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State Of The Art Slope Stability Analysis With Transient Seepage Forces

Case Study: C.W. BILL Young Regional Reservoir Upstream Slope Failures

FLORIDA EAST CENTRAL BRANCH
ASCE GEO-INSTITUTE CHAPTER

When: Wednesday, October 27, 2010
Where: Orlando Marriott Downtown

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Presentation Outline

1. Location of reservoir.

2. Purpose & description of facility.

3. Reservoir embankment cross-section with focus on the wedge.

4. Reservoir filling and emptying stage history since startup, and timing of distress observations. Comparison to design drawdown rates.

5. What does the distress look like? Photos and x-section and test pit photos and sketches.

6. Slope stability analysis methods:
   A. infinite
   B. DWW
   C. Coupled seepage/effective stress. Limitations of DWW (which is Army Corp recommendation).

Presentation Outline (Cont’d.)

7. Key soil properties of wedge fill: gradation, permeability, strength.
8. Coupled model results: animations, sensitivity analyses to input parameters
9. Concept fix and analysis of it's effectiveness in reducing pore pressure
10. Bonus materials:
    A. Additional scenarios
    B. Pore pressure animation
    C. Animation of SoilVision inputs and outputs

Part 1

LOCATION OF RESERVOIR

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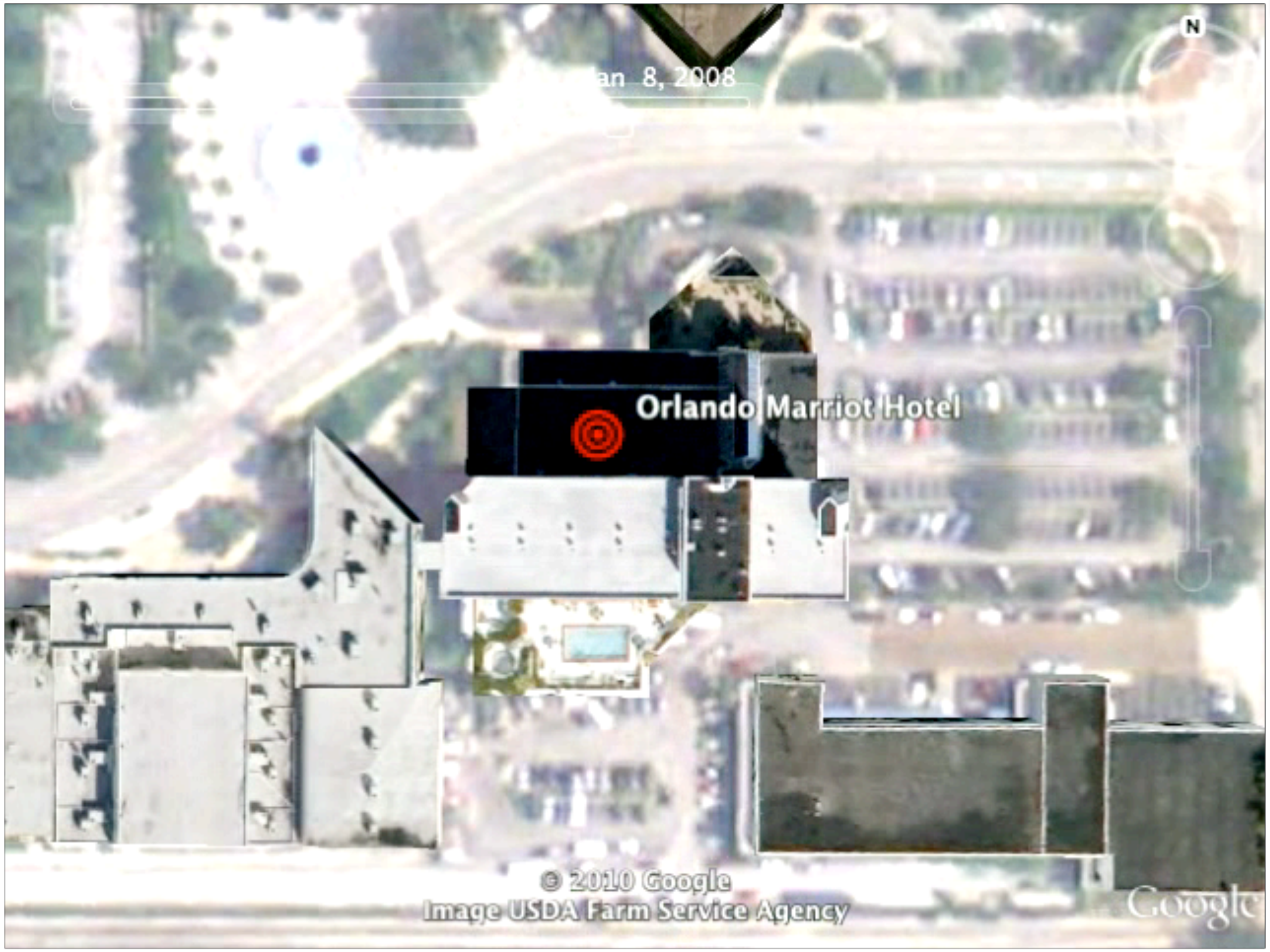

This slide includes movie file which you can download separately from www.devoeng.com

Location of Reservoir

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Part 2

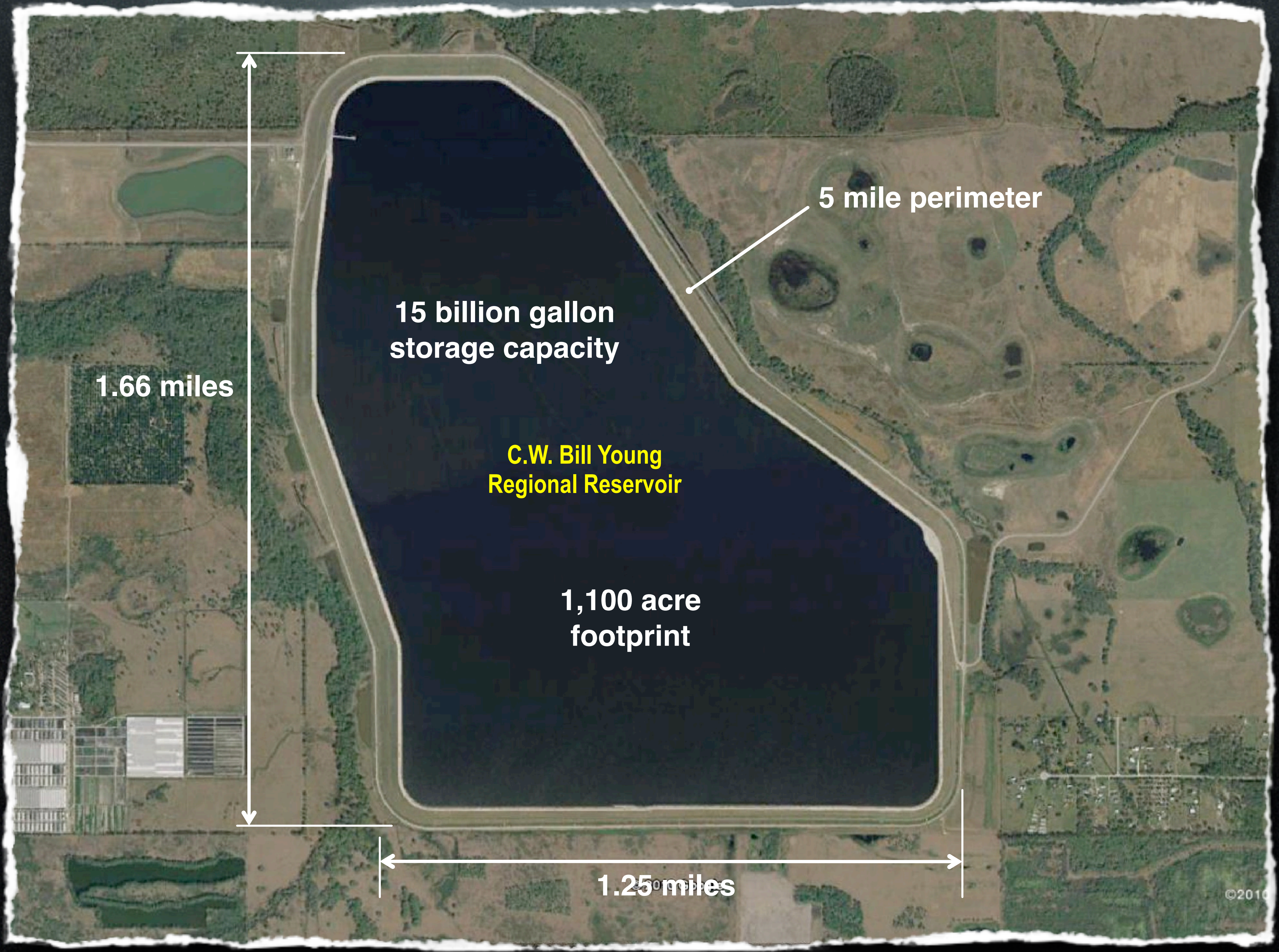
PURPOSE AND DESCRIPTION OF FACILITY

The C.W. Bill Young Regional Reservoir

- The C.W. Bill Young Regional Reservoir is an above ground earthen reservoir which is owned and operated by the Tampa Bay Water Authority.
- When surplus river water is available in the Tampa Bypass Canal, Alafia and Hillsborough rivers, it is sent to the reservoir for storage.
- During dry times, water from the reservoir is sent to the Tampa Bay Regional Surface Water Treatment Plant .
- When full, the reservoir can provide 25 percent of the region’s needs for more than six months.

Panoramic View

Panoramic View


5 mile perimeter
15 billion gallon storage capacity
1.66 miles
C.W. Bill Young Regional Reservoir
1,100 acre footprint
1.25 miles
©2010

TAMPA BAY WATER

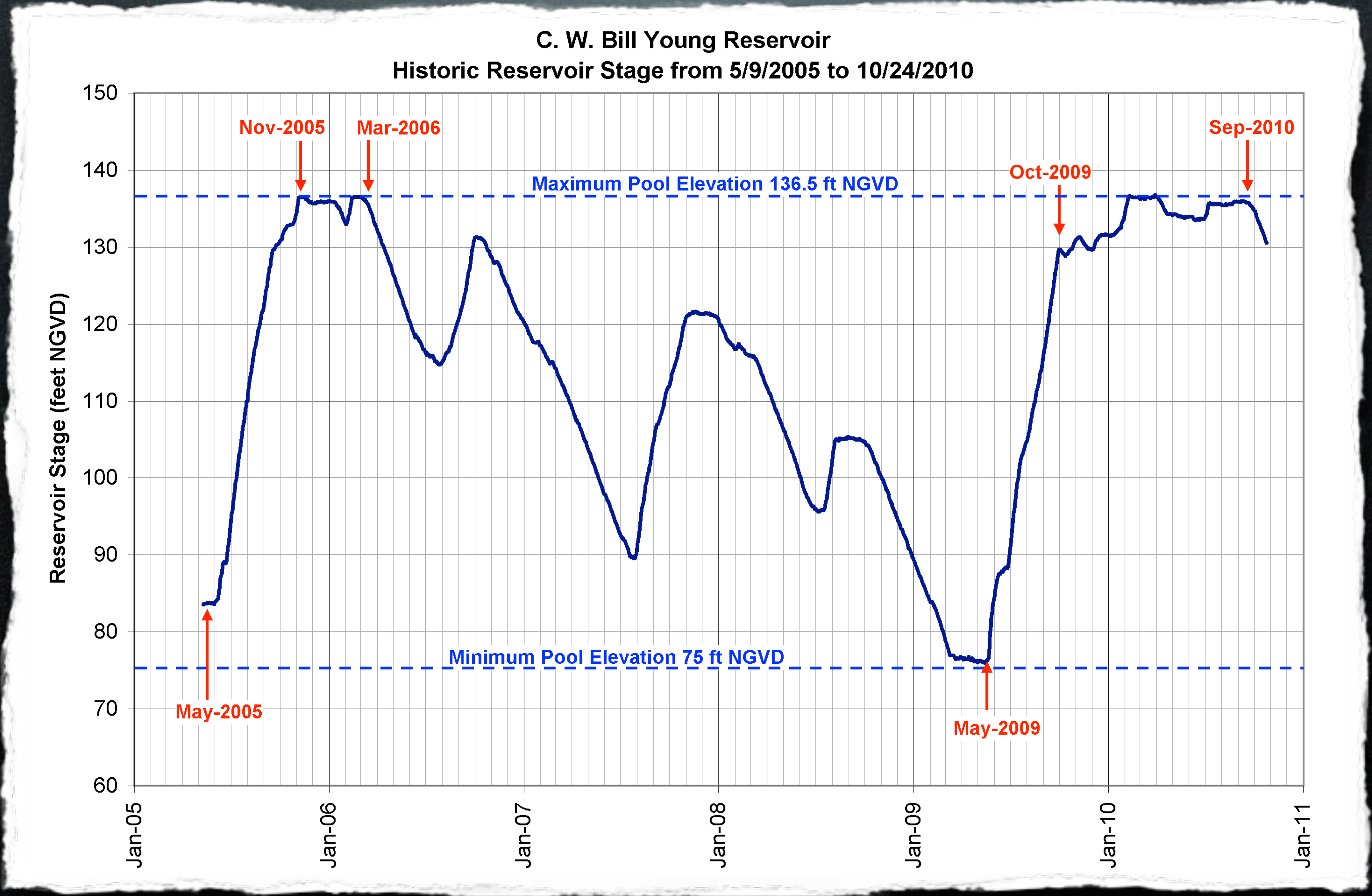
C.W. Bill Young Regional Reservoir Facts

- Holds 15-billion gallons of water-33 times the volume of Raymond James Stadium.
- Covers approximately 1,100 acres.
- When full, can provide the full capacity of the regional surface water treatment plant for 227 days.
- Is 2 miles long and 1 mile wide; berm perimeter at top is 5 miles.
- Can withstand sustained winds of 110 mph and 40-inches of rain in 24 hours without overtopping.
- During construction, more than 150 pieces of heavy equipment were used and more than 150 people were employed.
- More than 13 million cubic yards of earth were moved to build the reservoir-that's one dump truck every minute for 2 years straight.

Brief History

- Construction began in July 2002. Substantially completed by February 2005.
- Initial filling of reservoir began in May 2005, completed in November 2005.
- The reservoir was put into service in March 2006 (beginning of first drawdown cycle).

Historic Reservoir Stage from 5/9/2005 to 10/24/2010



Part 3

RESERVOIR EMBANKMENT CROSS-SECTION WITH FOCUS ON THE WEDGE

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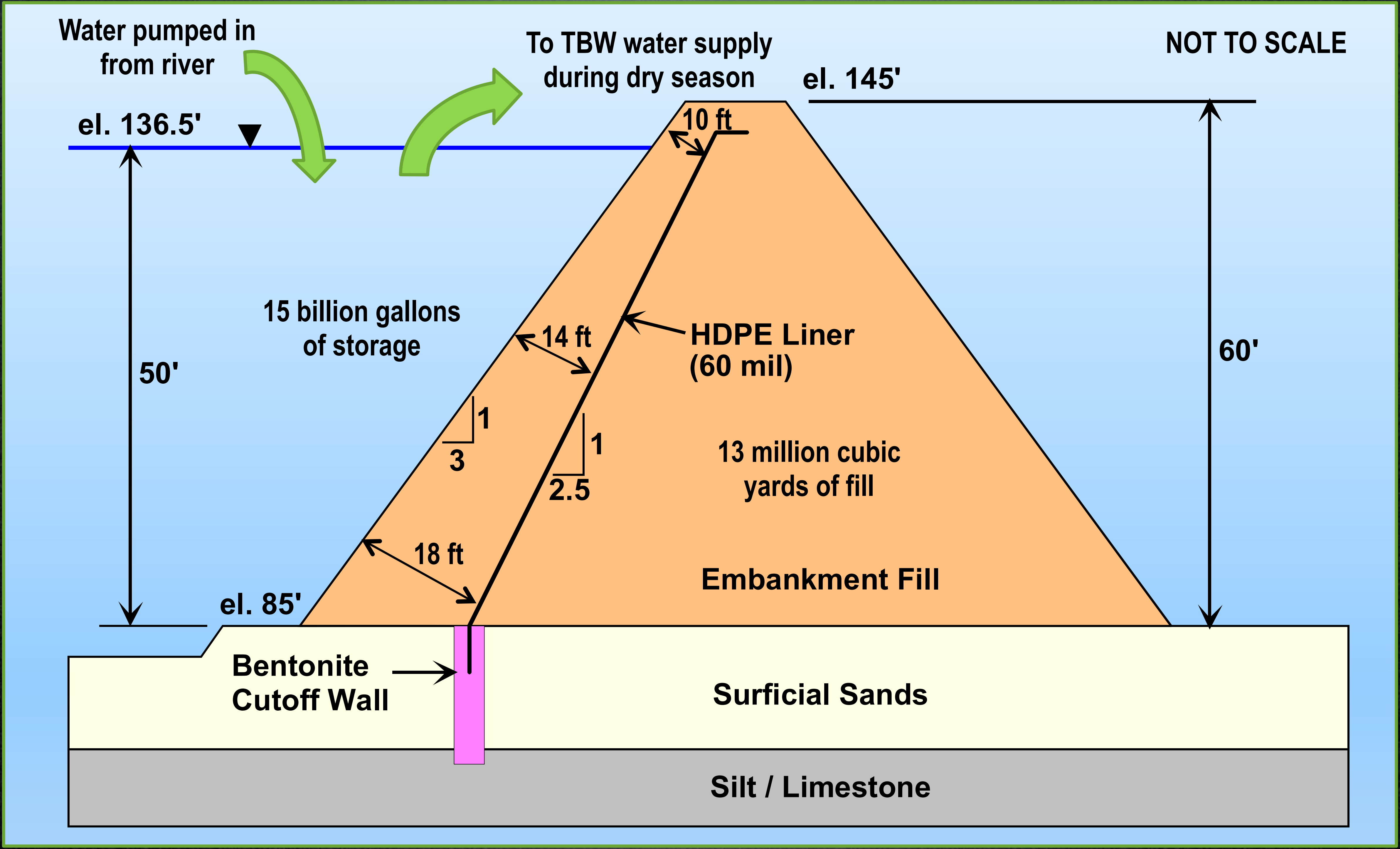
Sketch of Cross-Section



One of the more technically significant embankment fills in the state of Florida

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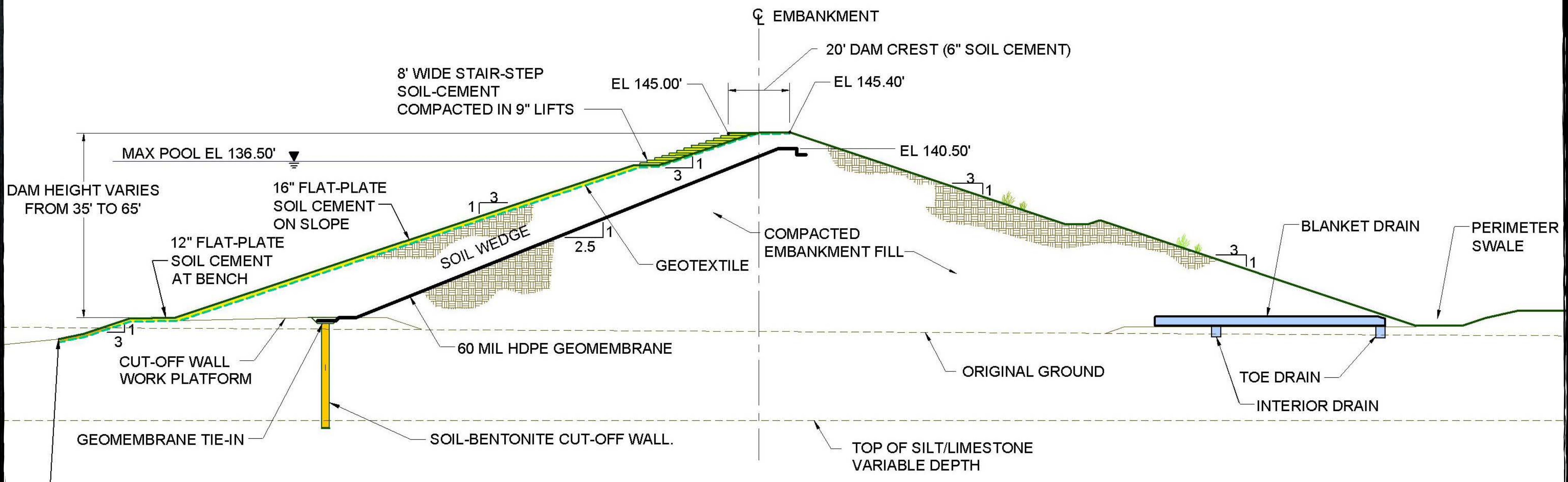
Typical Embankment Cross-Section



TYPICAL EMBANKMENT SECTION

AUGUST 2001 (FINAL DESIGN)

SCALE:1"= 50'

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Embankment Characteristics

- 1,100 acre reservoir footprint
- 5 miles long perimeter.
- 15 billion gallon storage capacity
- 13 million cubic yards of fill
- Embankment height varies from about 35 ft to 65 ft. Average embankment height of 55 ft.
- Height of water about 25 to 55 ft above grade. Average height of water of 45 ft.

Embankment Characteristics

- 3H to 1V upstream slope
- 16-inch thick flat plate soil-cement on upstream slope for wave protection, transitioning to stair step soil cement (above maximum pool elevation) for wave attenuation.
- Internal 60 mil geomembrane for seepage control placed at a slope of 2.5H to 1 V.
- Geomembrane ties into a soil-bentonite cutoff wall beneath embankment for seepage control.
- Constructed from onsite borrow material, predominately silty sands (SM) with average fines content of 17% passing #200 sieve.

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Part 4

RESERVOIR FILLING AND EMPTYING

STAGE HISTORY AND TIMING OF DISTRESS

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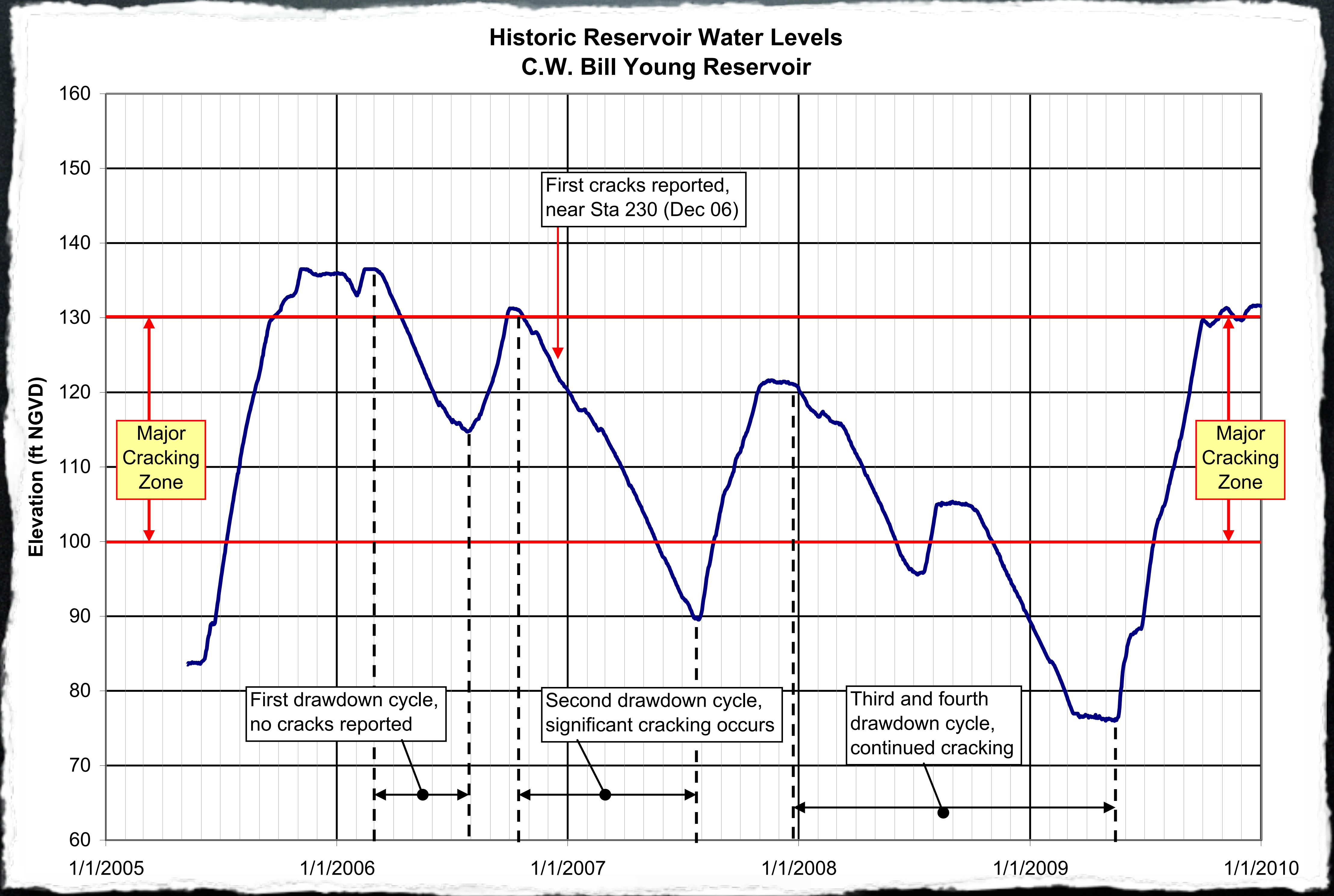
Historic Reservoir Water Levels



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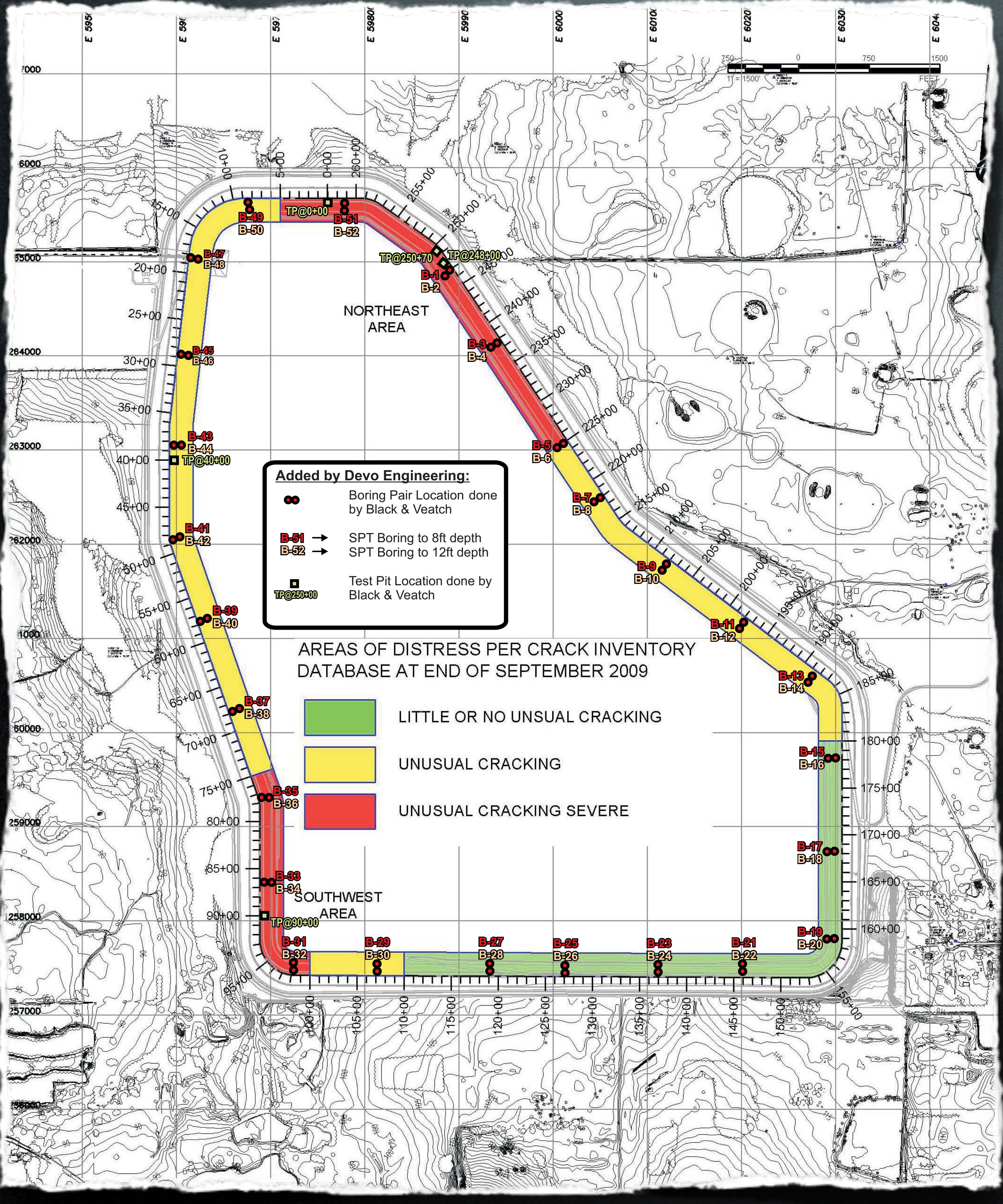
Design Drawdown Rate
vs
Actual Drawdown Rate

Description	Drawdown Rate (in/day)
Design Drawdown	
Operational Drawdown	2.7
Emergency Operational Drawdown	3.3
Rapid Drawdown	18.9
Historical Drawdown Rates	
First Drawdown Cycle	2.3
Second Drawdown Cycle	1.8
Third Drawdown Cycle	2.2
Fourth Drawdown Cycle	2.1

Cracking of Soil-Cement

- First cracking in soil-cement lining on the upstream face of the embankment was observed in December 2006, on the second drawdown cycle.
- Soil-cement cracking continued and worsened throughout second drawdown cycle, and during subsequent drawdown cycles.
- Cracking was most severe in the Northeast and Southwest corners of the reservoir.



