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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

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

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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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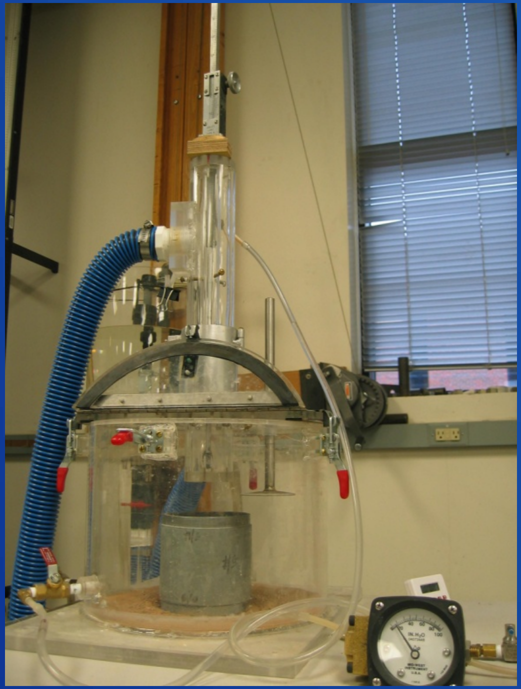
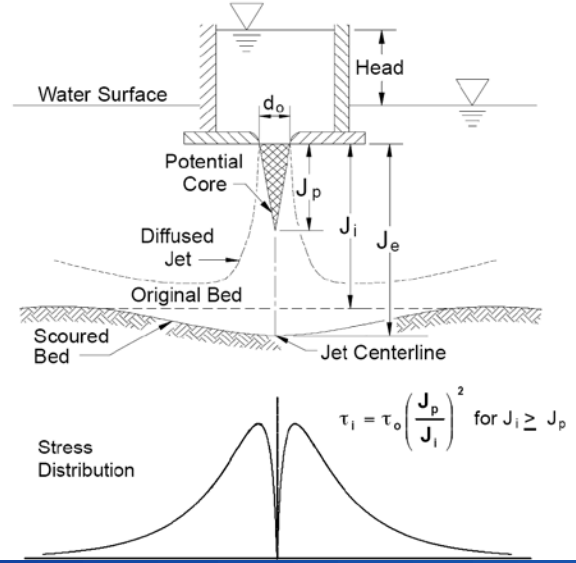
Submerged Jet Test - Erodibility





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Erodibility varies widely

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

ERODIBILITY OF COHESIVE STREAMBEDS

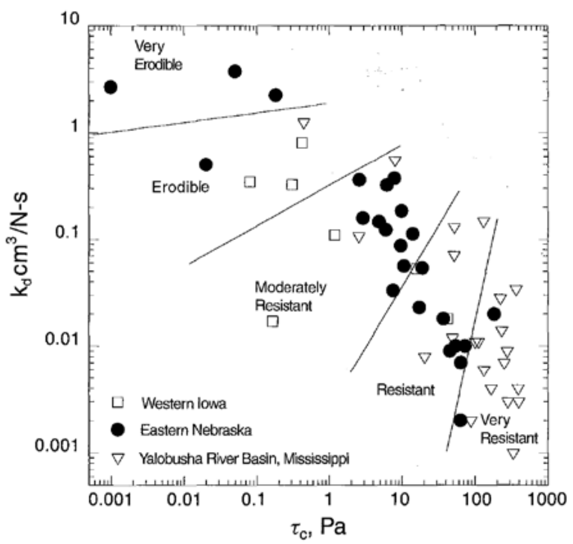
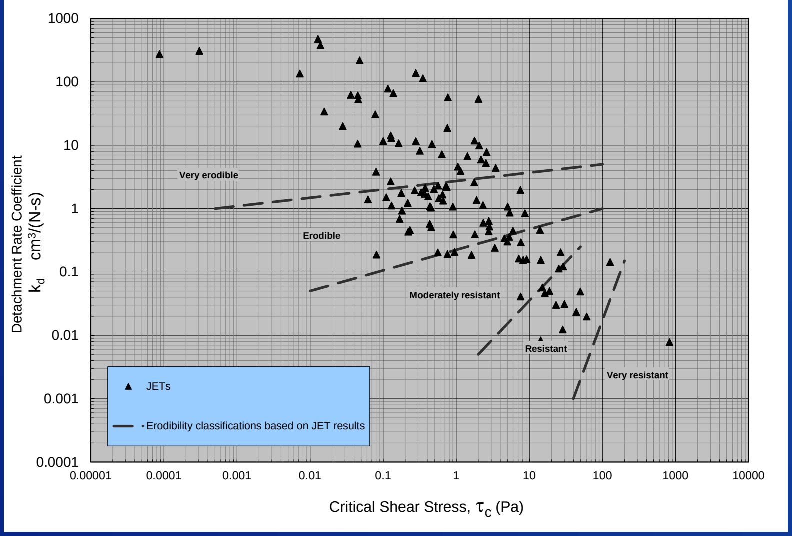


