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Dynamic processes of soil erosion by runoff on engineered landforms derived from expressway construction: A case study of typical steep spoil heap

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ABSTRACT

Soil erosion on newly engineered landforms severely threatens the ecological security of construction sites and their surrounding areas. A field scouring-erosion experiment was conducted on a typical spoil heap along the Shenmu–Fugu Expressway in China to investigate the processes of soil erosion by simulated runoff. A 2.5×12 m^2 runoff plot with 72.7% gradient was established on the spoil heap. Clean water was applied at the top of the plot with five different inflow rates of 0.167×10^{-3}, 0.25×10^{-3}, 0.33×10^{-3}, 0.417×10^{-3} and 0.5×10^{-3} m^3/s to simulate surface runoff processes. The variation of sediment concentration was greatly influenced by gravitational erosion which occurred at the critical inflow rates ranging from approximately 0.33×10^{-3} to 0.417×10^{-3} m^3/s. The process of sediment yield on the spoil heap, in terms of sediment transport rate, was characterized by three stages: abruption, fluctuation and stabilization. The spatial distribution of sediment yield in different slope segments at different inflow rates showed two trends: steady decreasing and drastically fluctuated decreasing. The flow over the spoil heap belonged to supercritical flow and the critical inflow rate controlling the transformation from transitional flow to turbulent flow for rill flow was between 0.33×10^{-3} and 0.417×10^{-3} m^3/s. Statistically, power, exponential and logarithmic-linear equations can be used to describe the interrelations of main hydraulic parameters including flow velocity, Reynolds Number, Froude Number and Darcy–Weisbach roughness coefficient. The three forms of equations were also appropriate for describing sediment concentration in relation to the hydraulic parameters mentioned. Slope length was more significant than inflow rate in affecting hydraulic parameters, which showed an exponential relation with the increase in distance from the top of the plot for all the parameters except Reynolds Number. Stream power was the best hydrodynamic parameter to simulate the changing trend of soil detachment rate. As for different control equations, mechanic parameters and energy parameters had some relative advantages in depicting the dynamic processes of sheet erosion and rill erosion, respectively.

1. Introduction

Over the past several decades, the soil erosion rates, as well as sediment load on the Loess Plateau in China have been significantly reduced by effective implementation of large-scale soil and water conservation measures such as terracing, afforestation, natural rehabilitation, and check-dam construction (Zhao et al., 2013). However, the benefits reaped from erosion control of severely eroded areas are being greatly weakened by quick increase in soil and water loss originating from massive infrastructure development and construction in many parts of China (Cao et al., 2013; Cheng et al., 2013; Wang et al., 2012). With increasingly intensified production and construction activities in China, the newly induced soil erosion in artificial landform, disturbed land and un-vegetated landscape has posed a considerable threat to ecological security of the production and construction areas. Largely motivated by the requirements of soil and water conservation, much attention has been focused on soil erosion prediction for engineered landforms over the past few decades. As a whole, preceding researches on this aspect were carried out on various reshaped landforms in line-type engineering such as highway and railway and block-type engineering such as hydropower station and mining, with special efforts on embankments and road cuttings (Cerdà, 2007; De Oña et al., 2009; Grismer and Hogan, 2005; Odemerho, 1986), surface-mined lands and reclaimed mine lands (Hartley, 1984; Hoomehr et al., 2010; McIsaac et al., 1987; Toy et al., 1999; West and Wali, 1999), mine spoils and rock dumps

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(de Souza et al., 2013; Hancock et al., 2008; Milder et al., 2013; Mukhopadhyay and Maiti, 2014; Raizada and Juyal, 2012; Riley, 1995; Saynor and Evans, 2001; Schroeder, 1987). Results from the researches have provided practical guidance for the design and implementation of precautions for sediment control and vegetation establishment on road cuts or embankments (Lee et al., 2013; De Oña et al., 2009; Ferrer et al., 2011; Jimenez et al., 2013; Osorio and Juan, 2006; Pengcheng et al., 2008), as well as strategies and guidelines for maintenance of long-term stability of engineered landforms, revegetation and erosion control of rehabilitated mine spoils or reclaimed overburden dumps (Carroll et al., 2000; de Souza et al., 2013; Haigh and Gentcheva-Kostadinova, 2002; Mukhopadhyay and Maiti, 2014; Raizada and Juyal, 2012; Willgoose and Riley, 1998). However, the empirical–statistical models developed in China based on the USLE framework (Wischmeier and Smith, 1978) are found to be of large uncertainty due to model conceptualization as well as arbitrary choice of model parameters. Thus these USLE-based models had limited success in estimating soil loss from areas affected by engineering works such as construction of freeway. Moreover, a large majority of researches were primarily conducted at plot scale under the conditions of natural rainfall, artificial rainfall and runoff, lacking dynamically located observations in details over a long term. A widely accepted classification scheme of soil erosion in the production and construction areas has not yet been available in China partly due to complicated and varied characteristics of soil erosion across sites distinguished from the established conditions of USLE. All in all, the feasibility of USLE needs considerable discussion and further consideration in the fields of soil erosion by engineered landforms in China.

