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Geotechnical and Structures Laboratory

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Field Jet Erosion Tests on Benbrook Dam, Texas

Johannes L. Wibowo and Jamie F. López-Soto

December 2021

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Final report

Prepared for U.S. Army Corps of Engineers, Fort Worth District
819 Taylor Street
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Abstract

This report summarizes the results of eight field Jet Erosion Tests (JETs) performed on Benbrook Dam, TX. The results from these tests will be used by the U.S. Army Corps of Engineers, Fort Worth District, in assessments of the erosion resistance of the Benbrook Dam with regards to possible overtopping by extreme flooding. The JETs were performed at four different locations, i.e., two locations at the lowest crest elevation and two locations at the mid-slope face of the downstream embankment. Variations in estimated critical hydraulic shear stress and erosion rate values may have been caused by differences in soil composition, i.e., when the material changed from silt/sand to clay. The resulting values of the Erodibility Coefficient, K_d, and Critical Stress, τ_c, are very useful information in assessing the stability of Benbrook Dam during an overtopping event. Because of the observed natural variability of the materials, combining the erosion parameters presented in this report with the drilling logs and local geology will be imperative for assessing erosion-related failure modes of Benbrook Dam.

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Preface

This study was funded under Account Code 8JGK75 by the U.S. Army Corps of Engineers, Fort Worth District, as part of a geotechnical investigation work plan in support of the ongoing Phase II Issues Evaluation Study (IES) risk assessment over concerns about the possible overtopping of Benbrook Dam due to extreme flooding.

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) performed this fieldwork 2018 NOV 27-30. 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 Technical Director for Water Resources Infrastructure Research. 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 Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

This study is part of a geotechnical investigation work plan proposed in the Benbrook Lake Proposed Field Investigation Program Plan (FIPP) report prepared by the MVS Risk Cadre and personnel from U.S. Army Corps of Engineers (USACE), Fort Worth District, in 2018. The report stated that several potential failure modes were considered during the risk assessment study.

1. Overtopping due to increased hydrologic loading.
2. Internal erosion of the embankment into the downstream filter/blanket drain.

The FIPP proposed to have in situ Jet Erosion Test (JET) performed at the dam site to investigate the embankment's erosion parameters.

1.1 Purpose

The purpose of this study was to determine the erosion parameters of the Benbrook Dam materials by performing in-situ JETs on the crest and downstream slope of the dam. As overtopping is one of the main driving risk factors for this dam, the soil erosion parameters need examination. The JET characterizes the soil erodability, which is a necessary parameter for modeling the breach process of dams. The modeling process is done using three models: a hydraulic model that predicts the hydraulic conditions where the soil detachment process will occur, a geotechnical model that analyzes the soil stability during the overtopping and an erosion model that analyzes the detachment process of the soil based on the expected hydraulic conditions (Zhang et al. 2016). The USACE, Fort Worth District (FWD), will assess erosion related failure modes of Benbrook Dam under a possible overtopping event using the results of these tests.

1.2 JET erosion tests

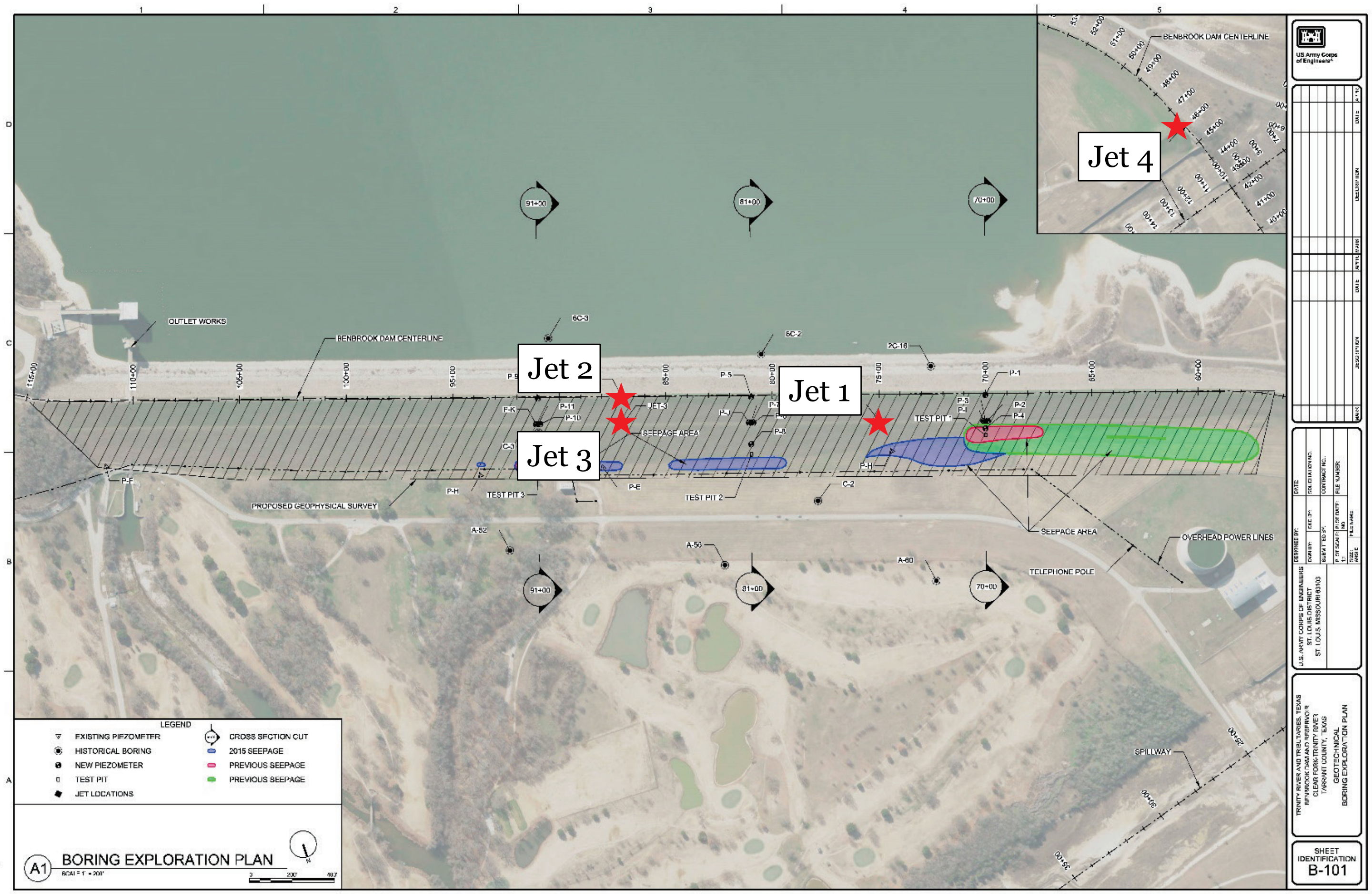
The U.S. Army Engineer Research and Development Center (ERDC) Geotechnical and Structures Laboratory team performed eight in-situ JETs at the Benbrook Dam. The tests were conducted in-situ to keep the soil in its actual condition during the test. To account for possible heterogeneity of soil at the Benbrook Dam and possible soil disturbance during site preparation, two JETs were performed at each test location. Variation of the erosion parameters was observed and is discussed herein.

