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Assessing dye-tracer technique for rill flow velocity measurements

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ABSTRACT

Rill erosion is considered one of the most important processes affecting soil because of the large amount of soil loss. The rill network acts as sediment source and is able to transport both rill flow-detached particles and those delivered from the interrill areas.

Small flow depth in a rill and steep slope values of its bed affect significantly flow hydraulics. When rill flow velocity is measured using a dye-tracing method, the mean velocity is calculated by multiplying the measured surface velocity of the leading edge of the tracer plume by a correction factor. The main uncertainty of the dye-tracing technique stands in the relationship between mean and surface flow velocity. In this paper, this relationship was firstly tested using the measured data pairs available from literature and then the influence of the adopted relationship on the estimate of the Darcy Weisbach friction factor was examined. The developed analysis showed that the applied estimate criteria of the correction factor do not affect the estimate performances of the theoretical flow resistance equation.

Finally a new flow resistance equation for rill flows which can be directly calibrated by surface velocity measurements was deduced. The proposed procedure for estimating the friction factor was calibrated by rill data available from literature and was positively tested by the rill velocity measurements carried out in this investigation.

1. Introduction

Measuring flow velocity in very shallow water, such as in rill flows (Bruno et al., 2008; Bagarello et al., 2015; Di Stefano et al., 2015), is useful for improving its hydraulic knowledge, which is necessary for developing process-based soil erosion models (Takken et al., 1998). In many soil erosion models, rill flow velocity is computed using uniform flow equation, such as Manning-Strickler equation, designed for river scale hydraulics (Govers et al., 2007) and having a limited application on rill flows which are characterized by variable interactions between flow, soil erosion and sediment transport (Nearing et al., 1997).

Many available technologies, such as hot film anemometry, acoustic Doppler velocimeter (ADV) and particle imaging velocimetry (PIV) have been developed for laboratory applications under controlled conditions, and they present numerous limitations when are used for field measurements of soil loss (Planchon et al., 2005). For example, ADV requires flow depths equal to or > 1.5 cm and the effect of transported particles on velocity measurement accuracy is not known. Hot film anemometry cannot be used to measure velocity in sediment laden flow (Ali et al., 2012). PIV technique is generally used in laboratory studies because of the required sophisticated equipment (Liu et al., 2001).

In the investigation of rill flow hydraulics, mean flow velocity V is usually calculated using other measured hydraulic variables (discharge, water depth, cross-section area) (Abrahams et al., 1996) or directly measured (Foster et al., 1984). When flow velocity has to be measured (Di Stefano et al., 2018; Peng et al., 2015), the dye-tracing is one of the most used techniques for measurements in flume experiments simulating rill flow (Gilley et al., 1990; Govers, 1992; Line and Meyer, 1988).

The main advantage of the dye-tracing method is that it can be applied without any instrumentation since the measurement is based on the visual observation of the tracer (Wirtz et al., 2010, 2012). Flow velocity is measured by recording the travel time of the leading edge of the dye cloud over the reach length. In particular, the ratio of the distance between the two sections (measurement section – end of the rill) to the travel time to cover this span is the surface velocity V_s of the leading edge of the dye cloud. Then, a correction factor α_v is applied to convert V_s to the mean flow velocity V (Zhang et al., 2010).

For the case of infinitely wide, laminar flow on a smooth and rigid bed, Horton et al. (1934) theoretically demonstrated that the correction factor α_v is equal to 0.67. Emmett's (1970) flume experiments showed

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that α_v increases with flow Reynolds number $Re = hV/\nu_k$, in which h is the water depth and ν_k is the kinematic viscosity, for transitional flow and is close to 0.8 for turbulent flow. In field experiments using a gravel bed, Luk and Merz (1992) obtained a mean value for α_v of 0.52 for laminar flow, while in laboratory experiments they observed a mean value of α_v equal to 0.75 for transitional and turbulent flow. In this way, Li et al. (1996) carried out an experimental investigation in a flume with a mobile sand bed in order to investigate the relationship between the correction factor α_v, the channel slope s and the flow Reynolds number. For flume slope values ranging from 4.7% to 17.7% and $910 \leq Re \leq 6097$, the experiments by Li et al. (1996) demonstrated that α_v is not equal to 0.67 for laminar flow and does not exhibit a value of 0.8 for turbulent flow even if the investigated range of Re did not allow establishing if α_v becomes independent of Re both in laminar and turbulent regime. The multiple regression equation proposed by Li et al. (1996) shows that the correction factor α_v varies inversely with slope and directly with Re. Li et al. (1996) did not explain why α_v should be related to slope and in a subsequent investigation Li and Abrahams (1997) suggested that the relationship could be a consequence of the flow sediment transport.

Li and Abrahams (1997) also showed the relationship between α_v and Re for both sediment-free and sediment-laden flow. For sediment-free flow, they carried out a set of experiments to measure α_v for an overland flow on a fixed bed, in which a well-sorted silica sand was glued, inclined at three slopes (2.1%, 6.1% and 9.6%). The correction factor ranged from 0.30 to 0.51 and had a mean value of 0.37 which was significantly less than the theoretical value of 0.67 in laminar flow. This discrepancy can be justified taking into account that the theoretical value (0.67) applies only to smooth beds and velocity distributions over a sand particle bed are steeper than those over a smooth surface and hence α_v decreases with bed roughness (Li and Abrahams, 1997). The correction factor increased rapidly with Re in transitional flow and more slowly with Reynolds number in turbulent flow ($Re \geq 2000$) assuming a quasi constant value equal to 0.8. For sediment free flows α_v did not vary with slope. Li and Abrahams (1997) also carried out experiments, with a flume inclined at a slope of 3.7°, in which the same silica sand was glued on the bed and supplied to the flow. For these sediment laden flows, a reduction of the correction factor was obtained because saltating sediment extracts momentum from flow and an inverse relationship between α_v and sediment load is likely.

