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Application of an improved PEEP system to bank erosion investigations on the River Wharfe, UK

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Abstract Knowledge of erosion event timing, frequency and magnitude, in relation to fluctuations in the driving forces, is vital to strong hydrological and geomorphological process inference. However, traditional manual monitoring techniques simply reveal net, temporally-lumped, change to the eroding surface since the previous measurement. This paper briefly reviews the original Photo-Electronic Erosion Pin (PEEP) system developed to collect data on the timing, frequency and magnitude of erosional and depositional events. The PEEP system allows, for the first time, the vital automatic monitoring of erosion and deposition events. The paper then briefly tabulates some of the recent improvements to the PEEP system. These are principally designed to generate even more accurate erosion event *timing* data, and facilitate monitoring of site thermal conditions. Results from the River Wharfe show how the modified PEEP-3 system can: (a) pinpoint more accurately the timing of bank retreat events with respect to the hydrograph (2 h before the flow peak on the Wharfe example here); (b) quantify the erosional impact of *individual*, rather than *aggregated*, flow events; (c) clarify the frequency and intensity of on-site bank freeze-thaw cycles; and (d) help to suggest or eliminate the likely bank destabilising processes. Eighteen research groups around the world now use the new PEEP-3 system.

Key words bank erosion; bank retreat events; bank temperature; flow events; freeze-thaw cycles; PEEP system; River Wharfe; Thermal Consonance Timing

INTRODUCTION

Bank and gully erosion processes are still not well understood or specified in river dynamics and sediment flux models. The field is particularly complicated by the lack of bank erosion data at the event timescale. The aims here, therefore, are to: (a) briefly summarize some recent improvements to the Photo-Electronic Erosion Pin (PEEP) automatic erosion and deposition monitoring system; (b) demonstrate its enhanced potential to establish more clearly the timing of individual bank erosion events; and (c) outline its usefulness in monitoring river bank thermal conditions.

RATIONALE

Conventional, manual, field erosion monitoring methods, typically erosion pins, cross-section resurveys or terrestrial photogrammetry (e.g. Lawler, 1993a), merely reveal net change in the position of a bank or gully surface since the previous measurement. They do not quantify the precise temporal distribution of that change. This means that erosion event magnitude, frequency and timing, and the precise bank response to individual flow or meteorological events, is generally uncertain. Because of the limitations of existing measurement methods, little knowledge has yet emerged of the dynamics of bank erosion and deposition events at a time resolution comparable to that available for flow and sediment transport rates (Lawler, 1992, 1994; Mitchell *et al.*, 1999). Clearly, bank erosion process explanations and model development and testing will be more securely based when: (a) the full episodicity of bank change is detected, to allow (b) magnitude/timing information for specific erosion and deposition events to be related to transient fluctuations in the suspected driving forces.

THE PHOTO-ELECTRONIC EROSION PIN (PEEP) SYSTEM

Work began in the late 1980s to try and solve some of these monitoring problems: this led to the development of the novel Photo-Electronic Erosion Pin (PEEP) system and its application to upland and lowland fluvial systems (e.g. Lawler, 1991, 1992, 1994; Lawler & Leeks, 1992). The PEEP sensor is a simple optoelectronic device containing a row of overlapping photovoltaic cells connected in series, and enclosed within a waterproofed, transparent, acrylic tube of 12 mm ID and 16 mm OD (Fig. 1(a)). The sensor generates an analogue voltage proportional to the total length of PEEP tube