This report summarizes the findings of the field JETs performed at the Benbrook Dam. The location and dates of each test performed are detailed in Table 1. The testing locations are shown in Figure 1.

Table 1. JETs performed at Benbrook Dam.

Test	JET Test No.	Depth (ft)	Station (ft)	Testing Date (month/day/yr)	Location
1	1A	1.0	+ 75.00	11 – 28 – 18	Bench
2	1B	1.0	+ 75.00	11 – 28 – 18	Bench
3	2A	1.0	+ 87.00	11 – 29 – 18	Dam Crest
4	2B	1.0	+ 87.00	11 – 29 – 18	Dam Crest
5	3A	1.0	+ 87.00	11 – 27 – 18	Bench
6	3B	1.0	+ 87.00	11 – 27 – 18	Bench
7	4A	1.0	+ 46.00	11 – 29 – 18	Next to Spillway
8	4B	1.0	+ 46.00	11 – 29 – 18	Next to Spillway

Figure 1. Location of the study area at the Benbrook Dam, Texas (USACE FWD 2018).



2 Jet Erosion Test Theory and Background

The generally accepted mathematical representation of erosion phenomena can be found in literature (Hutchinson 1972; Hanson 1991; Stein and Nett 1997; Hanson and Cook 2004) as

$$\varepsilon = k_d\left(\tau_e - \tau_c\right)^a \quad (1)$$

where

ε = erosion rate (m/s)
k_d = erodibility coefficient (m^3/N-s)
τ_e = effective hydraulic shear stress (Pa)
τ_c = critical hydraulic shear stress (Pa)
a = material specific exponent (typically assumed equal to 1).

The above equation describes the physical phenomena of erosion and states that the rate of erosion is proportional to the difference in effective hydraulic shear stress and critical hydraulic stress.

Hanson (1991) initiated the development of an erosion testing apparatus for various geologic materials, as shown schematically in Figure 2. The test is based on the concept that the depth of erosion in erodible material varies as a function of the applied hydraulic stress and time. The higher the applied stress, the faster the material will erode to a state of equilibrium. The details of the original procedure are described in American Society for Testing and Materials (ASTM) Standard D5852-07 (2007). As an enhancement to the procedure, Hanson and Cook (2004) removed the empiricism from the data reduction process by incorporating the work of Stein and Nett (1997), which computes the applied shear stress based on the diffusion principle of a submerged circular jet. Using this modified procedure, the initial shear stress is then expressed as

$$\boldsymbol{\tau_i} = \boldsymbol{\tau_o}\left(\frac{J_p}{J_i}\right)^2 \quad (2)$$

$$J_p = C_d d_o \quad (3)$$

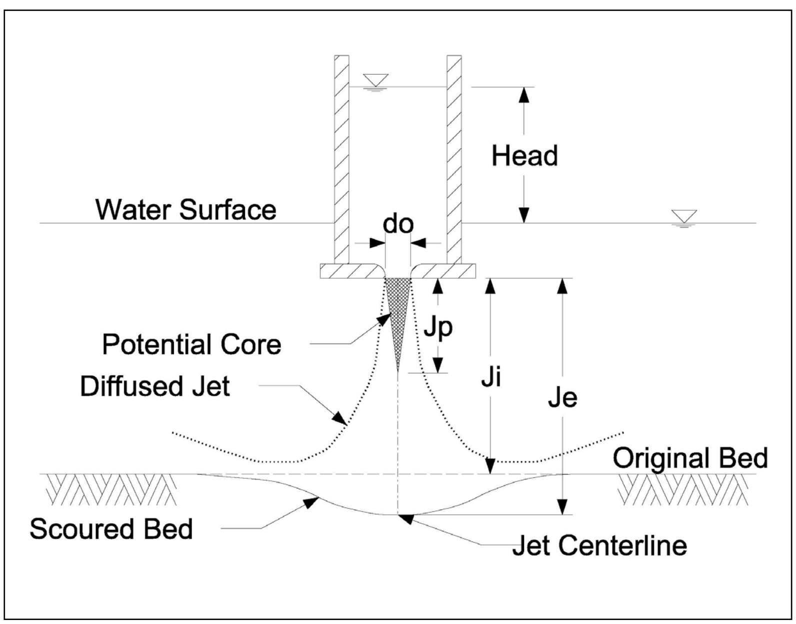
$$\tau_o = C_f \rho U_o^2 \quad (4)$$

$$U_o = \sqrt{2gh} \quad (5)$$

where

τ_i = initial shear stress before scour
τ_o = maximum stress within potential core
J_p = potential core length
J_i = initial soil surface depth
J_e = equilibrium erosion depth
C_d = diffusion constant = 6.3
d_o = nozzle diameter
C_f = friction coefficient
ρ = fluid density
U_o = velocity at the jet nozzle
g = acceleration due to gravity
h = differential head.

Figure 2. Schematic diagram of the jet erosion process (Hanson and Cook 2004).



To calculate the equilibrium scour depth, Hanson and Cook used the expression proposed by Blaisdell et al. (1981) that assumes the scour rate conforms to a logarithmic hyperbolic function. The excess stress parameter τ_c is determined by fitting the observed scour data to this logarithmic hyperbolic curve. Once the critical stress is computed using equations (2) through (5), the erodibility coefficient k_d is then determined by curve fitting the actual measurement of scour depth (H) versus time (t) to a non-dimensionalized form of equation 1. The detailed discussion of this procedure can be found in Hanson and Cook (1999; 2004).

Field jet erosion apparatus

The field JET apparatus consists of a constant pressure source and the jet erosion testing unit. The constant pressure supply consists of a 500-gal water reservoir, a 2-HP portable pump, 1.5-in.-diam inlet and outlet hoses, and a manifold for controlling the applied pressure. The jet erosion testing unit consists of a 12-in.-diam by 12-in.-high steel cylindrical chamber that is placed such that it penetrates 1 in. into the clean surface of the in-situ soil surface. A circular aluminum plate is placed on the top of the chamber to hold the pressure jet tube in place directly over the specimen. A digital pressure gauge is placed in this pressure jet tube. It is assumed that the pressure of water in the tube is the same as the pressure at the mouth of the 0.25-in.-diam orifice located at the bottom of the pressure jet tube. The erosion measurement is performed using a 0.25-in.-diam manual point gauge, which is extended to the soil surface through the pressure orifice. A movable deflector is placed 2 in. underneath the orifice to protect the sample by deflecting the jet of water between pressure adjustments (on versus off). The entire apparatus is shown in Figure 3. A more detailed explanation of the apparatus can be found in Hanson and Cook (2004).

Hanson and Simon (2001) developed an erosion susceptibility classification for geologic materials based on the measured values of τ_c and k_d. The classification uses five groups with regard to erosion resistance (Figure 4). The five groups are Very Erodible (VE), Erodible (E), Moderately Resistant (MR), Resistant (R), and Very Resistant (VR). The test findings for the Benbrook Dam were plotted and categorized using this erosion classification.

Figure 3. ERDC field JET apparatus.