Areas of Distress

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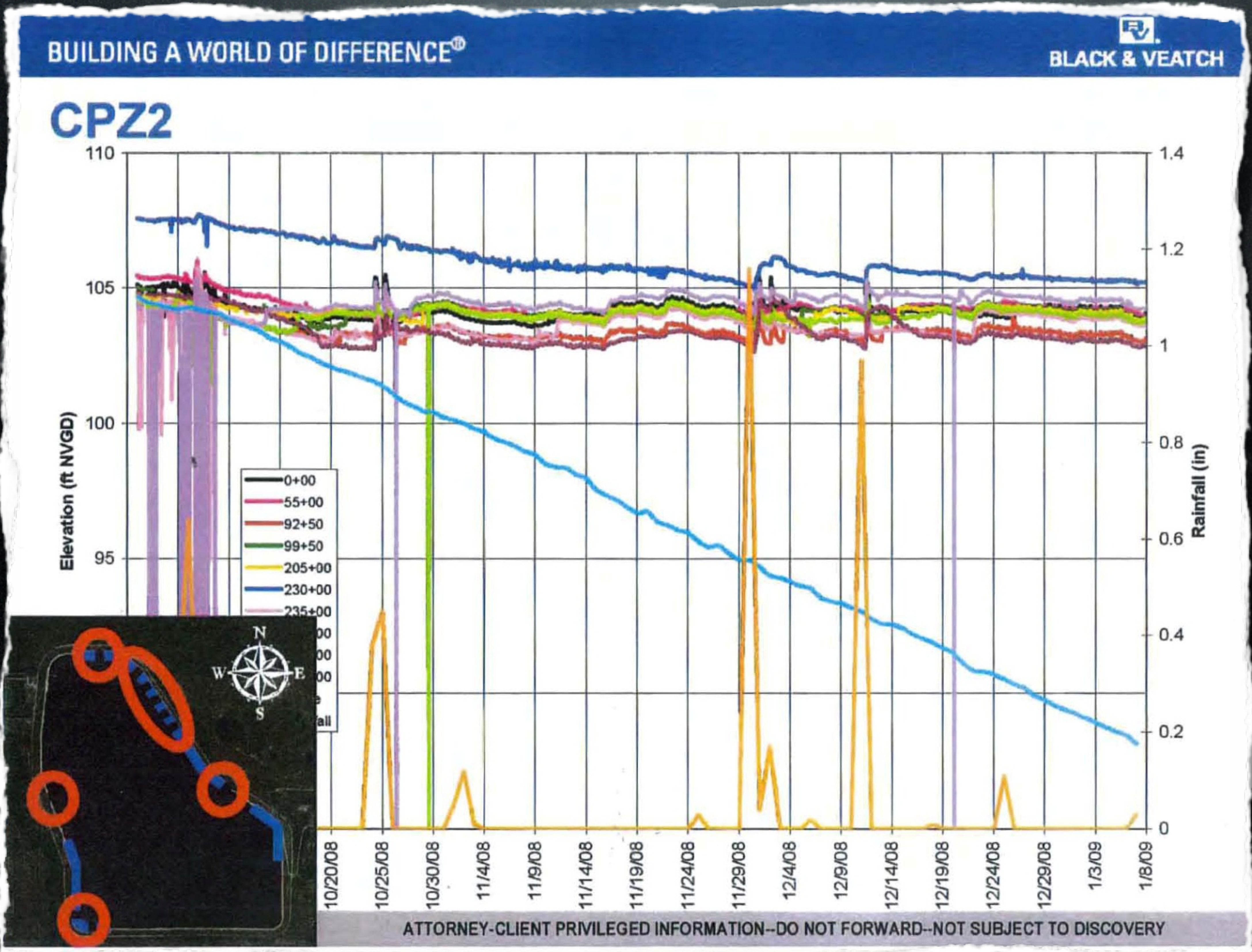
CPZ2 Piezometers



BUILDING A WORLD OF DIFFERENCE®

BLACK & VEATCH

CPZ2

ATTORNEY-CLIENT PRIVILEGED INFORMATION--DO NOT FORWARD--NOT SUBJECT TO DISCOVERY

Midway up
the slope,
shallow

Part 5

WHAT DOES THE DISTRESS LOOK LIKE?

Example of Gaping Cracks in Soil-Cement

07.23.2007

Example of Gaping Cracks in Soil-Cement


5-30-07

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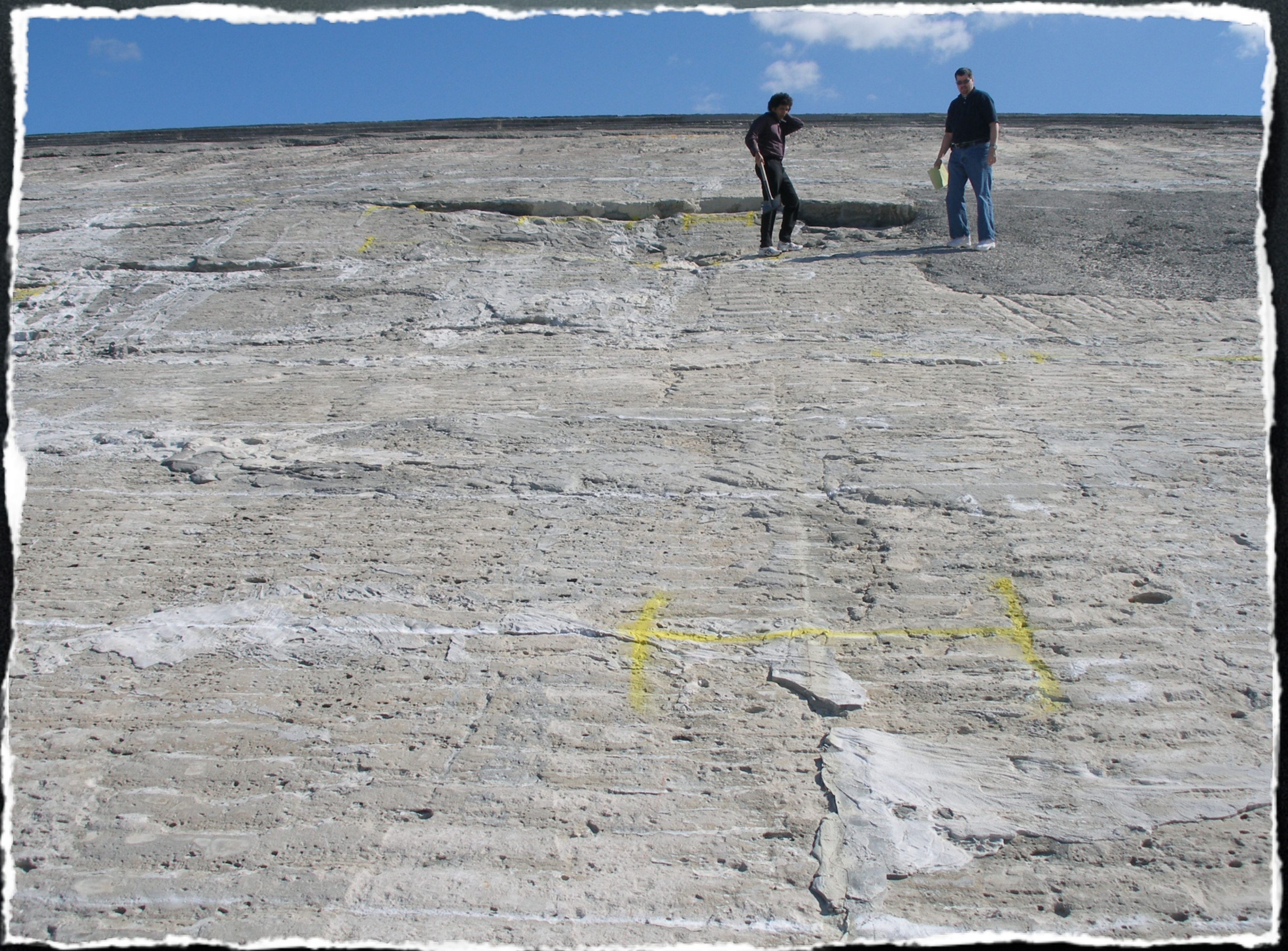
Example of Cracking and Subsidence of Soil-Cement

Example of Cracking and Subsidence of Soil-Cement



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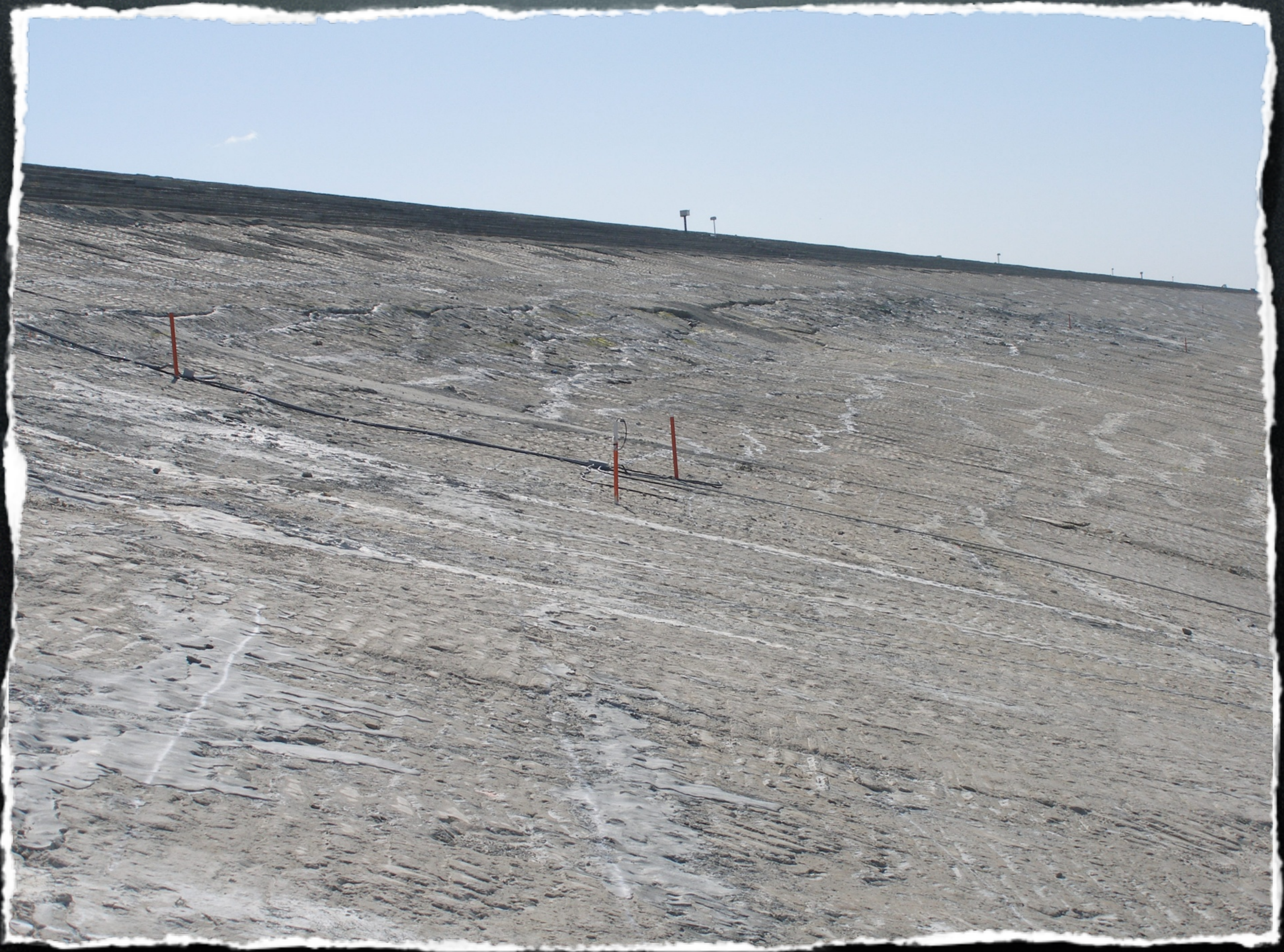
Example of Cracking and Subsidence of Soil-Cement



Example of Cracking and Subsidence of Soil-Cement

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Example of Cracking and Subsidence of Soil-Cement

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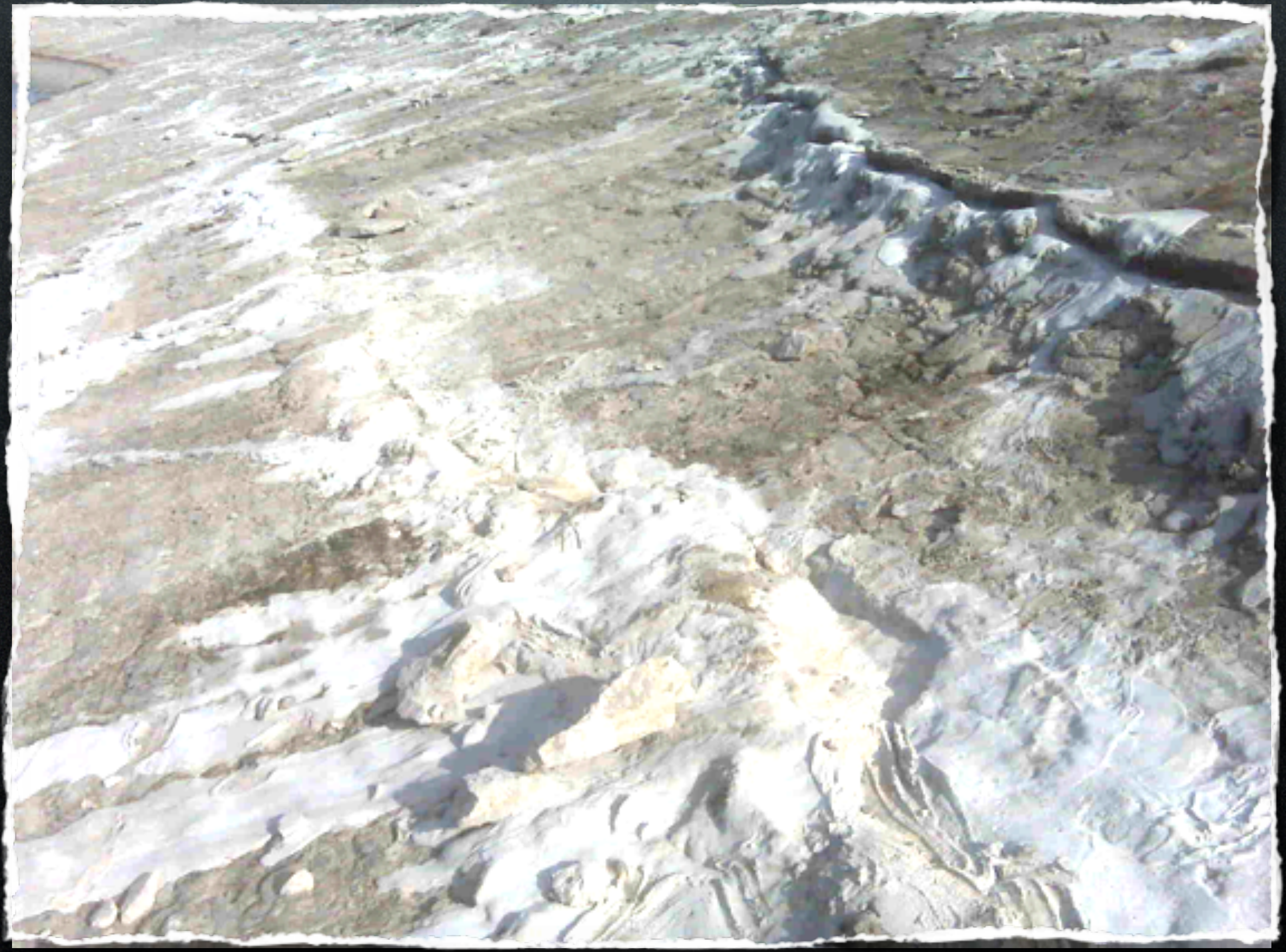

Example of Sag and Buldge

Soil-cement Displacement Near Test Pit

Example of Test Pit Showing Shear Plane

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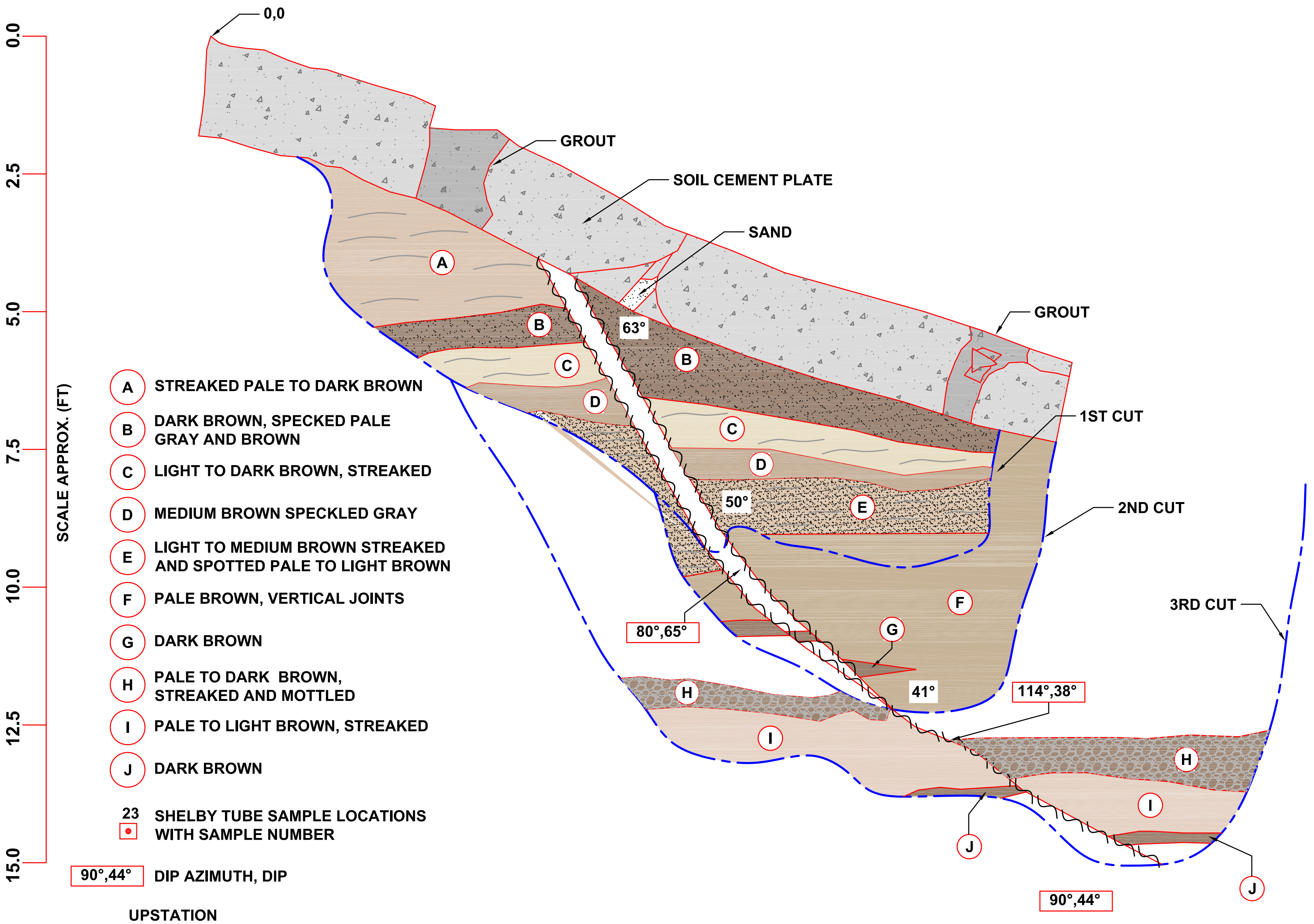
Close-up view of the shear failure plane on the southern pit wall

View looking at the shear failure plane on the northern pit wall

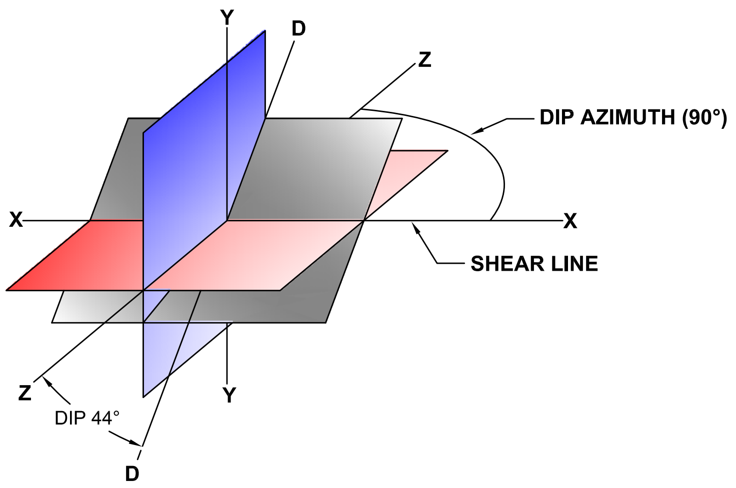
Close-up view of the shear failure plane on the northern pit wall

Test Pit Cross Section

Test Pit Cross Section



A	STREAKED PALE TO DARK BROWN
B	DARK BROWN, SPECKED PALE GRAY AND BROWN
C	LIGHT TO DARK BROWN, STREAKED
D	MEDIUM BROWN SPECKLED GRAY
E	LIGHT TO MEDIUM BROWN STREAKED AND SPOTTED PALE TO LIGHT BROWN
F	PALE BROWN, VERTICAL JOINTS
G	DARK BROWN
H	PALE TO DARK BROWN, STREAKED AND MOTTLED
I	PALE TO LIGHT BROWN, STREAKED
J	DARK BROWN
23 ●	SHELBY TUBE SAMPLE LOCATIONS WITH SAMPLE NUMBER
90°,44°	DIP AZIMUTH, DIP



NOTE:

PLAN AND CROSS-SECTIONAL VIEWS WERE REPRODUCED FROM BLACK AND VEATCH TEST PIT EXCAVATION PHASE 2 REPORT ISSUED ON APRIL 30, 2009

X - SECTION A-A'

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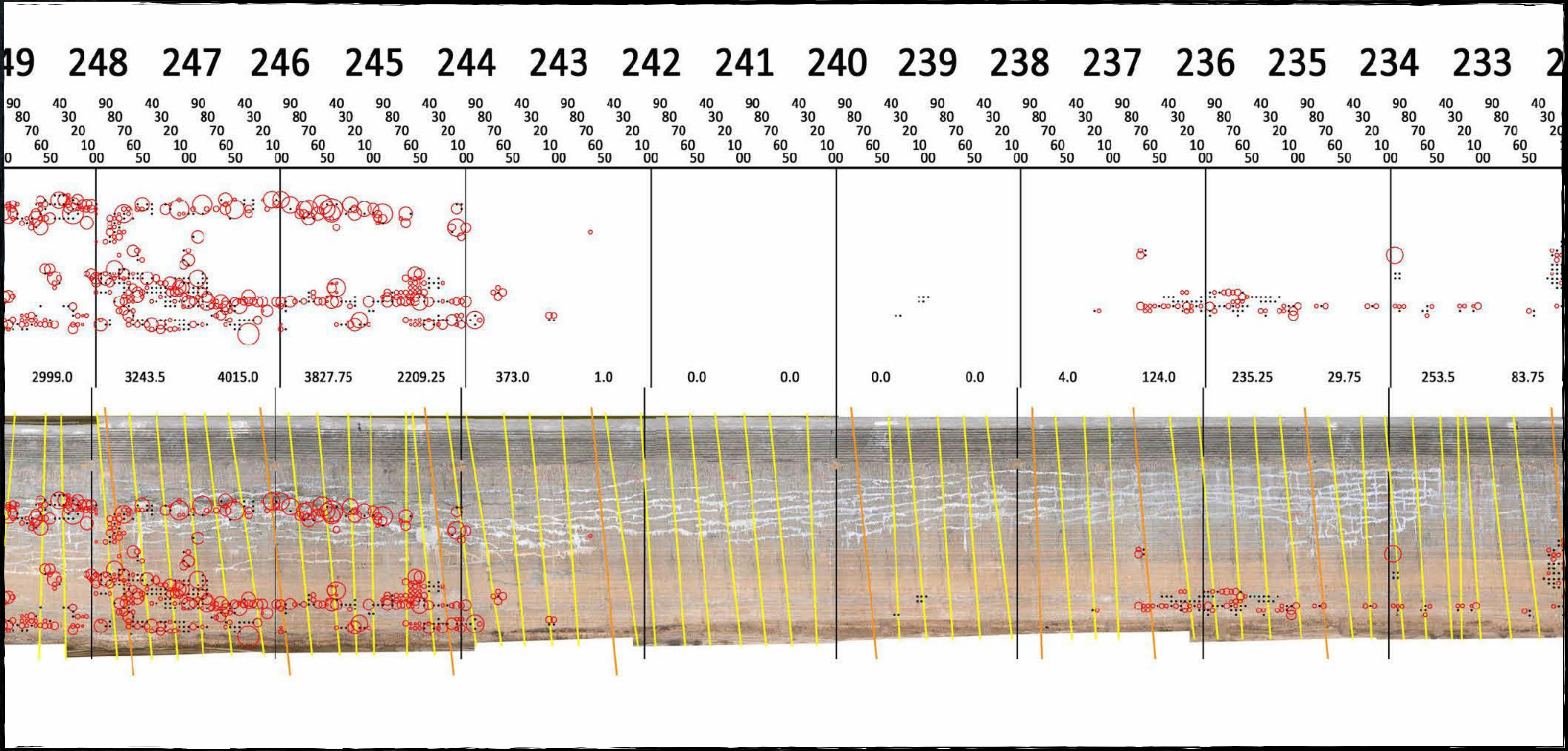
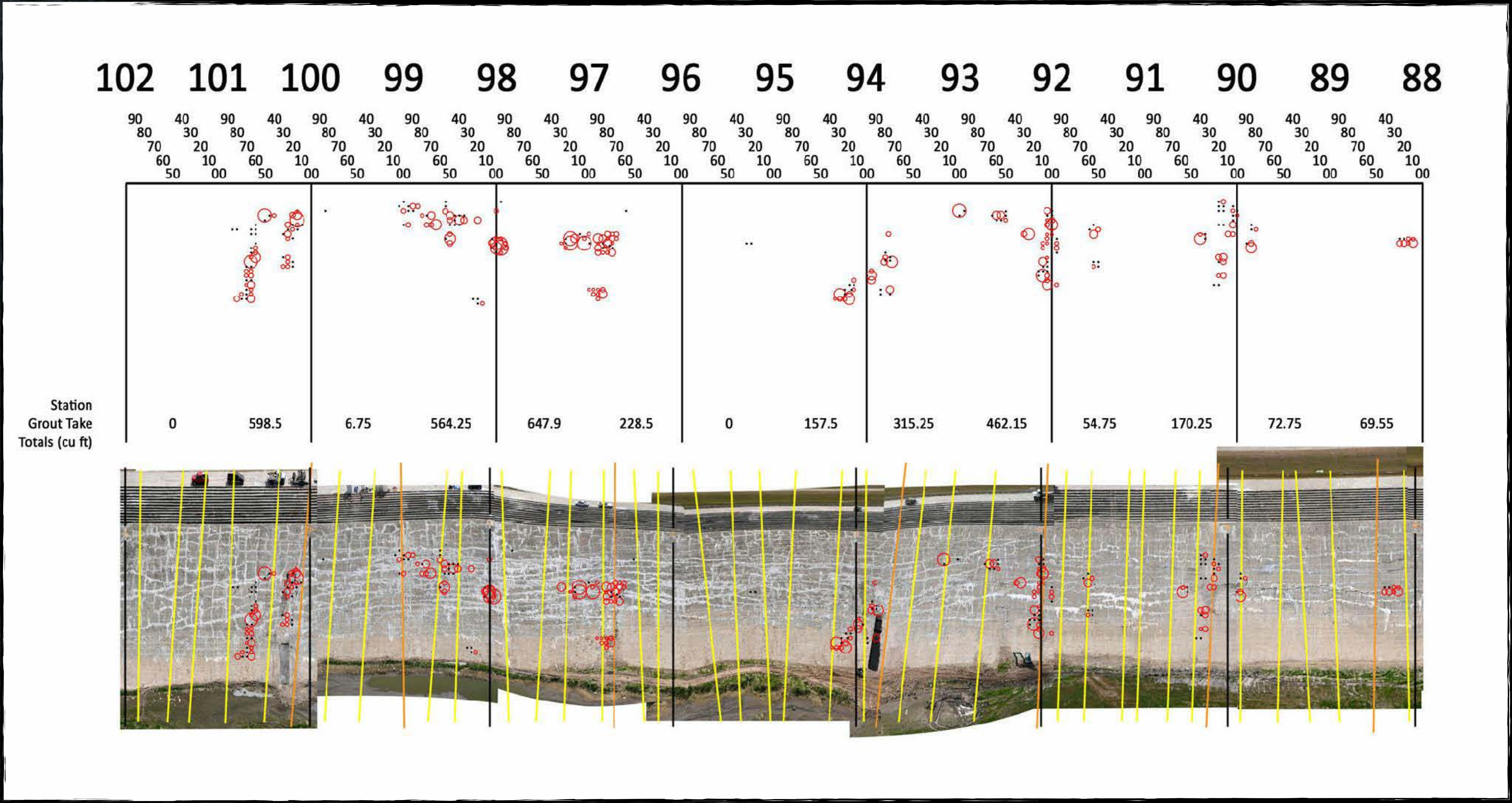
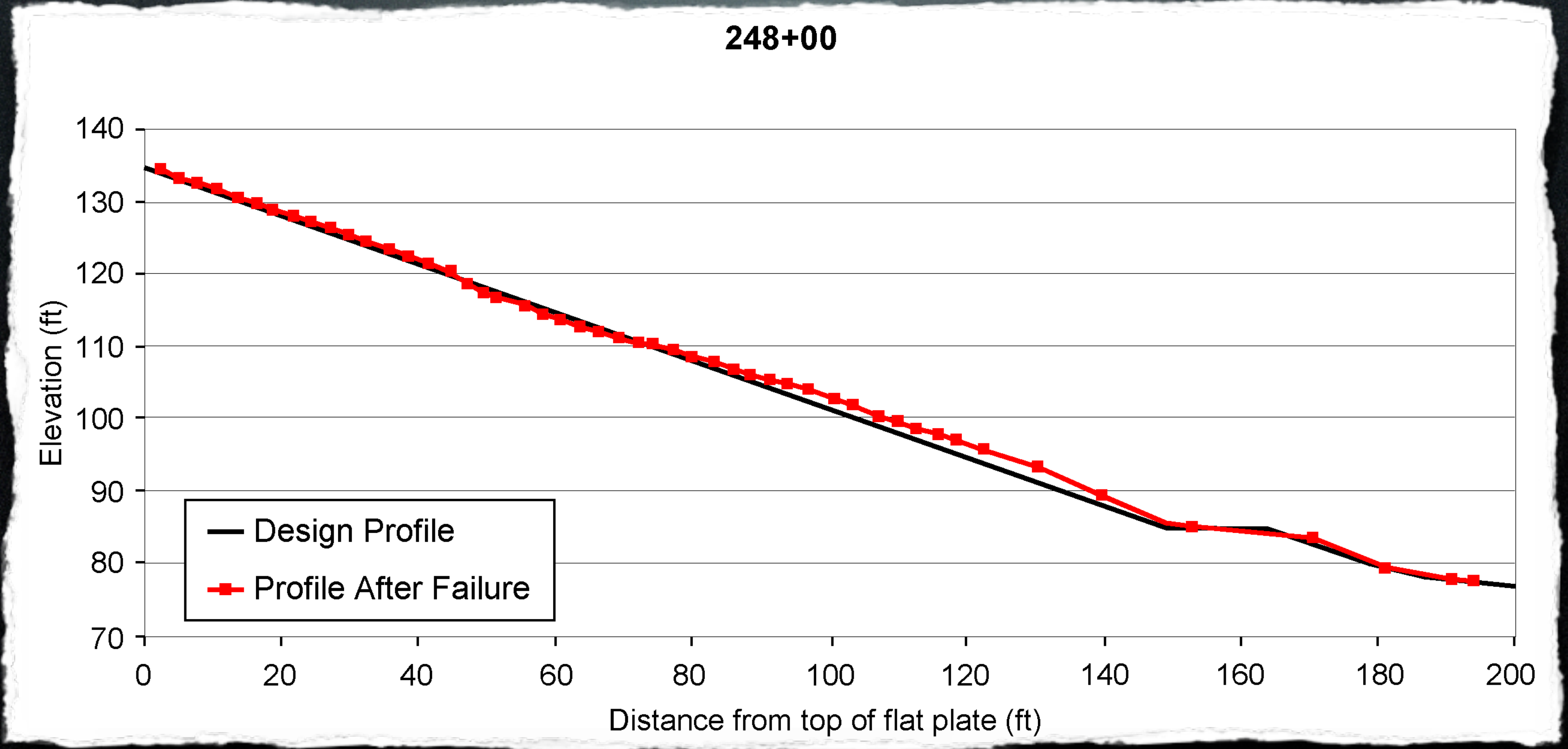
Panorama of soil-cement cracking in northeast corner



