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International Soil and Water Conservation Research

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

Original Research Article

Measuring flow velocity on frozen and non-frozen slopes of black soil through leading edge method

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ARTICLE INFO

Article history:
Received 18 October 2016
Accepted 27 February 2017

Keywords:
Flow velocity
Leading edge method
Frozen/ non-frozen soil

ABSTRACT

Flow velocity is a major parameter related to hillslope hydrodynamics erosion. This study aims to measure flow velocity over frozen and non-frozen slopes through leading edge method before being calibrated with accurate flow velocity to determine the correct coefficient for convenience of flow velocity measurement. Laboratory experiments were conducted on frozen and non-frozen soil slopes with flumes involving four slope gradients of 5°, 10°, 15°, and 20°and three flow rates of 1, 2, and 4 L/min with a flume of 6 m long and 0.1 m wide. The measurements were made with a stopwatch to record the time duration that the water flow ran over the rill segments of 2, 4 and 6 m long. Accurate flow velocity was measured with electrolyte trace method, under pulse boundary condition. The leading edge and accurate flow velocities were used to determine the correction coefficient to convert the former to the latter. Results showed that the correction coefficient on frozen soil slope was 0.81 with a coefficient of determination (R^2) of 0.99. The correction coefficient on non-frozen soil slope was 0.79 with R^2 of 0.98. A coefficient of 0.8 was applicable to both soil surface conditions. The accurate velocities on the four frozen black soil slopes were approximately 30%, 54%, 71%, and 91% higher than those on non-frozen soil slopes. By contrast, the leading edge flow velocities on the frozen soil slopes were 23%, 54%, 67%, and 84% higher than those on non-frozen soil slopes. The flow velocities on frozen soil slopes increased with flow rate at all four slopes, but they increased from 5 to 15° before getting stabilized. Therefore, rill flow velocity can be effectively measured with leading edge method by multiplying the leading edge velocity with a correction coefficient of 0.80. This study provides a strategy to measure rill flow velocity for studies on soil erosion mechanisms.

1. Introduction

Flow velocity is a significant parameter and basis for soil erosion and hydrogic process studies. Shallow water flow velocity on land surface plays an important role in soil erosion, which involves soil particle detachment, sediment transport, and sediment deposition. In erosion models, such as WEPP (Nearing, Foster, Lane, & Finkner, 1989) and GUEST (Misra & Rose, 1996; Rose, Williams, Sander, & Barry, 1983), water flow on soil surface supplies energy to detach soil particles, transport and deposit sediments. Numerous factors, including flow rate, slope gradient, topography, and soil surface condition affect velocity of water flow (Lei, Chuo, Zhao, Shi, & Liu, 2010; Zhang, Liu, Liu, He, & Nearing, 2003).

Several methods have been used to measure velocities of shallow rill flow. Trace method is generally employed to determine flow velocities by adding a material into water flow and then measuring the speed of the material, which represents the flow velocity. Common trace materials include dyes (Katz, Watts, & Burroughs, 1995; Zhang, Luo, & Cai, 2010), salt (Olivier et al., 2005; Lei, Xia, and Zhao, 2005), magnetic materials (Ventura, Nearing, & Norton, 2001), water isotopes (Berman, Gupta, Gabrielli, Garland, & McDonnell, 2009), and floating objects (Dunkerley, 2003). More or less, because of some limite, accurate velocity of water flow cannot be ensured with these methods and re-calibration is required.

Dye has been used as a trace material to measure flow velocities for long time (Dunne & Dietrich, 1980; Katz et al., 1995). With a dye tracer, the time interval from the injection point to the end of a given rill section is measured visually and manually. The distance from the injection point to the end of a given section

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Peer review under responsibility of International Research and Training Center on Erosion and Sedimentation and China Water and Power Press.

http://dx.doi.org/10.1016/j.iswcr.2017.02.004

Please cite this article as: Chen, C., et al. (2017), http://dx.doi.org/10.1016/j.iswcr.2017.02.004

divided by the time interval corresponds to the leading edge velocity, which is regarded as surface velocity.

The flow velocity measured using a dye as a trace material is not the actual mean velocity. To calculate the actual mean velocity, a correction coefficient must be used to compute the flow velocity.

Horton, Leach, and Vliet (1934) theorized that the coefficient for laminar flow is 0.67, which is also considered to calculate surface velocities in laboratory flume tests (Guy, Dickinson, Rudra, & Wall, 1990). Emmett (1970) conducted a laboratory experiment on surface velocity by using dye-arrival time on measured flow distances and found that the mean coefficients for laminar flow with $200 < \text{Re} < 2000$ (where Re is Reynolds number) and turbulent water flow were 0.576 and 0.8, respectively. Clear water and water carrying with sediment grains were also used to determine the coefficients for laminar flow ($\text{Re} < 2000$) (Li, Abrahams, & Atkinson, 1996; Li & Abrahams, 1997). The mean coefficient was determined to be 0.37, which was much lower than the values reported by Emmett (1970). All these led to confusing results. First, a stable flow field is needed to apply this method, and the regime of water flow cannot be easily determined when the coefficient was increases to obtain the actual mean flow velocity. Second, the dye in water flow will diffuse and disperse, thus resulting in the difficulty in observing it. Third, as the color of soil is dark and water flow carries sediment, it is visually difficult to observe the dye. Fourth, the stopwatch is pressed when the front of dye reaches the marked line. However, since the move is done by examiners, and it takes the brain some time to react, the time will lead to the error of results. Fifth, in order to make the dye visible after which has diffused and dispersed through a distance, the distance must be set to be short. But short distance will lead to less time when water flow passes through it. The shorter the time when water flow travels, the larger the proportion of response time to the total time is. Therefore, this method likely yields a high error in determining the mean flow velocity.

