MPC-688
May 24, 2022

Project Title

Response of Bed Shear Stress in Open-Channel Flow to a Sudden Change in Bed Roughness

University

South Dakota State University

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Research Needs

Sudden change in bed roughness can occur in many situations in open-channel flows. It can occur naturally in a river or stream due to sediment sorting. Near a river crossing, the bed roughness can change suddenly from that of the original riverbed to that of the riprap protection, and vice versa. In the laboratory, a flume with a smooth bottom can change abruptly to a sediment bed in the test section where the erosion of sediment is studied. In the erosion function apparatus (EFA), for example, an electric motor and a piston is used to push a soil sample out of a 7.62 mm-diameter thin-walled tube (Shelby tube) into a water tunnel and the time it takes to erode the soil protrusion is measured to determine the soil erosion rate (Briaud et al., 2001). In all the above, the response of flow characteristics such as turbulence intensity and bed shear stress to the roughness transition is of engineering interest and needs to be understood.

Flow over a sudden change in surface roughness has been studied mostly in external (e.g., atmospheric boundary layer) and close-conduit (e.g., wind tunnel) flows. A recent literature review can be found in Kadivar et al. (2021). When a flow encounters a sudden change in surface roughness, an internal boundary layer (IBL) will start at the roughness transition and grow outwards from the wall with distance downstream. If the surface downstream is of sufficient length a new fully developed turbulent boundary layer will be established eventually. Previous studies have shown that the wall shear stress would attain its new equilibrium value almost immediately, but flow quantities outside the internal boundary layer are determined by conditions before the transition and change only gradually with distance downstream. In a rough-to-smooth (RTS) transition, for example, experimental and numerical studies have found that the wall shear stress would be underestimated if determined from the mean velocity profile measured outside the internal boundary layer (e.g., Antonia and Luxton, 1972; Loureiro et al. 2010; Li et al. 2019).

Free-surface flow with a sudden change in bed roughness is much less well understood compared to external and close-conduit flows. Chen and Chiew (2003) measured the mean velocity, turbulence intensity and Reynolds stress profiles in an open channel with a sudden change (from smooth to rough) in bed roughness. They determined the bed shear stress and equivalent bed roughness by fitting the logarithmic law to the measured velocity profile. They found that the equivalent roughness height and bed shear stress increase gradually and take a transitional length of approximately 5-6 times the flow depth to reach the equilibrium condition downstream. Lee (2018) modeled the laboratory experiment by Chen and Chiew (2003) using the computational fluid dynamics (CFD) model OpenFOAM. His numerical results show a sharp increase in bed shear stress after a sudden transition in bed roughness in contrary to the experimental data by Chen and Chiew (2003). He suggested that the logarithmic law may not be used to compute the bed shear stress under transitional flow condition since the velocity profile outside the IBL is not in equilibrium. Most recently, Rathore et al. (2022) measured the turbulence characteristics due to a sudden change from a smooth bed to a rough bed in open-channel flow using a Particle Image Velocimetry (PIV) system. They found that the Reynolds stress and turbulence intensity increase with streamwise distance on the rough bed. They determined the bed shear stress by extending the measured Reynolds stress to the bed surface. They found that the bed shear stress does not change abruptly at the roughness transition, which is like the experimental results by Chen and Chiew (2003). Note that the above studies all dealt with smooth-to-rough transition in subcritical flows.

Figure 1 shows the composite flow profiles in two long channels that are identical except for the bed slope. When both channels are mild but channel 2 is milder (case a), a backwater (M1) curve will develop before the slope transition and the flow in channel 2 will be uniform. When both channels are steep but channel 1 is steeper (case b), the flow will be uniform in channel 1 and an S3 profile will occur in channel 2. Similar composite flow profiles can be produced by a sudden change in bed roughness instead of channel slope. Because the velocity profile must be related to the water surface profile, it is apparent that the response of bed shear stress to a sudden change in bed roughness in open-channel flow is different from that in internal and close-conduit flows; it would be more complicated. For example, for supercritical flow over a sudden change from a rough bed to a smooth bed, the water surface profile will be like that shown in Figure 1(c). An S2 curve will occur after the roughness transition so the bed shear stress cannot change abruptly at the junction of the two beds. The evolution of bed shear stress in different roughness transitions is the subject of the proposed research.