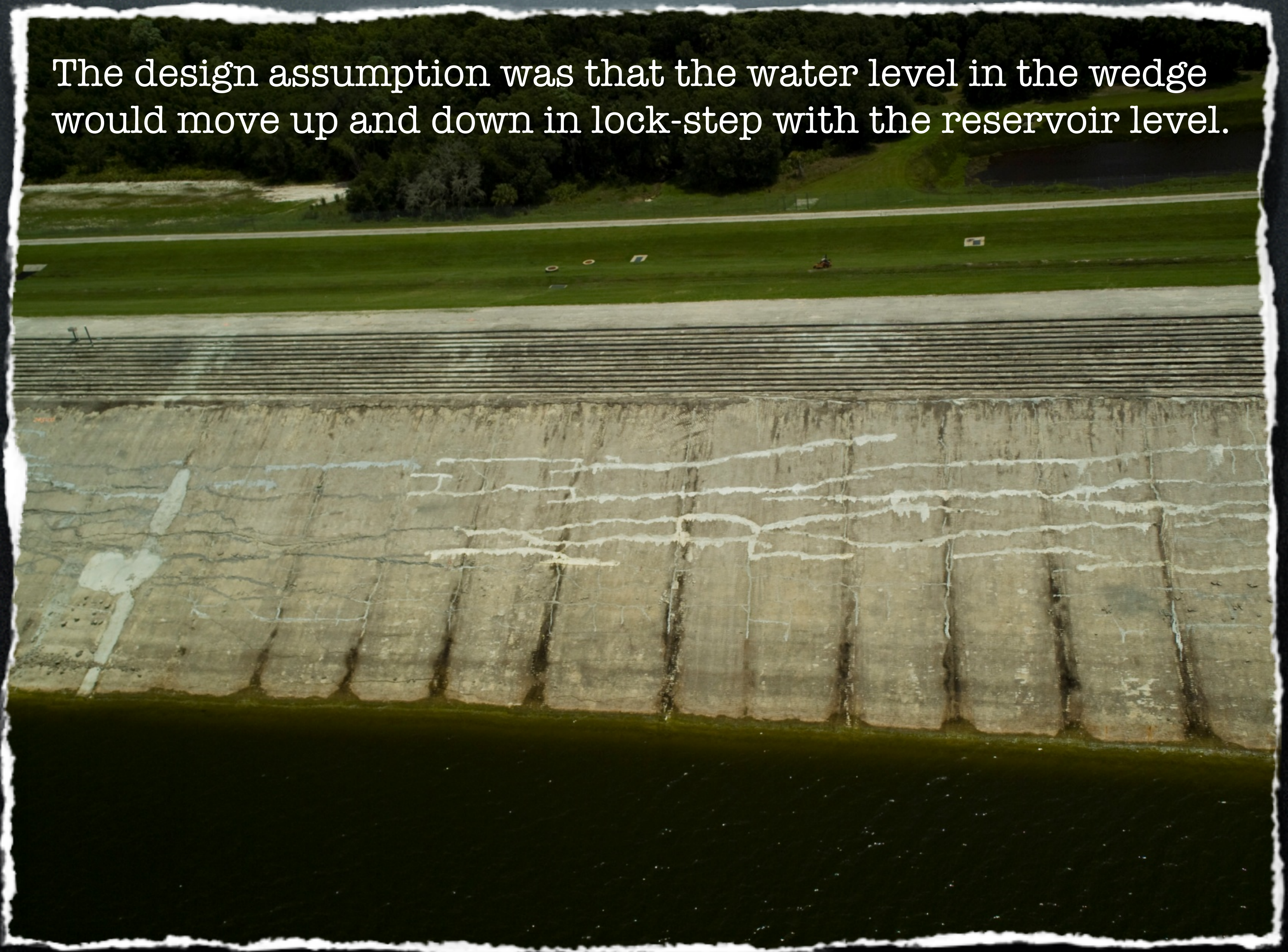
Panorama of soil-cement cracking in southwest corner



Survey of Embankment Profile at Station 248+00



Signs of Embankment Seepage Problem



The design assumption was that the water level in the wedge would move up and down in lock-step with the reservoir level.

Note signs of water seepage through soil-cement construction joints, indicative of poor drainage of embankment wedge.

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Failure During Construction

This slope failure occurred during construction, underneath the geomembrane seepage barrier (slope of 2.5H to 1V).

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Failure During Construction


03/25/2004

Failure During Construction

Failure During Construction

03/25/2004

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Part 6

METHODS OF SLOPE STABILITY ANALYSIS

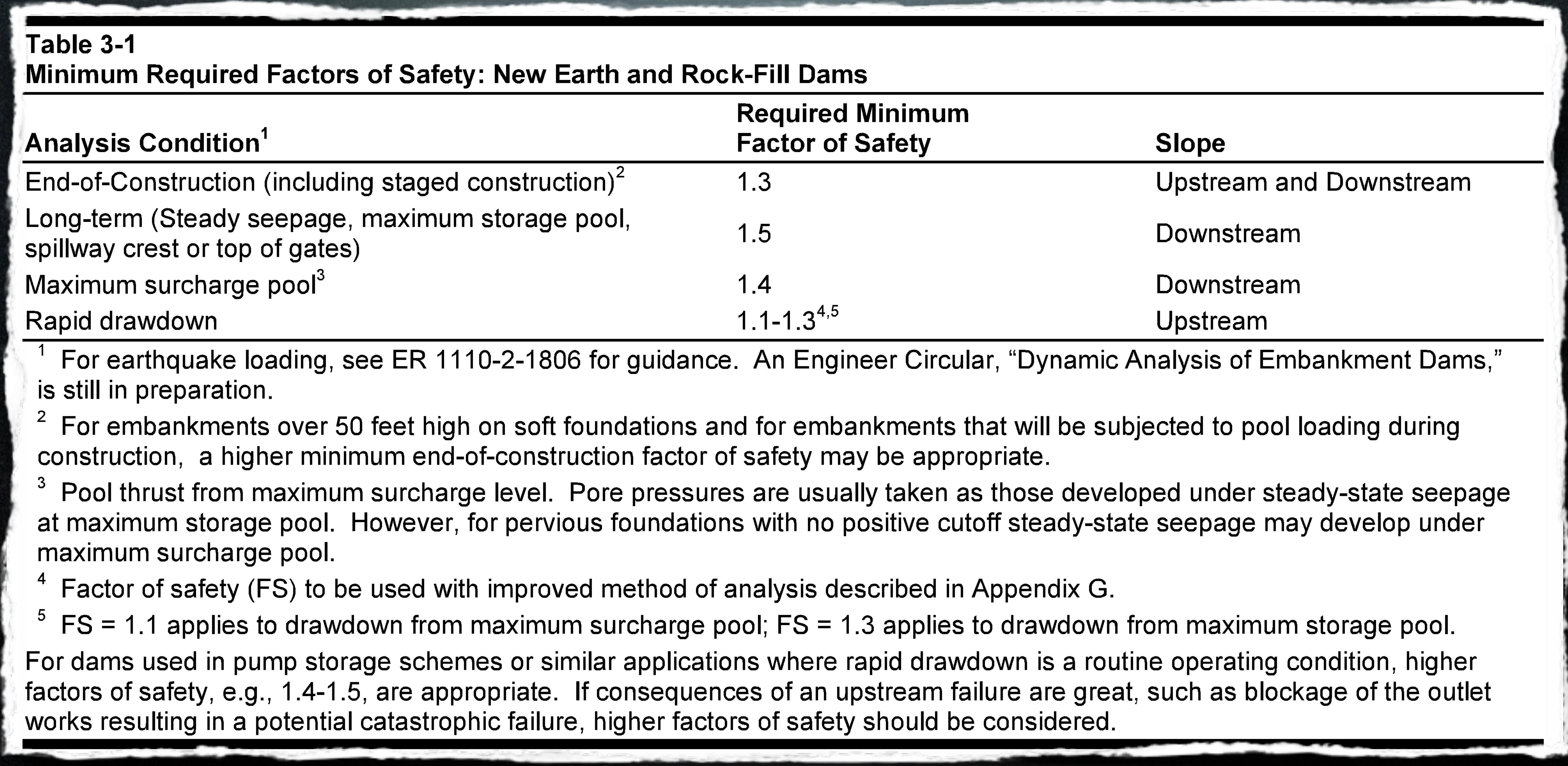


Table 3-1
Minimum Required Factors of Safety: New Earth and Rock-Fill Dams

Analysis Condition[1]	Required Minimum Factor of Safety	Slope
End-of-Construction (including staged construction)[2]	1.3	Upstream and Downstream
Long-term (Steady seepage, maximum storage pool, spillway crest or top of gates)	1.5	Downstream
Maximum surcharge pool[3]	1.4	Downstream
Rapid drawdown	1.1-1.3[4,5]	Upstream

[1] For earthquake loading, see ER 1110-2-1806 for guidance. An Engineer Circular, "Dynamic Analysis of Embankment Dams," is still in preparation.

[2] For embankments over 50 feet high on soft foundations and for embankments that will be subjected to pool loading during construction, a higher minimum end-of-construction factor of safety may be appropriate.

[3] Pool thrust from maximum surcharge level. Pore pressures are usually taken as those developed under steady-state seepage at maximum storage pool. However, for pervious foundations with no positive cutoff steady-state seepage may develop under maximum surcharge pool.

[4] Factor of safety (FS) to be used with improved method of analysis described in Appendix G.

[5] FS = 1.1 applies to drawdown from maximum surcharge pool; FS = 1.3 applies to drawdown from maximum storage pool.

For dams used in pump storage schemes or similar applications where rapid drawdown is a routine operating condition, higher factors of safety, e.g., 1.4-1.5, are appropriate. If consequences of an upstream failure are great, such as blockage of the outlet works resulting in a potential catastrophic failure, higher factors of safety should be considered.

Minimum Factors of Safety (US Army Corp)

Methods of Slope Analysis

- Slope Stability For Infinite Slope, with seepage forces. Back of envelope calculation.

- Total stress analyses, including modified total stress analysis such as the Duncan, Wright and Wong (DWW) method for rapid drawdown. The DWW method is currently recommended by the US Army Corp of Engineers

- Effective stress analysis. Requires transient pore water pressures. Performed using a coupled seepage/slope stability analysis which is available in the current generation of slope stability software packages, such as SoilVision software.

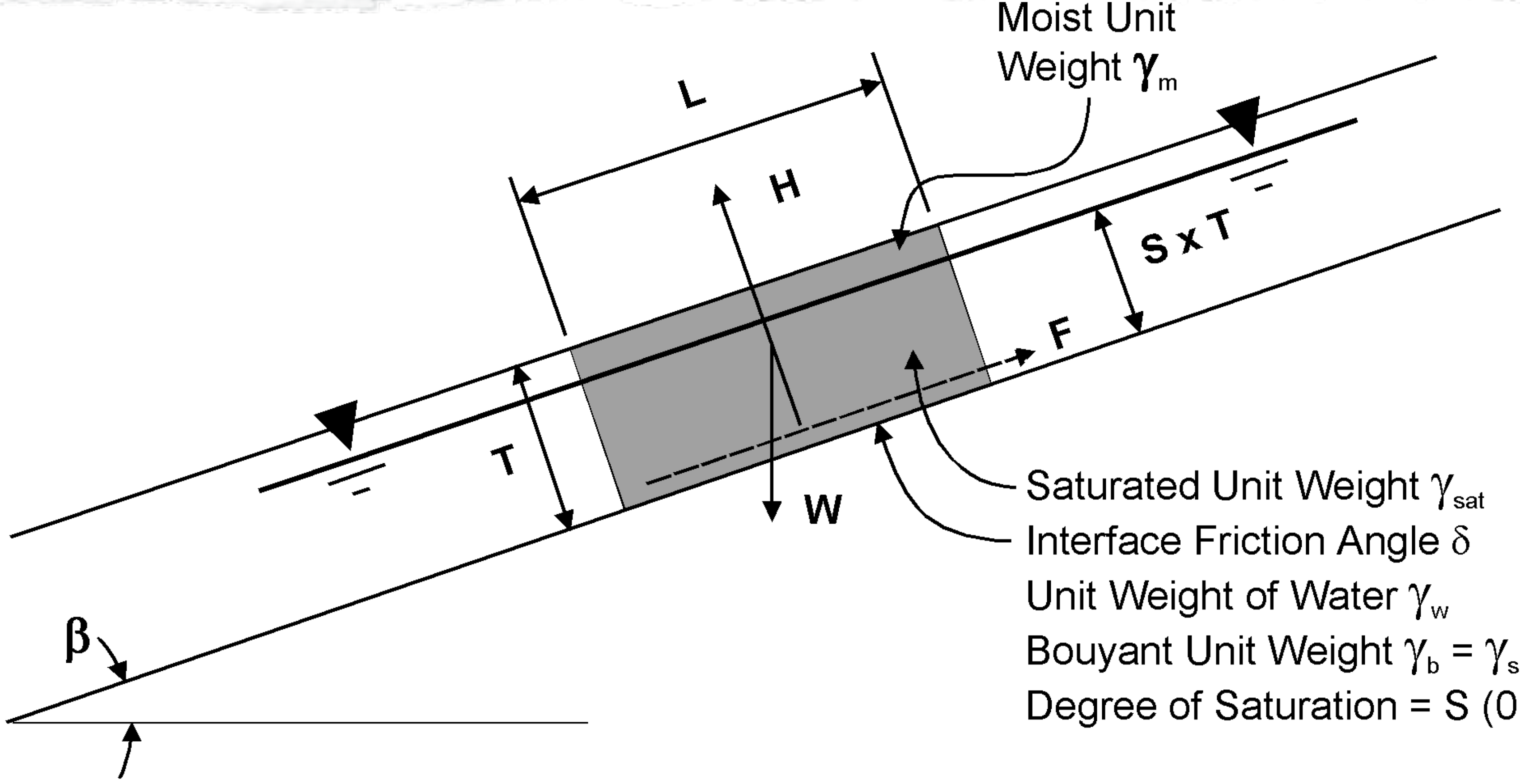
Stability of Infinite Slope

If the rate of drawdown exceeds the rate at which the slope can effectively drain, then the slope can remain saturated during drawdown.

The closed-form infinite slope stability equation (with full saturation and seepage force parallel to the slope) can provide a first look (back of envelope) approximation of the resulting slope stability.

However, additional analyses are recommended regardless of the results of the infinite slope stability calculation.

Stability Of Infinite Slope



Moist Unit Weight γ_m

Saturated Unit Weight γ_{sat}
Interface Friction Angle δ
Unit Weight of Water γ_w
Bouyant Unit Weight $\gamma_b = \gamma_{sat} - \gamma_w$
Degree of Saturation = S (0.0 to 1.0)

$\sum$ Forces parallel to slope

Resisting Force: $F = \{ \gamma_m T (1-S) L + L \gamma_b T S \} \tan\delta \cos\beta$
Seepage Force: $= \gamma_w T S L \sin\beta$
Weight: $= \{ \gamma_m T (1-S) L + L \gamma_b T S \} \sin\beta$

$$\text{Factor of Safety} = \frac{\text{Resisting Force}}{\text{Seepage Force + Weight}} = \frac{\tan\delta}{\tan\beta}\left\{\frac{\gamma_m (1-S) + \gamma_b S}{\gamma_w S + \gamma_m(1-S) + \gamma_b S}\right\}$$

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Example of Factor of Safety for Infinite Slope with Seepage Forces

Given:

Friction angle, ϕ' = 34 degrees

Saturation = 1.0

Slope = 3H to 1V

Saturated Unit Weight, γsat = 132 lb/ft3

Moist Unit Weight, γmoist = 116 lb/ft3

Then:

FS = 1.07 (not adequate)

Duncan, Wright and Wong (DWW) Rapid Drawdown Analysis

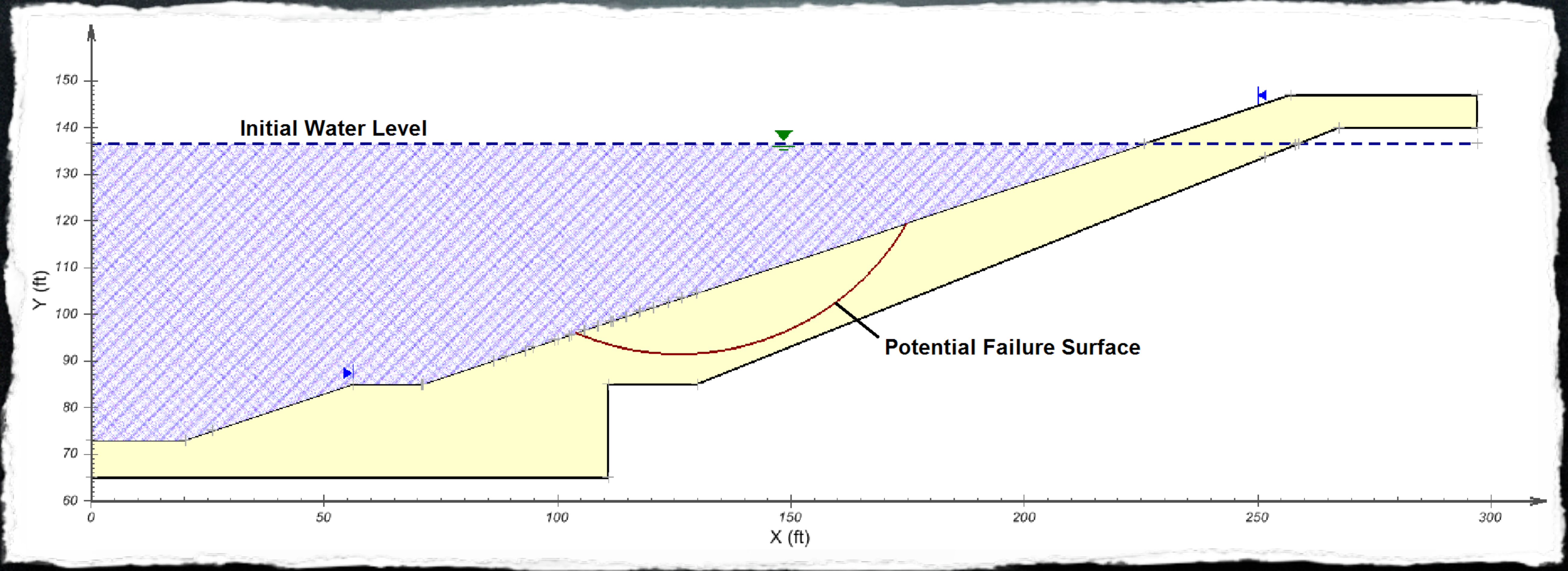
The Duncan, Wright and Wong (DWW) rapid drawdown analysis is a modified total stress analysis, which recognizes that negative pore pressures (which can lead to high safety factors) may not fully develop due to factors such as:

- Localized drainage within the soil
- Cavitation due to negative pore pressures

DWW is a three stage slope stability calculation which uses both undrained and drained soil strength parameters.

Note that this method was developed in late 1980's to early 1990's before computers were available for detailed seepage/pore water pressure calcs. This method is currently recommended by the US Army Corp of Engineers.

Duncan, Wright and Wong , Stage 1



Stage 1 is used to calculate the effective stresses along the base of a potential failure surface when the water level is at maximum steady stage pool elevation.

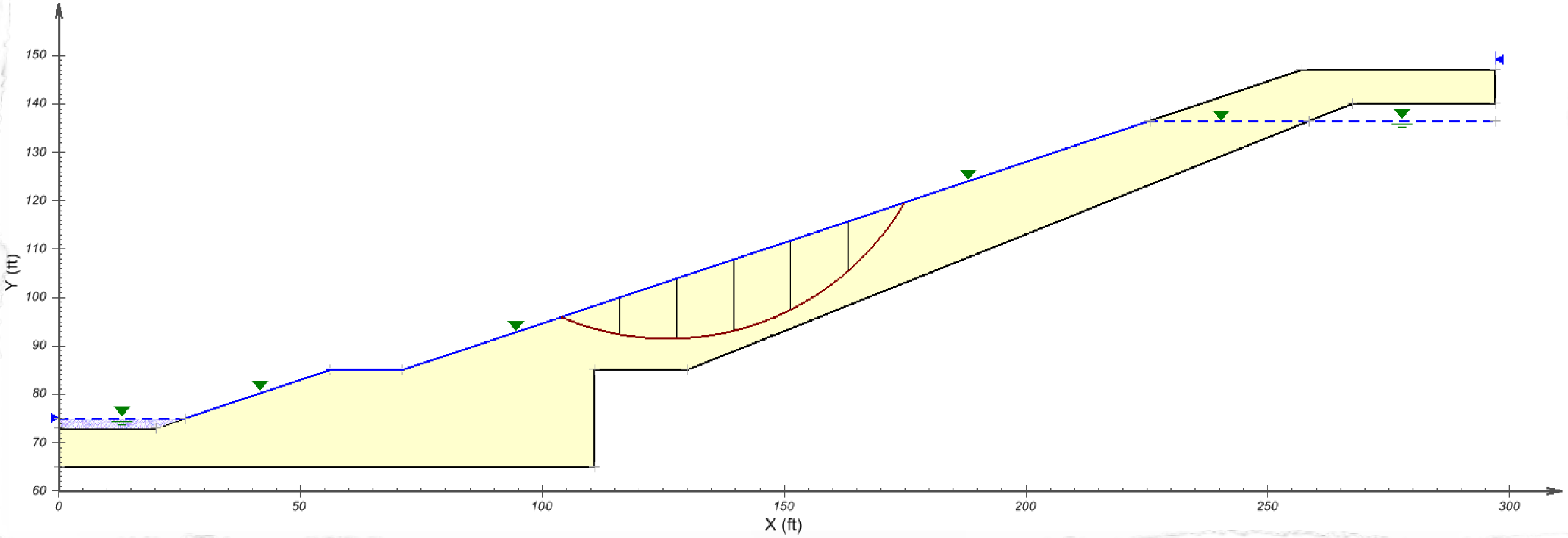
Duncan, Wright and Wong , Stage 2

In Stage 2, it is assumed that the pool water level is drawn down instantaneously to the final pool elevation.

For low permeability soils, the pore water pressures do not have time to dissipate, so the stresses experienced along a potential failure surface are the same as calculated in Stage 1.

The factor of safety calculated using the stresses calculated in Stage 1 along with the undrained strength parameters.

Duncan, Wright and Wong , Stage 3



Stage 3 assumes steady state pore water pressures are reestablished at the minimum pool level. The shear strength along a potential slip surface is recalculated using drained strength parameters, on a slice by slice basis. The factor of safety is recalculated, based on the minimum shear resistance from Stage 2 (undrained) or Stage 3 (drained), on a slice by slice basis.

Duncan, Wright and Wong , Stage 3

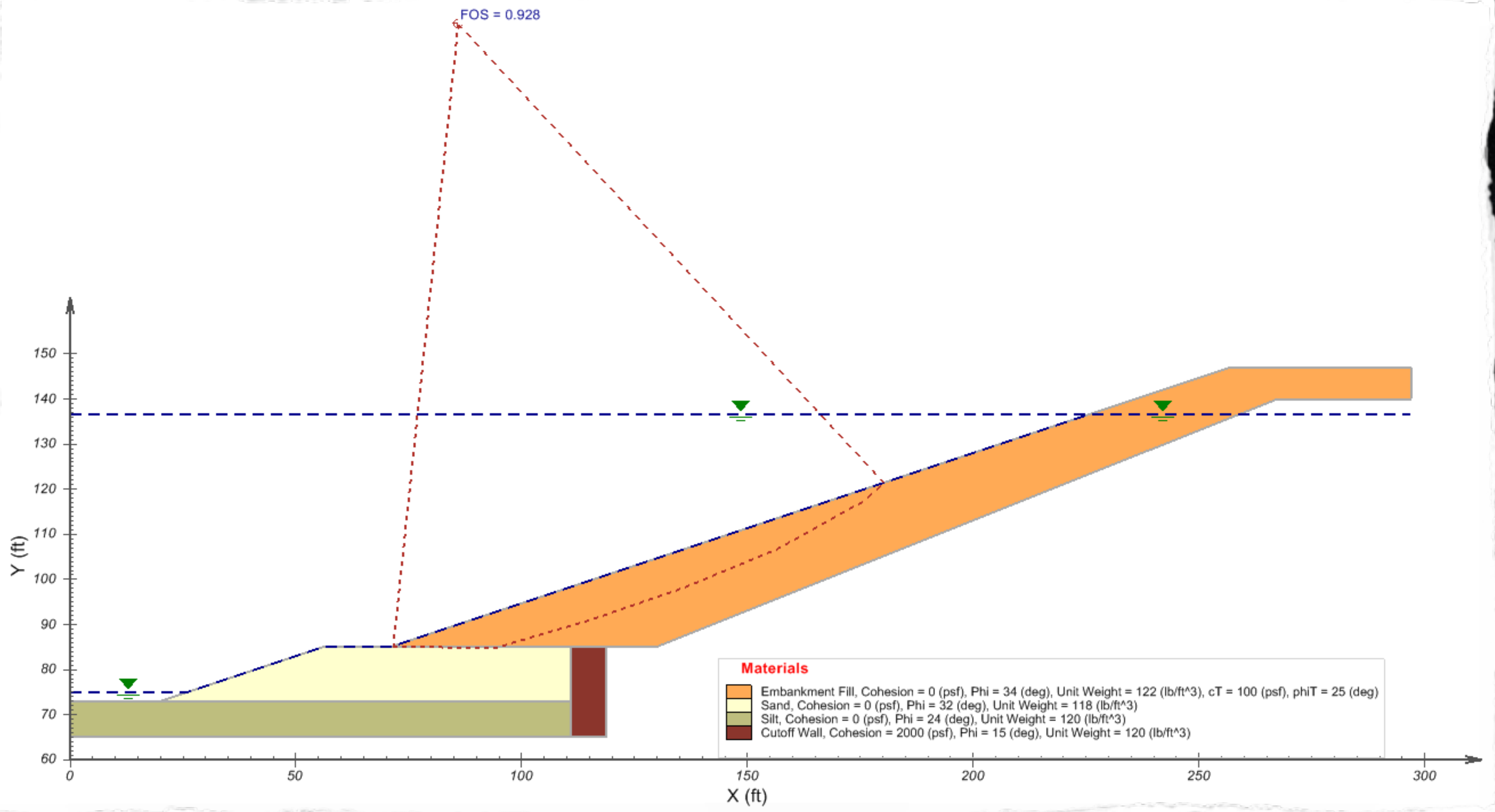
Consideration should be given as to what the final Stage 3 “steady state” water table should look like.

In this case, the embankment wedge does not drain efficiently, and the “steady state” final water table profile in the embankment is not necessarily horizontal, due to:

- Saturation within the wedge due to poor drainage
- Potential recharge from rainfall, etc.

Therefore, the final steady state water table for this embankment was conservatively modeled to represent a fully saturated embankment.

Factor of Safety For Raid Drawdown (DWW)



FS = 0.928

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Limitations of DWW Rapid Drawdown

- Undrained strength parameters must be evaluated based on the appropriate confining pressures, i.e., not a constant, varies with depth, etc.
- Requires care in determining the phreatic surface at “steady state” conditions.
- Assumes hydrostatic pore pressure distribution under the phreatic surface, and cannot account for complex pore pressure distribution.

