (dotted line) and a lee vortex, located behind the upper rear end of the obstacle. Illustration is not to scale. (Modified after Pattenden et al., 2005, p. 14).