Research Objectives

This research has two main objectives. First, conduct laboratory experiments in open-channel flows to measure the transformation of turbulent velocity profile and bed shear stress due to a sudden change in bed roughness from a smooth bed to a rough bed, and from a rough bed to a smooth bed. Second, evaluate the different methods for determining the bed shear stress near a roughness transition. Bed shear stress will be determined from the channel slope (when the flow is uniform), from the measured velocity profile using the logarithmic law, from the measured Reynolds stress distribution, and from direct measurement of bed shear stress (on a smooth bed) using a hot-film anemometer. Composite water surface profiles with a mix of subcritical and supercritical flow conditions will be investigated.

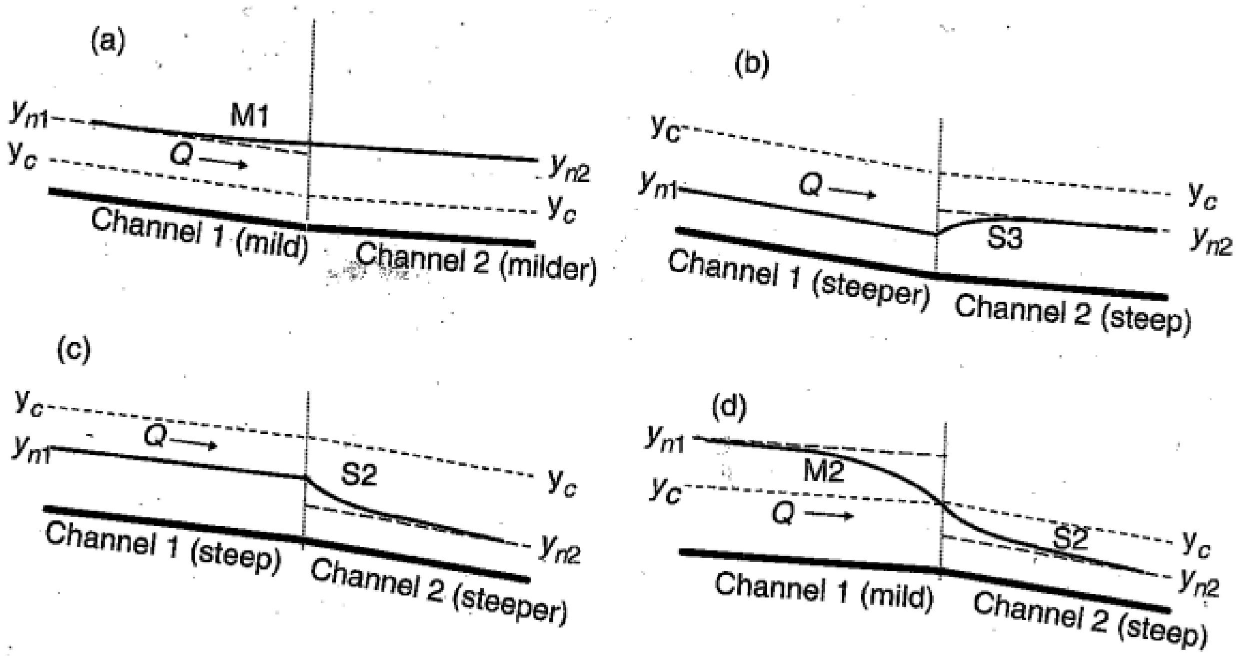

Figure 1. Various composite flow profiles due to a sudden change in bed slope (Akan, 2006). Similar water surface profiles can be produced by a sudden change in bed roughness on a constant slope.

