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Research papers

Application of short-range photogrammetry for monitoring seepage erosion of riverbank by laboratory experiments

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ABSTRACT

Temporal and spatial monitoring play a significant role in evaluating and examining the riverbank morphology and its spatiotemporal changes. Unlike the terrestrial laser scanners, other previously used methods such as satellite images, total station surveying, and erosion pins have limited application to quantify the small-scale bank variations due to the lack of rapid survey and resolution in data acquisition. High cost, lack of availability, specialized equipment and hard movement of laser scanners make it necessary to develop new accurate, economical and easily available methods. The present study aims to test the Kinect photogrametric technology for measuring and assessing riverbank variations in laboratory environment. For this purpose, three models of layered soil blocks for three different levels of groundwater (i.e. 24, 34 and 44 cm) were designed to investigate the seepage erosion behavior experimentally. The results indicate the high accuracy of Kinect in measuring the bank erosion cavity dimensions (i.e., 0.5% error) with high spatial resolution data (i.e. 300,000 points per frame). The high speed of Kinect in riverbank scanning enables the analysis of time variations of mechanisms such as seepage erosion which occurs rather rapidly. The results confirmed that there is a power relationship between the seepage gradient and the time of the bank failure with a determination coefficient of 0.97. Moreover, an increase in the level of groundwater on the riverbank increases the rate of undercutting retreat that caused more rapid failure of the riverbank.

1. Introduction

Riverbank erosion, as one of the most dynamic processes in riverbank morphology, is one of the essential problems in river management (Darby et al., 2000; Xia et al., 2014). The estimation of river erosion is of great importance due to negative effects on the river such as the loss of fertile agricultural soil (Amiri-Tokaldany et al., 2003; Haddadchi et al., 2014), surface water contamination by sediment transport (Hassan et al., 2013; Midgley et al., 2012), an increase in the suspended sediment load (Evans et al., 2006; Simon and Rinaldi, 2006), morphological deformation of the river which can affect submerged structures (Dotterweich, 2008; Millar, 2000; Rinaldi and Darby, 2007) and a reduction of the volume of reservoirs (Amitrano et al., 2013; De Araújo et al., 2006). Riverbank erosion processes are categorized into two groups based on the factors affecting the stability: 1) the fluvial erosion due to excess shear stresses imposed on the riverbank and 2) the mass wasting due to the role of the geotechnical instability factors such as seepage flow and subaerial process (Crosta and Prisco, 1999; Lawler et al., 1997; Rinaldi and Darby, 2007).

The lateral subsurface flow is known as one of the significant factors in destruction of riverbanks and production of sediment loads in many geographical regions of the world (Fox and Wilson, 2010; Fox et al., 2005; Masoodi et al., 2017; Wilson et al., 2007). The subsurface flow leads to erosion of non-consolidated materials along the riverbank by applying the shear stress on the cavities through the water flow or by utilizing drag force to the particles and entraining them by seepage flow (Dunne, 1990; Fox et al., 2006; Jones, 1997). The occurrence of subsurface erosion requires establishment of certain conditions such as excess flow and the exit point of water from the soil. In this regard, the excess flow is defined as the difference between seepage flow and the flow at which sediment is on the threshold of motion (Hagerty, 1991a; Hagerty, 1991b; Wilson et al., 2007).

Wilson et al. (2007) suggested that the heterogeneity of the hydraulic conductive in the riverbanks, such as a conductive layer bounded by two less-conductive layers at the top and bottom,

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causes concentration of subsurface flow resulting in seepage from the conductive layer. High stage conditions can also increase the water level in riverbanks which impacts riverbank stability. As the water level in the river decreases, the lateral subsurface water stored in the bank flows from the riverbank back into the river results in seepage erosion cavities (Fig. 1).

As illustrated in Fig. 1, the seepage erosion is the particle entrainment by the seepage flow from the riverbank, which causes undercutting and mass failure of the topsoil layer (Hagerty, 1991a). To investigate and recognize this failure mechanism of the riverbank, it is necessary to measure the volume of undercutting due to the seepage flow (Chu-Agor et al., 2008a). Most of the applied techniques in river morphology studies are related to large-scale morphological changes such as coastline displacement, river bed widening, and river pathway changes over time which are unable to monitor small-scale changes of the riverbank (Nasermoaddeli and Pasche, 2008). In this regard, most studies on erosion and sediment have suffered from a lack of continuous measurements as well as many constraints in spatial and temporal changes, based on morphological and sediment transport approaches (Ferguson, 1993). One of the factors causing the complexity of seepage erosion analysis is related to its three-dimensional nature (Chu-Agor et al., 2009; Crosta and Prisco, 1999). Although the non-uniform distribution of seepage erosion on the riverbank is evident in field, they are generally distinct by preferred flow pathways. The undercutting dimensions are substantial in terms of estimation of the eroded sediment and bank instability (Cancienne, 2008; Chu-Agor et al., 2008b; Karmaker and Dutta, 2013).

