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Simultaneous Bed Shear Stress Determination Using CFD in Erosion Testing

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ABSTRACT

Determining the critical shear stress of fine-grained soils through erosion testing is an essential aspect of the Federal Highway Administration’s (FHWA) NextScour research initiative. FHWA has developed the Ex-situ Scour Testing Device (ESTD), one of several devices designed by FHWA to conduct soil erosion testing. The ESTD erodes soil samples captured in a Shelby tube at varying flow rates. As the sample erodes, a laser scanner captures the soil surface, and an algorithm sends a signal to a piston that extrudes the soil to maintain a flush surface with the channel bed. The ESTD also features an innovative shear sensor that directly measures shear stress on the soil surface in a separate series of tests. With this shear data, flow rates are converted to shear stresses. One difficulty that can arise while using the shear sensor is the soil sample eroding during shear testing, which means the shear data can vary over time. As an alternative method to find resulting shear stresses, FHWA researchers conducted computational fluid dynamic (CFD) simulations on scans of the soil surface in a virtual domain. To calibrate the CFD model, nonerodible artificial samples were fabricated with two different roughness factors, where 2- or 3-mm-diameter sand grains were glued to circular discs. The samples were mounted in the ESTD for shear stress testing. High-resolution scans of the surfaces were captured and imported into a CFD domain and then simulated in two CFD software packages. The resulting data from the physical shear testing and the CFD simulations are within 10 percent for most flows, indicating that future shear stress determinations can be accomplished using CFD. A Python script was also developed to automatically create a CFD domain from any laser-scanned soil surface, compute the bed shear stress, and output the results with the erosion test recording for critical shear stress analysis.
INTRODUCTION

The Federal Highway Administration’s (FHWA’s) Scour Program provides oversight, guidance, technical assistance, and research efforts to ensure that bridges along the National Highway System are safe. To better align the Scour Program with other aspects of bridge design, FHWA is currently developing a next-generation scour research initiative, NextScour, to improve scour analysis for safe and economical bridge foundation design. NextScour recognizes that the phenomenon of scour consists of two major aspects or components: consideration of water and hydraulic forces (loads), and the erosion resistance of soils and their associated geotechnical effects (resistance). Consequently, the initiative consists of two focus areas: NextScour-Hydraulics and NextScour-Geotechnical (Shan et al. 2021a).

NextScour-Geotechnical focuses on improving estimates of the scour resistance, i.e., critical shear stress of layered soils, especially cohesive soils, through erosion testing. NextScour-Geotechnical emphasizes the importance of physical erosion testing in both laboratory and field settings and acknowledges the availability of different erosion testing devices, including the Ex-situ Testing Device (ESTD) (Shan et al. 2011, 2015), the In-situ Scour Testing Device (ISTD) (Zinner et al. 2016; Shan et al. 2018), the Portable Scour Testing Device (PSTD) (Shan et al. 2020), the erosion function apparatus (EFA) (Briaud et al. 2001), and the jet erosion test (Hanson 1991). Additional geotechnical tests are also conducted on these samples to fully characterize the soils tested. Correlations between erosion data and geotechnical index properties will be established as more data are collected. Eventually, improved correlation could eliminate the need for time-consuming erosion tests. As the dataset gets larger and the correlations to geotechnical data improves, FHWA aims to develop a subsurface erosion map that could include erosion resistance parameters with depth.

The ESTD, shown in Figure 1, is an automated erosion device developed by FHWA that measures the erodibility of a cylindrical soil sample under well-controlled flow conditions (Shan et al. 2021b). The ESTD features a 12-cm wide by 1.9-cm high by 0.91-m long rectangular acrylic test channel. The maximum flow capacity of the pump is 14 L/s, with a maximum flow velocity of 6 m/s. An underwater laser scanner mounted on an industrial robotic arm scans the soil surface every 20 s, sending a quasi-instantaneous signal to the control program (Figure 2). The control program averages the scan data and compares them to a reference point on the test channel surface. If the average value is less than this reference point, a command is sent to a piston that extrudes the soil to maintain a flush surface with the channel bed. The control program records the extraction rate data of the piston, which is used to calculate the erosion rate. An electromagnetic flowmeter continuously measures flow circulation, and two filtration tanks capture the eroded clay particles and keep the water clear for the laser scanner. An electromagnetic direct shear sensor, located upstream of the piston, directly measures the shear stress of the soil sample in a separate series of tests after erosion testing is complete. By comparing similar flow rates, one can develop a relationship between erosion rates and shear stresses, which is then used to determine the critical shear stress of the soil. Shan et al. (2021b) outlined in detail the ESTD test procedures.
ESTD DIRECT SHEAR SENSOR