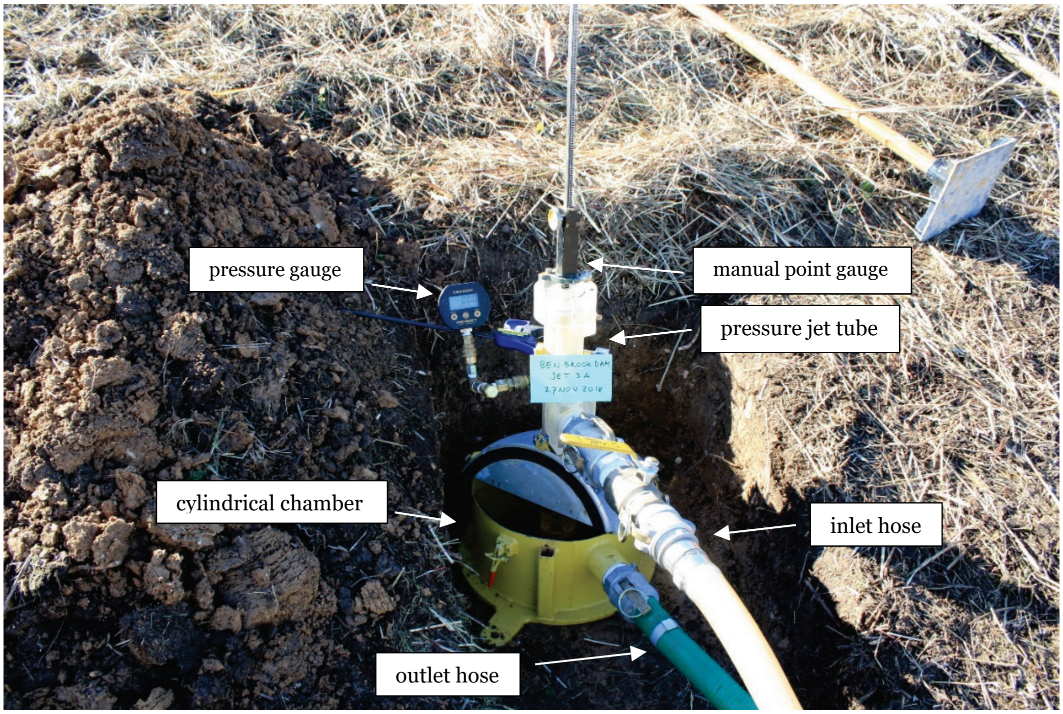
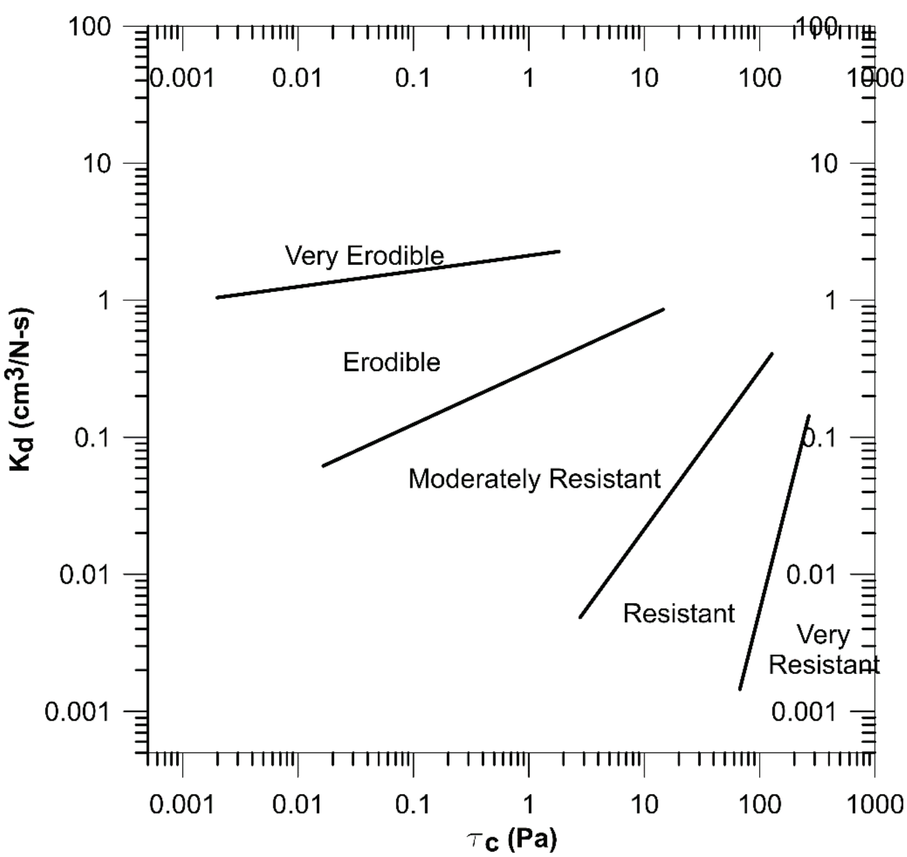


Figure 4. Hanson and Simon (2001) erosion classification.



3 Testing Procedures and Sample Preparation

The following is a summary of the field test procedure.

1. After selecting the test site, the equipment was mobilized to the site. Because the testing unit requires a constant water supply and the water source was more than 400 ft away, a 500-gal reservoir tank was used. A water truck provided by SWF supplied water to the testing unit. For each test location, two tests were performed to account for the possibility of material variability at the given location.
2. Each test site was cleaned as much as reasonably possible to be free of grass, roots, and any gravelly material. Two smooth surfaces were prepared about 10 ft. apart for the two JET test units, and photographs were taken of the original surface (Figure 5). Exposed material was tested with a pocket penetrometer to characterize the in-situ strength. Penetration tests were conducted on surfaces adjacent to the test sites so as to not influence the test data. Disturbed soil samples were obtained for water content measurements. The JET apparatus was then placed over the prepared surface.
3. The outer ring of the apparatus was driven about 1 in. into the soil surface using a special driving hammer (Figure 6). The Plexiglas cover composed of a Plexiglas tube frame, jet nozzle unit, manual point gauge unit, and pressure gauge was placed on top of the cylindrical chamber (Figure 6), and the inlet water supply hose was connected (Figure 7).
4. An initial reading determined the distance from the jet mouth to the ground surface. The chamber was then filled with water by opening the inlet valve with the deflector positioned in front of the jet nozzle to divert the flow and prevent premature surface erosion. The water pressure was adjusted to a target pressure.
5. Scour depth readings were recorded on a field-test data sheet. A recording time interval was set depending on the material. The more erodible material required a smaller time step interval than less erodible soils to ensure adequate resolution of the erosion process was obtained.
6. The test began by removing the deflector from the front of the jet nozzle and starting the stopwatch. The water jet eroded the ground surface and, at the chosen time interval, the test was stopped by positioning the deflector underneath the center of the jet and lowering the point gauge rod to close the jet nozzle. The point gauge rod was

then lowered to the eroded surface to measure the amount of erosion. After manually recording the data, the rod was positioned above the deflector plate, the deflector was again placed in front of the jet nozzle, the point gauge was raised thereby opening the jet nozzle, and the next time step test was begun.

7. After recording the depth/time readings from each of the two units, the water pressure was readjusted to the original value and the above procedures were repeated to obtain about 10 to 12 additional data points for each test. Figure 7 shows the JET in progress, and Figure 8 shows the soil surface after the test.

