BANK EROSION AND INSTABILITY MONITORING WITH A LOW COST TERRESTRIAL LASER SCANNER

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ABSTRACT: Among the dominant processes taking place in a river basin, especially mountain ones, sediments creation and transport play a key role in morphological processes. Studies usually focus on big mass movements, such as landslides and debris flows, or on wide spread slope erosion due to rainfalls, while bank erosion is neglected or not considered essential for sediment budget at basin scale. Nevertheless, authors consider bank erosion a process that deserve more careful studies; not only the sediment share from bank erosion is not negligible in steep mountain rivers, but also the process can threat structures on river sides due the possibility to have limited, but still significant, mass collapse of bank sections during intense events. The paper present an attempt to monitor bank erosion in a section of a river in Northern Italy Alps and to put it in relation with weather and water discharge. Survey campaign was set up at regular time intervals, or after particularly intense rainfalls, and uses a Terrestrial Laser Scanner (TLS) to acquire the bank surface. The tool was developed internally, at Politecnico di Milano, to meet requirements about low cost level and good accuracy. Successive acquisitions of point clouds were elaborated, via an ad-hoc MatLab code, to determine erosion, or deposition, volumes of sediments. These volumetric results have been evaluated in relation with rainfalls and freeze-thaw cycles looking for a relationship between environmental conditions and bank failures. Some interesting results are shown, such as a relation between erosion rates and temperature or water flow in the river. The path to a complete process understanding and modelling is long, however the results reported can be considered a first step towards objective.

Keywords: bank erosion, TLS, monitoring, river, erosion

INTRODUCTION

Among the dominant processes happening in a river basin, especially mountain ones, sediments creation and transport play a key role. Usual sediments' life cycle is being eroded from the valley slopes by endogenous and exogenous agents and successively involved in migration processes, such as landslides, debris flow, or solid transport in watercourses (Radice et al., 2011, Brambilla et al., 2011).

Small changes in the riverbank trigger large-scale morphological changes (Nasermoaddeli and Pasche, 2008). Sediment transport processes have a negative impact in rivers and streams life, both in functional and in critical conditions. In particular, it has a negative influence on floods, since there is a strong connection between modifications in riverbed morphology and increase of water level (Lane et al., 2007, Reid et al., 2007). Actually, sediment transport is larger during floods, leading to higher water levels and consequent higher probability of flood hazard (Brambilla et al., 2011). Moreover, the frequency of peak-flows and the shape of the flow hydrograph play an important role in morphological processes, especially bank erosion (Nasermoaddeli and Pasche, 2008). The degree of saturation of bank material increases with river stage; therefore, the frequency of bank failure is correlated to the frequency of flooding (Duan, 2005).

Why Mountain?

In lowlands, there is a sharp difference between the timescale of morphological evolution of the riverbed, due to sediment transport, and the timescale of a flood event, which is far shorter. In mountain areas, the difference in time scale between river geomorphology modification and

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flood events is small, or even inexistent (Klaassen, 1997). Event induced sediment yield from mountain valley slopes may represent a problem for landscape safety: mountain environments are often subjected to flash floods, due to the response of small and steep basins, very hazardous phenomena because of the short time scale and consequent short lead time. Due to limited time scale is necessary to use a fast and easy tool for bank erosion assessment, which does not take place over long seasonal periods but in short intense raining events and thus could require several successive acquisitions.

Riverbank Erosion

At basin scale, sediment production results from complex interactions between different processes: splash erosion, sheet erosion, rill erosion, gully erosion, bank erosion and mass movements (De Vente and Poesen, 2005). Not all processes are equally important in different basins: according to these two authors, the dominant sediment source and sink terms vary with the basin dimension.

For instance, bank erosion is of particular interest in a mountain basin. Riverbank erosion consists of three processes operating with differing magnitudes and frequencies: 1.basal erosion due to fluvial entrainment, which is defined as erosion of bank materials by running water; 2.mass failure occurring under the influence of gravity and 3.subaerial erosion, i.e. weakening of the bank face and subsequent fall of soil particles and small blocks.

The role of subaerial erosion in bank erosion is still uncertain since it can be a predisposing or triggering factor. According to some authors (Green et al., 1999, Thorne, 1990), subaerial erosion is due to two processes, which are controlled by climatic conditions: wetting drying and, especially, freeze-thaw action: freeze-thaw action that directly triggers subaerial erosion and indirectly contributes to mass failure and fluvial entrainment (Yumoto, 2006).

