T-Wall Design Procedure FLAC to Procedure

by

Neil Schwanz, P.E. and
Kent Hokens, P.E.

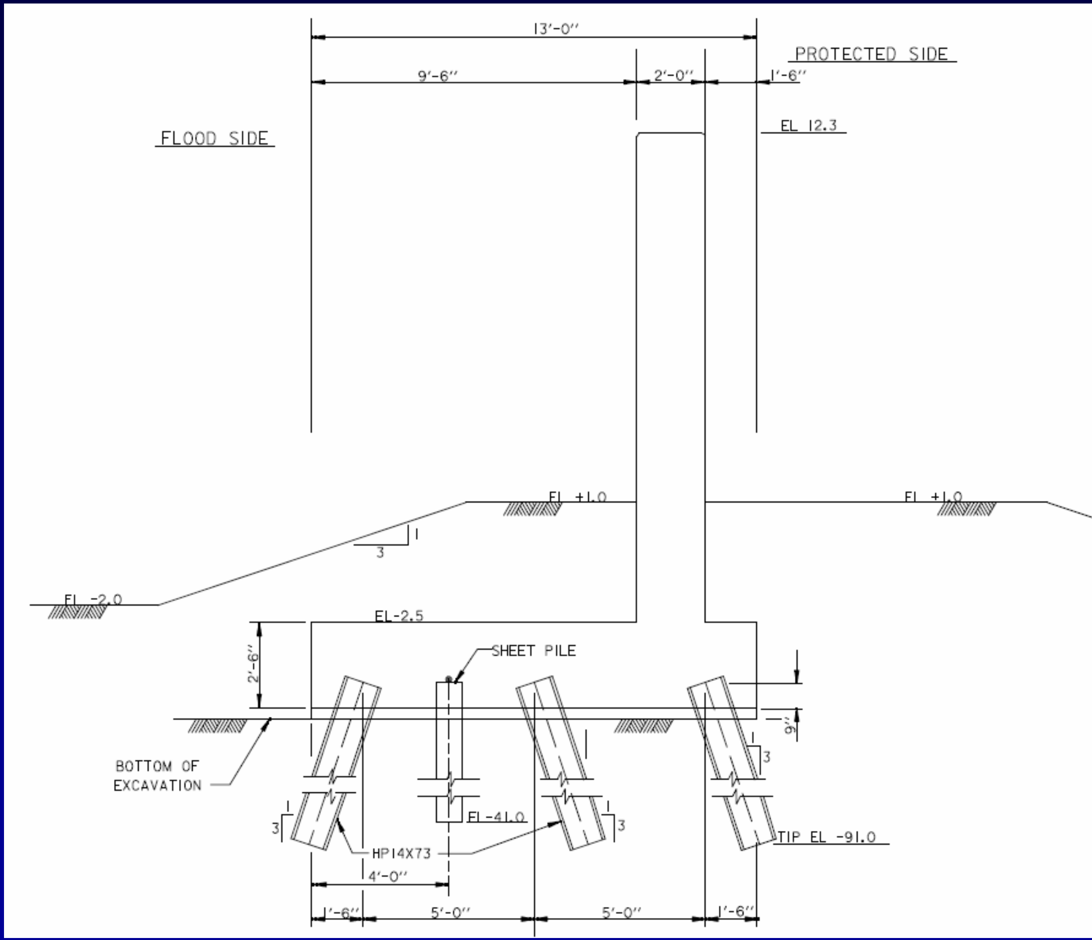
April 8, 2008

Purpose

US Army Corps of Engineers

Provide Overview of

- **How T-wall Design Procedure Was Developed so Designers Understand its Basis and Limitations**



Outline

- FLAC Overview
- GeoMatrix numercial analyses and report
- Product Delivery Team (PDT) analyses
- FLAC to Design Procedure

US Army Corps of Engineers

Soil Structure Interaction and Load Transfer Mechanism of Pile Supported T-Walls in New Orleans, LA

Michael Navin, Ph.D., P.E.

