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Laboratory Measurements of the Erodibility of Gravelly Soils

Jamie F. López-Soto and Bryant A. Robbins

November 2021

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Laboratory Measurements of the Erodibility of Gravelly Soils

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Final report

Approved for public release; distribution is unlimited.

Prepared for Risk Management Center, U.S. Army Corps of Engineers
Lakewood, CO 80228

Under Funding Account Code 8JGK75

Abstract

The critical shear stress and erodibility of soil are fundamental parameters for modeling embankment breaching. Unfortunately, very few studies have examined the erosion characteristics of soils consisting predominantly of particles larger than sand. This report presents results of an experimental study in which the erosion characteristics of gravelly soils were measured. A flume apparatus was developed in which 0.45-m-square samples were extruded into confined flow. A mechanical laser system allowed the measurement of scour in real time, resulting in a continuous and automated erosion test. The critical shear stress of a uniform gravel was found to match the expected values based on the Shields diagram, while tests that were composed largely of gravel but contained other soils, such as sand, silt, and clay, varied significantly with the critical shear stress and erodibility, depending highly on the characteristics of the finer soils.

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Preface

This study was conducted for the USACE Risk Management Center (RMC) under Funding Account Code 8JGK75 in support of Issue Evaluation Studies and Dam Safety Modification Studies. The program manager was Mr. Steve Townsley, Chief of the RMC Western Division.

The work was performed by the Geotechnical Engineering and Geosciences Branch (GSG) of the Geosciences and Structures Division (GS), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Mr. Christopher G. Price was Chief, GSG; Mr. James L. Davis was Chief, GS; and Dr. Michael K. Sharp, GZT, was the Technical Director for Water Resources Infrastructure. The Deputy Director of ERDC-GSL was Mr. Charles W. Ertle II, and the Director was Mr. Bartley P. Durst.

COL Teresa A. Schlosser was the Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

Nearly all embankment dam failures (94%) are due to erosion of earthen materials, either by overtopping of the embankment and appurtenant structures or by internal erosion (Foster et al. 2000). As such, erosion is a process that is commonly assessed as part of risk analysis for earthen dams. While numerous constitutive relationships have been proposed for describing the erosion of soil (e.g., Partheniades 1965, Wilson 1993, and Briaud et al. 1999), computer programs for the analysis of erosion of earth dams and spillways (Temple et al. 2006; Wu 2013) have relied primarily on the simple excess shear stress equation given by

$$E = K_d(\tau - \tau_c)^a \quad (1)$$

where

E = erosion rate (m/s)

K_d = erodibility coefficient ($\text{m}^3/\text{N}\cdot\text{s}$)

τ = applied hydraulic shear stress (Pa)

τ_c = critical shear stress for initiation of erosion (Pa)

a = empirical coefficient

In practice, it is common to take $a = 1$, resulting in a linear excess shear stress equation for describing the erosion process. This leaves only two material parameters, K_d and τ_c , that must be estimated to assess erosion-related failure modes for embankments. The critical shear stress, τ_c , describes the hydraulic conditions required to initiate erosion, whereas the erodibility coefficient, K_d , describes how quickly erosion will develop.

Numerous studies have been conducted to quantify the values of K_d and τ_c for various soil types (e.g., Hanson and Simon 2001, Briaud et al. 2017, and Wibowo and Robbins 2018). However, limited measurements have been made on materials consisting primarily of gravel-sized particles or larger ($>4.75\text{-mm-diam}$). While the lack of data for these soil types is not surprising due to the difficulty and cost associated with large-scale testing, it is rather unfortunate for the dam safety profession due to the common use of dirty gravels and rock fills in dam construction. These materials are exceptional embankment materials

due to their high strength, high stiffness, potentially low permeability, and erosion resistance. As such, many USACE dams (e.g., Hills Creek Dam and Cougar Dam) have been constructed from these types of materials. It is therefore necessary to predict the erosion characteristics of dirty gravels and rock fills for the purpose of risk analysis on dams. This study was undertaken to inform these predictions through large-scale measurements of the erosion characteristics of gravelly soils.

The primary objective of this study was to develop a large-scale laboratory device capable of measuring the critical shear stress (τ_c) and erodibility (K_d) of predominantly gravel soils. The device development included

- measurement validation through comparison of measured critical shear stress for gravel with previous incipient motion studies on gravel.
- initial measurements of critical shear stress and erodibility coefficients for select soils consisting predominantly of gravel.

The following chapters provide background information regarding previous erosion studies (with particular emphasis on gravel soils), an overview of the laboratory device, tested materials, test procedures, and test results.

2 Literature Review

Numerous studies have been conducted to develop devices for measuring the erosion characteristics of geologic materials. The following sections provide an overview of these devices, with comments where applicable, pertaining to testing of gravels.

2.1 Previous devices for erosion measurements

Early studies regarding the erosion of soils focused on quantifying the critical shear stress of cohesionless sediments for the purpose of designing stable channels (e.g., Shields 1936). In recent years, equipment has been developed for measuring both the critical shear stress and the erodibility coefficient of both cohesive and non-cohesive soils. The various types of equipment are described below.

2.1.1 Open channel incipient motion studies

Numerous studies regarding the incipient motion conditions of sediments have been conducted in open channel flumes (Buffington and Montgomery 1997). The majority of incipient motion data used in the development of the Shields diagram (Figure 1) were obtained in this manner. Further, these studies have included gravel-sized particles (e.g., Gilbert and Murphy 1914, Meyer-Peter and Müller 1948, and Coleman 1967). More recently, gravelly soils with cohesive fines have been tested in this manner (Kothyari and Jain 2008; Ahmad et al. 2018). While these types of studies are typically used only to investigate values of τ_c due to the limited shear stress range that can be applied, Criswell et al. (2016) was able to obtain estimates of K_d for sieved gravel from this type of experiment.

Figure 1. Shields curve (from Yalin 1977).

2.1.2 Sedflume

A confined flow erosion device called the Sedflume (Figure 2) was developed by the University of California to measure erosion characteristics of undisturbed sediment cores (McNeil et al. 1996). The device was also used to investigate the bulk properties (bulk density, average particle size, and particle size distribution, among others) that affected the erosion rate of soils with specific focus on cohesive soils (Lick and McNeil 2001).

Figure 2. Schematic diagram of Sedflume (McNeil et al. 1996).

The device allowed for collected core samples to be extruded into the incoming flow as the sediment eroded. As erosion occurred, the operator lifted the soil with the piston to keep the soil flush with the flume floor. For this test, the critical shear stress was defined as the shear stress required to cause 1 mm of erosion. The change in soil core length vs. time was used to calculate the erosion rate of the deposited soil. The study focused on the effects of soil parameters on the erosion rate throughout the core sample.

To calculate the applied hydraulic shear stress for this test, the friction factor was calculated by using an equation based on flow through a smooth pipe, as presented in equation 2. The calculated friction factor was used to calculate the shear stress using equation 3.

$$\frac{1}{\sqrt{f}} = 2 \log \left[\frac{UD\sqrt{f}}{\nu} \right] - 0.8 \quad (2)$$

where

f = the friction to be calculated
 U = mean flow velocity in the conduit
 D = hydraulic diameter
 ν = kinematic viscosity.

$$\tau = \frac{1}{8} f \rho U^2 \quad (3)$$

where

τ = shear stress
 f = the friction factor based on the Moody diagram
 ρ = mass density of water
 U = mean flow velocity in the conduit.

2.1.3 Erosion Function Apparatus (EFA)

A similar device to the Sedflume is known as the Erosion Function Apparatus (EFA). Perhaps the earliest mention of the EFA was made in Briaud et al. 1999, but it was formally presented in Briaud et al. 2001. The results of the tests in this device relate an exerted shear stress to an erosion rate through a function called the “erosion function.” The erodibility coefficient can then be calculated based on a linear regression of the erosion function. In this study, the shear stress (τ) was calculated as equation 3.

For the case of the EFA, the friction factor for the shear stress calculations in equation 3 is obtained from the Moody diagram, which relates the friction factor to the Reynolds number; therefore, important parameters for the shear stress calculation are water temperature, flow velocity, flow regime, and the pipe relative roughness.

The EFA device accepts a standard 3-in. Shelby tube such that undisturbed samples can be readily tested. The flume conduit cross section is a rectangular pipe of 101.6 mm x 50.8 mm. The soil sample is placed in the flume device, and the soil is extruded 1 mm into the rectangular channel. Briaud (2013) eliminated the 1-mm extrusion and suggested leveling the soil with the bottom of the conduit and extruding the sample when 1 mm of erosion had taken place. The erosion rate of the material is calculated based on the rate at which the soil needs to be extruded into the incoming flow to maintain a nearly flush sample surface. To obtain the erosion parameters of a specific soil sample, the test is conducted in a stepwise manner with increasing flow, recording the average flow velocity and the rate at which the soil is repositioned for each increment. The test requires a trained operator to assess the 1-mm erosion depth and activate the piston to push the soil back flush to the bottom floor of the conduit. Due to the irregular behavior of erosion, the soil extrusion is dependent on the observation and interpretation of the operator.

Classification of soil erodibility using the EFA is based on the erosion rate of a material and the shear stress or velocity (Briaud 2008). Erodibility classifications range from very highly erodible to non-erosive soil (Figure 3).

The EFA was used by Briaud et al. (1999) to test a sand and a gravel with median diameters of 3.38 mm and 7.90 mm, respectively. As these test results are some of the very few measurements in the literature for coarse-grained soils, they will be used for comparison to the results obtained in the present study.

Figure 3. Soil erodibility classification based on erosion rate relation to (A) shear stress and (B) average flow velocity (from Briaud 2008).

2.1.4 SETEG-System

The device developed by Kern et al. (1999) eroded a soil column 150 cm in length and 13.5 cm in diameter. The flume was developed to determine the erosion characteristics of cohesive sediments as a function of core depth. The test results were used to relate the mean particle diameter and bulk density of a soil sample to the critical shear stress of the material. Both Briaud et al.

(1999) and Kern et al. (1999) used the friction factor, fluid density, and average velocity to calculate the shear stress. Recently the device was modified to use a triangulation technique using a camera, a laser, and appropriate software to determine the soil volume loss in relation to time (Noack et al. 2015). The tested soils consisted mostly of silt and silty sands.

2.1.5 National Institute of Water and Atmospheric Research (NIWA) in-situ flume

The NIWA in-situ flume was developed by Aberle et al. (2003) to measure the critical bed shear stress and erosion rate of soils under various aquatic environments. The test was developed for cohesive sediments. The main difference between this flume and the EFA or Sedflume is that it is bottomless and consists of a rectangular section 1.20 m in length under which pressured water flows over the soil, thereby imparting a shear stress on in-situ sediment beds. The sediment concentration is monitored and used to measure the amount of eroded material. A similar device was used by Noack et al. (2015) to compare in-situ testing to a laboratory testing device similar to the SETEG-System. The in-situ device used by Noack et al. (2015) can be repositioned to investigate the erosion characteristics through multiple soil layers. This in-situ device relies on cameras to monitor the area being eroded.

2.1.6 Erodimetre

Le Hir et al. (2006) developed the Erodimetre, a clear, closed conduit flume with a rectangular cross section for in-situ erodibility testing. The portable closed conduit flume was able to test soil in a 9-cm cylinder. During testing, the soil is manually pushed with a piston into the incoming flow, similar to the Sedflume and the EFA. The eroded soil mass is measured continuously through the use of a turbidity sensor and the collection of the eroded sand. Initially the device was used on granular material and later used for sand-mud mixtures by Jacobs et al. (2011).