Constructing process-based soil erosion models is a major approach to fill the gaps and overcome the limitations mentioned above. Apparently, it is essential to understand dynamic processes of soil erosion originating from drastically disturbed soils and engineered landforms in the context of production and construction activities. Generally, predicting soil detachment by simple hydraulic indicators is an effective approach for practical application of soil detachment models, mainly including excess shear stress models and excess stream power models (Knapen et al., 2007). The controlling variables of soil detachment, by and large, involve slope of energy grade line, flow velocity, flow depth and hydraulic roughness. As combined indicators derived from these variables, total discharge or unit discharge, flow shear stress and stream power are commonly adopted in experimental studies and modeling works on rill or gully initiation (Knapen et al., 2007). The effectiveness of hydraulic parameters chosen as soil detachment predictors remains questionable; this is partly attributed to varied testing conditions and data availability. Many parameters validated in some investigations are prone to be invalid in others (Bryan, 2000). Besides, it appears that no direct evidence implies the relative advantages of employing one hydraulic parameter over the other (such as stream power vs shear stress) in depicting the dynamic processes of soil erosion (Nearing, 1991). To link soil detachment rate in artificial landforms with simple hydraulic indicators, hydraulics of slope runoff and responses of soil erosion in engineered landforms to different hydraulic parameters should be profoundly perceived. Despite extensive researches conducted with laboratory flumes under simplified conditions compared to field observations, the abundant consequences and conclusions obtained in laboratories should be verified, tested and transformed to field conditions at a certain scale, principally owing to unclearly defined extrapolation conditions which in most cases are different from those of laboratory conclusions. Therefore, field plot experiments and observations should be consolidated to ensure the reliability of laboratory results (Cerdà and Lasanta, 2005; Cerdà, 1998; Ziadat and Taimeh, 2013).

Abandoned spoil deposits are a major sediment source, albeit without adequate concerns in previous studies (Dong et al., 2012), contributing to 78% to 90% of the total sediment output during road construction (Yang et al., 2008). The amount of abandoned spoil deposits produced by per 100 km of highway construction may reach an estimated 5 million m^3 in China (Dong et al., 2011). As argued, further studies should be focused on the abandoned spoil deposits derived from road constructions, to lay a foundation for developing a process-based model of soil erosion for violently disturbed areas, especially engineered landforms. Therefore, a field runoff plot experiment was performed with the specific objectives of: (1) investigating the runoff and sediment yielding processes on a typical abandoned spoil heap of steep slope resulted from expressway construction for establishment of the relationships between runoff and sediment at different inflow rates; (2) examining the hydrodynamic characteristics of steep-slope runoff to quantify the responses of soil erosion rate to different hydrodynamic parameters; and (3) determining the best hydraulic parameter to predict soil erosion rate for the use in quantifying the values of erosion-related variables. This study may contribute to an improved understanding of steep-slope runoff hydraulics and soil erosion mechanisms on abandoned spoil heap derived from road constructions.

2. Experimental design

2.1. Description of the study area

The experimental site was situated on a representative spoil heap (geographical coordinates: 110°53′10.0″E, 38°56′15.5″N; elevation: 966 m) derived from the construction of the Shenmu–Fugu Expressway in the Shimachuan watershed of Fugu County, Shaanxi Province, China (Fig. 1). The Shimachuan watershed, characterized by a semi-arid landscape, belongs to the hilly and gully region of the Loess Plateau and has a temperate continental monsoon climate. Annual precipitation in the watershed averages 440 mm, mostly occurring between June and September. Average annual runoff from the watershed is 110 to 120 mm and average annual sediment load is 5.97×10^6 tonnes (Yang, 1994). The native vegetation is predominated by deciduous and broad-leaved shrub woods, with *Caragana korshinskii* Kom., *Hippophae rhamnoides* L. and *Ziziphus jujuba* var. *spinosus* mainly included. The prime type of natural soil is loessial sand, susceptible to rainfall and runoff detachment, which is responsible for a large amount of soil loss in the watershed. Annual soil erosion modulus of the original landscape at the experimental site averages 2×10^4 to 3×10^4 t/(km^2·a), mostly induced by concentrated flow resulted from strong rainstorms in short duration (Yang, 1994; Zhou, 1997).

2.2. Basic information on the abandoned spoil deposits

Before site selection, an overall field survey of the spoil deposits was conducted along the Shenmu–Fugu Expressway. A total of 120 spoil heaps were investigated, with platforms covering an area of 238.604 hm^2. Altogether, the spoil heaps can be classified into four groups by different side slope gradients: moderate steepness (57.7% to 70%), moderately large steepness (>70% to 83.9%), large steepness (>83.9% to 100%) and very large steepness (>100% to 119%), with different proportions of 7.5%, 67.5%, 11.7% and 3.3% in the spoil heaps investigated, indicating the prevalence of moderately large steepness. By taking the actual slope gradients and water availability into account, the spoil heap shown in Fig. 1 on the north bank of the Shimachuan River, a tributary of the Yellow River, was selected to carry out field trials. The spoil heap can be divided into two main parts: platform and steep side-slope. The platform is approximately 1000 m in perimeter, covering an area of 2.796 hm^2. The steep side-slope varies from 70 to 80 m (78 m on average) in length, with gradients ranging from 57.7% to 119% (72.7% on average) and a low degree of vegetation coverage as a consequence of natural restoration. The dominated species of restored vegetation are psammophytes, such as *Agriophyllum squarrosum* (L.) Moq., *Salix psammophila* and *H. rhamnoides* L. Basically, surface material of the spoil heap is a mixture of cultivated loessial soil and sandy soil. Particle sizes of the mixture are mostly smaller than 0.2 mm with a soil–rock ratio of about 9:1. The mixture has a silt loam texture with