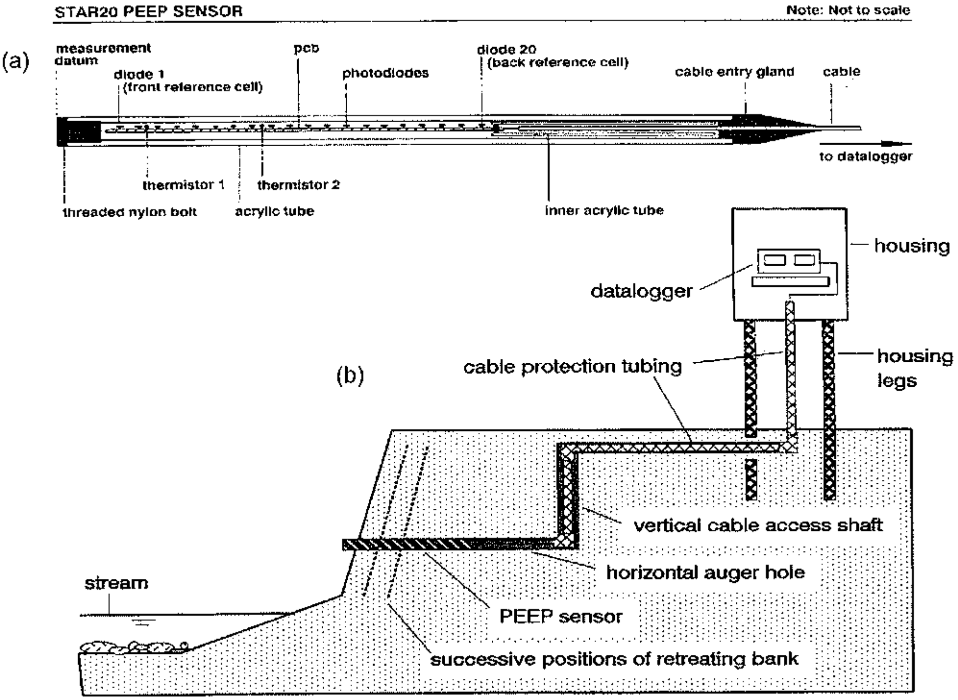

Fig. 1 The Photo-Electronic Erosion Pin (PEEP) erosion and deposition monitoring system: (a) The new PEEP-3 sensor, now extended to 660 mm length (200 mm active length), includes two reference cells and two thermistors for more precise erosion and deposition event timing; (b) typical installation of a PEEP sensor and datalogger at a river bank site.

exposed to light. A reference cell is used to adjust outputs for variations in light intensity (Fig. 1(a)). Small networks of PEEP sensors are normally inserted into carefully pre-augered holes in the bank face, and connected to a nearby datalogger set to record PEEP mV outputs at 15-min intervals, though any frequency is possible (Fig. 1(b)). Most dataloggers are compatible with PEEPs. Subsequent retreat of the bank face exposes more photo cells to light, which increases sensor voltage output (Fig. 1(b)). Deposition reduces voltage outputs. PEEP data thus reveal the magnitude, frequency and timing of individual erosion and deposition *events* much more clearly than has been possible before (Lawler, 1992, 1994). Various PEEP designs are possible to suit the application (e.g. bank, gully wall, channel bar, hillslope, cliff, dune, beach).

Laboratory calibration establishes relationships between PEEP outputs and exposed tube lengths. These relationships are encouragingly strong: the position of the sediment surface is generally known with 95% confidence to within ±2–4 mm (Lawler, 1992), although low light levels can reduce confidence. Further details of measurement principles and initial design, calibration, installation and applications can be found in Lawler (1991, 1992, 1994), with later applications in Lawler *et al.* (1997a, 2001), Prosser *et al.* (2000) and Stott (1999).

However, research has proceeded to address some limitations of the original PEEP systems. For example, being a visible-light system, nocturnal events are not detected until the following morning, although temporal resolution is still much better than with traditional manual methods. Data gaps at night could be plugged with programmed bursts of artificial light. Some PEEP data are occasionally degraded in low-light conditions, or when the bank is covered by snow, snagged vegetation or highly turbid water. Also, as with traditional erosion pins, PEEPs are invasive (although their small size minimizes this), and they may be less suitable for gravel materials or for large mass-failure situations.

PEEP DESIGN IMPROVEMENTS

The early generation of PEEP sensors were 0.40 m long, and were equipped with an array of 10 photovoltaic cells to provide an active length of 90 mm. However, to address some of the limitations, redesign work in 1996 and 2001, summarized below, has led to the new PEEP-3 sensors:

(a) sensors were lengthened to 660 mm to improve suitability for more dynamic sites;
(b) the active portion of the sensor (i.e. the length of the photovoltaic cell array) was lengthened to 200 mm to allow for higher erosion and deposition rates;
(c) a second "back" reference cell was added to the "interior" end of the sensor (Fig. 1(a)), to confirm minimum erosion magnitudes for large events, and to permit installation in both "top-down" or "top-up" positions to increase the range of suitable sites;
(d) physical design enhancements were made to improve strength (e.g. increasing tube wall thickness from 2 mm to 3 mm), waterproofing, and the security of electronics mounting;
(e) two thermistors were incorporated to generate bank temperature data at the sediment surface and at 68 mm depth, to help evaluate bank freeze-thaw, desiccation

and biological (e.g. vegetation growth) processes. However, the key advantage, is that the thermistor pairs now allow nocturnal erosion and deposition events to be timed much more accurately through the use of the Thermal Consonance Timing (TCT) concept.

