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Managing Water in the West

Erosion Testing of Zoned Rockfill Embankments

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Bureau of Reclamation

Overview

- **Three dam breach tests 2015-2017**
  - **First test funded by Reclamation Dam Safety**
    - **Homogeneous silty clay soil (CL-ML), internal erosion**
    - **Baseline for subsequent tests, same soil later used as core of zoned embankments**
  - **NRC-funded tests**
    - **Zoned embankment – overtopping**
    - **Zoned embankment – internal erosion**
      (this test is not discussed in this presentation)

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Dam Breach Test Facility

Denver, Colorado

- 13-ft wide, 3-ft high embankment
- Inclined abutment (1:10), acrylic for viewing
- Large tailbox to contain breach outflow
- Headbox spillway with adjustable crest to maintain steady reservoir level

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Imaging Equipment

Objectives

- **Observe erosion and breach development mechanics, compare to numerical models**
- **Materials**
  - **Establish erodibility parameters of soils**
  - **Demonstrate consistent relationships between applied stress, erosion resistance, and observed erosion**

$$\varepsilon_r = k_d(\tau - \tau_c)$$

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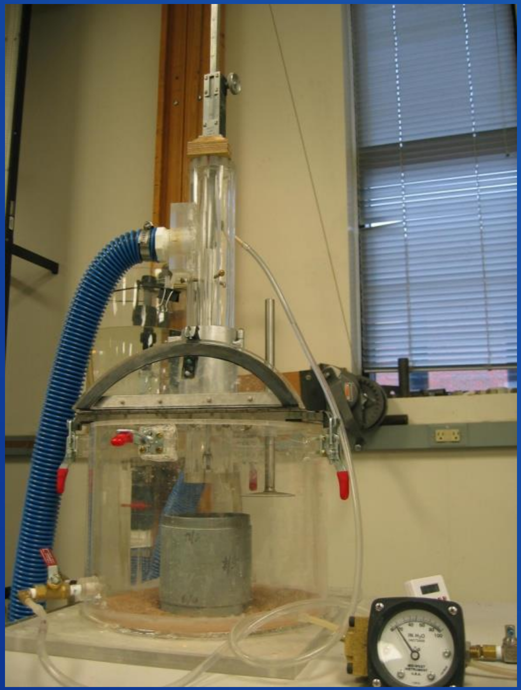
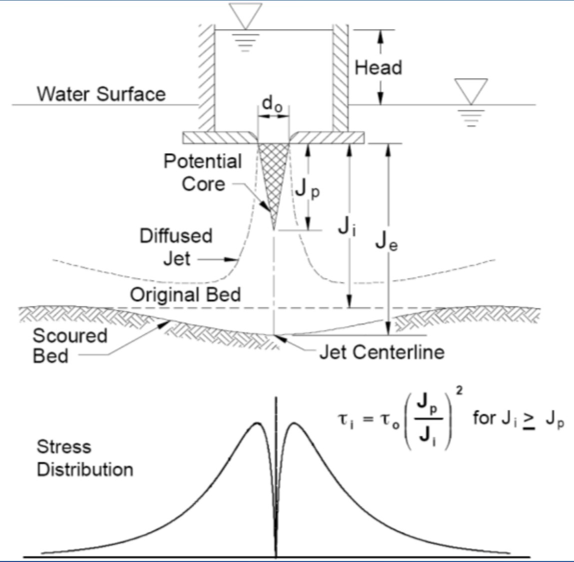
Submerged Jet Test - Erodibility





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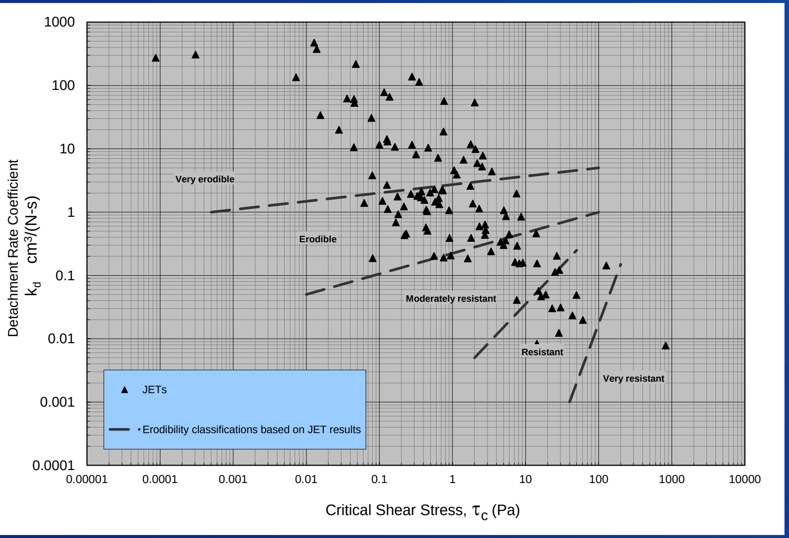
Erodibility varies widely