Research Methods

The experimental study will be carried out in a 17-feet long, 8-inch-wide, and 17-inch-deep tilting flume with a stainless-steel bottom and side walls fabricated of clear Plexiglas. The flume is mounted on a beam assembly and can be tilted manually from 0% horizontal to 4.5% positive slope using a screw jack. The facility was decommissioned in 2002 when a new research flume (25 m long, 0.9 m wide and 0.75 m deep) was built, but the channel is still in good condition and will be refurbished and upgraded for use in this project. In the refurbished system, water will be fed from a fiberglass tank situated beside the flume using a centrifugal pump (maximum discharge 0.5 ft^3/s). The flow rate will be controlled using a globe valve and measured using an ultrasonic flow meter installed in the water supply piping. Manually operated undershot headgate and tailgate will be provided at the upstream and downstream ends of the channel to control the flow depth. Perforated metal screens and straighteners will be installed in the entrance section to dampen flow disturbances. At the downstream end, the running water will discharge freely into the fiberglass tank for recirculation.

The rough bed will be constructed by gluing a single layer of sand or gravel to the flume floor. The median grain diameter will be selected based on the flow condition to be studied to create a hydraulically rough bed. The smooth bed will be created by fastening acrylic sheets to the flume floor so that its top surface is aligned with the crest level of the rough bed.

Table 1 shows a list of proposed experimental conditions. The discharge and flow depth will be determined during the trial runs. After steady flow is established, water surface profile will be measured using a point gage mounted on an instrument carriage. Then, PIV measurements will be made on a vertical plane along the centerline of the flume at several locations from upstream to downstream of the roughness transition to capture overlapping velocity fields in the streamwise direction. A 200 mJ Dual Nd: YAG laser will provide the light source for the PIV measurements. Images of the illuminated "light sheet" will be captured using a PowerView Plus 4MP camera (2048×2048 pixels, 12-bit intensity dynamic range) operating in the frame straddling mode (7.25 Hz velocity capture rate). The captured images of the seeding particles (2 to 3 μm diameter titanium dioxide) will be processed using the INSIGHT 4G^{TM} software by TSI. Details of the PIV system and its operation can be found in Ting and Kern (2022).

Table 1. Experimental Conditions

Test	Bed Surface (Upstream)	Bed Surface (Downstream)	Water Surface Profile (Upstream)	Water Surface Profile (Downstream)	Flow Condition
1	Smooth	Rough	M1	N	Subcritical → Subcritical
2	Smooth	Rough	N	S3	Supercritical → Supercritical
3	Rough	Smooth	M2	N	Subcritical → Subcritical
4	Rough	Smooth	N	S2	Supercritical → Supercritical
5	Rough	Smooth	M2	S2	Subcritical → Supercritical

The velocity measurements will be analyzed to obtain the vertical distributions of mean velocity, turbulent kinetic energy, and Reynolds stress to study their responses to a sudden change in bed roughness and the development of the internal boundary layer. Of particular interest is the distribution of bed shear stress downstream of a rough-to-smooth transition (Tests 3, 4 and 5). Based on wind tunnel experiments (see Loureiro et al., 2010; Li et al., 2019), researchers have found that the wall shear stress in internal flows (no free surface) would adjust immediately to a new surface condition, even though the internal boundary layer is still evolving. It was also found that wall shear stress calculated based on the slope of a semi-logarithmic plot of the measured velocity profile would underestimate the wall shear stress, whereas that based on measurements of Reynolds shear stress would overestimate the wall shear stress. These studies concluded that the only reliable methods for determining the wall shear stress are those based on flow measurements in the wall region. These include the velocity gradient method in the viscous sublayer and direct measurements of wall shear stress using a hot-film anemometer. It will be interesting to determine whether the bed shear stress behaves in the same manner in the presence of a free surface. Our PIV system has a spatial resolution of around 0.1 mm perpendicular to the bed, which would not be sufficient to resolve the viscous sublayer. In the proposed research, we will measure the bed shear stress on the smooth bed directly using four hot-film sensors flush mounted to the smooth bed (acrylic sheet) at various distances downstream of the rough-to-smooth transition. The device will be calibrated in-situ under uniform flow condition. After calibration, the upstream section will be replaced by a rough bed and the evolution of bed shear stress on the smooth bed due to the roughness transition can then be examined.