2.1.7 Conduit flume

To test the erosion characteristics of soils along stream banks, Sutarto et al. (2014) developed a rectangular conduit flume. During the experimental setup, the soil sample was subjected to multiple flows without raising or moving the soil sample. The sample was set flush with the flume floor, the flow was then initiated, and the fluid eroded the sample. Since the soil was not pushed back to the flume floor as

erosion occurred, sediment concentrations were obtained at 10-min intervals; at the end of the 10-min interval, the flow was raised. This methodology is useful for small flow and erosion rates.

The material used for this analysis was fine soils consisting mostly of silts and sands from streambanks with mean particle sizes ranging from 0.020 mm to 0.130 mm. The critical shear stress was found by extrapolating the shear stress vs. erosion rate curve to the point at which the erosion rate is zero, similar to Briaud et al. (2001). The sample was obtained directly from the site in a 30-cm-long by 10-cm-wide by 5-cm-deep rectangular sampler. The sample length is parallel to the flow, while the width is perpendicular to the flow.

2.1.8 Jet erosion test

The jet erosion test (JET) (Hanson 1991) consists of a submerged water jet placed perpendicular to a soil surface, as shown in Figure 4A. As the water jet erodes the soil surface, the distance between the nozzle and the soil increases, causing increased jet diffusion and lower shear stresses. As such, the erosion rate decreases over time, and the erosion record can be used to estimate values of τ_c and K_d (Hanson and Cook 2004). Similar to the EFA, a categorization system for soil erodibility has been proposed for the JET, as shown in Figure 4B (Hanson and Simon 2001).

Testing gravelly soils with the JET is difficult due to the fact that the water jet is approximately 6 mm in diameter. As such, a single gravel particle can obstruct the flow and change the test results. Nevertheless, attempts have been made to test gravelly soils with the JET. To minimize the impact of the gravel-sized particles, Wahl (2014) attempted two approaches: (1) orienting the jet horizontally such that gravel particles fell out of the scour hole immediately after detaching and (2) manually removing gravel from the scour hole during the test. Boucher et al. (2018) constructed a JET with a larger nozzle diameter and also manually removed gravel from the scour hole.

Figure 4. Illustration of (A) jet erosion test (Hanson 1991) and (B) corresponding soil erosion categorization system (Hanson and Simon 2001).

2.1.9 Hole erosion test

The hole erosion test (Wan and Fell 2004) is conducted by monitoring the pressure drop and flow rate through an initially drilled hole in a soil sample as the hole enlarges. The “effective diameter” of the hole is estimated from pipe hydraulic equations based on the flow rate and head loss. As erosion progresses, an estimate of the pipe diameter over time is obtained that can be used to derive values for τ_c and K_d . As noted by Wahl et al. (2008), the hole erosion test is difficult to run on soils with minimal cohesion, as the hole may locally collapse and/or develop non-uniformly. Further, testing gravelly soils in the HET using traditional sample sizes presents issues due to the initial hole’s diameter being the size of a gravel particle. While larger HET tests could be developed for gravels, stability of the hole may be an issue and high flow rates would be required.

2.2 Considerations for testing gravels

In designing the apparatus for this study, considerable thought was given to how the gravel particles would influence the erosion process. It was desired to avoid configurations in which gravel particles might substantially influence the test hydraulics (e.g., the JET and HET devices). Additionally, it was necessary to be able to generate shear stresses sufficient to erode compacted clays. Therefore, open flume configurations were deemed impractical due to the large depth and/or slope required to obtain the necessary shear stresses. Therefore, a closed conduit flume design, similar to the EFA and Sedflume designs, was selected for this study. The flume was designed with a much larger sample size than those of previous flumes to ensure that the presence of gravel particles would not alter the results.

3 Methodology

3.1 Equipment

A large aluminum flume with an acrylic top that could readily be modified for this testing program was available at the ERDC, as shown in Figure 5. The flume was 2.29 m long, 0.3 m deep, and 0.45 m wide. The acrylic top was 3.8-cm-thick acrylic bolted to the flume edges.

Figure 5. Uncovered large aluminum flume.

The flume was modified for this study by adding internal components to create a flow transition zone, a high-velocity flow channel, a soil sample area, and a downstream zone for deposition of eroded materials. The initial construction of internal components made use of marine-grade plywood. Once found satisfactory, the internal components were constructed out of aluminum to increase the device's durability. A detailed schematic drawing of the device is shown in Figure 6, while internal dimensions are recorded in Table 1. Tests on poorly graded gravel (GP), poorly graded gravel with silt and sand (GP-GM), and clayey sand (SC) were conducted using wooden components, while tests on poorly graded gravel with clay and sand (GP-GC) were conducted using aluminum components.

Figure 6. Large flume internal components.

3.1.1 Flow transition zone

A flow transition zone, [1] on Figure 6, was added inside the flume to gradually transition the flow from the water inlet into the high-velocity flow channel. The ramp was placed at 47.5° to maximize the space available inside the flume.

3.1.2 High-velocity flow channel

Water flowed through the high-velocity channel ([2] on Figure 6), passed over the soil sample, and exited the channel into the soil deposition area. The height of this channel was a function of the material used to create the internal components. Dimensions are presented in Table 1, and schematics of the flow channel and soil area are shown in Figure 7.

Table 1. Test surface area dimension.

	Wooden setup	Aluminum setup
Channel gap height (mm)	15.0	11.3
Channel width (mm)	450	450
Soil length (flow direction) (mm)	450	450
Soil width (perpendicular to flow) (mm)	410	425
Average soil depth (mm)	113	133

Figure 7. Flow channel details.

3.1.3 Soil sample area

The soil was directly placed over a movable false bottom (Figure 8A), and the entire soil sample area ([3] on Figure 6) was filled with soil (Figure 8B). This false bottom allowed the soil to be raised when needed.

Figure 8. (A) False bottom detail. (B) Clayey gravel being placed in the soil sample area. Both details are with the aluminum interior components.

The soil sample area is directly underneath the high-velocity channel. It is in this area where the soil is placed and compacted. The area of interest is at the interface where the fluid meets the top layer of soil. To capture the erosion process, five laser sensors were placed outside the flume overlooking this area, as shown in Figure 9. Details regarding these sensors are discussed in the “Instrumentation and Controls” section.

Figure 9. Top view of test setup.

3.1.4 Soil deposition area

The eroded soil would exit the flow channel and deposit in the downstream area of the flume, as shown in Figure 10. The soil deposition area was situated as far from the outlet as possible to decrease the possibility of soil exiting through the outlet and recirculating back into the pump. Later it was found nearly all coarse-grained soil deposited out into this area, making clean up rapid and easy.

Figure 10. Soil deposition area. Details shown with wooden components.

3.2 Instrumentation and controls

The instrumentation for the test included distance laser sensors that were installed on a moving carriage, linear position potentiometers, pore pressure sensors, a flow meter, and a pneumatically controlled air bellow for sample positioning. The output from the instrumentation was fed into a computer that analyzed the obtained data in real time to decide when to raise the soil sample. A schematic of the instrumentation is shown in Figure 11.

Figure 11. Schematic cross-sectional drawing of sensor setup.

3.2.1 Carriage and distance laser sensors

The laser sensors consisted of five Wenglor® OPT2006 sensors with a range of 300 mm and a resolution of 80 μm read at a frequency of 500 Hz. The five laser sensors, spaced at 9-cm intervals, were attached to a carriage above the soil sample that moved along the full length of the sample surface during testing (Figure 12). The laser sensors' calibration factors were corrected for refraction due to acrylic and water mediums. The soil surface profile was directly measured throughout the test. The carriage was connected to a guided sleeve that was driven along the guiderails by a gear motor. Limit switches positioned at the edge of the sample triggered a change in direction of the motor, allowing the lasers to travel back and forth along the sample top to scan the surface continuously.

3.2.2 Data acquisition (DAQ)

All sensor readings (laser distance sensors, pressure transducers, and flowmeter) were collected using a NI USB-6255 M series screw terminal data acquisition (DAQ) device. The average velocity of the carriage was 0.15 m/s resulting in a time of 3 sec being required to scan the eroded surface. A 0.3-Hz data output was selected as an appropriate data acquisition rate to guarantee a complete scan of the soil surface. This soil surface was analyzed for each entry in the data record.

Figure 12. Carriage and equipment details.

3.2.3 Linear position transducers

Two linear position potentiometers were used during testing. One potentiometer was used to monitor the position of the lasers horizontally along the top of the sample. The linear potentiometer for the horizontal position was a Unimeasure PA-80-S11-D1S-10C with a range of 2.0 m and a linearity of 2 mm. The other linear position potentiometer, (Unimeasure HX-P510-15-N10-NoS-36N) was a water-resistant type and was placed beneath the soil sample to measure the displacement of the bottom of the soil sample as it was extruded into flow. The range was 380 mm with a linearity of 0.7 mm.

3.2.4 Pressure transducers

Pore pressure ports were placed along the acrylic top with a spacing of 20 cm between ports. To prevent pressure ports from interfering with the laser measurements, the ports were placed 5 mm from the edge of the sidewall of the flume. The differential pressure sensors were Honeywell 26PC Series wet-wet sensors with a pressure range of ± 1 psi. All differential pressure transducers were connected on one side to the pressure transducer at the downstream of the sample and on the other side to the pore pressure port, thus capturing the difference in pressure

between their position at the top of the sample and the downstream zone of the flume. The pressure transducer in the downstream was a 15-psi wet-wet transducer that measured the difference in pressure between the inside of the flume and the atmospheric pressure. Figure 13 shows the connection of the pressure transducers' setup. The valve and hose arrangement at the ends of the pressure transducers allowed for saturation of the hoses and prevented entrapped air from entering into the pressure lines by maintaining a constant connection to the pressure transducers.

Figure 13. Pressure and valve connections (A) while saturating manometer with two open valves and (B) while testing with one valve closed.

3.2.5 Flow meter and flow controls

The flow was supplied from four pumps in parallel. Each pump had a valve that allowed a controlled flow regulation throughout testing. Careful valve control and pump selection were key in achieving target flows. The water source was a 3,785-L reservoir with a water level approximately 2.75 m from the flume inlet. The water was recirculated throughout the test. A filter in the outlet prevented the eroded gravel from recirculating. A schematic of the plumbing and electrical wiring is presented in Figure 14.

Flow measurements were obtained from a GPI TM300-N-GG flow meter that had a range from 151 LPM to 1,530 LPM and an accuracy of $\pm 3\%$ of the reading. During testing, the digital readout of the instrument was continuously monitored and compared against the values recorded by the DAQ system.

3.2.6 Air bellow

The air bellow was positioned under the false bottom, as seen in the Figure 11 schematic and the Figure 12 photograph, which shows the air bellow

without the false bottom in place. The air bellow was inflated as needed throughout the test to raise the soil surface to its original position.

3.2.7 Overview of instrumentation and mechanical components

Figure 14 shows a diagram of the components used in the current testing program and the relationships between them. The upper left side of the diagram shows the hydraulic components that are needed to regulate flow into the flume. The upper right side illustrates the flume and instrumentation. The bottom illustrates the pneumatic controls, controlled by an electronic valve, used to control the inflow into the air bellow for repositioning the sample.

3.3 Software

The DAQ software was developed using the MATLAB DAQ toolbox with a custom Graphical User Interface (GUI). The software was written to allow the automation of the erosion testing. This was achieved using the output from the distance laser sensors, the signal outputs from the data acquisition software, and the linear position potentiometer under the soil.