There are three types of freeze-thaw cycles: diurnal, annual and millennial. Diurnal freeze-thaw action causes needle ice creep during the freezing period. According to Yumoto, the maximum rate of subaerial erosion occurs during the thawing period, when there is an increase in water content and a decrease of soil hardness: diurnal and annual freeze-thaw action directly induces significant subaerial erosion that contributes to deepening of notches. After complete thawing of seasonal frost, mass failure and fluvial entrainment dominate the bank erosion.

As stated by De Vente and Poesen (2005), while most studies recognise that bank retreat is the integrated product of three interacting processes (namely, weathering and weakening, fluvial erosion, and mass failure), simplified approaches are adopted, and interactions between different groups of processes are not usually considered .

Three factors have also to be taken into account when dealing with processes dominance in bank erosion:

1) limitations of present field monitoring techniques;
2) temporal change in bank erodibility
3) downstream change in bank erosion processes.

Few studies have focused on geomorphological event structure (timing, magnitude, frequency and duration of individual erosion and deposition events), in relation to applied stresses, because of the absence of key monitoring methodologies.

MONITORING TECHNIQUES

In order to understand the process of bank erosion phenomenon, it’s important to estimate the rates and the timing of its occurrence. In literature the most common instruments to measure bank erosion are Total station survey, Real time Kinematic Global Positioning System, Photo-Electronic Erosion Pin (PEEP) system and Thermal Consonance Timing (TCT), terrestrial photogrammetry, airborne LiDAR and 3D terrestrial laser scanner (Nasermoaddeli and Pasche, 2008; O’Neal et al., 2011). Usually these techniques involve the use of expensive and voluminous commercial laser scanners, with the ability to scan huge point clouds in seconds.

This research will focus on the presentation of a new approach to laser scanning survey for mountain rivers banks. The use of a little, portable and inexpensive laser scanner, with the capability to work on batteries add to the method a new flexibility that allows for repetitive measure of critical areas even if not easily reachable.

TEST SITE DESCRIPTION

The test bank is located in Valle dei Mulini, a small catchment in northern Italy, 70 km north from Milan. The basin extents from 480 m.a.s.l. to 2367 m.a.s.l. and although being snow covered during winter period its river is perennial with a little discharge even in cold months. Water flow was present at each measure campaign, even if an automated flow meter is not available on the site.

In the measured area, a narrow bed, cut into bedrock, with typical steps and pools structure, characterizes the river (Figure 1). Karst phenomena are widespread in the whole basin; problems related to excessive sediment yield are common during the rainy periods, in particular during autumn, and affect not only the little village on the alluvial fan, subjected to little floods and gravel deposits but also the drinking water supply facilities. The test site has been individuated in a small bank in a steep narrow canyon just upstream of the alluvial fan; the objective was to monitor the evolution of the bank to assess its role in debris discharge. The bank is roughly ten meters long, two high and formed by angular pieces of rock coming from a fault. This kind of material is quite different from usual studies, which focus on plain rivers eroding thin materials such as sand or clay. (Nasermoaddeli & Pasche, 2008).

Figure 1. Test bank

The laser scanner used was developed by ISSweb srl, a spin off society of Politecnico di Milano, starting by a Sick bi-dimensional commercial laser (Figure 2). The laser works on TOF (time of flight) principle and in its original version is used to scan a plane around itself for industrial safety purpose; coupling this laser to a stepper engine is possible to scan different lines rotating the scanner, and thus the scanning plane, and obtain a 3D point cloud. The laser management software does the transformation from angular coordinates to Cartesian one automatically and data are saved as x y z coordinates of each point scanned. This laser scanner is normally employed for contactless measure and recognition systems in industrial applications at close distance; due to this general purpose during tool design scan speed was preferred to measurement accuracy and resolution. Laser can acquire a complete scan of 180° both in vertical and horizontal direction, acquiring the complete scene in front of it, in less than 2 seconds. The scanner is not able to record the reflectivity of the objects but only the mere distance not allowing for high reflectivity targets recognition for point clouds alignment.

In order to employ this tool for bank erosion measure three issues needed to be solved: measure accuracy assessment at long range, point cloud interpolation and repositioning error of the scanner.