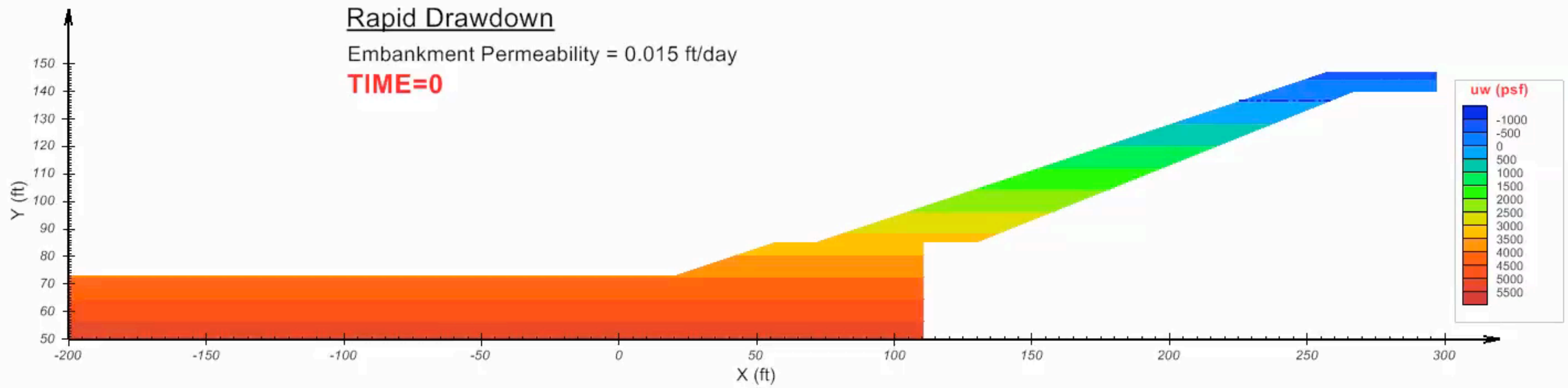
Effective Stress Analysis Using Coupled Seepage/Slope Stability Model

It is common misconception that a total stress analysis is most useful for a rapid draw-down case while an effective stress analysis is most useful for a long-term draw-down scenario.

The difficulty in performing an effective stress analysis for transient and/or rapid drawdown is in defining the transient pore water pressures, which requires a coupled seepage/slope stability analysis. Today's generation of software is capable of performing this analysis.

The effective stress analysis is a more rigorous analysis than the total stress analysis and has the benefit of providing a detailed picture of the performance of pore-water pressures during a draw-down scenario.

Pore pressures during rapid drawdown for K = 0.015 ft/day



Rapid Drawdown

Embankment Permeability = 0.015 ft/day

TIME=0

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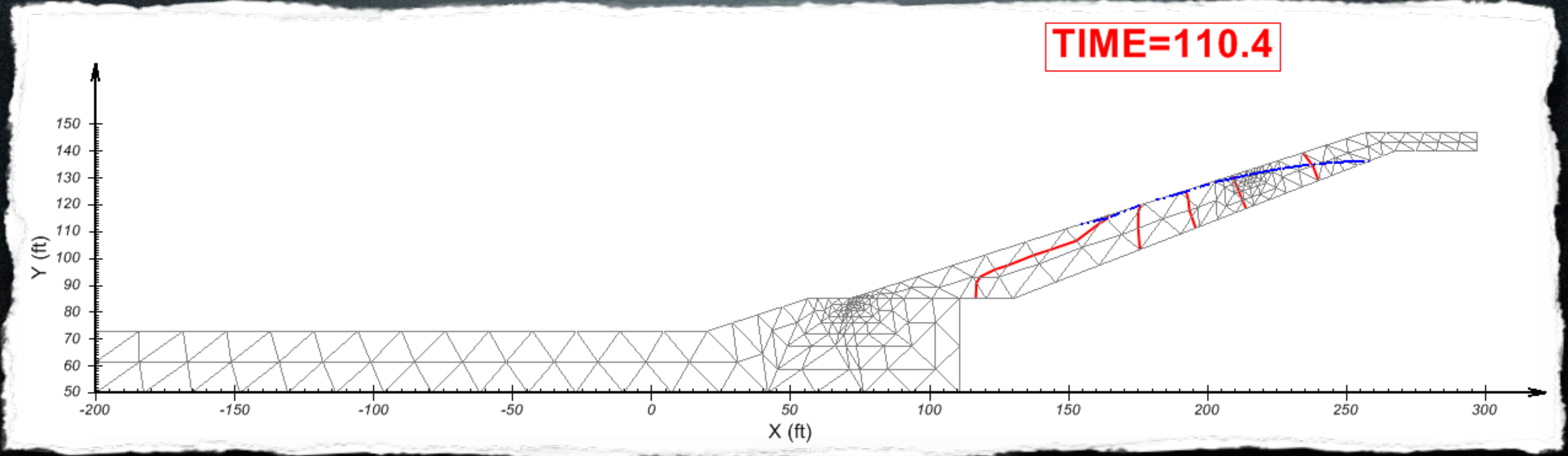
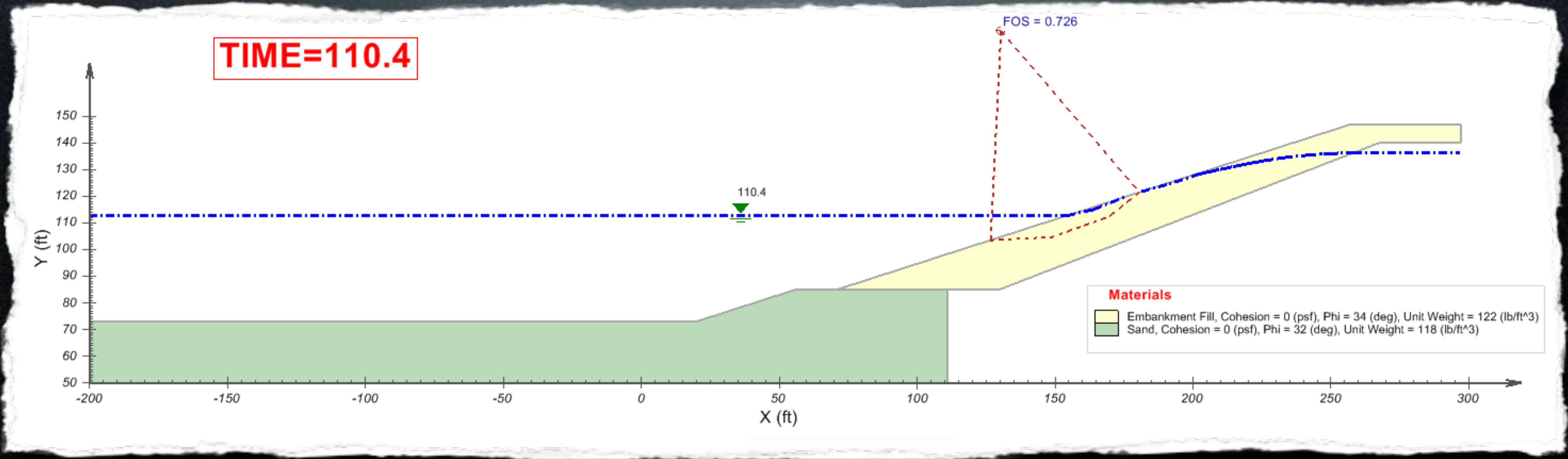
Step 1 – Transient Seepage Analysis



Note that the direction of groundwater flow is perpendicular to the head contours. In this example, an upward seepage force is generated (not hydrostatic), which further decreases stability. This phenomenon is not considered in the DWW rapid drawdown analysis.

Step 2 - Transient Slope Stability Analysis



Uses pore water pressure distribution previously calculated in Step 1.

Part 7

KEY SOIL PROPERTIES OF WEDGE

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Embankment Materials

- The embankment was constructed using onsite borrow materials from interior floor of the reservoir, excavated to a depth of up to approximately 15 ft.
- The construction specifications allowed for the use of soil types classified as SP, SM, SC, SP-SM, SP-SC.
- As constructed, 85% of the soils used in the embankment wedge are classified as SM materials, with an average fines content of 17% passing the #200 sieve, based on testing performed after the upstream slope failures.
- A total of 13 million cubic yards was placed in the construction of the embankment.

Embankment Properties

Design Assumptions:

- The embankment was designed using an assumed permeability of 0.5 ft/day, based on the results of 17 permeability tests on remolded samples with an average percentage of fines of 12% passing the #200 sieve (compacted to 95% of Modified Proctor).

As built:

- Based on testing performed after the upstream slope failures, the average fines content of the in-place embankment fill is 17% passing the #200 sieve, with a resulting average permeability of about 0.015 ft/day. This permeability is 33 times less than the assumed design permeability.

Post-Failure Testing Program

A testing program (Black & Veatch) within the upstream embankment wedge was initiated following the distress to the upstream embankment, which included the following:

- Five (5) Test Pit Excavations
- Fifty Two (52) Standard Penetration Test borings
- Approx. 400 fines content tests (-200 sieve)
- Forty nine (49) laboratory permeability tests on undisturbed samples
- Forty one (41) direct shear tests
- Sixteen (16) Triaxial tests
- And more...

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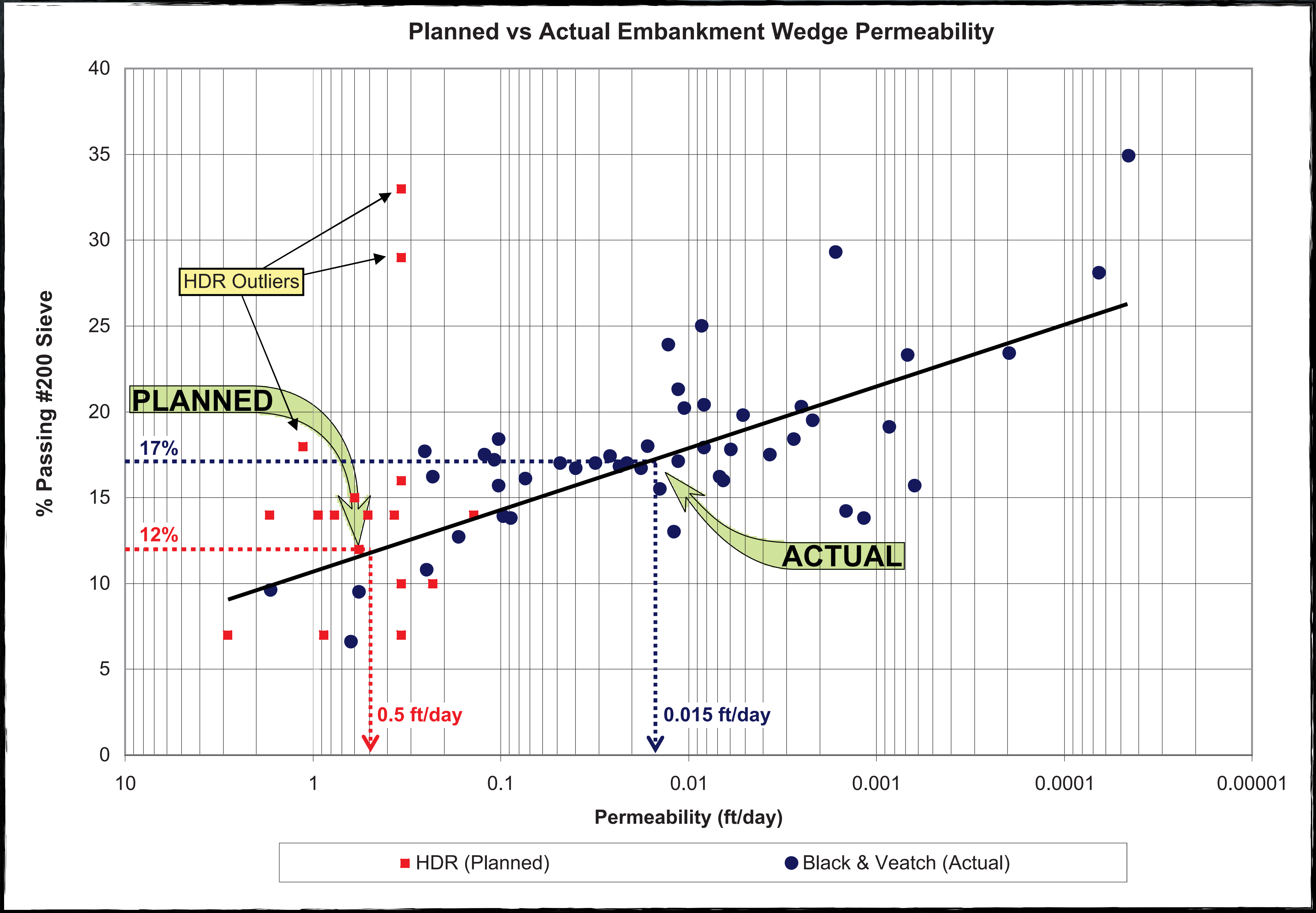
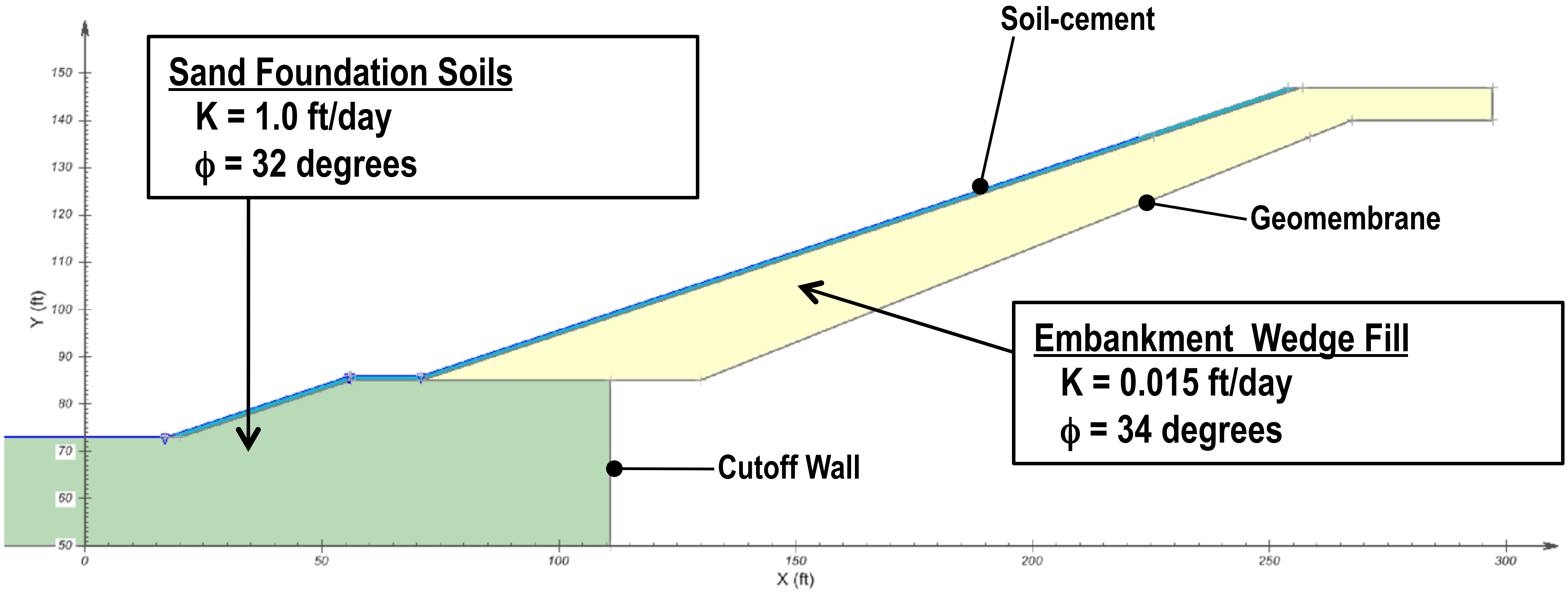
Embankment Permeability Test Results



Idealized Embankment Soil Properties



Sand Foundation Soils

K = 1.0 ft/day

ϕ = 32 degrees

Embankment Wedge Fill

K = 0.015 ft/day

ϕ = 34 degrees

Importance of Permeability

- The actual permeability of the materials used in construction of the embankment wedge was about 33 times less than was assumed during design.
- As a result, the water level in the embankment wedge does not draw down in step with the reservoir pool elevation, leading to the development of high pore water pressures in the wedge.
- These high pore water pressures result in a lower factor of safety than was anticipated.

Note on Soil-Cement Permeability

Note that the literature suggests that the permeability of a soil-cement mix will be less than the permeability of the parent material.

However, permeability tests performed on soil-cement core samples taken from the embankment do not support this, with permeabilities equal to or greater than the permeability of the embankment fill.

The actual permeability of the soil-cement is still a matter of debate. Therefore, a range of soil-cement permeabilities was considered in order to assess the sensitivity of this parameter.

Part 8

COUPLED MODEL RESULTS: ANIMATIONS, SENSITIVITY ANALYSES TO INPUT PARAMETERS

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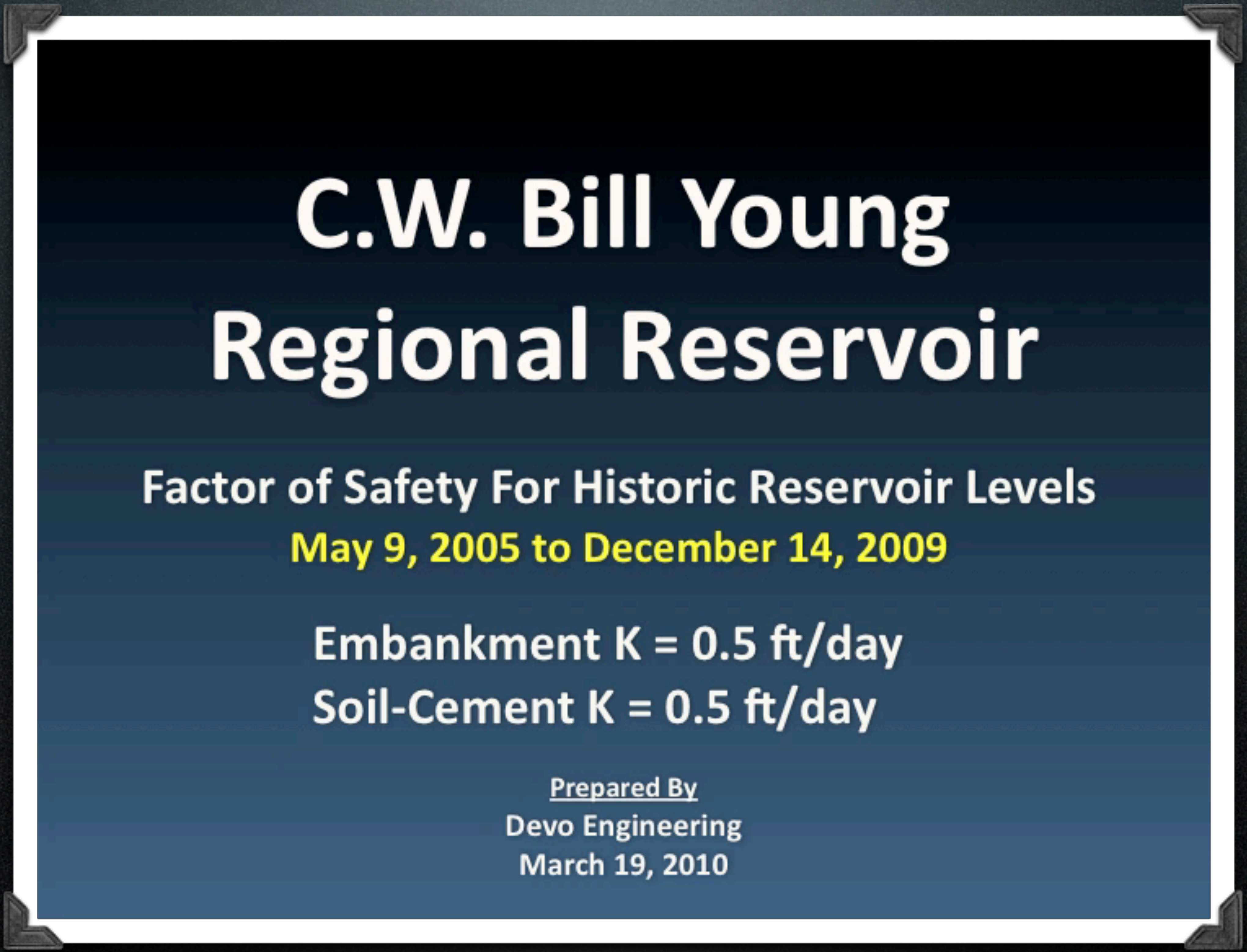


C.W. Bill Young
Regional Reservoir

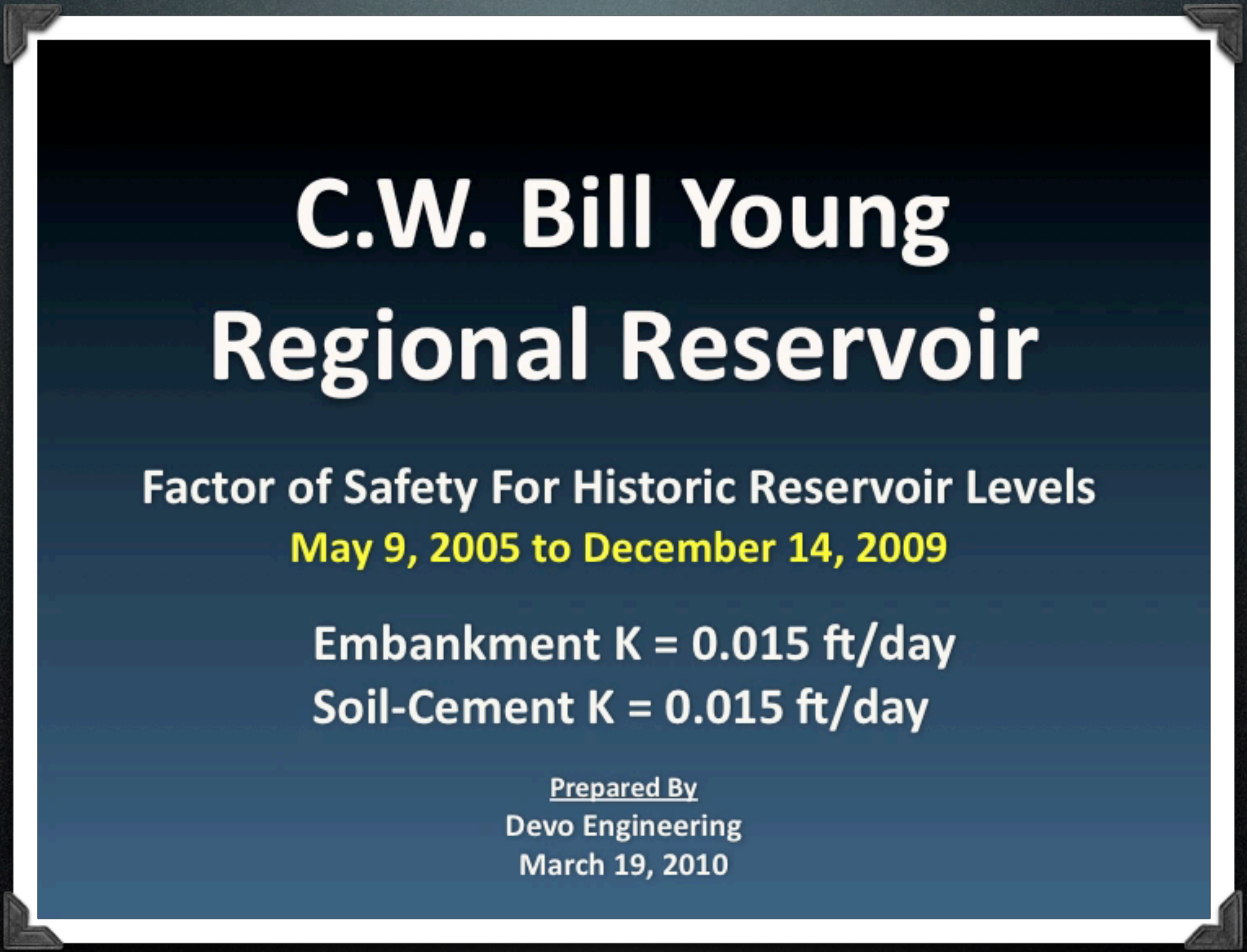
Factor of Safety For Historic Reservoir Levels

May 9, 2005 to December 14, 2009

Embankment K = 0.5 ft/day
Soil-Cement K = 0.5 ft/day

Prepared By
Devo Engineering
March 19, 2010

Animation 1, using design permeabilities:
Ks = 0.5 ft/day | Ksc = 0.5 ft/day



C.W. Bill Young Regional Reservoir

Factor of Safety For Historic Reservoir Levels

May 9, 2005 to December 14, 2009

Embankment K = 0.015 ft/day
Soil-Cement K = 0.015 ft/day

<u>Prepared By</u>
Devo Engineering
March 19, 2010

Animation 2, using actual embankment permeability:
Ks = 0.015 ft/day | Ksc = 0.015 ft/day

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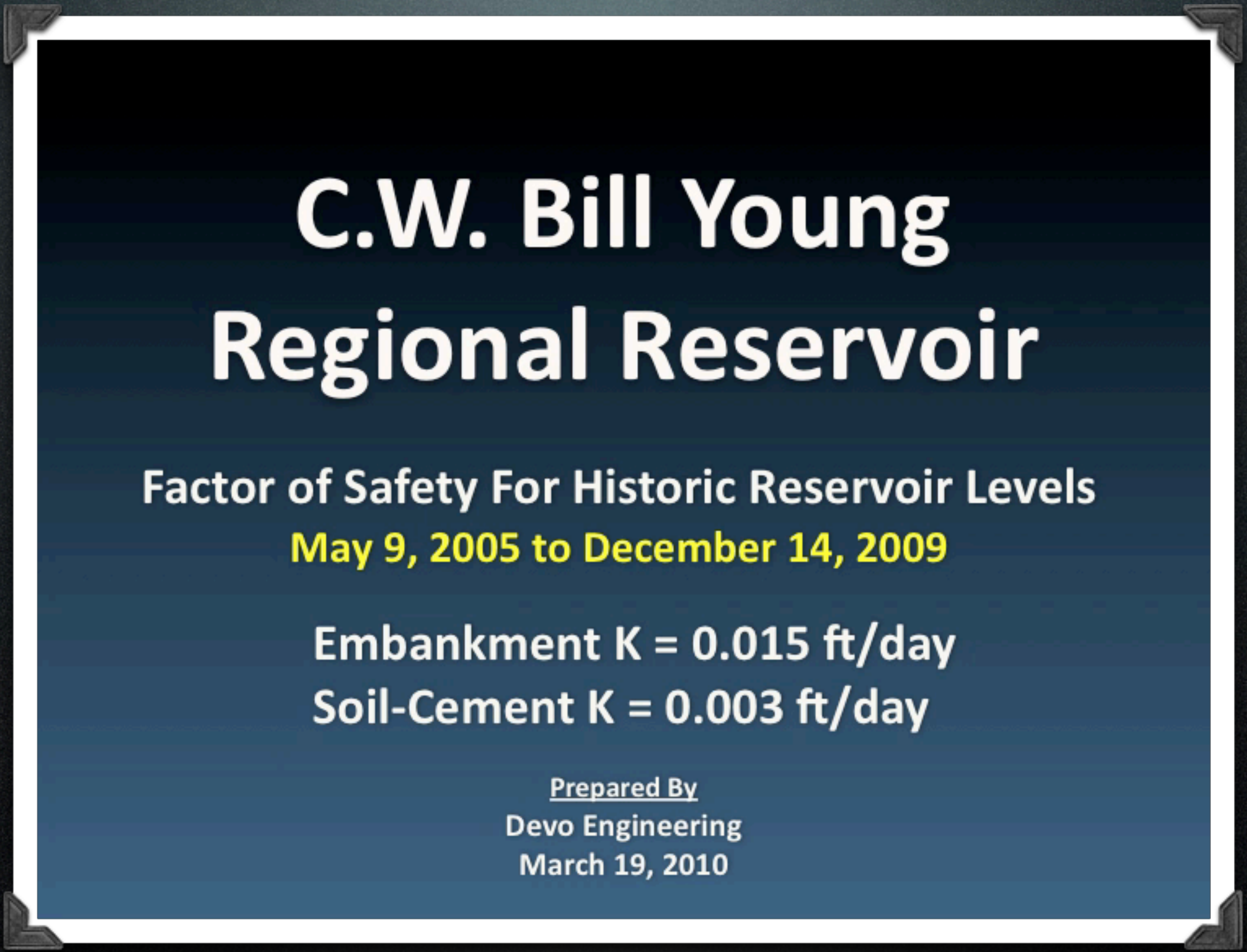


