International Soil and Water Conservation Research 4 (2016) 142–147

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Contents lists available at ScienceDirect

International Soil and Water Conservation Research

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

Original Research Article

Study on the facilities and procedures for meltwater erosion of thawed soil

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ARTICLE INFO

Article history:
Received 8 October 2015
Received in revised form
14 April 2016
Accepted 24 April 2016
Available online 17 May 2016

Keywords:
Melt-frozen
Soil erosion
Method
Facilities
Procedures

ABSTRACT

High erosion rate of seasonal thawed soils by snow- and ice-melting runoff in the high altitude and latitude cold regions has great impacts on ecological systems, industries, agriculture and various man-made infrastructures as well as people's lives. The facilities and procedures are of great importance for the studies on simulating erosion processes of melt-frozen soil. This study focuses on the method and facility for simulating the thawing process of frozen soil. The facility includes soil freezing system, melt-water supply system and experimental flume system for thawed soil erosion. The soil freezing system provides enough space to freeze soil columns in flumes. The water supply system deliveries snow- or ice-melting water flow of constant-rate at 0 °C. The soil flumes of 200 or 300 cm long, 10 cm wide and 12 cm high are designed to be assemble and convenient for soil freezing before they are thawed in one-dimensional manner from top to bottom. The one-dimensional thawing process is realized as follows. The frozen soil flume is put on ice boxes and thermally insulated with heat-insulating materials all around to prevent frozen soil from being thawed from sidewalls and bottom. The soil thaws with this system shows that it can meet the requirements of simulating the process of soil thawing from top to bottom. The thawed soil flumes are connected from end to end to form rills of 6–8 m long to run the erosion experiments under different designed hydraulic condition. The equipment provides facility, method and operation process for simulating one-dimensional soil thawing to serve research on the effect of thawed soil depth on erosion process.

1. Introduction

High mountain areas covered with snow and glacier are widely distributed throughout the world, and most of melt water flow and sediment transport are mainly controlled by glacier or/and snow melt water (Singh, Haritashya, & Ramasastri, 2005). In those regions, the special climate, soil and terrain conditions, and human activities intensify the melt water erosion processes. Glacier and snow melt water confluences contribute most downstream rivers, lakes and reservoirs, which are the primary runoff sources of these cold regions and become the dominating driver that should be responsible for soil loss of these areas (Emmanuel, Douglas, & Beth, 2008). High erosion regions with melt snow and glacier are featured with complicated driving conditions. Much soil loss occurs due to the impacts of glacier and snow melt water on soil surface during thawing period (Birhan, 2000). The special soil types and constructions induced by frequent freeze and thaw conditions lead to that those areas are highly susceptible to rill erosion which is the leading slope soil erosion form results in high rates of slope sediment discharge. Rills can easily form on previously frozen soils, even during low intensity rainfall and runoff (Van Klaveren, 1987).

The increase in temperature caused by climate warming has been paid more and more attentions in recent several decades (Bloomfield, Jackson, & Stuart, 2013; Menberg, Blum, Schaffitel, & Bayer, 2013). In this century, the world wide air temperature has increased 1.0–3.0 °C (Lewis, 2013). The warmer global climate, which results in the more melt snow and glaciers, leads to aggravated soil erosion (Zhang, Luo, Cai, Shen, & Zhang, 2010; Zhang, Zhao, Fang, & Zeng, 2010). The global warming has more significant influence on the high-latitude and high-altitude regions (IPCC, 2007). Higher temperature means less snow fall and cover, more rain, more frequent freeze-thaw cycles (Freppaz, Celi, Marchelli, & Zanini, 2008; Groffman et al., 2011), and larger daily or seasonal soil temperature variations (Groffman et al., 2011).

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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.2016.04.003
2095-6339/

Smaller glacier area (Romshoo, Dar, Rashid, Marazi, Ali, & Zaz, 2015) and rose snowline (Freppaz et al., 2008) has been observed. It has especially significant meaning to high-latitude and high-altitude regions. Soil freezing and thawing effect are directly related to air temperature. This increasing temperature has caused irreparable soil degradation and available land area decrease, and increase in downstream river sedimentation.

Most researchers focused on snowmelt water quantity and soil properties (Demidov, Ostroumov, & Nikitishena, 1995; Gregor, Irina, & Ralph, 2006; Hayhoe, Pelletier, & Coote, 1995) than the quantitative study of thaw depth impact on snowmelt erosion (Fan, Wu, & Zhou, 2010). On account of this complexity, Benoit and Voorhees (1990) and Kok and McCool (1990) reported that freeze-thaw effects were the least understood aspects of soil erosion processes. Several investigators had recognized that freeze-thaw generally increased soil erodibility (Bryan, 2000), and the extent of this effect changed with soil moisture, texture, and extent of freezing and thawing. There existed contradictory experimental results. Laboratory rill erosion experiments made by Van Klaveren and McCool (1998) revealed that there was slightly higher erodibility of thawed frozen soils after a single freeze–thaw cycle compared to a soil which never experienced freezing effect. Žabenskál and Dumbrovský (2015) found that a small amount of surface runoff could result in serious erosion of thawed soil due to the specific soil properties. Physical changes induced by freeze-thaw process, which affected soil-particle cohesion (Van Klaveren, 1987), density (Zhang, Lai, & Sun, 2007) and strength (Jamshidi & Lake, 2015), surface soil moisture, infiltration capacity (Bajracharya & Lal, 1992), run-off production and soil-surface geometry, which, in turn, affected soil erodibility (Žabenskál & Dumbrovský, 2015) and run-off erosivity (Ferrick & Gatto, 2005). A thaw-weakened soil was highly susceptible to water erosion (Kok & McCool, 1990) and mass failures (Carson & Kirkby, 1972).