The distance laser sensors were key in the automation process, as the sensors continuously scanned the soil sample's surface. With these

measurements, the average depth of the sample was obtained every 3 sec and compared to a threshold value for sample advancement set by the test operator. For other tests, such as the Sedflume and the EFA, this threshold had been 1 mm; but for particles such as gravel, this threshold would have proven too small, as the gaps between gravel particles create an uneven surface that is detected by the laser's sensors and can surpass the 1-mm threshold when initially placed. Thus, in this case, the threshold was selected to be between 3 mm and 4 mm, which is half of the D_{50} of the gravel soils tested.

When the threshold depth was reached, a normally closed electronic valve was opened to fill the air bellow under the soil sample. The air bellow inflated and acted as a piston, lifting the soil into its original position parallel to the floor. The movement of the air bellow was monitored by a linear position transducer beneath the soil sample. As soon as the linear position sensor indicated that the soil sample had moved back into position, the DAQ would cut the signal to the electronic valve, thus shutting the airflow to the air bellow and stopping the soil sample movement. The rate of erosion was estimated based on the rate at which soil was extruded into the fluid. This was directly measured by a string potentiometer. A flowchart diagram of the algorithm developed for soil extrusion is presented in Figure 15.

Figure 15. Flowchart of soil extrusion algorithm and data recording.

Real-time sensor readings were visible to the test operator and refreshed every 3 sec. A typical output window is shown in Figure 16. The output window is divided into four sections: pressure transducer readings, laser sensor readings, flowmeter readings at specified intervals, and calculated measurements. The pressure transducer readings are the readings based on the position of the transducer where the sensor at 0 is located upstream before the flow reaches the soil. The sensor located at position 20 was located 2.5 cm from the upstream edge of the soil. The sensor located at position 40 was placed in the center of the sample, and the sensor located at position 60 was located 2.5 cm before the downstream edge of the soil sample. The sensor located at position 80 was outside the soil sample in the downstream section. A linear fit of the PPTs was used to provide a visual reference of the hydraulic gradient for the operator. The slope gradient and correlation coefficient of this linear fit are shown in the calculated measurements of the output window. The average gradient was also calculated based on just the first and last pressure sensor over the 80-cm length.

The laser sensors measured the depth of the soil surface relative to the horizontal position (X). Since the sensors were zeroed outside the soil sample on a flat surface (this is further explained in the test procedure chapter), the horizontal X position is relative in each test, but it aides in the visualization of gap locations.

The flow meter readings plot was updated at intervals set by the user, although the readings are being recorded to file every 3 sec and shown in the flow rate section of the calculated measurement section of the output window.

Figure 16. Real-time sensor output window.

3.4 Material

Four different soil mixtures composed mostly of gravel were tested. Table 2 provides the properties of the parent soils used to create the test soils. The gravel and sand material had sub-rounded shapes (Figure 17). Both the gravel and sand tested had a similar angle of repose and uniformity coefficient.

Table 2. Soil properties of parent soils.

Parent Soil	USCS Classification	D ₅₀ mm	C _u	SG	LL	PL	Angle of Repose θ Degrees (°)
Gravel	GP	7.229	1.67	2.59	-	-	34.3
Masonry Sand	SP	0.350	1.61	2.65	-	-	33.9
Silt	ML	0.009	-	2.68	29	27	-
Kaolinite Clay	MH	0.00035	-	2.60	59	32	-

Figure 17. Microscopic image of (A) gravel and (B) masonry sand.

The parent soils were used to create four soil mixtures presented in Table 3. Three of the mixtures were designed to be mostly gravelly soils while one of them, the clayey sand (SC), was designed to contain no gravel particles. The SC mixture was selected to allow a direct comparison between the flume device developed in this study and the JET apparatus. The poorly graded gravel with clay and sand (GP-GC) was designed to be a gravel with voids infilled by the SC. The poorly graded gravel with silt and sand (GP-GM) mixture was selected to look into the influence of smaller particles on the erosion characteristics. Detailed information about the soil properties (grain size analysis, compaction, and plasticity) can be found in Appendix D.

Table 3. Soil mixtures.

USCS Symbol	Composition Percent				D ₅₀ mm	Specific Gravity	Optimum Moisture Content %	Maximum Dry Density kg/m ³	Maximum Dry Unit Weight kN/m ³
	Gravel	Sand	Silt	Clay					
GP	100%	-	-	-	7.2	2.59	-	1,714.0	16.8
GP-GM	60%	30%	10%	-	5.1	2.59	6.0%	2,130.5	20.9
GP-GC	60%	28%	-	12%	5.1	2.59	7.7%	2,120.8	20.8
SC	-	70%	-	30%	0.3	2.68	10.4%	1,991.1	19.5

Soil mixtures were created on-site and immediately placed in the test apparatus. Each mixture was composed of the appropriate percentage by weight, based on Table 3, to create a total sample weight of approximately 68 kg. The soil was mixed with a flat beater in a Globe SP60 mixer with a volume capacity of 0.056 m³. All soil mixtures were mixed dry first, and then water was slowly introduced into the mixture. For soils containing clay, the mixture was above optimum moisture content to increase workability and handling. Soil mixtures containing silt were mixed in a damp or near-dry state (near 2% water content) that allowed the material to mix without segregating. Soils were immediately placed in the flume and, when setup was completed, the test was initiated.

4 Test Procedure

4.1 Test preparation

A typical test preparation procedure followed these steps.

1. The soil was mixed until a homogeneous soil mixture was observed.
2. Water was slowly let into the flume, allowing it to fill the area where the air bellow and linear potentiometer were located with approximately 10 cm of water.
3. The outer walls of the false bottom and the area where the sample was prepared were lightly lubricated with vacuum grease to reduce friction while pushing the soil sample.
4. The false bottom floor was installed to cover the top of the air bellow and was attached to the submerged linear string potentiometer.
5. The soil was placed in the sample area in 2.5-cm lifts. To ensure proper compaction efforts, a steel hand-tamper was used to compact the soil inside the flume.
6. After sample placement, the edges of the aluminum flume were covered with a thin layer of vacuum grease to help seal the acrylic top of the flume.
7. A 3.81-cm acrylic sheet was placed on top of the aluminum flume and fastened with bolts. The acrylic had a rubber gasket around the edges that, along with the vacuum grease, created a water-resistant confined flume.
8. Water was gravity-fed into the flume with the tailwater slightly raised to let air out through the downstream air release valve.
9. The hoses connecting the differential pressure transducers to the flume were saturated (see Figure 13A) and then connected to the pressure ports on the top of the acrylic sheet.
10. The top string pot and lasers were connected to the DAQ.
11. All sensors were zeroed.
12. To obtain the gauge pressure inside the flume, the differential 15-psi pressure sensor located at the tailwater was zeroed with both sides at atmospheric conditions and then reattached to the pressure sensor board.
13. To ensure a proper readout of the sample's physical boundary, the speed of the motor and position of limit switches were adjusted.
14. The carriage motor was activated, thus moving the lasers along the top of the acrylic. The software ran an initial 30-sec scan that allowed sensor response verification.

15. The user entered the average laser gap width threshold into the software. This is the distance the user wanted the soil to erode before raising the soil (approximately half D_{50}).

4.2 Test execution

When all of the above steps were completed, the soil sample and test device were ready for testing. Each test then followed these test procedures:

1. The sample was completely even with the horizontal plate when flow was started. Usually, initial flow rates were set to approximately 150 lpm.
2. The lasers continuously scanned the sample to monitor erosion.
3. Flow was increased at 5-min intervals unless the operator observed significant change in the soil surface. In the event of visible soil detachment that did not trigger the threshold depth, the soil was left for longer periods of time until the measured depth remained constant. The flow at which constant erosion occurred was used as a baseline to estimate the critical shear velocity and shear stress. Once continuous erosion was achieved, the flow rate was left constant to measure the erosion rate.
4. The distance lasers on top of the sample determined a mean erosion distance. If this distance determined by the lasers exceeded the maximum erosion depth threshold set by the operator, the air bellow was automatically activated and the sample was raised so the soil remained at the same level as the floor of the channel.
5. The test was stopped when one of two conditions occurred: either the sample had eroded entirely, or the water turbidity restricted the laser sensors' measurements.

5 Results and Discussion

5.1 Calculating erosion parameters

To quantify the erosion rate of each soil mixture, the soil sample was subjected to a constant flow rate, which induced a shear stress. The calculated shear stress varied over time due to the dynamic process of erosion. As the soil eroded, the gap height increased, increasing the cross-sectional area of the fluid channel on top of the soil sample. The increase in cross-sectional area resulted in a slightly reduced flow velocity that was continuously calculated based on the average gap height measured by the lasers and the flow rate. From this average velocity, calculation of the average shear stress was obtained per equation . The average erosion rate was calculated as a linear fit of the stepwise erosion behavior (Figure 18).

The erosion rate was calculated by the rate at which the soil was raised into the flow. To determine the erosion function of a specific soil mixture, multiple soil samples were required due to the limited depth of the soil sample (11-13 cm). Additional soil samples were prepared in the same way and subjected to different flow rates. This step was repeated as necessary to create shear stress vs. erosion rate curves.

5.1.1 Granular material

5.1.1.1 Poorly graded gravel (GP)

Air-dried poorly graded gravel (GP) was placed on a movable false bottom piece, which was lifted by the air bellow. An initial test determined the shear stress necessary to constantly erode the material, thus setting a baseline flowrate for erosion to initiate. Photographs of the gravel testing are provided in Figure 19.

Figure 19. Gravel (A) before erosion and (B) during erosion.

For the GP, a linear trend was observed between erosion rate and the applied hydraulic shear stress (Figure 20).

Figure 20. GP erosion rate vs. (A) shear stress and (B), average flow velocity.

The erosion rate can also be analyzed in terms of the flow velocity. The average velocity was determined from the cross-sectional area of the

apparatus and the flow rate. Changes in cross-sectional area were measured by the distance laser sensors on top of the soil sample. This change was taken into consideration to determine the average velocity and average shear stress experienced by the soil.

The extrapolation of shear stress to the point at which the erosion rate is zero from Figure 20 estimates the critical shear stress at 11.3 Pa, while the erodibility coefficient, which is taken from the slope of this linear fit, was estimated at 127 cm³/N-s. A summary of the tests is presented at the end of this chapter in Table 4.

5.1.1.2 Poorly graded gravel with silt and sand (GP-GM)

A poorly graded gravel with silt and sand (GP-GM) was also tested in the confined flume apparatus (Figure 21). The sample was mixed at 1%-2% moisture content. Mixing the soil at a low moisture achieved a homogeneous, workable soil mixture with minimal segregation during placement. The optimum moisture content for this soil mixture was found to be near 6.0%. The soil mixture, although composed largely of gravel (60% by weight), was found to have a lower critical shear stress (2.7 Pa) than a uniform gravel (11.3 Pa).

During testing it was observed that the sand and silt mixture was eroded from the gravel matrix at flow rates much lower than required to erode gravel alone. Furthermore, gravel particles detached from this sample at shear stresses less than that required to initiate erosion in gravel alone.

Figure 21. GP-GM mixture under different tests:
(A) after soil placement and (B) during erosion.

Based on current findings, although initially linear, the behavior of the soil mixture tends to shift off this linear behavior (Figure 22). When

compared to the gravel test, this break occurs near the critical shear stress of uniform gravel (11-12 Pa). Briaud et al. (2001) found that concave shapes are the most common erosion curves. To identify the critical shear stress of this soil, a linear regression of the first two points was extrapolated to the point where erosion is zero.

Figure 22. GP-GM erosion rate vs. (A) shear stress (B) average flow velocity.