Figure 2. Tool deployed on field

Measure Accuracy Assessment

The laser has a certified accuracy of +\- 30 mm and is usually employed in close range, high speed contactless measure; the raw result obtained from a single scan is far from being even acceptable due to the low density of points measured. Moreover the features of the stepping motor are unknown so a campaign of tests was set up to determine the angular resolution and the measurement accuracy; a second objective was to test if a multi scan approach could improve significantly the quality of data and which is the number of scan needed to reach a target accuracy. Two different synthetic case were set-up: a plane surface as training case and a real bank with artificial erosion spots as testing case.

Scanning the plane surface allows for an easy and direct determination of resolution: angular resolution was 0.5° on horizontal line and 2.1° on vertical line. The standard deviation on point positioning is calculated in 37 mm and is the sum of errors in both distance measure and angle measure due to the transformation from spherical to Cartesian coordinates. Due to the intrinsic positioning error of the stepper motor each time the laser finishes a scan cycle and moves back to the starting position a little difference between the final and initial position exists; this difference leads to a progressive thickening of the cloud, as seen in Figure 3. This result is highly positive and give the chance to acquire dense point clouds useful for bank erosion assessment. These dense clouds, including millions of points, can be cleaned and interpolated to improve data quality; the objective of the interpolation is double: regularize the cloud and eliminate possible errors.

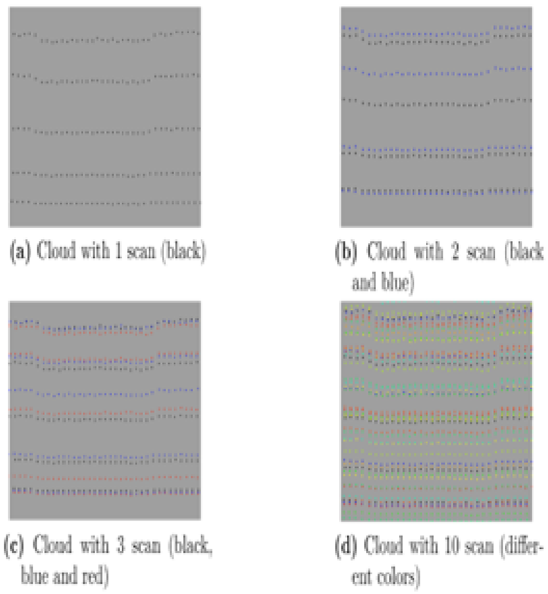

Figure 3. Clouds thickening due to multiscan procedure

This operation is executed in one single passage by a specifically Matlab developed algorithm: a square window move through the point cloud space from (Min x; Min y) to (Max x; Max y) and put a single point in each square whose x and y coordinates are the ones of the square centre, while z values is the mean of z values of each points inside the window. Comparison between different acquisition is made by a simple point to point comparison of different scans, that need to be of the same dimension.

THE APPLICATION

The test site has been surveyed after every rain event, thanks to the easy deployment of the laser scanner and tools needed. Each measure campaign consisted in a multiple acquisition of the same area of the bank, from the same station point, until the target number of scan is acquired. This technique usually referred to as multiscan and its aim is to increase the number of point acquired and thus the resolution of the point cloud in respect of a single scan. This passage is extremely important when dealing with a low resolution scanner allowing for an inexpensive increase of tool performance. The scanner is not able to record the reflectivity of the objects but only the mere distance, due to this limitation is possible to relocate the tool in the same point at any epoch but not to measure high reflectivity targets for point clouds alignment.

The survey campaign consisted of nine measures from Nov 30th 2013 to Apr 12th 2014, including the most interesting periods of year, when freeze thaw cycles and high discharges rates take place. The key input to analyse and understand data are: precipitation, number of freeze thaw cycles, erosion measured. Data are summed up in Table 1.

Table 1. Raw data, FT (Freeze-Thaw cycles), Erosion in [m3]

Time	Surveys	Rain	FT	Erosion
30/11-1/3	5	Snowy	40	0.071
1/3-2/4	3	Normal	5	0.451
2/4-12/4	1	Stormy	0	0.002

The entire period of monitoring has been divided into three sub periods: a first one featuring low temperatures, high number of freeze thaw cycles and low erosion rates, a middle one with high erosion rates linked to rain and a last one that enclose basically just one intense storm when temperature where higher than zero. The comparison it is always made form an epoch to the successive one and the results are grouped because they represent different behaviours in different weather conditions. Erosion maps have been developed, different colours indicates erosion or deposition of material on the bank. Some example of these maps are reported as Figure 4. This step is important to understand which processes take place on the bank and if there are areas more subjected to erosion or not.