- Hanson and Simon (2001) study of streambed soils
- USBR studies of remolded soils



ERODIBILITY OF COHESIVE STREAMBEDS

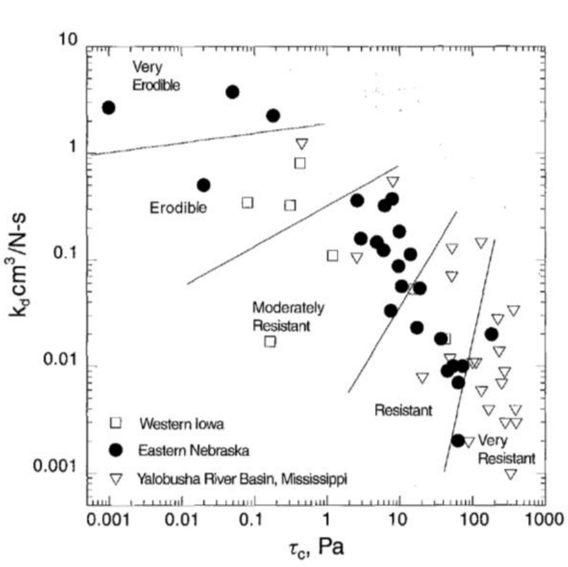


Figure 8. τ_c versus k_d from cohesive streambed tests

Jet test was developed primarily for cohesive soils

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Test 1

- **Homogeneous embankment of Silty Clay (CL-ML), internal erosion triggered at mid-depth by withdrawing 0.5-inch rebar**
- **k_d=5.5 ft/hr/psf τ_c=0.0015 psf (from pre-test JETs) (Very erodible)**

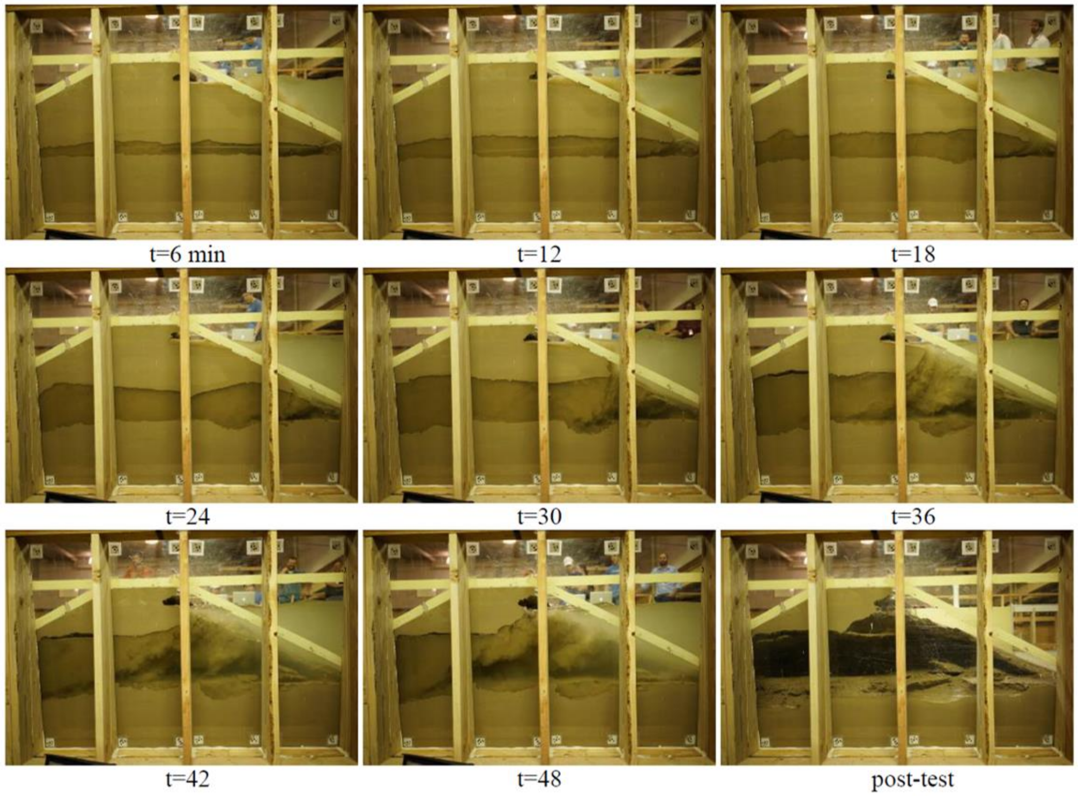

Figure 6. — Incremental erosion during internal erosion test of homogeneous silty clay embankment.