Singh, Ramashastri, Singh, GerganGergan, and Dobhal (1995) used wooden floats to trace water flow velocity, through the travel time measured with a stopwatch. They also used wooden floats to measure the velocity of melt water stream (Singh, Haritashya, and Ramasastri, 2005). For rill water flow, wooden objects might be too big to be carried to trace the water flow.

João de Lima and Abrantes (2014) used infrared thermography to measure the velocity of shallow water flow. In this technique, a dye tracer is used to verify the velocity measured with a thermal tracer. A thermal tracer method was used to trace shallow water flow velocity.

Bradley, Kruger, Meselhe, and Muste (2002) and Muste, Xiong, Schöne, and Li (2004) employed image velocimetry techniques to measure the velocity of water flow under laboratory and field conditions. Creutin Muste, and Li (2002) and Fujita and Tsubaki (2002) used large-scale particle image velocimetry (LSPIV) to determine free-surface velocities in rivers.

Muste et al. (2014) applied LSPIV to measure the velocity of shallow water flow. High-speed digital cameras were utilized to record images during water flow to capture the condition of surface flow. This method required expensive devices that were inconvenient for field experiments. This method also involved a key step in which a camera captured the movement of cypress wood in water flow, but velocity cannot be easily determined with this method when water flow contained sediments.

Lei, Xia, and Zhao (2005) proposed an electrolyte tracer method to measure the velocity of shallow water flow by detecting the variations in the concentration of electrolyte solution when water flow passed a sensor. The sensor then detected the electrolyte tracer dissolved in water flow. The velocity measured with this method can represent the velocity of flow profile. Therefore, this method can be applied to determine velocity accurately without calibration.

In this study, a stopwatch was used to measure the time at which the leading edge water passed a distance of the flume before velocity is estimated. The velocity of the shallow water flow was determined by the flume length divided by the time measured using the stopwatch. Correction coefficient was estimated for calibrating the flow velocity.

2. Methodology

2.1. Leading edge method

Leading edge flow velocity was measured with a stopwatch to determine the time duration from the moment the water flow was introduced into the rill segment, until that the flow reaches the outlet of the flume.

$$V = L/t \tag{1}$$

where V is the velocity of water flow, m/s; L is the distance between the upper starting point and the outlet of the flume, m; and t is the time duration for water to cover the given distance, s.

The accuracy of velocity, V in Eq. (1), depends on the measurement accuracies of distance (L) and time (t), as defined in Eq. (1).

There are at least three factors influence the measurement accuracy of velocity: the accuracies of L and t measurements as well as the influence of hydrodynamic dispersion of tracer materials.

With longer measurement distance, i.e. greater L in Eq. (1), the relative errors in determining both the travel length and time duration of tracer movement should be reduced. The hydrodynamic dispersion reminds a factor needing correction. Accurately-measured flow velocity with electrolyte trace method can be used to estimate coefficient to correct the velocity measured with leading edge method.

2.2. Experimental Materials and Methods

The black soil materials were collected from a cultivated field in Liaoning province, northeast China. After being air-dried under the sun, the soil was passed through a 4 mm sieve. The laboratory measurement determined that the soil consisted of 49.7% sand, 33.6% silt, and 16.7% clay particles.

Soil flumes, 3 m long, 10 cm wide and 12 cm deep were made of steel (Ban, Lei, Liu, & Chen, 2016). The prepared soil materials were filled into the flume to 10 cm depth, before they were saturated with water. To reduce the side wall effect, the soil surface was slightly lower in the middle of the flume. Sufficient water was added into flume to ensure saturation of the soil materials. Soil-filled flumes were kept for 24 h to be further saturate and consolidated, to ensure the homogeneity of initial water content and eliminate the effects of uneven packing of soil materials. Part of the soil-filled flumes were placed into the freezer for 24 h at the temperature between −15 °C and −20 °C.

The frozen soil flumes were taken out of the freezer an hour before starting the experiments to prevent water flow being affected too much by the very low temperature of the frozen soil. Frozen and non-frozen soil flumes were placed on a platform which can be adjusted to different slopes from 0° to 35°. Two flumes were connected end-to-end to form a flume of 6 m long.

A peristaltic pump with adjustable flow rates from 1 to 60 L/min, was used to provide a steady and calibrated water flow. The flow was supplied from a tank of about 200 L in which the water was mixed with to acquire ice water at temperature of about 0 °C.

Water flow was introduced into the flume at the upper end of

Please cite this article as: Chen, C., et al. (2017), http://dx.doi.org/10.1016/j.iswcr.2017.02.004