C.W. Bill Young
Regional Reservoir

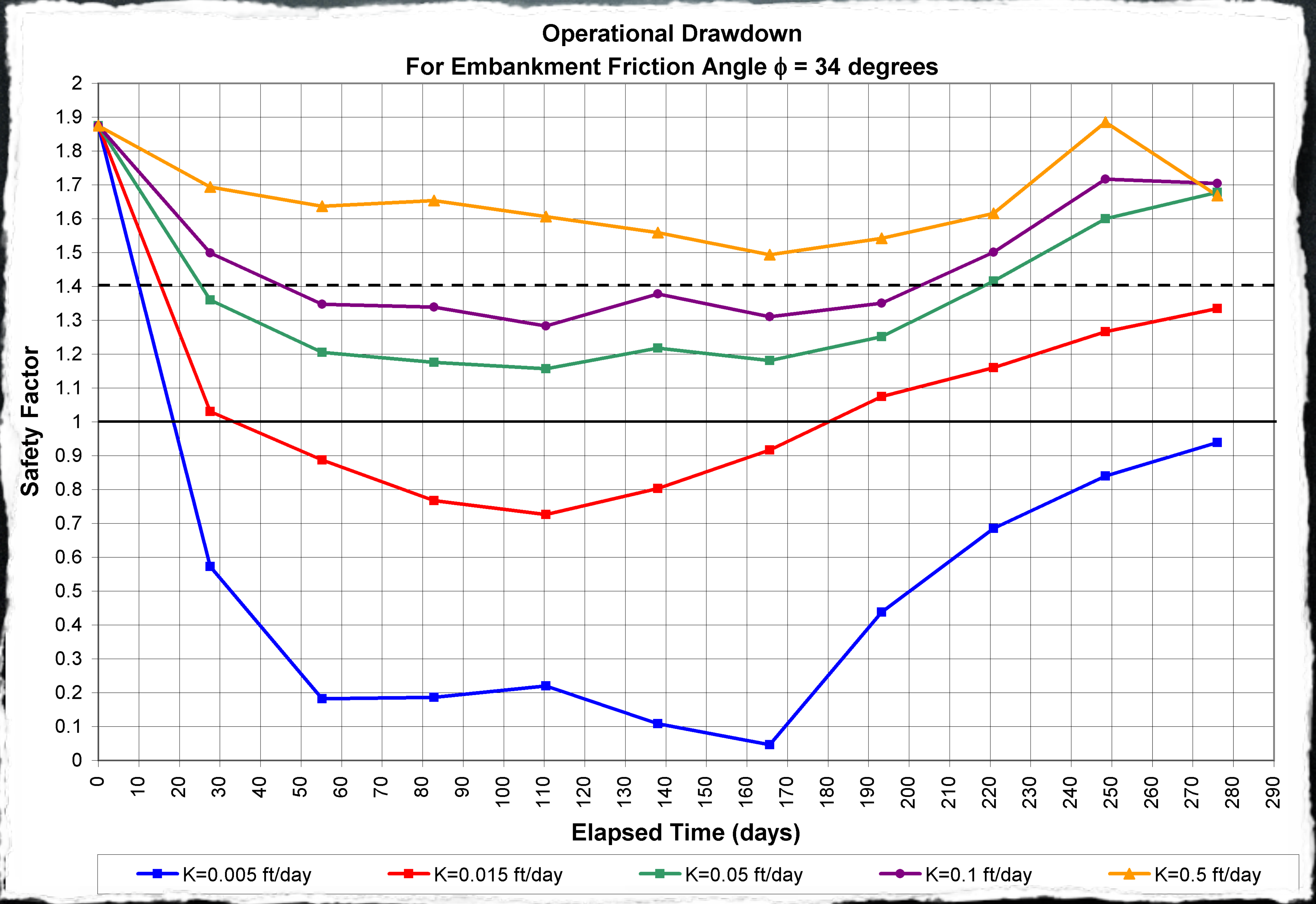
Factor of Safety For Historic Reservoir Levels
May 9, 2005 to December 14, 2009

Embankment K = 0.015 ft/day
Soil-Cement K = 0.003 ft/day

Prepared By
Devo Engineering
March 19, 2010

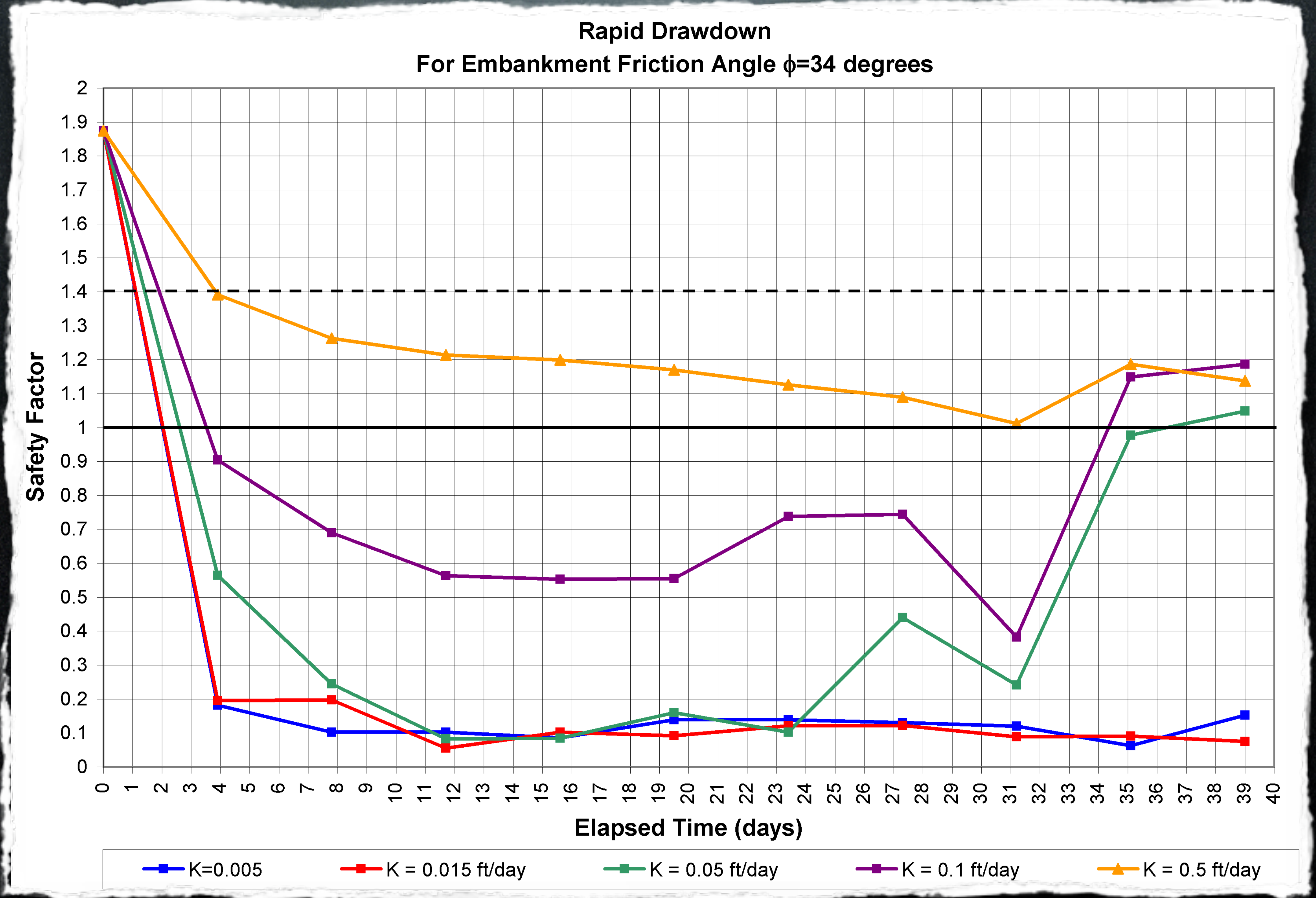
Animation 3, using lower permeability soil-cement:
Ks = 0.015 ft/day | Ksc = 0.003 ft/day

Design Operational Drawdown, 2.7 in/day



Note this example assumes the permeability of the soil-cement is the same as the permeability of the embankment fill.

Design Rapid Drawdown, 18.9 in/day



Note this example assumes the permeability of the soil-cement is the same as the permeability of the embankment fill.

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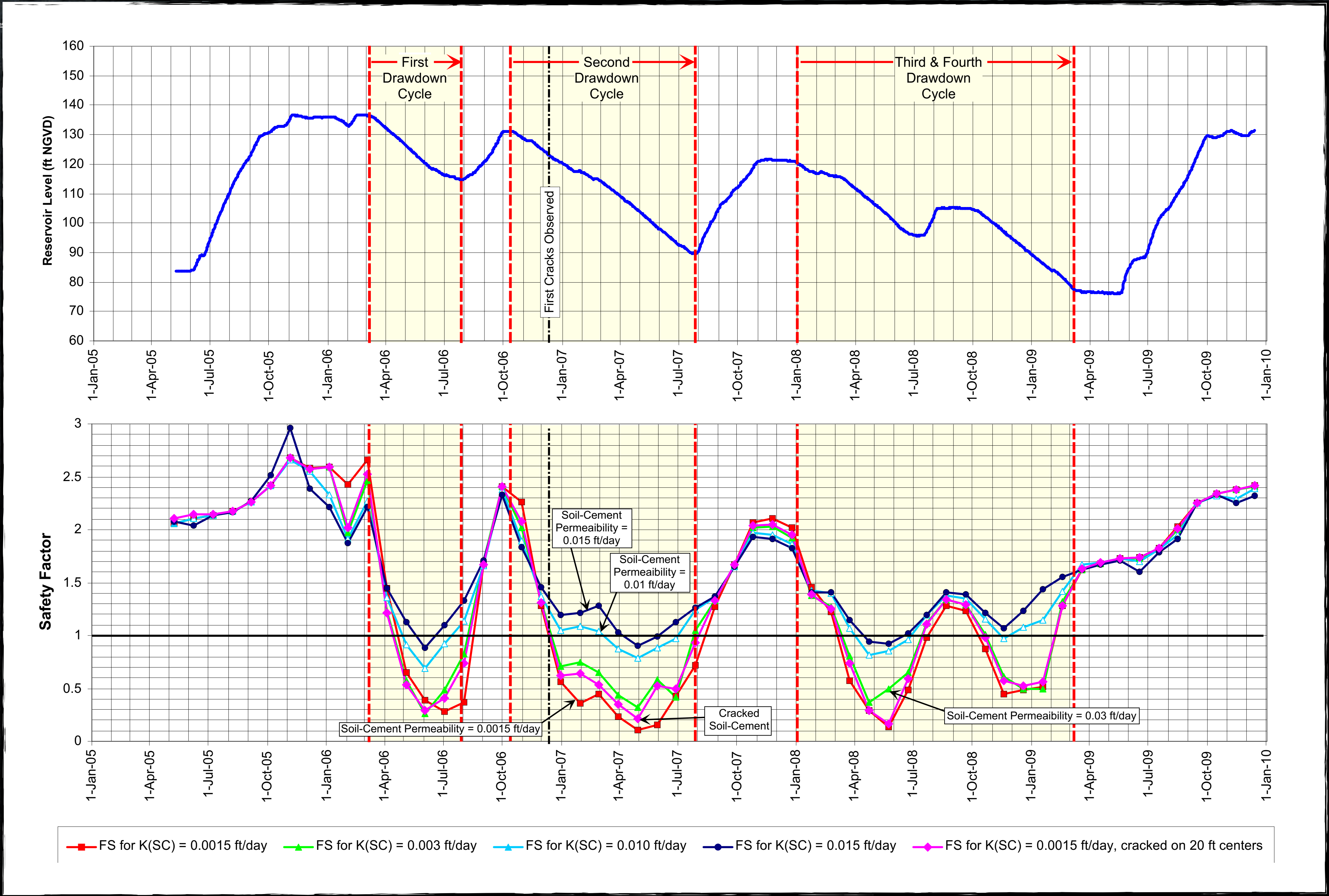
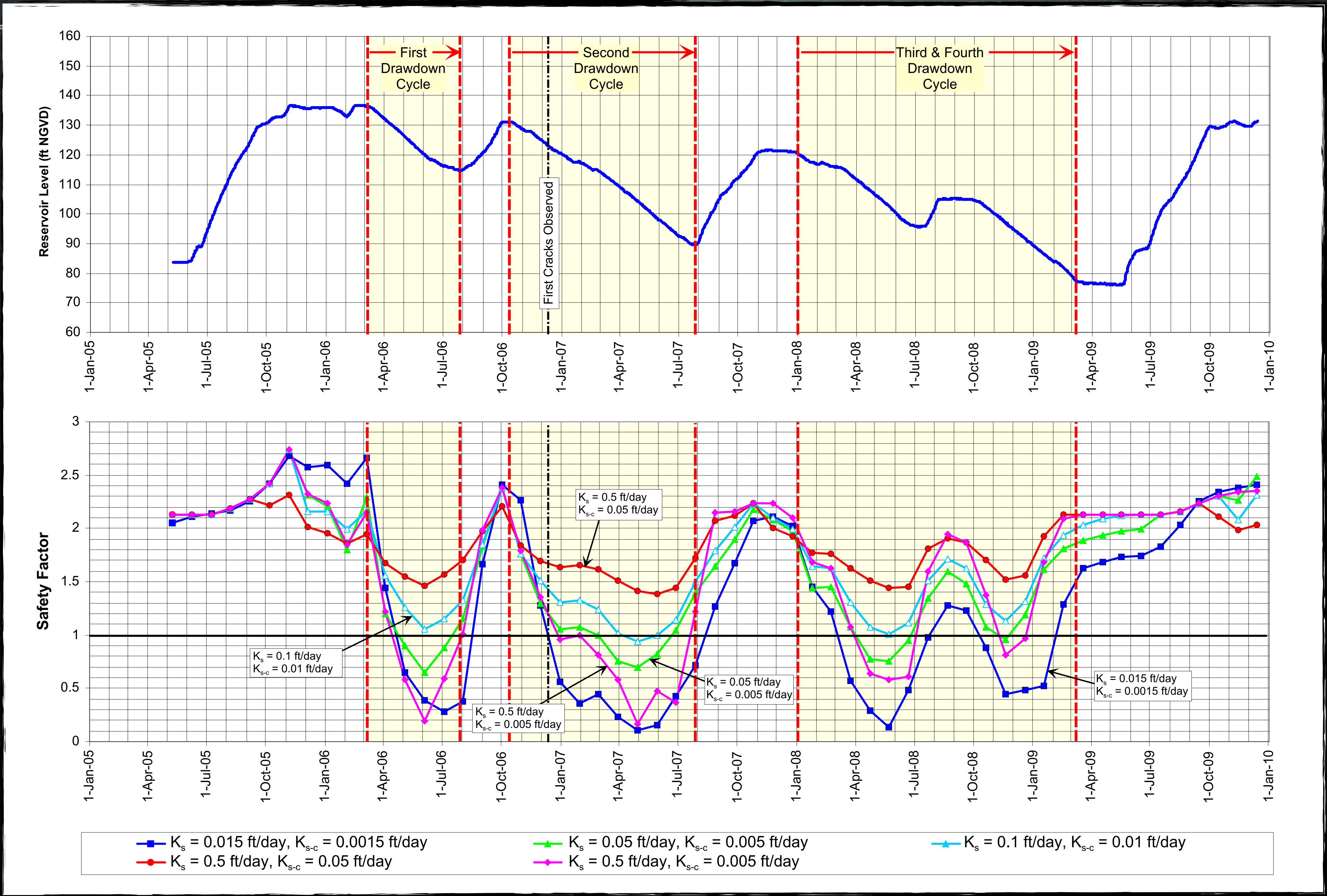
For embankment wedge permeability of 0.015 ft/day, and a range of assumed soil-cement



For a range of embankment permeabilities and soil-cement permeabilities



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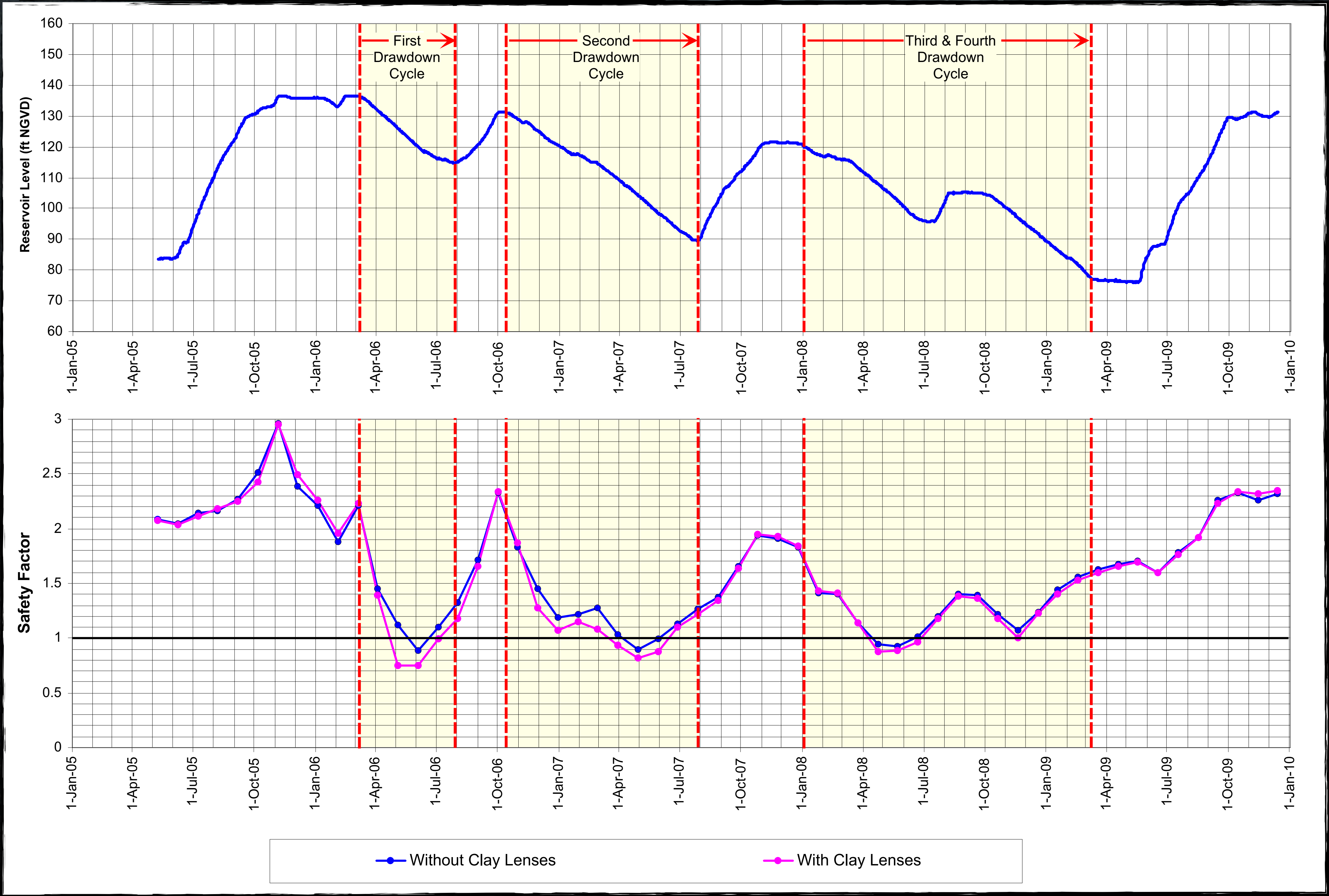
With inclusions of low strength clay lenses



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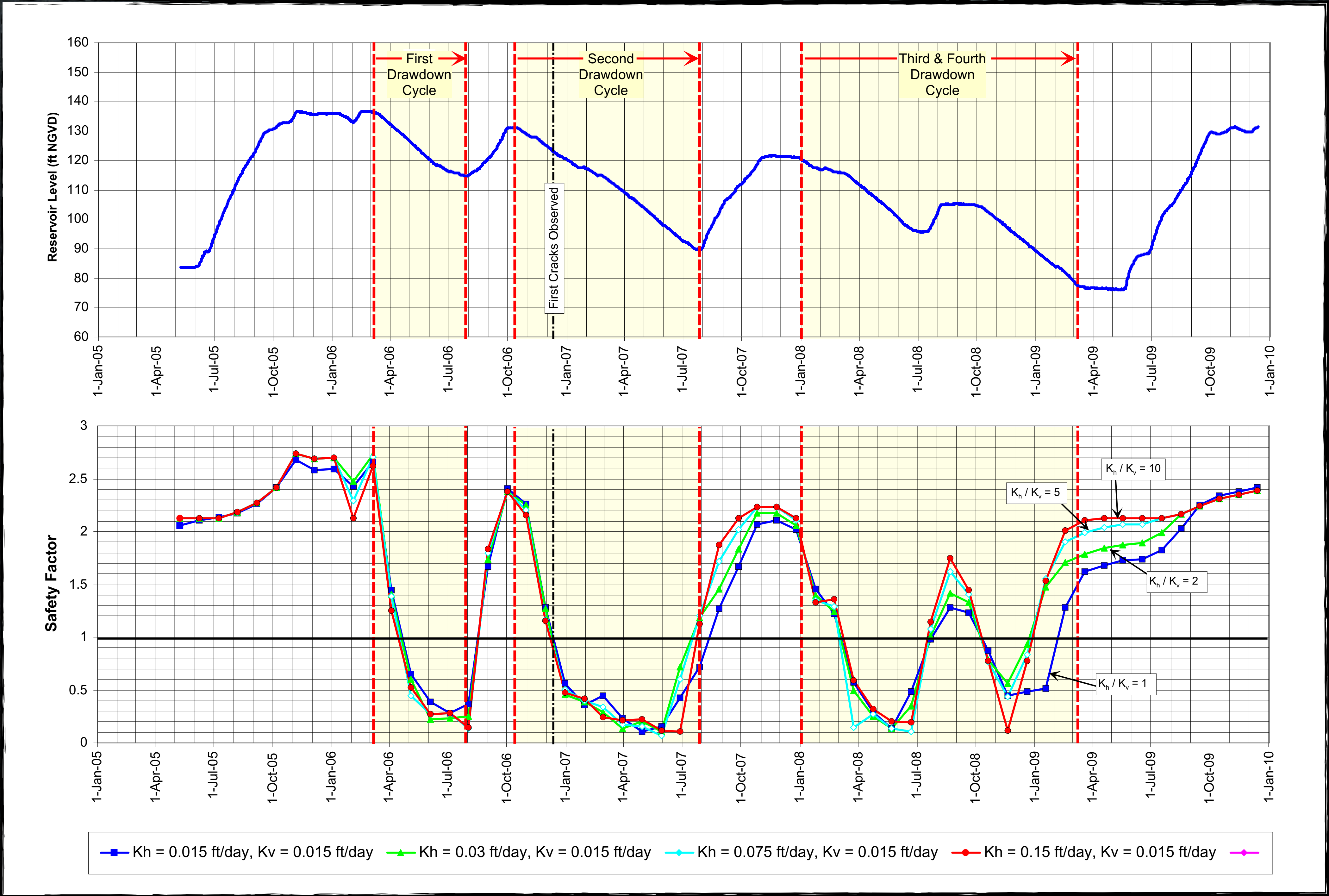
For varying degrees of anisotropy



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Part 9

CONCEPT FIX AND ANALYSIS OF ITS EFFECTIVENESS

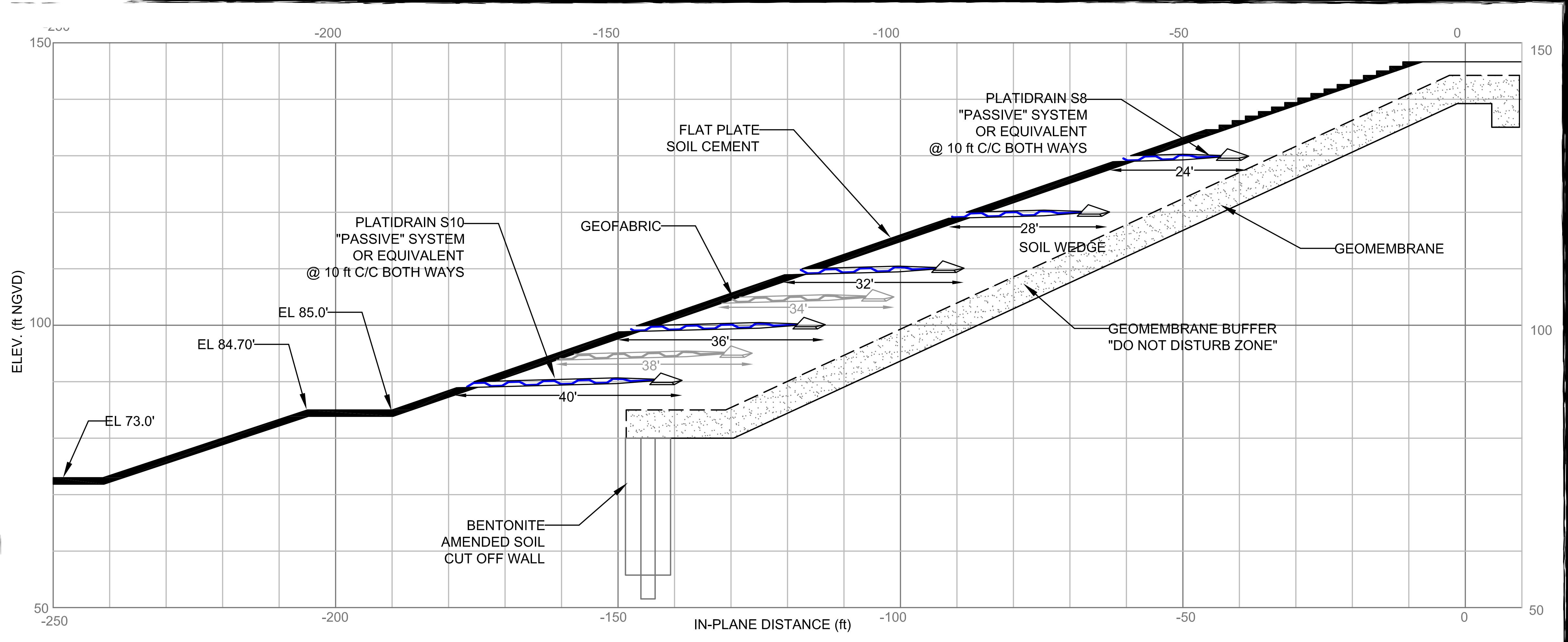
Conceptual Retrofit

- A conceptual retrofit for the upstream embankment at the C.W. Bill Young Reservoir must address the build up of pore pressures within the embankment wedge soils, which adversely effects the slope stability of the upstream wedge.

- Several retrofit concepts have been proposed, by various parties, and with a wide range of estimated costs.

- Devo Engineering has proposed a system of drains (Platidrain™ S10, or equivalent) on a 10 ft grid spacing, installed via percussive drilling, for pore water pressure relief.

Proposed fix



CROSS SECTION A-A'

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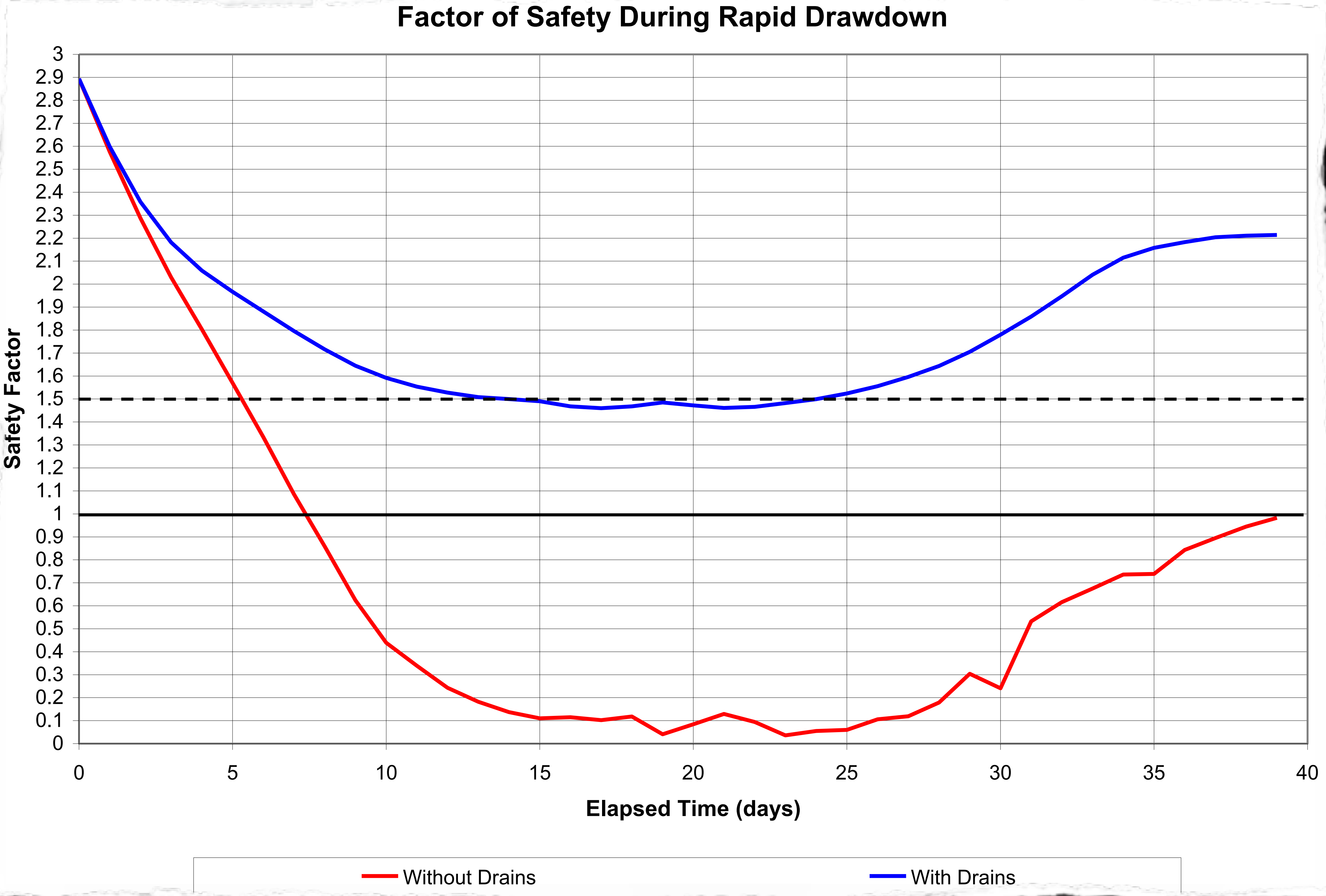
Slope Stability for Proposed Retrofit



