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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

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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.

In order 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 particularly accurate because the operator has to 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 flow characteristics and local shear stress over an eroding soil sample in an EFA type facility. Second, use the measured data to quantify the effects of soil surface roughness and sample protrusion on the flow characteristics and measured soil critical shear stress and erosion rates. Third, measure the erosion function of cohesive soil samples collected from the site of a new bridge over a waterway in South Dakota and use the SRICOS method to predict the scour history of the bridge over the project live as a demonstration project for implementing the complete SRICOS-EFA method including hydrograph generation.

Research Methods

The experiment will be carried out in a 25-m-long, 0.9-m-wide and 0.75 m-deep open-channel flume in the Fluid Mechanics Laboratory at South Dakota State University (SDSU). The research flume can be tilted from 0% horizontal to 3% positive slope by a system of synchronized jacks. The flume is equipped with a 1.2-m-long, 0.9-m-wide and 0.2-m-deep sediment recess for performing erosion measurements on block samples or a prepared sediment bed. Two centrifugal pumps provide recirculating flow and the discharge can be varied continuously from 0 to 0.227 m^3/s (8.0 ft^3/s) using two variable frequency inverters. The flow rate is monitored by a pressure transducer with digital readout connected to a low head loss venturi meter installed in the supply pipe. Flow depth is controlled by motorized head gate and tail gate.

Existing EFA type devices use an open-channel flume or water tunnel to re-circulate water. Because most of these devices have smooth walls, the local shear stress developed over 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 the flume to produce fully developed turbulent flow over a rough surface, so that the erosive action of the flowing water is controlled by the boundary-layer turbulence generated upstream and not by the surface roughness of the soil sample. A 3-inch-diameter cutout will be made in the gravel bed to accommodate a circular soil sample extruded from a thin walled tube. After steady, uniform flow is established by adjusting the channel slope and tail gate, the three-dimensional (3D) turbulent velocity field over the protruding sample will be measured by using a volumetric three-component velocimetry (V3V) system. The instrument employs a 3D camera to capture the positions of fluid tracers in an $120 \times 120 \times 100$ mm^3 flow volume at sampling rate of 15 Hz. The images are then processed to obtain the three-component, three-dimensional (3C3D) turbulent velocity field (see Ting et al., 2013). The 3D geometry of the eroding surface can also be determined from the 3D images, which will be verified using point gage measurements.

For a range of channel flow velocities, the fluid velocity field over the gravel bed will be measured to quantify the characteristics of the approach flow. The velocity measurements will be analyzed to obtain the vertical distributions of mean velocity, turbulent kinetic energy and Reynolds stress, from which the bed shear stress can be estimated (see, for example, Nezu and Nakagawa, 1993). Bed shear stress will also be measured directly using a hot-film sensor flushed mounted on the bed plate. For a gravel bed with a median particle diameter of 5 mm, the maximum bed shear stress that can be produced at 3% channel slope and the maximum discharge is about 30 N/m^2. Higher flow velocities and bed shear stresses can be produced by installing a false wall to reduce the width of the flume.

Flow over the soil sample will then be investigated. Thin walled tube samples will be collected from several locations along the Big Sioux River and James River in Eastern South Dakota. Laboratory testing will be conducted to determine the basic geotechnical properties of the site soils and classify the soil types. Circular specimens extruded from the thin walled tubes will be placed in a cutout in the gravel bed. The 3D fluid velocity field over the soil sample will be measured as the sample erodes and the measured data will be analyzed in the same manner as the flow over the gravel bed. The purpose of the experiments is to determine if the surface roughness of the eroding sample and height of soil protrusion have any significant effects on the flow characteristics and local bed shear stress. The results will be used to improve the design of the testing facility to minimize the measurement uncertainties in the critical shear stress and soil erosion rates.

Expected Outcomes

Proposed research will improve our understanding of the soil erosion process in an EFA type testing facility by directly measuring the flow characteristics 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 enable 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 could conduct erosion testing on soil samples collected from river 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. The principal investigator (PI) has been working with SDDOT and USGS to develop the SRICOS method for bridge scour evaluation in South Dakota. We will coordinate our work to ensure that the research findings will be transferred to the practitioners.

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 (http://openprairie.sdstate.edu) following the data management plan for MPC (https://www.mountain-plains.org/resources/researchers.php). Patents will also be obtained on any new innovations related to the testing facility.

Work Plan

The project will include the following tasks:

(1) Conduct a meeting with SDDOT and USGS to review project scope, discuss issues and review the work plan.
(2) Conduct a literature review on cohesive sediment erosion. Compile a list of existing laboratory and field erosion test devices and review the advantages and disadvantages of each device.
(3) Design an experiment to be conducted in the research flume to measure the flow characteristics over a thin walled tube soil sample and the soil critical shear stress and erosion rates. The basic setup will be a tilting open channel with a fixed gravel bed to ensure fully developed rough turbulent flow. The roughened bed will have a circular cutout to accommodate a soil core extruded from an ASTM standard thin walled tube. The flume already has an in-floor sediment recess to accommodate block samples if they are used.
(4) Measure the three-dimensional (3D) turbulent velocity field over the gravel bed for a range of flow velocities by using a volumetric three-component velocimetry (V3V) system. 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 three different methods: logarithmic law, Reynolds stress distribution, and slope of the energy grade line. The bed shear stress will also be measured directly using a hot-film sensor mounted on the gravel bed.
(5) Measure the turbulent velocity field over the soil sample and the soil erosion rate for a range of soil types and heights of sample protrusion. Compare the measured flow characteristics and bed shear stress measured over the gravel bed and the soil sample to determine if the surface geometry and height of the protrusion have any significant effects on the flow and local bed shear stress.

(6) Work with SDDOT to select a new bridge over waterway in South Dakota for use as a case study. Project information required from the SDDOT will include bridge plans, channel bathymetry and floodplain terrain data, borehole data, and soil samples for geotechnical laboratory and EFA testing.

(7) Conduct geotechnical laboratory testing to evaluate the basic index and geotechnical engineering properties of the soil samples collected.

(8) Measure the erosion-rate-versus-shear-stress curves of the soil samples and determine the critical shear stress using the experimental setup developed in tasks 3, 4 and 5.

(9) Conduct a SRICOS analysis to compute the scour history and probability distribution of final scour depth and compare the predictions with the results from the HEC-18 method.

(10) Prepare a final report and present major findings of the project to the SDDOT and USGS.

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. Meet with SDDOT and USGS	■																							
2. Conduct literature review	■	■	■																					
3. Construct testing facility and conduct calibration tests			■	■	■	■	■	■																
4. Conduct flow measurements over gravel bed and analyze measured data						■	■	■	■															
5. Conduct flow and soil erosion rate measurements over soil samples and analyze data										■	■	■	■	■	■									
6. Collect thin walled tube samples from bridge site															■	■	■	■	■	■				
7. Conduct geotechnical laboratory testing															■	■	■	■	■	■				
8. Conduct EFA tests on thin walled tube samples															■	■	■	■	■	■				
9. Conduct SRICOS analysis															■	■	■	■	■	■				
10. Write final report and make oral presentation to SDDOT and USGS																					■	■	■	■

Project Cost

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

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