Total elapsed time = 48 minutes

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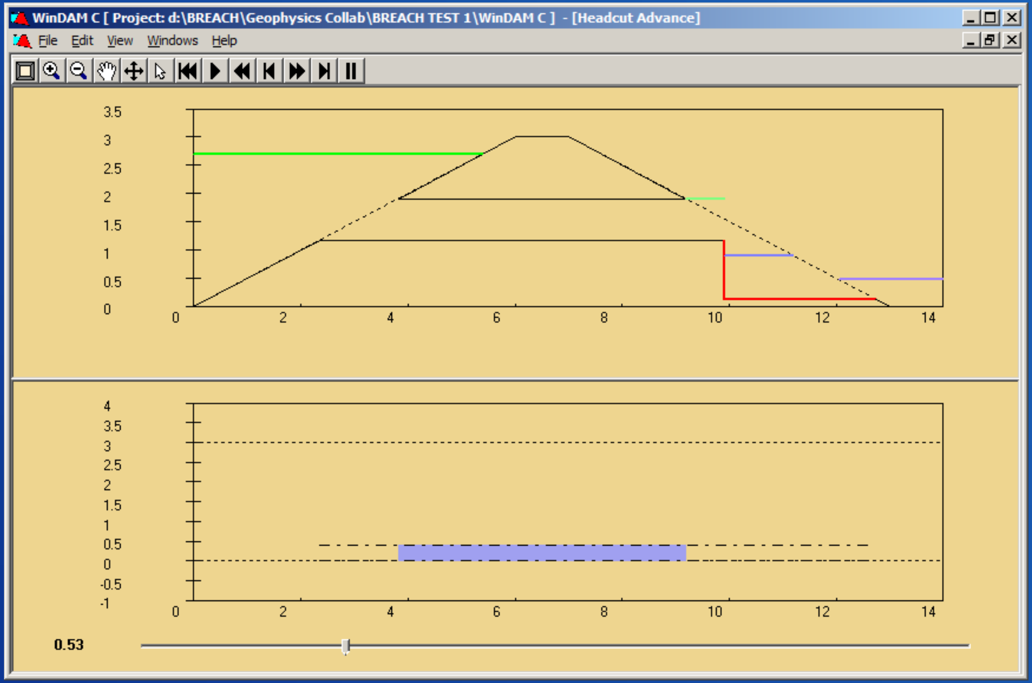
Post-test modeling: WinDAM C

- WinDAM C is a dam breach model developed by USDA to simulate overtopping and internal erosion failures of homogeneous cohesive embankments



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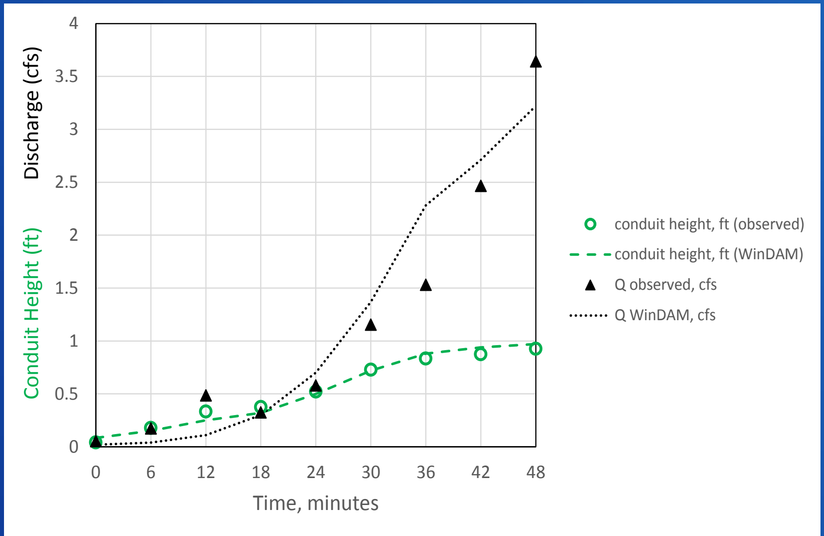
Post-test modeling: WinDAM C

- Good match of predicted breach outflows and internal erosion conduit sizes when we used k_d=2 ft/hr/psf and initial conduit size of 1 inch
- Close to actual conditions:
  - 0.5-inch rebar could have disturbed a larger area
  - k_d = 5.5 ft/hr/psf measured with JET



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Zoned Embankment Objectives

- Not much experience with failure of rockfill dams
- Rockfill dams are difficult to evaluate
  - What are erodibility parameters (especially k_d) for gravelly soils?
  - How do different zones interact and affect one another?
- There are rockfill dams upstream from several U.S. nuclear facilities