Figure 8. τ_c versus k_d from cohesive streambed tests



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)

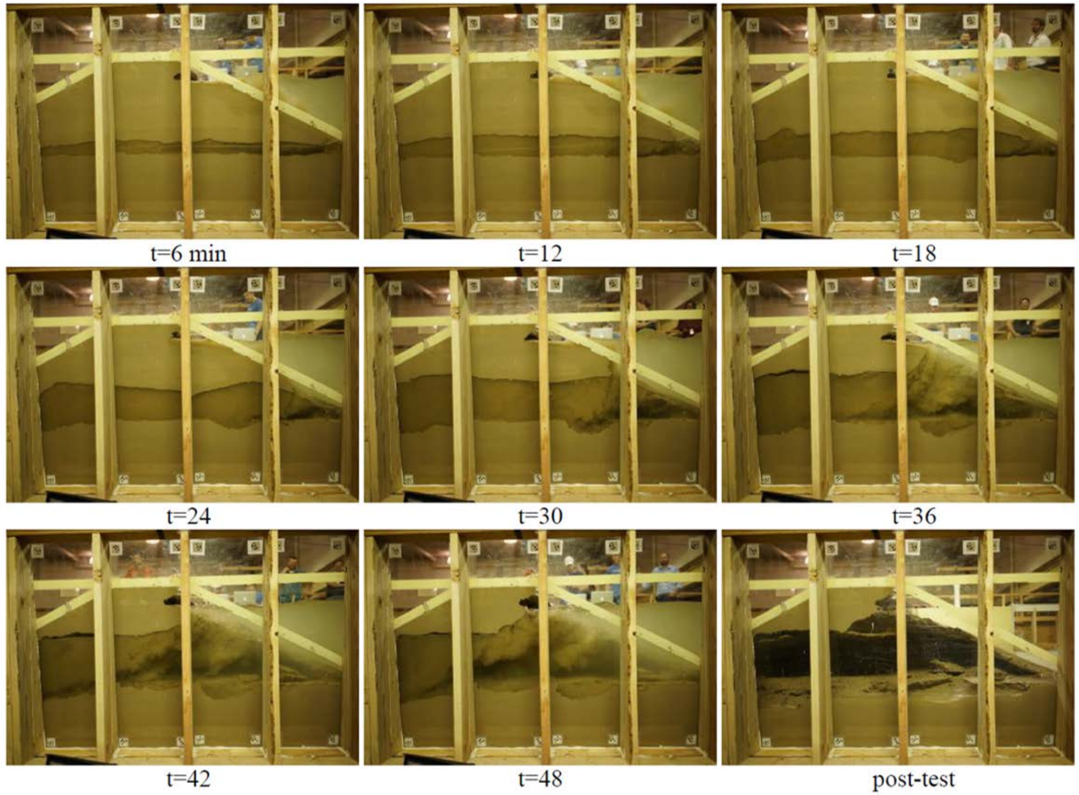

Figure 6. — Incremental erosion during internal erosion test of homogeneous silty clay embankment.

Total elapsed time = 48 minutes

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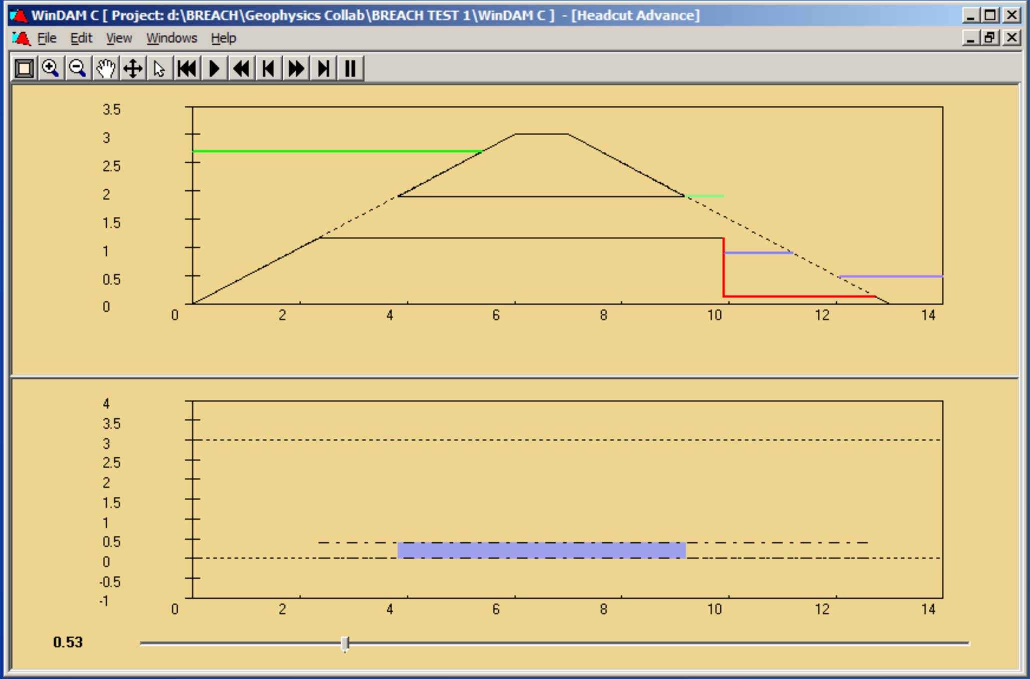
Post-test modeling: WinDAM C

