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Effect of stone content on water flow velocity over Loess slope: Frozen soil

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ABSTRACT

Soils in high-altitude or -latitude regions are commonly rich in stone fragments, which are frequently frozen. The hydrodynamics of water flow over frozen, stony slopes must be investigated to understand soil erosion and sediment transportation. The objective of this laboratory experiments was to measure water flow velocity over frozen slopes with different stone contents by using electrolyte trace method. The experiments were performed under slope gradients of 5°, 10°, 15°, and 20°; flow discharge rates of 1, 2, 4, and 8 L/min; and stone contents of 0%, 10%, 20%, and 50% on mass basis. Nine equidistant sensors were used to measure flow velocity along flume from the top of the slope. Results indicated that stone content significantly affected flow velocity under increasing slope gradient. The increase in stone content rapidly reduced the flow velocity. The flow velocities over frozen slopes were 1.21 to 1.30 times of those over non-frozen slopes under different slope gradients and flow rates. When the stone content increased from 0% to 20%, proportions gradually decreased from 52% to 25% and 13%. Additionally, flow velocities over frozen and non-frozen soil slopes became gradually similar with increasing stone content. This study will help elucidate the hydrodynamics, soil erosion, and sediment transport behaviors of frozen or partially unfrozen hillslopes with different stone contents.

1. Introduction

Most permafrost areas are located in high-latitude regions around the Arctic and Antarctic or in high-altitude mountainous regions, such as China (Fang et al., 2015), Sweden (Johnsson and Lundin, 2011), Canada (Hayhoe et al., 1992), and Antarctic Peninsula (Golledge, 2014). In China, permafrost regions account for approximately 20% of exposed land in both high-latitude and -altitude regions, where diurnal freeze-thaw (FT) cycles occur during summer. Approximately 50% of the national territory experiences seasonal and daily FT cycles. Seasonally frozen soil is commonly eroded in these cold regions, in northern parts of China, and in high-altitude regions in Loess, Mongolia, and Tibet Plateaus. Water flowing from melted snow and glaciers in high-latitude and -altitude regions primarily drives serious seasonal soil erosion (Chen et al., 2015). Unfrozen soil slopes in regions covered with snow or glaciers may be eroded and transported by water flow over frozen slope, which contains more sediments than non-glacier-fed basins (Singh et al., 2009).

Flow of meltwater over frozen soil surface affects flow velocity (Kurylyk et al., 2014). Under this circumstance, flow velocity is influenced by factors, such as discharge rate, hillslope gradient, geomorphology, topography, and surface roughness of soil slope (Lei et al., 2010; Zhang et al., 2003). Rauws (1988) reported that smooth soil surfaces induced greater flow velocity than rougher surfaces. Ban et al. (2016a) reported that flow velocities were significantly higher over frozen slopes than over thawed or non-frozen ones. The flow velocities over frozen soil slopes were approximately 25% to 40% higher than those over non-frozen slopes under slope gradients ranging from 5° to 15° and at flow rates of 1 L/min to 4 L/min. Moreover, the water flow velocity over a frozen soil surface is expectedly higher than that over a thawed one due to the reduced frictional resistance of frozen soil slope to water flow and to the more uniform slope morphology caused by minimal scouring of frozen soil; such soil type exhibits high sheer strength and thus resists the scouring of water flow. Frictional coefficient of ice is lower than that of soil. Therefore, the resistance of frozen soil slope depends on the proportion between

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soil particle surfaces between ice of frozen soil and contact with water flow. The resistance of frozen soil surface to water flow is significantly lower than that of thawed, un-frozen, or non-frozen soil surfaces, thereby increasing the flow velocity and inducing severe soil erosion and sediment transportation (Nadal-Romero et al., 2013; Rahma et al., 2013; Shi et al., 2014). In addition, surface morphology of frozen soil is less likely to be altered by soil erosion, and frozen soil rills without headcut displays a high amount of energy to accelerate water flow. Thus, water flow along a frozen soil rill is likely to display increased flow velocity.

Stones are commonly found in FT soils in high-altitude or -latitude regions. This phenomenon is mainly influenced by natural and anthropogenic factors (Guo et al., 2010). Soils with stone or rock fragments significantly affect soil properties, including water hydrological characteristics related to resistance to water flow, which in turn affect water flow velocity and sediment transportation (Leighton-Boyce et al., 2003; Van Wesemael et al., 2006; Martínez-Zavala and Jordán, 2008; Urbanek and Shakesby, 2009). Water flow velocity is speculated to decrease with increasing percentage of stone or rock fragments exposed to water flow (Agassi and Levy, 1991; Poesen, 1992; Poesen et al., 1994; Nyssen et al., 2001; Guo et al., 2010; Majed et al., 2011). Bunte and Poesen (1993) reported that the average flow velocity over stony slopes decreased exponentially with rock coverage of soil surface ranging from 0% to 25%. Simulated rainfall experiments conducted by Guo et al. (2010) indicated that flow velocity measured by using dye tracer method decreased from 0.24 m/s to 0.16 m/s when stone coverage increased from 5.1% to 20.8%. Han et al. (2016) experimentally indicated that increase in rock fragment content led to reduced flow velocity. The experimental results of Ban et al. (2017) indicated that the flow velocity significantly decreased as the stone content in the soil-stone mixture increased from 10% to 50%. Other researchers reported that the percentage of stone or rock fragments coverage exposed to water flow reduced the runoff and soil erosion due to the lowered flow velocity (Mandal et al., 2005; Martínez-Zavala and Jordán, 2008; Majed et al., 2011; Wang et al., 2013). Generally, horseshoe-shaped headcuts contain upside stones (Boyer and Roy, 1991; Poesen et al., 1994), resulting in reduced kinetic energy, soil erosion, and runoff. Stones consumed flow energy and obstructed sediment transport (Majed et al., 2011), and the retardant effect of stones decreased the flow velocity and prevented soil erosion caused by water flow. Altered rill morphology, which strongly affects flow path around stones, may also influences flow velocity. Research showed that water flow energy and accommodation space for such energy were two essential conditions that could lead to increased flow velocity (Yu et al., 2015). Flow velocity becomes susceptible to stones due to energy dissipation.