Edwards and Burney (1987) made laboratory simulation study on rill erosion processes of thawed soil. Soil flumes used in their experiment had dimensions of 905 mm in length, 133 mm in height, and 300 mm in width. The flumes were packed with soil materials and frozen in cold storage at temperature of −15 °C for 10 days. Their laboratory experimental results with rainfall simulator determined that freeze–thaw of a bare soil increased sediment loss by 90%, and even more soil loss increased with added overland flow. Gatto (2000) carried out experiments with a plywood bin of 1.2 m wide, 2.4 m long and 0.6 m deep to measure the effects of rill geometry on soil erosivity under soil freeze–thaw cycling. The bin was filled with clayey silt and a rectangular rill of 10 cm deep and 20 cm wide was dug to simulate a rill. The freeze–thaw cycle period lasted for about a month. It turned out that the freeze–thaw cycling increased the water content at of thawed soil surface and reduced soil cohesion and hydraulic radius of the rill to increase the speed of flow. In addition, freeze–thaw induced more erosive flow would transport more sediments if a rill was long enough. Mudflows, soil slumps, and soil slides occurred along the rill which resulted in rill geometry became wider. Ferrick and Gatto (2005) used soil bins to construct rectangular rills to measure soil erosions of unfrozen and thawed soils, including. The bins were 79 cm long, 37 cm wide and 13 cm deep and packed with equal soil volume of 38 L. They quantitatively testified the hypothesis that soil freeze–thaw processes significantly increase the eroded capacity by run-off flow. Soil trough, 5 m long, 1 m wide and 0.3 m deep, was designed by Qiu, Fan, Wu, Zhou, and Jia (2014) to study effect of slope length, slop gradient, and flow rate on meltwater snowmelt erosion process. The trough was built on a platform and movement was unavailable. These facilities were all the pioneer work used for studies the impacts of freeze–thaw cycling on soil erosivity. However, all the methods and/or facilities mentioned above used large volume of soil in a single experiment flume. Large soil volume needed long time to freeze and thaw which made it impossible for rapid freezing-thawing to limit the number of experiments. The large flume could not be used to make experiments in large quantities for various experimental conditions such as different flow rates, slope gradients and thawed depth. Also the big size of the flumes made lowered movability. Short effective length of the flumes made the experiments impossible to produce the whole soil erosion and sediment transport processes of thawed soil rills. At present, there is little research on freezing and thawing soil erosion process. The lack of experimental method limits the study on freeze-thaw effect on soil erosion process. Laboratory experiment facilities and conditions of freezing and thawing alternations have not been well simulated for studies in this regard. Quantitative parametric understanding about the relationship between freeze–thaw and erosion does not yet exist.

The objective of this study focuses on the facilities and procedures for simulating the erosion of melt frozen soil, to meet the requirements of simulating the process of soil thawing from top to bottom. The equipment provides facility, method and operational procedures for one-dimensional soil thawing simulation to serve research on the effect of soil thawing depth on thawed erosion process.

2. The experiment facilities system

2.1. *The assemble flume for one-dimensional thawing of frozen soil*

The assemble soil flume used for indoor melt water erosion test is shown in Fig. 1. The flume was 200 or 300 cm long and 10 cm wide. The heights of the side and end wells were 12 and 10 cm, respectively. One of the end plates was designed to be assemble to connect two or three flumes end to end and form a flume of 600–800 cm long. The size of surrounding ice box (lateral ice box) was in dimensions of 150, 5 and 10 cm, respectively. These ice boxes were used to keep the flume sidewalls cold and protect the soil inside the flume from being thawed from both sides to the middle part. The ice box was divided into three sections by dividers to prevent its deformation during freezing process. The flume bottom was also lined with ice boxes, which were in dimensions of 150, 45 and 5 cm, respectively, to prevent the frozen soil from being thawed from the bottom to top as much as possible. Two ends of the flume were also isolated by ice plug boxes to avoid the frozen soil from thawing from the flume ends. In cases of more than two frozen soil flumes were needed to be thawed, the gaps between the soil flumes were filled with ice boxes and insulation materials. By these means, the temperature of the sidewalls and bottoms of the flumes were kept at a temperature of lower than 0 °C to ensure the frozen soil flume to be thawed only from top to bottom. This made the thawing process is quite similar to the actual field situation. The soil flume assembled with lateral and bottom ice boxes, end ice plugs, and heat insulation cotton whose coefficient of thermal conductivity was 0.03 W/(m k) was used to fill gaps. The soil fumes were placed onto a platform which was adjustable to the desired slope from 0° to 30° to thaw to the designed depths. The experiments were performed when the frozen soil was thawed to the designed depths. One-dimensional soil thawing simulation was realized to serve the researches on the effect of soil thawing depth on erosion process of thawed soil.

2.2. *Soil freezing system*

To freeze the soil materials, a special freezing storeroom system of 7.8 kW, with dimensions of 3.8 m long, 3.0 m high, and 2.4 m wide, respectively. The controllable temperature ranged between