- 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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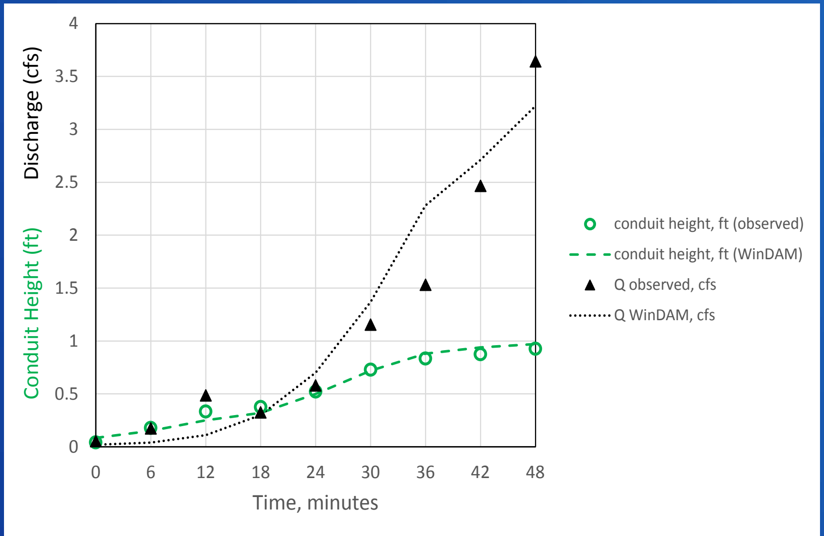
Post-test modeling: WinDAM C

- 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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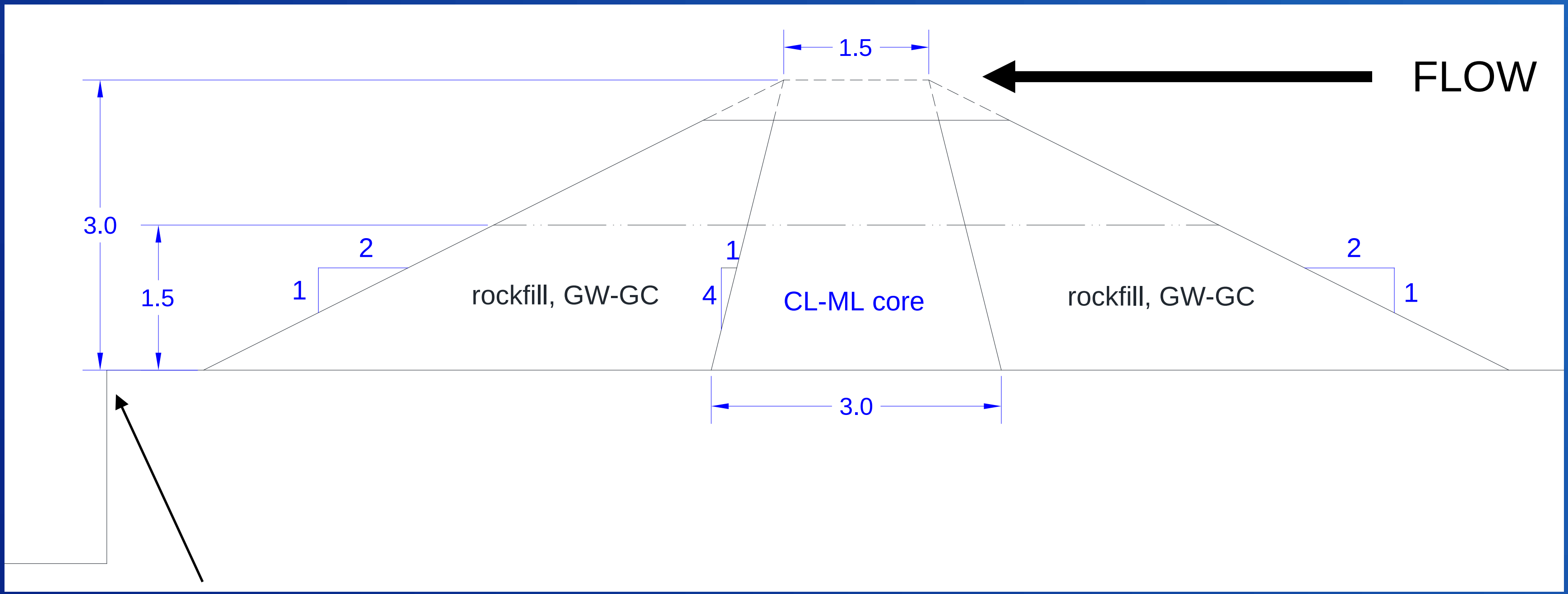
What is rockfill?

