Restoration of the Salton Sea

Volume 2: Embankment Designs and Optimization Study

Appendix 2E: Optimization Seepage and Stability Analyses

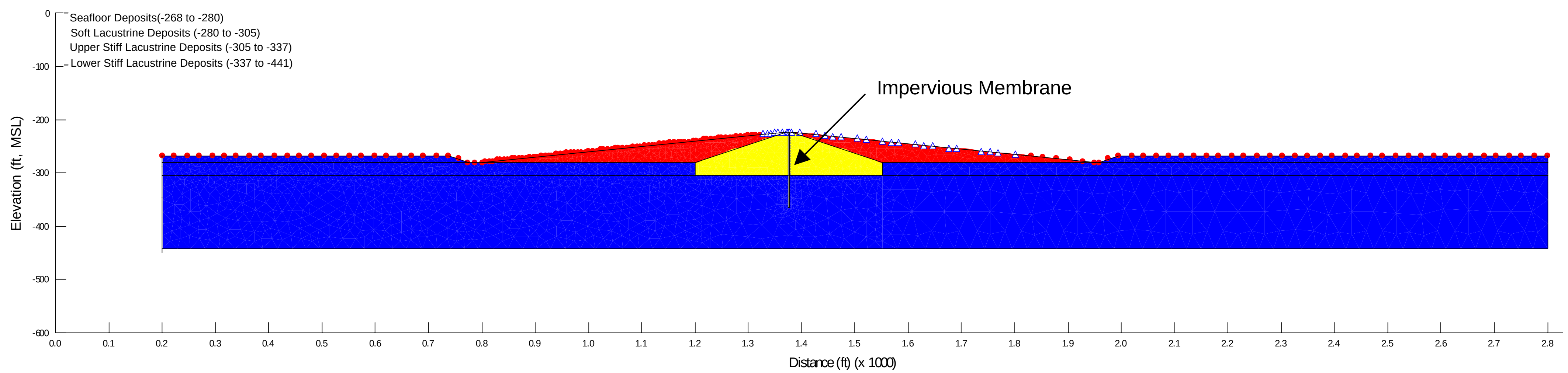
Prepared for:
U.S. Department of the Interior
Bureau of Reclamation
Lower Colorado Region
Boulder City, Nevada

Prepared by:
Kleinfelder, Inc.
Golden, CO 80401
Project No. 71100

April 2007

Optimized Stability Analyses
(Options A through E, and Perimeter Dike)

Section Geometry and Boundary Conditions



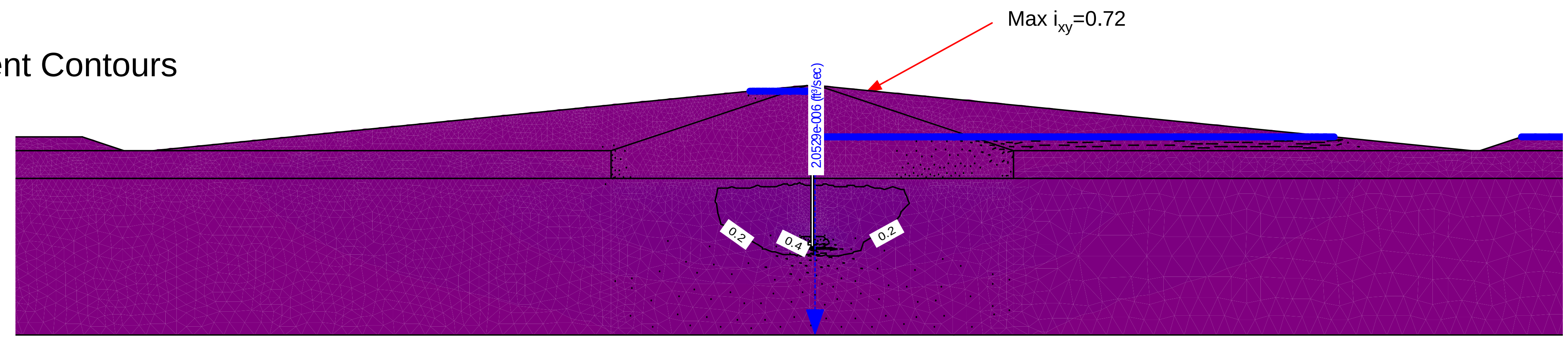
Boundary Conditions Legend

- Constant Total Head
- Seepage Exit Boundary

Material Properties Legend

Material	Kh ft/sec	Kv/Kh	Color
Rock Fill	3.28×10^{-2}	0.25	Red
Seafloor Deposits	3.28×10^{-7}	0.1	Blue
Soft Lacustrine	3.28×10^{-7}	0.1	Blue
Stiff Lacustrine	3.28×10^{-7}	0.1	Blue
Stone Column	3.28×10^{-2}	0.25	Yellow
Membrane	Impervious		

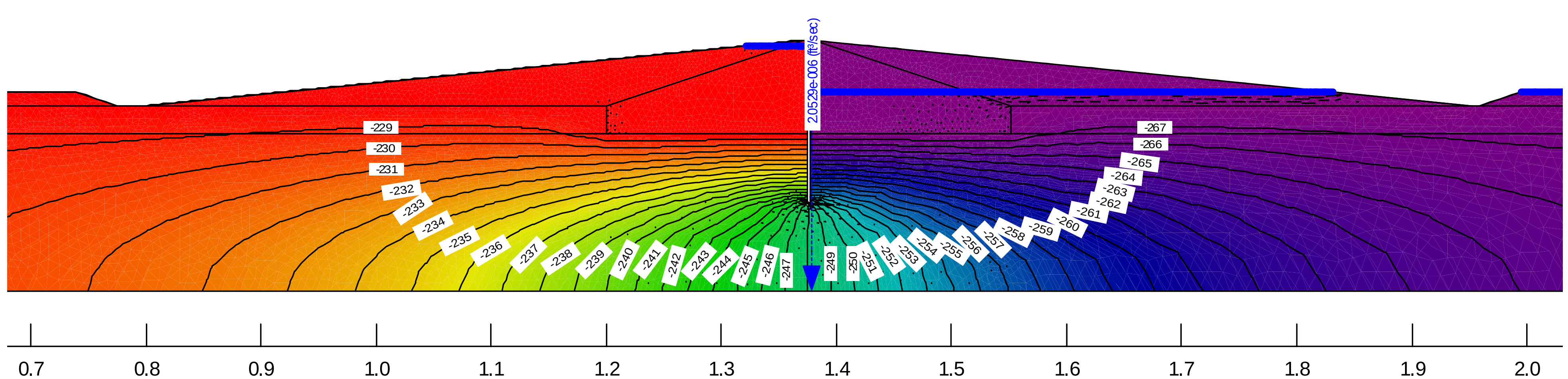
XY Gradient Contours



XY Gradient i_{xy} Contours Legend

i_{xy} =0 — i_{xy} =8

Total Head Contours



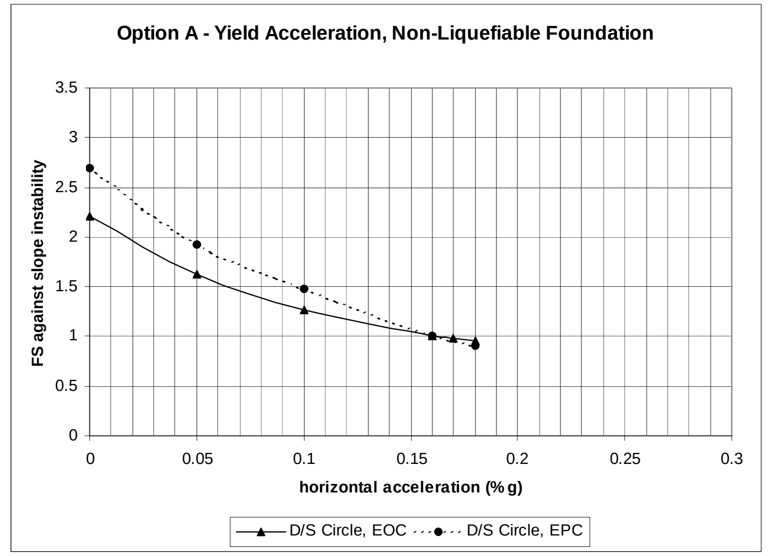
Total Head Contours Legend

-268 ft — -228 ft

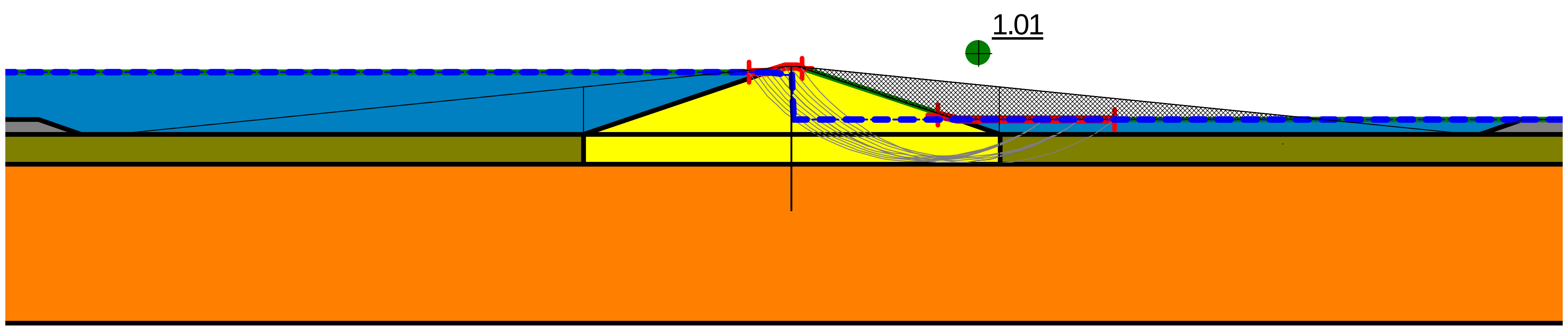
United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Seepage Analyses		Seepage Analysis Option A – Sand Dam with Stone Columns
KLEINFELDER	Project 71100	By E. Sossenkina	September 2006

FIGURE E-1

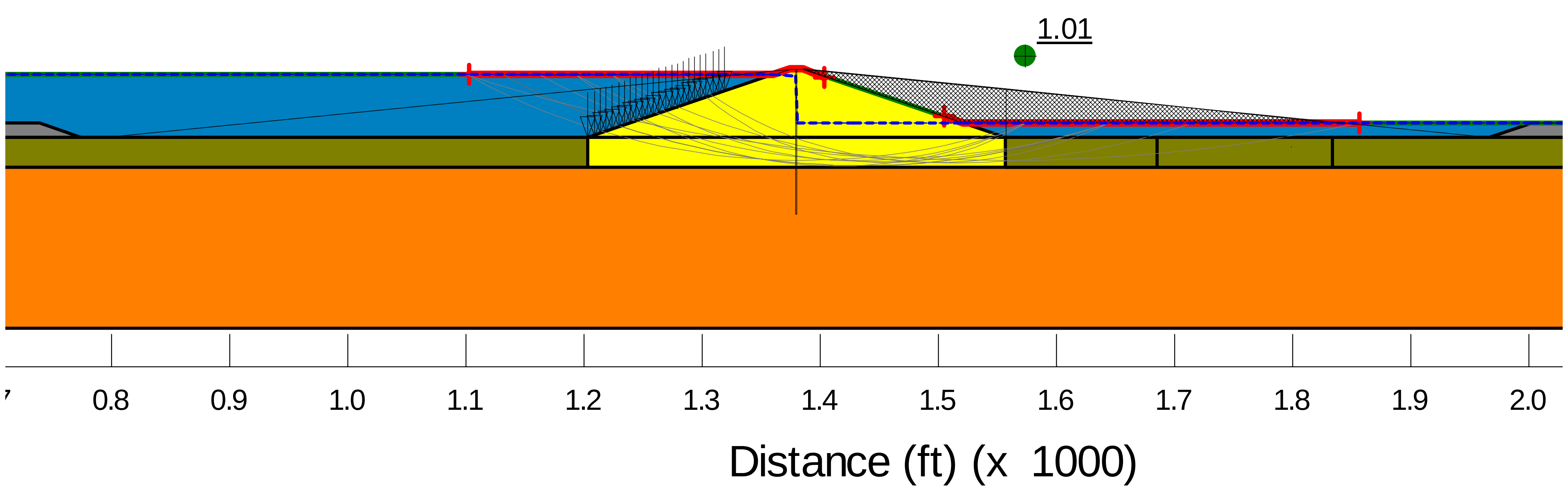
71100/DEN6R101



D/S Circles, EOC, Ky=0.16g



D/S Circles, EPC, Ky=0.16g



End of Construction (EOC)

EOC Material Properties

Material #: 14
Description: Seafloor Deposit - EOC Seismic
Model: SFnDatum
Wt: 98
C-Datum: 13
C-Rate of Increase: 15.4
Limiting C: 600
Elevation: -268
Piezometric Line: 1

Material #: 8
Description: Upper Stiff Lacustrine
Model: MohrCoulomb
Wt: 118
Cohesion: 200
Phi: 33
Unit Wt. Above WT: 118
Phi-B: 0
Anisotropic Fn: 1
Piezometric Line: 1

Description: Soft Lacustrine - EOC Seismic
Wt: 115
C-Datum: 13
C-Rate of Increase: 15.4
Limiting C: 600
Elevation: -268
Unit Wt. Above WT: 115
Anisotropic Fn: 1
Piezometric Line: 1

Material #: 1
Description: Sand Embankment with Stone Columns - Liquefied
Model: MohrCoulomb
Wt: 120
Cohesion: 1000
Phi: 0
Piezometric Line: 1

End of Primary Consolidation (EPC)

EPC Material Properties

Material #: 1
Description: Sand Embankment with Stone Columns - Liquefied
Model: MohrCoulomb
Wt: 120
Cohesion: 1000
Phi: 0
Piezometric Line: 1

Material #: 15
Description: Seafloor Deposit - EPC Seismic
Model: MohrCoulomb
Wt: 98
Cohesion: 0
Phi: 12.5
Piezometric Line: 1

Description: Soft Lacustrine - EPC Seismic
Wt: 115
Cohesion: 0
Phi: 17
Unit Wt. Above WT: 115
Anisotropic Fn: 1
Piezometric Line: 1

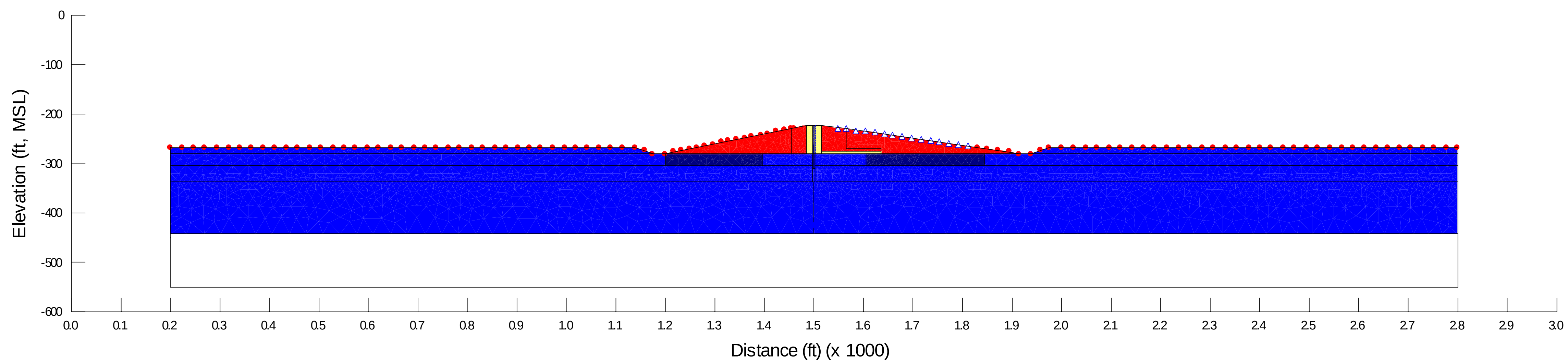
Description: Soft Lacustrine - EPC Seismic 1
Wt: 115
C-Datum: 740
C-Rate of Increase: 15.4
Limiting C: 1600
Elevation: -268
Piezometric Line: 1

Material #: 8
Description: Upper Stiff Lacustrine
Model: MohrCoulomb
Wt: 118
Cohesion: 200
Phi: 33
Unit Wt. Above WT: 118
Phi-B: 0
Anisotropic Fn: 1
Piezometric Line: 1

Description: Soft Lacustrine - EPC Seismic 2
Wt: 115
C-Datum: 530
C-Rate of Increase: 15.4
Limiting C: 1600
Elevation: -268
Piezometric Line: 1

United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Optimized Stability Analyses	Seismic Stability Analysis Option A – Sand Dam with Stone Columns
KLEINFELDER	Project 71100 / By E. Sossenkina / September 2006	**FIGURE E-2**

Section Geometry and Boundary Conditions



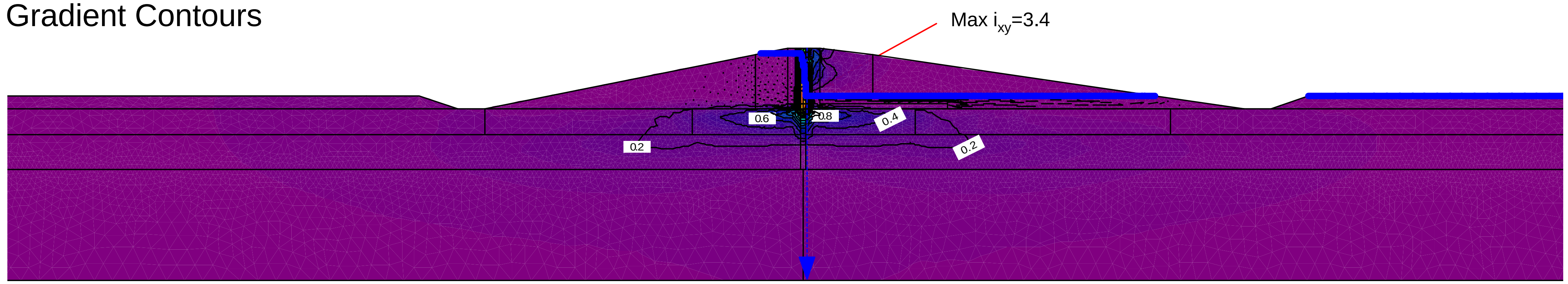
Boundary Conditions Legend

Constant Total Head
Seepage Exit Boundary

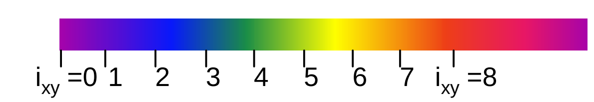
Material Properties Legend

Material	Kh ft/sec	Kv/Kh	Color
Rockfill	$3.28*10^{-2}$	0.25	
Fine Rockfill	$3.28*10^{-2}$	0.25	
Filter Blanket	$1.77*10^{-4}$	1	
Sand Gravel Core	$3.28*10^{-4}$	0.25	
Slurry Wall	$3.28*10^{-8}$	1	
Seafloor Deposits	$3.28*10^{-7}$	0.1	
Soft Lacustrine	$3.28*10^{-7}$	0.1	
Stiff Lacustrine	$3.28*10^{-7}$	0.1	
Jet-grouted Lacustrine	$4.92*10^{-8}$	1	