Rapid Drawdown, ϕ’=34º and c’=200 psf

Part 10-A

ADDITIONAL SCENARIOS

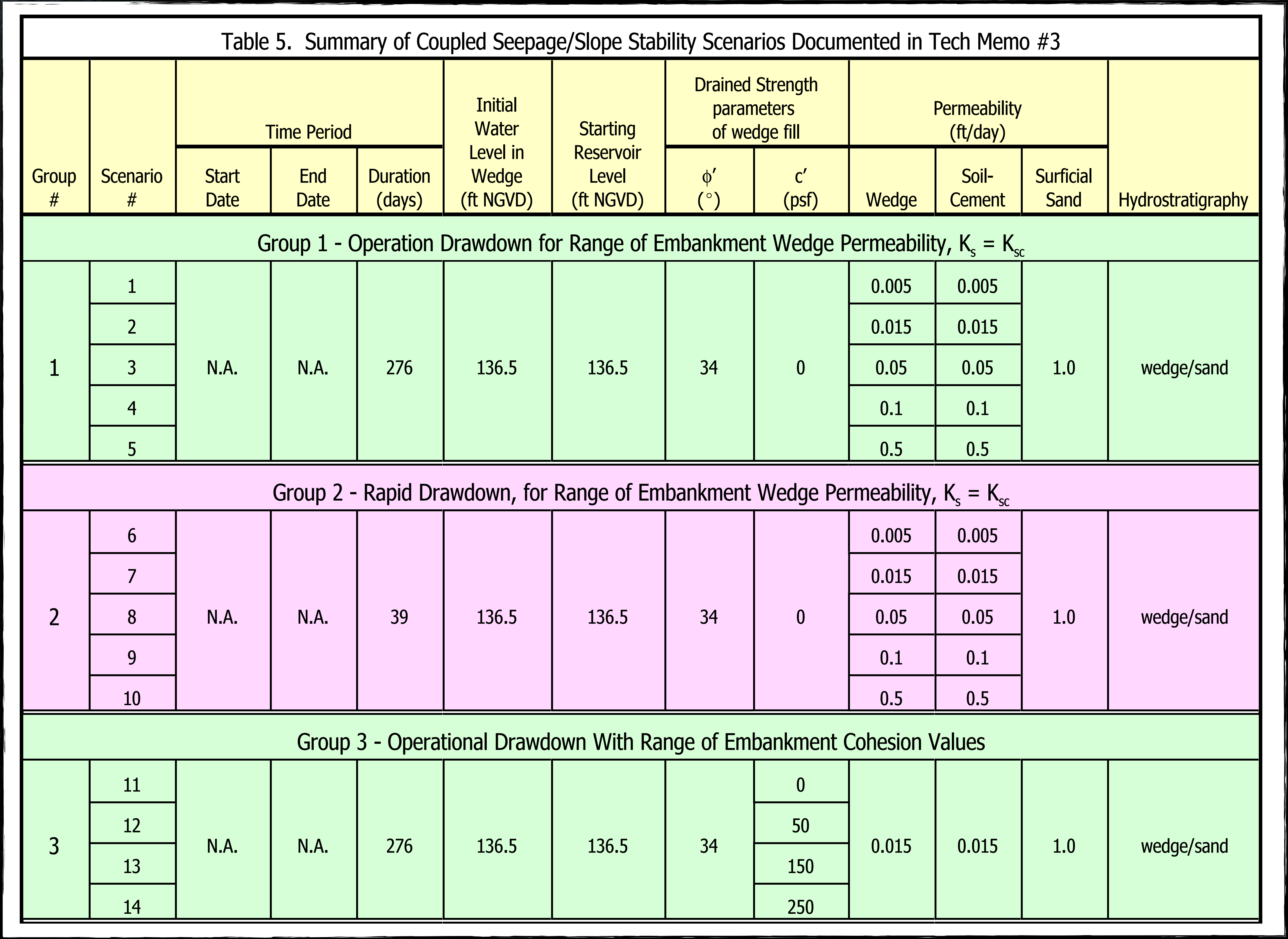


Table 5. Summary of Coupled Seepage/Slope Stability Scenarios Documented in Tech Memo #3

Group #	Scenario #	Time Period			Initial Water Level in Wedge (ft NGVD)	Starting Reservoir Level (ft NGVD)	Drained Strength parameters of wedge fill		Permeability (ft/day)			Hydrostratigraphy
		Start Date	End Date	Duration (days)			ϕ′ (°)	c′ (psf)	Wedge	Soil-Cement	Surficial Sand	
Group 1 - Operation Drawdown for Range of Embankment Wedge Permeability, $K_s = K_{sc}$												
1	1	N.A.	N.A.	276	136.5	136.5	34	0	0.005	0.005	1.0	wedge/sand
	2								0.015	0.015		
	3								0.05	0.05		
	4								0.1	0.1		
	5								0.5	0.5		
Group 2 - Rapid Drawdown, for Range of Embankment Wedge Permeability, $K_s = K_{sc}$												
2	6	N.A.	N.A.	39	136.5	136.5	34	0	0.005	0.005	1.0	wedge/sand
	7								0.015	0.015		
	8								0.05	0.05		
	9								0.1	0.1		
	10								0.5	0.5		
Group 3 - Operational Drawdown With Range of Embankment Cohesion Values												
3	11	N.A.	N.A.	276	136.5	136.5	34	0	0.015	0.015	1.0	wedge/sand
	12							50				
	13							150				
	14							250				

List of Scenarios Evaluated

Table 5. Summary of Coupled Seepage/Slope Stability Scenarios Documented in Tech Memo #3

Group #	Scenario #	Time Period			Initial Water Level in Wedge (ft NGVD)	Starting Reservoir Level (ft NGVD)	Drained Strength parameters of wedge fill		Permeability (ft/day)			Hydrostratigraphy
		Start Date	End Date	Duration (days)			ϕ' (°)	c' (psf)	Wedge	Soil-Cement	Surficial Sand	
Group 4 - Rapid Drawdown With Range of Embankment Cohesion Values												
4	15	N.A.	N.A.	39	136.5	136.5	34	0	0.015	0.015	1.0	wedge/sand
	16							50				
	17							150				
	18							250				
Group 5 - Second Reservoir Drawdown Cycle with Range of Embankment Permeability, $K_s = K_{sc}$												
5	19	14Oct06	19Jul07	279	131	131	34	0	0.005	0.005	1.0	wedge/sand
	20								0.015	0.015		
	21								0.05	0.05		
	22								0.1	0.1		
	23								0.5	0.5		
Group 6 - Second Reservoir Drawdown Cycle with Range of Permeability for Surficial Sands												
6	24	14Oct06	19Jul07	279	131	131	34	0	0.015	0.015	0.1	wedge/sand
	25										0.5	
	26										1.0	
	27										5.0	
	28										10.0	

List of Scenarios Evaluated (cont'd.)

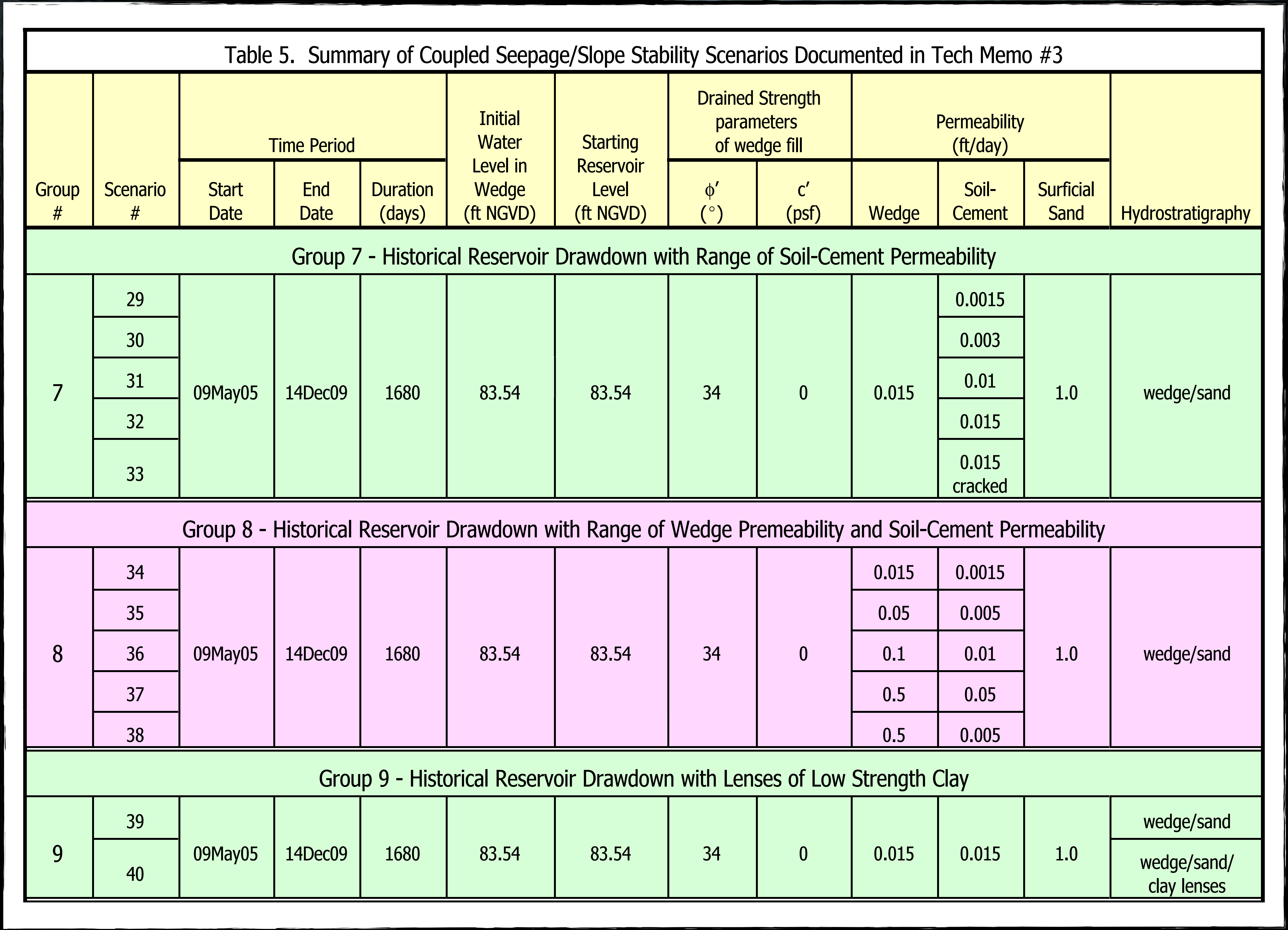


Table 5. Summary of Coupled Seepage/Slope Stability Scenarios Documented in Tech Memo #3

Group #	Scenario #	Time Period			Initial Water Level in Wedge (ft NGVD)	Starting Reservoir Level (ft NGVD)	Drained Strength parameters of wedge fill		Permeability (ft/day)			Hydrostratigraphy
		Start Date	End Date	Duration (days)			ϕ' (°)	c′ (psf)	Wedge	Soil-Cement	Surficial Sand	
Group 7 - Historical Reservoir Drawdown with Range of Soil-Cement Permeability												
7	29	09May05	14Dec09	1680	83.54	83.54	34	0	0.015	0.0015	1.0	wedge/sand
	30									0.003		
	31									0.01		
	32									0.015		
	33									0.015 cracked		
Group 8 - Historical Reservoir Drawdown with Range of Wedge Premeability and Soil-Cement Permeability												
8	34	09May05	14Dec09	1680	83.54	83.54	34	0	0.015	0.0015	1.0	wedge/sand
	35								0.05	0.005		
	36								0.1	0.01		
	37								0.5	0.05		
	38								0.5	0.005		
Group 9 - Historical Reservoir Drawdown with Lenses of Low Strength Clay												
9	39	09May05	14Dec09	1680	83.54	83.54	34	0	0.015	0.015	1.0	wedge/sand
	40											wedge/sand/ clay lenses

List of Scenarios Evaluated (cont'd.)

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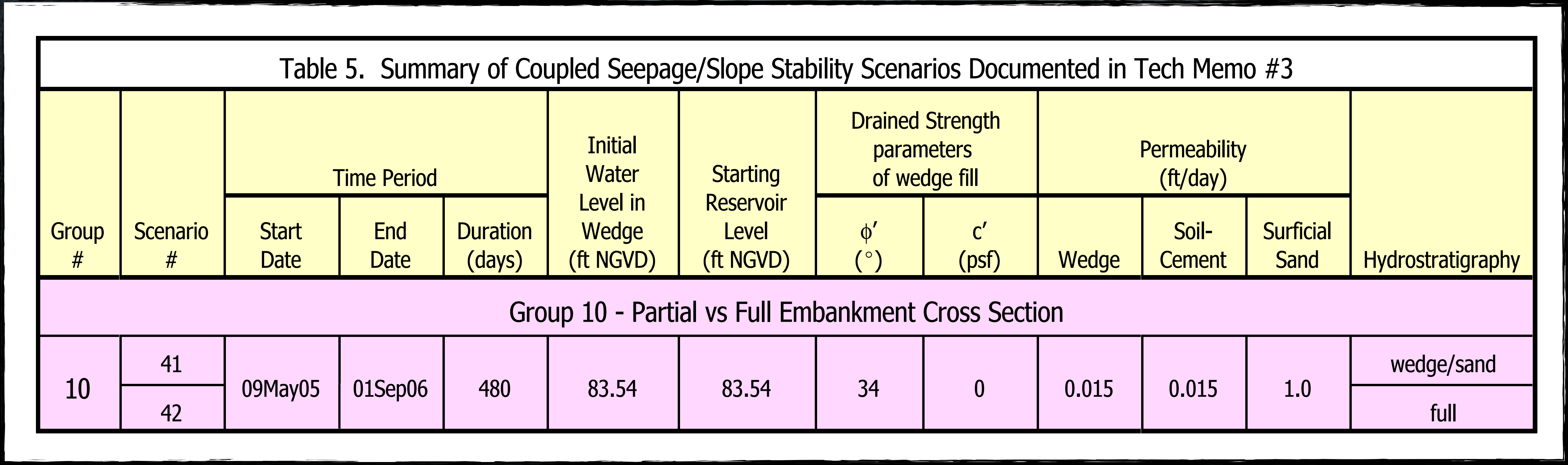

Table 5. Summary of Coupled Seepage/Slope Stability Scenarios Documented in Tech Memo #3

		Time Period			Initial Water Level in Wedge	Starting Reservoir Level	Drained Strength parameters of wedge fill		Permeability (ft/day)			
Group #	Scenario #	Start Date	End Date	Duration (days)	(ft NGVD)	(ft NGVD)	ϕ' (°)	c′ (psf)	Wedge	Soil-Cement	Surficial Sand	Hydrostratigraphy
Group 10 - Partial vs Full Embankment Cross Section												
10	41	09May05	01Sep06	480	83.54	83.54	34	0	0.015	0.015	1.0	wedge/sand
	42											full

List of Scenarios Evaluated (cont'd.)

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List of Scenarios Evaluated (cont'd.)

Table 6. Additional Scenarios

Group #	Scenario #	Time Period			Initial Water Level in Wedge (ft NGVD)	Starting Reservoir Level (ft NGVD)	Drained Strength parameters of wedge fill		Permeability (ft/day)			Hydrostratigraphy
		Start Date	End Date	Duration (days)			φ′ (°)	c′ (psf)	Wedge	Soil-Cement	Surficial Sand	
Group 11 - Sensitivity to Anisotropy												
11	1	09May05	14Dec09	1680	83.54	83.54	34	0	K_h=0.03 K_v=0.015	0.0015	1.0	wedge/sand
	2								K_h=0.075 K_v=0.015			
	3								K_h=0.15 K_v=0.015			
Group 12 - Factor of Safety For High Strength Embankment Fill, Phi=40 degrees												
12	1	09May05	14Dec09	1680	83.54	83.54	40	0	0.015	0.0015	1.0	wedge/sand
	2									0.003		
	3									0.01		
	4									0.015		
Group 13 - Rapid Drawdown with High Permeability Wedge Fill												
13	1	N.A.	N.A.	39	136.5	136.5	34	0	1	none	1.0	wedge/sand
	2								2	none		
	3								3	none		
	4								5			

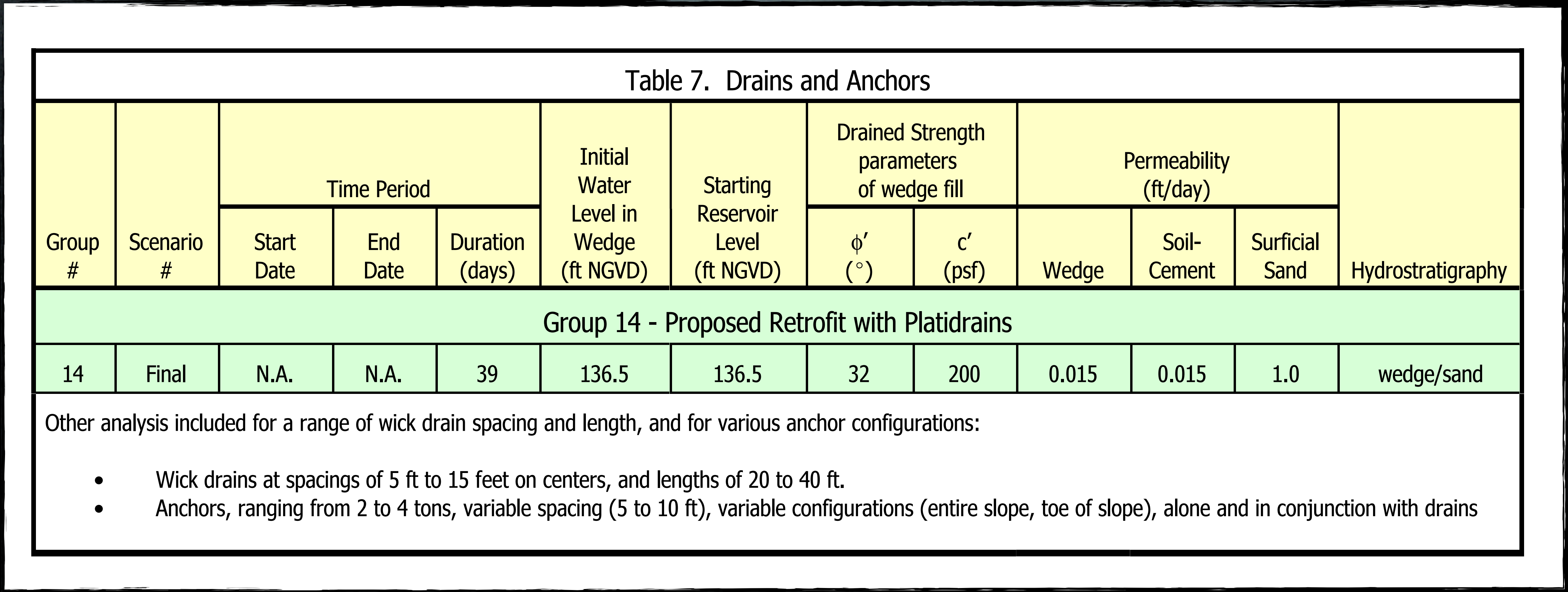


Table 7. Drains and Anchors

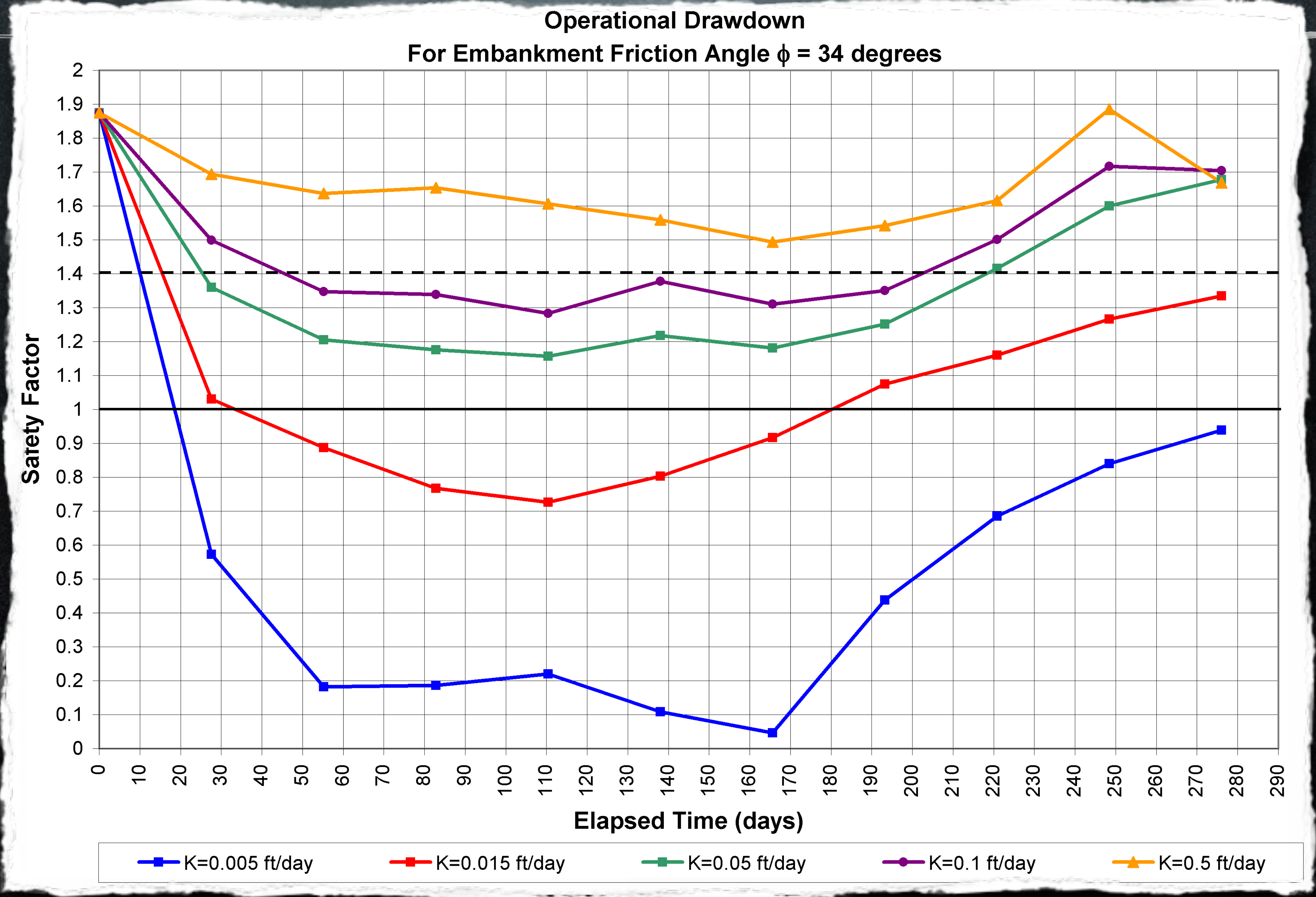
Group #	Scenario #	Time Period			Initial Water Level in Wedge (ft NGVD)	Starting Reservoir Level (ft NGVD)	Drained Strength parameters of wedge fill		Permeability (ft/day)			Hydrostratigraphy
		Start Date	End Date	Duration (days)			ϕ′ (°)	c′ (psf)	Wedge	Soil-Cement	Surficial Sand	
Group 14 - Proposed Retrofit with Platidrains												
14	Final	N.A.	N.A.	39	136.5	136.5	32	200	0.015	0.015	1.0	wedge/sand

Other analysis included for a range of wick drain spacing and length, and for various anchor configurations:

- Wick drains at spacings of 5 ft to 15 feet on centers, and lengths of 20 to 40 ft.
- Anchors, ranging from 2 to 4 tons, variable spacing (5 to 10 ft), variable configurations (entire slope, toe of slope), alone and in conjunction with drains

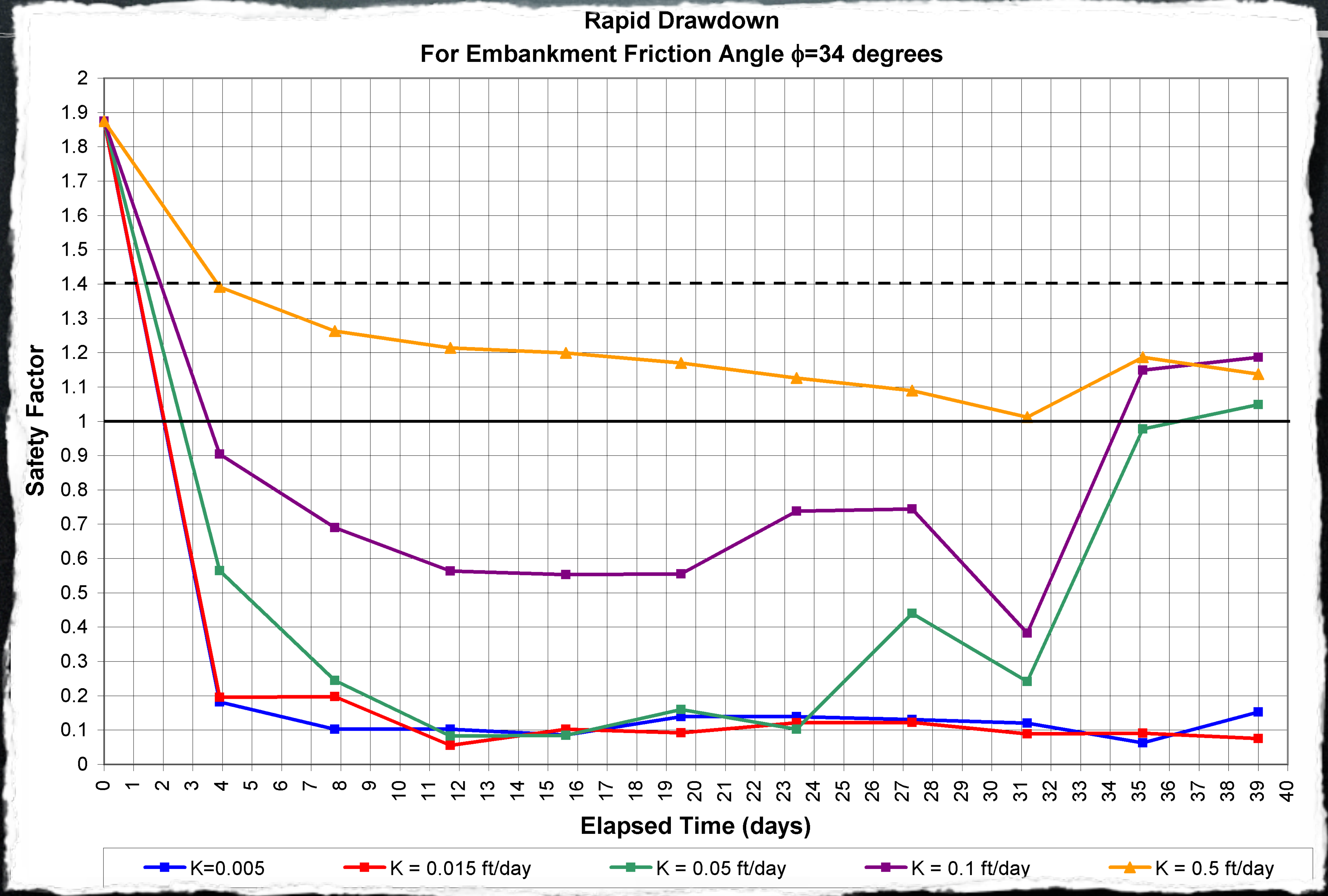
List of Scenarios Evaluated (cont’d.)