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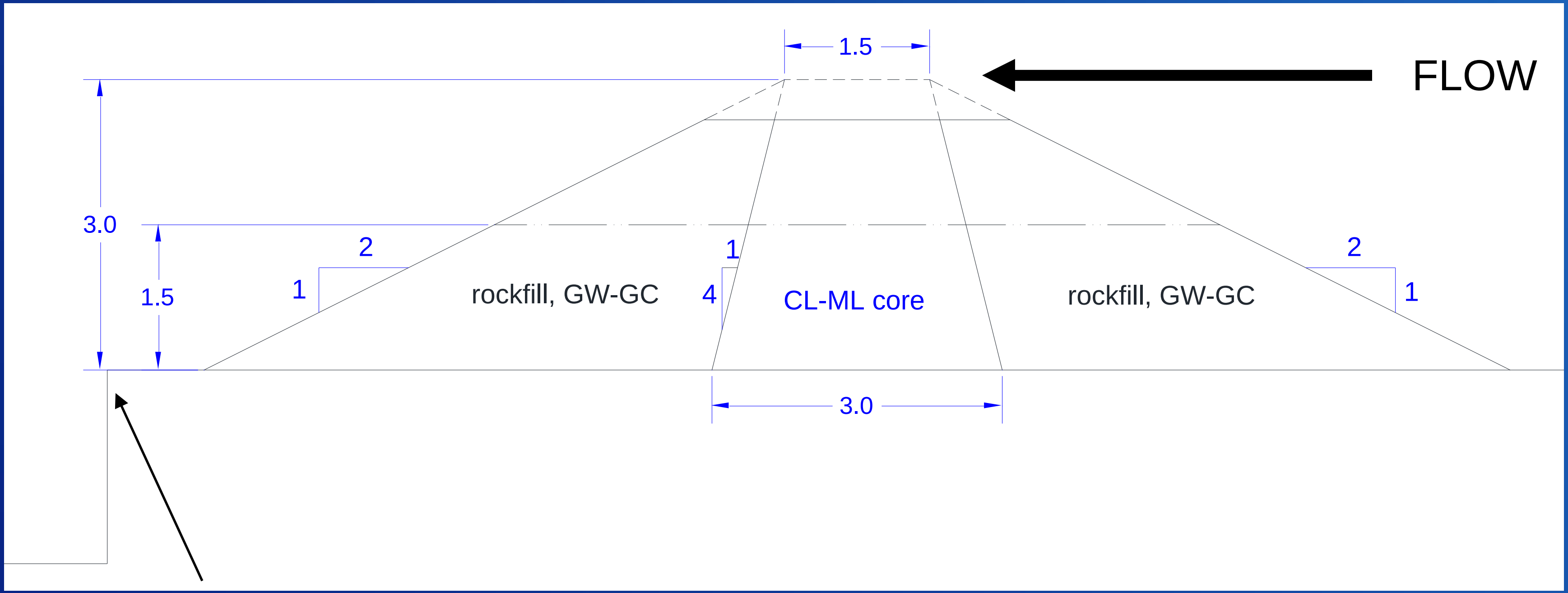
What is rockfill?

- Consultations with embankment designers at USBR, USACE, etc.
  - Materials in rockfill dams vary widely
  - Usually broadly graded
  - Often “dirtier” than expected
  - Variability of behavior is common because segregation and layering often occur during construction

Zoned Embankments

- Modeled a relatively simple embankment design
  - Did not include modern features such as filters, drains, etc.



Note overfall immediately below embankment

Soils

- Rockfill zones represented by a Class 6 road base soil from local aggregate supplier
  - GW-GC (Well-Graded Gravel with Clay and Sand)
  - 12% fines (passing #200 sieve) with CL-ML (Silty Clay) classification

    LL=25, PI=6
- Core is also CL-ML (Silty Clay)