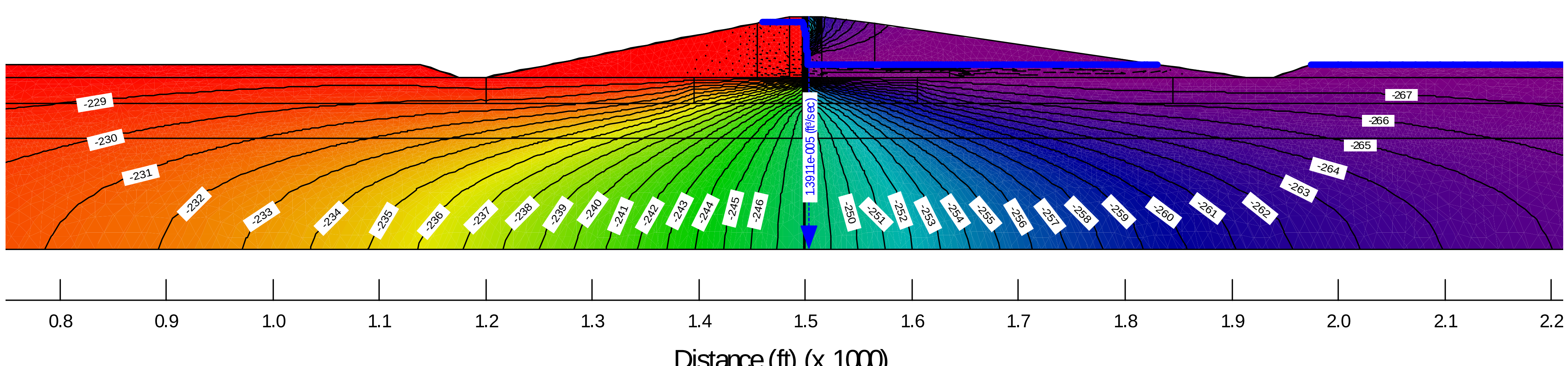
XY Gradient Contours



XY Gradient i_{xy} Contours Legend



Total Head Contours



Total Head Contours Legend

Seafloor Deposits(-268 to -280)
Soft Lacustrine Deposits (-280 to -305)
Upper Stiff Lacustrine Deposits (-305 to -337)
Lower Stiff Lacustrine Deposits (-337 to -441)

United States Department of the Interior Bureau of Reclamation

KLEINFELDER

SALTON SEA RESTORATION PROJECT
EMBANKMENT DESIGNS AND OPTIMIZATION STUDY
Appendix 2E – Seepage Analyses

Seepage Analysis
Option B - Rockfill with Jet Grouted Foundation

Project 71100	By E. Sossenkina	September 2006	**FIGURE E-3**

71100/DEN6R101

Description: Rockfill
Wt: 115
Cohesion: 0
Phi: 45
Piezometric Line: 1

Description: Core - Clean Sand & Gravel
Wt: 120
Cohesion: 0
Phi: 30
Piezometric Line: 1

Description: Fine Rockfill
Wt: 118
Cohesion: 0
Phi: 42
Piezometric Line: 1

Description: SCB Slurry Wall
Wt: 120
Cohesion: 100
Phi: 30
Piezometric Line: 1

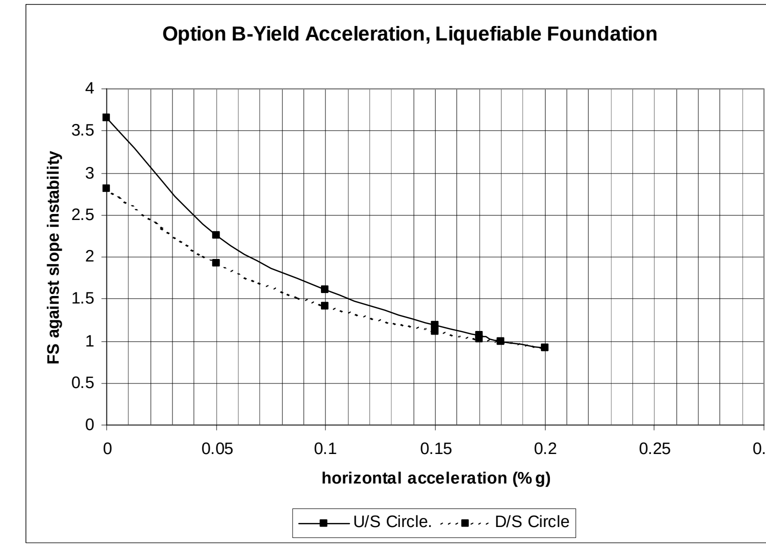
Description: Filter Blanket-Liquefied
Wt: 125
Cohesion: 150
Phi: 0
Piezometric Line: 1

Description: Untreated Lacustrine - Liquefied
Wt: 115
Cohesion: 250
Phi: 0
Piezometric Line: 1

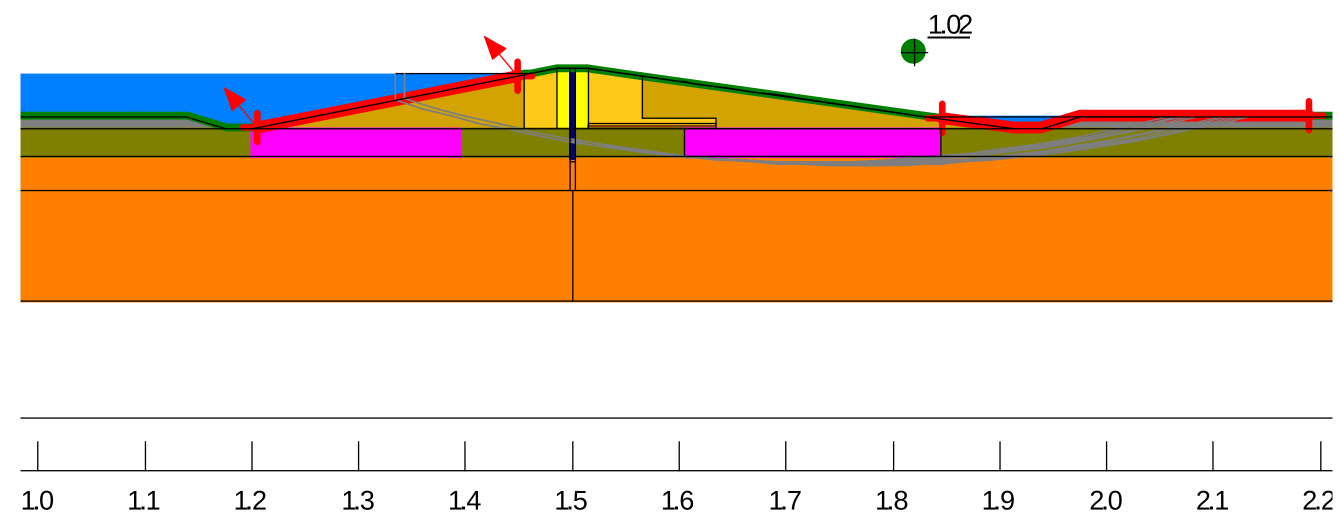
Description: Upper Stiff Lacustrine, Seismic
Wt: 118
Cohesion: 200
Phi: 33
Unit Wt. Above WT: 118
Phi-B: 0
Anisotropic Fn: 1
Piezometric Line: 1

Description: Seafloor Deposit - Seismic
Wt: 98
C-Datum: 13
C-Rate of Increase: 15.4
Limiting C: 600
Elevation: -268
Piezometric Line: 1

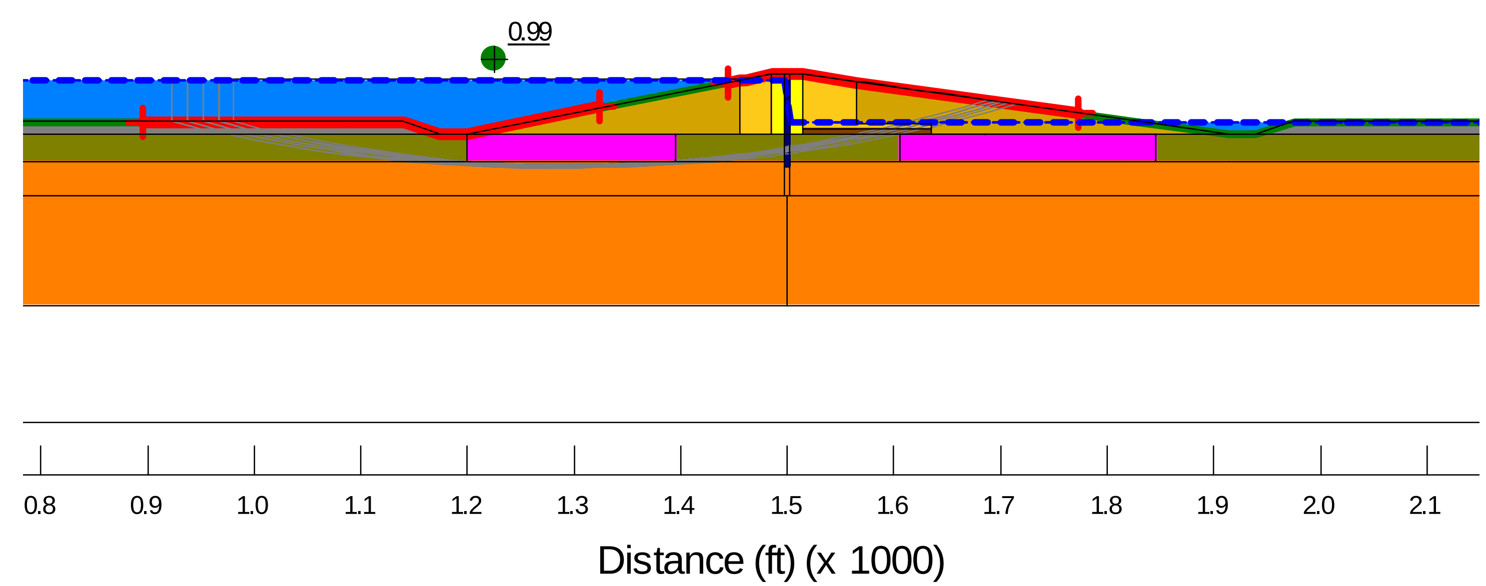
Description: Jet Grouted Lacustrine
Wt: 120
Cohesion: 7200
Phi: 0
Piezometric Line: 1



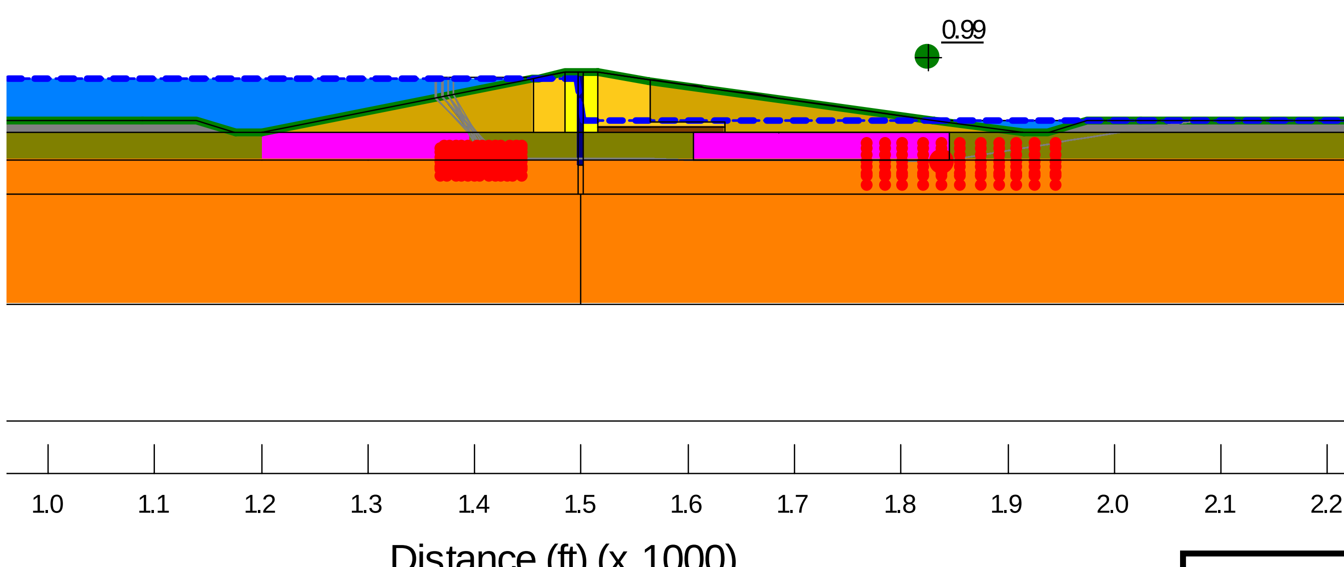
D/S Circles Ky =0.18g



U/S Circles Ky=0.18g

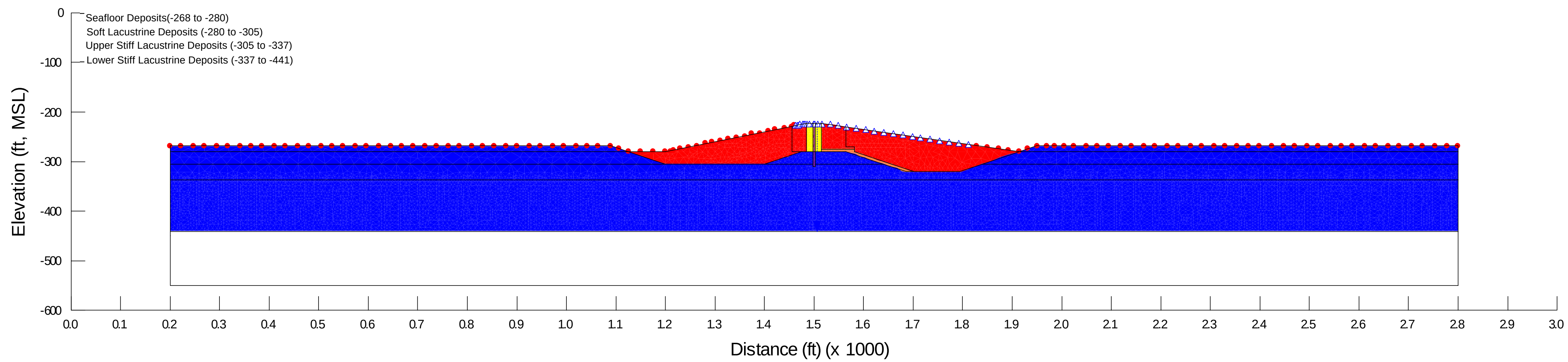


D/S Wedge Ky=0.17g

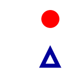


United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Optimized Stability Analyses		Seismic Stability Analysis Option B - Rockfill Dam with Jet-grouted Foundation
KLEINFELDER	Project 71100	By E. Sossenkina	September 2006	**FIGURE E-4**

Section Geometry and Boundary Conditions



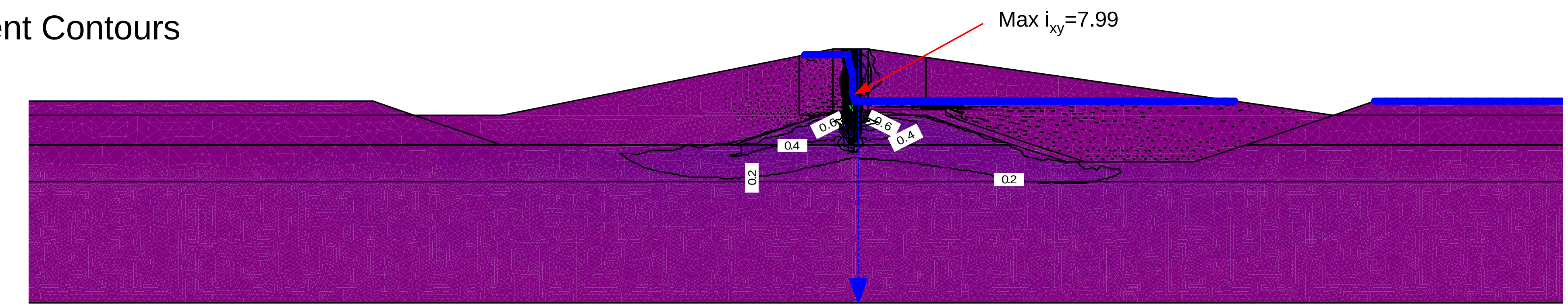
Boundary Conditions Legend



Material Properties Legend

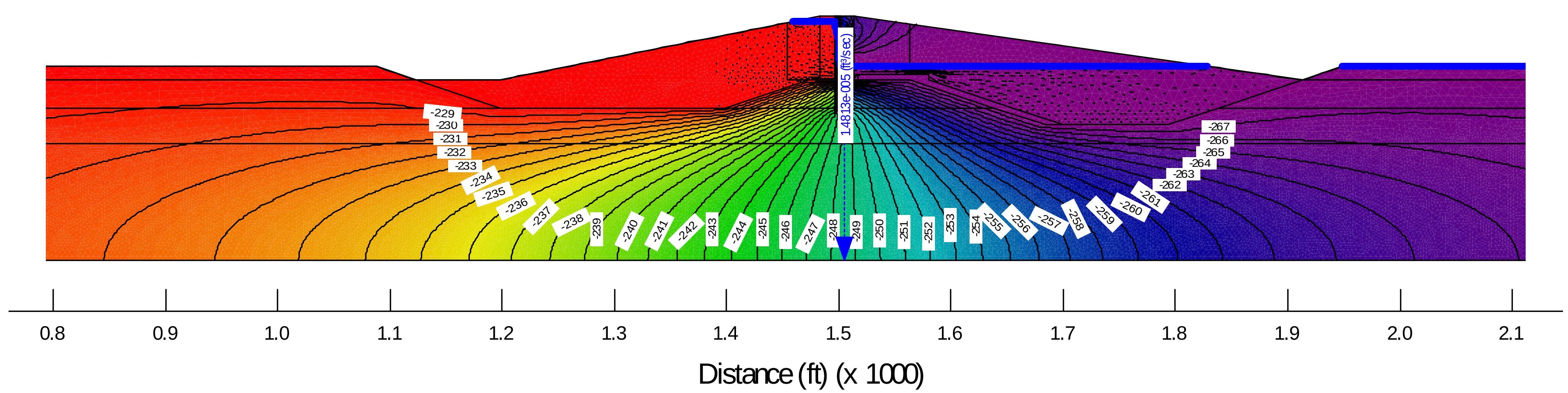
Material	Kh ft/sec	Kv/Kh	Color
Rockfill	$3.28*10^{-2}$	0.25	
Fine Rockfill	$3.28*10^{-2}$	0.25	
Filter Blanket	$1.77*10^{-4}$	1	
Sand Gravel Core	$3.28*10^{-4}$	0.25	
Slurry Wall	$3.28*10^{-8}$	1	
Seafloor Deposits	$3.28*10^{-7}$	0.1	
Soft Lacustrine	$3.28*10^{-7}$	0.1	
Stiff Lacustrine	$3.28*10^{-7}$	0.1	