Group 1 Slope Stability Results



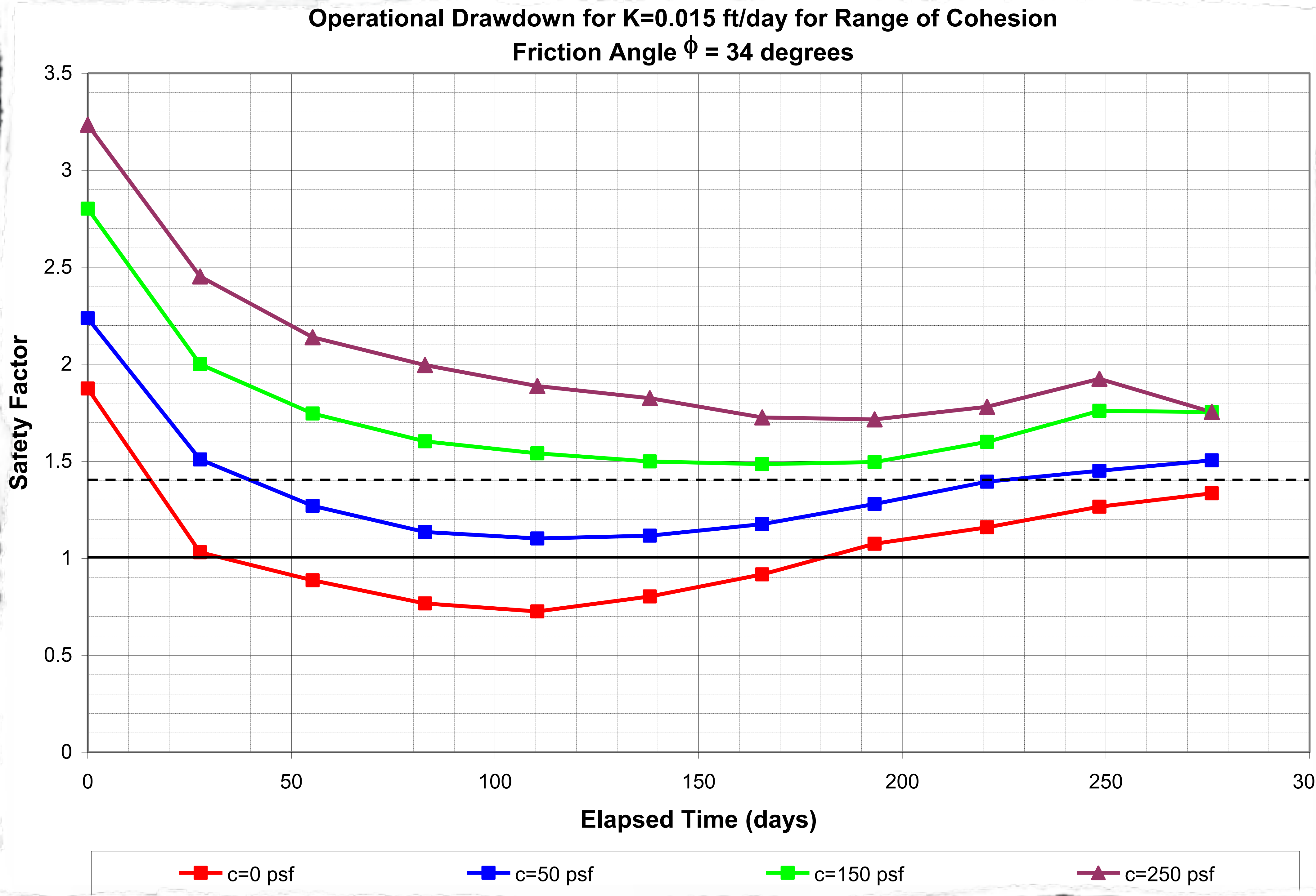
Operational Drawdown (276 days), for a range of embankment permeabilities, Ksoil = Ksoil-cement

Group 2 Slope Stability Results



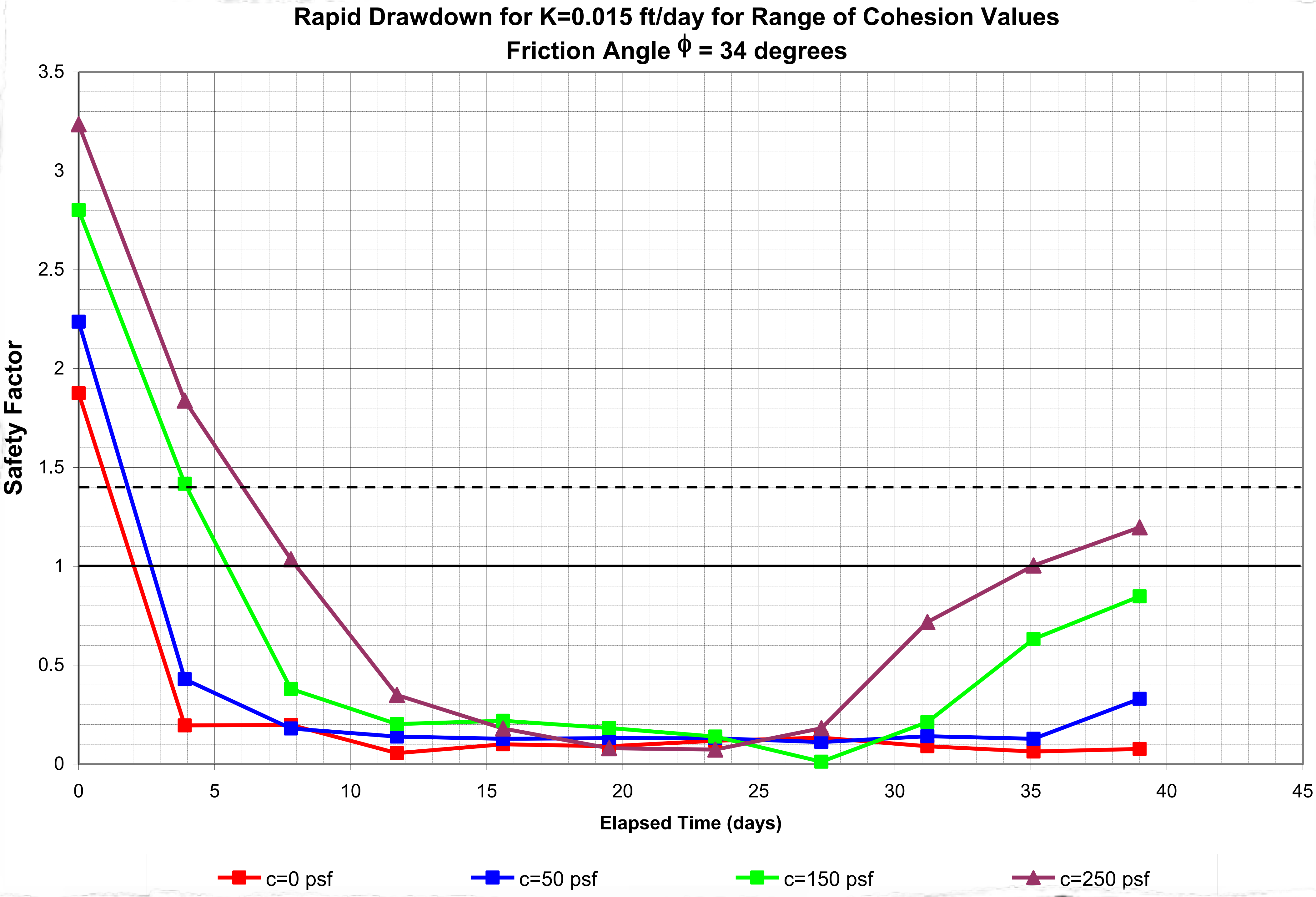
Rapid Drawdown (39 days), for a range of embankment permeabilities, Ksoil = Ksoil-cement

Group 3 Slope Stability Results



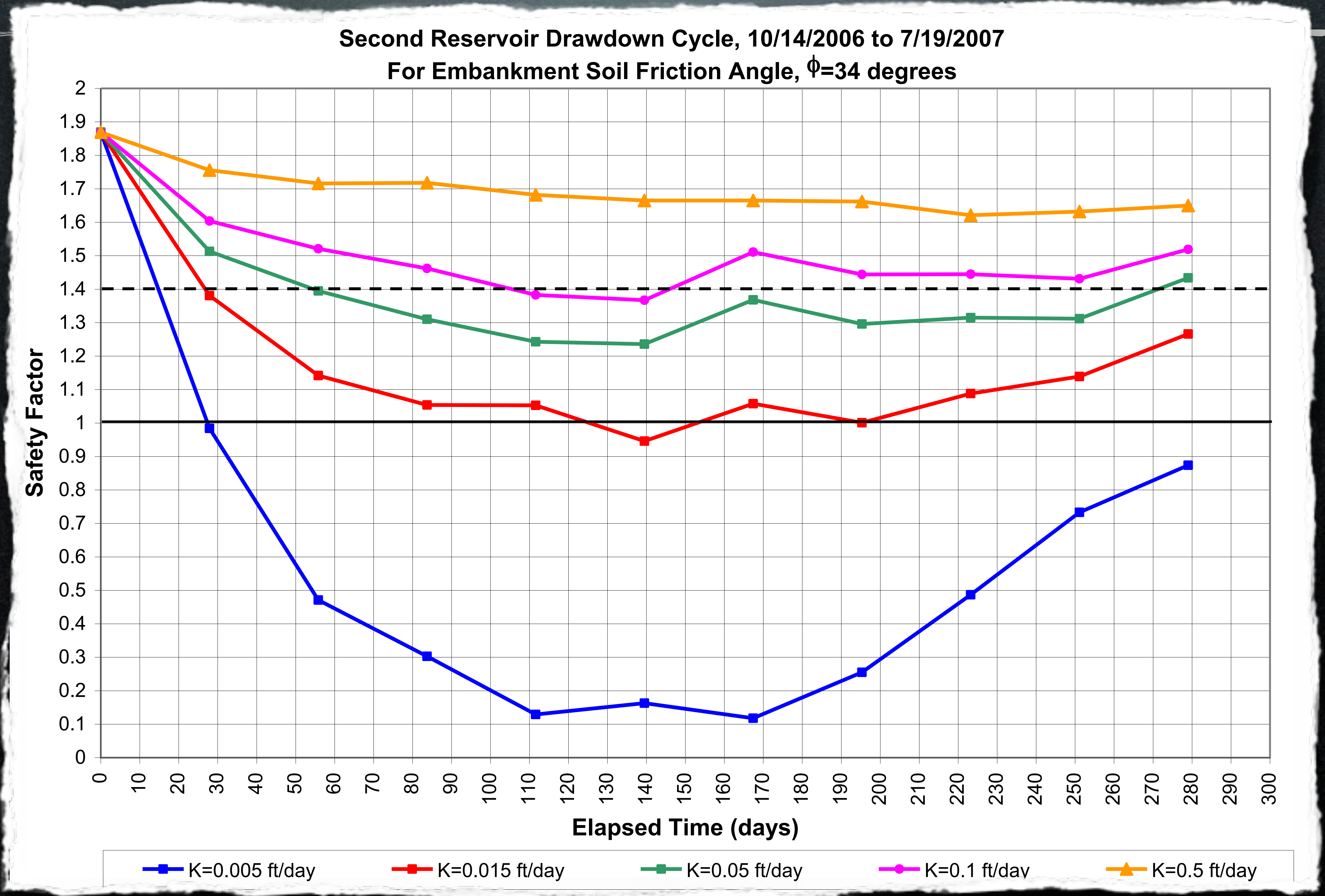
Operation Drawdown (276 days), with varying degrees of cohesion, Ksoil = Ksoil-cement

Group 4 Slope Stability Results



Rapid Drawdown (39 days), with varying degrees of cohesion, Ksoil = Ksoil-cement

Group 5 Slope Stability Results



Second Reservoir Drawdown Cycle, for range of embankment permeabilities, Ksoil = Ksoil-cement

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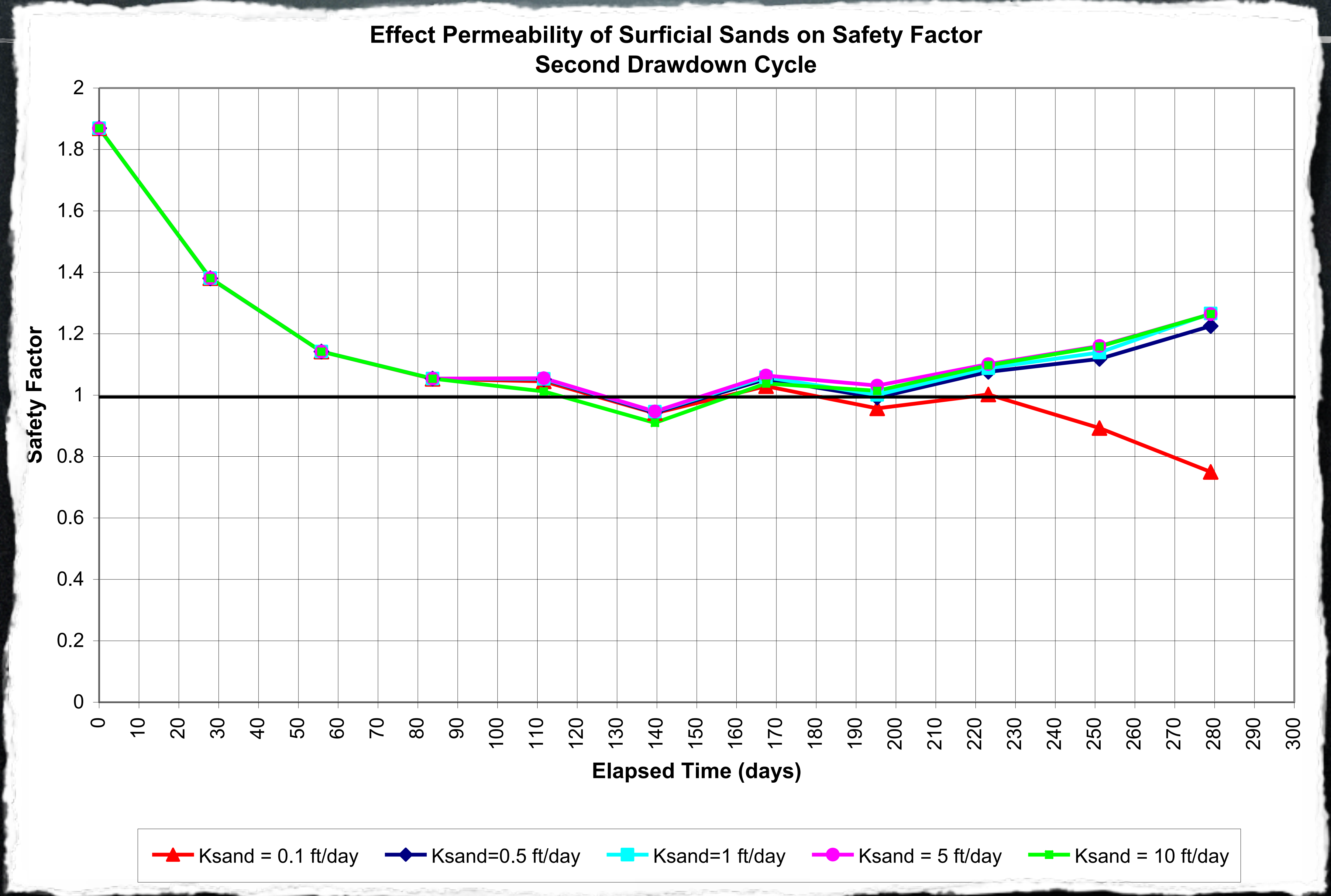
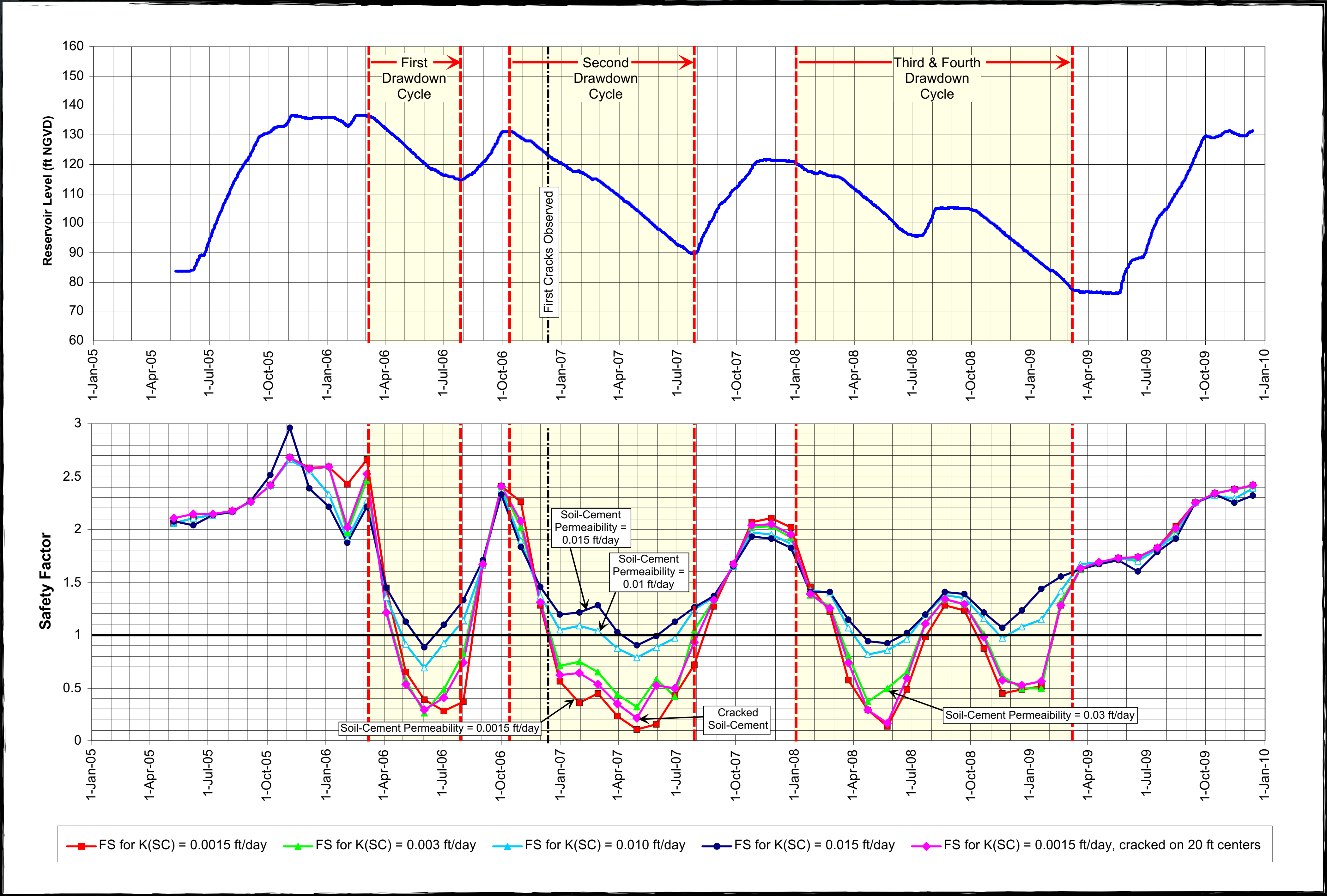
Group 6 Slope Stability Results



Second Reservoir Drawdown Cycle, Sensitivity to permeability of sand layer

Group 7 Slope Stability Results



For embankment wedge permeability of 0.015 ft/day, and a range of assumed soil-cement permeabilities.

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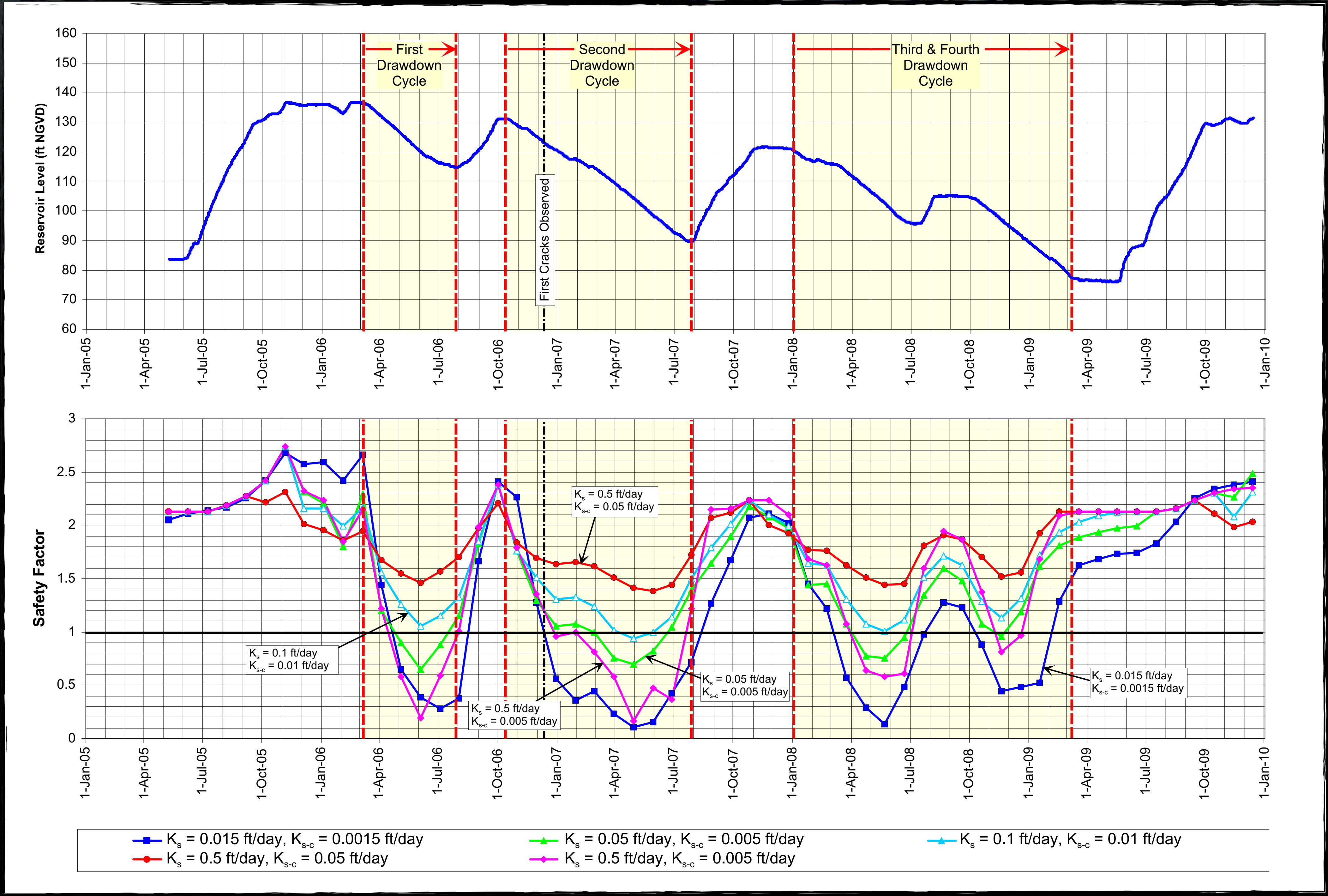
Group 8 Slope Stability Results



For a range of embankment permeabilities and soil-cement permeabilities

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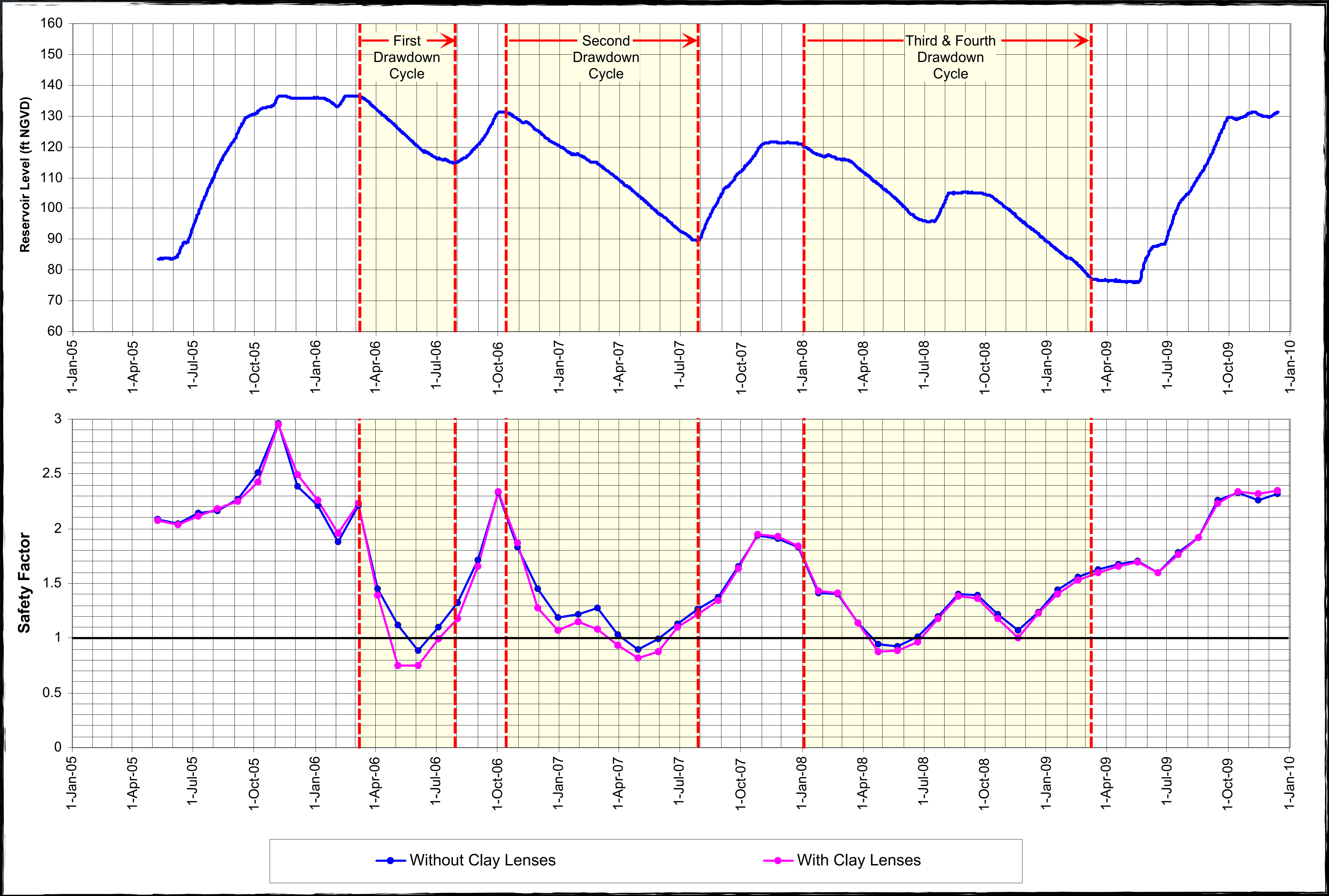
Group 9 Slope Stability Results



With inclusions of low strength clay lenses

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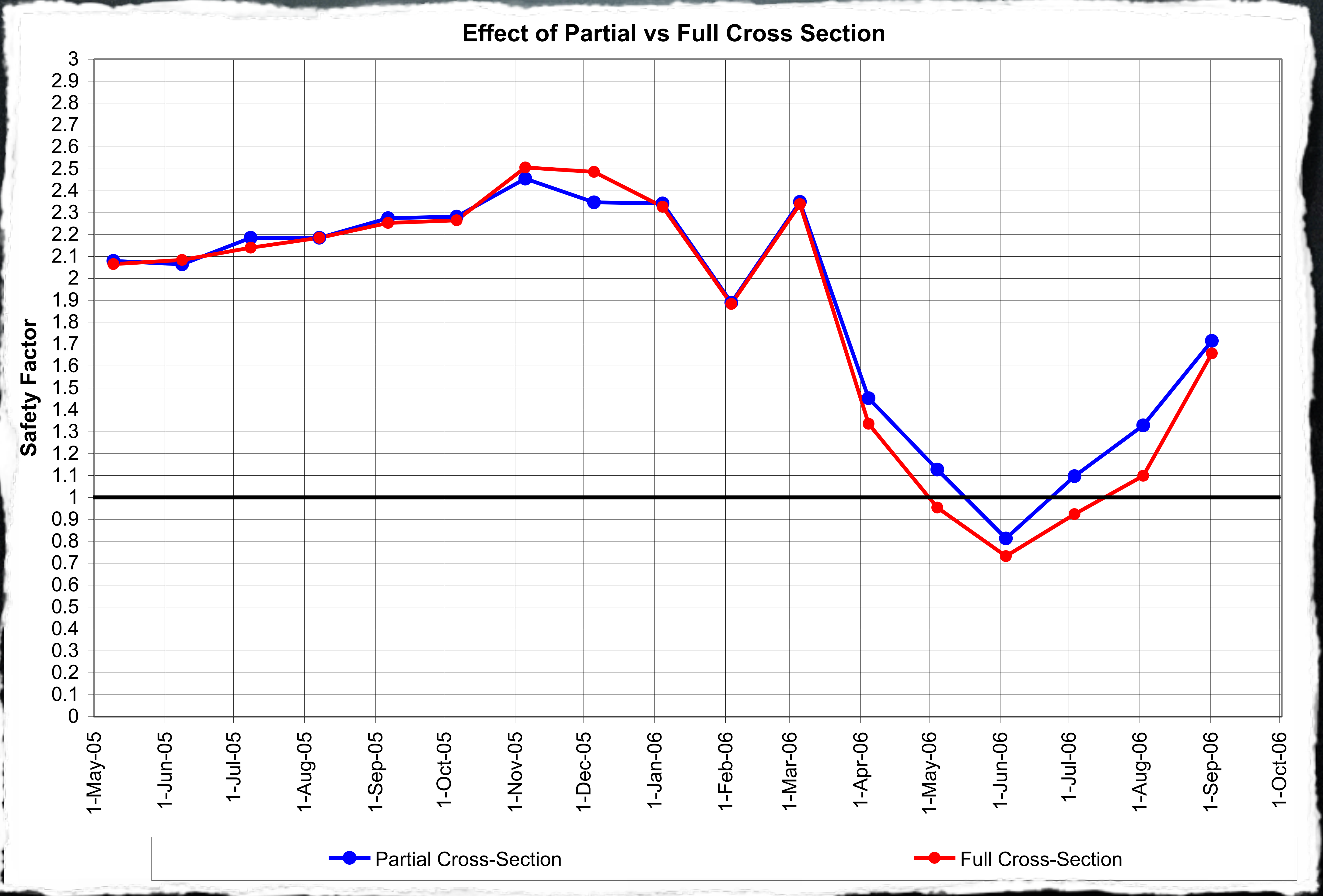
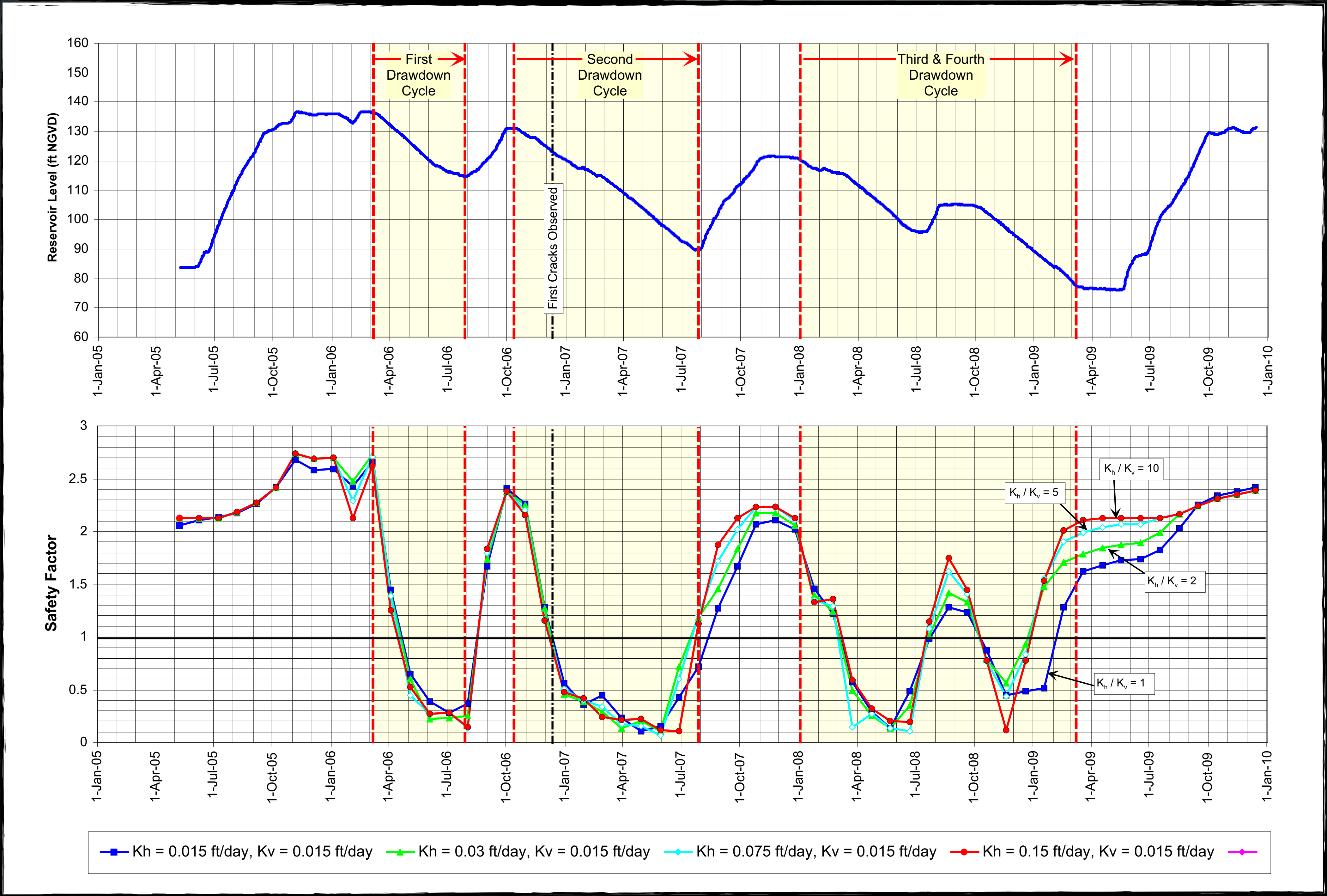
Group 10 Slope Stability Results