    86% fines
    LL=27, PI=6

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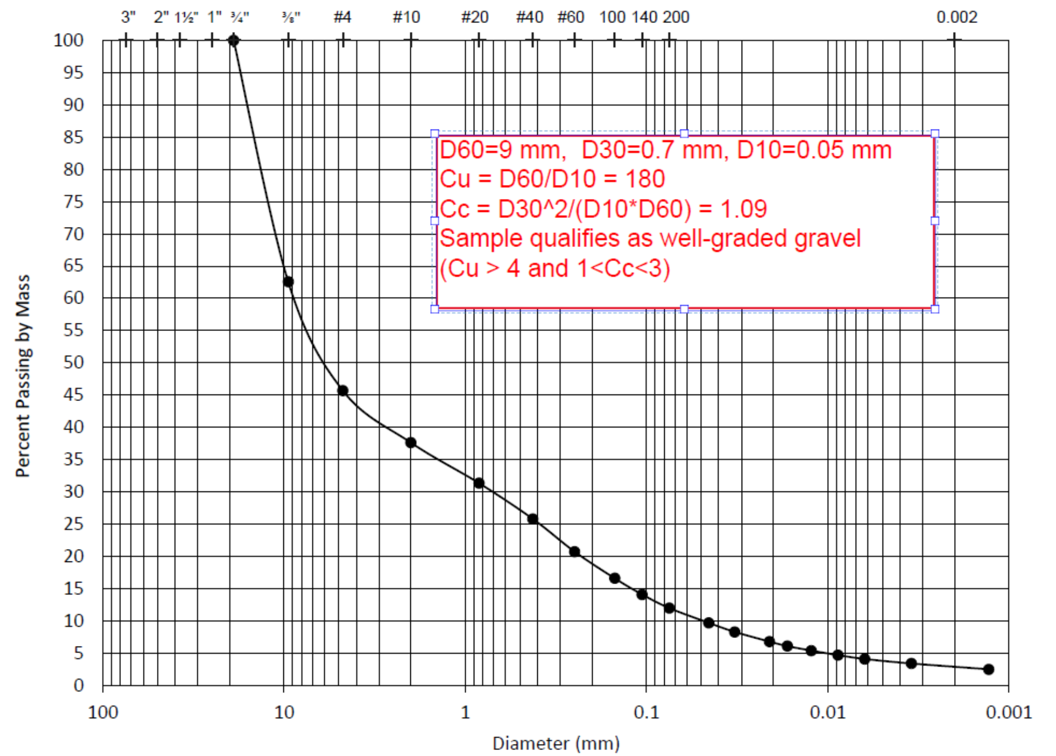
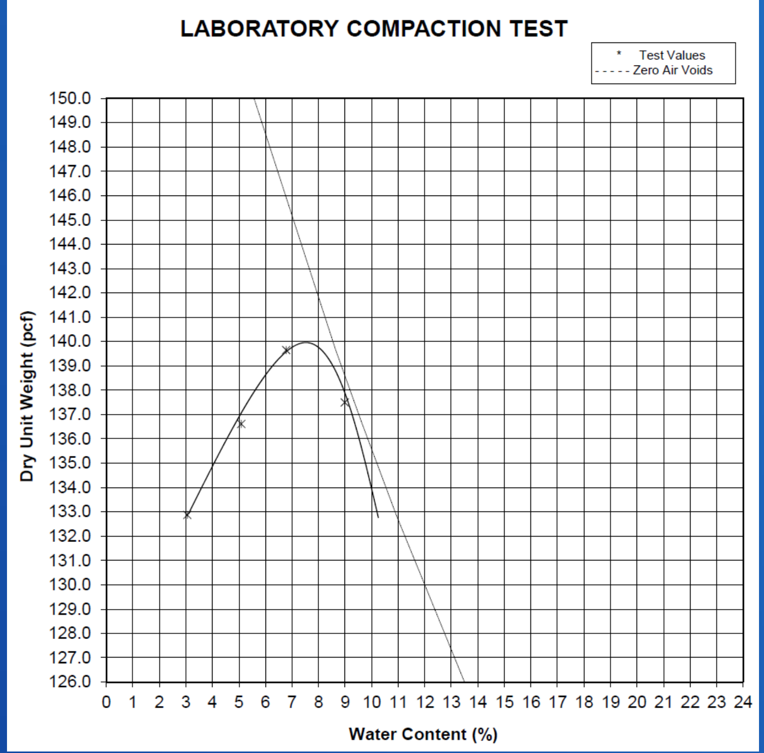
GW-GC Rockfill



Cobbles (%)	Gravel (%)		Sand (%)			Fines (%)	
	54.3		33.7			12.0	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
		54.3	8.1	11.8	13.8	9.2	2.8