XY Gradient Contours



XY Gradient i_{xy} Contours Legend

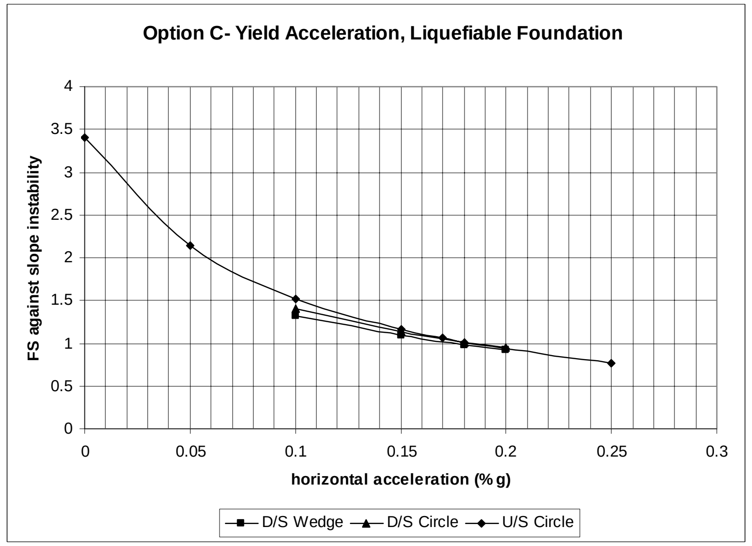
Total Head Contours



Total Head Contours Legend

United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Seepage Analyses		Seepage Analysis Option C – Modified Rock Notches Dam with Minimum Seepage Filter
K L E I N F E L D E R	Project 71100	By E. Sossenkina	September 2006
			FIGURE E-5

71100/DEN6R101



Material #: 1
Description: Slurry Cut-Off Wall
Model: MohrCoulomb
Wt: 120
Cohesion: 100
Phi: 30
Piezometric Line: 1

Material #: 2
Description: Core
Model: MohrCoulomb
Wt: 120
Cohesion: 0
Phi: 30
Piezometric Line: 1

Material #: 3
Description: Fine Rock Fill
Model: MohrCoulomb
Wt: 118
Cohesion: 0
Phi: 42
Piezometric Line: 1

Material #: 4
Description: Rock Fill
Model: MohrCoulomb
Wt: 115
Cohesion: 0
Phi: 45
Piezometric Line: 1

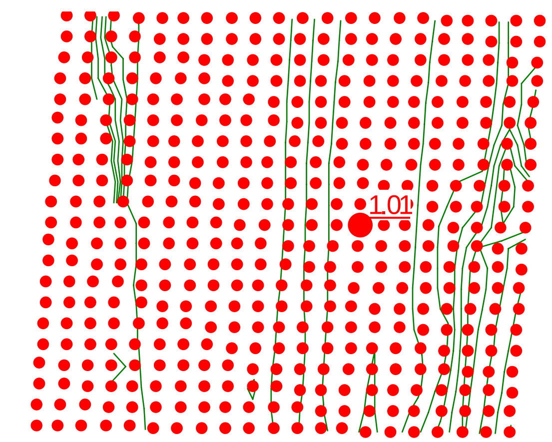
Material #: 5
Description: Filter Blanket
Model: MohrCoulomb
Wt: 125
Cohesion: 150
Phi: 0
Piezometric Line: 1

Material #: 6
Description: Untreated Lacustrine Deposites
Model: UndrainedPhiZero
Wt: 115
Cohesion: 250
Piezometric Line: 1

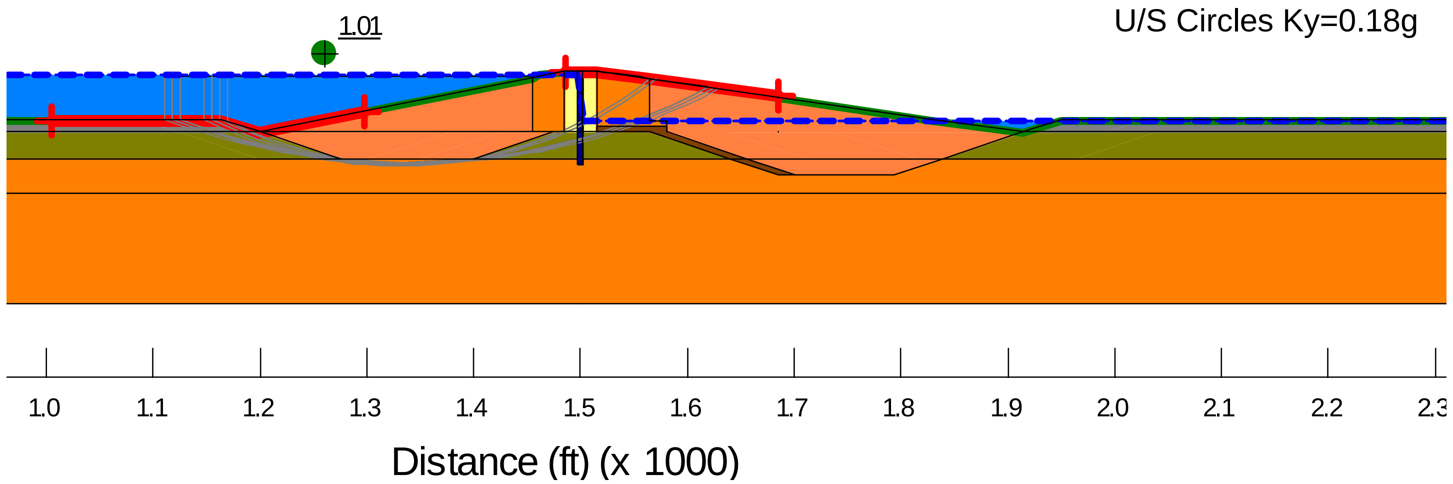
Material #: 7
Description: Seafloor Deposites
Model: SFnDatum
Wt: 98
C-Datum: 13
C-Rate of Increase: 15.4
Limiting C: 600
Elevation: -268
Piezometric Line: 1

Material #: 8
Description: Stiff Lacustrine Deposites
Model: MohrCoulomb
Wt: 118
Cohesion: 200
Phi: 33
Unit Wt. Above WT: 118
Phi-B: 0
Anisotropic Fn: 1
Piezometric Line: 1

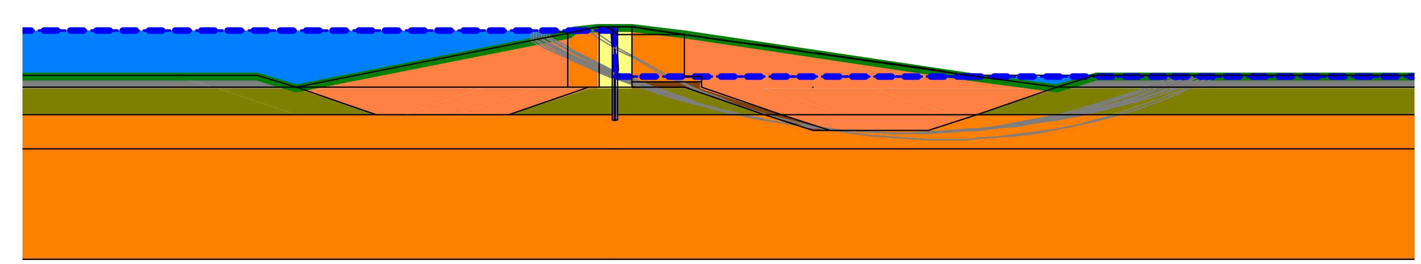
Note:
Anisotropic Fn1=Sh/Sv=0.9



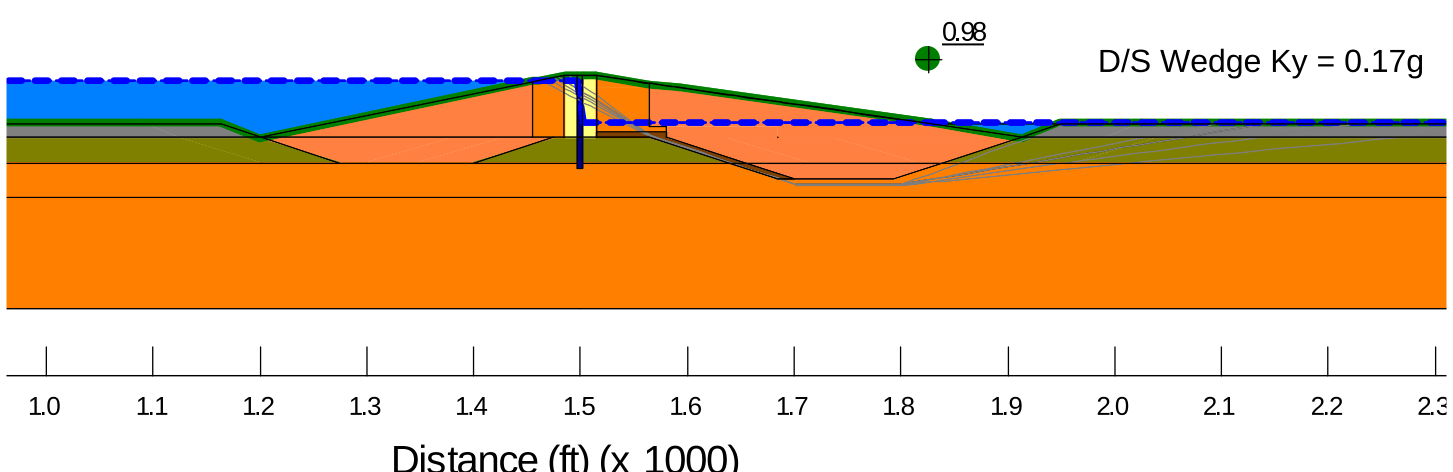
U/S Circles Ky=0.18g



D/S Circle Ky = 0.18g



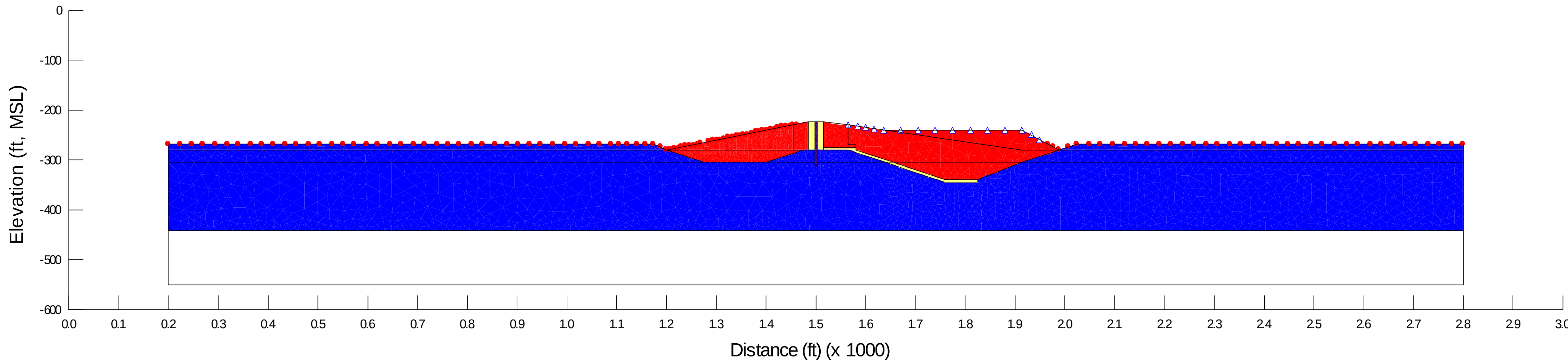
D/S Wedge Ky = 0.17g



United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Optimized Stability Analyses		Seismic Stability Analysis Option C - Modified Rock Notches Dam with Minimum Seepage Filters
KLEINFELDER	Project 71100	By E. Sossenkina	September 2006	**FIGURE E-6**

71100/DEN6R101

Section Geometry and Boundary Conditions



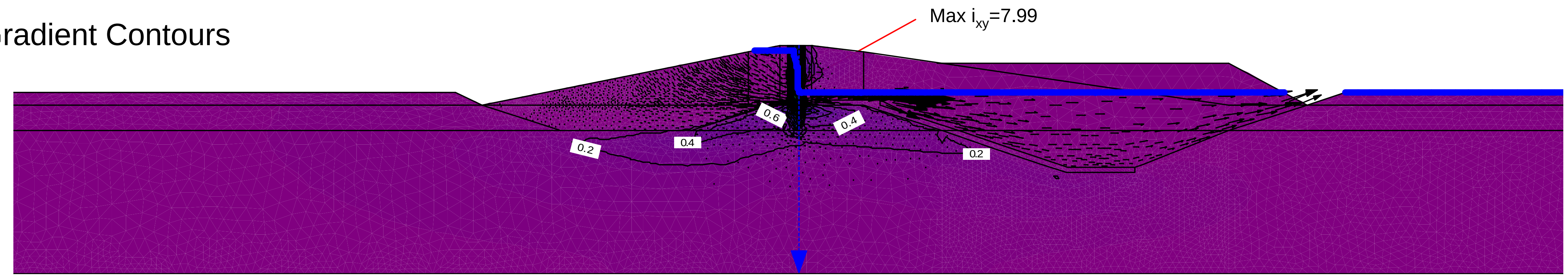
Boundary Conditions Legend

- Constant Total Head
- Seepage Exit Boundary

Material Properties Legend

Material	Kh ft/sec	Kv/Kh	Color
Rockfill	$3.28 \cdot 10^{-2}$	0.25	
Fine Rockfill	$3.28 \cdot 10^{-2}$	0.25	
Filter Blanket	$1.77 \cdot 10^{-4}$	1	
Sand Gravel Core	$3.28 \cdot 10^{-4}$	0.25	
Slurry Wall	$3.28 \cdot 10^{-8}$	1	
Seafloor Deposits	$3.28 \cdot 10^{-7}$	0.1	
Soft Lacustrine	$3.28 \cdot 10^{-7}$	0.1	
Stiff Lacustrine	$3.28 \cdot 10^{-7}$	0.1	

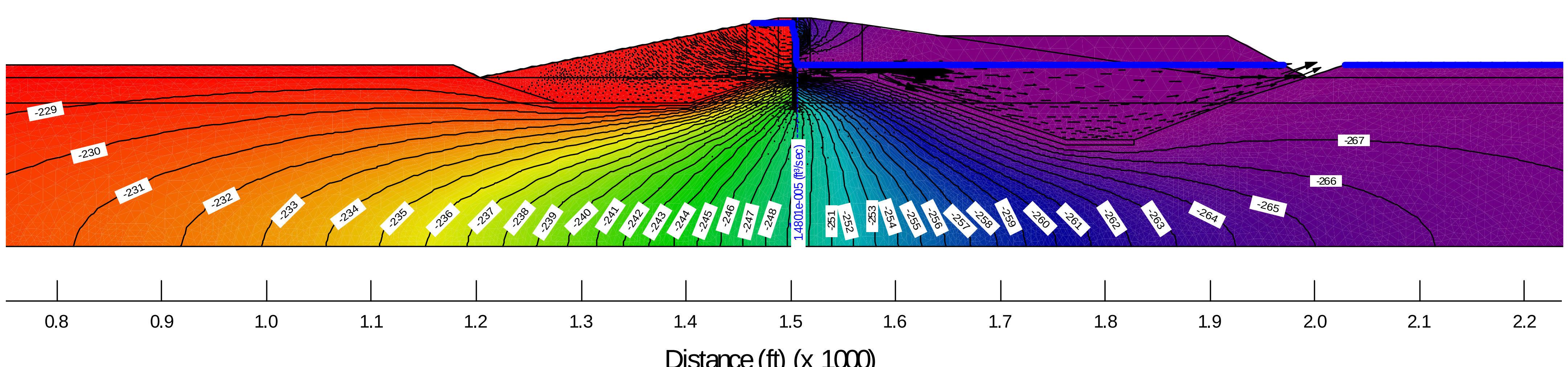
XY Gradient Contours



XY Gradient i_{xy} Contours Legend

i_{xy} =0 1 2 3 4 5 6 7 i_{xy} =8

Total Head Contours



Total Head Contours Legend

-268 ft -228 ft

Seafloor Deposits(-268 to -280)
Soft Lacustrine Deposits (-280 to -305)
Upper Stiff Lacustrine Deposits (-305 to -337)
Lower Stiff Lacustrine Deposits (-337 to -441)

United States Department of the Interior Bureau of Reclamation

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SALTON SEA RESTORATION PROJECT
EMBANKMENT DESIGNS AND OPTIMIZATION STUDY
Appendix 2E – Seepage Analyses

Seepage Analysis
Option D - Modified Rock Notches Dam With Maximum Seismic Filters

Project 71100	By E. Sossenkina	September 2006	**FIGURE E-7**

71100/DEN6R101

Material #: 1
Description: Slurry Cut-Off Wall
Model: MohrCoulomb
Wt: 120
Cohesion: 100
Phi: 30
Piezometric Line: 1

Material #: 2
Description: Core
Model: MohrCoulomb
Wt: 120
Cohesion: 0
Phi: 30
Piezometric Line: 1

Material #: 3
Description: Fine Rock Fill
Model: MohrCoulomb
Wt: 118
Cohesion: 0
Phi: 42
Piezometric Line: 1

Material #: 4
Description: Rock Fill
Model: MohrCoulomb
Wt: 115
Cohesion: 0
Phi: 45
Piezometric Line: 1

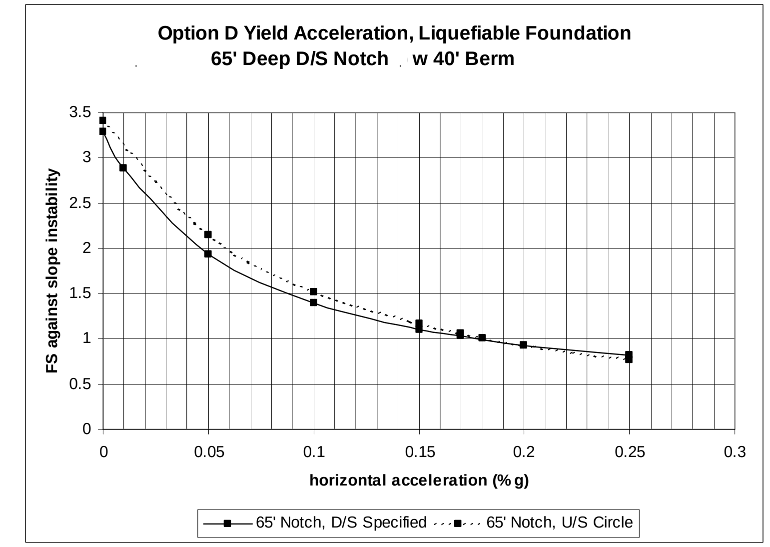
Material #: 5
Description: Filter Blanket
Model: MohrCoulomb
Wt: 125
Cohesion: 150
Phi: 0
Piezometric Line: 1