Lawler et al. (1997) reviewed and categorized the various methods used to monitoring riverbank erosion and its changes, e.g. erosion pins, terrain photogrammetry and PEEP[1]. Erosion mechanisms identification and their roles are required to estimate sedimentation rate.

Pizzuto et al. (2010) argued that the study of temporal and spatial variations of riverbank erosion is important based on two perspectives: 1) improved recognition of the riverbank erosion process can help to develop the conceptual models of the river response; and 2) spatial and temporal variations of riverbank erosion can be useful in estimating sediment load and riverbank retreat which is required for river management programs.

With the advancement of technology in hardware and software, surveying and data acquisition can be performed with higher accuracy and speed both in field and laboratory. Recently, various approaches have been used to study the morphology of the riverbank. For example, Fuller et al. (2003) measured the sediment transport values for the fluvial equilibrium after the chute cutoff, using surveying with Total Station Camera and producing a digital elevation model (DEM). Although Total Station technique is highly accurate, it includes a low spatial resolution and is associated with a considerable error in the steep or vertical slopes (Nasermoaddeli and Pasche, 2008). With the development of the photogrammetric techniques, Brasington et al. (2000) studied the three-dimensional morphodynamics of braided rivers, using a high precision real-time global positioning system (GPS). The GPS technique has a limited utilization on steep and vertical slopes, and it is less accurate than the Total Station. Recently, Wells et al. (2016) presented a method for monitoring rill and ephemeral gully erosion spatiotemporally based on close-range digital photogrammetric techniques. Aerial laser scanning (ALS) method is regarded as another application of remote sensing techniques in rivers which is based on the limitation and identification of light (Longoni et al., 2016). This technique could measure the retreat of the riverbank surficially from the plan. However, it may not distinguish the erosion on the riverbank accurate enough, because the banks have often steep slopes and the viewing angle in these techniques is oblique. Therefore, it is preferable to record the erosion variations from above and to understand morphological changes of the banks. The changes may appear as undermining and small-scale frequent failures of the banks which are not generally recorded and could only be recordable when the failure affects the upper surface of the bank (Hicks et al., 2007; Mitasova et al., 2002; Thoma et al., 2005). Despite the high precision and high spatial resolution, this method may be suffering from high uncertainties. For example, it may be confronted with time resolution limit to interpret at large levels (Heritage and Hetherington, 2007; Milan et al., 2007).

Terrestrial laser scanning (TLS) is another technique used in recent years, in geomorphic studies and large-scale riverbank erosion measurements due to its high accuracy (Bitelli et al., 2004; Milan et al., 2007; Nasermoaddeli and Pasche, 2008). Rosser et al. (2005) recorded changes in the dimensions of a coastal cliff, using TLS techniques, which can measure the failure variations on vertical or relatively vertical slopes with high speed and accuracy. In addition, the time-series of terrestrial scanning was used to measure volumetric variations of stratigraphic layers at the riverbank (Lyons et al., 2015; Starek et al., 2013).

Nasermoaddeli and Pasche (2008) conducted their studies on riverbank erosion and how it was relocated using TLS techniques. Milan et al. (2007) used this technique to evaluate the displacement and riverbank deformation. For this purpose, they monitored a small reach of the river in two flood periods by TLS. By creating DTMs and their comparison, they analyzed how the erosion and sedimentation processes affect the riverbank. To understand more about the relationship between the extent of riverbank erosion as well as weather conditions and river flow rates, Longoni et al. (2016) applied TLS techniques to monitor the riverbank over a period of time and found that the method is an efficient and effective way for achieving the purpose. Chu-Agor et al. (2009) also studied geometry and dimensions of undercutting using 3D high-accuracy medium-range laser scanner to monitor for different periods. A single-layer simulated riverbank of sand material by $50 \times 20 \times 25$ cm dimensions was utilized in this regard. Although laser scanners have high accuracy, their heavy weight causes problems for their movement. On the other hand, it is expensive and costly in comparison to other procedures.

According to the mentioned methods, it is not possible to introduce an optimal method for all applications practically, as each includes a different ability fitting to the intended application. To select the type of measurement method, some factors such as accuracy, cost, number of measurement points and their disparity, deformation rate, environmental conditions, adequate time for measurement, access to the target body, the material of the target body, texture status and the color of the body surface should be taken into consideration (Salvi et al., 1998; Wells et al., 2016).

Most of the previous studies are based on long periods of time such as satellite images, sediment traps, and ALS. Despite all the techniques previously introduced, there are problems to obtain high resolution morphological data. This is due to the fact that the adequacy of the data plays an influential role in examining the changes on short temporal and medium spatial scales based on the economic conditions.

To scan morphological changes resulting from seepage erosion, it is necessary to have a measuring device with high spatial and temporal accuracy, due to the rapid temporal variations and the probability of occurrence in small spatial reaches. As the seepage erosion process often lasts less than a few hours, it is necessary to make surveys more rapidly and frequently.

Measurement methods which have been used in the riverbank erosion often provide a set of data which are spatially or temporally dispersed and have high uncertainty or sometimes limited

[1] Photo-Electronic Erosion Pin.