- 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

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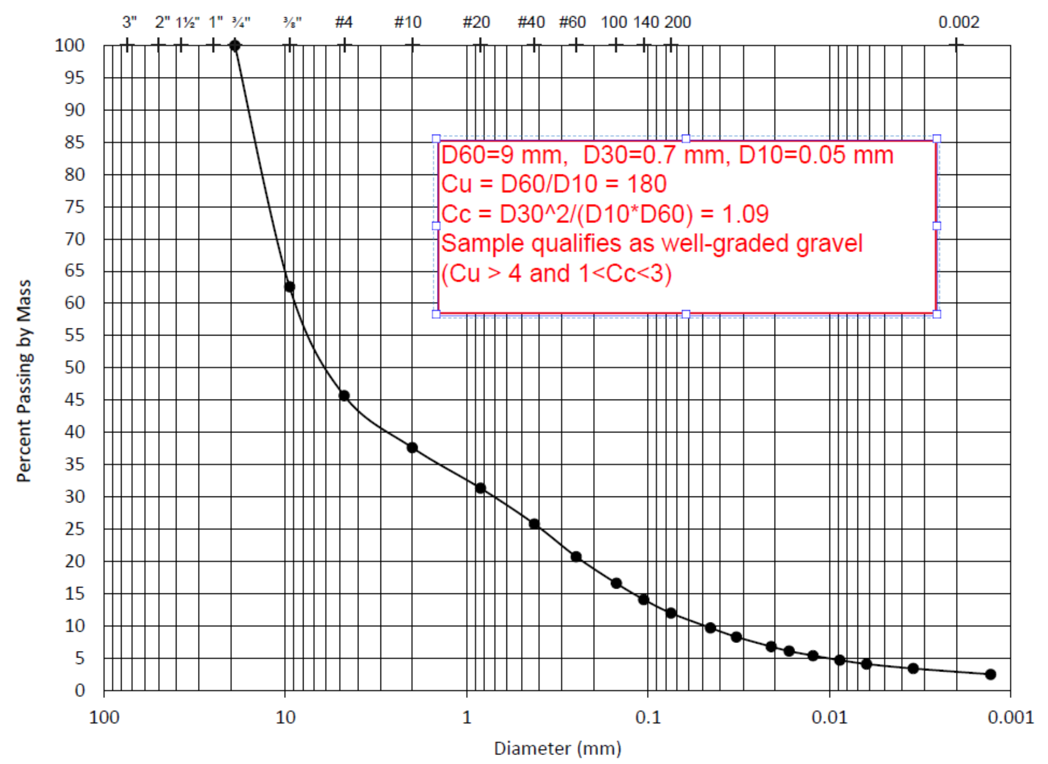
Soils

- 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

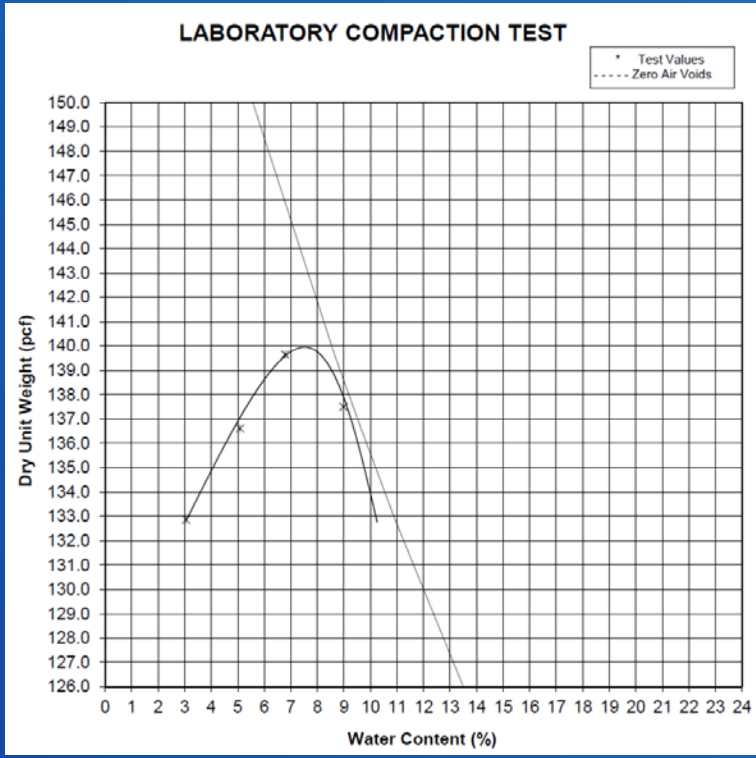
    LL=25, PI=6
- Core is also CL-ML (Silty Clay)