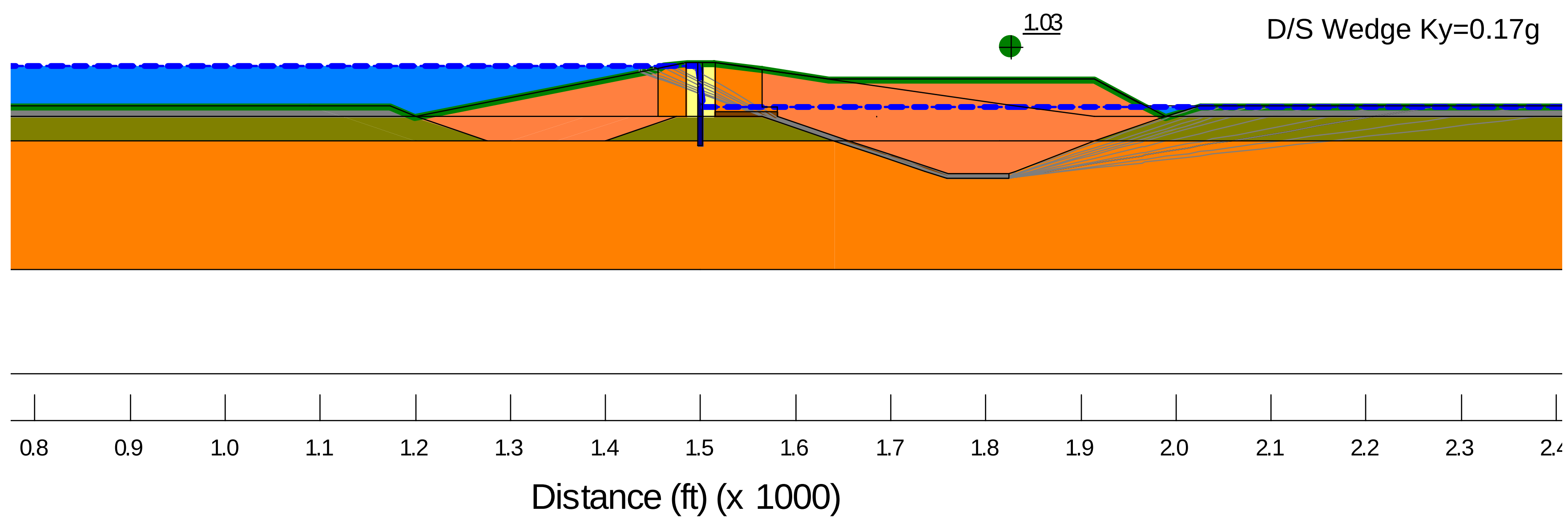
Material #: 6
Description: Untreated Lacustrine Deposites
Model: UndrainedPhiZero
Wt: 115
Cohesion: 250
Piezometric Line: 1

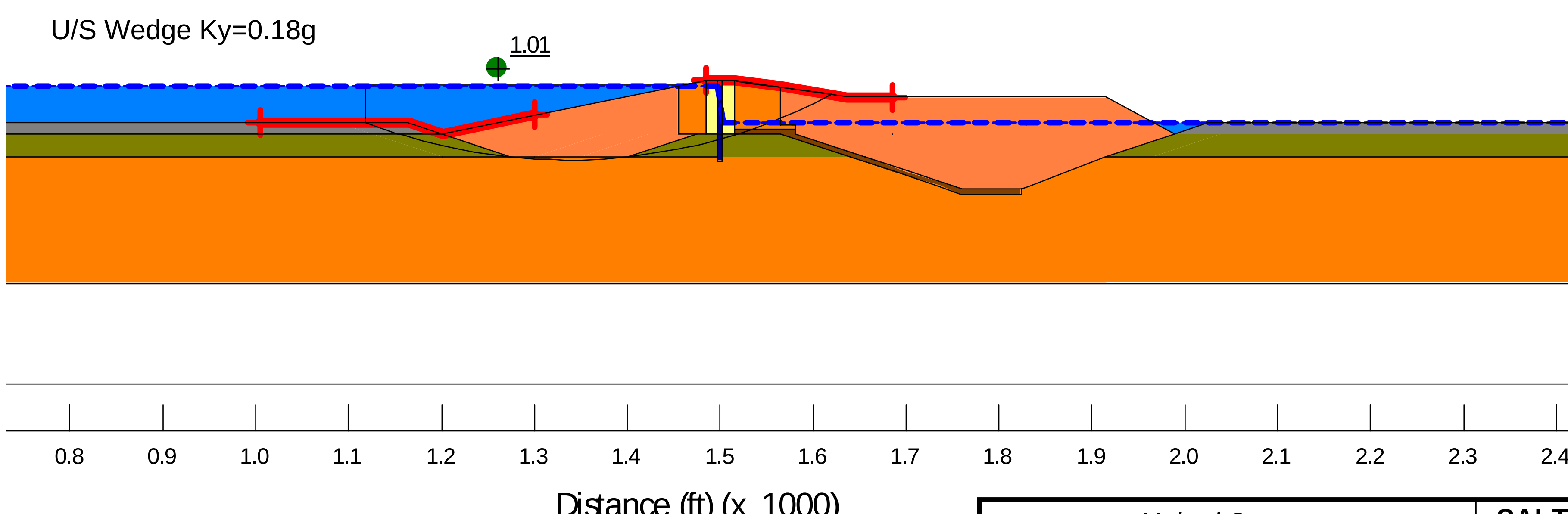
Material #: 7
Description: Seafloor Deposites
Model: SFnDatum
Wt: 98
C-Datum: 13
C-Rate of Increase: 15.4
Limiting C: 600
Elevation: -268
Piezometric Line: 1

Material #: 8
Description: Stiff Lacustrine Deposites
Model: MohrCoulomb
Wt: 118
Cohesion: 200
Phi: 33
Unit Wt. Above WT: 118
Phi-B: 0
Anisotropic Fn: 1
Piezometric Line: 1

Note:
Anisotropic Fn1=Sh/Sv=0.9







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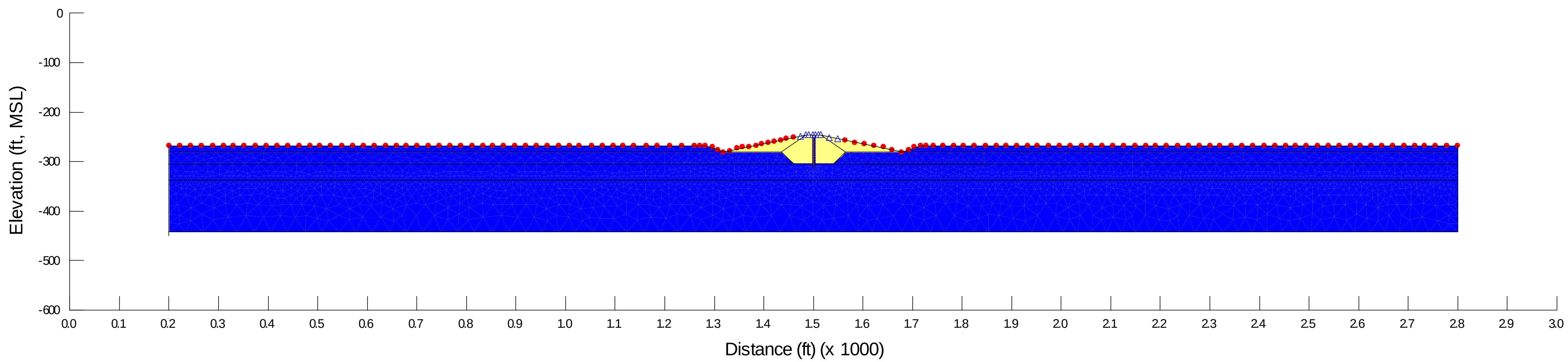
SALTON SEA RESTORATION PROJECT
EMBANKMENT DESIGNS AND
OPTIMIZATION STUDY
Appendix 2E – Optimized Stability Analyses

Seismic Stability Analysis
Option D - Modified Rock Notches Dam
With Maximum Seismic Filters

Project 71100	By E. Sossenkina	September 2006	**FIGURE E-8**

Section Geometry and Boundary Conditions



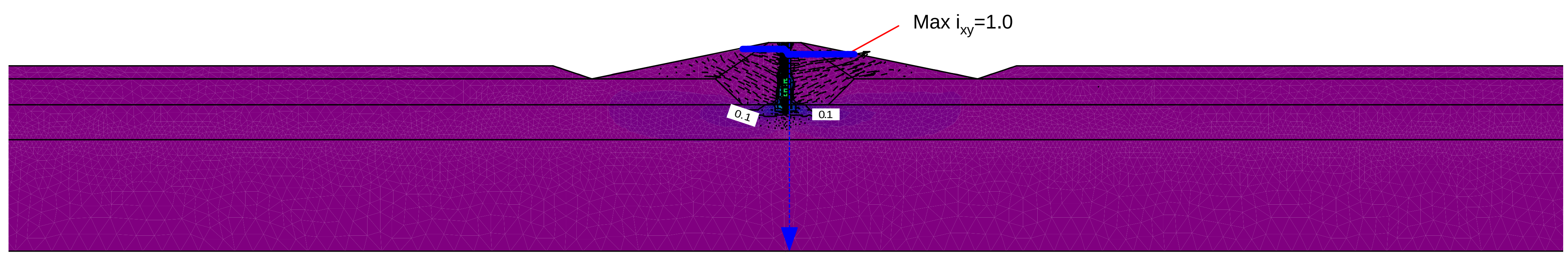
Boundary Conditions Legend

- Constant Total Head
- Seepage Exit Boundary

Material Properties Legend

Material	Kh ft/sec	Kv/Kh	Color
Soft Lacustrine	$3.28 \cdot 10^{-7}$	0.1	
Stiff Lacustrine	$3.28 \cdot 10^{-7}$	0.1	
Seafloor Deposits	$3.28 \cdot 10^{-7}$	0.1	
SCB Slurry Wall	$3.28 \cdot 10^{-8}$	1	
Sand/Gravel Type A	$3.28 \cdot 10^{-4}$	0.25	
Sand/Gravel Type B	$3.28 \cdot 10^{-4}$	0.25	

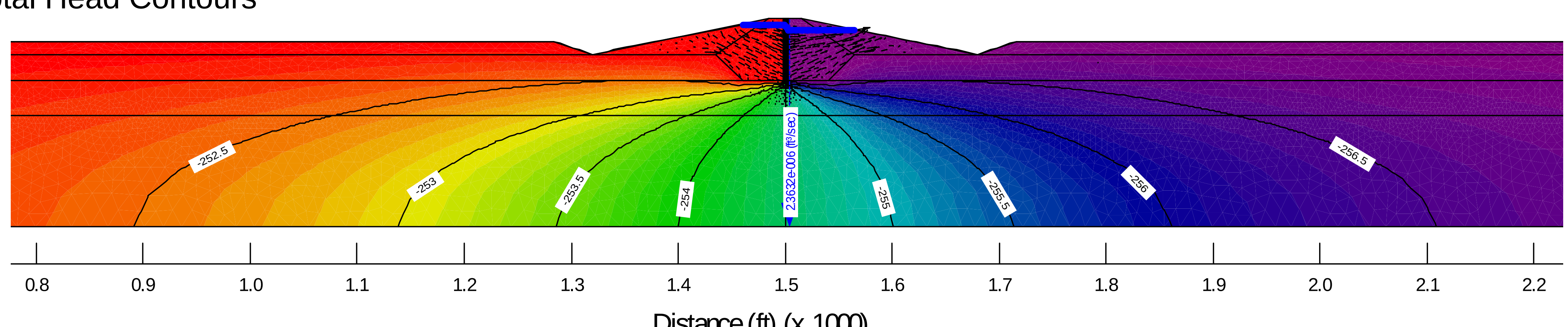
XY Gradient Contours



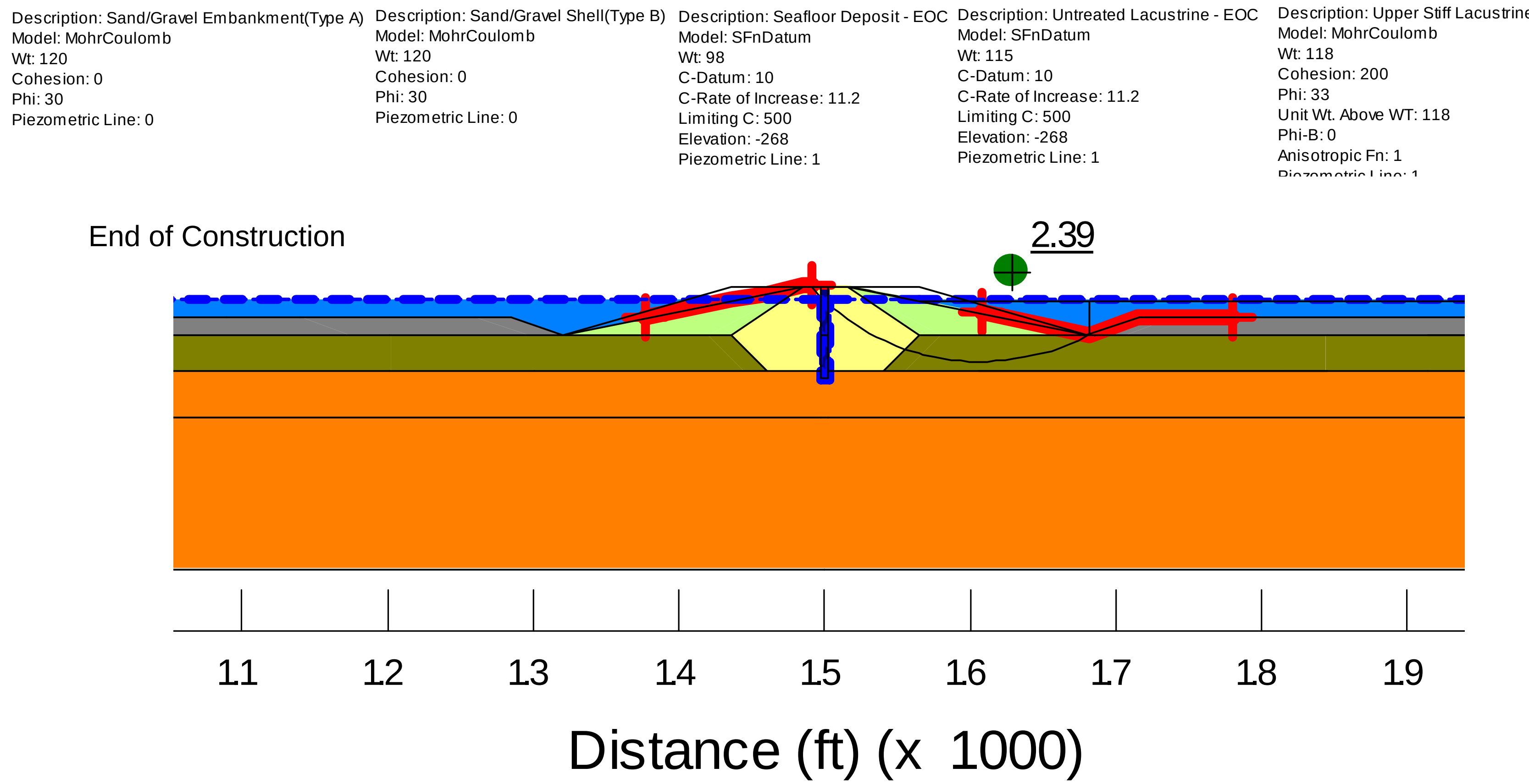
XY Gradient i_{xy} Contours Legend

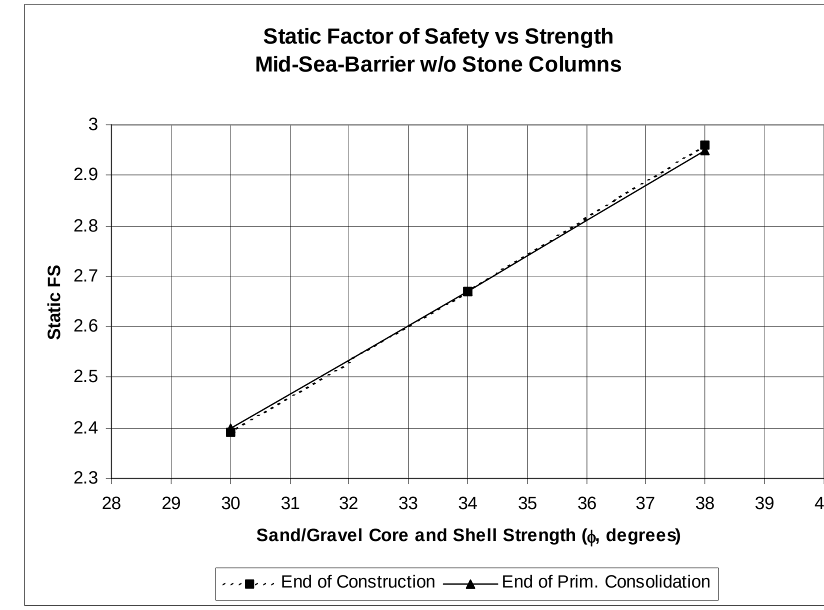
Total Head Contours Legend

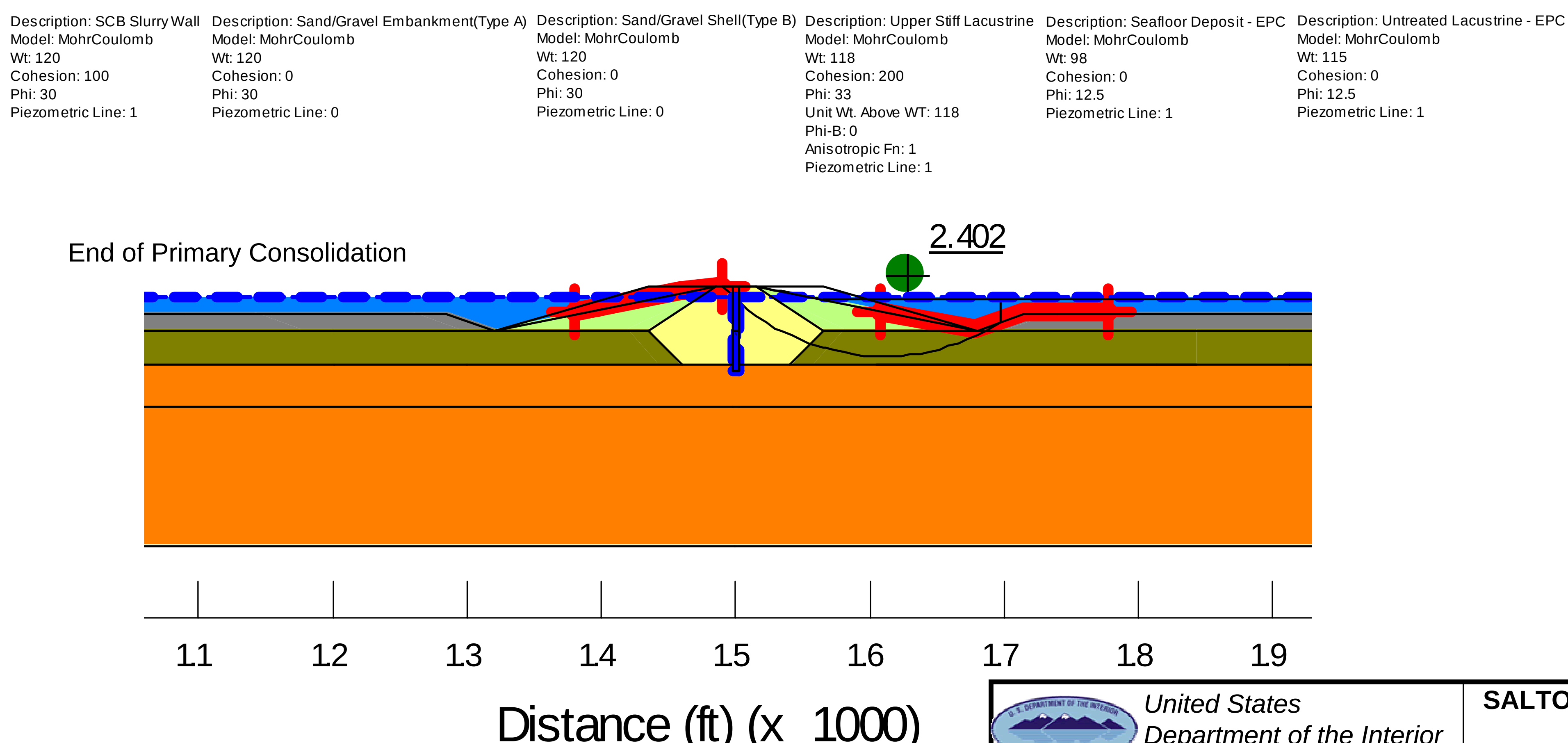
Total Head Contours



United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Seepage Analyses			Seepage Analysis Option E – Optimized Mid-Sea Barrier Without Stone Columns
KLEINFELDER	Project 71100	By E. Sossenkina	September 2006	**FIGURE E-9**