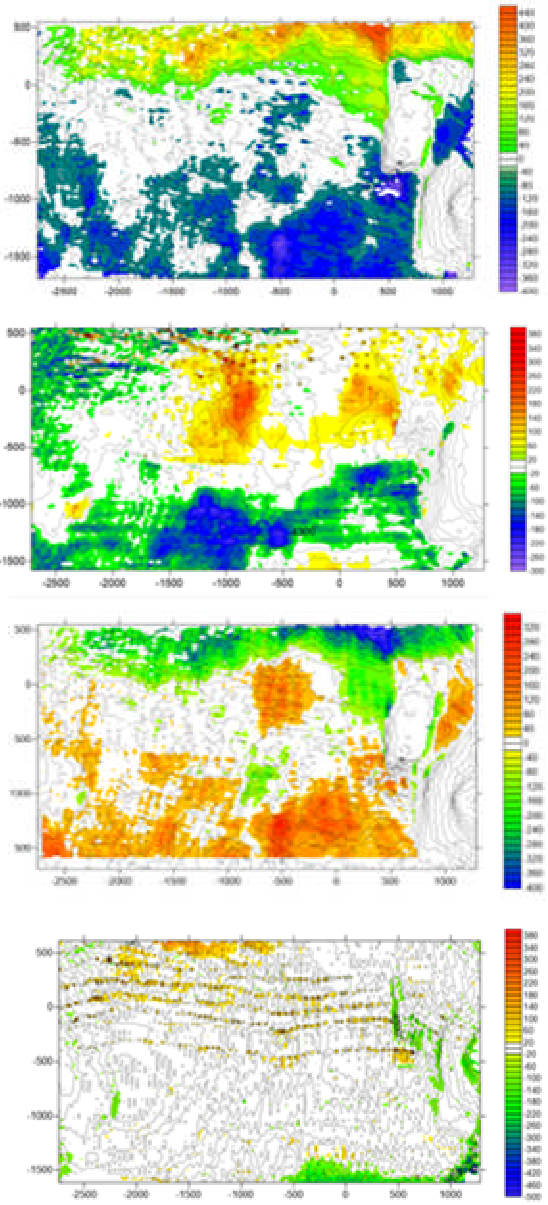

Figure 4. Erosion maps: blue areas are deposition areas, red areas are erosion areas. First two maps are from first period, third one from high erosion second period and last one from low erosion third period

RESULTS DISCUSSION

Data about erosion could give little insights in the processes if not analyzed together with rainfalls and temperature data. As stated in the introduction, freeze thaw cycles are one of the most important predisposing factors of erosion, while water flow is crucial to remove the loose soil from the bank. To sum up all the relevant weather data two graph have been drawn. The first graph, Figure 5, collects data relative to climate condition.

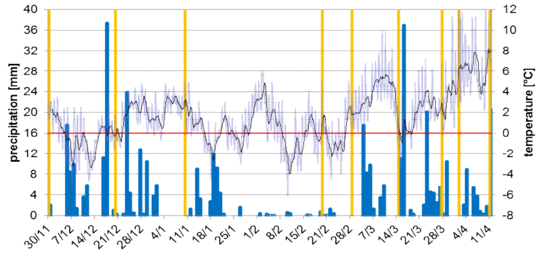

Figure 5. Rainfalls and temperature variations (blue bars indicates rainfalls, black line mean temperature, grey line hourly temperature, red line zero Celsius degrees and yellow bars indicate the surveys dates)

Daily rainfalls are reported as blue bars while temperature is reported as black (hourly) or grey (24h mean) line. A preliminary assessment of weather during the surveyed period shows a concentration of rain in December and in March and April, while January and February features very limited rain but as expected, various freeze thaw cycles.

As the number of freeze thaw cycles is reported in table 1, their distribution can been seen in Figure 5, where the red line indicates zero Celsius degrees. Figure 6 focus on erosion rates: brown bars stand for erosion rate in dm^3/day, blue bars precipitation in mm/day (if white it was snowing) and red marks indicates the number of freeze-thaw cycles. This graph actually resume all the results of this research: is possible to notice how erosion actually take place from the end of February, when precipitations increase and the freeze thaw cycles stops. In the previous period little erosion was measured, while precipitation was mostly in snow form, and various freeze thaw cycles took place. This duality in the behaviour is perfectly compatible with studies found in literature. Freeze thaw cycles are considered as predisposing factors (Gatto, 1995; Lawler, 1985) while rainfalls and thus water flow in stream is considered a triggering factor (Johnson, 2002-2006, Lawler, 1985; Stott, 1995).

