Geomorphology 186 (2013) 174–180

Contents lists available at SciVerse ScienceDirect

Geomorphology

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

The legacy of impact conditions in morphometrics of percussion marks on fluvial bedrock surfaces

Andrew Wilson [a,*], Jérôme Lavé [b]

[a] Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, United Kingdom
[b] Centre de Recherches Pétrographiques et Géochimiques (CRPG), UPR 2300, CNRS-Université de Lorraine, 15 rue Notre Dame des Pauvres, 54501 Vandoeuvre les Nancy, Cedex, France

ARTICLE INFO

Article history:
Received 30 August 2012
Received in revised form 19 December 2012
Accepted 21 December 2012
Available online 7 January 2013

Keywords:
Percussion marks
Impact craters
Bedload abrasion
Bedrock rivers
Erosion

ABSTRACT

Percussion, or impact, marks are a common type of bedrock bedform found on many fluvial bedrock channels and have been attributed to bedload impact. Little is known about the conditions under which they form and how these affect morphology and dimensions of impact mark craters. We present data from a set of experiments exploring the formation of percussion marks by bedload impact under controlled conditions (impact velocity, angle, and particle diameter) by quartz spheres onto polished marble plates through a water interface. Particle impact causes impact craters consisting of a central depressed pit and a surrounding raised crater rim under all impact conditions. Data from 699 impact experiments show that crater rims are always circular and crater diameter (ϕ_c, in m) scales with the kinetic energy of the particle normal to the surface immediately prior to impact (*K.E.*, in J) by the relationship $K.E. = 2.48 \times 10^7\ \phi_c^{3.188}$. We test this relationship on impact marks produced in a series of controlled flume experiments for a range of surface inclinations found in natural fluvial channel outcrops. Measurements of impact crater diameter were used to estimate *K.E.* using our empirical equation. Our model estimates very similar *K.E.* for impact craters produced in this quasinatural setting to those calculated from flume conditions when realistic values for mean impact velocity and mean impact angle are assumed. Applying this relationship to measurements of crater rim diameter in natural settings will allow the mapping of impact *K.E.* along and across channel reaches where these bedforms are found. Future numerical models of fluvial bedrock erosion based on impact *K.E.* could be field calibrated from measurements of percussion marks in marble channels or from installed marble slabs in other bedrock channel reaches.

1. Introduction

Bedrock bedforms (e.g., Alexander, 1932; Allen, 1971; Springer and Wohl, 2002; Johnson and Whipple, 2007; Goode and Wohl, 2010; Johnson and Whipple, 2010) are sculpted forms found in fluvial bedrock channels (Turowski et al., 2008) that represent the erosion processes producing them rather than any intrinsic properties of the bedrock (Richardson and Carling, 2005; Wilson et al., 2013). One such bedrock bedform is the millimetre-scale percussion mark, or impact mark, thought to be formed by the impact of saltating bedload particles onto the rock substrate (Richardson and Carling, 2005) (Fig. 1). Our understanding of the processes leading to the formation of percussion marks is limited, and other than their indication that bedload abrasion is active in the channel reach (Wilson et al., 2013) they have been of little use. Understanding what erosion mechanisms are occurring in bedrock channels, their distribution, and their controls is important for calibrating numerical models predicting fluvial bedrock erosion, particularly so in the dynamic effects within such systems to variable discharges caused by climate variability.

In this paper, we present results from a set of laboratory impact rig experiments that demonstrate the control of kinetic energy (*K.E.*) of a particle orientated normal to the target surface, at the moment prior to impact, on the morphology and size of impact craters formed on marble substrates. We then test the relationship using a set of impact marks produced by impact of saltating, subspherical natural pebbles and cobbles on rock plates inclined at 15° increments from 15° to 90° in a flume setting. This demonstrates that our empirical relationship between *K.E.* prior to impact and impact crater diameter could be used to reliably estimate particle *K.E.* when applied to appropriately collected field data. The terms *impact crater* and *percussion mark* are synonymous and we use impact crater throughout this contribution.

2. Impact rig experiments

2.1. Apparatus and method

A new purpose-designed, free-fall impact apparatus was produced for this study. This consists of (i) a movable stage for the mounting of

* Corresponding author at: Department of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, United Kingdom. Tel.: +44 1908 679246.
E-mail address: andrew.wilson@open.ac.uk (A. Wilson).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2012.12.033

Fig. 1. Percussion marks on marble bedrock exposed at the base of the Liwu River, Taiwan. Impact craters are easily identified as they are lighter in colour than adjacent undeformed rock and are only found in areas adjacent to intense abrasion by bedload.