Figure 5. Site preparation for JET.

Figure 6. The JET steel chamber driven to the soil surface to keep the soil surface under water during the test.

Figure 7. Benbrook JET 3A in progress.

Figure 8. Soil surface after testing.

4 Test Results/Discussions

JET measurements of the sample JET 3A from Benbrook Dam located near STA 87+00 at approximately 1 ft below the ground surface are shown in Figure 9. The soil sample was dark brown, plastic, sandy clay (visually classified as a CL). The soil encountered seemed similar to the description provided in the boring log for holes P-9 and P-1 at a depth of 10 ft. The soil was described as a clay (CL) with 0-10% silt, 0-10% sand, 0-5% subrounded to rounded gravel. The test was initiated at 1.0-psi pressure with 0.5-min reading intervals. Constant monitoring of erosion provided insight of when to adjust the pressure accordingly to maintain a constant erosion rate. During this test, erosion progressed at a constant rate after 5.0 min at which point erosion depth was monitored, and pressure adjustments were made to continue erosion. The pressure adjustments reached up to 5.0 psi to ensure significant erosion and, after about 85.0 min, the accumulated erosion was about 2.5 cm. The test was terminated with 12 data points. This is typical of a good data record for a moderately erosion resistant soil. Pocket penetrometer measurements estimate an unconfined compression strength of 2.7 ton/ft^2, which is classified as an over-consolidated very stiff material.

Figure 9. JET data of sample from Benbrook Dam JET 3A.

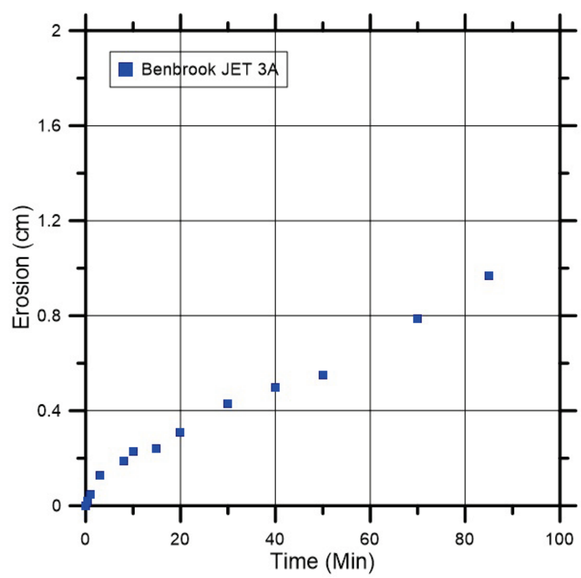


Figure 10 shows a hyperbolic fit of the erosion data from Benbrook JET 3A. The data points closely match with the hyperbolic equation. This plot was used to calculate the value of equilibrium erosion depth, J_E, which was then used to calculate the critical stress τ_c using Equation 2. Figure 11 shows the data fit to the dimensionless form of the scour function (Equation 1). The dimensionless time and depth fit were used for calculating the value of the erosion coefficient K_d. Detailed discussion of the theory can be found in Hanson and Cook (2004). For Benbrook JET3A, the value of the erodibility coefficient was 0.298 cm^3/N-s, and the value of the critical shear stress was 12.25 Pa. As will be discussed later, this sample was categorized as Moderately Resistant (MR) material.

Figure 10. Blaisdell analysis for finding the equilibrium erosion depth of sample from Benbrook Dam JET 3A.

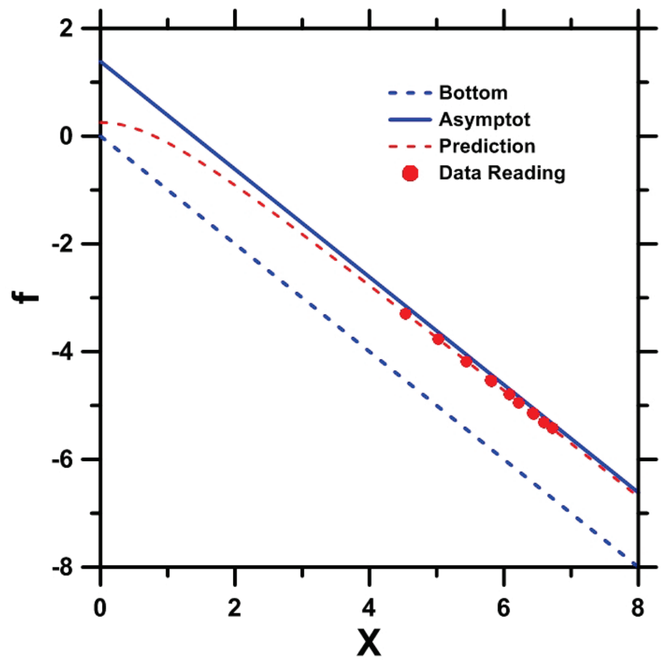
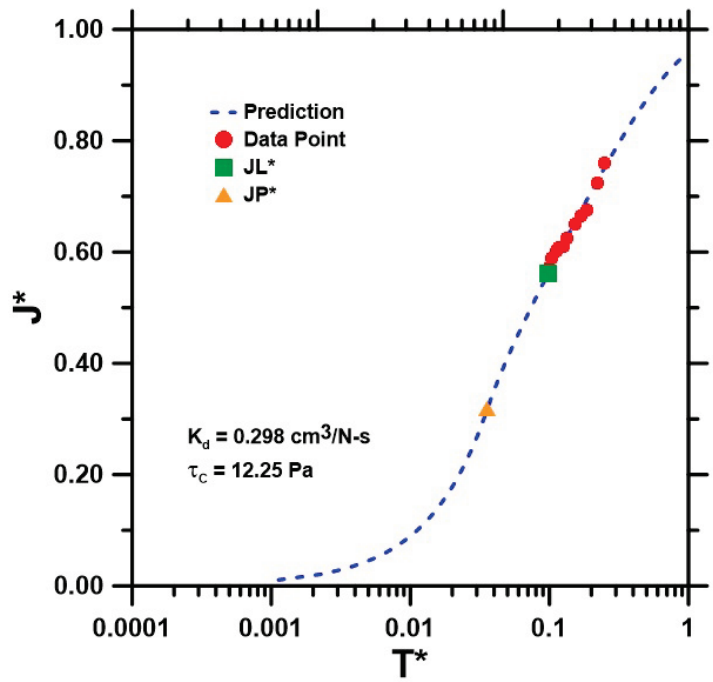


Figure 11. Blaisdell analysis for finding the erosion coefficient of sample from Benbrook Dam JET 3A.



The summary of JET results for the eight tests is shown in Figure 12, which categorizes the data points as suggested by Hanson and Simon (2001). As shown, the data clusters close to the boundary of Very Erodible (VE) and Moderately Resistant (ME) material. Although considered a homogeneous embankment dam, there are considerable variations in the test results. Tables 2 and 3 document variation in the tested soil's description and classification as well as the cohesion, as estimated using the pocket penetrometer test results. In general, the tested dam embankment material is composed of two soil types, i.e., plastic silty clay and plastic sandy clay, with an average water content of 23.8%. Based on the JET results, the lower-bound values of the erodibility parameters are a critical shear stress of τ_c = 1.04 Pa and an erodibility coefficient of K_d =2.865 cm^3/N-s, and the upper-bound values are a critical shear of stress τ_c = 11.85 Pa and an erodibility coefficient of K_d =0.172 cm^3/N-s. During future analysis, it is recommended that both the lower and upper bounds of the erodibility parameters be considered. All erosion data, along with photographs of the soil surface before and after the JETs, are provided in Appendix A.