    86% fines
    LL=27, PI=6

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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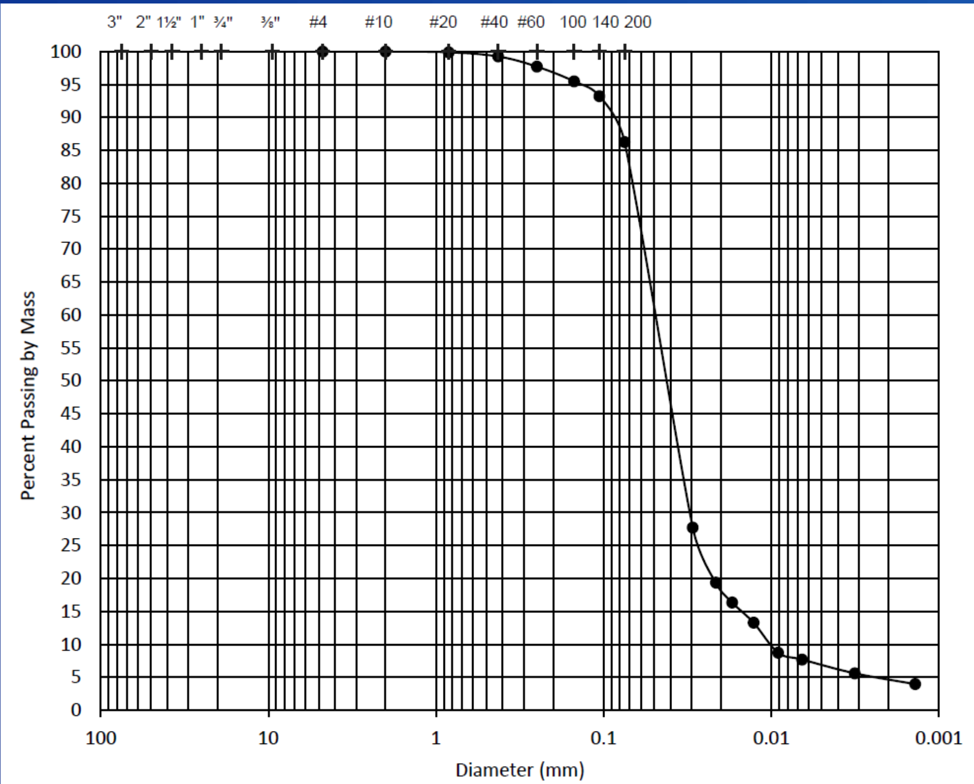
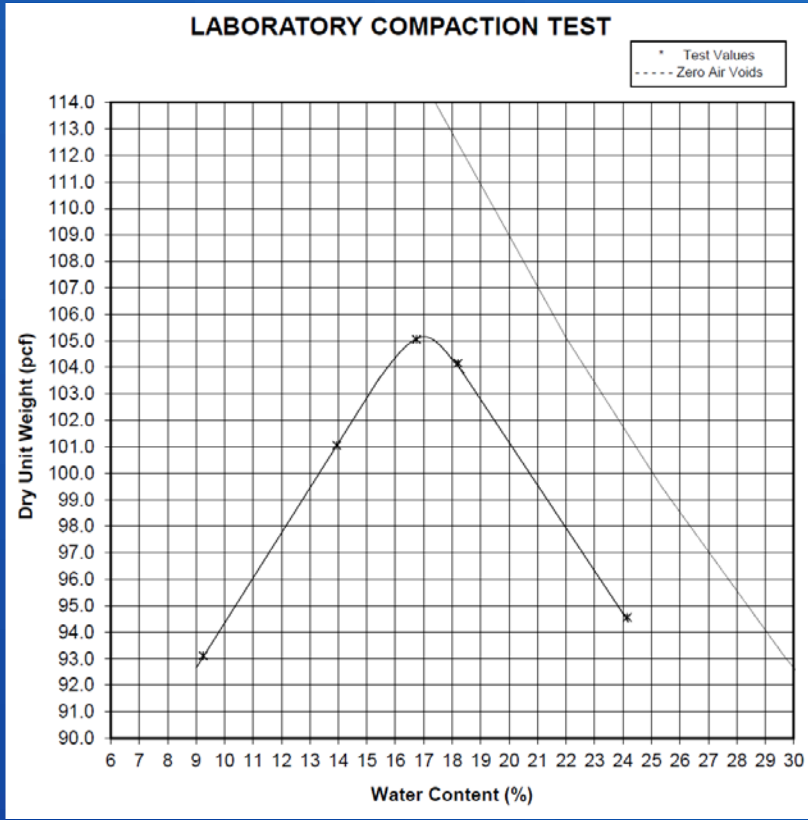
CL-ML Core



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



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

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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