The electromagnetic direct shear sensor is a sensitive force-feedback instrument that provides an output voltage proportional to the measured force. The feedback circuit ensures that the sensor disk remains in a fixed position relative to the sensor chamber with a residual deflection in micrometers. The fixed position maintains a small gap between the sensor disk and the aperture ring. The sensor is specifically designed to precisely measure small forces in a wet environment. A rubber membrane separates the sensor into an upper wet and a lower dry area. The core of the sensor is a platform held by a bronze leaf spring. On top of the platform sits the sensor disk, whose deflection indicates the magnitude of the shear force. A diagram of the shear sensor is shown in Figure 3 (Shan et al. 2015).

The direct shear sensor detects a fluid-induced force, $F_w$, as the force pushes the platform to the right, as shown in Figure 3. A small horizontal deflection will occur. The sensor then generates a current, and a magnetic counterforce, $F_m$, results from the change of magnetic electronic fields, pushing the sensor disk to the left with a residual deflection (less than 68 µm at
100 Pa). A more detailed discussion of the direct shear sensor can be found in the paper by Shan et al. (2011).

Figure 3. Force measurement principle of the direct shear sensor (Shan et al. 2015).

The direct shear sensor detects shear stresses using a 15-mm-thick soil sample extruded into a stainless steel ring. The ring is mounted to a small bowl that attaches directly to the sensor disk. The bowl's interior has a raised circular platform, which pushes the soil out about 2 mm above the edge of the ring. After the bowl is mounted on the shear sensor, the sensor disk height is adjusted until the soil surface is flush with the test-channel surface. A minimum of one flow rate was run on each sample to record the shear stress of that flow for about 60 s. If the sample did not erode, additional flow rates were tested. In total, five soil samples were tested, covering a flow range of 2–12 L/s. Figure 4 plots a typical shear stress recording of a soil sample at increasing flow rates.
Figure 4. A typical shear stress recording at varied flow rates.

The shear stress ($\tau$) and flow rate ($Q$) data were used to formulate a relationship to convert erosion test flow rates into shear stresses (Figure 5).

Figure 5. Relationship between measured shear stresses and flow rates.

The shear test samples only experienced the flow for a short period of time so the surfaces remained reasonably flat. Thus, the shear stress measurement could be compared to the computation using Moody’s diagram. Shan et al. (2015) reported that the largest difference between the shear stress measurement and the computation was 20 percent.

A few limitations of separate shear tests include the following: 1) Erosion can happen on shear test samples at high flow rates, as was shown in Figure 4, i.e., the shear stress increased while the flow rate increased from 2 L/s to 6 L/s, and it dropped before reaching the 9.5 L/s flow rate. It is because the soil surface was eroded before flow increased to 9.5 L/s. When significant regions of the soil surface eroded beneath the plane of the ESTD channel bed, less hydraulic shear force acted on the sample, and the shear stress decreased. Thus, selecting the appropriate
data range to calculate the shear stress for the flow was sometimes challenging. 2) The surface of shear test samples was typically much flatter compared to the surfaces in the erosion tests, meaning the measured shear stress would be smaller than that in the erosion test. 3) Separate shear tests cannot capture the variation of simultaneous shear stresses for different soil surfaces. Therefore, the researchers investigated CFD modeling with laser-scanned soil surfaces to provide simultaneous shear stresses for eroded samples.