AN EXAMPLE APPLICATION FROM THE RIVER WHARFE, YORKSHIRE, UK

The brief bank erosion event data reported here were generated from the Easedike site on the River Wharfe, near York, UK. Bank monitoring was focused on the fluvial and estuarine part of the entire Swale-Ouse-Wharfe river system in northern England from January 1996 to April 1998, as part of the much larger LOIS project (Lawler *et al.*, 1999). Discharge data were available from the Environment Agency gauging station at Tadcaster, 2 km downstream of Easedike. At Tadcaster, the Wharfe drains an area of 818 km^2 (Webb *et al.*, 1997). Average annual precipitation (1961–1990) is 1139 mm, rising to over 1500 mm in the headwater areas. Banks here are high (>2.5 m), very steep and are formed from fine-grained sediments.

In addition to networks of erosion pins and repeat-survey methods, up to six PEEP-3 sensors were deployed at eight key bank sites throughout the river network to give clearer details of erosion events. All sensors, including PEEPs, were connected to Campbell-Scientific CR10X dataloggers scanning at 1-min intervals and storing data as 15-min means. All timings are in GMT (Greenwich Mean Time).

RESULTS

Bank thermal conditions

The addition of two thermistors permits the automatic collection of data for on-site bank temperature (surface and near-surface), and bank temperature gradients, which is a substantial improvement on usual procedures which rely on off-site air meteorological station information. Bank temperature data has very rarely been published anywhere, despite its importance for controlling the erodibility of cohesive sediments (e.g. Lawler, 1993b). Figure 2 shows a one-week sequence of bank temperature, light incidence and river flow data for the Wharfe site in mid-November 1996. Note how temperatures respond rapidly to the diurnal input of radiation, as indexed here by PEEP reference cell data, peaking just after the daily light-reception maxima (Fig 2; 14–17 November). Also, the great sensitivity of bank air temperature to early morning radiation receipts is shown for 13 November, where a short-lived maximum temperature for the week, 13.7°C, is achieved (Fig. 2). Of great geomorphological interest, however, is the detection of five freeze-thaw cycles during two freezing nights (13–14 November and 18 November), three for the earlier period and two for the later sequence (Fig. 2). Such subtle oscillations about the zero-degree threshold, and their important freeze-thaw implications (e.g. Lawler, 1993b), are likely to be missed with the use of off-site air temperature data.