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

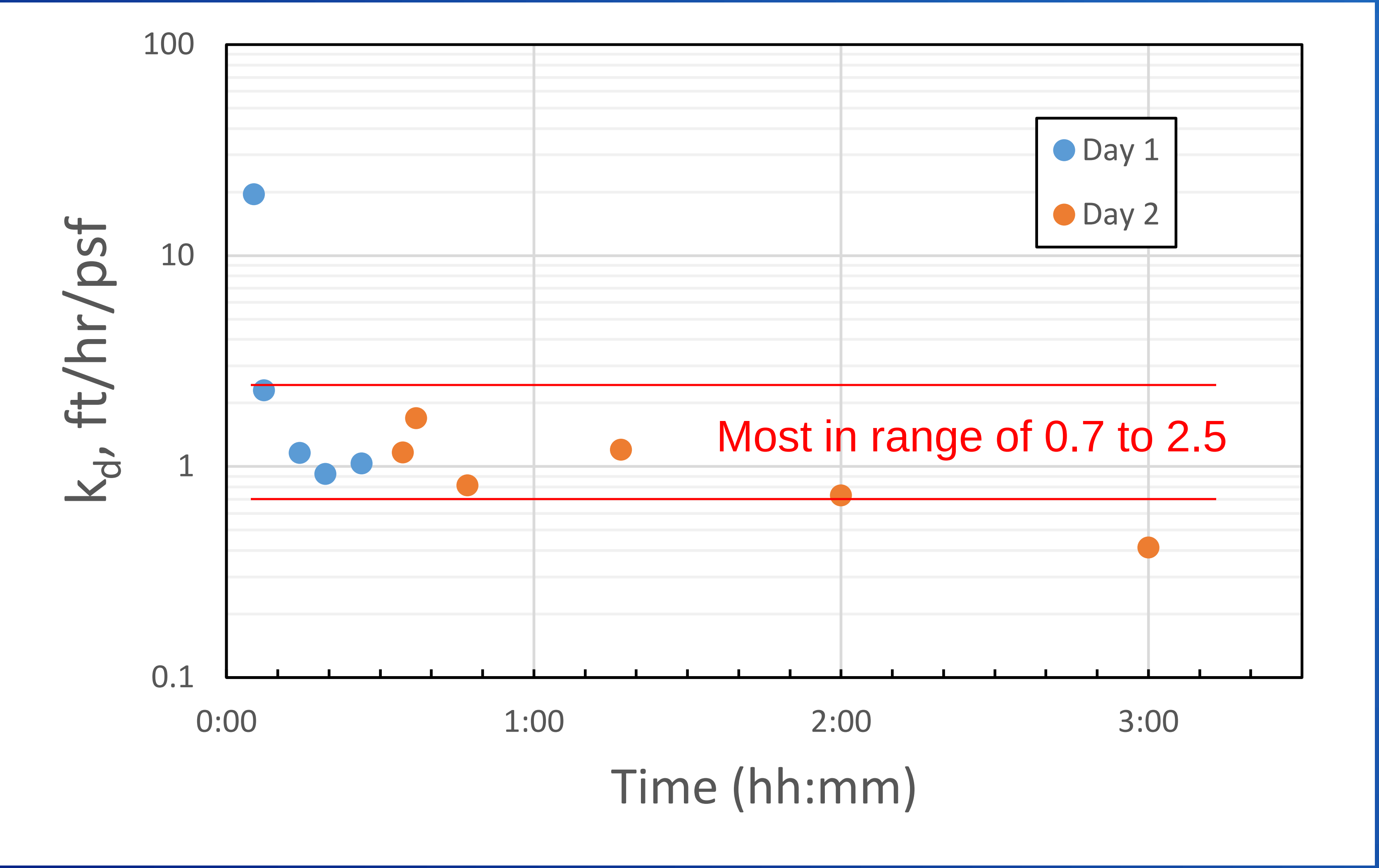
- Compare to Jet Erosion Tests (JETs) of soil in downstream rockfill zone

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

Estimates of k_d from photos



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

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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/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

- 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, γ_{d-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/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
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JETs

Minus No. 4 (3/16”)

minus 3/8”

full gravel up to ¾”

Piping Test (Internal Erosion)

- **Embankment was reconstructed only in the area affected by first test (near abutment)**

½" rebar
18 inches below crest

Piping Test

- Took place over four days (48 hours of flow)
  - Day 1
    - Reservoir was filled and rebar withdrawn
    - Initial flow through “pipe” probably less than 5 gpm
    - Initially turbid, but gradually cleared
    - Within 90 minutes, flow stopped completely
    - Pipe healed itself
    - No erosion was ever visible through the acrylic left abutment wall