VALIDATION OF CFD MODELING

Prior to implementing the CFD model, its accuracy was validated by reproducing physical shear measurements of nonerodible sand samples. The samples were fabricated by gluing sand grains with 2-mm and 3-mm nominal sizes to circular discs. The 2-mm sand grains passed through a No. 8 sieve (2.36 mm) and were retained on a No. 10 sieve (2 mm). The 3-mm sand grains passed through a No. 6 sieve (3.35 mm) and were retained on a No. 7 sieve (2.8 mm). Due to the size variation and irregular shapes of sand grains, the discs had peaks and valleys. This surface unevenness unavoidably creates a form drag from the flow, especially if sand particles were higher than the channel bed during the calibration tests. Fortunately, the shear sensor and CFD model can capture pressure’s contribution to the horizontal force on the sample surface.

A series of tests were conducted with the nonerodible discs in the ESTD, where the channel bottom was aligned with either the top, middle, or bottom of the sand particles. In each test, the operator carefully marked the flow direction on the edge of the discs so that CFD models maintained the same sample alignment. However, the operator visually estimated the vertical alignment of the disc and the channel bottom. A high-resolution scanner laser-scanned each sand sample to import the model for CFD simulation. Figure 6 shows the elevation contour of the 3-mm sand sample. The vertical zero elevation in Figure 6 was considered the ESTD channel bottom elevation in the CFD models.

![Elevation contour of the 3-mm sand sample.](image)

Figure 6. Elevation contour of the 3-mm sand sample.

Figure 7 plots the shear stress measurement results of the 3-mm sand sample at the three vertical alignments, including multiple runs of the top alignment. As seen in the plot, variation in the three top alignment data series increased with higher flow rates. The variation was likely due
to very slight differences in the vertical position of the sample, which was set manually by the operator. This variation proves that the direct shear sensor is extremely sensitive to vertical alignment. Also, as the sample protruded more into the flow, i.e., the alignment shifted to the middle and bottom of the sand grains, the measured shear stress increased due to the form drag.

Two CFD software packages, i.e., OpenFOAM and StarCCM+, were used in the shear stress modeling. OpenFOAM was used to model the middle alignment for 2-mm and 3-mm sand samples, while StarCCM+ was used to model the top alignment, middle alignment, and additional positions shifted in 5–10 percent increments of the sand sizes, up to 70 percent. Both CFD models reproduced the exact dimension of the ESTD test channel and upstream and downstream pipe lengths. The inlet of both models was a flow rate inlet, and the outlet was set as a pressure outlet. The mesh size in both models was 1 mm. Therefore, the rectangular ESTD channel cross section and the sand sample surface were set to be smooth walls. Both models used the unsteady Reynolds-averaged Navier-Stokes (URANS) solver with a $k$-epsilon turbulence model to solve the momentum equations. The simulation result analysis included both surface friction and pressure components in the horizontal direction, and the summary of the two was compared with the shear sensor measurement.

![Graph](image)

Source: FHWA.

**Figure 7.** Measured shear stress of the 3-mm sand sample using the direct shear sensor.

Figure 8 compares the CFD simulation results to the shear sensor measurements for the 3-mm sand disc. Vertical error bars show ±10-percent offset from the sensor measurements. As evident in the plot, StarCCM+ and OpenFOAM produced similar results for the middle alignment, although StarCCM+ results were generally larger than those of OpenFOAM. StarCCM+ agreed with the test 2 sensor measurement within the 10 percent error for the top alignment. After the StarCCM+ model shifted the sample surface up by 0.3 mm (10 percent of sand size), the difference between StarCCM+ and test 3 reduced to within 5 percent.
Figure 9 compares the CFD simulation results to the shear sensor measurements for the 2-mm sand disc. After the vertical position of the sample was shifted in StarCCM+ up by 0.6 mm (30 percent) relative to the channel bottom, CFD-calculated shear stresses were within a 5-percent difference from the two sets of sensor measurements for the top alignment. Although StarCCM+ and OpenFOAM produced similar results for the middle alignment, the results were significantly less than the sensor measurements. Again, StarCCM+ produced shear stresses that were generally larger than those of OpenFOAM. From the middle alignment plots of Figures 8 and 9, the 3-mm sample disc had a shear stress of 130 Pa at 6 L/s flow rate. In contrast, the 2-mm sample had a higher shear stress of 170 Pa at the same flow rate. The comparison indicates that the 2-mm middle alignment sensor measurements need to be investigated further before they can be compared with the CFD results.
Overall, both CFD models’ results were close to each other for each configuration. Five sets of CFD simulation results were comparable to five sets of sensor measurements for both 2-mm and 3-mm sand samples. These results gives researchers confidence that CFD simulations can compute simultaneous shear stresses on soil samples during erosion tests.