Expected Outcomes

Proposed research will improve our understanding of the response of turbulent velocity profile and bed shear stress to a sudden change in bed roughness. A non-equilibrium turbulent boundary layer can occur in many situations in highway transportation system including flow through highway culverts, flow around bridge piers and abutments, and overtopping of roadways in the floodplain. A sudden change in bed roughness can also occur in the laboratory when soil erosion is studied using a sediment recess in an open-channel flume or water tunnel. In all the above, understanding the response of the bed shear stress to the roughness transition is important for accurate prediction of sediment erosion rate and scour.

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. Proposed research is related to the bridge scour research conducted by the principal investigator (PI) under several MPC projects. South Dakota Department of Transportation (SDDOT) currently uses methods developed for non-cohesive soils to evaluate bridge scour. These methods do not consider the rate of soil erosion. Accounting for the time rate of scour using methods like SRICOS (see Larsen et al., 2011; Rossell and Ting, 2013) could reduce the predicted final scour depth in cohesive soils but would require the soil erosion-rate-versus-shear-stress curve to be determined. In a current project (MPC-596), the PI is studying the bed shear stress induced by an eroding soil sample in an EFA type facility. The proposed research is an extension of this project where the bed shear stress over a wider range of roughness surfaces and surface transitions will be investigated.

Educational Benefits

The proposed project will be the subject of a Master of Science (MS) thesis. One graduate student will be supported on this project for a period of 9 months. Under the supervision of the PI, the student will learn the techniques of measuring flow velocity using PIV and bed shear stress using various methods and write MATLAB scripts to analyze the measured data. He or she will also gain a solid foundation in fluid mechanics and boundary-layer theory.

An open-channel flume that is currently unused will be refurbished and recommissioned for conducting research projects and teaching undergraduate and graduate laboratory courses. The PI has developed a suite of experiments in the courses he teaches (CEE 331 Fluid Mechanics Laboratory, CEE 436/536 Advanced Hydraulic Engineering, CEE 438/538 Environmental Fluid Mechanics) to give students hands-on experience with different fluid mechanics measurement techniques. The infrastructure building provided by this research project, which will include equipment acquisition and the development of experimental techniques and procedures for bed shear stress and flow measurements, would enhance these educational activities.

Technology Transfer

The findings of this research project will be published in peer-reviewed journals, in addition to 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 (https://www.mountain-plains.org/resources/researchers.php).

Work Plan

The project will include the following tasks:

(1) Conduct a literature review on turbulent flow over smooth and rough beds including the effect of streamwise roughness inhomogeneity.
(2) Design and rebuild a 17-feet long open-channel flume including the water supply, pumping system, headbox and tail box, and flow control and measurement.
(3) Conduct test runs on measuring the fluid velocity field over smooth and rough beds using a 2D PIV system, and the bed shear stress on a smooth bed using a hot-film anemometry system.
(4) Conduct water surface elevation, flow velocity, and bed shear stress measurements over various bed roughness transitions in subcritical and supercritical flows.
(5) Analyze the measured data to understand the response of turbulent velocity profile and bed shear stress to a sudden change in bed roughness.
(6) Evaluate different methods for determining the bed shear stress in open-channel flow near a roughness transition.
(7) Prepare and submit papers for publication in refereed journals.
(8) Prepare a final report.