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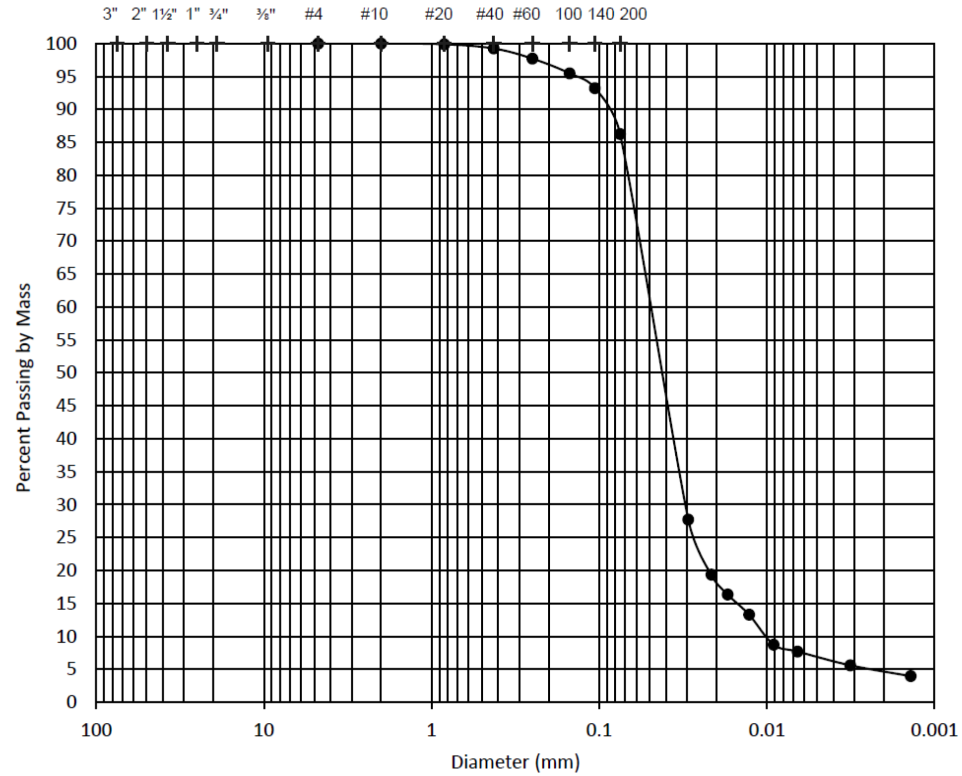
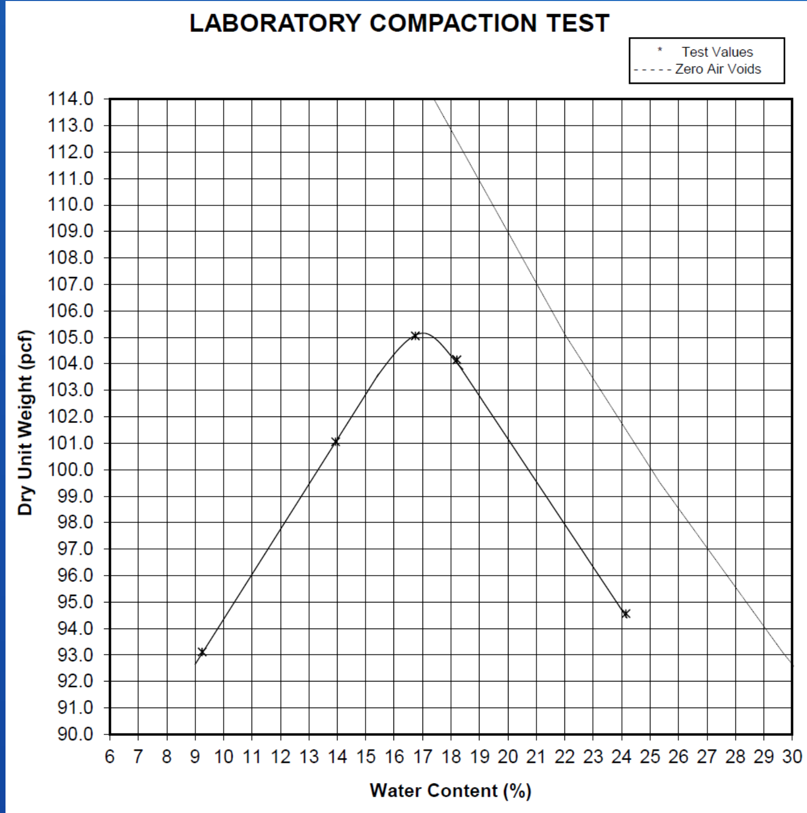
CL-ML Core



Cobbles	Gravel		Sand			Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay

Cobbles (%)	Gravel (%)		Sand (%)			Fines (%)	
			13.7			86.3	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
				0.8	13.0	79.5	6.7



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Embankment Construction

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JET test of core

Sand cone tests also performed to measure density of core and gravel zones

Approx. 100% of standard Proctor for all zones

Overtopping Test – 3 minutes

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Overtopping Test – 5 minutes

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Overtopping Test – 7 minutes

Overtopping Test – 14 minutes

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Overtopping Test – 19 minutes

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Overtopping Test – 26 minutes

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Overtopping Test – 33 minutes

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Overtopping Test – 37 minutes

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Overtopping Test – 47 minutes

Overtopping Test – 77 minutes

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Overtopping Test – 120 minutes

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Overtopping Test – 180 minutes

End of Test

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End of Test

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Material Behavior - cohesive

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Observations

- **Although core and gravel zones both showed cohesive behavior (near-vertical sidewalls), erosion did not adopt a headcut pattern**
- **Surface erosion was dominant**
  - **Lack of tailwater pool to provide recirculation and accelerate erosion at toe**

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Post-Test Analysis

- Estimate erosion rates and hydraulic stresses from photo records and use to estimate values of k_d

$$\varepsilon_r = k_d(\tau - \tau_c)$$

- Compare to Jet Erosion Tests (JETs) of soil in downstream rockfill zone

Estimate k_d from photos

Table 1. — Flow and breach channel properties used to estimate value of k_d for gravel zone.

