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Comparative study of erosion processes of thawed and non-frozen soil by concentrated meltwater flow

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ABSTRACT

Investigating the erosion processes of freeze–thaw-affected soils caused by concentrated snow/glacier meltwater flow can be challenging. Experimental data can help improve our understanding and modeling of the phenomenon. Laboratory experiments were conducted to assess the effects of slope gradient and flow rate on soil erosion by concentrated meltwater flow over thawed and non-frozen soil surfaces. Flumes were filled with the silty–sandy soil materials collected from a watershed delta formed by deposited sediments before being saturated and stored in a freezer to freeze the soil. After the soil was completely frozen, the flumes were taken out of the freezer and placed in the experimental hall to thaw the soil for a period of sufficient length until all the soil materials were thawed. Similarly, flumes which were filled with the same soil in the same procedures without undergoing the freezing and thawing process were used for the comparative experiments. Meltwater was simulated with a tank filled with ice water mixture to supply water flow at a temperature of 0 °C. The erosion experiments involved four slope gradients of 5°, 10°, 15°, and 20° and three flow rates of 1, 2, and 4 L/min, with seven rill lengths of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 m, as determined by the distance between the water inlets and exit sill. Sediment concentrations at the seven locations formed a rill erosion process, which increased exponentially with rill length to approach a limiting value. The sediment concentrations were positively correlated with flow rate and slope gradient. However, the effect of flow rate on sediment concentration was not as significant as that of slope gradient. The effect of flow rate on sediment concentration decreased with the increase in slope gradient. The maximum sediment concentrations in water flow over thawed slopes were higher than those over non-frozen slopes. Results from these experiments will be useful for estimating erosion model parameters for predicting erosion by meltwater.

1. Introduction

The high erosion rate of seasonal frozen soils by snow/glacier melt runoff is the primary erosion form in high-altitude and cold regions, such as in America, Europe, Asia and Antarctic Peninsula (Johnsson and Lundin, 1991; Vasilyev, 1994; Golledge, 2014). The erosion area caused by the freeze–thaw (FT) cycle in the Qinghai–Tibet Plateau is approximately 1.64 million km^2 (Guo et al., 2015). Daily circulations and seasonal fluctuations of air temperature cause fluctuations of temperatures in surface soil and water, which cause permafrost, snow, and glacier thawing, can significantly alter soil erosion (Kurylyk et al., 2014). The top soil saturated or near-saturated by snow or glacier melt water flow in the thawed soil layers reveals the daily fluctuation cycle of FT. The Cambosols following Aridosols are the dominant soil textures in the Qinghai–Tibet Plateau (Fang et al., 2015) that exhibit a low degree of development, which is an apparent characteristic of parent materials, coarse particles, and detritus particle distribution; this characteristic makes Cambosols susceptible to erosion. With these loosened or soft thawed soil materials, a small amount of meltwater flow can induce serious erosion (Žabenská1 and Dumbrovský, 2015). Soil loss occurs on the thawed soil surface during glacier and snow melt periods (Birhan, 2000).

Van Klaveren and McCool (1998) determined that thawed soils exhibited a slightly higher erodibility under controlled moisture tension after a single FT cycle than non-frozen soil. Frame et al. (1992) conducted laboratory tests on FT cycled soils, which yielded a mean sediment concentration of 25% higher than that without freezing. Their results showed that the effects of FT on soil erosion vary and that a quantitative parametric understanding of the sediment transport process does not yet exist.

FT causes the rearrangement of soil particles (Liu et al., 2009), which results in certain physical changes in soil properties (Gullu and Khudir, 2014; Lin et al., 2011) that affect permeability (Kurylyk and Watanabe,

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2013), soil stability (Oztas and Fayetorbay, 2003), density (Zhang et al., 2007), and strength (Jamshidi and Lake, 2015) and leads to changes in soil erodibility and erosivity (Ferrick and Gatto, 2005). Soil properties play a significant role in determining soil susceptibility to erosion. Li et al. (2013) evaluated the relationship between soil anti-scouribility and FT-induced soil physical properties, soil disintegration, sediment loss, and total sediment yield, as compared with those without FT cycle. Results showed that the sediment yield increased by 19.4% and 6.7% in treatments of fallow (CK) and low density (LD), but high density (HD) had little influence. Meanwhile, the disintegration rate increased by 20.6%, 18.8% and 7.3% under conditions of CK, LD and HD. Given the changes in structural stability, erodibility, meltwater runoff, and infiltration rates of frozen subsoil (Bajracharya and Lal, 1992), soil may be more susceptible to erosion during the thaw periods (Bajracharya et al., 1998).

Staricka and Benoit (1995) determined that FT cycles decreased the stability of wet aggregates in 85 of 96 soil cores. Øygarden (2000) demonstrated that soil erosion was particularly enriched by rain and snow melt runoffs on partially thawed soil and that rills can easily form on soils that previously underwent FT cycles (Van Klaveren, 1987). The reason was that the inherent susceptibility of soil to detachment and transport was increased by rain and runoff (Ellison, 1945). Several studies had shown that erodibility increased when frozen soil thaw in winter (Kok and McCool, 1990; Bajracharya and Lal, 1992). These studies have led to increased interest in how soil properties are influenced by FT cycles, which in turn influence soil erosion and sediment transport processes.

