Measurement 47 (2014) 393–400

Contents lists available at ScienceDirect

Measurement

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

Estimation of fractional critical tractive stress from fractional bed load transport measurements of unimodal and bimodal sediments

S.B. Patel [a,*,1], P.L. Patel [b,2], P.D. Porey [c,3]

[a] Water Resources Engineering, Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology, Surat 395007, India
[b] Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology, Surat 395007, India
[c] Sardar Vallabhbhai National Institute of Technology – SVNIT, Surat 395007, India

ARTICLE INFO

Article history:
Received 31 January 2013
Received in revised form 7 July 2013
Accepted 19 August 2013
Available online 29 August 2013

Keywords:
Bed load
Bimodal
Critical tractive stress
Nonuniform sediment
Unimodal

ABSTRACT

Experimental investigation on estimation of fractional critical tractive stress of nonuniform unimodal and bimodal sediment mixtures is reported. The observed data on fractional bed load transport rates for different flow strength, under equilibrium condition, have been used to estimate critical tractive stress (CTS) of each size fraction in sediment mixture from reference transport method (RTM). Further, the accuracy of these estimated CTS values are assessed by comparing the same with CTS values estimated using largest grain method (LGM). The estimated CTS values of individual size fractions for different sediment mixtures have been used to assess the performance of CTS relationship recently proposed by Patel et al. [12].

1. Introduction

The entrainment condition of a sediment particle is described as the incipient motion condition at which the sediment particle just starts moving on river bed. Out of several theories defining incipient motion condition, the critical tractive stress (CTS) concept (Shields [1]) has been found favors amongst hydraulic engineers. The shear stress acting on a sediment particle at incipient motion condition is defined as its critical tractive stress. The entrainment of sediments and their subsequent movement along alluvial streams, has been a challenging problem for river engineering fraternity. The problems related to the design of stable channels, computation of sediment load and river bed level variation can be tackled with adequate knowledge on entrainment of sediments in alluvial channel bed. Uncertainties in the selection of CTS can lead to large errors in computation of bed load transport rates as it is a nonlinear function of flow strength. These effects are particularly more important in the range of flows slightly above the threshold for movement, wherein transport rate increases by orders of magnitude for small change in shear stress [2]. The prediction of CTS of nonuniform sediments have been accomplished in the past by many investigators [3–9], viz. Egiazaroff [3], Ashida and Michiue [4], Hayashi et al. [5], Parker et al. [6], Wilcock [7], Patel and Ranga Raju [8] and Wu et al. [9]. All above relationships use the CTS relationships for a particular size fraction in a sediment mixture as ratio of the dimensionless CTS of particular size to the dimensionless CTS of some representative sizes as a function of their representative size ratio. Generally, such relationship can be represented as

$$\frac{\tau_{*ci}}{\tau_{*cR}} = \left(\frac{d_i}{d_R}\right)^{-\beta} \qquad (1)$$

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* Corresponding author. Tel.: +91 9227574775.
E-mail addresses: shals125@live.com (S.B. Patel), premlalpatel@yahoo.com (P.L. Patel), pdporey@svnit.ac.in (P.D. Porey).

[1] Research Scholar
[2] Professor
[3] Director

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http://dx.doi.org/10.1016/j.measurement.2013.08.025

where $\tau_{*ci} = \tau_{ci}/\Delta\gamma_s d_i$ and $\tau_{*cR} = \tau_{cR}/\Delta\gamma_s d_R$, in which $\Delta\gamma_s = (\gamma_s - \gamma_w)$, with γ_s and γ_w as unit weights of sediment (subscript s) and water (subscript w) respectively, τ_{ci} and τ_{cR} = CTS of size d_i and d_R, respectively, d_i = particular size fraction of sediment mixture, subscript R denotes representative size of sediment mixture and β is a parameter indicating size selective entrainment characteristics of sediment mixture. For $\beta \sim 1$, all sediments move at the same bed shear stress, i.e., at equal threshold. On the other hand, $\beta \sim 0$, all particles move independently, i.e., they do not feel the effect of the neighboring particles. An overview of β-values, from both field measurements and flume experiments, were given by Buffington and Montgomery [10] in the range of 0.29–1.0, indicating strong size selective entrainment as well as equal entrainment mobility in sediment mixtures analyzed by them. Solari and Parker [11] developed a relationship which explicitly takes into account the effect of channel bed slope on CTS of sediments to study the reversal process of downstream fining at larger slopes of coarse gravel bed rivers. The relationship developed by them relates ratio of CTS of a size fraction and geometric mean size with respective size ratio and slope of the channel bed. The uncertainties involved in prediction of CTS of nonuniform sediments, particularly for bimodal sediments, Patel et al. [12] assessed the adequacy of existing relationships using available unimodal and few bimodal sediment data with them from past investigations and proposed a new relationship for prediction of CTS of each size fraction as a function of geometric standard deviation, σ_g and Kramer's uniformity coefficient, M.