St. Louis District

2007 Infrastructure Conference

June 28th 2007

US Army Corps of Engineers

FLAC
(Fast Lagrangian Analysis of Continua)

Two-dimensional continuum code for modeling soil, rock and structural behavior.

- **General Program – model together soil, structure, pressures, etc. to evaluate deformation, loads stresses**
- **Linear or Non-linear soil models**
  - Mohr-Coulomb (bilinear: linear elastic perfectly plastic LEPP)
  - Fully non-linear
- **Soil Structure Interaction**
- **Factor of Safety (c-phi reduction technique)**

T-Wall Product Delivery Team (PDT)

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Headquarters

- Anjana Chudgar, P.E.
- Don Dressler, P.E.

ERDC

- Reed Mosher, Ph.D.
- Noah Vroman, P.E.
- Ronald Wahl
- Don Yule, P.E.

GeoMatrix

- C. Y. Chang
- Faiz Makdisi, Ph.D, P.E.
- Z. L. Wang

New Orleans District

- Charles Brandstetter, P.E.
- Thomas Hassenboehler, P.E.
- Richard Pinner, P.E.
- Mark Woodward, P.E.
- **OTHERS**

Mississippi Valley Division

- Allen Perry, P.E.
- Kent Hokens, P.E.
- Michael Navin, Ph.D., P.E.
- Neil Schwanz, P.E.

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of Enginee

Soil-Structure Interaction and Load Transfer Mechanism of Pile-Supported T-Wall for New Orleans Levees

Prepared for:

U.S. Army Engineer Research & Development Center

Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Prepared by:

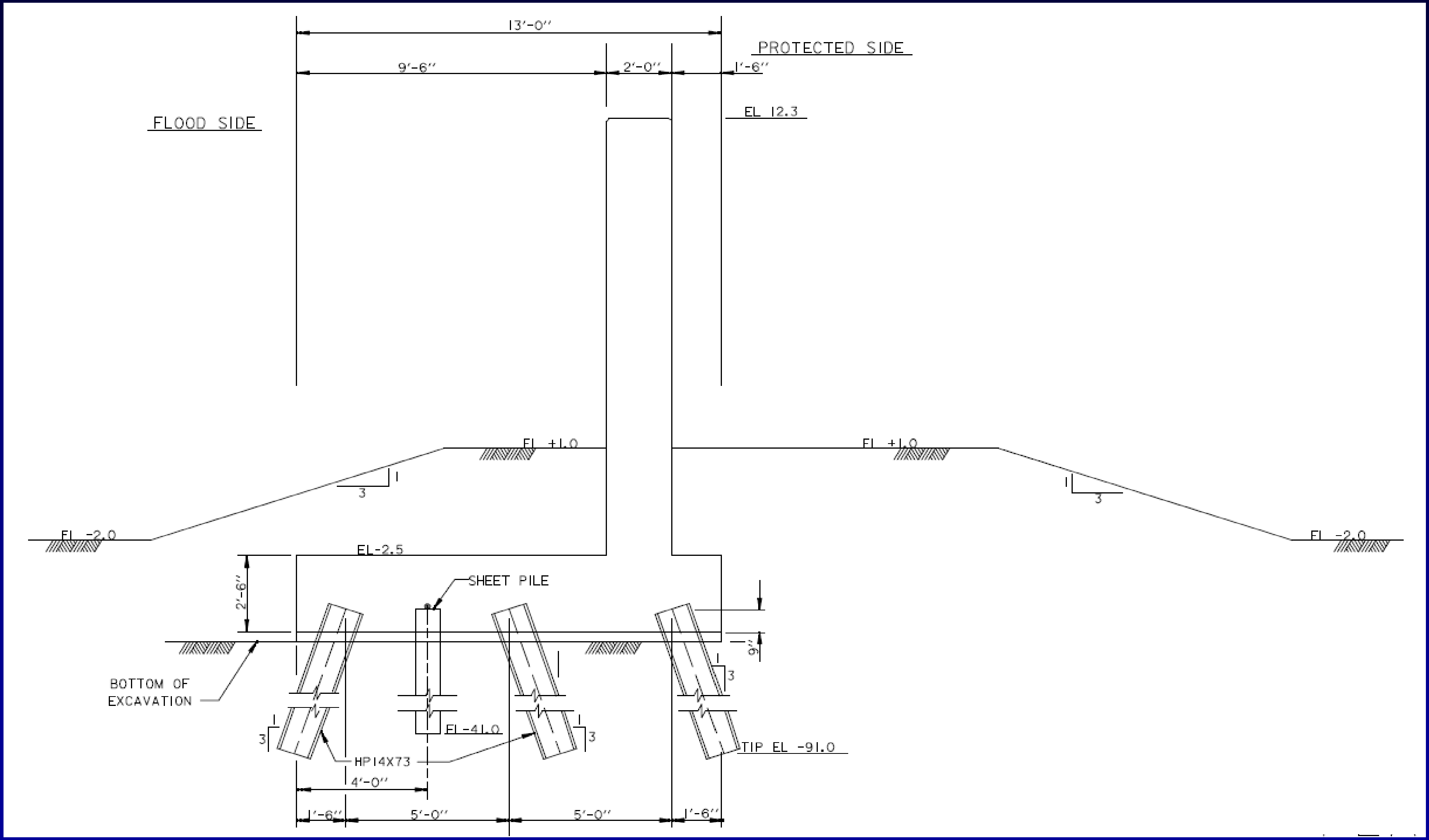
Geomatrix Consultants, Inc.
2101 Webster Street, 12th Floor
Oakland, California 94612