Effect of Full vs Partial Cross Section

Group 11 Slope Stability Results



For varying degrees of anisotropy

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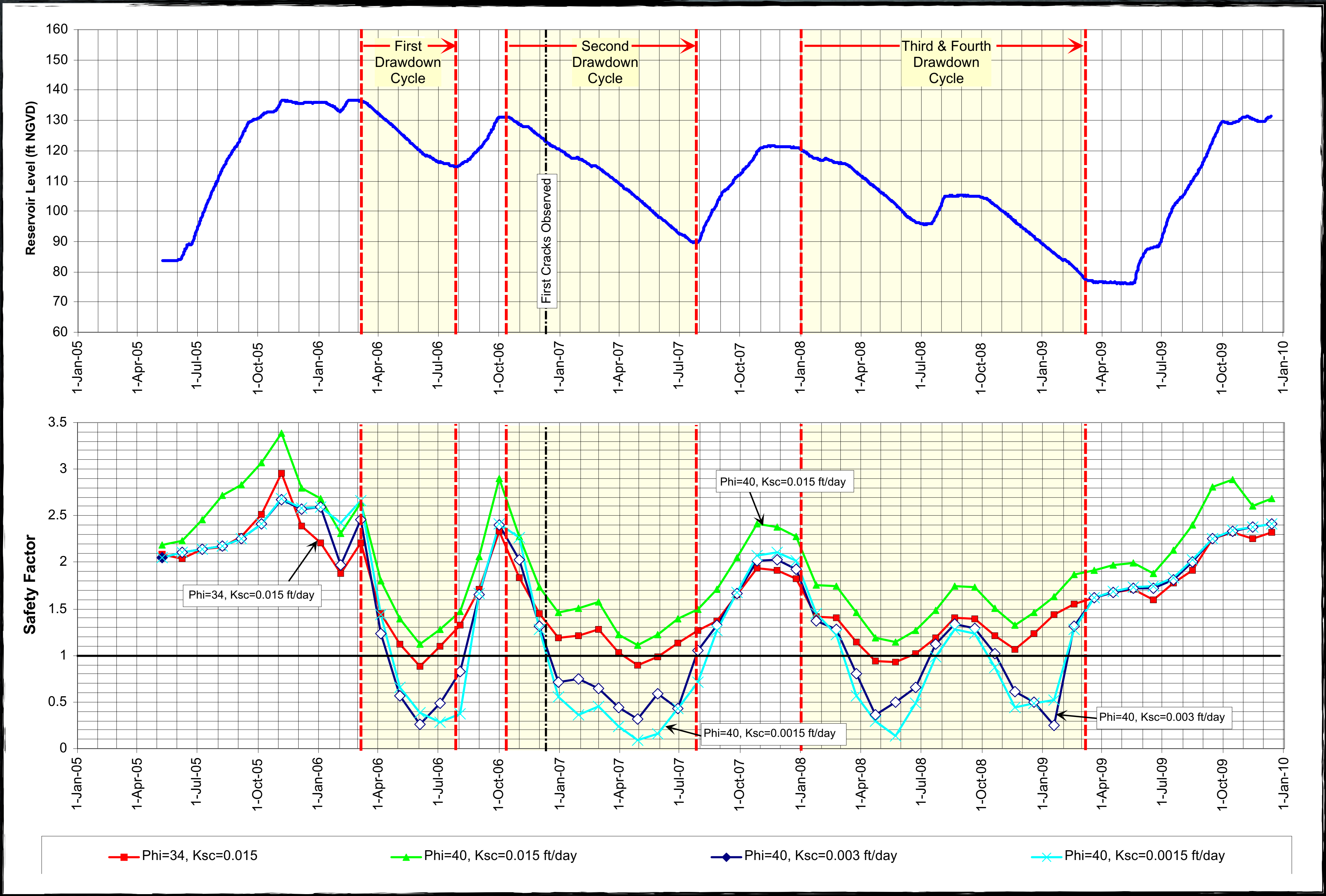
Group 12 Slope Stability Results



For high strength embankment soil, ϕ = 40º

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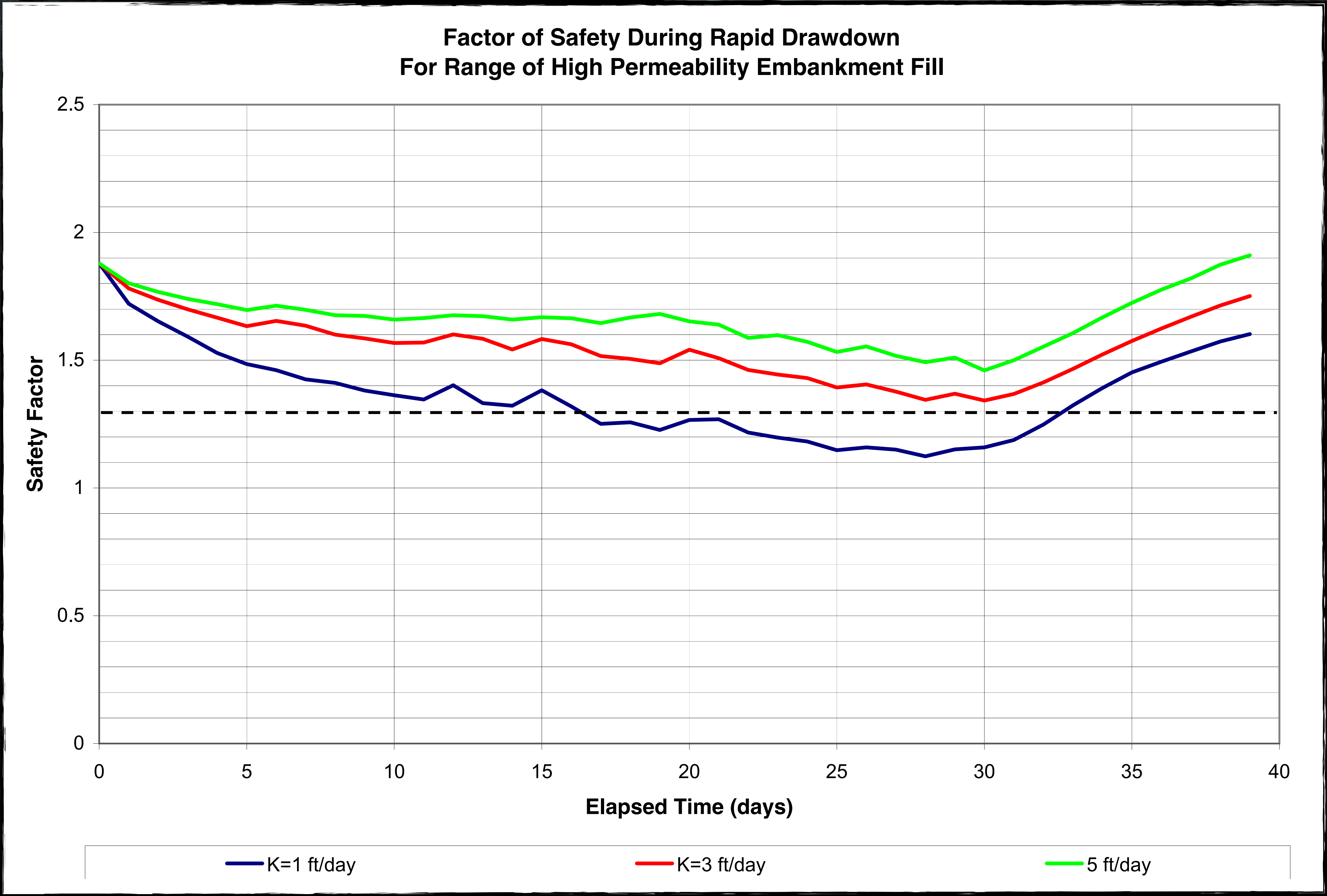
Group 13 Slope Stability Results



Rapid drawdown with high permeability fill, Kwedge = 1 to 5 ft/day

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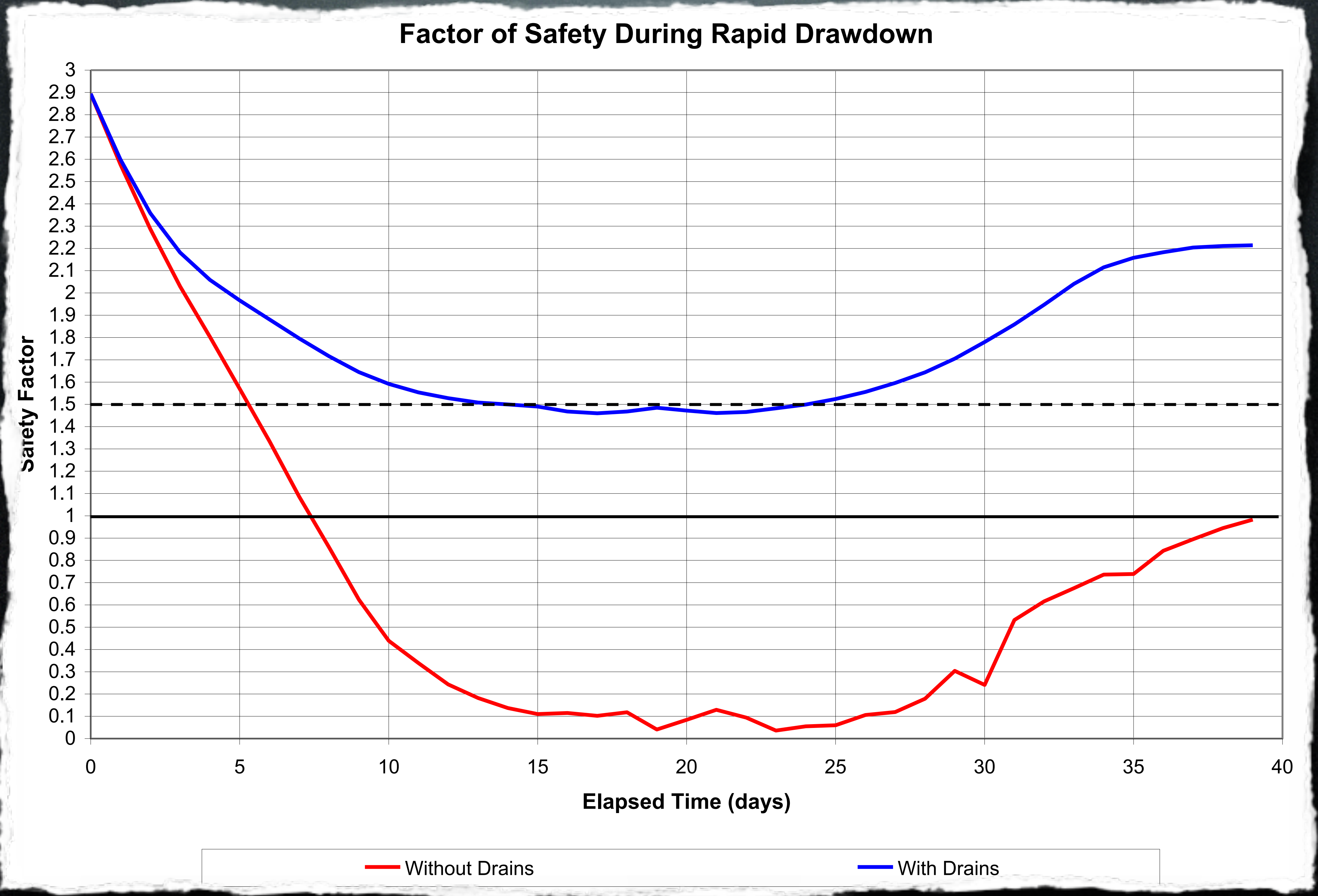
Group 14 - Slope Stability Results For Proposed Retrofit



Rapid Drawdown, φ'=34º and c'=200 psf

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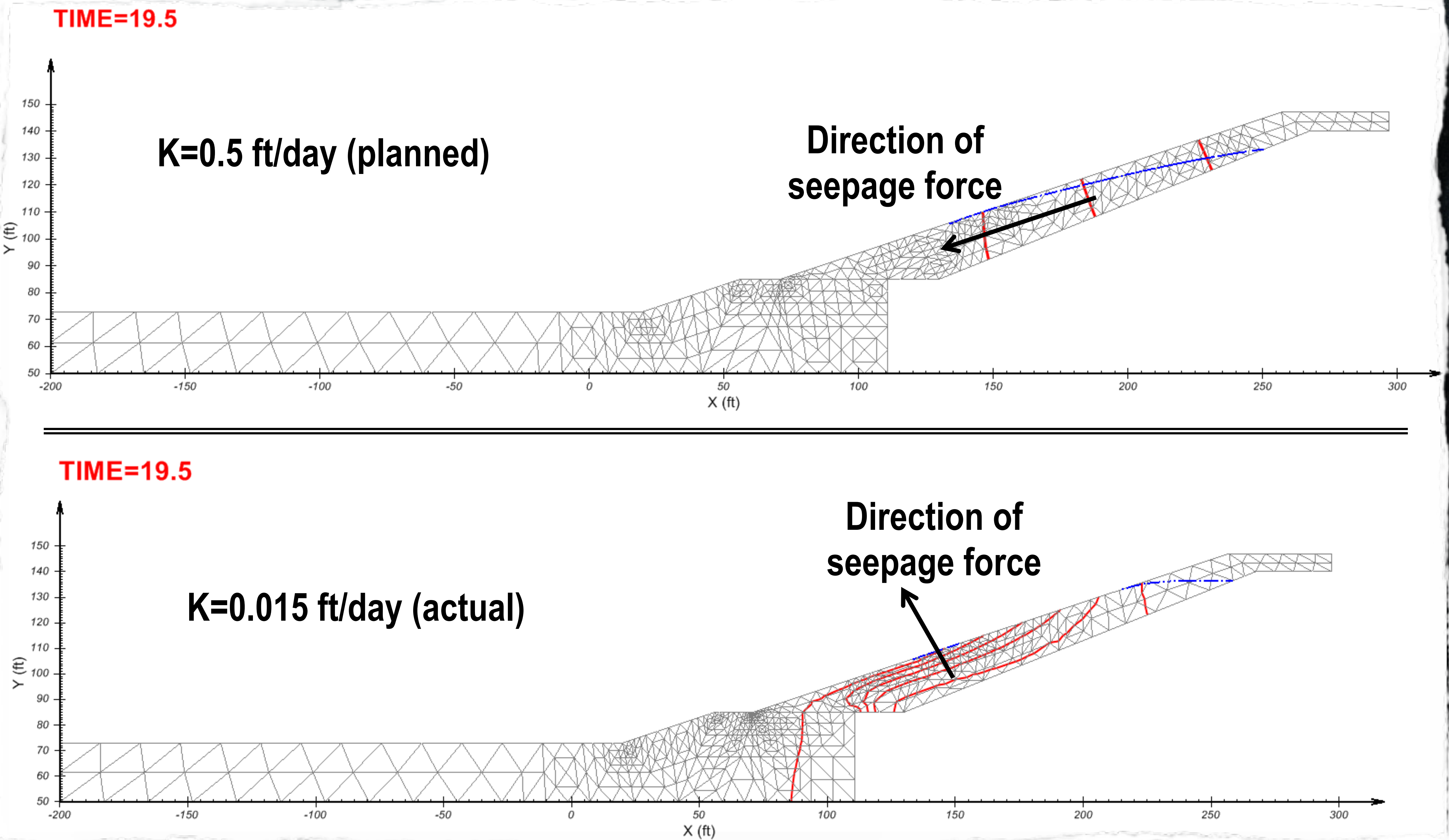
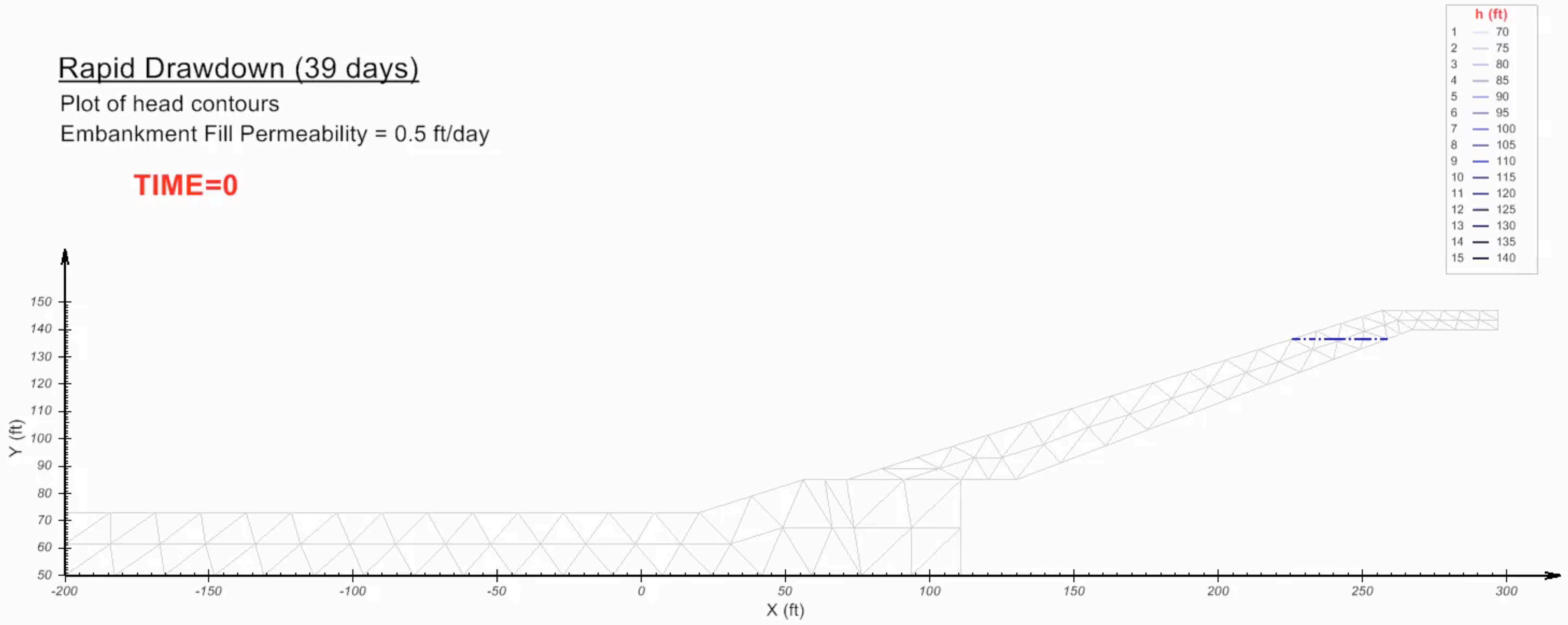
Part 10-B

PORE PRESSURE ANIMATIONS



Comparison of Head Contours in Embankment Wedge
During Rapid Drawdown, for K=0.5 ft/day vs K=0.015 ft/day

Rapid Drawdown Head Contours for K=0.5 ft/day



Rapid Drawdown (39 days)

Plot of head contours

Embankment Fill Permeability = 0.5 ft/day

TIME=0

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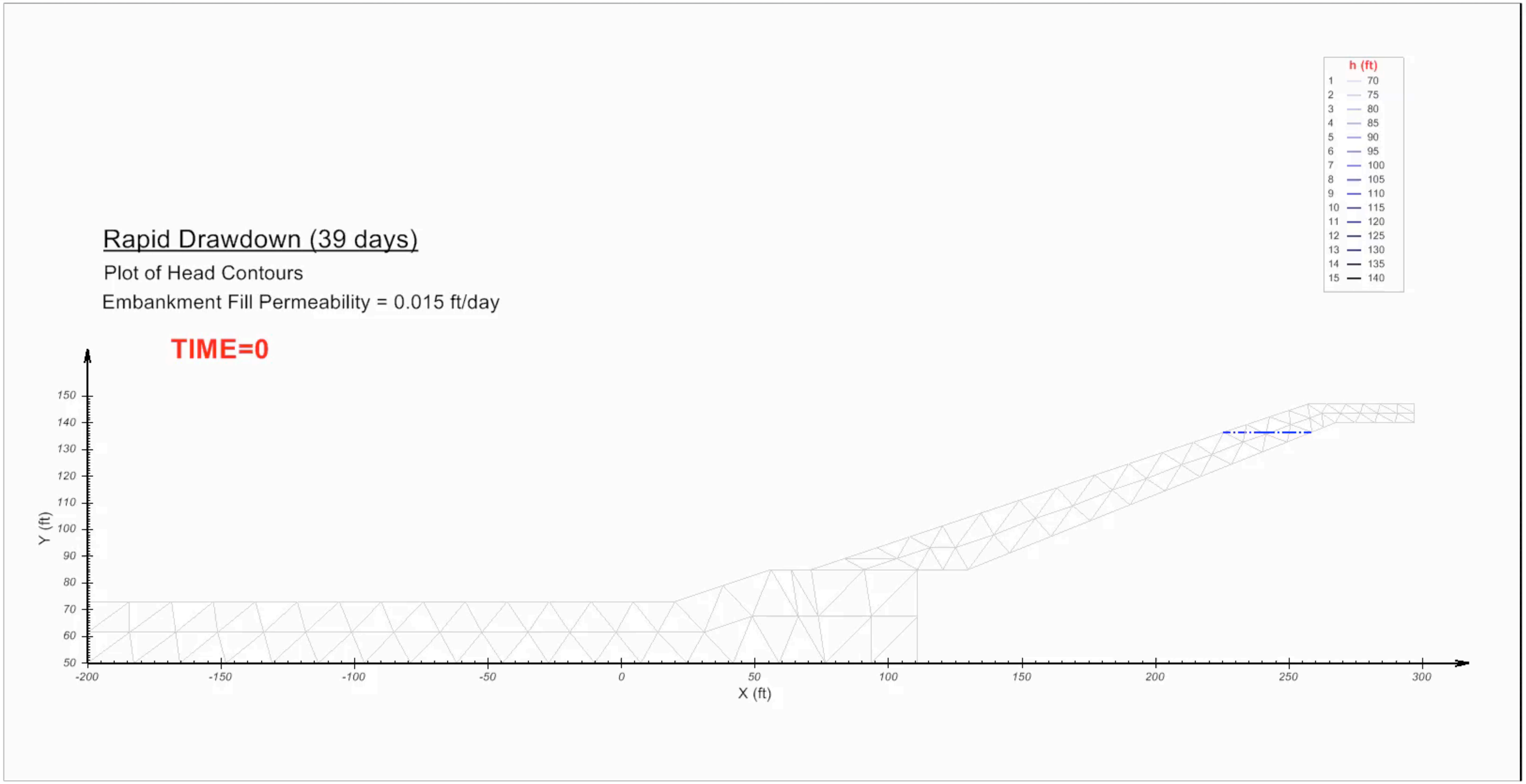
Rapid Drawdown Head Contours for K=0.015 ft/day



Rapid Drawdown (39 days)

Plot of Head Contours

Embankment Fill Permeability = 0.015 ft/day

TIME=0

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Part 10-C

ANIMATION OF SOILVISION INPUTS AND OUTPUTS

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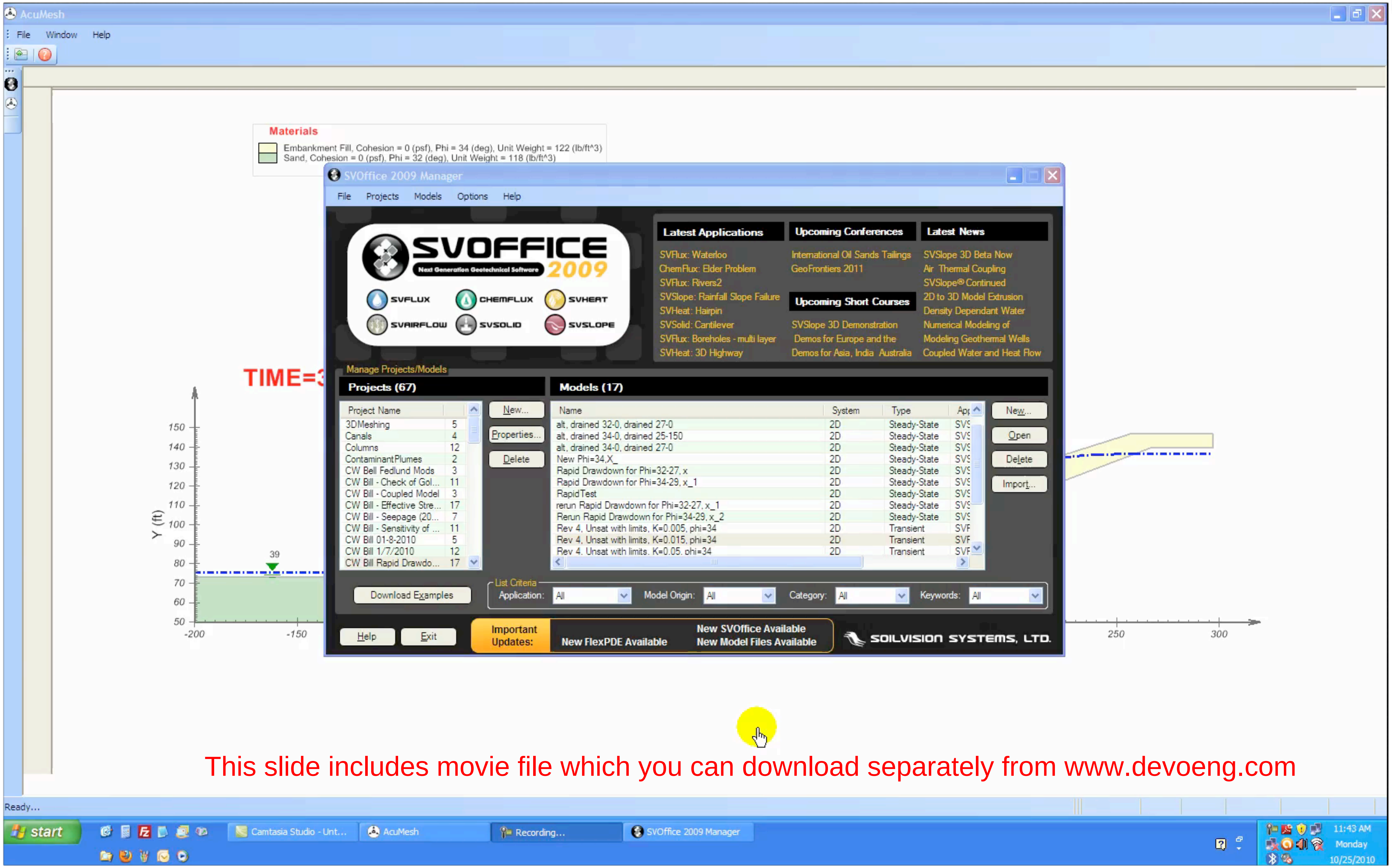

Materials

- Embankment Fill, Cohesion = 0 (psf), Phi = 34 (deg), Unit Weight = 122 (lb/ft^3)
- Sand, Cohesion = 0 (psf), Phi = 32 (deg), Unit Weight = 118 (lb/ft^3)

Latest Applications

- SVFlux: Waterloo
- ChemFlux: Elder Problem
- SVFlux: Rivers2
- SVSlope: Rainfall Slope Failure
- SVHeat: Hairpin
- SVSolid: Cantilever
- SVFlux: Boreholes - multi layer
- SVHeat: 3D Highway

Upcoming Conferences

- International Oil Sands Tailings
- GeoFrontiers 2011

Upcoming Short Courses

- SVSlope 3D Demonstration
- Demos for Europe and the
- Demos for Asia, India Australia

Latest News

- SVSlope 3D Beta Now
- Air Thermal Coupling
- SVSlope® Continued
- 2D to 3D Model Extrusion
- Density Dependant Water
- Numerical Modeling of
- Modeling Geothermal Wells
- Coupled Water and Heat Flow

Manage Projects/Models

Projects (67)

Project Name	
3DMeshing	5
Canals	4
Columns	12
ContaminantPlumes	2
CW Bell Fedlund Mods	3
CW Bill - Check of Gol...	11
CW Bill - Coupled Model	3
CW Bill - Effective Stre...	17
CW Bill - Seepage (20...	7
CW Bill - Sensitivity of ...	11
CW Bill 01-8-2010	5
CW Bill 1/7/2010	12
CW Bill Rapid Drawdo...	17

Models (17)

Name	System	Type	Ap
alt, drained 32-0, drained 27-0	2D	Steady-State	SVS
alt, drained 34-0, drained 25-150	2D	Steady-State	SVS
alt, drained 34-0, drained 27-0	2D	Steady-State	SVS
New Phi=34,X_	2D	Steady-State	SVS
Rapid Drawdown for Phi=32-27, x	2D	Steady-State	SVS
Rapid Drawdown for Phi=34-29, x_1	2D	Steady-State	SVS
RapidTest	2D	Steady-State	SVS
rerun Rapid Drawdown for Phi=32-27, x_1	2D	Steady-State	SVS
Rerun Rapid Drawdown for Phi=34-29, x_2	2D	Steady-State	SVS
Rev 4, Unsat with limits, K=0.005, phi=34	2D	Transient	SVF
Rev 4, Unsat with limits, K=0.015, phi=34	2D	Transient	SVF
Rev 4, Unsat with limits, K=0.05, phi=34	2D	Transient	SVF

List Criteria

Application: All

Model Origin: All

Category: All

Keywords: All

Important Updates: New FlexPDE Available

New SVOffice Available

New Model Files Available

This slide includes movie file which you can download separately from www.devoeng.com

SoilVision SVFlux and SVSlope

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Thank you...

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