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Project Title
Measurement of Turbulent Flow Characteristics and Bed Shear Stress in Laboratory Soil Erosion Tests

University

South Dakota State University

Principal Investigators

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Research Needs

The Scour Rate In COhesive Soils (SRICOS) method is recommended in the Hydraulic Engineering Circular No. 18 (HEC-18, Arneson et al., 2012) as an alternative approach for evaluating scour at bridge sites with cohesive soils. The SRICOS method uses a flood hydrograph and a soil erosion function to predict the time history of scour. For highly erosion resistant cohesive soils, accounting for the time rate of scour may significantly reduce the predicted final scour depth. A practical method for hydrograph generation was developed in Project MPC-531/SD2014-16. The hydrograph generation method utilizes a series of maximum annual floods sampled randomly from the Log Pearson Type III distribution. The project also developed a screening tool for identifying bridge sites where use of the SRICOS method may be beneficial or more appropriate than the traditional HEC-18 method.

To implement the SRICOS method, an apparatus to measure soil critical shear stress and erosion rates is needed. Briaud et al. (2001) developed the erosion function apparatus (EFA). The device uses an electric motor and a piston to push a soil sample out of a 7.62 mm-diameter thin-walled tube (Shelby tube) into a water tunnel and measures the time it will take to erode the soil protrusion to determine the erosion rate. The EFA has the advantage that soil samples collected at specified depths can be tested at prototype flow velocities relatively undisturbed. The original design, however, is not very accurate because the operator must monitor the erosion rate and decide when to advance the soil sample. In addition, the applied shear stress is calculated using the Moody chart or Colebrook equation (Munson et al., 2013) for pipe flows. When a soil sample erodes non-uniformly, vortices and eddies are formed on the unevenly eroded surface. The erosive action of the flowing water on a soil sample with a highly irregular surface can be quite different from that on a smooth wall. It is also difficult to determine when to advance the soil sample. Consequently, there are large uncertainties in both the measured critical shear stress and soil erosion rates. Various improvements to the original design have been made by researchers (e.g., Lee et al., 2004; Crowley et al., 2012; Shan et al., 2015). The ex-situ erosion testing device (ESTD) by Shan et al. (2015), for example, employs a direct force gage to measure the shear stress on the soil surface and the soil sample is automatically advanced to maintain a constant bed shear stress throughout the test period to determine the erosion rate. They found that the difference between the bed shear stress measured by the direct force gage and using the Moody chart is about 20%.

Research Objectives

This research has three main objectives. First, conduct laboratory experiments to measure the turbulent velocity field over an eroding soil sample in an EFA type facility and determine the bed shear stress from the measured velocity field. Second, determine the effects of soil properties on the soil critical shear stress and erosion rate. Third, study the effect of soil erosion depth on the induced bed shear stress.

Research Methods

The experiment will be conducted in an A-8 hydraulic flume manufactured by Engineering Laboratory Design (ELD). The dimensions of the flume are like the EFA facility employed by Briaud et al. (2001), but it uses open-channel flow instead of flow in a close conduit to better mimic the erosive action of water on a river or stream bed. The working channel is 0.15 m wide, 0.3 m deep and 1.825 m long with a slope that is continuously adjustable from 0 to12%. The flow is delivered by a 0.5 HP, 1750 RPM centrifugal pump with a maximum capacity of 4.5 L/s. The discharge is regulated by a gate value and measured using an orifice meter. Flow depth is controlled by a manually operated tailgate and measured using a point gate. Perforated metal screens and flow straighteners are installed in an entrance section before the working channel to dampen flow disturbances.

Because most of existing EFA type devices have smooth walls, the local bed shear stress developed on the soil sample can be much higher than the wall shear stress computed using the Moody chart or Colebrook equation. The actual shear stress also varies with the height of soil protrusion into the flow. When the soil surface is eroding non-uniformly the configuration of the soil protrusion is constantly changing. Therefore, a constant and uniform shear stress cannot be maintained over the soil surface, making it difficult to determine the erosion rate. Various sensing devices have been employed by researchers to monitor the position of the eroding surface and automatically advance the soil sample without the need for operator intervention, but with varying degrees of success.

In the proposed experiments, gravel will be glued to bed plates and installed in a flume to produce fully developed turbulent flow over a rough surface. A 3-inch-diameter sediment recess will be made in the gravel bed to accommodate a circular soil sample. After steady, uniform flow is established by adjusting the channel slope and tail gate, the turbulent velocity field over the gravel bed and the soil sample will be measured using a Particle Image Velocimetry (PIV) system. The instrument employs a 2D camera to capture the positions of fluid tracers in the flow area of interest at sampling rate of up to 15 Hz. The images will be processed to obtain the horizontal velocity profiles over the soil sample at different stages of erosion. The location of the eroding surface will be determined from the PIV images and verified using point gage measurements. The measured data will be used to quantify the effect of soil erosion depth on the induced bed shear stress.

The effect of selected soil properties on the soil critical shear stress and erosion rates will be investigated in a parallel set of experiments. Straub and Over (2010) found a strong correlation between the critical shear stress of cohesive soils and unconfined compression strength. Soil samples will be prepared in the Geotechnical Laboratory using Nora Moody Clay with a range of unconfined compression strength by varying the water content. The prepared soil sample will be placed in the sediment recess and the erosion rate will be measured over a range of induced bed shear stress values to determine the soil-erosion-rate-versus-shear-stress curve, from which the critical shear stress will be determined.