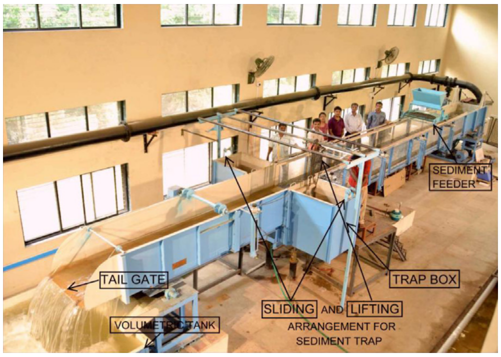
Keeping in view the paucity of data on CTS of bimodal sediment mixture, and assess the performance of recently proposed Patel et al. [12] relationship for computation of CTS of unimodal and bimodal sediment mixture, it was felt worthwhile to develop a new experimental set-up for collection of data on fractional bed load transport rates of unimodal and bimodal sediment mixtures with wide range of nonuniformity and bimodality indices. Present paper includes complete description of experimental set-up, preparation of sediment mixtures with different characteristics, procedure for data collection on fractional bed load transport rates and estimation of CTS of individual size fractions using reference transport method (RTM) and largest grain method (LGM); and subsequently, validation of recently proposed CTS relationship (Patel et al., [12]), based on CTS data from present investigation.

2. Experimental set-up and data collection

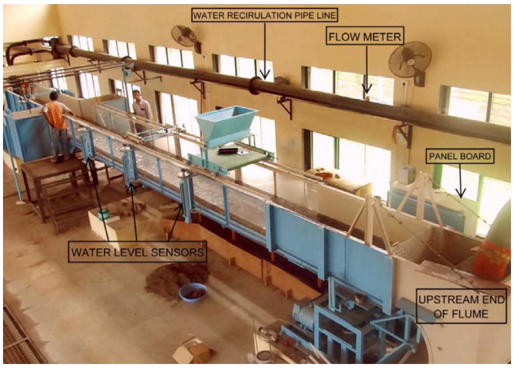
2.1. Description of experimental set-up

The experimental set-up for measurement of bed load transport rates was designed and developed in the Advanced Hydraulics Laboratory of Civil Engineering Department at Sardar Vallabhbhai National Institute of Technology (SVNIT-Surat) in India. The tilting flume of size 15.0 m × 0.89 m × 0.6 m (L × B × H) with complete arrangements like centrifugal pumps, recirculation pipe, connection with digital flow meter, tail gate, sediment traps, sediment feeder with conveyor belt, water level sensors, downstream water collection tank, both sides railing, pointer gauge and stilling arrangement at the inlet of the flume are shown in Photograph 1. The water at upstream of the flume was supplied from downstream reservoir (45,000 l capacity) using two 7.5 H.P. centrifugal pumps (one pump connect with variable frequency drive) and a recirculating pipe line. The water discharge, entering into the upstream end of the flume, was measured using a digital flow meter (VATS JT-121 make) is mounted in the water return pipe of 25 cm diameter. The Flow sensor in the flow meter is a paddle wheel insertion type, makes use of the Faraday's law of electromagnetic induction and generates frequency and signal proportional to the flow rates. The calibration of flow meter, obtained from the manufacturer, was again verified in the laboratory flume using available volumetric tank. Flow rate ranging from 24 l per second (LPS) to 240 LPS can be measured with flow meter with accuracy of +/−1 percent (%). The compete recirculation arrangement of water flow in the experimental set-up is shown in Fig. 1.

The desired longitudinal slope of the channel was maintained, for an experimental run, using motorized box gear arrangement, by tilting the flume pivoted at the downstream end point by means of screw-jack drive arrangement located at the upstream end of the flume. The water levels in the flume were measured using a pointer gauge (least count of 1 mm) connected to an instrument



(a) Downstream view



(b) Upstream view

Photograph 1. Experimental set-up for measurement of bed load transport.