5.1.2 Cohesive material

5.1.2.1 Poorly graded gravel with clay and sand (GP-GC)

To observe the effect of plasticity in the soil, a poorly graded gravel with clay and sand (GP-GC) was created. The clay portion, which, based on the findings of Raudkivi (1990), controls the initiation of the erosion process, was more than 10% of the soil by weight. Because of the amount of clay used, compaction resulted in a “smeared” top surface on the sample. This surface was scarified before the test to obtain a more representative value of critical shear stress for field conditions. Figure 23 shows the top layer after some erosion had taken place.

The optimum moisture content of the soil mixture was around 8%. Samples were prepared near optimum moisture content at 9% to increase workability of the material for placement. Zhang et al. (2016) stated that maximum cohesive forces develop near optimum moisture content; thus, low erosion rates were expected. Erosion initiation occurred at a higher shear stress (22.1 Pa) when compared to the other soils tested in the study. The critical shear stress for this soil was

estimated using only two points from the three tests since, based on current testing efforts, there is an abrupt variation in erosion behavior for one of the measurement points (Figure 24). Compaction efforts and sample placement were similar amongst the three specimens, and void ratios ranged from 0.17 to 0.19. The erosion occurred with flakes of clay being eroded initially; once the gravel was exposed, chunks of clay and individual particles of gravel were dislodged from the soil matrix.

Figure 23. (A) Placement of GP-GC and (B) exposed gravel after some erosion.

Figure 24. GP-GC erosion rate vs. (A) shear stress (B) average flow velocity.

5.1.2.2 Clayey sand (SC)

The soil was composed of 70% sand and 30% clay by weight. The soil was mixed at a 13% moisture content, and void ratios for the tested soils ranged from 0.40 to 0.44. A sample before being exposed to incoming fluid is observed in Figure 25A. Once erosion initiated, a non-uniform

erosion pattern was observed for all tests of this soil mixture. Figure 25 documents a sequence of pictures of the typical erosion experienced in the clayey sand mixture. The material started to erode in small flakes of clay into the downstream area, and a channel began to form through the center of the sample (Figure 25B). The channel then began to propagate, and soil began to erode the sides of the crack. Once the crack propagated and widened, large masses of material detached from the soil matrix into the eroding channel (Figure 25C). Eroded soil masses observed were 1.5 cm in diameter or larger. The size is inferred, as some of the chunks were observed for brief seconds entrapped in the fluid channel gap until these chunks were eroded by the incoming fluid. The test was stopped when the lasers were not able to accurately read the surface as the water became turbid with the eroded clay. Kothyari and Jain (2008) describe similar erosion behavior as line and mass erosion. In their study, this behavior is seen with gravel-clay mixtures having a clay content greater than 30%. Jacobs et al. (2011) also experienced an uneven erosion pattern after experiencing an initial longitudinal crack in the soil specimen.

Figure 25. Erosion propagation on clayey sand mixture. Sequence from A to D.

This was the only soil mixture that exhibited this line erosion behavior. The soil exhibited a linear relationship for both shear stress and velocity comparisons, as observed in Figure 26.

Figure 26. SC- Erosion rate vs. (A) shear stress and (B) average flow velocity.

Table 4. Summary of results.

GP Summary		τ_c Pa	K_d cm ³ /N·s	γ_{ave} kN/m ³	n_{ave} -	e_{ave} -						
		11.3	126.8	15.6	0.38	0.63						
Test No.		τ Pa	E mm/hr	γ kN/m ³	n -	e -	V_{ave} m/s	ω %	Depth to scour mm	Elapsed time of erosion sec	Calculated erosion depth mm	Eroded sample %
GP-4		13	1080	16.04	0.37	0.58	0.99	0	4	305	82	75
GP-5		21	4320	15.13	0.40	0.68	1.30	0	4	27	32	28
GP-6		20	4284	15.79	0.38	0.61	1.24	0	4	84	100	89
GP-7		17	1800	15.54	0.39	0.63	1.16	0	4	104	53	47
GP-GM Summary		τ_c Pa	K_d cm ³ /N·s	γ_{ave} kN/m ³	n_{ave} -	e_{ave} -						
		2.7	19.81	19.7	0.23	0.30						
Test No.		τ Pa	E mm/hr	γ kN/m ³	n -	e -	V_{ave} m/s	ω %	Depth to scour mm	Elapsed time of erosion sec	Calculated erosion depth mm	Eroded sample %
GP-GM-6		6	257	19.60	0.24	0.32	0.62	2	4	513	37	32
GP-GM-7 ¹		18	799	19.56	0.25	0.32	1.14	2	4	327	73	64
GP-GM-8		12	671	20.05	0.21	0.27	0.94	-	4	352	66	58
GP-GC Summary		τ_c Pa	K_d cm ³ /N·s	γ_{ave} kN/m ³	n_{ave} -	e_{ave} -						
		22.1	0.0867	22.8	0.18	0.21						
Test No.		τ Pa	E mm/hr	γ kN/m ³	n -	e -	V_{ave} m/s	ω %	Depth to scour mm	Elapsed time of erosion sec	Calculated erosion depth mm	Eroded sample %
GP-GC-2-2 ²		73	16	22.9	0.10	0.17	2.15	9	3	5524	24	18
GP-GC-3 ¹		95	7	23.1	0.09	0.16	2.46	9	3	6599	13	10
GP-GC-5		41	6	22.4	0.12	0.19	1.62	9	3	8809	14	11
SC Summary		τ_c Pa	K_d cm ³ /N·s	γ_{ave} kN/m ³	n_{ave} -	e_{ave} -						
		6.8	0.570	20.9	0.21	0.26						
Test No.		τ Pa	E mm/hr	γ kN/m ³	n -	e -	V_{ave} m/s	ω %	Depth to scour mm	Elapsed time of erosion sec	Calculated erosion depth mm	Eroded sample %
SC-01		13	7	21.0	0.29	0.40	0.94	12	3	7530	16	14
SC-01-2 ²		12	26	21.0	0.29	0.40	0.91	12	3	2990	22	20
SC-02		19	8	20.9	0.30	0.43	1.16	14	3	3448	8	7
SC-03		34	62	20.7	0.31	0.44	1.53	14	3	917	16	14
SC-04		37	61	20.8	0.30	0.43	1.59	13	3	719	12	11

¹Test not used for linear regression but presented in figures as example of non-linear behavior.

²Test divided into two tests at different flow rates.

5.2 Comparison to EFA

The erodability of each soil was categorized using the curves developed by Briaud (2008) as shown in Figure 3. The GP and GP-GM were classified as high erodibility while the GP-GC and the SC were classified as having medium erodibility (Figure 27). As expected, the addition of clay into a granular material will increase the erosion resistance of the soil. When comparing the clayey sand with the clayey gravel, it was observed that, although they have the same erosion classification, the gravel having a 12% clay content was more resistant to erosion than the clayey sand, which had 30% clay content by weight.

The results of this study were compared to EFA results presented by Briaud et al. (1999) and Kwak (2000) on coarse sand, gravel, silty sandy gravel, and porcelain clay. The coarse sand was reported by Briaud et al. (1999) as a clean sand with a mean particle size of 3.38 mm, while the fine gravel reported by Kwak (2000) was acquired in the field with 11.5% fines and a mean particle diameter of 6 mm. From the comparisons in Figure 27, it is seen that the results obtained by using the confined flume in this study are quite similar to the results obtained on similar soils in the EFA. The fine gravel tested by Kwak (2000) was classified as having high erodibility as were the GP and GP-GM tested in this study. The main differences are the erosion rates, which were lower for the soil tested by Kwak (2000) and can be attributed to the plasticity added by the fines. This suggests that the 3-in. sample diameter used in the EFA may not have a substantial effect on the measurements of erosion characteristics of gravels. Further, it is readily observed that the clean gravels have erosion rates similar to that of sand.

5.3 Comparison to Shields diagram

The estimated critical shear stresses for the cohesionless soils tested were also compared in an initiation of motion diagram to compare current findings with previous studies. The parameters needed for the comparison were the Shields parameter (equation 4) and the grain Reynolds number (equation 5).

Based on García (2008), the Shields parameter is a non-dimensional parameter based on the boundary shear stresses and is calculated as

$$\tau_c^* = \frac{\tau_{bc}}{\rho g R D} \quad (4)$$

where

$\tau_{bc} = (\rho u_{*c}^2)$ = critical bed shear stress for initiation of motion

u_{*c} = critical shear velocity- fluid velocity at incipient motion

ρ = water density (1000 kg/m³)

ρ_s = sediment density

g = acceleration of gravity (9.81 m/s²)

$R = \frac{\rho_s - \rho}{\rho}$ = submerged specific gravity of the sediment

D = sediment particle diameter (median particle diameter d_{50}).

The critical bed shear stress for initiation of motion was found experimentally as the extrapolation of the linear fit to the point at which the erosion rate was zero. A summary of the test results from this study is presented in Table 5.

The specific gravity (SG) was directly measured for the gravel and is needed to calculate the sediment density (ρ_s). The diameter was selected as the median particle size based on the results of sieve analyses.

Table 5. Critical shear stress for each soil.

	Specific gravity	Estimated critical shear stress (Pa)
Soil	SG	τ_{bc}
GP	2.59	11.3
GP-GM	2.59	2.7
GP-GC	2.59	22.1
SC	2.68	6.7

The results were compared to the diagram of initiation of motion of particles compiled by Yalin and Karahan (1979) as presented by García (2008). Figure 28 compares the results from this study and other studies focused on gravelly soils. The diagram is based on the Shields parameter $Y_{cr} = \tau_c^*$ and the grain Reynolds number X_{cr} . Yalin and Karahan (1979) and García (2008) expressed the grain Reynolds number as Re_* , which they defined as

$$Re_* = \frac{u_{*c} * D}{\nu} \quad (5)$$

where

ν = kinematic viscosity of water (1.186*10⁻⁶ m²/s at 20° C)

D = equivalent spherical particle diameter.

Results indicated that the critical shear stresses measured in the new test apparatus were consistent with the Shields curve and other studies on cohesionless soils. The additional test results on soil mixtures

showed that an increase in smaller particles such as sand and small amounts of silt in a soil mixture decreased the erosion parameters of the soil mixture, therefore reducing the calculated Shields parameter Y_{cr} . The addition of clay into a gravel soil mixture increased the calculated Shield's parameter Y_{cr} . The findings also illustrate that the Shield's curve for initiation of motion applies only to clean homogenous granular material and cannot be used to predict the critical shear stress of soil mixtures or soils containing a large amount of fines.

It is worth noting that the gravel studies conducted by Criswell et al. (2016) are located below the Shields curve. This behavior may be due to the placement procedure employed in the test, as the soil sample was not densified when placement occurred. The tests conducted by Wahl (2014) were conducted on a tilted JET using soils with a significant amount of fines.

Figure 28. Diagram for initiation of motion (Yalin and Karahan 1979), including this test and other gravel studies.

5.4 Comparison to JET

To compare the critical shear stress and erodibility measured by the confined flume apparatus to JET measurements, the SC mixture was tested in a JET (Figure 29). The JET tests were conducted at multiple moisture contents to capture the influence of water content and density on

the erodibility of the soil. The JET erosion test results for each test conducted are provided in Appendix C. For the flume tests, the erodibility coefficient (K_d) was taken as the slope of the linear fit of the erosion rate and the shear stress. Data for the calculation are presented in Table 6.

Figure 29. JET on a clayey sand.