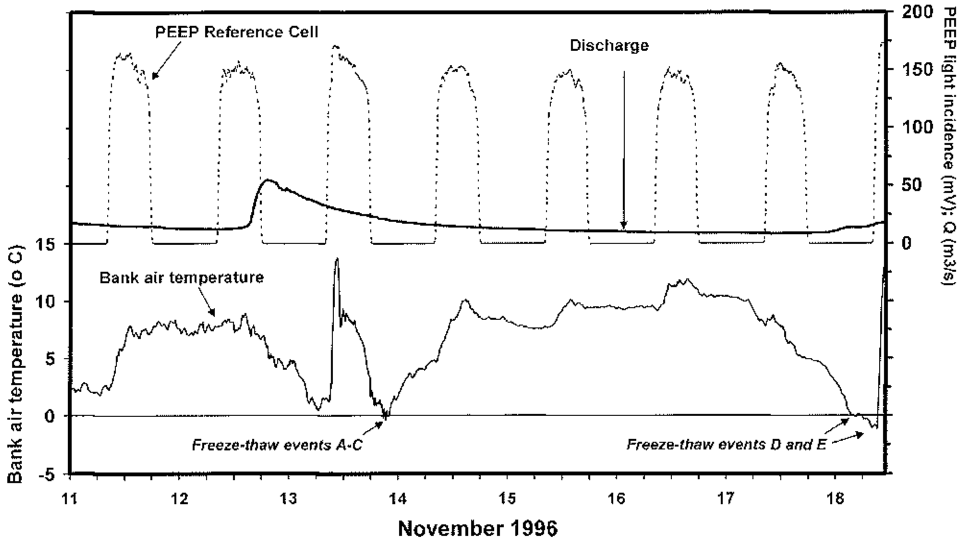

Fig. 2 Time series (15-min) of near-bank air temperature, river discharge and light incidence, the latter indexed by Photo-Electronic Erosion Pin (PEEP-3) photovoltaic reference cell outputs: Easedike site, River Wharfe, UK, 11–18 November 1996.

An example bank erosion event

Focus here is on an example bank erosion event sequence in November 1996 at Easedike to illustrate how original and modified PEEP approaches can clarify bank erosion event timings with respect to the hydrograph. Figure 3 illustrates typical sequences of diurnal PEEP data for early November 1996, which reduce to zero at night. The sudden increase in PEEP cell series outputs on 7 November, however, clearly reveals that a substantial (>150 mm) erosion event has occurred in association with a large flow event (Fig. 3). Maximum readings for the new PEEP-3 back reference cell also reconfirm that erosion was at least 150 mm. Figure 3 shows that the PEEP optical signals successfully define the "erosion event window". Thus, conventional, light-based, PEEP data reveal that the erosion event took place within an 18-h "window" between 14.15 h on 6 November and 08.15 h on 7 November (Fig. 3). This confines the event to an 18-h period straddling the flow peak. Such confirmation of an association of erosion event with the hydrograph is useful diagnostic information when unravelling processes, especially given that much bank erosion activity can take place after hydrographs (Lawler *et al.*, 1997c) or be independent of flow events (Lawler, 1994), suggesting that many other processes besides fluid entrainment can be at work (Lawler *et al.*, 1997b). However, with the improved PEEP-3 sensor, we can now refine the timing much more precisely, as briefly discussed below.

Timing the erosion event

Although defining the "erosion event window" as above is very useful, and a significant improvement over traditional measurement methodologies, the moment of

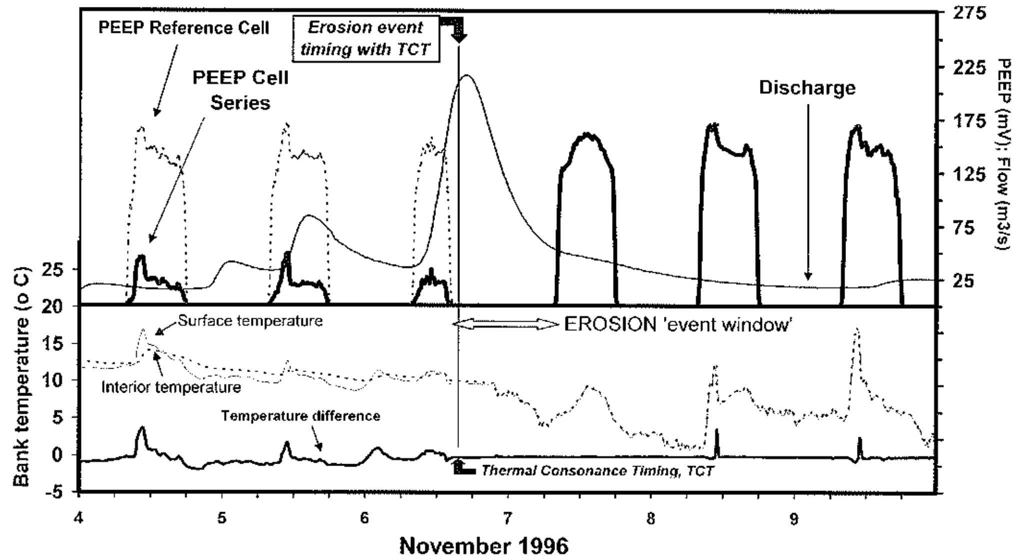

Fig. 3 Definition of the 'erosion event window' with conventional 15-min PEEP data, and the precise timing of the bank erosion event fixed using the Thermal Consonance Timing (TCT) approach made possible with the new PEEP-3 sensor. This erosion event occurs on the rising limb of the hydrograph on 6 November, 15.00 GMT: Easedike, River Wharfe, UK.