United States
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Bureau of Reclamation

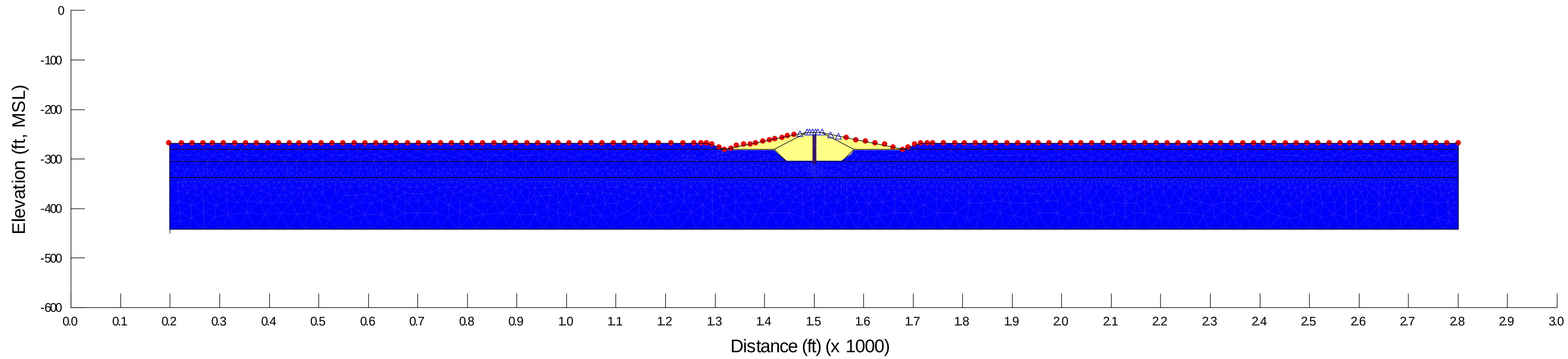
K L E I N F E L D E R

SALTON SEA RESTORATION PROJECT
EMBANKMENT DESIGNS AND
OPTIMIZATION STUDY
Appendix 2E – Optimized Stability Analyses

Static Stability Analysis
Option E – Optimized Mid-Sea Barrier
Without Stone Columns

Project 71100	By E. Sossenkina	September 2006	**FIGURE E-10**

Section Geometry and Boundary Conditions



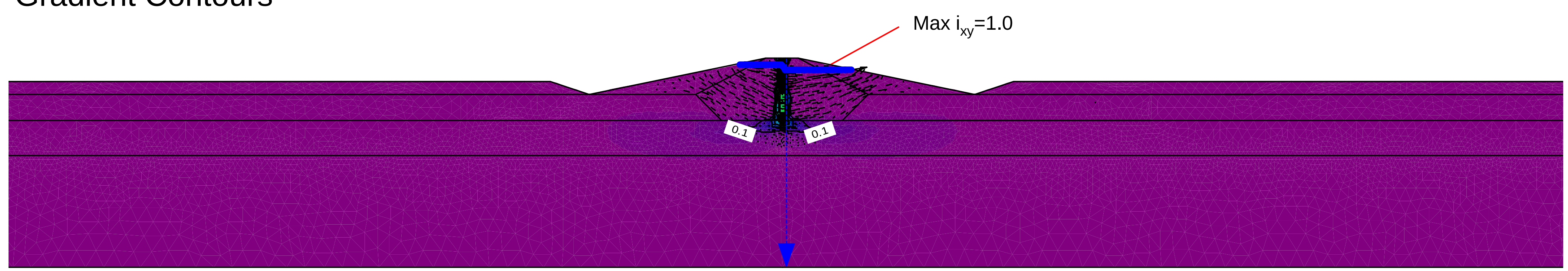
Boundary Conditions Legend

- Constant Total Head
- Seepage Exit Boundary

Material Properties Legend

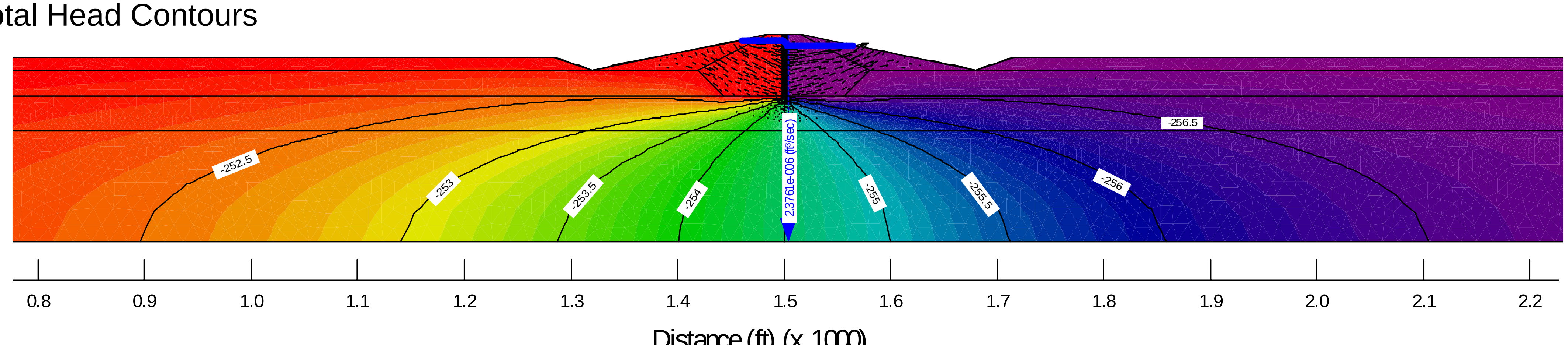
Material	Kh ft/sec	Kv/Kh	Color
Soft Lacustrine	$3.28*10^{-7}$	0.1	
Stiff Lacustrine	$3.28*10^{-7}$	0.1	
Seafloor Deposits	$3.28*10^{-7}$	0.1	
SCB Slurry Wall	$3.28*10^{-8}$	1	
Sand/Gravel Type A	$3.28*10^{-4}$	0.25	
Sand/Gravel Type B	$3.28*10^{-4}$	0.25	

XY Gradient Contours



XY Gradient i_{xy} Contours Legend

Total Head Contours



Total Head Contours Legend

United States Department of the Interior Bureau of Reclamation

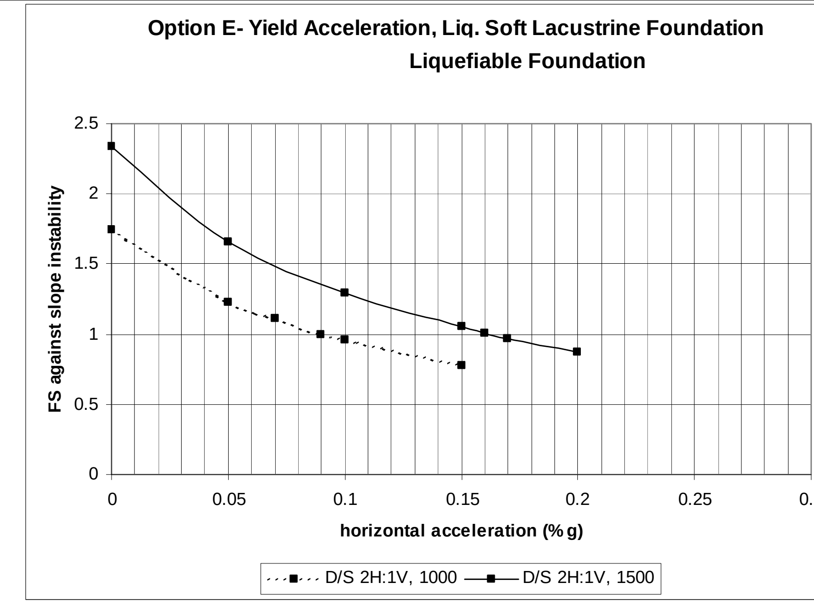
KLEINFELDER

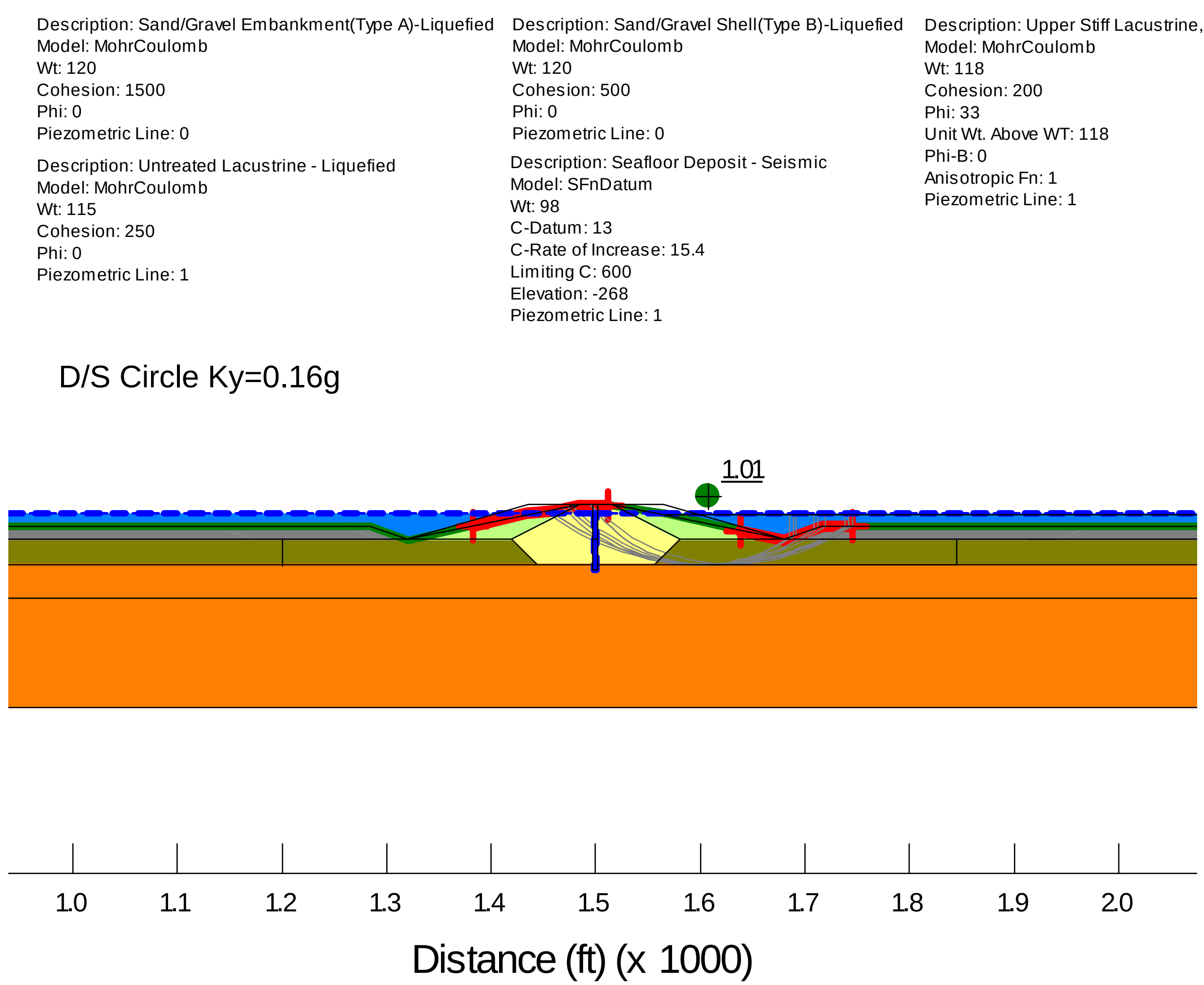
SALTON SEA RESTORATION PROJECT
EMBANKMENT DESIGNS AND OPTIMIZATION STUDY
Appendix 2E – Seepage Analyses

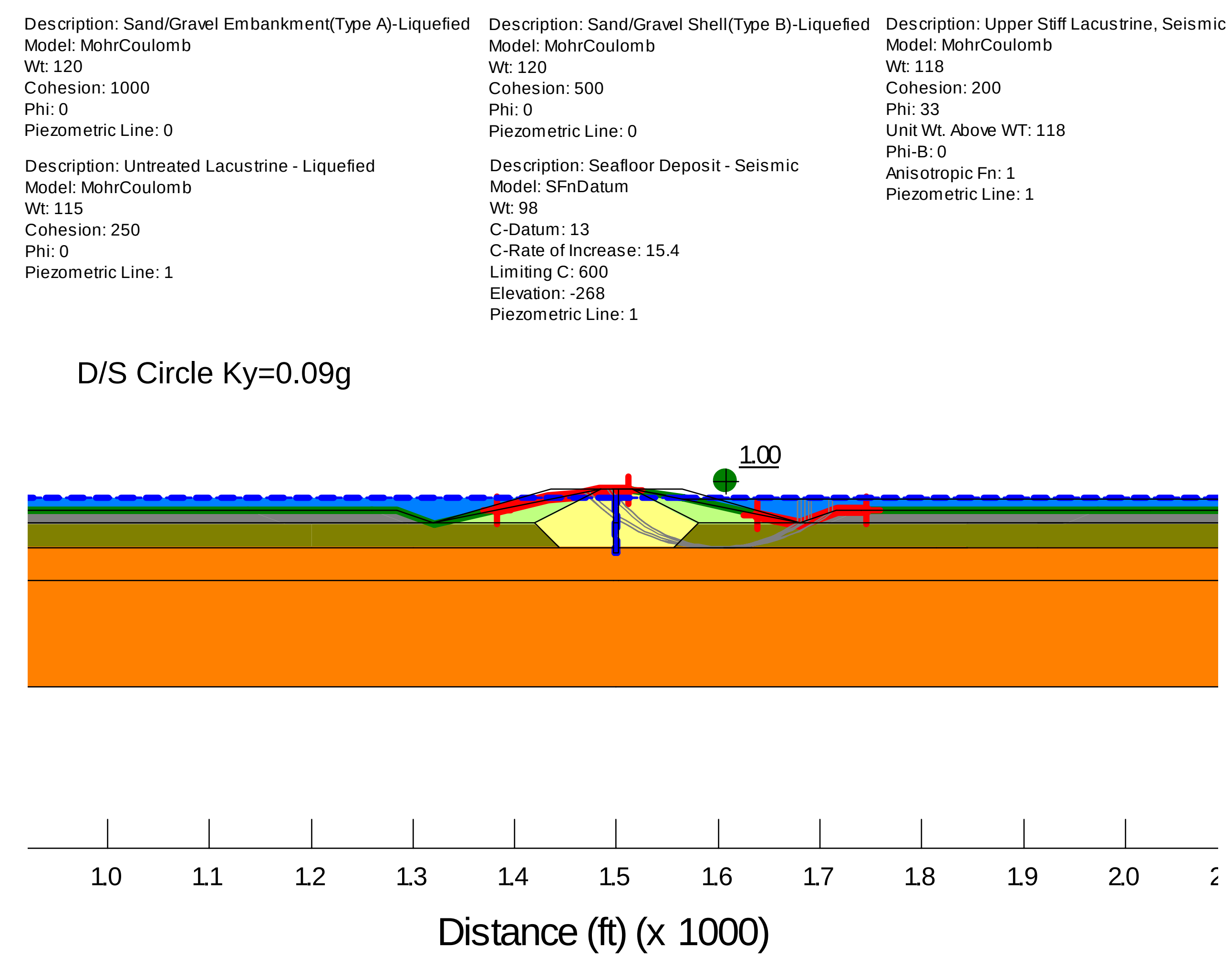
Seepage Analysis
Option E – Optimized Mid-Sea Barrier With Stone Columns

Project 71100	By E. Sossenkina	September 2006	**FIGURE E-11**

71100/DEN6R101

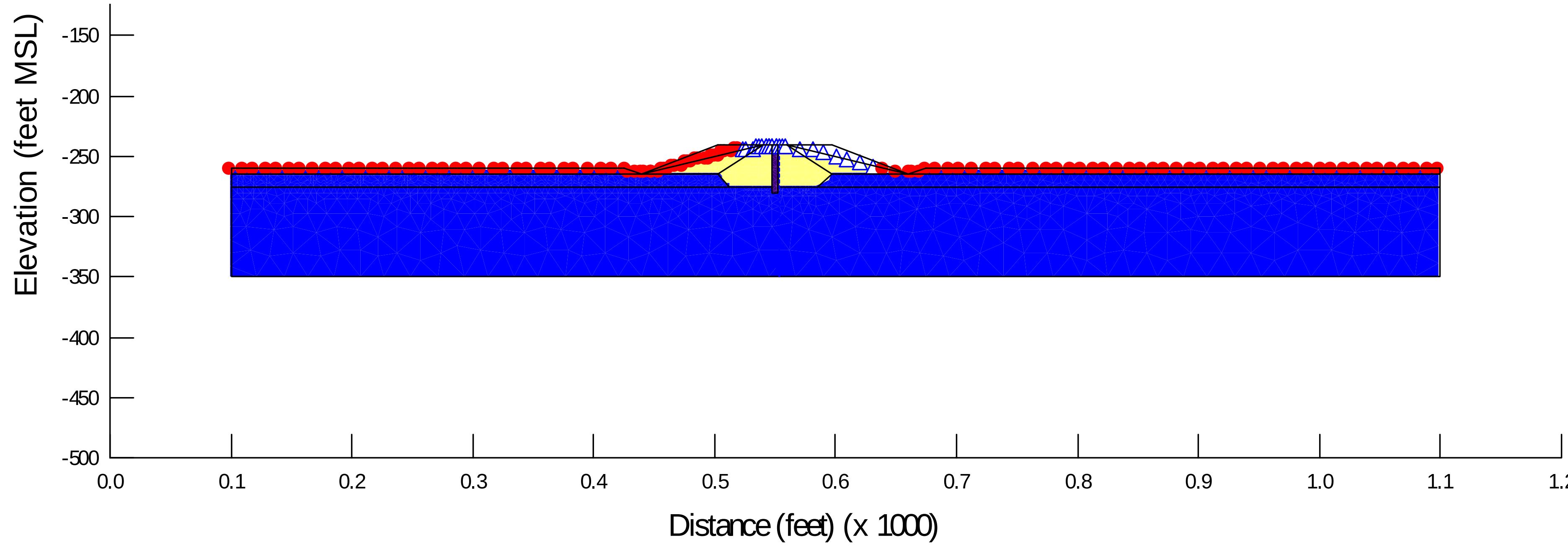






United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Optimized Stability Analyses	Seismic Stability Analysis Option E – Optimized Mid Sea Barrier With Stone Columns
KLEINFELDER	Project 71100 | By E. Sossenkina | September 2006	**FIGURE E-12**