Figure 30 shows the JET results and confined flume results along with the erosion categories developed by Hanson and Simon (2001). The JET categorized the clayey sand as a very erodible material, while the results for the confined flume classify the material as an erodible or moderately resistant material. These results indicate that the JET may not yield measurements consistent with the confined flume flow device.

Table 6. Results for clayey sand (SC) in confined flume device.

Shear Stress		Erosion Rate		K_d	
Pa (N/m ²)	N/cm ²	m/s	cm/s	Slope(cm ³ /N-s)	R ²
11.823	0.001182	0.00000735	0.000735	0.569676	0.799128
12.893	0.001289	0.00000208	0.000208		
18.622	0.001862	0.00000223	0.000223		
33.891	0.003389	0.00001722	0.001722		
36.944	0.003694	0.00001695	0.001695

5.5 Advantages and limitations of current testing

5.5.1 Advantages

The test was automated to eliminate subjectivity of when the soil needs to be raised. The test operator determines the threshold erosion depth based on device limitations and expected soil behavior. The equipment used allows continuous test monitoring by directly measuring the eroded surface. This constant, automated monitoring allows personnel to quickly become familiar with the equipment and ensures continuous data records and consistent sample extrusion.

5.5.2 Limitations

The device uses recirculating water to ensure a constant flow of water. Once constant erosion begins, the fines begin to disperse, and the test can run for only a limited amount of time before decreased visibility stops the laser measurements from being accurately read.

Also, the current device relies on soil that is prepared or remolded on-site. This reliance makes it difficult for undisturbed samples to be tested or for the device to be used in the field. Other devices, including the JET or confined flumes such as the ones developed by Kern et al. (1999) and Le Hir et al. (2006) and discussed in Section 2.1, have been developed for in-situ testing.

The sample depth was between 113 and 133 mm, which is a limitation in terms of how much soil can be tested at any given time, limiting the measurement duration in many instances.

Flow rate limitations were present during the testing. Flowmeter measurements were accurate starting at 151 lpm; therefore, this was the starting point for accurate measurements. The maximum flow that was run during testing was close to 1,100 lpm, at which point the pressure buildup was significant enough to bend the acrylic, and the flow needed to be decreased.

6 Conclusions

An automated erosion measurement device had been designed for testing large soil samples containing gravel particles. The device relied on the use of high accuracy laser distance sensors traveling along the top of the sample to determine the average erosion along the surface of the sample. Once a threshold depth previously determined by the test operator was reached, the device pushed the soil sample until the sample was flush with the flume bottom. This allowed the measurement of the erosion rate of the tested soils. By conducting multiple tests on a soil at different applied shear stresses, the critical shear stress and erodibility coefficient of the material were determined.

The new device was used to measure τ_c and K_d for a poorly graded gravel (GP), poorly graded gravel with clay and sand (GP-GC), and poorly graded gravel with silt and sand (GP-GM). The critical shear stress measured for the uniform fine gravel compared favorably to the Shields diagram, indicating that the device's measurements were consistent with previous studies. As expected, the introduction of clay increased the critical shear stress of the soil, and silt decreased the critical shear stress.

The device accurately predicts the initiation of motion of a clean fine gravel, and measurements compared favorably with results from similar soils in the EFA. Results of the erodibility coefficient obtained in this test are lower than those for the same soil tested on a JET by up to two orders of magnitude. The addition of fine particles, such as sand and silt, into a gravel lowered the critical shear stress and erodibility coefficient when compared to a clean fine gravel. As expected, gravel soils containing plastic fines had a higher critical shear stress and a lower erodibility coefficient than the fine gravel alone.

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Unit Conversion Factors

Multiply	By	To Obtain
bars	100	kilopascals
centistokes	1.0 E-06	square meters per second
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
knots	0.5144444	meters per second
microinches	0.0254	micrometers
microns	1.0 E-06	meters
miles per hour	0.44704	meters per second
ounces (mass)	0.02834952	kilograms
ounces (U.S. fluid)	2.957353 E-05	cubic meters
pints (U.S. liquid)	4.73176 E-04	cubic meters
pints (U.S. liquid)	0.473176	liters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
quarts (U.S. liquid)	9.463529 E-04	cubic meters
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
tons (force)	8,896.443	newtons
yards	0.9144	meters

Appendix A: Large Aluminum Flume

SCALE 1/1" = 1'-0"

A	DRAWN	2/5/2019	TITLE				A
	JAMIE LOPEZ						
	CHECKED						
	QA						
	MFG	LARGE ALUMINUM FLUME					
	APPROVED						
			SIZE		DWG NO		
		A		FLUME			
		SCALE	1/17		SHEET 1	OF 1	
	2				1		

Appendix B: Summary of Test Results

Soil Properties

Soil Description	GP	Moisture content (%)	0
Test #	4	Dry Soil Mass (Kg)	33.12
Surface area (m ²)	0.1845	Soil Weight (Kg)	33.12
Sample height (mm)	110	Sample Volume (m ³)	0.0202
Erosion depth threshold (mm)	3	Density (Kg/m ³)	1635.6
Specific gravity	2.59	Unit Weight (kN/m ³)	16.04
		Void ratio	0.58

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 12.974 Pa
Average Flow Velocity = 0.991894 m/s

Erosion Rate = 0.0002699681651 m/s

Soil Description	GP	Moisture content (%)	0
Test #	5	Dry Soil Mass (Kg)	32.74
Surface area (m ²)	0.1845	Soil Weight (Kg)	32.74
Sample height (mm)	115	Sample Volume (m ³)	0.0212
Erosion depth threshold (mm)	4	Density (Kg/m ³)	1542.1
Specific gravity	2.59	Unit Weight (kN/m ³)	15.123
		Void ratio	0.68

Soil Description	GP	Moisture content (%)	0
Test #	6	Dry Soil Mass (Kg)	33.12
Surface area (m ²)	0.1845	Soil Weight (Kg)	33.12
Sample height (mm)	112	Sample Volume (m ³)	0.0206
Erosion depth threshold (mm)	4	Density (Kg/m ³)	1609.8
Specific gravity	2.59	Unit Weight (kN/m ³)	15.788
		Void ratio	0.61

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 19.7466 Pa
Average Flow Velocity = 1.23689 m/s

Erosion Rate = 0.001192287757 m/s

Soil Description	GP	Moisture content (%)	0
Test #	7	Dry Soil Mass (Kg)	33.08
Surface area (m ²)	0.1845	Soil Weight (Kg)	33.08
Sample height (mm)	113	Sample Volume (m ³)	0.0209
Erosion depth threshold (mm)	4	Density (Kg/m ³)	1584
Specific gravity	2.59	Unit Weight (kN/m ³)	15.534
		Void ratio	0.63

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 17.2271 Pa
Average Flow Velocity = 1.15568 m/s

Erosion Rate = 0.00050942891 m/s

Soil Description	GP-GC	Moisture content (%)	9%
Test #	2-2	Dry Soil Mass (Kg)	54.031
Surface area (m ²)	0.19125	Soil Weight (Kg)	58.84
Sample height (mm)	132	Sample Volume (m ³)	0.0252
Erosion depth threshold (mm)	3	Density (Kg/m ³)	2331.4
Specific gravity	2.59	Unit Weight (kN/m ³)	22.864
		Void ratio	0.17

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 72.6918 Pa
Average Flow Velocity = 2.15257 m/s

Erosion Rate = 4.391661456E-006 m/s

Soil Description	GP-GC	Moisture content (%)	9%
Test #	3	Dry Soil Mass (Kg)	55.161
Surface area (m ²)	0.19125	Soil Weight (Kg)	59.96
Sample height (mm)	133	Sample Volume (m ³)	0.0254
Erosion depth threshold (mm)	3	Density (Kg/ m ³)	2357.3
Specific gravity	2.59	Unit Weight (kN/m ³)	23.118
		Void ratio	0.16

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 94.9993 Pa
Average Flow Velocity = 2.46455 m/s

Erosion Rate = 1.961332028E-006 m/s

Soil Description	GP-GC	Moisture content (%)	9%
Test #	5	Dry Soil Mass (Kg)	53.206
Surface area (m ²)	0.19125	Soil Weight (Kg)	58
Sample height (mm)	133	Sample Volume (m ³)	0.0254
Erosion depth threshold (mm)	3	Density (Kg/m ³)	2279.7
Specific gravity	2.59	Unit Weight (kN/m ³)	22.357
		Void ratio	0.19

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 40.9847 Pa
Average Flow Velocity = 1.62405 m/s

Erosion Rate = 1.644781604E-006 m/s

Soil Description	GP-GM	Moisture content (%)	2%
Test #	6	Dry Soil Mass (Kg)	40.765
Surface area (m ²)	0.1845	Soil Weight (Kg)	41.58
Sample height (mm)	113	Sample Volume (m ³)	0.0208
Erosion depth threshold (mm)	4	Density (Kg/m ³)	1998.6
Specific gravity	2.59	Unit Weight (kN/m ³)	19.601
		Void ratio	0.32

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 6.34434 Pa
Average Flow Velocity = 0.621349 m/s

Erosion Rate = 7.155087585E-005 m/s

Soil Description	GP-GM	Moisture content (%)	2%
Test #	7	Dry Soil Mass (Kg)	40.961
Surface area (m ²)	0.1845	Soil Weight (Kg)	41.78
Sample height (mm)	114	Sample Volume (m ³)	0.0209
Erosion depth threshold (mm)	4	Density (Kg/m ³)	1994.4
Specific gravity	2.59	Unit Weight (kN/m ³)	19.559
		Void ratio	0.32

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 17.7031 Pa
Average Flow Velocity = 1.1432 m/s

Erosion Rate = 0.0002218722213 m/s

Soil Description	GP-GM	Moisture content (%)	2%
Test #	8	Dry Soil Mass (Kg)	41.725
Surface area (m ²)	0.1845	Soil Weight (Kg)	42.56
Sample height (mm)	113	Sample Volume (m ³)	0.0208
Erosion depth threshold (mm)	4	Density (Kg/m ³)	2044.7
Specific gravity	2.59	Unit Weight (kN/m ³)	20.052
		Void ratio	0.27

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 12.155 Pa
Average Flow Velocity = 0.94088 m/s

Erosion Rate = 0.0001865399925 m/s

Soil Description	SC	Moisture content (%)	12%
Test #	1	Dry Soil Mass (Kg)	39.393
Surface area (m ²)	0.1845	Soil Weight (Kg)	44.12
Sample height (mm)	112	Sample Volume (m ³)	0.0206
Erosion depth threshold (mm)	3	Density (Kg/ m ³)	2144.3
Specific gravity	2.68	Unit Weight (kN/m ³)	21.029
		Void ratio	0.40

Soil Description	SC	Moisture content (%)	12%
Test #	1-2	Dry Soil Mass (Kg)	39.393
Surface area (m ²)	0.1845	Soil Weight (Kg)	44.12
Sample height (mm)	112	Sample Volume (m ³)	0.0206
Erosion depth threshold (mm)	3	Density (Kg/ m ³)	2144.3
Specific gravity	2.68	Unit Weight (kN/ m ³)	21.029
		Void ratio	0.40

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 11.823 Pa
Average Flow Velocity = 0.912509 m/s

Erosion Rate = 7.351916752E-006 m/s

Soil Description	SC	Moisture content (%)	14%
Test #	2	Dry Soil Mass (Kg)	38.982
Surface area (m ²)	0.1845	Soil Weight (Kg)	44.44
Sample height (mm)	113	Sample Volume (m ³)	0.0209
Erosion depth threshold (mm)	3	Density (Kg/m ³)	2129.4
Specific gravity	2.68	Unit Weight (kN/m ³)	20.883
		Void ratio	0.43

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 18.6221 Pa
Average Flow Velocity = 1.16564 m/s

Erosion Rate = 2.225127769E-006 m/s

Soil Description	SC	Moisture content (%)	14%
Test #	3	Dry Soil Mass (Kg)	39.211
Surface area (m ²)	0.1845	Soil Weight (Kg)	44.7
Sample height (mm)	115	Sample Volume (m ³)	0.0211
Erosion depth threshold (mm)	3	Density (Kg/m ³)	2114.6
Specific gravity	2.68	Unit Weight (kN/m ³)	20.738
		Void ratio	0.44

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 33.8909 Pa
Average Flow Velocity = 1.53278 m/s

Erosion Rate = $1.721698138 \times 10^{-5}$ m/s

Soil Description	SC	Moisture content (%)	13%
Test #	4	Dry Soil Mass (Kg)	39.239
Surface area (m ²)	0.1845	Soil Weight (Kg)	44.34
Sample height (mm)	114	Sample Volume (m ³)	0.0209
Erosion depth threshold (mm)	3	Density (Kg/m ³)	2118
Specific gravity	2.68	Unit Weight (kN/m ³)	20.771
		Void ratio	0.43

Test Overview

Test measurements upon exceeding erosion depth threshold

Average Shear Stress = 36.9443 Pa
Average Flow Velocity = 1.58794 m/s

Erosion Rate = 1.694851655E-005 m/s

Appendix C: Jet Test Results for SC Soil Mixture

Table C1. JET results for clayey sand soil mixture.