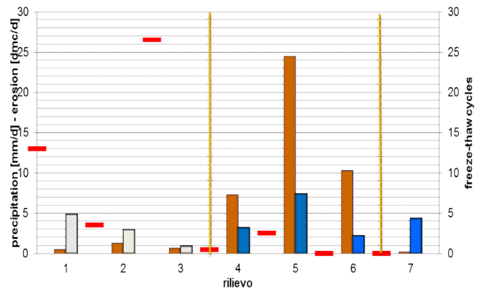

Figure 6. Rainfalls and erosion rates (brown bars stand for erosion rate in dm3/day, blue bars precipitation in mm/day (if white it was snowing) and red marks indicates the number of freeze-thaw cycles)

CONCLUSION

Riverbank erosion is a key factor to understand the dynamic of sediments inside basin being one important source of material that can be find in streams and can influence the flooding during extreme events. The objective of the paper was to test an innovative tool for a rapid assessment of river bank erosion; secondarily an attempt to link measured erosion and weather condition is done. First objective is completely met by the laser scanner, it proved to be reliable, easy to use and can be deployed easily in the field. Various test have been done to prove its precision, not all reported here for synthesis sake and its error is low enough to assure usable results. Erosion rates do not need high precision measure, since the uncertainty of all the ruling parameters is high. Moreover, the other sediment sources, as slope erosion or concentrated sources cannot be estimated with high precision, lowering the need for very precise bank erosion evaluation.

Second objective was partially met: the study was indeed able to give insights on bank erosion dynamics. However, these results do not add much to the pre-existing knowledge about bank erosion and, due to the limited span of time and space, cannot be translated in a correlation between weather conditions and erosion rate. The role of temperature is confirmed as predominant in the process and in particular, freeze thaw cycles are the most critical phenomenon in loosening soil, making it erosion easier. More yearly survey campaign are needed to look for a strong correlation between erosion and weather conditions.

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REFERENCES

B. Wieczorek and J. Kuczynska. Usefulness of terrestrial laser scanner for determining bank of the river. Institute of river and coastal engineering, 2010.

Brambilla, D., Longoni, L., Papini, M., Giorgetti, E., & Radice, A. (2011). On analysis of sediment sources toward proper characterization of hydro-geological hazard for mountain environments. International journal of safety and security engineering, 1(4), 423-437.

De Vente, J., & Poesen, J. (2005). Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth-Science Reviews, 71(1), 95-125.

Duan, J. G. (2005). Analytical approach to calculate rate of bank erosion. Journal of hydraulic engineering, 131(11), 980-990.

Green, T. R., Beavis, S. G., Dietrich, C. R., & Jakeman, A. J. (1999). Relating stream-bank erosion to in-stream transport of suspended sediment. Hydrological Processes, 13(5), 777-787.

Klaassen, G.J., FRIMAR: Flooding RIsks in Mountain AReas. Available at the web address http://www.hrwallingford.co.uk/Mitch/papers/klaassen.pdf, 1997.

Lane S.N., Tayefi V., Reid S.C., Yu D., Hardy R.J., Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. Earth Surface Processes and Landforms, 32, 429-446, 2007.

Nasermoaddeli, M. H., & Pasche, E. (2008). Application of terrestrial 3D laser scanner in quantification of the riverbank erosion and deposition. Proceedings of Riverflow, 3-5.

O'Neal, M. A., & Pizzuto, J. E. (2011). The rates and spatial patterns of annual riverbank erosion revealed through terrestrial laser-scanner surveys of the South River, Virginia. Earth Surface Processes and Landforms, 36(5), 695-701.

Radice, A., Giorgetti, E., Brambilla, D., Longoni, L., & Papini, M. (2012). On integrated sediment transport modelling for flash events in mountain environments. Acta Geophysica, 60(1), 191-213.

Reid S.C., Lane S.N., Berney J.M., Holden J.,The timing and magnitude of coarse sediment transport events within an upland, temperate gravel-bed river. Geomorphology, 83, 152-182, 2007.

Thorne, C. R. (1990). Effects of vegetation on riverbank erosion and stability. Vegetation and erosion, 125-144.

Yumoto, M., Ogata, T., Matsuoka, N., & Matsumoto, E. (2006). Riverbank freeze-thaw erosion along a small mountain stream, Nikko volcanic area, central Japan. Permafrost and Periglacial Processes, 17(4), 325-339.