Section Geometry and Boundary Conditions



Boundary Conditions Legend

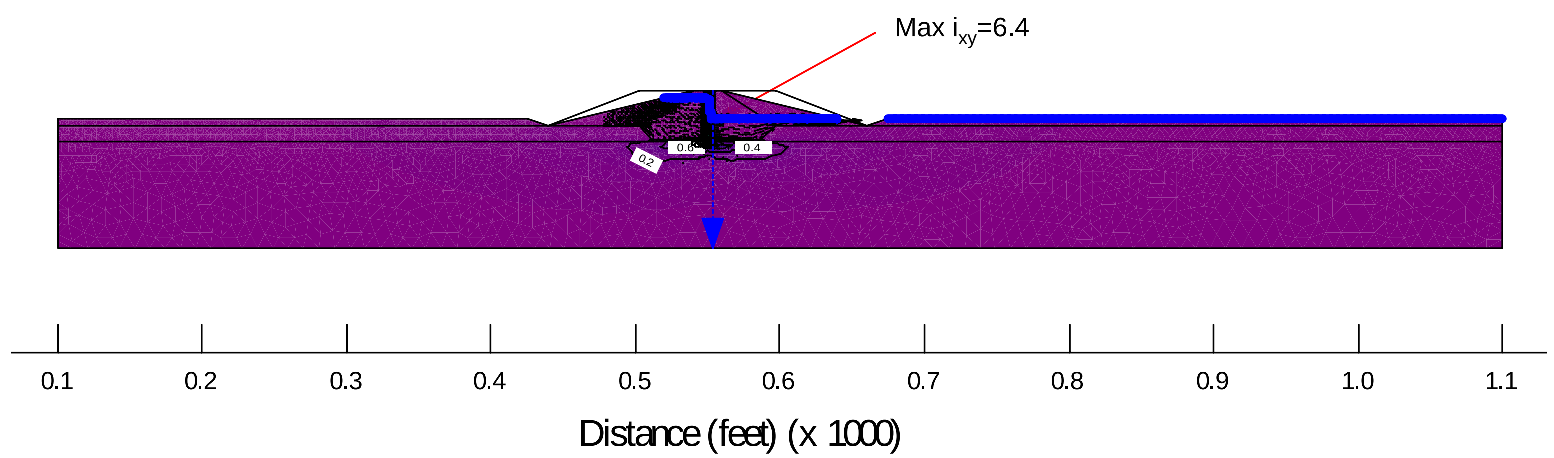
Constant Total Head

Seepage Exit Boundary

Material Properties Legend

Material	Kh ft/sec	Kv/Kh	Color
Soft Lacustrine	$3.28*10^{-7}$	0.1	
Stiff Lacustrine	$3.28*10^{-7}$	0.1	
Seafloor Deposits	$3.28*10^{-7}$	0.1	
SCB Slurry Wall	$3.28*10^{-8}$	1	
Sand/Gravel Type A	$3.28*10^{-4}$	0.25	
Sand/Gravel Type B	$3.28*10^{-4}$	0.25	

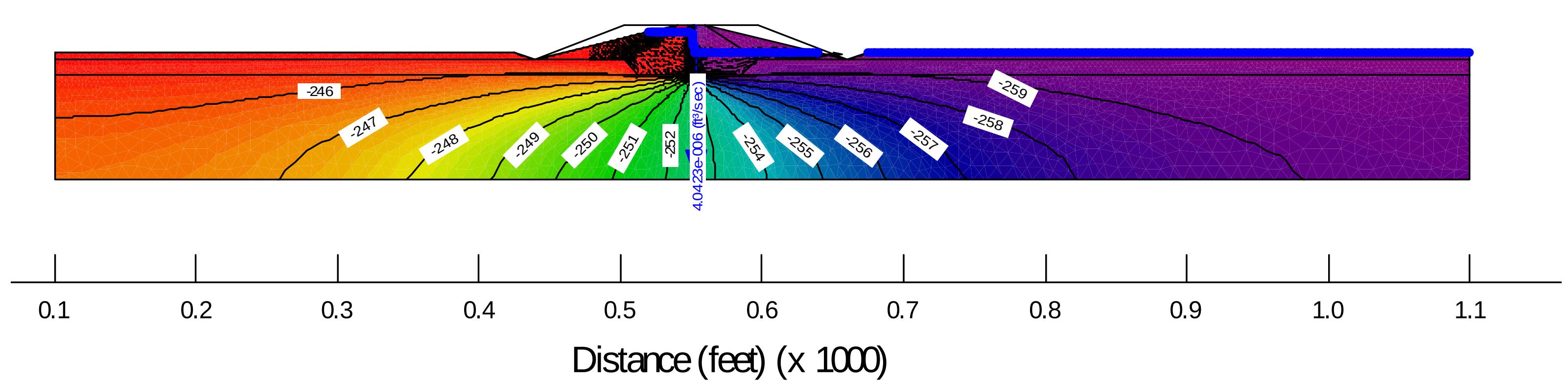
XY Gradient Contours



XY Gradient i_{xy} Contours Legend

Total Head Contours Legend

Total Head Contours



United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Seepage Analyses		Seepage Analysis Option F – Perimeter Ring Dike
KLEINFELDER	Project 71100	By E. Sossenkina	September 2006
			FIGURE E-13

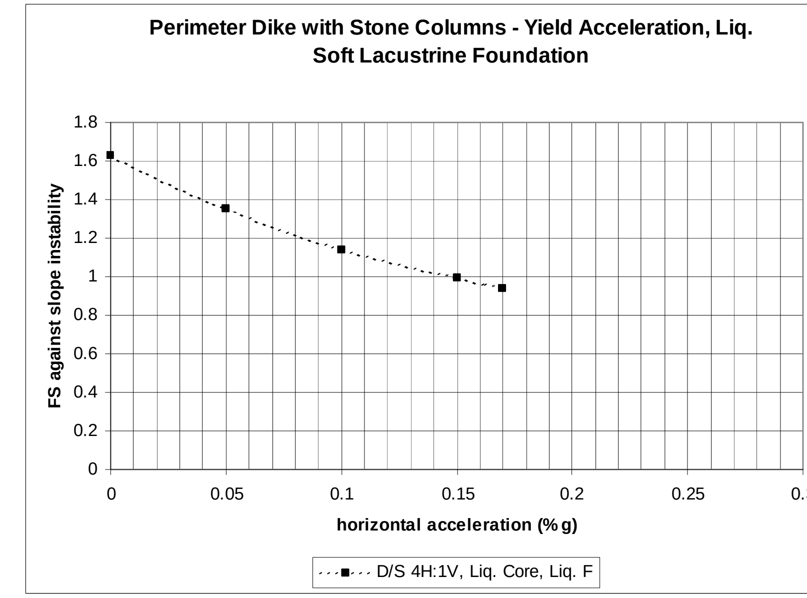
Description: Sand/Gravel Embankment Fill-Type A
Model: MohrCoulomb
Wt: 120
Cohesion: 1000
Phi: 0
Piezometric Line: 1

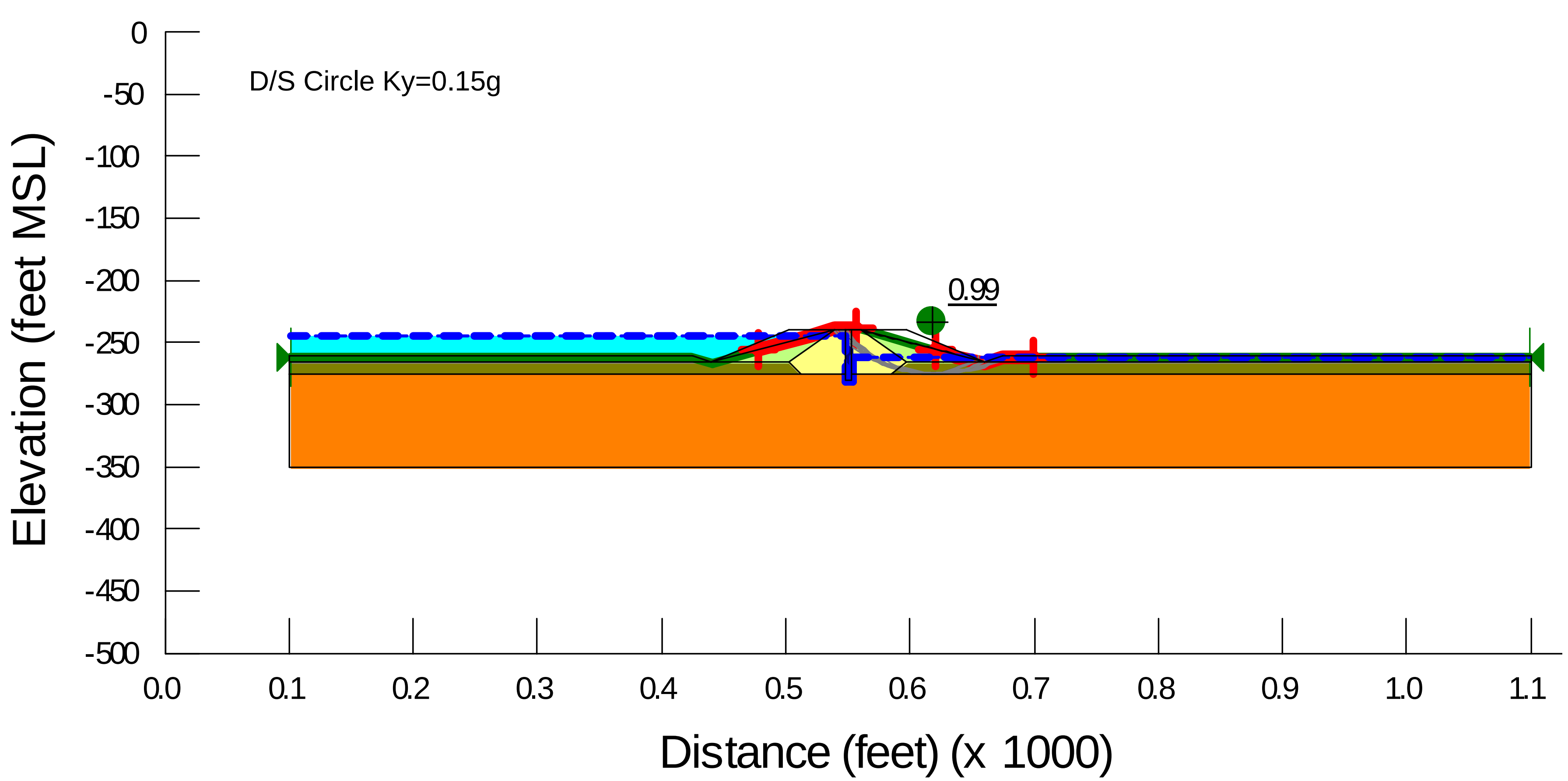
Description: Sand/Gravel Embankment Fill-Type B
Model: MohrCoulomb
Wt: 120
Cohesion: 500
Phi: 0
Piezometric Line: 1

Description: Untreated Lacustrine-Liquefied
Model: MohrCoulomb
Wt: 115
Cohesion: 250
Phi: 0
Piezometric Line: 1

Description: Seafloor Deposits - EOC-Seismic
Model: SFnDatum
Wt: 98
C-Datum: 13
C-Rate of Increase: 15.4
Limiting C: 600
Elevation: -260
Piezometric Line: 1

Description: Upper Stiff Lacustrine
Model: MohrCoulomb
Wt: 118
Cohesion: 200
Phi: 33
Unit Wt. Above WT: 118
Phi-B: 0
Anisotropic Fn: 1
Piezometric Line: 1





United States Department of the Interior Bureau of Reclamation	**SALTON SEA RESTORATION PROJECT** EMBANKMENT DESIGNS AND OPTIMIZATION STUDY Appendix 2E – Optimized Stability Analyses		Seismic Stability Analysis Optimized Perimeter Dike With Stone Columns
KLEINFELDER	Project 71100	By E. Sossenkina	September 2006	**FIGURE E-14**

71100/DEN6R101

Hand Calculation For Estimating Yield Acceleration Based on Filter Blanket Length

CALCULATION COVER SHEET

Date: 7/26/06

Calculation No.: 1
Calculation Title: Filter Blanket Extent, Mid Sea Dam Case 4-1
Project No. & Title: Salton Sea Restoration Project # 71100
Design Verification Required: ☐ Yes ☐ No
Calculation Type: ☐ Scoping ☐ Preliminary ☐ Final
☐ Superseded by Calculation No.: ___ ☐ Voided

ORIGINAL AND REVISED CALCULATIONS/ANALYSIS APPROVAL

	Rev. 0 Printed Name/Signature/Initials/ Date	Rev. ___ Printed Name/Signature/Initials/ Date	Rev. ___ Printed Name/Signature/Initials/ Date
Originator:	J. Yu 7/26/06		
Checked By:	E. Sossenkina 7/27/06		
Approved By:			
Other:			

AFFECTED DOCUMENTS

Document Number	Document Title	Rev. Number	Responsible Project Manager initials

RECORD OF REVISION

Rev.	Reason for Revision

ATTACHMENTS

Attachment #	Title	Total Pages
A	Yeild acceleration of lined landfills	9
B		
C		

TOTAL CALCULATION PAGE COUNT ___ 17

KLEINFELDER

SHEET 1 OF 7

PROJECT NO. 71100

PROJECT Salton Sea REVIEWED BY ESS DATE 7/31/2006

SUBJECT FILTER BLANKET STABILITY CALC BY J. YU DATE 7/27/2006

PURPOSE: ESTIMATE FILTER BLANKET LENGTH, L, FOR yield acceleration 0.17g

METHODOLOGY: PERFORM HAND CALCULATIONS FOR a BLOCK FAILURE THROUGH LIQUEFIED FILTER BLANKET IN ACCORDANCE WITH "YIELD ACCELERATION OF LINED LANDFILLS" SEE ATTACHEMENT A.

- CALCULATE MAXIMUM FILTER LENGTH FOR YIELD ACCELERATION $a = 0.17g$
- USE CROSS SECTION FOR MID-SEA DAM, CASE 4-1 JETGROUTED SOFT LACUSTRINE, SHOWN ON FIGURE 1.
- CONSIDER A BLOCK FAILURE THROUGH FILTER BLANKET, ASSUMING FILTER BLANKET LIQUEFIES. ($c = 150$ psf, $\varphi = 0$)
- ASSUME ENTRY ANGLE OF $60°$ and exit angle of a FAILURE SURFACE OF $30°$ USE AVERAGE SATURATED UNIT WEIGHT $\gamma = 115$ pcf FOR ALL ZONES. USE FRICTION ANGLE $\varphi = 45°$ FOR SAND/GRAVEL CORE, FINE ROCKFILL AND RANDOM ROCKFILL
- DEVELOP a FORMULA TO CALCULATE YIELD ACCELERATION AS A FUNCTION OF FILTER BLANKET LENGTH, ASSUMING a BLOCK FAILURE, DESCRIBED ABOVE.

M-4A

PROJECT NO. 71100
PROJECT Salton Sea REVIEWED BY ESS DATE 7/31/2006
SUBJECT Filter Blanket Stability Hand Calcs BY E. Sossenkina / J. Yu DATE 7/27/2006

1. AERA CALCULATIONS (SEE SECTION GEOMETRY ON FIGURE 1)

$$A_1 = \frac{1}{2}\, 33' \cdot 57' = 940\ (ft^2)$$

$$A_2 = \left[\left(57 - \frac{L}{7}\right) + 57\right] \cdot \frac{L}{2} = \frac{(798 - L) \cdot L}{14}\ (ft^2)$$

$$A_3 = \frac{\left(57 - \frac{L}{7}\right)^2}{2(\cot 60^\circ + \cot 81.8^\circ)} = \frac{\left(57 - \frac{L}{7}\right)^2}{1.45}\ (ft^2)$$

2. FORCES (SEE FREE BODY DIAGRAM ON FIGURE 2)

$$W_1 = A_1 \cdot \gamma = 470\,(115 - 64) + 470 \cdot 115$$ — Weight

$$= 23970 + 54050 = 78020\ (lb/ft)$$

$$N_1 = W_1 \cdot \cos 60^\circ = 78020 \cdot \cos 60^\circ = 39010\ (lb/ft)$$ — NORMAL FORCE

$$R_1 = N_1 \tan\phi = 39010 \cdot \tan 45^\circ = 39010\ (lb/ft)$$ — RESISTING FORCE

$$I_1 = W_1 \cdot 0.17 = 13263.4\ (lb/ft)$$ — INERTIAL FORCE WITH ACCELERATION $a = 0.17g$

$$W_2 = A_2 \cdot \gamma = \frac{798L - L^2}{14} \cdot 115 = (798 - L) \cdot 8.2 \cdot L\ \ (lb/ft)$$

$$N_2 = W_2$$

$$R_2 = S \cdot L = 150 \cdot L\ \ (lb/ft)$$

$$I_2 = W_2 \cdot 0.17 = 1.4 \cdot L\,(798 - L)\ \ (lb/ft)$$

$$W_3 = A_3 \cdot \gamma = \frac{\left(57 - \frac{L}{7}\right)^2}{1.45} \cdot 115 = 79.3\left(57 - \frac{L}{7}\right)^2$$

$$N_3 = W_3 \cos 30^\circ = 68.7\left(57 - \frac{L}{7}\right)^2$$

$$R_3 = N_3 \tan\phi = N_3 \cdot \tan 45^\circ = 68.7\left(57 - \frac{L}{7}\right)^2$$

$$I_3 = W_3 \cdot 0.17 = 13.5\left(57 - \frac{L}{7}\right)^2$$

PROJECT NO. 71100
PROJECT Salton Sea REVIEWED BY ________ DATE 7/31/2006
SUBJECT Filter Blanket Stability Hand Calc BY E. Sossenkina/J. Yu DATE 7/27/2006

$DF = N_1 \cdot \sin\theta_1 - N_3 \sin\theta_2 = N_1 \cdot \sin 60^\circ - N_3 \sin 30^\circ$ — DRIVING FORCES