Figure 12. Summary of test data of boring at the Benbrook Dam Jet Erosion Tests.

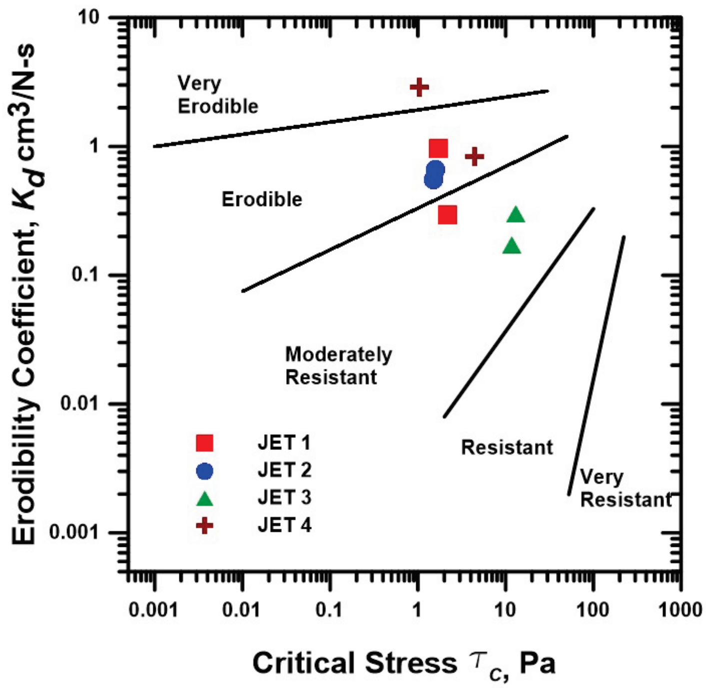


Table 2. Summary of JETs of Benbrook Dam, Fort Worth District.

JET #	Location	Depth, ft	Soil Type	τ_c Pa	K_d cm³/N-s	Erosion Depth, cm	Time, min	Category	Pressure, kPa (Psi)	*Cohesion, Kg/cm² (psf)	*Unconfined compression strength. Kg/mm² (ton/ft²)
JET 1A	Bench	1	Dark brown plastic sandy clay	1.698	0.960	6.558	56	E	7 – 21 (1 – 3)	1.48 (3029)	0.028 (2.84)
JET 1B		1	Dark brown plastic sandy clay	2.132	0.295	4.636	82	MR	7 – 35 (1 – 5)	1.70 (3482)	0.032 (3.26)
JET 2A	Dam crest	1	Dark brown plastic silty clay	1.530	0.547	5.460	53	E	7 – 49 (1 – 7)	1.24 (2542)	0.023 (2.38)
JET 2B		1	Dark brown plastic silty clay	1.589	0.659	7.503	51	E	7 – 49 (1 – 7)	1.19 (2437)	0.022 (2.28)
JET 3A	Bench	1	Light brown plastic silty clay	12.252	0.298	2.471	85	MR	3.5– 35 (0.5 – 5)	1.51 (3099)	0.028 (2.9)
JET 3B		1	Light brown plastic silty clay	11.845	0.172	2.318	83.5	MR	3.5 – 49 (0.5 – 7)	1.38 (2820)	0.026 (2.64)
JET 4A	Next to Spillway	1	Blackish plastic silty clay	4.411	0.827	2.532	61	E	3.5 – 28 (0.5 – 4)	1.65 (3777)	0.031 (3.17)
JET 4B		1	Blackish plastic silty clay	1.043	2.865	7.686	56	VE	3.5 – 21 (0.5 – 3)	1.48 (3029)	0.028 (2.84)

Note: V-E = Very Erodible, E = Erodible, M-R = Moderately Resistant, R = Resistant, V-R = Very Resistant, SM = Silty Sand, CL = Clay (low plasticity), ML = Silt.

*The cohesion was determined by In-situ Pocket Penetrometer Test (Geotester Pocket Penetrometer with 10-mm tip)

Table 3. Summary of soil mechanics tests at JET locations of Benbrook Dam, Fort Worth District.

JET #	Location	GPS		Water Content
		Latitude	Longitude	(%)
JET 1A	Bench	N 32° 39.282’	W 97° 27.547’	21.6
JET 1B				24.2
JET 2A	Dam crest	N 32° 39.201’	W 97° 27.323’	24.2
JET 2B				21.8
JET 3A	Bench	N 32° 39.218’	W 97° 27.327’	19.9
JET 3B				21.6
JET 4A	Next to Spillway	N 32° 39.492’	W 97° 28.015’	29.2
JET 4B				28.2

5 Summary

Eight in-situ JETs were performed on clean soil surfaces at the Benbrook Dam in Texas. Four tests were performed around the lowest elevation crest area and the other four at the middle downstream slope area. The JETs were performed to assess the uncertainty of the erodibility of the Benbrook Dam material. In general, the tested dam embankment soils were composed of two types, i.e., plastic silty clay and plastic sandy clay. Based on eight JETs results, the lower-bound values of the erodibility parameters are a critical shear stress of τ_c = 1.04 Pa and an erodibility coefficient of K_d = 2.865 cm^3/N-s, and the upper bounds of the measured parameters are a critical shear stress of τ_c = 11.85 Pa and an erodibility coefficient of K_d = 0.172 cm^3/N-s.

Due to the encountered variation of embankment soils and the measured erosion parameters, which may be caused by these variations in the tested soils, during future analysis it is recommended that consideration be given to both the lower and upper bound of the erodibility parameters.

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Unit Conversion Factors

Multiply	By	To Obtain
cubic inches	1.6387064 E-05	cubic meters
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
pounds (force)	4.448222	newtons
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
square inches	6.4516 E-04	square meters

Appendix A: Erosion Data

Figure A1. Soil surface before and after JET with erosion data of Benbrook Dam JET 1A.