Rapid climate warming has been the focus of considerable attention in recent decades (Bloomfield et al., 2013; Menberg et al., 2013). The increase in temperature in some high-altitude and cold regions produces more glacier and snow meltwater, which are the main runoff source and the dominating driver of soil erosion in these areas (Emmanuel et al., 2008). The glacier area of Ladder tributary in the Upper Indus Basin of the Himalayas has decreased from 46.09 km^2 in 1962 to 33.43 km^2 in 2013 and the proportion of snow coverage is depleting year by year (Romshoo et al., 2015) as a result of increasing temperatures (Barry, 2006; UNEP, 2010). This phenomenon, which is associated with global warming, will substantially alter the upper land and streamflow characteristics and ultimately increase meltwater erosion in cold areas (Immerzeel et al., 2009; Thorsteinsson et al., 2013). The exacerbated FT erosion has been more severe because of the continuously increasing temperature and precipitation. Research showed that nearly all of the rivers in the Tibetan region of China were considerably muddy during the thaw period from April to June (Sun et al., 2008). Most of the major flooding and soil erosion events were connected with snow or glacier meltwater in some FT regions of US (Johnson and McArthur, 1973).

Melting of snow and glaciers and other driving conditions in high-erosion regions and special soil types with high susceptibility for detachment and transportation by water flow make the slope highly susceptible to rill erosion. Rill flows with more energy and turbulence will detach and transport more sediment (Foster et al., 1984; Gilley et al., 1990). A study on rill erosion in high-altitude and cold regions caused by meltwater will be useful for estimating erosion by meltwater in those areas.

Most of the current studies on FT erosion in the Qinghai–Tibet Plateau mainly focus on field monitoring of erosion distribution or laboratory experiments of soil density, permeability, stability, vegetation, nitrogen, and moisture (Bai et al., 2012; Caviezel et al., 2014; Lee and Lee, 2002). However, research on the soil erosion process is limited because of the lack of experimental methods and facilities. The most important defects of previous facilities are its large volume, long experimental process, low mobility, and short effective length (Edwards and Burney, 1987; Gatto, 2000; Ferrick and Gatto, 2005). Guo et al. (2015) stated that the FT erosion process should be investigated to predict and improve the environment.

The objectives of this experiment were to investigate (1) the procedures in simulating the freezing and thawing processes of soil for erosion study, (2) the erosion process of thawed soil under different slope gradients and flow rates, and (3) the comparative differences of sediment concentration distributions along the eroding rills between thawed and non-frozen soils.

2. Materials and methods

2.1. Experimental materials

The experimental system is shown in Fig. 1. The flume was made to be 3 m long and 0.1 m wide. The height of side wall and end plate was 0.12 and 0.1 m, respectively. One of the end plates was designed as assembled style for conveniently jointing two flumes to be a flume of 6 m long. So the experimental flume was 6 m long and 0.1 m wide (Ban et al., 2016a, 2016b).

The deposited soil material was air-dried and passed through a 2-mm sieve prior to measuring its particle distribution. It contained 4.10% of organic component, 27.99% of sand, 64.24% of silt and 7.77% of clay particles. The deposited sediments were at altitude of 3682 m, where longitude and latitude was 36°21.823, N and 101°26.833, E, on the Qinghai-Tibetan Plateau of China. It was eroded from higher mountains that underwent thousands of years of FT cycles and exhibited soil properties similar to those in high-altitude and cold regions. Therefore, representative soil materials can be used to simulate meltwater erosion. The prepared materials were filled into the flume to a depth of 10 cm, with no compaction. The soil was saturated and allowed to equilibrate for a day (24 h) before each experimental run. Parts of the soil flumes were kept non-frozen in the experimental hall at room temperature of 20 °C to 30 °C. Parts of the flumes were stored in a freezer for no <24 h at temperatures of −25 °C to −15 °C. After the soil was completely frozen, the flumes were taken out of the freezer and thawed at room temperature. The experiments were started after the soil materials in the flumes were totally thawed.

Meltwater was simulated using a tank filled with a mixture of water and ice cubes to control water temperature at approximately 0 °C. A peristaltic pump with valves was used to control the flow rates.

The experiments involved two treatments with four slope gradients of 5°, 10°, 15°, and 20°; seven down-slope distances of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 m; and three flow rates of 1, 2, and 4 L/min (0.06, 0.12, and 0.24 m^3/h). Three replicates were adopted for a total of 504 experimental runs.

The experiments, that test lengths ranged from 0.5 to 3 m, were conducted directly on one of the flumes. Before each experimental run that test lengths were longer than 3 m, two 3 m-long flumes were placed on the platform to be jointed end to end to form a 6 m-long flume. The platform was raised to the desired slope.

2.2. Experimental methods

From the concepts suggested by Lei et al. (1998, 2002), sediment concentration in the water flow along an eroding rill increased with rill length. Sediment concentration gradually reached a steady maximum value at a sufficiently long distance down the rill. Under these conditions, the sediment yields of steady-state water flow were experimentally measured through a series of rill lengths before they were integrated into the sediment concentration distribution function along the rill length.

The simulated meltwater was regulated to the designed flow rate and introduced into the flume at certain locations with the distances of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 m from the sill, as shown in Fig. 1b. The slope length was determined by the distance between water inlet and flume sill. The sediment yield at different slope lengths distributed differently. When water flow in the rill run out of the exit sill 2 or 3 s and became steady, four runoff samples were taken from the outlet of the