$= 39010 \cdot \sin 60^\circ - 68.7(57-\frac{L}{7})^2 \sin 30^\circ$

$= 33784 - 34.5(57-\frac{L}{7})^2$

$= -0.7L^2 + 559.5L - 77819$

$IF = I_1 + I_2 + I_3$ — Inertial FORCES

$= 13263 + 1.4L(798-L) + 13.5(57-\frac{L}{7})^2$

$= 13263 + 1117.2L - 1.4L^2 + 43862 - 220.1L + 0.28L^2$

$= -1.12L^2 + 897L + 57125$

$RF = R_1 \cos 60^\circ + R_2 + R_3 \cos 30^\circ$ — RESISTING FORCES

$= 19505 + 150L + 68.7(57-\frac{L}{7})^2 \cdot 0.87$

$= 19505 + 150L + 59.5(3249 - 16.3L + \frac{L^2}{49})$

$= 1.2L^2 - 820L + 212821$

HORIZONTAL FORCES EQUILIBRIUM EQUATION

$DF + IF = -1.82L^2 + 1456.5L - 20694 = RF = 1.2L^2 - 820L + 212821$

$= -3.02L^2 - 2276.5L + 233515 = 0$

min. LENGTH OF FILTER REQUIRED TO get yield ACCELERATION $a = 0.17g$ →

$L = \dfrac{2276.5 \pm \sqrt{2276.5^2 - 4 \cdot 3.02 \cdot 233515}}{6.04}$

$= \dfrac{2276.5 \pm 1537}{6.04}$

$\therefore$ $L_1 = \dfrac{739.5}{6.04} = 122.4'$ ✓

$L_2 = \dfrac{3813.5}{6.04} = 631.4'$

KLEINFELDER SHEET 4 OF 7

PROJECT NO. 71100

PROJECT Salton Sea REVIEWED BY ____ DATE 7/31/2006

SUBJECT Filter Blank Stability Hand Calcs BY E. Sossenkina / J. Yu DATE 7/27/2006

$$IF = a(W_1 + W_2 + W_3) = a\left[78020 - 8.2L^2 + 6543.6L + 79.3\left(57 - \frac{L}{7}\right)^2\right]$$

$$= a\left[78020 - 8.2L^2 + 6543.6L + 79.3\left(3249 - 16.3L + \frac{L^2}{49}\right)\right.$$

$$= a\left[-6.6L^2 + 5251L + 335665.7\right)$$

$$DF = -0.7L^2 + 559.5L - 77819$$

$$RF = 1.2L^2 - 820L + 212821$$

$$IF = RF - DF$$

$$\therefore\ a\left[-6.6L^2 + 5251L + 335665.7\right] = 1.9L^2 - 1379.5 + 290640$$

$$\therefore\ a = \frac{1.9L^2 - 1379.5L + 290640}{-6.6L^2 + 5251L + 335666}$$ ✓

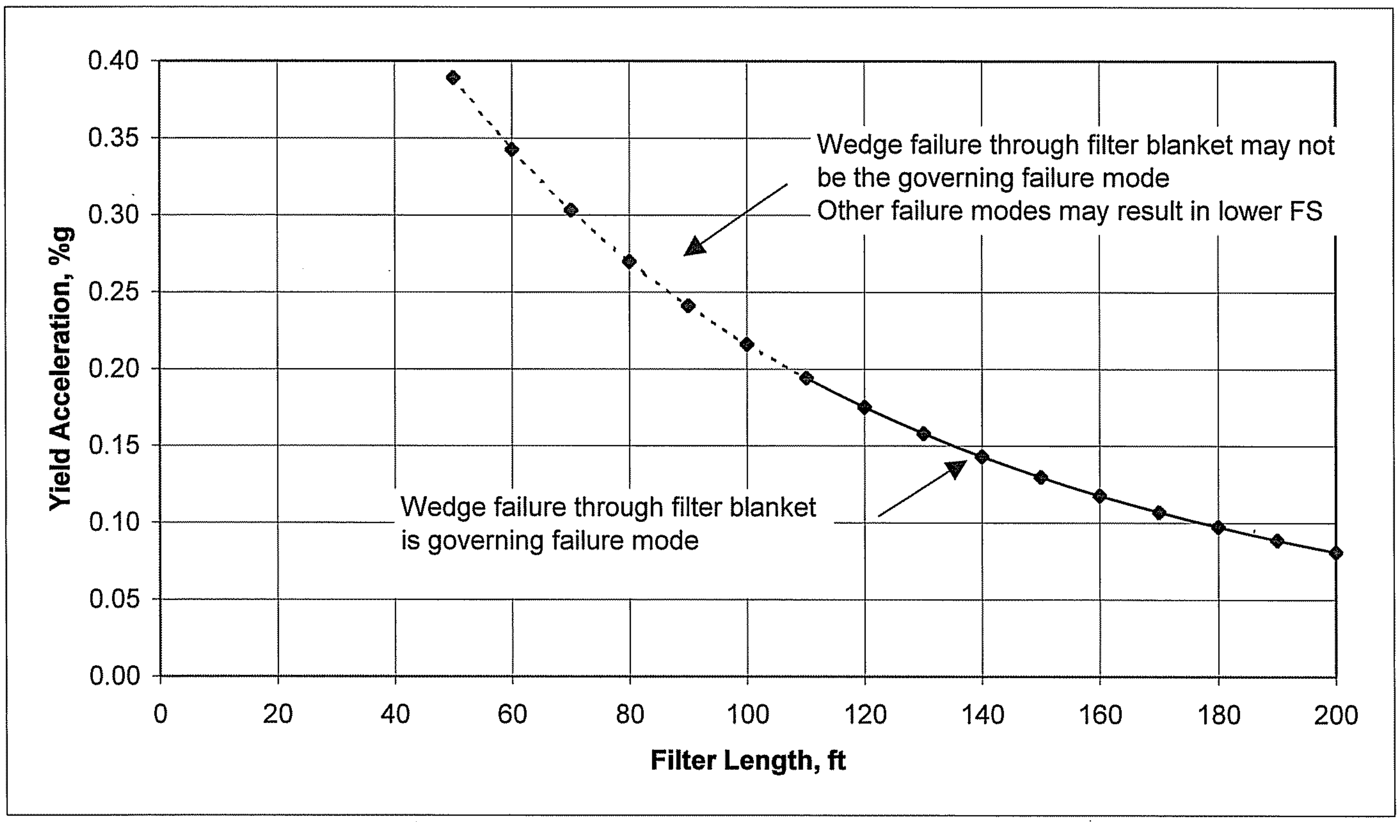
– yield acceleration as a function of filter length

M-4A

Sheet 5 of 7
ESS 7/31/2006
J. Yu 7/27/2006

Hand Calculations, Mid-Sea Dam, Case 4-1
Slope Stability and Yiled Acceleration Evaluation

Filter Blanket Length, L	Yield Acceleration, %g Ky
50	0.39
60	0.34
70	0.30
80	0.27
90	0.24
100	0.22
110	0.19
120	0.17
130	0.16
140	0.14
150	0.13
160	0.12
170	0.11
180	0.10
190	0.09
200	0.08



$\theta_1 = 60^\circ$ - ENTRANCE ANGLE

$\theta_2 = 30^\circ$ - EXIT ANGLE

$\varphi = 45^\circ$ - ANGLE OF INTERNAL FRICTION IN ROCKFILL, FINE ROCKFILL AND CORE

$\gamma = 115$ pcf - SATURATED UNIT WEIGHT

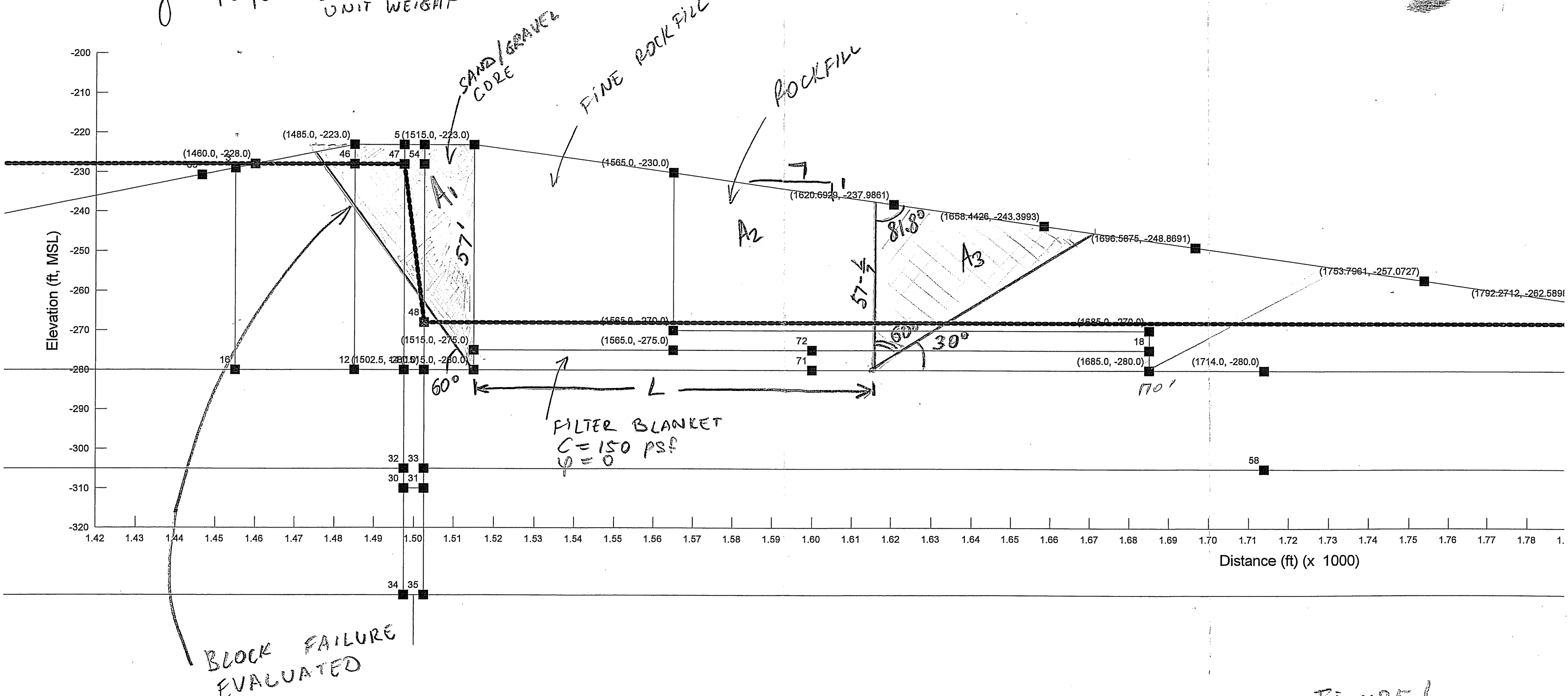
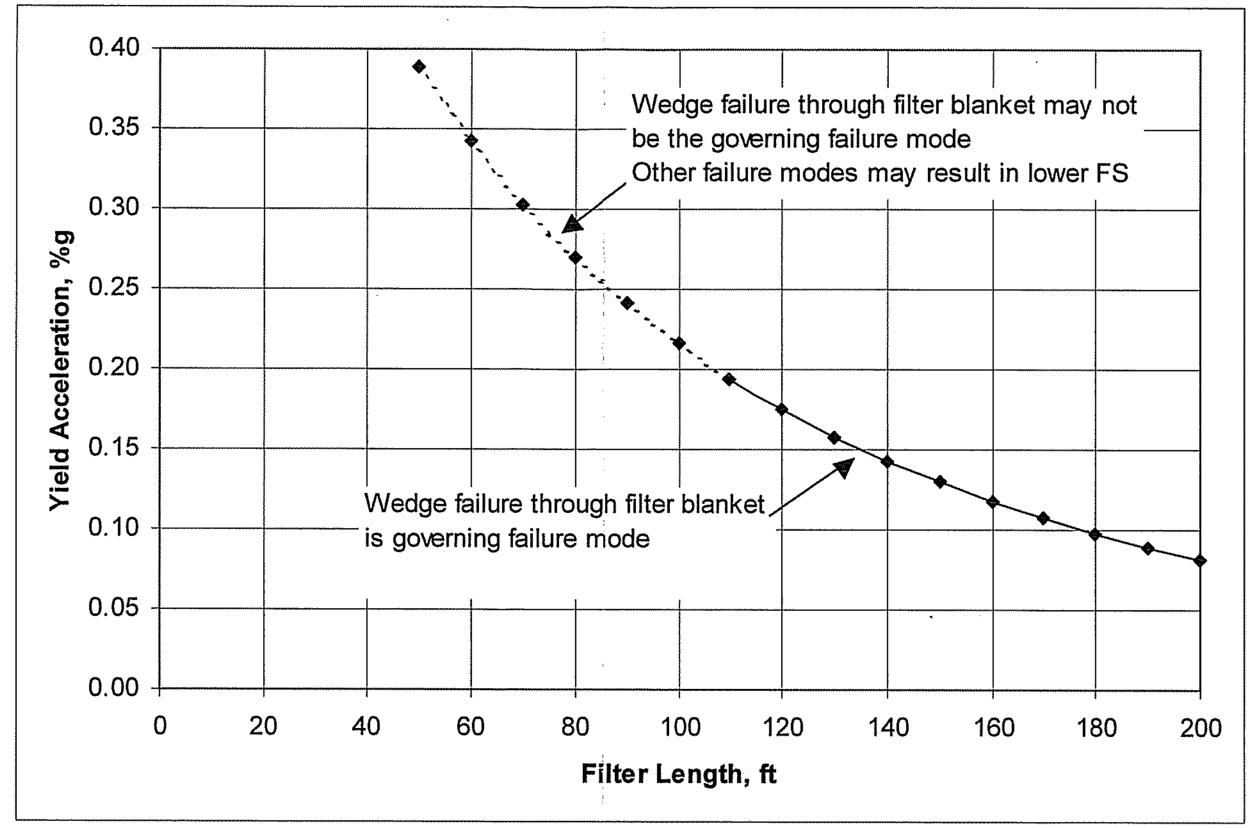
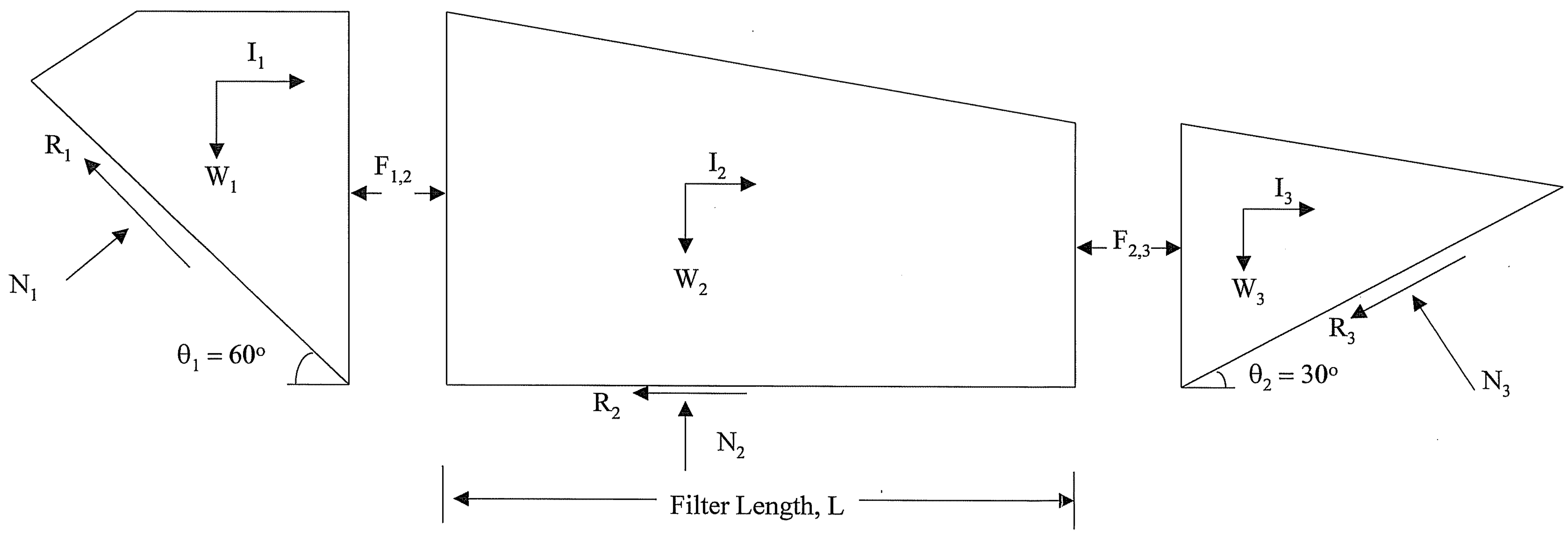


FIGURE 1
SECTION GEOMETRY

$DF + IF = RF$	Force Equilibrium Equation
$DF = N_1 \sin\theta_1 - N_3 \sin\theta_2$	Driving Forces
$IF = I_1 + I_2 + I_3$	Inertial Forces
$RF = R_1 \cos\theta_1 + R_2 + R_3 \cos\theta_2$	Resisting Forces

$W_1 = A_1\gamma$	$W_2 = A_2\gamma$	$W_3 = A_3\gamma$	Weight
$N_1 = W_1 \cos\theta_1$	$N_2 = W_2$	$N_3 = W_3 \cos\theta_2$	Normal Force
$R_1 = N_1 \tan\phi$	$R_2 = cL$	$R_3 = N_3 \tan\phi$	Resisting Force
$I_1 = W_1 a$	$I_2 = W_2 a$	$I_3 = W_3 a$	Inertial Force





KLEINFELDER		Seismic Slope Stability Analysis Wedge Failure Hand Calculations Case 4-1 (Jet Grouted Foundation) Salton Sea Project Bureau of Reclamation	PLATE 2
Graphic By: E. Sossenkina Project No. 71100	Date: 6/20/06 Filename:		

JOURNAL OF GEOTECHNICAL ENGINEERING, vol. 122 no. 2, Feb 1996, pp. 156-158. Compendex DLI Extended Citation

Yield Acceleration of Lined Landfills

Scott E. Shewbridge, ➧ [1]

Note ➧ Member, ASCE

Abstract

A simplified block analysis to evaluate yield accelerations of a refuse mass founded on a weak interface is presented. Comparison with results obtained from conventional slope stability evaluations indicate excellent agreement. The simplified solution reduces independent variables to interface friction angle, backfill slope, face slope, and height and length of the refuse mass. Design charts are presented for two typical landfill configurations; backslopes of 2 and 4 horizontal (h) to 1 vertical (v) and face slopes of 2h:1v during staged construction.

INTRODUCTION

Current environmental legislation requires that modern waste disposal facilities be constructed with liners that retard the migration of contaminants. The liners are generally constructed with low permeability materials or geosynthetics that have low interface shear strength (Yegian and Lahlaf 1992; Seed and Mitchell 1990; Martin et al. 1984). Often, interfaces in the liners have low friction angles with little to no cohesion. Under static conditions, because of the relative flat configuration of the bottom of the landfill, low shear stresses are mobilized across the liner, resulting in acceptable and often high static factors of safety. During an earthquake, however, inertial forces in the refuse mass may result in the mobilization of shear stresses in excess of the dynamic shear strengths of the liner materials.

To evaluate the magnitude of displacements that can accrue across the interface when shear strength is exceeded, the Newmark method is often used (Newmark 1965). For a given mass, limit equilibrium methods are used to evaluate the yield acceleration. The yield acceleration is the value of acceleration that, when multiplied by the total weight of the sliding mass, gives a large enough inertial driving force to make the factor of safety equal to one. To evaluate total displacement, the anticipated induced accelerations in excess of the yield acceleration can be integrated with respect to time to evaluate relative velocities, which can then be integrated to evaluate displacements.

In the present technical note, a simplified limit equilibrium method is presented and used to evaluate horizontal yield accelerations for a generalized lined landfill. The results of this analysis are compared to the results of conventional slope stability calculations, indicating excellent agreement. Example design charts to evaluate yield accelerations for typical staged-construction landfills using the simplified method are presented. Charts such as these, together with site specific estimates of induced accelerations, can be used to estimate seismically induced displacements. The method and the charts can be used to confirm the results of conventional stability analyses, typically requiring several hours of engineering effort. They can also be used directly for evaluating preliminary designs. The method can be augmented to account for different landfill configurations, such as sloping bases.

PROBLEM FORMULATION

Fig. 1 [Figure ➧] shows the general configuration of a landfill of height, H, consisting of a block resting on a lined backfill slope at an inclination of s_1 horizontal to 1 vertical, a lined main block of length, L, and a lined face slope at an inclination of s_2 horizontal to 1 vertical. The liner interface is at the bottom of each block, and the blocks are composed of refuse of unit weight γ.

For the analysis, the following assumptions are made:

1. Only failures at the liner are considered.
2. Blocks act as rigid bodies.
3. Shear strength at the interface is uniformly mobilized.