Before JET After JET

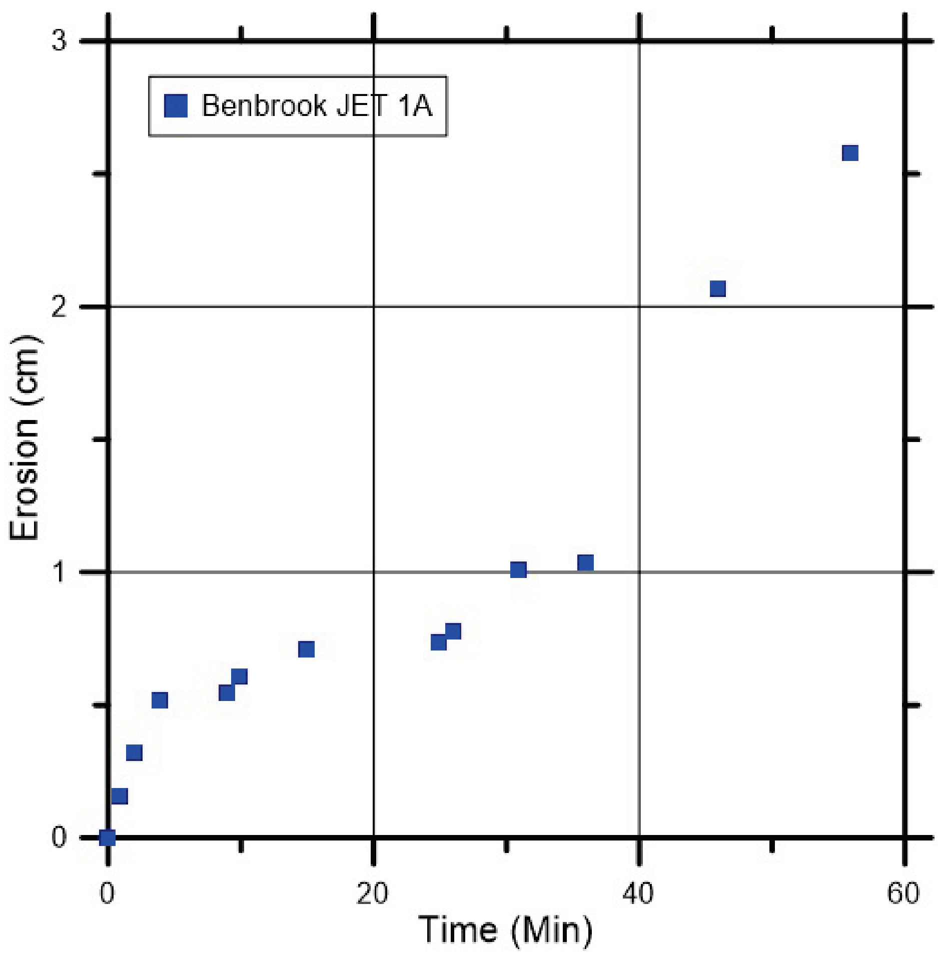


Figure A2. Soil surface before and after JET with erosion data of Benbrook Dam JET 1B.

Before JET

After JET

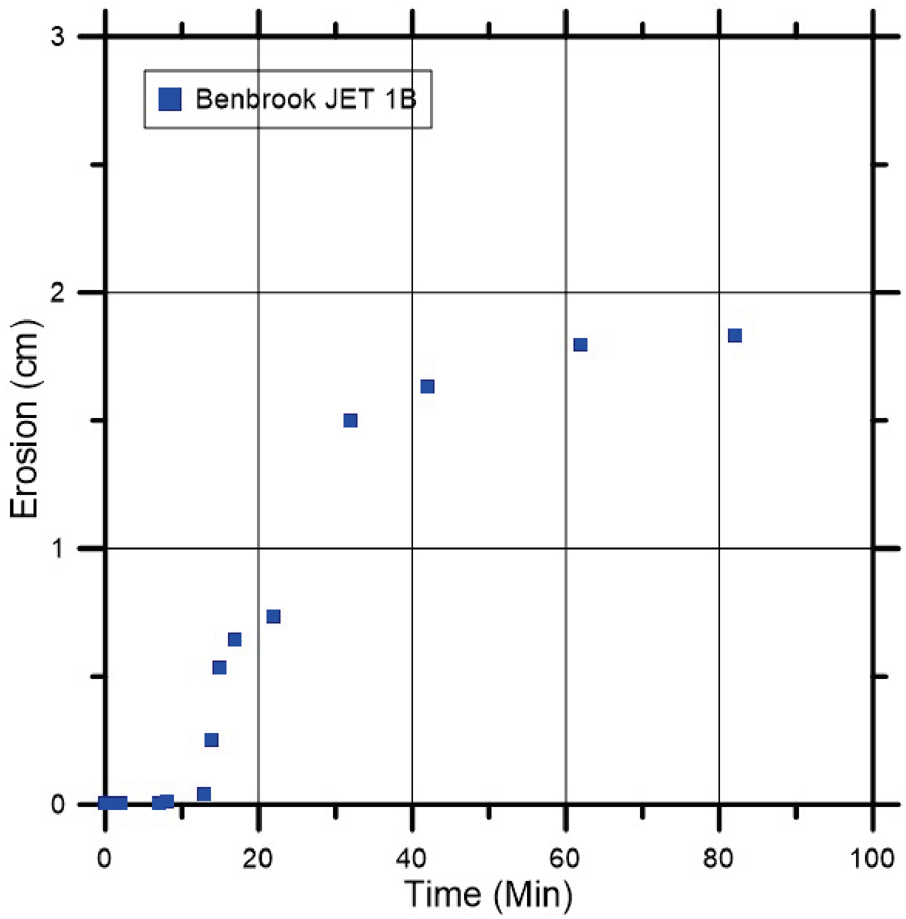


Figure A3. Soil surface before and after JET with erosion data of Benbrook Dam JET 2A.

Before JET

After JET

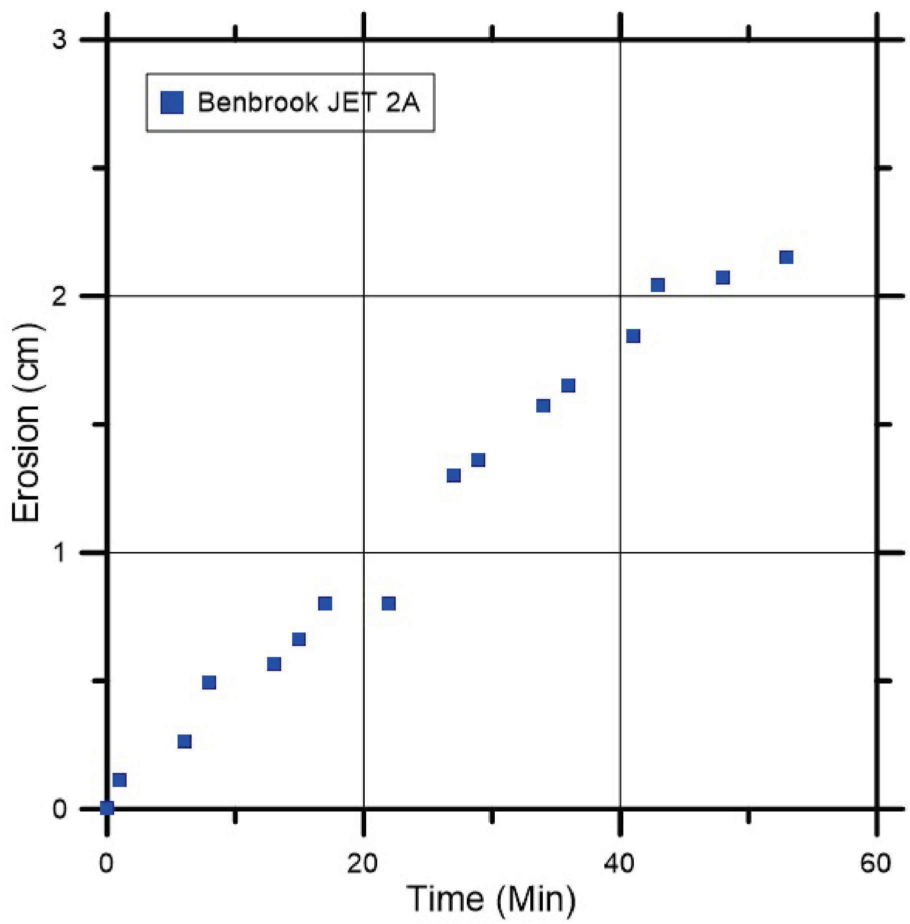


Figure A4. Soil surface before and after JET with erosion data of Benbrook Dam JET 2B.