Soil Sample	γ	ω	γ_{dry}	e	n	τ_c	K_d
	KN/m ³	%	KN/m ³	-	-	Pa	cm ³ /Ns
MS-K030-13	21.37	10	19.41	0.35	0.26	0.48	10.5
MS-K030-14	17.40	10	15.80	0.66	0.40	0.15	1916.7
MS-K030-15	21.19	10	19.23	0.37	0.27	0.82	10.0
MS-K030-07	21.21	12	18.87	0.39	0.28	0.25	29.5
MS-K030-05	21.29	12	19.02	0.38	0.28	0.15	51.2
MS-K030-06	21.23	13	18.86	0.39	0.28	0.19	43.8
MS-K030-04	20.53	14	17.99	0.46	0.32	0.45	24.8
MS-K030-01	20.63	14	18.06	0.46	0.31	0.78	7.4
MS-K030-02	20.62	14	18.08	0.45	0.31	0.43	26.9
MS-K030-03	20.79	14	18.31	0.44	0.30	0.57	20.9
MS-K030-16	20.11	16	17.33	0.52	0.34	0.85	10.4

Appendix D: Standard Soil Test Results

Poorly graded gravel- (GP)

GRAIN SIZE DISTRIBUTION TEST DATA						8/14/2013				
Project: Internal Erosion Study Location: Stockpile Sample Number: Pea Gravel Material Description: Gravel (GP), Brown Tested by: LDD										
Sieve Test Data										
Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer					
1238.30	0.00	0.00	1/2 IN	0.00	100.0					
			3/8 IN	203.70	83.6					
			1/4 IN	819.10	33.9					
			#4	1104.60	10.8					
58.20	0.00	0.00	#6	51.80	1.2					
			#10	56.90	0.2					
			#16	57.60	0.1					
			#20	57.70	0.1					
			#30	57.80	0.1					
			#40	57.90	0.1					
			#50	58.10	0.0					
			#70	58.10	0.0					
			#100	58.10	0.0					
			#140	58.10	0.0					
			#200	58.10	0.0					
Fractional Components										
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	89.2	89.2	10.6	0.1	0.1	10.8			0.0
D₁₀	D₁₅	D₂₀	D₃₀	D₅₀	D₆₀	D₈₀	D₈₅	D₉₀	D₉₅	
4.6738	5.1124	5.4858	6.1271	7.2288	7.7914	9.1849	9.6822	10.3448	11.3015	
Fineness Modulus	C_u	C_c								
6.05	1.67	1.03								
CEERD-GS-E										

RELATIVE DENSITY MINIMUM AND MAXIMUM DENSITY DETERMINATIONS					
PROJECT <u>Internal Erosion Study</u>			DATE <u>8 Aug. 13</u>		
BORING NO. <u>Stockpile</u>			SAMPLE NO. <u>Pea Gravel</u>		
CLASSIFICATION			PLATE HEIGHT, H_p , IN. = <u>0.506</u>		
MOLD NO. <u>1</u>	MOLD DIAMETER, IN. = <u>5.985</u>		HEIGHT OF MOLD, H_m , IN. = <u>6.110</u>		
VOLUME OF MOLD, V_m , CM ³ = <u>2816.829</u>			END AREA OF MOLD, A_m , IN ² = <u>28.133</u>		
MINIMUM DENSITY - ASTM D 4254					
METHOD USED - Unless otherwise noted, the method used is A					
TRIAL NO.		1	2	3	4
MOLD (OR TARE) AND DRY SOIL, g		W	7812	7798	
MOLD (OR TARE), g		W_m	3722	3722	
DRY SOIL, g		W_s	4090	4076	
MIN DRY DENSITY, LB/FT ³ = W_s/V_m		γ_d	90.6	90.3	
MIN DRY DENSITY, AVERAGE			90.5 LB/FT ³		
MAXIMUM DENSITY - ASTM D 4253					
METHOD USED - Unless otherwise noted, the method used is 1A					
TRIAL NO.		1	2	3	4
LEFT DIAL READING 1, IN.		h_{L1}	0.138	0.233	
LEFT DIAL READING 2, IN.		h_{L2}	0.119	0.186	
RIGHT DIAL READING 1, IN.		h_{R1}	0.114	0.192	
RIGHT DIAL READING 2, IN.		h_{R2}	0.139	0.132	
AVERAGE DIAL = $(h_l + h_r)/2$, IN.		h_{avg}	0.127	0.186	
INITIAL DIAL READING, IN.		h_o	0.000	0.000	
HEIGHT CHANGE = $h_{avg} - h_o$		Δh	0.127	0.186	
NEW SPECIMEN HEIGHT = $H_m - (H_p + \Delta h)$, IN.		H_s	5.477	5.418	
VOLUME OF SOIL, V, CM ³		V	2524.889	2497.919	
MOLD (OR TARE) AND DRY SOIL, g		W	7812	7798	
MOLD (OR TARE), g		W_m	3722	3722	
DRY SOIL, g		W_s	4090	4076	
MIN DRY DENSITY, LB/FT ³ = W_s/V		γ_d	101.1	101.9	
MAX DRY DENSITY, AVERAGE			101.5 LB/FT ³		
REMARKS <u>8 min. @ 55, used scoop to place soil in mold</u>					
TECHNICIAN <u>CEC</u> COMPUTED BY <u>CEC</u> CHECKED BY <u></u>					

Revised 4/21/08

Masonry Sand (SP)

GRAIN SIZE DISTRIBUTION TEST DATA

8/14/2013

Project: Internal Erosion Study

Location: Stockpile

Sample Number: Mason Sand

Material Description: Sand (SP), Brown

Tested by: LDD

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
92.00	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	0.00	100.0
			#16	0.00	100.0
			#20	0.20	99.8
			#30	2.70	97.1
			#40	18.50	79.9
			#50	57.30	37.7
			#70	85.30	7.3
			#100	90.50	1.6
			#140	91.10	1.0
			#200	91.20	0.9

Fractional Components

Cobbles	Gravel			Sand				Fines	
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay
0.0	0.0	0.0	0.0	0.0	20.1	79.0	99.1		0.9

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
0.2213	0.2385	0.2535	0.2805	0.3306	0.3571	0.4255	0.4518	0.4887	0.5517

Fineness Modulus	C _u	C _c
1.64	1.61	1.00

CEERD-GS-E

RELATIVE DENSITY MINIMUM AND MAXIMUM DENSITY DETERMINATIONS					
PROJECT <u>Internal Erosion Study</u>			DATE <u>8 Aug. 13</u>		
BORING NO. <u>Stockpile</u>			SAMPLE NO. <u>Mason Sand</u>		
CLASSIFICATION		PLATE HEIGHT, H_p , IN. = 0.506			
MOLD NO. <u>1</u>	MOLD DIAMETER, IN. = 5.985	HEIGHT OF MOLD, H_m , IN. = 6.110			
VOLUME OF MOLD, V_m , CM ³ = 2816.829		END AREA OF MOLD, A_m , IN ² = 28.133			
<u>MINIMUM DENSITY - ASTM D 4254</u>					
METHOD USED - Unless otherwise noted, the method used is A					
TRIAL NO.		1	2	3	4
MOLD (OR TARE) AND DRY SOIL, g	W	7985	7991		
MOLD (OR TARE), g	W_m	3722	3722		
DRY SOIL, g	W_s	4263	4269		
MIN DRY DENSITY, LB/FT ³ = W_s/V_m	γ_d	94.5	94.6		
MIN DRY DENSITY, AVERAGE		94.5 LB/FT ³			
<u>MAXIMUM DENSITY - ASTM D 4253</u>					
METHOD USED - Unless otherwise noted, the method used is 1A					
TRIAL NO.		1	2	3	4
LEFT DIAL READING 1, IN.	h_{L1}	0.352	0.304		
LEFT DIAL READING 2, IN.	h_{L2}	0.320	0.300		
RIGHT DIAL READING 1, IN.	h_{R1}	0.303	0.318		
RIGHT DIAL READING 2, IN.	h_{R2}	0.305	0.330		
AVERAGE DIAL = $(h_l + h_r)/2$, IN.	h_{avg}	0.320	0.313		
INITIAL DIAL READING, IN.	h_o	0.000	0.000		
HEIGHT CHANGE = $h_{avg} - h_o$	Δh	0.320	0.313		
NEW SPECIMEN HEIGHT = $H_m - (H_p + \Delta h)$, IN.	H_s	5.284	5.291		
VOLUME OF SOIL, V, CM ³	V	2436.027	2439.254		
MOLD (OR TARE) AND DRY SOIL, g	W	7985	7991		
MOLD (OR TARE), g	W_m	3722	3722		
DRY SOIL, g	W_s	4263	4269		
MIN DRY DENSITY, LB/FT ³ = W_s/V	γ_d	109.3	109.3		
MAX DRY DENSITY, AVERAGE		109.3 LB/FT ³			
REMARKS <u>8 min. @ 55</u>					
TECHNICIAN <u>CEC</u>		COMPUTED BY <u>CEC</u>		CHECKED BY <u></u>	
Revised 4/21/08					

Poorly graded gravel with clay and sand (GP-GC)