January 2007

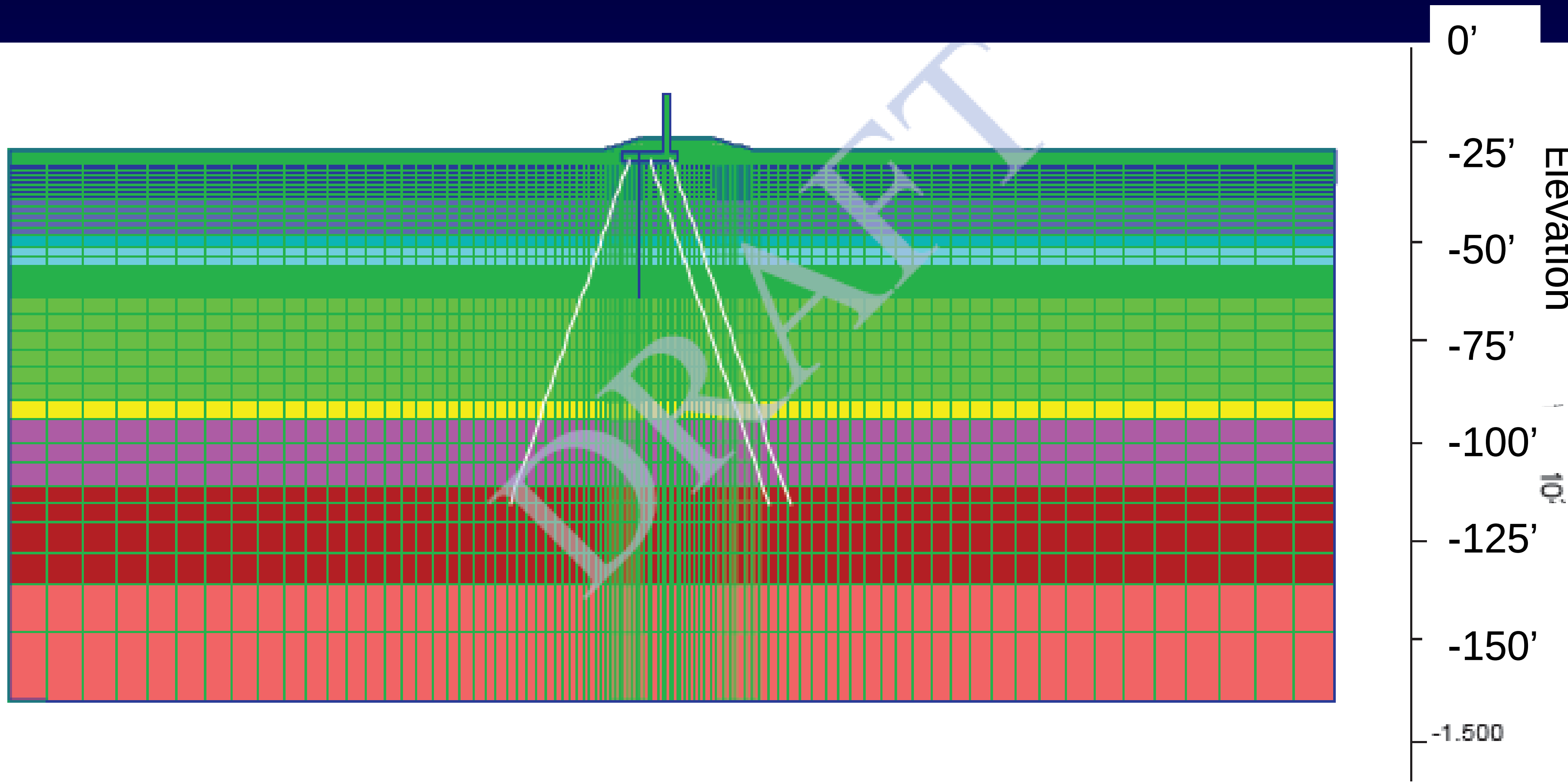
Project No. 12048.001

Geomatrix

Example used in GMX FLAC analysis