Elapsed time	Channel width	Flow depth	Discharge	Velocity	Channel slope	Manning's n	Shear stress, $\tau_e = \gamma RS(n_s/n)^2$	Bed position normal to slope, ft	k_d
hh:mm:ss	ft	ft	ft^3/s	ft/s	ft/ft	-	lb/ft^2	ft	$ft/hr/lb/ft^2$
0:03:20	1.10	0.23	0.61	2.42	0.51	0.130	0.158	0.34	---
0:05:20	1.16	0.23	0.73	2.69	0.53	0.122	0.193	0.45	19.59
0:07:20	1.22	0.24	0.84	2.92	0.57	0.118	0.225	0.47	2.31
0:14:20	1.42	0.24	1.17	3.43	0.58	0.105	0.305	0.51	1.16
0:19:20	1.57	0.24	1.50	3.94	0.60	0.095	0.398	0.54	0.93
0:26:20	1.77	0.25	1.81	4.13	0.60	0.093	0.432	0.59	1.04
0:34:28	2.07	0.25	2.01	3.88	0.62	0.104	0.376	0.64	1.17
0:37:00	2.08	0.26	2.01	3.79	0.58	0.103	0.357	0.67	1.70
0:47:00	2.10	0.29	2.21	3.61	0.53	0.112	0.313	0.71	0.82
1:17:00	2.16	0.38	2.5	3.02	0.49	0.148	0.204	0.82	1.21
2:00:00	2.25	0.61	3.63	2.66	0.45	0.201	0.141	0.88	0.73
3:00:00	2.38	0.64	4.55	3.00	0.32	0.157	0.177	0.95	0.41

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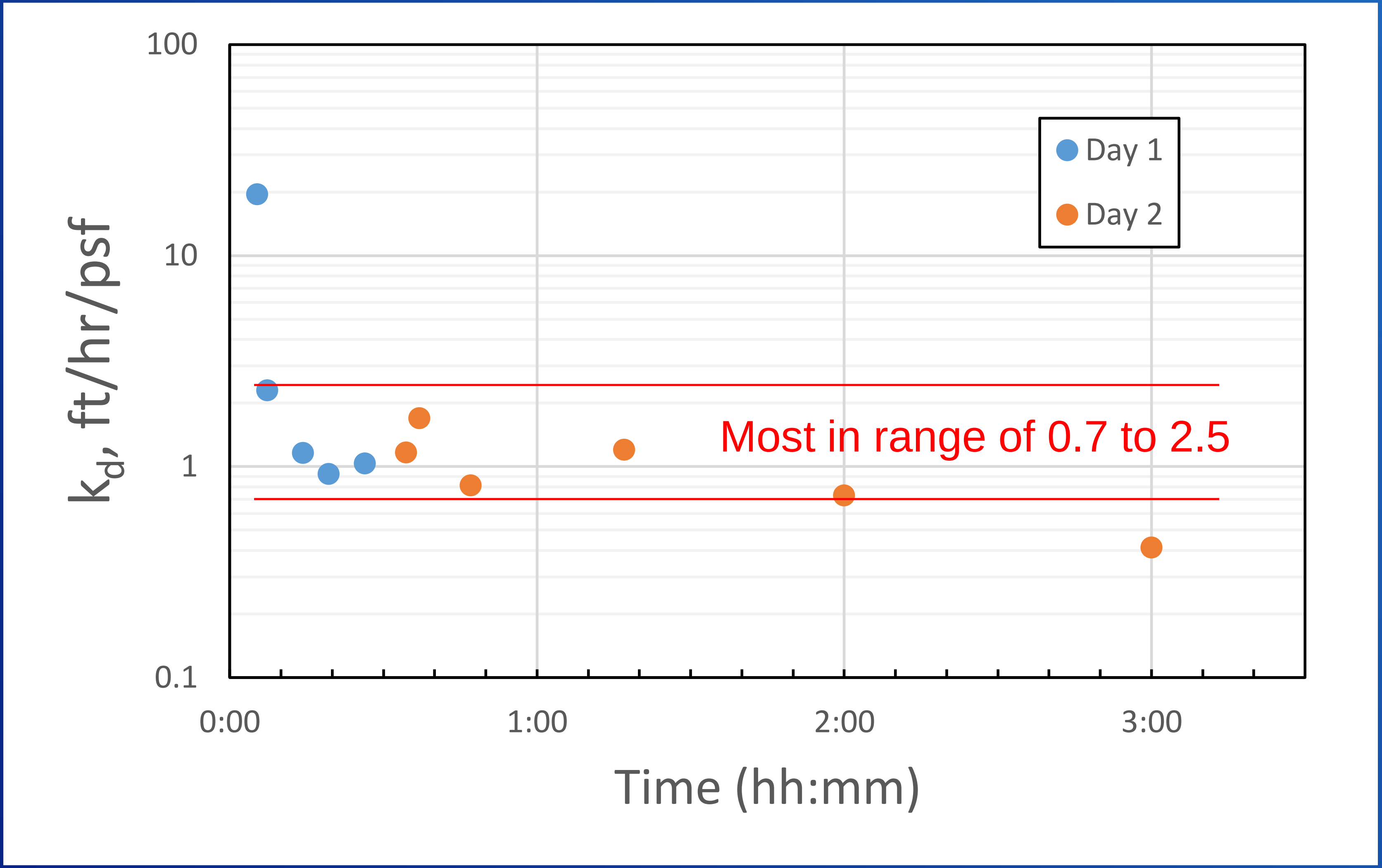
Estimates of k_d from photos