Despite its importance, flow velocity over frozen, stony soil surfaces has not yet been sufficiently investigated. Flow velocity is one of the most dominant parameters used to study slope hydrological and erosional processes, including those over stony and frozen slopes (Chen et al., 2008; Lei et al., 2010). Flow velocity on frozen and stony soil must be accurately estimated to calculate water flow kinetic energy and predict the effect of stone or rock fragments on frozen soil erosion (Nadal-Romero et al., 2013; Rahma et al., 2013; Shi et al., 2014). Interaction among flow rate, slope gradient, stone content, and frozen condition on flow velocity has not yet been investigated. Therefore, flow velocity measurement and model parameter estimation are essential to elucidate and quantify the effect of stone or rock fragments on hydrodynamics over frozen soil slopes in relation to soil erosion.

Electrolyte tracer method is used to determine the flow velocity of shallow water (Lei et al., 2005, 2010), water over frozen soils (Ban et al., 2016a), and water within the gravel layer (Lei et al., 2013). This study used electrolyte tracer method under pulse boundary condition according to the method described by Lei et al. (2005). The method was employed to: 1) measure the velocity of water flow over frozen-stony soil slopes; 2) quantify the influences of slope gradient, flow rate, and stone content on flow velocity; and 3) compare flow velocities over frozen slopes with different stone contents with those over non-frozen slopes under different hydraulic conditions.

2. Methodology

2.1. Solute transport model

Electrolyte tracer method can accurately measure shallow water flow velocity by tracing salt transport in water flow that passes over sensors located at different distances. This method accurately estimates flow velocity at different distances from the location of an electrolyte injector. The input boundary condition can be reasonably treated as a pulse input to determine the salt transport process in water flow. In this study, this method was used to measure water flow velocity. Salt solution was dissolved and transported by water flow and sensed by the sensors. The computational equation used to calculate flow velocity during solute transportation in water flow is a time-dependent function and was given by Lei et al. (2005):

$$C(x,t) = C_0 \frac{x}{2t\sqrt{\pi D_H t}} \exp\left(-\frac{(x-ut)^2}{4D_H t}\right) \quad (1)$$

where C represents electrolyte concentration (kg·m^{-3}), x corresponds to the slope length along rill (m), u stands for the flow velocity (m·s^{-1}), t is time (s), and D_H is the hydrodynamic dispersion coefficient (m^2·s^{-1}). Flow velocity (u) was determined by fitting the experimentally obtained electrolyte concentration process with Eq. (1) based on the least square method (Lei et al., 2005).

3. Experimental materials and methods

Loessial soil material used in the experiments was a typical silt loam and collected from Loess Plateau (37°32′N and 108°24′E) in Ansai County. Ansai is located in the hilly gullied and FT region of the Loess Plateau in Shaanxi Province, Northwest China. The soil sample was air-dried before being passed through a 2 mm sieve. The composition of soil fractions included 23.80% sand, 64.57% silt, and 11.63% clay particles. Stones used in the experiments exhibited diameters ranging from 0.01 m to 0.03 m, irregular shapes, prismatic angles, and rough surfaces. The stones were the same as those used by Ban et al. (2017).

The flumes used were 8.0 m long, 0.1 m wide, and 0.1 m deep (Ban et al., 2016b). Weighted soil materials were thoroughly mixed with stones to reach the desired stone contents before being transferred into the flumes. Subsequently, the soil and stone mixture in the flumes was saturated and allowed to equilibrate for a day, frozen in a freezer for no less than 24 h at temperature between −15 °C and −25 °C.

The prepared frozen soil flumes were placed onto a platform for measurement of flow velocity over frozen soil surface under different combinations of flow rates, slope gradients, and stone contents. A steady water flow was introduced into the upper end of the flume at a controlled and constant rate and at approximately 0 °C. A flow velocity measurement system was installed as described by Ban et al. (2016a). Fig. 1 shows the experimental setup. The solute injector was set in a water distributor 0.10 m from the upper end of the flume. Nine electrolyte sensors connected to the data logger were inserted into the frozen soil on the surface of the flume at 0.1, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, and