SIEVE ANALYSIS ASTM D 421-63 (Reapproved 2002), ASTM D 422-85 (Reapproved 2002), ASTM C 117-03, and ASTM C 136-01						
					Date: 24-Aug-17	
Project: Erodibility of Gravelly Soils				Location:		
Boring No.:				Sample No.: 2		
Initial weight of sample (gm) * = 1000.0		Difference between Initial and final weight = 8.44%				
Final weight of sample (gm) = 915.6		Acceptance requirements (<0.3% Mat'l loss) = NO				
Weight of material > #4 sieve = 535.2		Fineness Modulus = 4.08				
Note: Blue lettered fields are input and those with red stars are required input for calculations.						
Sieve Openings		US Standard Sieve Size or Number	Weight * Retained (gm)	Percent Retained		Percent Finer by Weight
Inches	Millimeters			Partial	Total	
3.00	76.20	3-in		0.00	0.00	
2.00	50.80	2-in		0.00	0.00	
1.50	38.10	1-1/2-in		0.00	0.00	
1.00	25.40	1-in		0.00	0.00	
0.750	19.10	3/4-in		0.00	0.00	
0.500	12.70	1/2-in	0.0	0.00	0.00	100.00
0.375	9.52	3/8-in	98.4	18.39	9.84	90.16
0.250	6.35	No. 3	298.2	74.10	39.66	60.34
0.187	4.76	No. 4	138.6	100.00	53.52	46.48
		Pan	464.8			
0.132	3.36	No. 6	57.6	12.39	59.28	40.72
0.094	2.38	No. 8	0.0	12.39	59.28	40.72
0.079	2.00	No. 10	6.0	13.68	59.88	40.12
0.047	1.19	No. 16	0.6	13.81	59.94	40.06
0.033	0.84	No. 20	0.6	13.93	60.00	40.00
0.023	0.59	No. 30	7.6	15.56	60.75	39.25
0.0165	0.42	No. 40	48.2	25.92	65.57	34.43
0.0117	0.297	No. 50	118.8	51.47	77.44	22.56
0.0098	0.250	No. 60		51.47	77.44	
0.0083	0.210	No. 70	85.1	69.78	85.96	14.04
0.0059	0.149	No. 100	16.0	73.22	87.55	12.45
0.0041	0.105	No. 140	1.7	73.58	87.72	12.28
0.0029	0.074	No. 200	0.3	73.64	87.75	12.25
		Pan	0.28	73.70	87.78	12.22
	0.0083		3.03	74.35	88.08	11.92
	0.0059		5.55	75.55	88.63	11.37
	0.0042		2.02	75.98	88.84	11.16
	0.0029		7.06	77.50	89.54	10.46
	0.0012		20.17	81.84	91.56	8.44
Remarks: <div style="text-align: center; padding: 10px;"> Sieve analysis was calculated for this soil based on the parent materials and soil mixture composition </div>						
Technician:		Input By:		Checked By:		Revised: 31-Mar-06

COMPACTION TEST REPORT											
Project: Gravelly Erosion						Date: 22-Aug-17					
Location: Erosion Lab											
Boring No.:						Sample No.: 60% Gravel -28% Mason Sand- 12% Kaolinite					
ASTM D 698 (Standard)						ASTM D 1557 (Modified)					
Method A:		Mold - 4"	Layers - 3	Blows/Layer - 25	Method A:		Mold - 4"	Layers - 5	Blows/Layer - 25		
Method B:		X Mold - 4"	Layers - 3	Blows/Layer - 25	Method B:		Mold - 4"	Layers - 5	Blows/Layer - 25		
Method C:		Mold - 6"	Layers - 3	Blows/Layer - 56	Method C:		Mold - 6"	Layers - 5	Blows/Layer - 56		
Mold Number: 1		Mold volume, cm³: 941.62		Mold constant: 0.06627		Specific Gravity*: 2.650					
Water Content of Air-Dried Soil											
Tare number:		1		Water, gm:		0.42		Water content, %:		0.15	
Tare & wet soil, gm*:		447.6		Tare, gm*:		170.3					
Tare & dry soil, gm*:		447.2		Dry soil, gm:		276.9					
Specimen number		1	2	3	4	5	6				
Water Content of Trimmings											
Tare number:		N-7		N-8		N-9		N-10			
Tare & wet soil, gm*:		300.18		254.17		366.99		380.92			
Tare & dry soil, gm*:		284.27		230.62		338.69		362.98			
Water, gm:		15.91		23.55		28.30		17.94		0.00	
Tare, gm*:		89.25		87.58		89.32		89.19			
Dry soil, gm:		195.02		143.04		249.37		273.79		0.00	
Water content, %:		8.16		16.46		11.35		6.55		#DIV/0!	
Preparation of Sample											
Air-dried soil, gm*:		2268.0		2268.0		2268.0		2268.0			
Initial water content, %:		0.15		0.15		0.15		0.15		0.15	
Target water content, %*:		8.00		12.00		10.00		6.00			
Required water, gm:		177.7214		268.30		223.01		132.43		0.00	
Compacted Specimen											
Mold number:		1		2		X-6		x-4		1	
Mold & wet soil, gm*:		6324.2		6247.9		2168.9		2107.1			
Mold & dry soil, gm*:		6165.4		6043.7		1966.5		1988.1			
Water, gm:		158.8		204.2		202.4		119.0		0.0	
Mold tare, gm*:		4167.2		4147.9		18.9		18.9			
Dry soil, gm:		1998.2		1895.7		1947.6		1969.2		0.0	
Water content, %:		7.95		10.77		10.39		6.04		#DIV/0!	
Wet density, gm/cc:		2.291		2.230		2.283		2.218		0.000	
Dry density, gm/cc:		2.122		2.013		2.068		2.091		0.000	
Wet density, pcf:		142.9		139.1		142.4		138.3		0.0	
Dry density, pcf:		132.4		125.6		129.0		130.4		0.0	
Remarks: 12% Might be too wet, Sample at mold #3 were extruded and placed in an aluminum pan for drying. Thus Weight of mold is actually the aluminum pan and not the large mold were we do the sample. For sample 3 Im going to take the moisture content from the trimmings as our moisture content. If when I extruded not all comes out. 6% Water content felt Solid.											
Note: All blue field are user input and field with red stars are required input.											
Technician: Jamie F López-Soto				Computed By:				Checked By:		Revised: 17-May-05

Poorly graded gravel with silt and sand (GP-GM)

SIEVE ANALYSIS ASTM D 421-63 (Reapproved 2002), ASTM D 422-85 (Reapproved 2002), ASTM C 117-03, and ASTM C 136-01						
					Date: 24-Aug-17	
Project: Erodibility of Gravelly Soils				Location:		
Boring No.:				Sample No.: 3		
Initial weight of sample (gm) * = 1000.0		Difference between Initial and final weight =		13.89%		
Final weight of sample (gm) = 861.1		Acceptance requirements (<0.3% Mat'l loss) =		NO		
Weight of material > #4 sieve = 535.2		Fineness Modulus =		3.89		
Note: Blue lettered fields are input and those with red stars are required input for calculations.						
Sieve Openings		US Standard Sieve Size or Number	Weight * Retained (gm)	Percent Retained		Percent Finer by Weight
Inches	Millimeters			Partial	Total	
3.00	76.20	3-in		0.00	0.00	
2.00	50.80	2-in		0.00	0.00	
1.50	38.10	1-1/2-in		0.00	0.00	
1.00	25.40	1-in		0.00	0.00	
0.750	19.10	3/4-in		0.00	0.00	
0.500	12.70	1/2-in	0.0	0.00	0.00	100.00
0.375	9.52	3/8-in	98.4	18.39	9.84	90.16
0.250	6.35	No. 3	298.2	74.10	39.66	60.34
0.187	4.76	No. 4	138.6	100.00	53.52	46.48
		Pan	464.8			
0.132	3.36	No. 6	57.6	12.39	59.28	40.72
0.094	2.38	No. 8	0.0	12.39	59.28	40.72
0.079	2.00	No. 10	6.0	13.68	59.88	40.12
0.047	1.19	No. 16	0.6	13.81	59.94	40.06
0.033	0.84	No. 20	0.6	13.93	60.00	40.00
0.023	0.59	No. 30	8.1	15.68	60.81	39.19
0.0165	0.42	No. 40	51.6	26.78	65.97	34.03
0.0117	0.297	No. 50	12.7	29.51	67.24	32.76
0.0098	0.250	No. 60		29.51	67.24	
0.0083	0.210	No. 70	91.2	49.13	76.36	23.64
0.0059	0.149	No. 100	17.1	52.81	78.07	21.93
0.0041	0.105	No. 140	1.8	53.20	78.25	21.75
0.0029	0.074	No. 200	0.3	53.26	78.28	21.72
		Pan	0.3	53.33	78.31	21.69
	0.016		33.1	60.45	81.61	18.39
	0.010		12	63.03	82.81	17.19
	0.006		18	66.90	84.61	15.39
	0.004		6	68.19	85.21	14.79
	0.003		6	69.48	85.81	14.19
	0.001448333		0	69.48	85.81	14.19
	0.000603173		3	70.13	86.11	13.89
Remarks: <div style="text-align: center; font-size: 1.2em;">Sieve analysis was calculated for this soil based on the parent materials and soil mixture composition</div>						
Technician:		Input By:		Checked By:		Revised: 31-Mar-06

Sandy Clay (SC)

GRAIN SIZE DISTRIBUTION TEST DATA

4/15/2016

Project: Erodibility of Gravelly Soils

Location: MSK030

Material Description: Clayey Sand (SC), Light Gray

PL: 11

LL: 21

PI: 10

Tested by: AT

Checked by: TRJ

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
85.30	0.00	0.00	#10	0.00	100.0
			#16	0.00	100.0
			#20	0.20	99.8
			#30	2.10	97.5
			#40	13.90	83.7
			#50	41.30	51.6
			#70	60.80	28.7
			#100	64.60	24.3
			#140	65.00	23.8
			#200	65.20	23.6

Hydrometer Test Data

Hydrometer test uses material passing #10

Percent passing #10 based upon complete sample = 100.0

Weight of hydrometer sample = 85.3

Automatic temperature correction

Composite correction (fluid density and meniscus height) at 20 deg. C = -4.7

Meniscus correction only = -0.5

Specific gravity of solids = 2.68 est

Hydrometer type = 151H

Hydrometer effective depth equation: $L = 16.294964 - 0.2645 \times R_m$

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	22.5	1.0171	1.0127	0.0131	16.6	11.9	0.0320	23.8
5.00	22.5	1.0171	1.0127	0.0131	16.6	11.9	0.0202	23.8
15.00	22.5	1.0171	1.0127	0.0131	16.6	11.9	0.0117	23.8
30.00	22.5	1.0168	1.0124	0.0131	16.3	12.0	0.0083	23.2
60.00	22.5	1.0162	1.0118	0.0131	15.7	12.1	0.0059	22.1
120.00	22.5	1.0160	1.0116	0.0131	15.5	12.2	0.0042	21.7
250.00	22.5	1.0152	1.0108	0.0131	14.7	12.4	0.0029	20.3
1440.00	22.5	1.0131	1.0087	0.0131	12.6	13.0	0.0012	16.3

CEERD-GEGB

Fractional Components											
Cobbles	Gravel			Sand				Fines			Total
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total	
0.0	0.0	0.0	0.0	0.0	16.3	60.1	76.4	1.7	21.9	23.6	

D ₅	D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₄₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
			0.0028	0.2173	0.2599	0.2947	0.3277	0.4052	0.4329	0.4713	0.5357

Fineness Modulus
1.27

CEERD-GEGB

MOISTURE DENSITY TEST DATA

4/15/2016

Client: Jamie Lopez Soto

Project: MS-K030

Project Number: 1316

Location: MS-K030

Depth: Surface

Sample Number: 1

Description: Sandy Clay

USCS Classification: Clayey Sand (SC), Light Gray

Natural Moisture: 12.8

Liquid Limit: 21

Plastic Limit: 11

Sample Date: 2/24/16

Testing Remarks: Clayey Sand, blended by Jamie Lopez Soto of GEGB. Blended at or near optimum. Specific Gravity Estimated

Percent passing #4 sieve: 100

Test Data and Results For Curve 1

Test Specification:

Type of Test: ASTM D 698-12 Method A Standard

Mold Dia: 4.00 Hammer Wt.: 5.5 lb. Drop: 12 in. Layers: three Blows per Layer: 25