Soil Stratigraphy of GMX FLAC analysis



GMX mesh around the T-Wall

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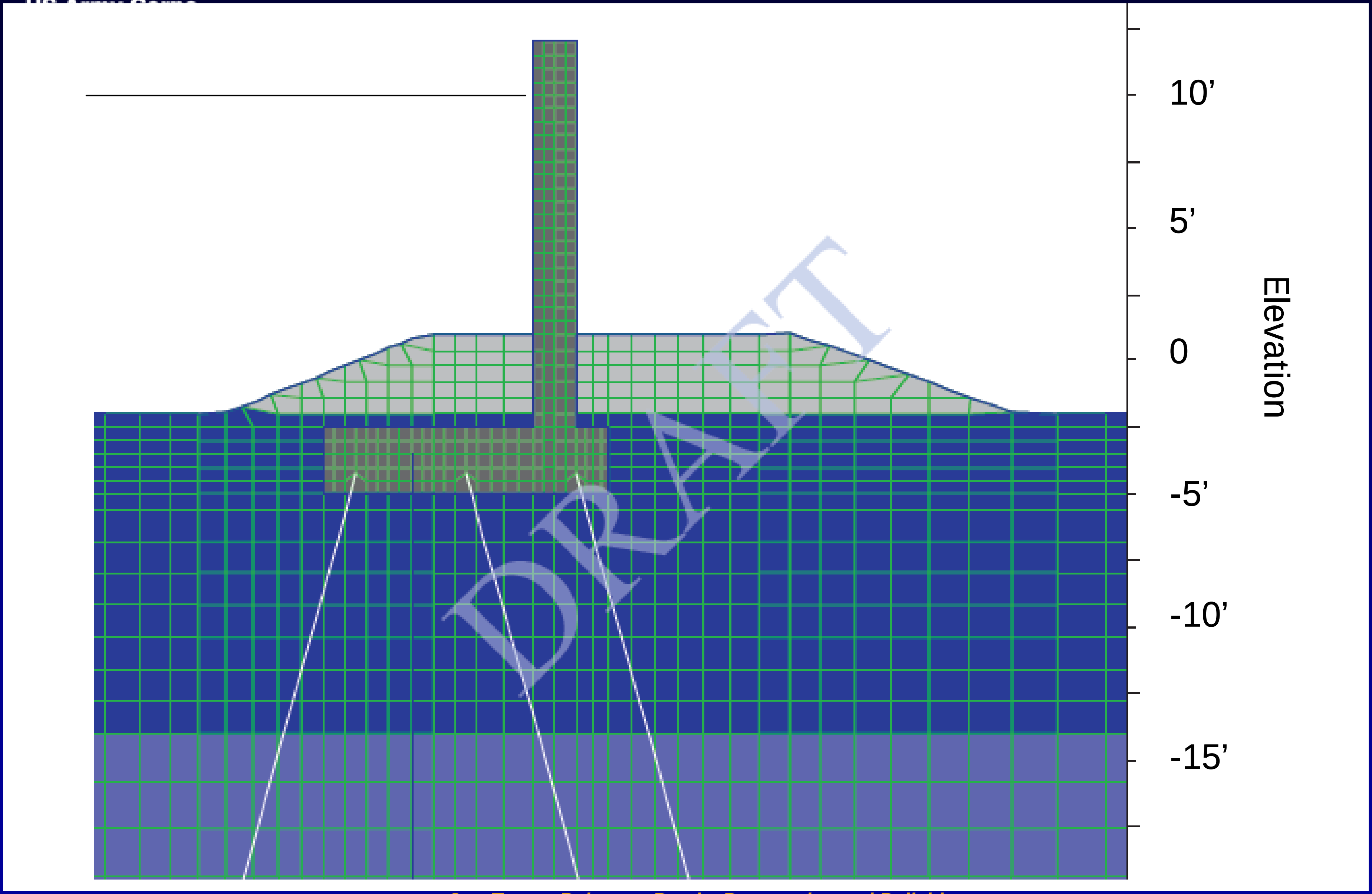