Healing of Pipe

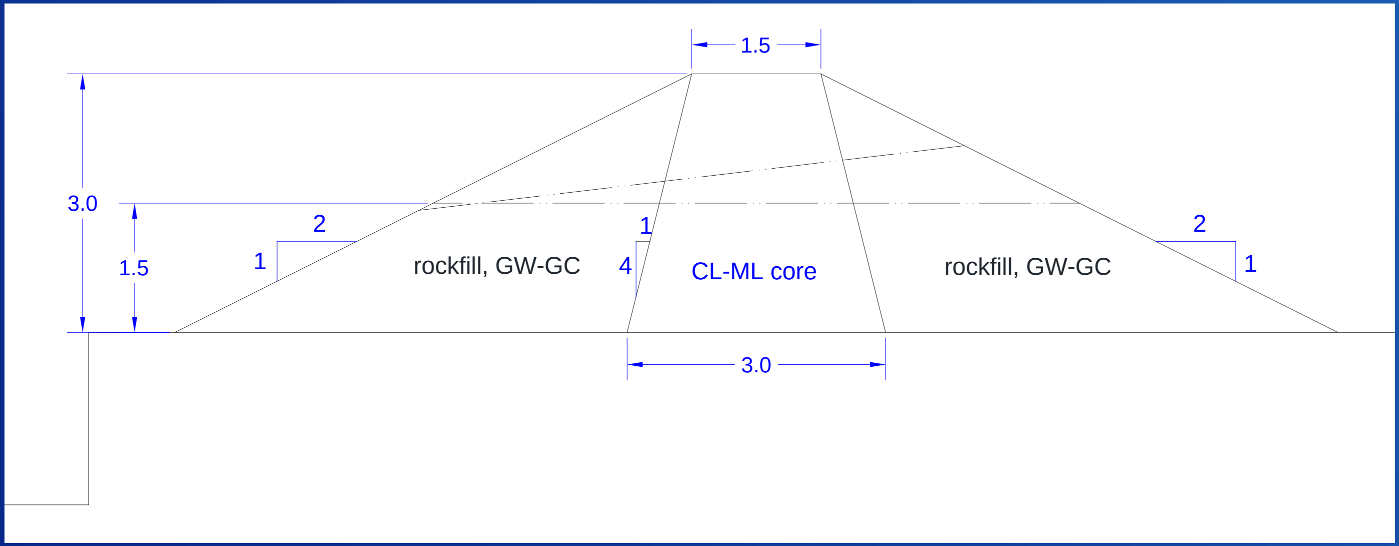
- Gravel zone met basic criteria to serve as a filter for the core

$$\frac{D_{15,filter}}{D_{15,base}} \geq 5 \qquad \frac{0.12\ mm}{0.015\ mm} = 8.0$$

$$\frac{D_{15,filter}}{D_{85,base}} \leq 5 \qquad \frac{0.12\ mm}{0.07\ mm} = 1.7$$

Day 2

- **Interventions to try to initiate a failure and then observe erosion processes**
  - **Reinserted rebar and withdrew again**



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Day 2

- Flow was again initially turbid, then cleared
- Flow rate remained steady (about 5 gpm)
- Hole through downstream gravel zone gradually became more distinct as fines and fine sand were carried away
  - Further growth of hole was limited by medium to coarse sand and fine gravel left behind
  - Enlargement of hole through core zone became visible after 19 minutes

Internal Erosion – 1 minute

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Internal Erosion – 5 minutes

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Internal Erosion – 10 minutes

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Internal Erosion – 20 minutes

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Internal Erosion – 30 minutes

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Internal Erosion – 45 minutes

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Internal Erosion – 60 minutes

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Internal Erosion – 90 minutes