4. Vertical interblock forces are small and are ignored.
5. Foundation accelerations, a, expressed as the ratio of earthquake acceleration to gravitational acceleration, do not change the normal stress on the failure surface.
6. Strength along the failure surface can be described by the Mohr-Coulomb criterion, with a friction angle, ϕ, and no cohesion intercept.
7. Foundation acceleration is primarily horizontal.

Fig. 2 [Figure ➧] shows free-body diagrams for each block and solutions for each of the individual forces acting on the blocks.

To solve for the horizontal yield acceleration, the sum of the driving forces (DF) due to the mass of the refuse and the inertial forces (IF) which must be overcome to horizontally accelerate the mass are set equal to the resisting forces (RF) due to full mobilization of friction at the liner interface in the horizontal direction. The driving force is given by the following expression:

$$\mathrm{DF}=N_1 \sin\theta_1=\gamma\cos\theta_1 \sin\theta_1 (s_1 H^2/2) \tag{1}$$

The sum of the inertial forces is given by

$$\mathrm{IF}=I_1+I_2+I_3=a\gamma[(s_1+s_2)H^2/2+HL] \tag{2}$$

The sum of the resisting forces is given by

$$\mathrm{RF}=R_1\cos\theta_1+R_2+R_3=\gamma\tan\phi[(s_1 H^2/2)\cos^2\theta_1$$

$$+HL+(s_2 H^2/2)] \tag{3}$$

Setting DF + IF = RF, and solving for a, acceleration:

$$a = \frac{\left(\frac{s_1 H}{2}\cos^2\theta_1 + L + \frac{s_2 H}{2}\right)\tan\phi - \cos\theta_1 \sin\theta_1 \frac{s_1 H}{2}}{((s_1+s_2)/2)\,H+L} \tag{4}$$

Since frictional strength at the liner interface and the inertial and gravity driving forces in the refuse mass are directly proportional to the refuse weight, unit weight of refuse drops out of the equation.

Results from this simplified analysis have been compared to results from conventional slope-stability calculations. Fig. 3 [Figure ➧] shows calculated yield accelerations for four landfill configurations: backslopes of 4h:1v and 2h:1v, fillslopes of 2h:1v, heights of 40 units, and lengths of 100, 180, 320, and 400 units. Yield accelerations were evaluated using the program UTEXAS3 (Wright 1990) and the simplified analysis. For the slope stability calculations, Spencer's method and noncircular failure surfaces located at the base of the refuse mass were used. Liner strengths were modeled using a thin layer of frictional material (ϕ equal to 8°, 10°, 12°, 15°, 20°, 25°, and 30°) with no cohesive strength. Review of the results indicates that the simplified method gives slightly lower estimates of yield acceleration.

Typically, when designing a landfill, the backfill slope and fill-face slope are prescribed. Yield acceleration for the landfill during staged filling can then be expressed as a function of liner friction angle, and the ratio of landfill stage length to stage height. Fig. 4 [Figure ➧] presents example charts for evaluating yield accelerations for two typical landfill configurations: backfill slopes of 2 and 4h to 1v and fill slopes of 2h to 1v. Charts such as these can be developed for other landfill configurations, or the equations can be used directly.

Review of these charts indicate that when length-to-height ratios are high, yield acceleration is primarily a function of interface friction angle and becomes asymptotic to the tangent of the friction angle. At low length-to-height ratios, backfill slope has a significant impact on yield acceleration, with steeper slopes having lower yield accelerations. These results also indicate that yield accelerations for failures along landfill liners are likely to be low, with a high likelihood of deformation during seismic loading. In seismically active areas, such as the western United States, if deformation of the liner is excessive, or unacceptable, design of the staged landfill will have to incorporate additional stabilizing features. These might include base-slope buttresses, toe buttresses, or symmetrical filling plans. For landfills with sloped bases, such as canyon landfills, yield accelerations will be even larger. Mitigation of seismic deformation along the liner will likely be a key design constraint.

CONCLUSION

A simplified block analysis has been presented for evaluating the horizontal yield acceleration of a lined refuse mass. For typical liners that have interfaces with only frictional dynamic strength, yield acceleration is found to be a function of interface friction angle, backfill slope, face slope, and height and length of the refuse mass. Comparisons with conventional slope stability computations indicate good to slightly conservative results.

APPENDIX. REFERENCES

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Yegian, M. K., and Lahlaf, A. M. (1992). “Dynamic interface shear strength properties of geomembranes and geotextiles.” *J. Geotech. Engrg.*, ASCE, 118(5), 760–779. Compendex

Footnotes

[1] Prin. Engr., Scott Shewbridge Associates, Inc., 454 Forest Ave., Palo Alto, CA 94301-2608.

Note. Discussion open until July 1, 1996. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this technical note was submitted for review and possible publication on July 8, 1994. This technical note is part of the ***Journal of Geotechnical Engineering***, Vol. 122, No. 2, February, 1996. ©ASCE, ISSN 0733-9410/96/0002-0156–0158/$4.00 + $.50 per page. Technical Note No. 8806.

Figures

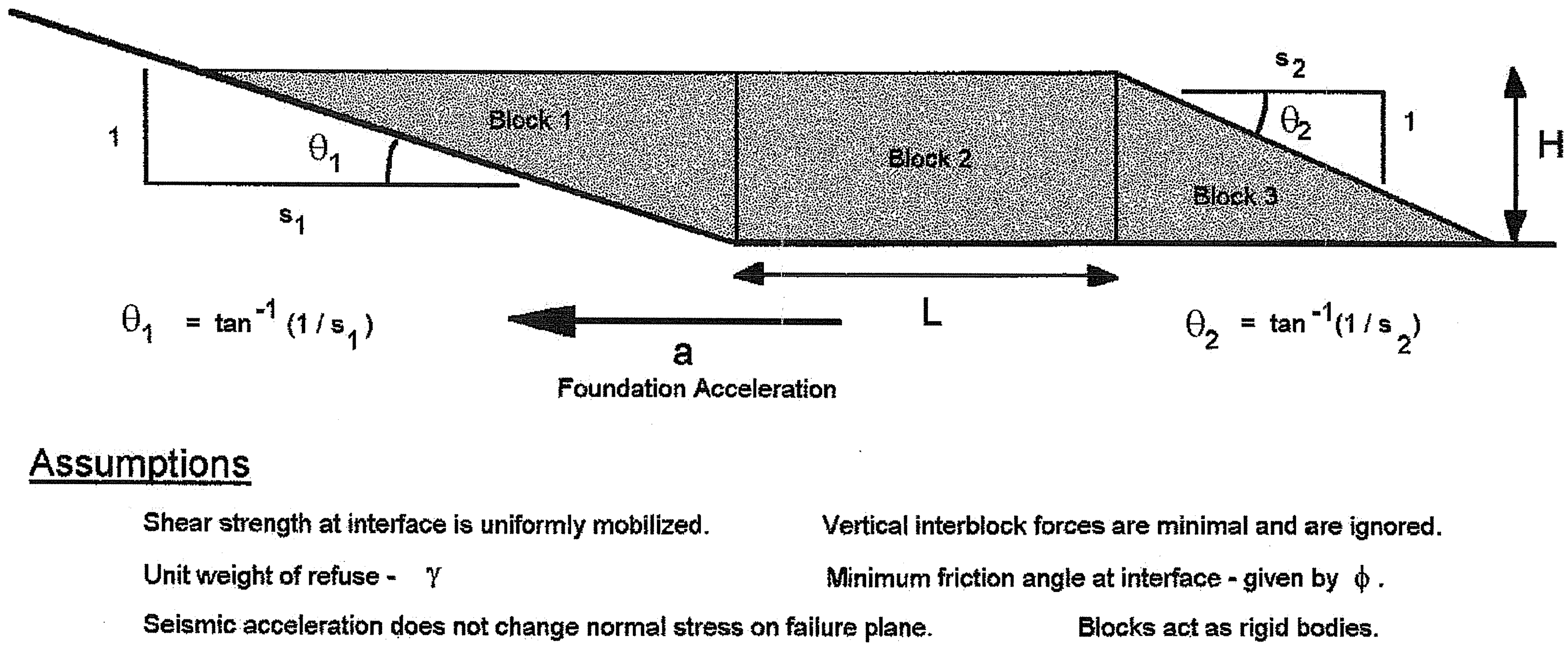
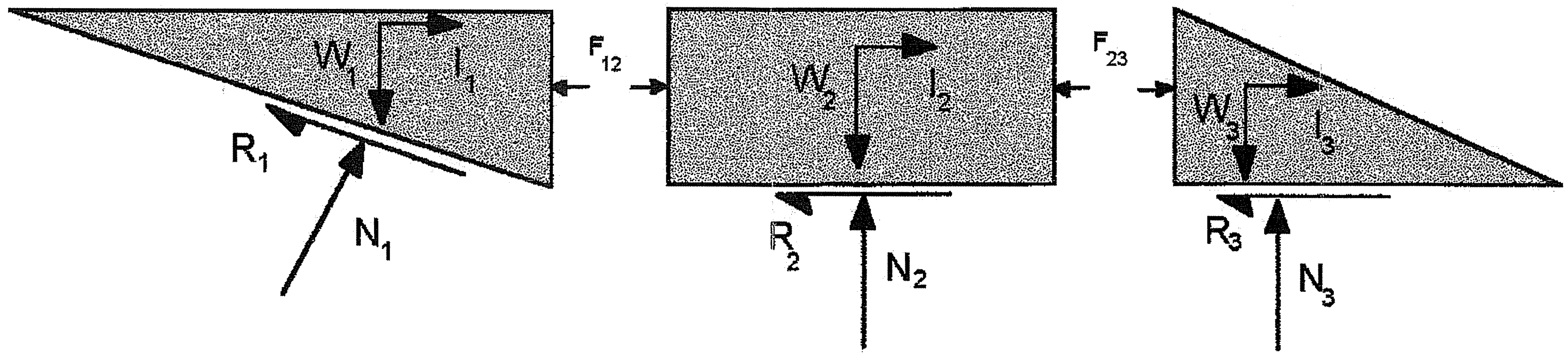


FIG. 1. General Configuration of Idealized Landfill and Analytical Assumptions

Free body Diagrams:



Solutions for Weight (W), Normal (N), Limit Shear (R) and Inertial (I) Forces:

$W_1 = 1 * (s_1 H^2 / 2)\ \gamma$	$W_2 = 1 * (H L)\ \gamma$	$W_3 = 1 * (s_2 H^2 / 2)\ \gamma$
$N_1 = W_1 \cos \theta_1$	$N_2 = W_2$	$N_3 = W_3$
$R_1 = N_1 \tan \phi$	$R_2 = N_2 \tan \phi$	$R_3 = N_3 \tan \phi$
$I_1 = a * W_1$	$I_2 = a * W_2$	$I_3 = a * W_3$

FIG. 2. Free Body Diagrams of Landfill Blocks and Resolution of Forces

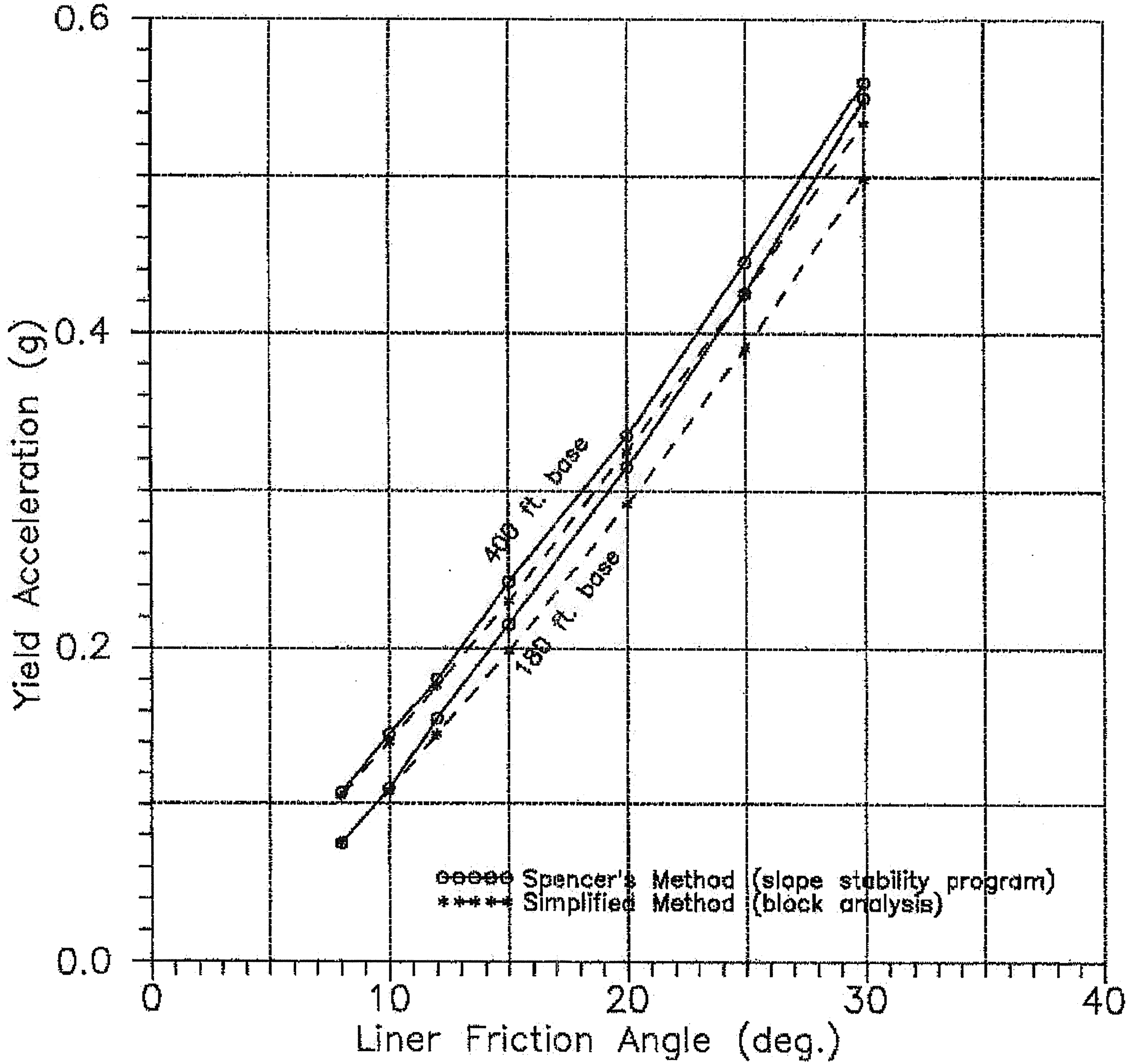

0.6
0.4
0.2
0.0
Yield Acceleration (g)
0
10
20
30
40
Liner Friction Angle (deg.)
400 ft. base
180 ft. base
Spencer's Method (slope stability program)
Simplified Method (block analysis)

FIG. 3. Comparison of Simplified Solution to Spencer's Solution for Fill Slopes of 2h:1v and Backfill Slopes of the Following: (a) 2h:1v; (b) 4h:1v

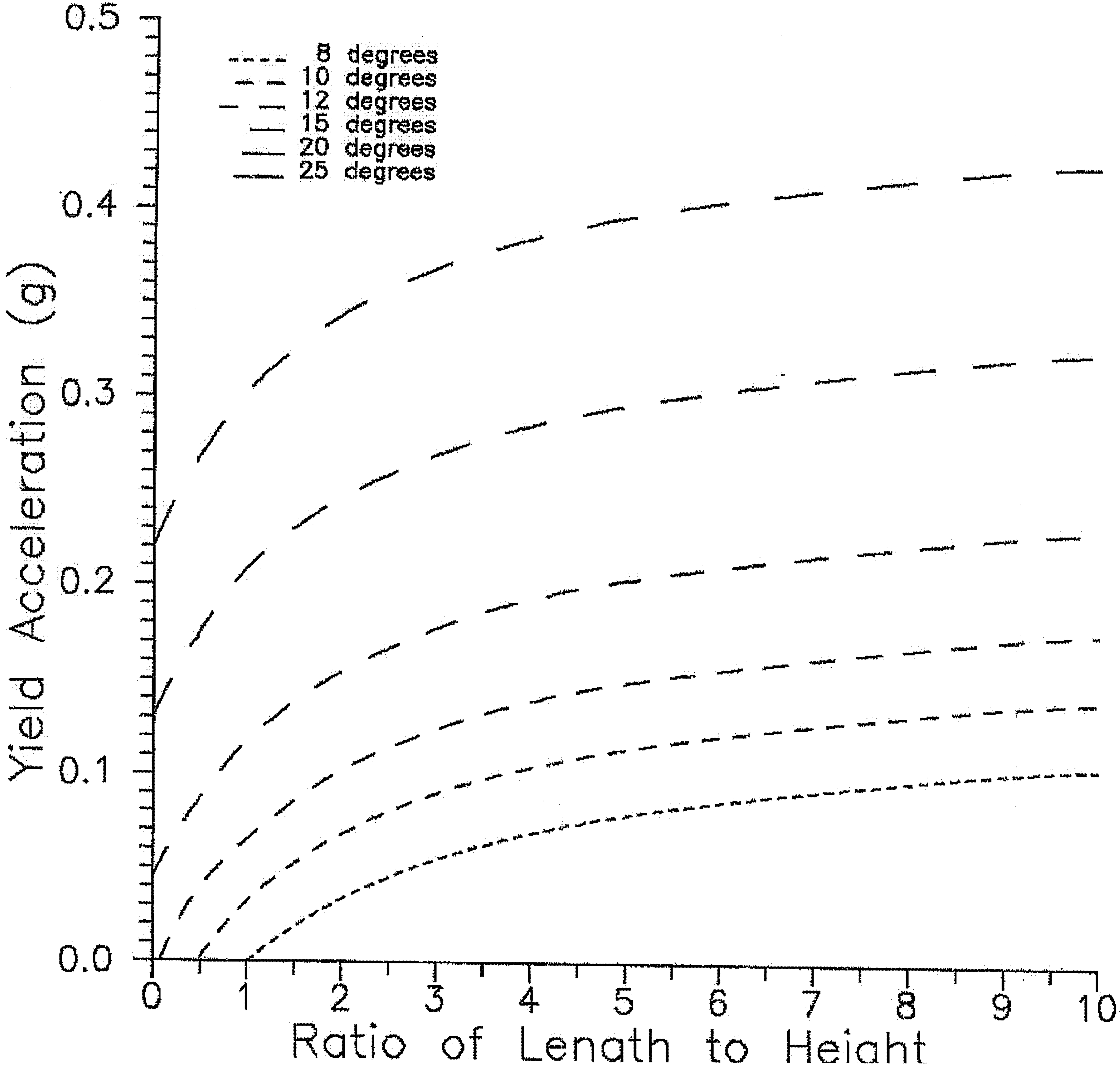

8 degrees
10 degrees
12 degrees
15 degrees
20 degrees
25 degrees
Yield Acceleration (g)
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4
5
6
7
8
9
10
Ratio of Lenath to Heiaht

FIG. 4. Design Charts for Evaluating Yield Accelerations for Lined Landfills with Liner Strengths of 8°, 10°, 12°, 15°, 20°, and 25°, Fill Slopes of 2h:1v and Backfill Slopes of (a) 2h:1v and (b) 4h:1v. (Yield acceleration is for failures at liner only; other failure modes, such as through foundation or refuse mass, should also be considered.)