FLAC and numerical stress-strain analyses

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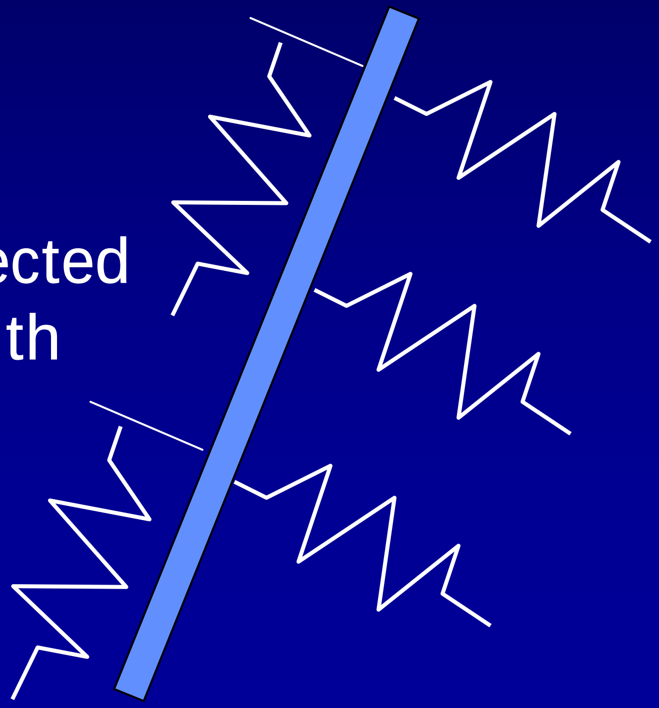
- Increasingly used to evaluate embankment stability – same FS as limit equilibrium methods like Spencer's Procedure.
- Valuable for complex or unusual site conditions.
- Piles included as structural elements with p-y and t-z springs.

Piles connected to mesh with springs.



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GeoMatrix used the FLAC model to perform sensitivity analyses.