material removal can be further fine-tuned through what I have called Thermal Consonance Timing (TCT). PEEP-3 sensors now include two thermistors, one at the bank surface and one at 68 mm depth (Fig. 1(a)). Under normal conditions, micrometeorological theory and field data suggest that thermal regimes at the soil surface are much more extreme than at depth. This is what emerges from the empirical evidence. Note how, before the 6 November flood, bank surface temperatures tend to be higher during the day and lower during the night than for the bank interior (Fig. 3). However, bank retreat then "reveals" both thermistors, causing them to experience very similar microclimates and therefore minimal thermal differences: hence, they achieve the state of thermal consonance. Thus, the time when sustained thermal consonance is first established reveals the moment of bank material removal. This timing facility is especially useful for those periods when PEEP sensors do not generate strong signals (e.g. at night, or when inundated by turbid water). A simple plot of the temperature difference (TD) time series reveals when thermal consonance has been established (see Fig. 3), i.e. when thermal differences become uniform and very low ($-0.3°C < TD < 0.3°C$).

For example, in Fig. 3, TCT suggests that the bank erosion event occurred on 6 November at 15.00 GMT. This was 1.5 h after inundation and 2 h before the flow peak (Fig. 3). In this case, therefore, at least 68 mm (the inter-thermistor distance) of the 150 mm bank erosion recorded was achieved as a rising limb event. Data on the timing of material removal with respect to the hydrograph can help to clarify the minimum fluid shear stresses required for entrainment. Delayed retreat events, 6 h after the flow peak, have also been detected by this method: this points towards mass failure processes as the main retreat mechanism, which may occur on falling stages, partly because of time-lags in achieving critical soil pore water pressures (e.g. Lawler *et al.*, 1997b). Thus, improved data on erosion timing can help to advance or eliminate certain controlling processes. Future parallel investigations of the variables driving such mechanisms should therefore provide a method of evaluating competing process-control hypotheses, and for testing erosion and sediment supply and transport models.

DISCUSSION AND CONCLUSIONS

This application of the PEEP-3 system has demonstrated that details of the bank erosion process can be determined much more clearly than was possible hitherto—especially the timing and magnitude of individual erosional and depositional events in relation to fluctuations in river flow and hydrometeorological conditions (e.g. Fig. 3). Recent design developments incorporated in the PEEP-3 system, briefly listed here, allow better information on site thermal conditions and erosion and deposition timings to be collected at a fuller range of sites, regardless of the time of day. The results presented show how PEEP-3 sensors can: (a) clarify the frequency and intensity of on-site bank freeze-thaw cycles; (b) pinpoint the timing of bank retreat events with respect to the hydrograph; (c) quantify the impact of individual, rather than aggregated, flow events; and (d) help to indicate or discount likely bank destabilising processes.

PEEP techniques have been used to improve the temporal resolution of erosion and deposition monitoring on other river systems (e.g. Lawler, 1991, 1994; Lawler & Leeks, 1992; Lawler *et al.*, 1997a,c). Newer PEEP-3 systems are now also being applied by around 18 international research teams to different environmental contexts, including beaches, tidal creek and mudbank systems, drainage ditches, artificial channels and even to snowpack ablation and accumulation problems (e.g. Mitchell *et al.*, 1999; Prosser *et al.* 2000; Stott, 1999). Exciting potential also exists for their application to gully, rill and other slope erosion events, dynamics and responses, and for coastal or desert sand dune systems: it should be possible to obtain similar improvements in process understanding to those emerging for bank erosion investigations (e.g. Lawler, 1994; Lawler *et al.*, 2001). In the case of river bank erosion, such high-resolution temporal information is vital to sound process identification, including threshold identification, the mechanics of bank instability, the fate of failed blocks, and the operation of basal clean-out cycles (Lawler *et al.*, 1997b). High-resolution monitoring is also crucial to improved understanding of the links between bank sediment input and fluvial sediment transport and budgets. There is an urgent need for further research, however, to refine existing techniques and to develop new methods for the continuous monitoring of erosion and deposition events in many geomorphological contexts.

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