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Jet Erosion Tests

- Hypothesis is that erodibility of mixed soils (granular & cohesive) is primarily determined by the cohesive fraction
  - Presence of gravel may also add marginally to erosion resistance (armoring, shielding)
- Used ASTM D4718 procedure to calculate a gravel correction to determine effective density and water content of the finer fractions of the well-graded gravel
  - Minus No. 4 and minus 3/8" fractions

JET specimens

- Two minus No. 4's compacted by hand to achieve calculated target densities (comparable to 100% standard Proctor)
- Two minus No. 4's using modified Proctor (4.5 times more energy) (109-114%)
- One minus 3/8" at standard Proctor
- One minus 3/8" at modified Proctor
- One whole gravel specimen at standard Proctor

JET results

Minus No.4, standard compaction specimens were a little more erodible than gravel zone in embankment, but in same order of magnitude

ID	Specimen	Water content, w, %	Dry density, γ_d, lb/ft³	Water content of minus No. 4, w_{-4}, %	Dry density of minus No. 4, γ_{d-4}, lb/ft³	Compaction method	Detachment rate coefficient, k_d, ft/hr/lb/ft²	Critical shear stress, τ_c, lb/ft²
-	Reference	7.0	140.0	12.4	114.3	-	-	-
1	Minus No. 4 fraction	12.4	113.2	12.4	113.2	5-layers, target γ_d = 114 lb/ft³ w = 12.5%	5.1	0.00024
2	Minus No. 4 fraction	12.8	112.9	12.8	112.9	5-layers, target γ_d = 114 lb/ft³ w = 12.5%	4.9	0.00029
3	Minus No. 4 fraction	13.0	124.8	13.0	124.8	modified Proctor, 56,250 ft-lb/ft³	0.63	0.025
4	Minus No. 4 fraction	11.4	130.3	11.4	130.3	modified Proctor	0.45	0.046
5	Minus 3/8-inch	11.0	132.3	14.2	121.7	standard Proctor, 12,375 ft-lb/ft³	1.01	0.0056
6	Minus 3/8-inch	10.3	133.7	13.2	123.3	modified Proctor	0.31	0.044
7	Full sample	8.4	140.3	15.5	114.8	standard Proctor	3.1	0.07

JET results

- Minus No.4, modified compaction showed increased erosion resistance.
- Lower layers of embankment may have been overcompacted when upper layers were added.

ID	Specimen	Water content, w, %	Dry density, γ_d, lb/ft^3	Water content of minus No. 4, w_{-4}, %	Dry density of minus No. 4, γ_{d-4}, lb/ft^3	Compaction method	Detachment rate coefficient, k_d, ft/hr/lb/ft^2	Critical shear stress, τ_c, lb/ft^2
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JET results

- Minus 3/8" specimens both showed more erosion resistance than comparable minus No. 4 specimens.
- Could be due to other factors. More testing needed to confirm trend.

ID	Specimen	Water content, w, %	Dry density, γ_d, lb/ft³	Water content of minus No. 4, w_{-4}, %	Dry density of minus No. 4, $\gamma_{d\text{-}4}$, lb/ft³	Compaction method	Detachment rate coefficient, k_d, ft/hr/lb/ft²	Critical shear stress, τ_c, lb/ft²
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JET results

Full gravel specimen was more erodible again, but still close to range of estimates for embankment rockfill zone. This specimen is probably pushing the limits for doing a valid JET test (too much gravel, too big).

ID	Specimen	Water content, w, %	Dry density, γ_d, lb/ft^3	Water content of minus No. 4, w_{-4}, %	Dry density of minus No. 4, γ_{d-4}, lb/ft^3	Compaction method	Detachment rate coefficient, k_d, ft/hr/lb/ft^2	Critical shear stress, τ_c, lb/ft^2
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JETs

Minus No. 4 (3/16”)

minus 3/8”

full gravel up to ¾”

Summary

- Overtopping test
  - Erodibility (k_d) of gravel zone estimated from embankment test observations matches well with JET tests
  - Understanding erodibility of mixed gravel & cohesive soils is a big challenge as ratio of coarse-to-fine soil changes
  - This gravel had enough fines to behave like a cohesive soil, but what about…
    - Cleaner rockfills ???
    - Cobbles and boulders???
  - There is still uncertainty predicting when headcut erosion or surface erosion will take place