Table 2. Task Time Schedule

TASK YEAR/ MONTH	YEAR 1												YEAR 2	
	1	2	3	4	5	6	7	8	9	10	11	12	1	2
1. Conduct literature review	■	■	■											
2. Refurbish open-channel flume	■	■	■											
3. Construct test runs with PIV and hot-film anemometry systems				■	■	■								
4. Conduct Tests 1 to 5							■	■	■	■	■	■		
5. Analyze measured data							■	■	■	■	■	■		
6. Evaluate methods for determining bed shear stress							■	■	■	■	■	■		
7. Prepare journal papers												■	■	■
8. Write final report												■	■	■

Project Cost

Total Project Costs:	$165,537
MPC Funds Requested:	$ 80,872
Matching Funds:	$ 84,665
Source of Matching Funds:	South Dakota State University, financial support, in-kind support, and facilities

References

Akan, A. O. (2006). *Open Channel Hydraulics,* 1st Edition, Butterworth-Heinemann, 376 pp.

Antonia, R. A. and Luxton, R. E. (1972). "The response of turbulent boundary layer to a step change in surface roughness. Part 2. Rough-to-smooth." *Journal of Fluid Mechanics*, 53, 737-757, doi.org/10.1017/S002211207200045X.

Briaud, J.-L., Ting, F. C. K., Chen, H. C., Cao, Y., 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, doi.org/10.1061/(ASCE)1090-0241(2001)127:2(105).

Chen, X. and Chew, Y.-M. (2003). "Response of velocity and turbulence to sudden change of bed roughness in open-channel flow." *Journal of Hydraulic Engineering*, 129(1), 35-43, doi.org/10.1061/(ASCE)0733-9429(2003)129:1(35).

Kadivar, M., Tormey, D. and McGranaghan, G. (2021). "A review on turbulent flow over rough surfaces: Fundamentals and theories." *International Journal of Thermofluids*, doi.org/10.1016/j.ijft.2021.100077.

Larsen, R. J, Ting, F. C. K. and Jones, A. L. (2011). "Flow velocity and pier scour prediction in a compound channel: Big Sioux River Bridge at Flandreau, South Dakota." *Journal of Hydraulic Engineering*, 137(5), 595-605, doi:10.1061/(ASCE)HY.1943-7900.0000334.

Lee, C-H (2018). "Rough boundary treatment method for the shear-stress transport k - ω model." *Engineering Applications of Computational Fluid Mechanics,* doi.org/10.1080/19942060.2017.1410497.

Li, M., de Silva, C. M., Rouhi, A., Baidya, R., Chung, D., Marusic, I. and Hutchins, N. (2019). "Recovery of wall-shear stress to equilibrium flow conditions after a rough-to-smooth step change in turbulent boundary layers." *Journal of Fluid Mechanics*, 872, 472-491, doi:10.1017/jfm.2019.351.

Loureiro, J. B. R., Sousa, F. B. C. C., Zotin, J. L. Z. and Silva Freire, A. P. (2010). "The distribution of wall shear stress downstream of a change in roughness." *International Journal of Heat and Fluid Flow*, 31, 785-793, doi:10.1016/j.ijheatfluidflow.2010.06.006.

Rathore, V., Penna, N., Dey, S. and Gaudio, R. (2022). "Response of open-channel flow to a sudden change from smooth to rough bed." *Environmental Fluid Mechanics*, 22, 87-112, doi.org/10.1007/s10652-021-09830-5.

Rossell, R. P. and Ting, F. C. K. (2003). "Hydraulic and contraction scour analysis of a meandering channel: James River Bridges near Mitchell, South Dakota." *Journal of Hydraulic Engineering*, 139 (12), doi.org/10.1061/(ASCE)HY.1943-7900.0000791.

Ting, F. C. K. and Kern, G. S. (2022). "Finding the bed shear stress on a rough bed using the log law." *Journal of Waterway, Port, Coastal, and Ocean Engineering*, doi.org/10.1061/(ASCE)WW.1943-5460.0000707 (In Press).