Xia et al. (2003) stated the effect of sediment concentration on correction factor α_v using a flume having a slope ranging from 0.9 to 20.8% and a sediment concentration less than or equal to 60.2% (Zhang et al., 2010). They found that α_v increases with sediment concentration obtaining a result which is not consistent with the conclusion of Li and Abrahams (1997).

Zhang et al. (2010) investigated the effect of sediment load on correction factor α_v, using a flume having an adjustable slope up to 60%, for carrying out an experimental study under a wide range of hydraulic conditions and sediment load. For a sediment-free flow, the results showed that the correction factor decreases when slope increases and Re decreases assuming a mean value of 0.659. According to the authors, the correction factor α_v could be estimated by a logarithmic function of slope and flow Reynolds number. For a sediment-laden flow, Zhang et al. (2010) established that α_v decreases as sediment load increases and Re decreases. Combining sediment-free and sediment-laden flows, the correction factor varies from 0.233 to 0.783 and assumes a mean value of 0.505.

Ali et al. (2012) studied the effects of discharge, grain size and slope on mean flow velocity by flume experiments carried out by a well-sorted sand having a median grain size, D_{50}, equal to 0.230, 0.536, 0.716 and 1.022 mm. Their experimental results established that the mean value of the correction factor α_v increases when the grain size increases. The mean values of the correction factor α_v for D_{50} equal to 0.230, 0.536, 0.716 and 1.022 mm were 0.44, 0.77, 0.82 and 0.82, respectively. The positive impact of sediment particle size on α_v for flow velocity on mobile beds is due to variations of both the vertical velocity profile with grain size and the bed morphology due to sediment uptake and deposition (Li and Abrahams, 1997).

Pan et al. (2015) carried out 291 tests in a flume with different roughness conditions (smooth glass, sandpaper and sandpaper glued with plastic grass clusters) for investigating the overland flow hydraulics. For laminar flow, the authors attributed the α_v values less than the theoretical one (0.67) to the greater spatial variability in overland flow compared with channel flow. The obtained α_v values were approximately 0.8 for turbulent flows and α_v varied positively with flow Reynolds number for each investigated surface. According to Pan et al. (2015), the relationship between correction factor and slope should be dependent on the bed type and the condition of submerged or non-submerged roughness elements.

All previously cited studies revealed that the selection of an appropriate correction factor has become a challenge for current research because of the variety of α_v values resulting from the different experimental investigations. Very few studies have been carried out to estimate mean flow velocity in rills (Abrahams et al., 1996; Di Stefano et al., 2017b; Rodrigo-Comino et al., 2017). Furthermore, to the best of our knowledge, the available studies of rill flow resistance generally assumed a value of the calibration factor (*i.e.* Govers (1992), Li et al. (1996)) without testing the effect of the estimate uncertainty of α_v on the Darcy-Weisbach friction factor.

Thereby, the main goals of this paper were: i) establishing the relationship between surface velocity V_s and mean flow velocity V using the measurements carried out for the overland flows by Li et al. (1996), Li and Abrahams (1997), Zhang et al. (2010), Ali et al. (2012) and for the rill flows by Di Stefano et al. (2017b); ii) testing the influence of the adopted V- V_s relationship on the estimate of the Darcy-Weisbach friction factor; and, iii) deducing a new flow resistance equation for rill flows which can be directly calibrated by surface velocity measurements.

2. Materials and methods

2.1. Experiments by Li et al. (1996)

Li et al. (1996) carried out 40 laboratory experiments using a flume 5.2 m long, 0.4 m wide, having smooth Plexiglass walls and a lower part, 3.6 m long, with a mobile sand-cover bed. The sand was a well-sorted silica sand (ASTM C – 190) with a median diameter D_{50} of 0.74 mm. For these experiments the lower part of the flume had a slope s equal to 4.7, 9.6 and 17.7%. In each experiment the same well-sorted silica sand was supplied by a sediment feed system located at the upper part of the flume. Mean flow velocity, edge velocity of a saline plume down the flume and flow depth h are listed in Table 1 of the paper by Li et al. (1996).

The experimental values of the Froude number $F = V g^{-1/2} h^{-1/2}$, in which g is acceleration due to gravity, and Reynolds number corresponded to different flow regimes ($910 \leq Re \leq 6098$) and supercritical flow conditions ($1.09 \leq F \leq 2.71$).

2.2. Experiments by Li and Abrahams (1997)

Li and Abrahams (1997) carried out 105 experimental runs using the same flume of Li et al. (1996) with a sediment-free flow on a fixed sand-covered bed. This set of experiments was conducted on a bed in which a well-sorted silica sand (ASTM C – 190), with a D_{50} of 0.74 mm, was glued. For these experiments the lower part of the flume had a slope s equal to 2.1, 6.1 and 9.6%. Mean flow velocity, edge velocity of a saline plume down the flume and flow depth are listed in Table 1 of the paper Li and Abrahams (1997). The experimental values of the Reynolds and Froude number generally corresponded to different flow regimes ($420 \leq Re \leq 3994$) and to a wide range of flow conditions ($0.398 \leq F \leq 3.165$).