Before JET

After JET

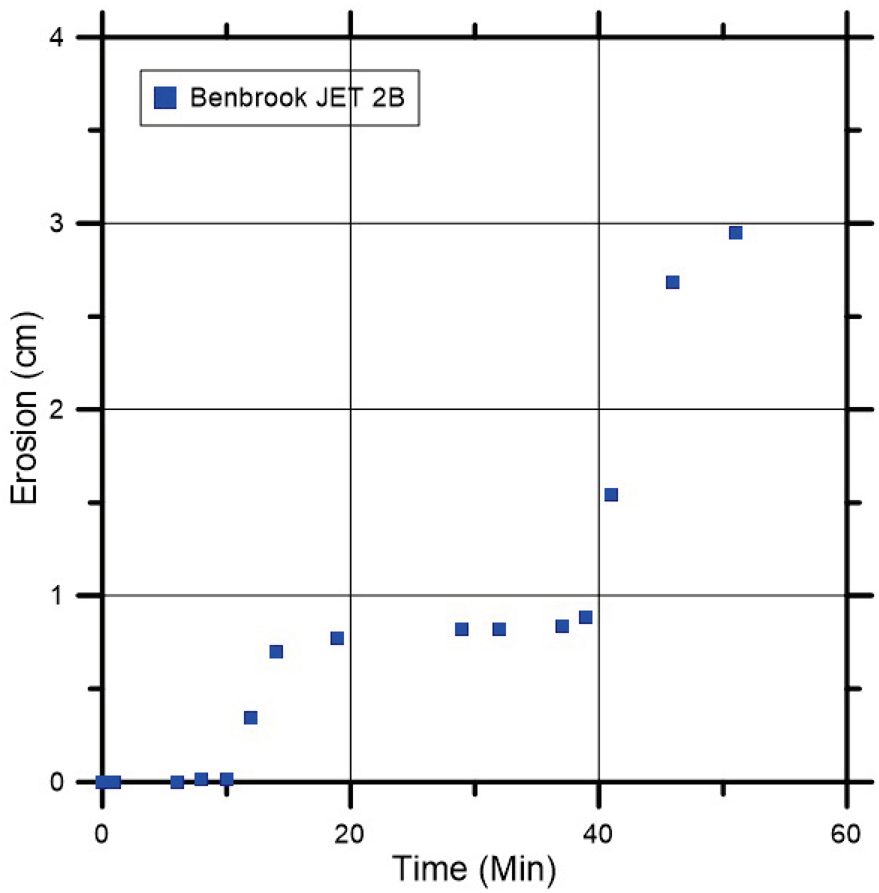


Figure A5. Soil surface before and after JET with erosion data of Benbrook Dam JET 3A.

Before JET

After JET

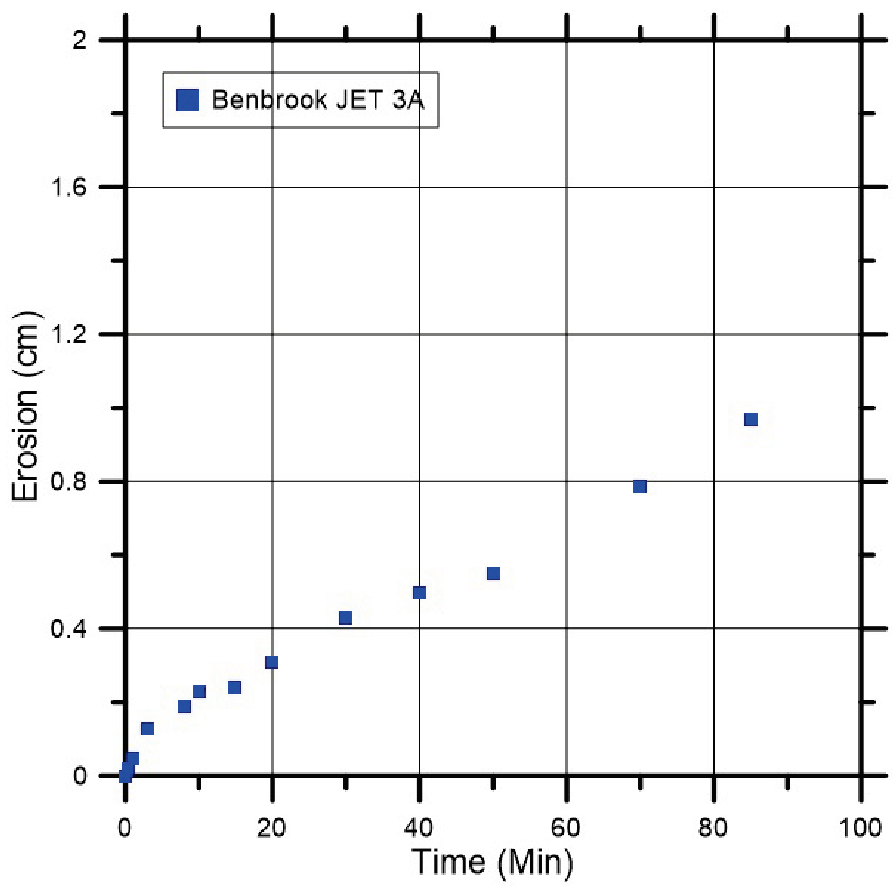


Figure A6. Soil surface before and after JET with erosion data of Benbrook Dam JET 3B.