**AUTOMATED CFD SIMULATIONS**

One automated ESTD erosion test usually lasts for 60–90 min, in which time the laser scanner collects between 200 and 300 laser-scanned soil surfaces. Typically, multiple erosion tests are conducted on a field soil sample, especially for low-erodible soils. Therefore, an automated script was necessary to automatically generate the stereolithography (STL) files from the scanned soil surface for CFD simulations, perform the CFD simulations, and analyze and export the simulation results. Considering the magnitude of the simulation and needed computation resources, the researchers used OpenFOAM because it is open-source software.

The automated CFD simulation script first reads the raw data recording after one ESTD erosion test is completed. The simulation script selects needed information, such as the scanned surface point cloud and associated flow rate for each scan. A critical piece of information in the raw ESTD recording is the average soil surface relative to the ESTD channel bottom based on the piston position. Then, OpenFOAM generates an STL file from the soil surface point cloud. The quality of the STL file is inspected by the script, and then the file is inserted into the STL file of the ESTD piping. Next, the flow and boundary conditions are set up to start the simulation. The script exports the shear stress results with the flow information for all scans associated with the erosion test. Another Python script can import the output to automatically analyze the critical shear stress with soil erosion data (Shan et al. 2021b).

As a preliminary test, the shear stresses of one ESTD erosion recording containing 90 laser-scanned soil surfaces with 3 flow rates of 2, 4, and 6 L/s were modeled using the Python script. Each case of simulation took 2–4 h. The base mesh size was 1 mm, and the maximum allowable time step was 0.005 s. The simulation time was 10 s, which provided enough time for the flow to become stable. The roughness height in the simulation was twice the median size of the cohesive soils, which was assumed to be 75 μm.

Figure 10 shows the 90 simulation shear stresses and the 3 shear stresses measured by the direct shear sensor separately using soils from the same Shelby tube from the erosion test. Both shear stress results were close at the three discrete flow rates. Since soil surfaces in erosion tests and shear stress measurements differ, evaluating the relative accuracy of the OpenFOAM simulations is not easy. Nevertheless, the automation of OpenFOAM simulations was realized using the Python script. Subsequent research will focus on the accuracy of the simulation results.
CONCLUSION

FHWA’s NextScour-Geotechnical research aims to improve estimates of the soil erosion resistance, i.e., critical shear stress. As erosion testing is an essential tool to determine the critical shear stress of fine-grained soils, ESTD and other erosion testing devices will continue to play a significant role in the NextScour research initiative. The determination of shear stress from flow during the erosion test is vital. Currently, flow shear stress measured using the direct shear sensor on the ESTD may not represent the simultaneous shear stress acting on the soil surface during the erosion process. Therefore, this paper explored the possibility of using CFD simulations with quasi-simultaneous laser-scanned soil surfaces captured during erosion testing. CFD simulation results and shear sensor measurements on nonerodible sand samples were similar, with a maximum difference of 10 percent and usually within 5 percent. These results prove that CFD can provide simultaneous shear stress measurements on soil surfaces.

A Python script was written to automate the CFD simulations on a cluster to convert the flow information to simultaneous bed shear stress on collected soil surfaces in the erosion test. When used with the other automation Python script designed to automatically compute the critical shear stress based on ESTD erosion data, automated CFD simulations will achieve better accuracy for critical shear stress measurements (Shan et al. 2021b).

REFERENCES

Shan, H., Pagenkopf, J., Kerenyi, K., and Huang, C. (2020) “NextScour for Improving Bridge