Expected Outcomes

Proposed research will improve our understanding of the soil erosion process in an EFA type testing facility by measuring the velocity profile and bed shear stress over an eroding sample in different flow and soil surface conditions. Understanding the effects of a test sample on the flow and the resulting bed shear stress and soil erosion rate will enable the design of more reliable facilities for soil erosion testing. The reduction in measurement uncertainties would in turn lead to more accurate predictions of bridge scour depths.

Relevance to Strategic Goals

The proposed project and its expected outcomes are related to the following strategic goals of MPC: State of Good Repair and Safety. Accurate data of erodibility of cohesive soils is imperative for correctly predicting the time rate of scour and final scour depth in cohesive soils. SDDOT currently uses methods developed for non-cohesive soils to evaluate bridge scour. The SRICOS method could reduce foundation costs in cohesive soils and increase the confidence level of foundation designs for some bridge sites and projects. A future extension of this project would conduct erosion testing on soil samples collected from rivers and streams across South Dakota to develop a soil erodibility chart for different soil types. This information should be valuable in many highway projects including bridge scour, stream bank erosion, channel migration, and surface erosion at construction sites and highway embankments.

Educational Benefits

One graduate student will work on this project and complete a Master of Science (MS) thesis. The student will attend and present his/her work at a national conference such as the annual Transportation Research Board (TRB) Meeting. Conference and journal papers will be published to disseminate the results of this project to the practitioners. The information developed by this project will also be used in seminar presentations and case studies in the undergraduate and graduate courses taught by the PI.

Technology Transfer

The findings of this research project will be published in peer-reviewed journals and conference proceedings, in addition to technical presentations and a final project report. After the project is completed, project data will be archived and deposited in SDSU's institutional data repository Open Prairie (https://openprairie.sdstate.edu/) following the data management plan for MPC.

Work Plan

The project will include the following tasks:

(1) Conduct a literature review on cohesive sediment erosion. Compile a list of existing laboratory and field test devices and review the advantages and disadvantages of each method.
(2) Design an experiment to be conducted in an open channel to measure the velocity field over a prepared soil sample and the soil erosion rates. The basic setup will be a tilting flume with a fixed gravel bed to produce a fully developed, rough, turbulent flow. The rough bed will have a circular recess to accommodate a prepared or extruded soil sample. The bed shear stress will be varied by tilting the flume and adjusting the flow rate.
(3) Measure the two-dimensional (2D) turbulent velocity field over the gravel bed for a range of flow conditions by using a Particle Image Velocimetry (PIV) system. The water surface profile in the flume will be measured using a point gage. The bed shear stress will be determined from the measured data using various methods including the logarithmic law and depth-slope method.
(4) Measure the turbulent velocity field over the prepared soil sample at different depths of erosion and determine the effect of soil erosion depth on the induced bed shear stress.
(5) Conduct geotechnical laboratory testing to evaluate the basic index and geotechnical engineering properties of the prepared soil samples.
(6) Measure the erosion-rate-versus-shear-stress curves of the prepared soil samples using the experimental setup described in tasks 2, 3 and 4. Analyze the measured data to determine the effects of selected soil properties on the critical shear stress and soil erosion rates.
(7) Prepare a final report and present the major findings of the project.

Table 1 Task Time Schedule

TASK YEAR/ MONTH	YEAR 1												YEAR 2											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1. Conduct literature review	■	■	■																					
2. Construct testing facility and conduct preliminary flume tests			■	■	■	■	■	■																
3. Conduct flow measurements over gravel bed and determine the bed shear stress						■	■	■	■															
4. Conduct flow measurements over prepared soil samples and determine the bed shear stress at different soil erosion depths										■	■	■	■	■	■									
5. Conduct geotechnical laboratory testing															■	■	■	■	■	■				
6. Measure soil erosion history and determine the effect of selected soil properties on the soil critical shear stress and erosion rate															■	■	■	■	■	■				
7. Prepare final report and publications																					■	■	■	■

Project Cost

Total Project Costs:	$151,894
MPC Funds Requested:	$ 74,007
Matching Funds:	$ 77,887
Source of Matching Funds:	South Dakota State University

References

Arneson, L. A., Zevenbergen, L. W., Legasse, P. F. and Clopper, P. E. (2012). "Evaluating scour at bridges." Fifth Edition, *Hydraulic Engineering Circular No. 18*, Federal Highway Administration, Washington, D.C.

Briaud, J.-L., Ting, F. C. K., Chen, H. C., Han, S. W. and Kwak, K. W. (2001). "Erosion function apparatus for scour rate predictions." *Journal of Geotechnical and Geoenvironmental Engineering*, 127(2), 105-113.

Crowley, R. W., Bloomquist, D. B., Shah, F. D. and Holst, C. M. (2012). "The sediment erosion rate flume (SERF): a new testing device for measuring soil erosion rate and shear stress." *Geotechnical Testing Journal*, 35(4), 649-659.

Lee, C., Wu, C. H. and Hoopes, J. A. (2004). "Automated sediment erosion testing system using digital imaging." *Journal of Hydraulic Engineering*, 130(8), 771-782.

Munson, B. R., Okiishi, T. H., Huebsch, W. W. and Rothmayer, A. P. (2013). Fundamentals of Fluid Mechanics. John Wiley & Sons, 747 pages.

Nezu, I. and Nakagawa, H. (1993). Turbulence in open-channel flows. A. A. Balkema, 281 pages.

Shan, H., Shen, J., Kilgore, R. and Kerenyi, K. (2015). "Scour in cohesive soils." Report No. FHWA-HRT-15-033, Federal Highway Administration, McLean, Virginia.

Straub, T. D. and Over, T. M. 2010. "Pier and Contraction Scour Prediction in Cohesive Soils at Selected Bridges in Illinois." *Illinois Center for Transportation, Research Report* ICT-10-074. Rantoul, IL.