Before JET After JET

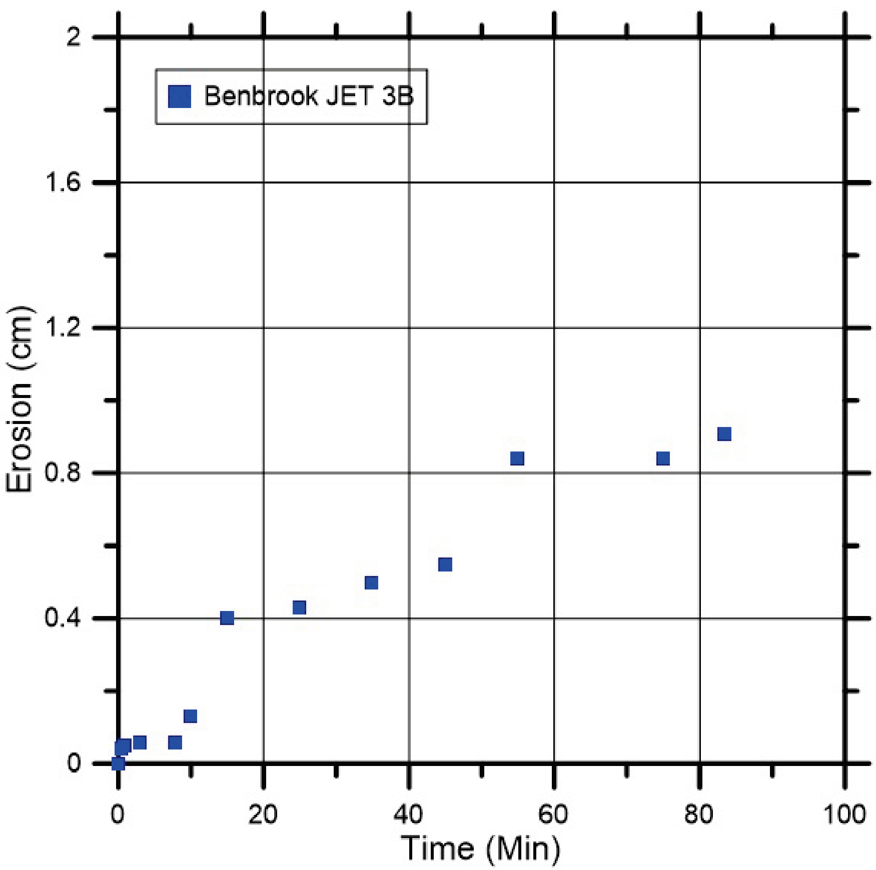


Figure A7. Soil surface before and after JET with erosion data of Benbrook Dam JET 4A.

Before JET

After JET

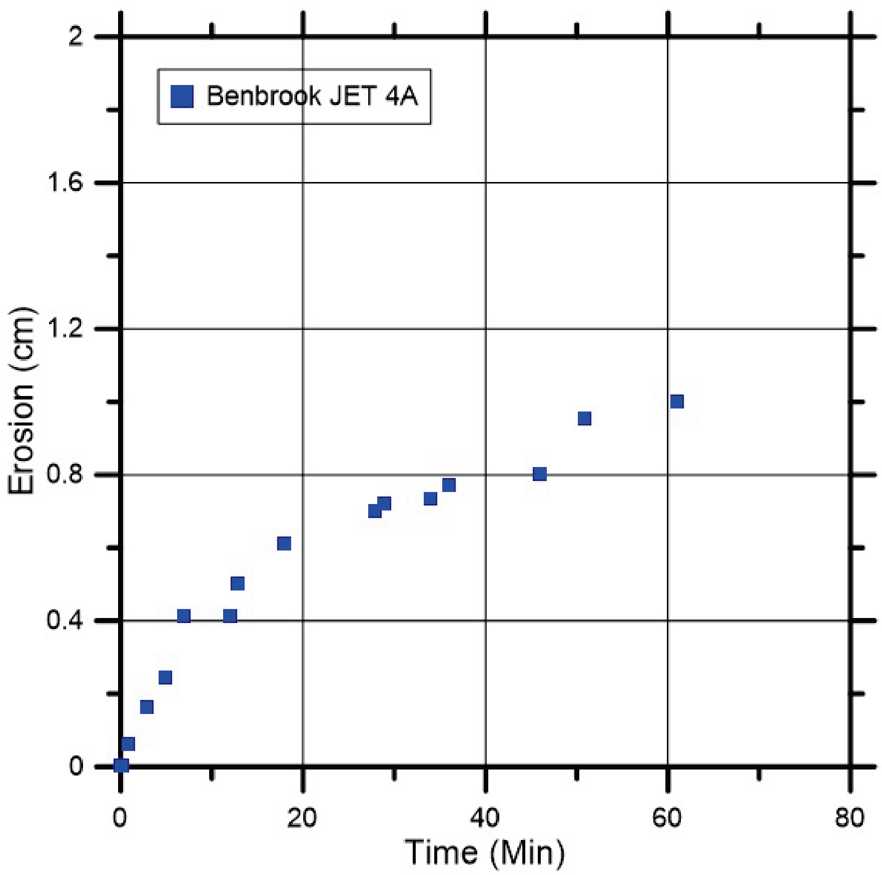
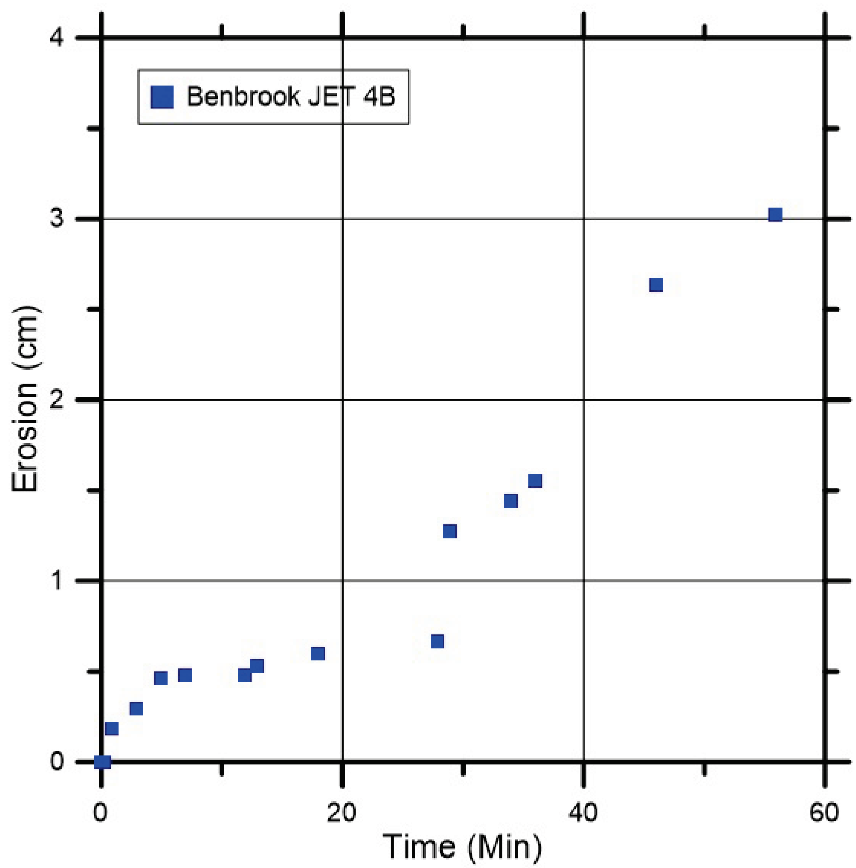


Figure A8. Soil surface before and after JET with erosion data of Benbrook Dam JET 4B.

Before JET After JET



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14. ABSTRACT

This report summarizes the results of eight field Jet Erosion Tests (JETs) performed on Benbrook Dam, TX. The results from these tests will be used by the U.S. Army Corps of Engineers, Fort Worth District, in assessments of the erosion resistance of the Benbrook Dam with regards to possible overtopping by extreme flooding. The JETs were performed at four different locations, i.e., two locations at the lowest crest elevation and two locations at the mid-slope face of the downstream embankment. Variations in estimated critical hydraulic shear stress and erosion rate values may have been caused by differences in soil composition, i.e., when the material changed from silt/sand to clay. The resulting values of the Erodibility Coefficient, K_d, and Critical Stress, τ_c, are very useful information in assessing the stability of Benbrook Dam during an overtopping event. Because of the observed natural variability of the materials, combining the erosion parameters presented in this report with the drilling logs and local geology will be imperative for assessing erosion-related failure modes of Benbrook Dam.

15. SUBJECT TERMS

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