rock target plates that can be tilted in 15° increments by inserting aluminium prisms below, (ii) a laser targeting system to accurately place impacts, (iii) laser gates and oscilloscope to record velocity prior to impact, and (iv) a water delivery system to coat the rock surface with water prior to impact to simulate subaqueous conditions (Fig. 2). The rock targets used were commercially sourced, polished marble plates 20 mm thick, 110 mm wide, and of variable length dependent upon the desired impact angle (longer for shallower impact angles). Marble is used as a target material as it is a lithology upon which bedrock bedforms can commonly be found in the Liwu River, Taiwan (Wilson et al., 2013). The surface finish was highly reflective, equivalent to a 9-μm or finer diamond grit polished finish. Polished marble plates were used because they allow a planar initial topography to be assumed prior to impact and aid measurement by a surface profiler (see below). Commercially sourced, polished quartz spheres were used to simulate bedload with diameters of 20, 30, 35 and 65 mm. Spheres were used, not natural pebbles, because they produce well-constrained impact geometries. Additionally, polished spheres were used to isolate the loading/unloading deformation and limit cutting, ploughing, and scratching. Water in the test environment has been shown to be an important factor in the evolution of Hertzian cone cracking during indentation (Lawn, 1998). This is particularly important in crack initiation where the presence of water has been shown to decrease the load required to initiate cone cracks in soda–lime glass, relative to air (Langitan and Lawn, 1970). For this reason, a low velocity, gravity fed, jet of water wetted the rock surface to be impacted via a water hose connected to a distilled water reservoir. The load required to initiate cone crack growth is also decreased by increasing water temperature (Langitan and Lawn, 1970). For this reason, ambient temperature was kept within 20–25 °C. This apparatus is capable of investigating the following range of impact conditions: (i) impact angle of 90–15° in 15° increments (to ±0.5°), (ii) impact velocity of <7 m s^{-1} but varied in our experiments by predefined increments of 1 m s^{-1}, (iii) erodent grain size of <80 mm, and (iv) wet or dry conditions.

Experiments proceeded by dropping a sphere from stationary, at heights above the plate calculated from equations of motion to attain the required impact velocity, onto a marble plate through a thin layer of water running over the surface. Approximately 10 impact experiments

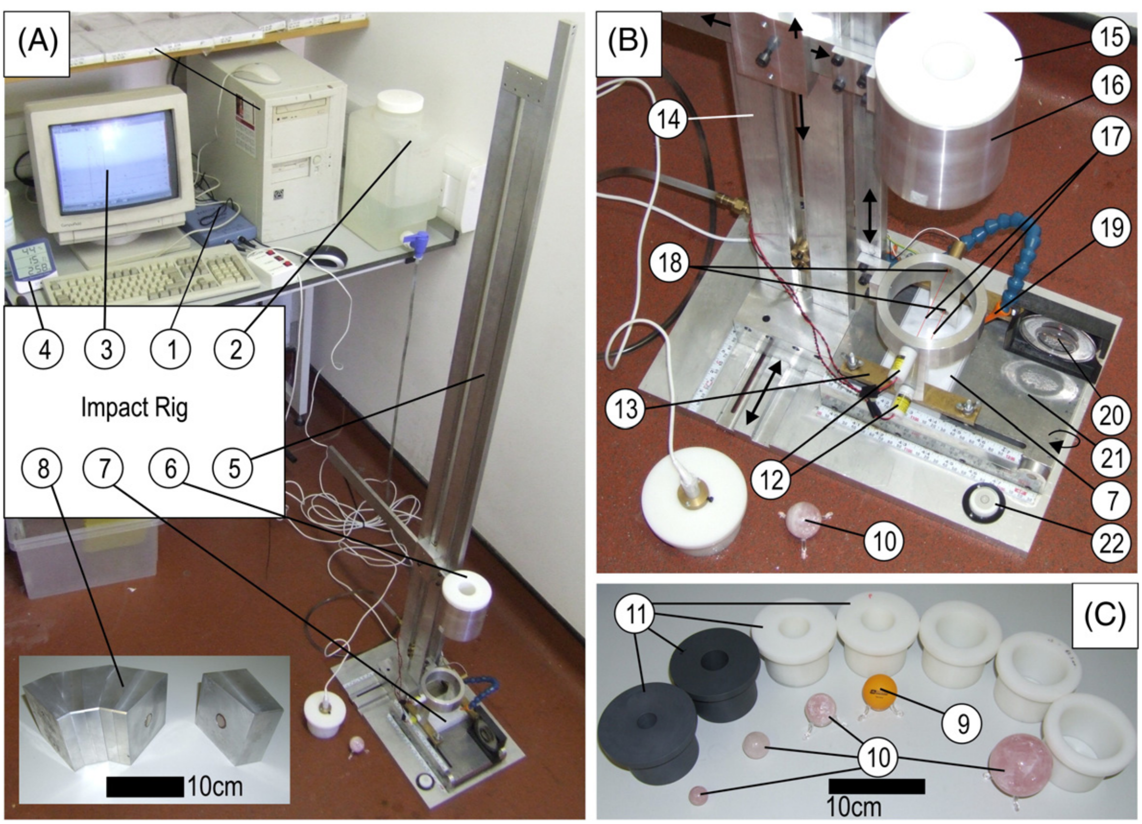

Fig. 2. Impact rig apparatus. (A) Facility overview. (B) Close up of the tiltable sample holder and targeting mechanism. (C) Quartz spheres and barrels for targeting impacts. Key: (1) PC oscilloscope to measure the time between a sphere cutting two light gates (17) to calculate impact velocity; (2) distilled water reservoir; (3) desktop PC; (4) humidity and temperature sensor; (5) impact rig; (6), (11), and (15) targeting barrels; (7) rock sample in holder; (8) sample stage tilt prisms, inserted under the stage; (9) ping-pong ball test sphere (40-mm diameter); (10) quartz spheres; (12) lasers; (13) sample vice; (14) main beam (*z*-axis); (15) barrels; (16) barrel housing; (17) light gates; (18) light sensitive diodes; (19) water delivery nozzle and nozzle arm; (20) inclinometer; (21) sample stage; and (22) spirit level.