Point No.	1	2	3	4	5
Wt. M+S	3842.7	4065.0	4137.0	4067.0	4006.0
Wt. M	2061.4	2061.4	2061.4	2061.4	2061.4
Wt. W+T	2134.2	2527.7	2584.0	2523.5	2456.8
Wt. D+T	2022.4	2362.3	2387.2	2296.9	2196.2
Tare	356.3	525.9	510.4	521.0	520.1
Moist.	6.7	9.0	10.5	12.8	15.5
Dry Den.	110.4	121.6	124.3	117.6	111.3

Test Results: Max. Dry Den.= 124.3 pcf Opt. Moist.= 10.4%

CEERD-GEGB

LIQUID LIMIT, PLASTIC LIMIT, AND PLASTICITY INDEX OF SOILS							
ASTM D 4318							
WORK ORDER NO.	MD1316			DATE	4/8/2016		
PROJECT	Erodibility of Gravelly Soils						
BORING NO.	MS-K030			SAMPLE NO.			
LIQUID LIMIT							
Run No.	1	2	3	4	5	6	7
Tare No.	60	53	52	31			
Tare Plus Wet Soil, g	40.25	43.67	38.38	36.46			
Tare Plus Dry Soil, g	36.68	39.32	34.32	32.56			
Water, g	3.57	4.35	4.06	3.90			
Tare, g	18.19	18.15	15.34	15.31			
Dry Soil, g	18.49	21.17	18.98	17.25			
Water content, %	19.3	20.5	21.4	22.6			
Number of Blows	35	29	22	16			
				LL	21		
				PL	11		
				PI	10		
				Symbol from plasticity chart			
				CL			
Plastic LIMIT							
Run No.	1	2	3	4	5	6	7
Tare No.	110	94					
Tare Plus Wet Soil, g	32.78	30.49					
Tare Plus Dry Soil, g	31.30	29.25					
Water, g	1.48	1.24					
Tare, g	18.39	18.42					
Dry Soil, g	12.91	10.83					
Water content, %	11.5	11.4					
Plastic Limit	11.5						
Remarks	Clay (CL), Light Gray						
	Washed over #40 sieve.						
Technician	AT		Computed By	AT		Checked By	TRJ
	Revised 5/21/09						

Spec white Kaolin Clay (MH)

Atterberg Limits Data Sheet

ASTM D4318-10

Project Name: Spec White Kaolin- Surface Erosion Tested By: JFLS Date: 10/31/18
 Location: ERDC Checked By: _____ Date: _____
 Boring No: _____ Test Number: 1
 Sample Depth: _____ Gnd Elevation: _____

USCS Soil Classification: _____

TEST			PLASTIC LIMIT				LIQUID LIMIT			
Variable	NO		1	2	3	4	1	2	3	4
	Var.	Units								
Number of Blows	N	blows					35	24	21	
Can Number	---	---	G-3				632	70	415	
Mass of Empty Can	M _C	(g)	37.30				36.87	36.89	30.50	
Mass Can & Soil (Wet)	M _{CMS}	(g)	43.42				80.09	82.76	82.82	
Mass Can & Soil (Dry)	M _{CDS}	(g)	41.94				64.62	65.55	63.14	
Mass of Soil	M _S	(g)	4.64				27.75	28.66	32.64	0.00
Mass of Water	M _W	(g)	1.48				15.47	17.21	19.68	0.00
Water Content	w	(%)	31.9				55.7	60.0	60.3	#DIV/0!

Liquid Limit (LL or w _L) (%)	59
Plastic Limit (PL or w _P) (%)	32
Plasticity Index (PI) (%)	27
USCS Classification:	MH

PI at "A" Line = 0.73(LL-20)

One Point Liquid Limit Calculation:

$$LL = w_p (N/25)^{0.12}$$

PROCEDURE USED

- ☐ Wet Preparation Multipoint
☐ Dry Preparation Multipoint
☒ Procedure A Multipoint
☐ Procedure B One-Point

Hydrometer Analysis

Date: 02/08/16

Project	TRAINING	Sample No.	Bulk
Location		Boring No.	Spec White Kaolin
Specimen No.	1	Depth	ft
		Classification	
Dish No.	YY	Dish Weight:	167.75
		Hydrometer No.	742556
Dish+Wet Soil:	218.08 g	Wet Soil:	50.33 g
		Wt. soil solids:	50.33 g
Composite Correction: 0.0045			
Gs: 2.6 assumed measured			

Date/Time	Elapsed time	Temp °C	Actual Hyd. Reading R_a	Corr. Hyd. Reading R_c	L from table 6-5	L/t	K from table 6-4	D, mm	Percent finer	Coeff. of Viscosity (poises)
2/8/2016 14:35	0							0.074	100.00	
2/8/2016 14:37	2	21.7	1.0355	1.031	1.035	0.5	0.0137	0.01577	100.09	0.00981
2/8/2016 14:40	5	21.7	1.0355	1.031	1.035	0.207	0.0137	0.00997	100.09	0.00981
2/8/2016 14:50	15	21.7	1.035	1.031	1.035	0.069	0.0137	0.00576	98.48	0.00981
2/8/2016 15:05	30	21.7	1.034	1.030	1.034	0.034	0.0137	0.00407	95.25	0.00981
2/8/2016 15:35	60	21.7	1.0325	1.028	1.032	0.017	0.0137	0.00287	90.40	0.00981
2/8/2016 17:00	145	21.7	1.03	1.026	1.03	0.007	0.0137	0.00185	82.33	0.00981
2/9/2016 7:31	1016	21.1	1.025	1.021	1.025	0.001	0.0137	0.00070	66.19	0.00981
2/9/2016 14:35	1440	21.7	1.025	1.021	1.025	0.001	0.0137	0.00058	66.19	0.00981
2/12/2016 14:05	5730	22.2	1.0165	1.012	1.016	0.000	0.0135	0.00029	38.74	0.00958

<u>Hygroscopic correction</u>	
Tare Number:	YY
Tare Weight:	167.75 g
Tare + Wet Soil:	218.08 g
Tare + Dry Soil:	218.08 g
Wet Soil:	50.33 g
Dry Soil:	50.33 g
Water Content:	0.0%
Correction factor:	1.000
<u>After No. 200 Wash</u>	
Dish + Dry Soil	167.75 g
Percent Retained	0.0%

Silt (ML)

Hydrometer Analysis

Date: 09/08/17

Project	Surface Erosion Test - Silt		Sample No.	1	
Location	ERDC Soil Lab		Boring No.	Depth	ft
Specimen No.			Classification	ML	
Dish No.	P2	Dish Weight:	217.73	Hydrometer No.	H-4242
Dish+Wet Soil:		1537.13 g	Wet Soil:	1319.40 g	Wt. soil solids: 53.38 g
Composite Correction:			assumed	66	18.88889
		Gs: 2.65	assumed	measured	

Date/Time	Elapsed time	Temp °C	Actual Hyd. Reading R_a	Corr. Hyd. Reading R_c	L from table 6-5	L/t	K from table 6-4	D, mm	Percent finer	Coeff. of Viscosity (poises)
9/8/2017 10:50	0	19.44	1.032					0.07400		
9/8/2017 10:51	1	19.4	1.027		1.027	1.0	0.0138	0.02311	(3,008.7)	0.01030
9/8/2017 10:52	2	19.4	1.022	1.022	1.022	0.511	0.0138	0.01630	66.19	0.01030
9/8/2017 10:55	5	19.4	1.018	1.018	1.018	0.204	0.0138	0.01029	54.16	0.01030
9/8/2017 11:05	15	19.4	1.012	1.012	1.012	0.067	0.0138	0.00592	36.10	0.01030
9/8/2017 11:20	30	19.4	1.01	1.010	1.01	0.034	0.0138	0.00419	30.09	0.01030
9/8/2017 11:50	60	19.4	1.008	1.008	1.008	0.017	0.0138	0.00296	24.07	0.01030
9/8/2017 15:00	250	19.4	1.008	1.008	1.008	0.004	0.0138	0.00145	24.07	0.01030
9/9/2017 10:50	1440	19.4	1.007	1.007	1.007	0.001	0.0138	0.00060	21.06	0.01030

Hygroscopic correction

Tare Number:	P-2
Tare Weight:	217.73 g
Tare + Wet Soil:	1537.13 g
Tare + Dry Soil:	271.11 g
Wet Soil:	1319.40 g
Dry Soil:	53.38 g
Water Content:	2372%
Correction factor:	0.040

After No. 200 Wash

Dish + Dry Soil	g
Percent Retained

Tested By:	Checked By:	Approved By:
SGF		

Atterberg Limits Data Sheet

ASTM D4318-10

Project Name: Silt LL Test - Surface Erosion Tested By: SGF Date: 9/7/17
 Location: ERDC Checked By: _____ Date: _____
 Boring No: _____ Test Number: _____
 Sample Depth: _____ Gnd Elevation: _____

USCS Soil Classification: ML

TEST			PLASTIC LIMIT				LIQUID LIMIT			
Variable	NO		1	2	3	4	1	2	3	4
	Var.	Units								
Number of Blows	N	blows					31	24	17	12
Can Number	---	---	70				79	89	99	F-9
Mass of Empty Can	M _C	(g)	30.61				30.70	30.87	30.60	31.06
Mass Can & Soil (Wet)	M _{CMS}	(g)	43.26				61.07	52.02	63.20	64.80
Mass Can & Soil (Dry)	M _{CDS}	(g)	40.60				54.42	47.27	55.78	56.82
Mass of Soil	M _S	(g)	9.99				23.72	16.40	25.18	25.76
Mass of Water	M _W	(g)	2.66				6.65	4.75	7.42	7.98
Water Content	w	(%)	26.6				28.0	29.0	29.5	31.0

Liquid Limit (LL or w _L) (%)	29
Plastic Limit (PL or w _P) (%)	27
Plasticity Index (PI) (%)	2
USCS Classification:	ML

PI at "A" Line = 0.73(LL-20)

One Point Liquid Limit Calculation:

$$LL = w_n (N/25)^{0.12}$$

PROCEDURE USED

- ☐ Wet Preparation Multipoint
- ☐ Dry Preparation Multipoint
- ☒ Procedure A Multipoint
- ☐ Procedure B One-Point

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY) November 2021		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Laboratory Measurements of the Erodibility of Gravelly Soils				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Jamie F. López-Soto and Bryant A. Robbins				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Geotechnical and Structures Laboratory U.S. Army Engineer Research and Development Center 3909 Halls Ferry Road Vicksburg, MS 39180-6199				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/GSL TR-21-35	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Risk Management Center, U.S. Army Corps of Engineers Lakewood, CO 80228				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES Funding Account Code 8JGK75					
14. ABSTRACT The critical shear stress and erodibility of soil are fundamental parameters for modeling embankment breaching. Unfortunately, very few studies have examined the erosion characteristics of soils consisting predominantly of particles larger than sand. This report presents results of an experimental study in which the erosion characteristics of gravelly soils were measured. A flume apparatus was developed in which 0.45-m-square samples were extruded into confined flow. A mechanical laser system allowed the measurement of scour in real time, resulting in a continuous and automated erosion test. The critical shear stress of a uniform gravel was found to match the expected values based on the Shields diagram, while tests that were composed largely of gravel but contained other soils, such as sand, silt, and clay, varied significantly with the critical shear stress and erodibility, depending highly on the characteristics of the finer soils.					
15. SUBJECT TERMS		Gravel		Levees	
Erosion		Soil		Soils	
Erodibility		Dams		Soil dynamics	
Embankments		Earth dams		Soil erosion	
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	SAR	105	19b. TELEPHONE NUMBER (include area code)