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Internal Erosion – 2 hours

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Internal Erosion – 3 hours

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Internal Erosion – 4 hours

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Internal Erosion – 6 hours

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Internal Erosion – 9 hours

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Internal Erosion – 12 hours

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Internal Erosion – 15 hours

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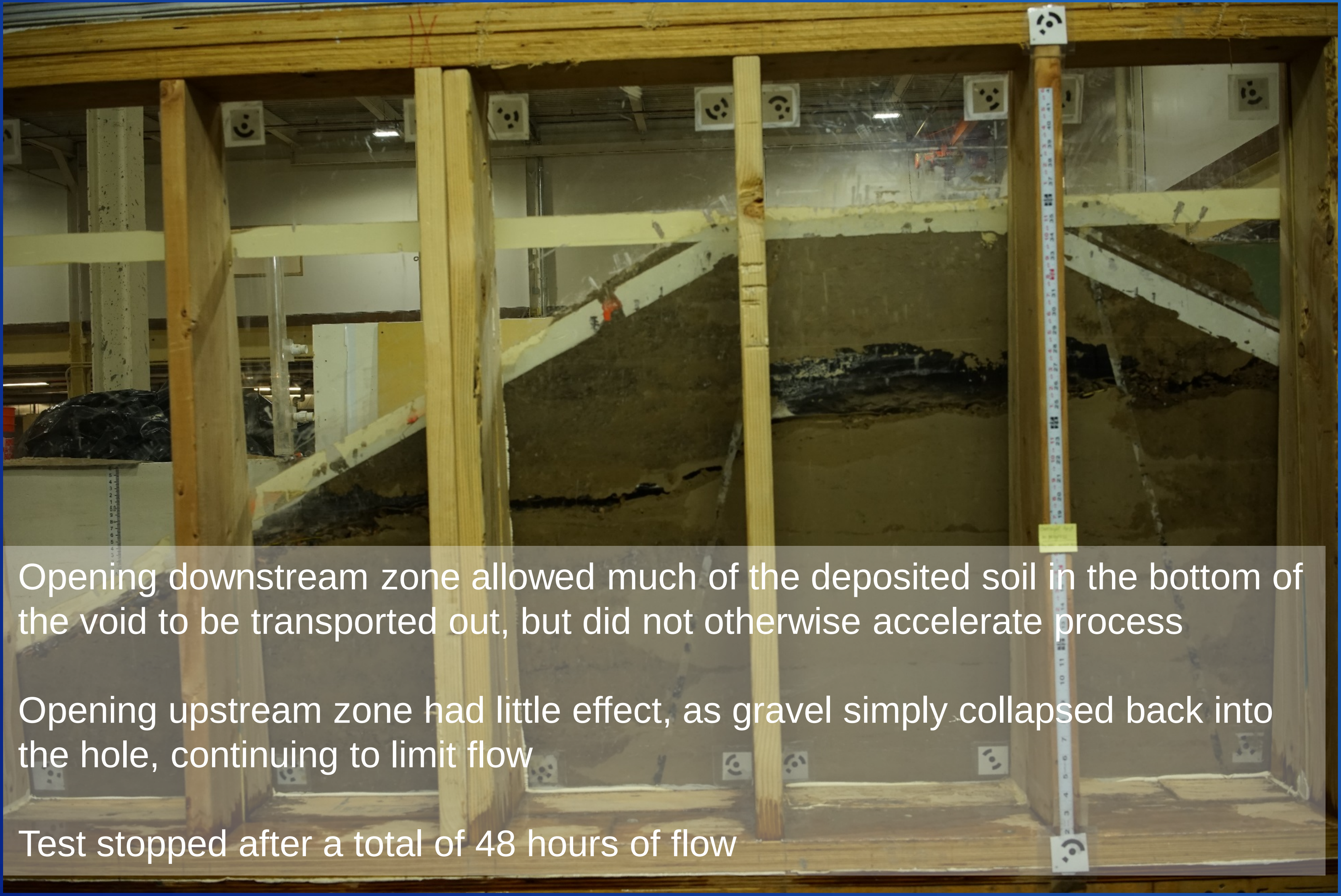
Failure Modes

- Erosion process is leading to a slow "stoping" failure
  - Upward migration of erosion channel as roof slowly collapses and void increases in size
  - As stope rises, this could eventually cause a collapse of the crest that could produce…
    - Overtopping
    - Shortened seepage path -- increased hydraulic gradient
- Downstream and upstream gravel zones limiting flow, keeping process slow

Internal Erosion – 24 hours

Internal Erosion – 36 hours



Opening downstream zone allowed much of the deposited soil in the bottom of the void to be transported out, but did not otherwise accelerate process

Opening upstream zone had little effect, as gravel simply collapsed back into the hole, continuing to limit flow

Test stopped after a total of 48 hours of flow

Takeaways from Piping Test

- Numerical models of embankment breach by internal erosion assume a concentrated leak and model only the detachment and removal of soil to enlarge that leak
  - Re-deposition of material collapsing from roof is not modeled
  - Simulating the “stoping” mechanism is beyond capabilities of current models
- Limitation of flow by upstream/downstream gravel zones is also not well represented in numerical models

Internal Erosion "Toolbox"

- **USBR and US Army Corps of Engineers (USACE)**
  - Best Practices in Dam and Levee Safety Risk Analysis
    - Chapter IV-4, Internal Erosion Risks for Embankments and Foundations, https://www.usbr.gov/ssle/damsafety/risk/methodology.html
- **Set of empirical and experienced-based procedures for analyzing the sequence of events (event-tree) needed for internal erosion failure modes**

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Typical Internal Erosion Event Tree

- Water level at or above threshold level
  - Initiation – Erosion starts
    - Continuation – Unfiltered or inadequately filtered exit exists
      - Progression – Continuous stable roof and/or sidewalls
        - Progression – Constriction or upstream zone fails to limit flows
          - Progression – No self-healing by upstream zone
            - Unsuccessful detection and intervention
              - Breach (uncontrolled release of impounded water)

- **For this embankment, projected breach rate is Rapid to Medium, 1 to 7 days**

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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

Summary

- Internal erosion
  - Complex interactions of different zones are possible
  - Available numerical models are not equipped for all of the possibilities
  - Empirical internal erosion toolbox provides best approach for understanding event trees for internal erosion failure of zoned embankments