Mohr-Coulomb vs. fully non-linear soil models

Soil modulus values

- Shear modulus ratio based on pressuremeter tests
- Shear modulus ratio based on triaxial tests

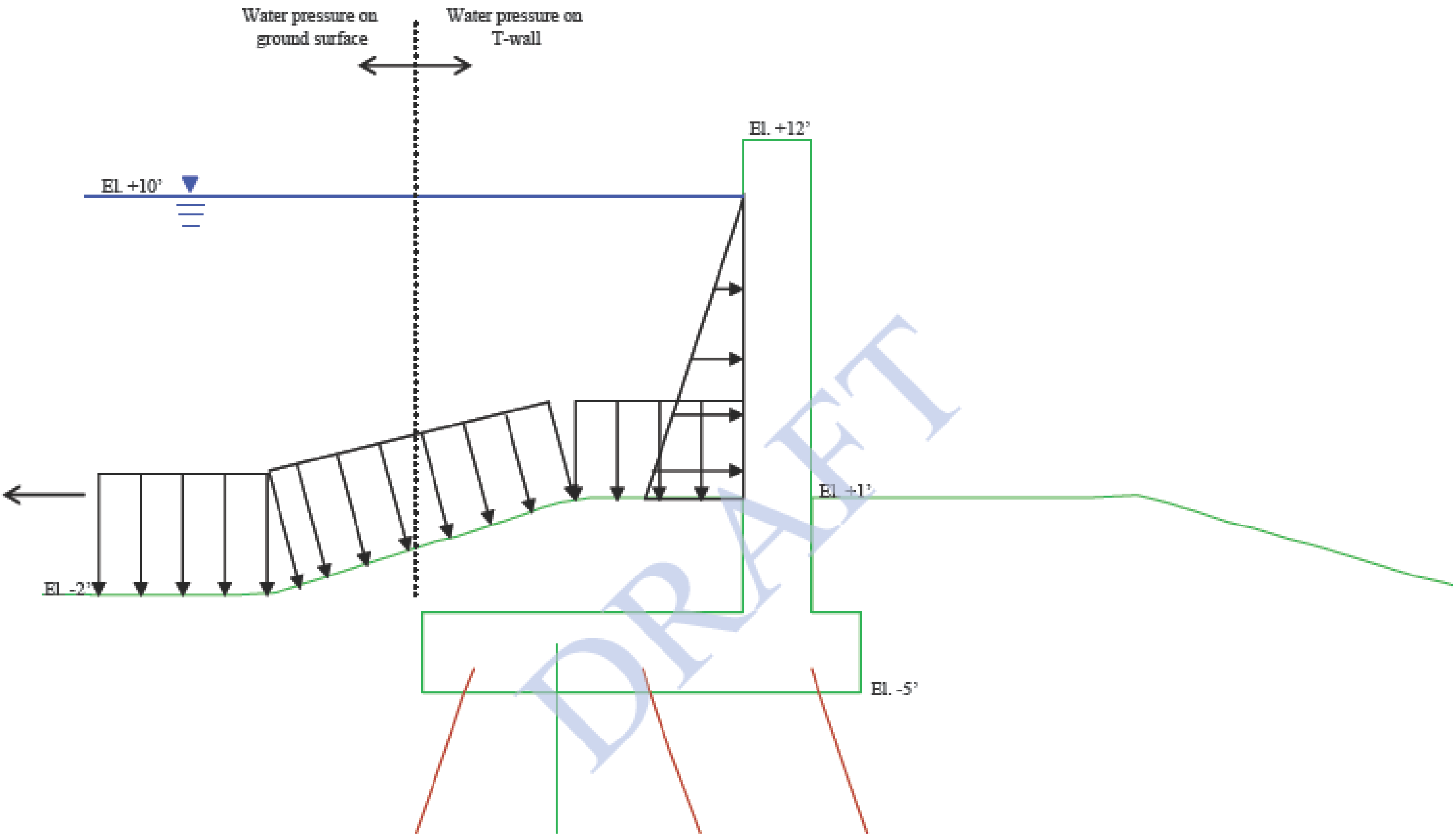
Pile – soil spring stiffness

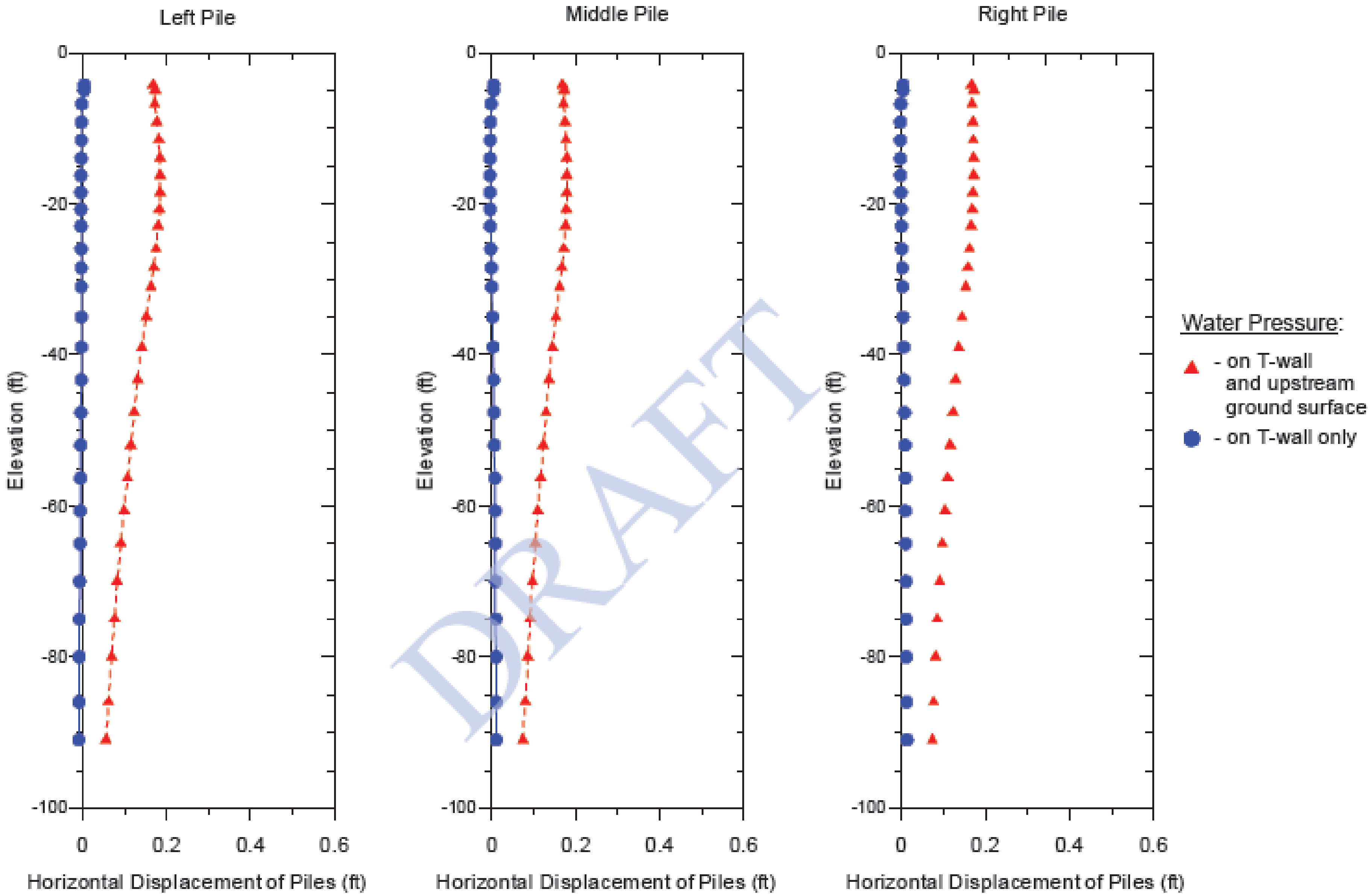
Water load on T-Wall vs. load on ground surface

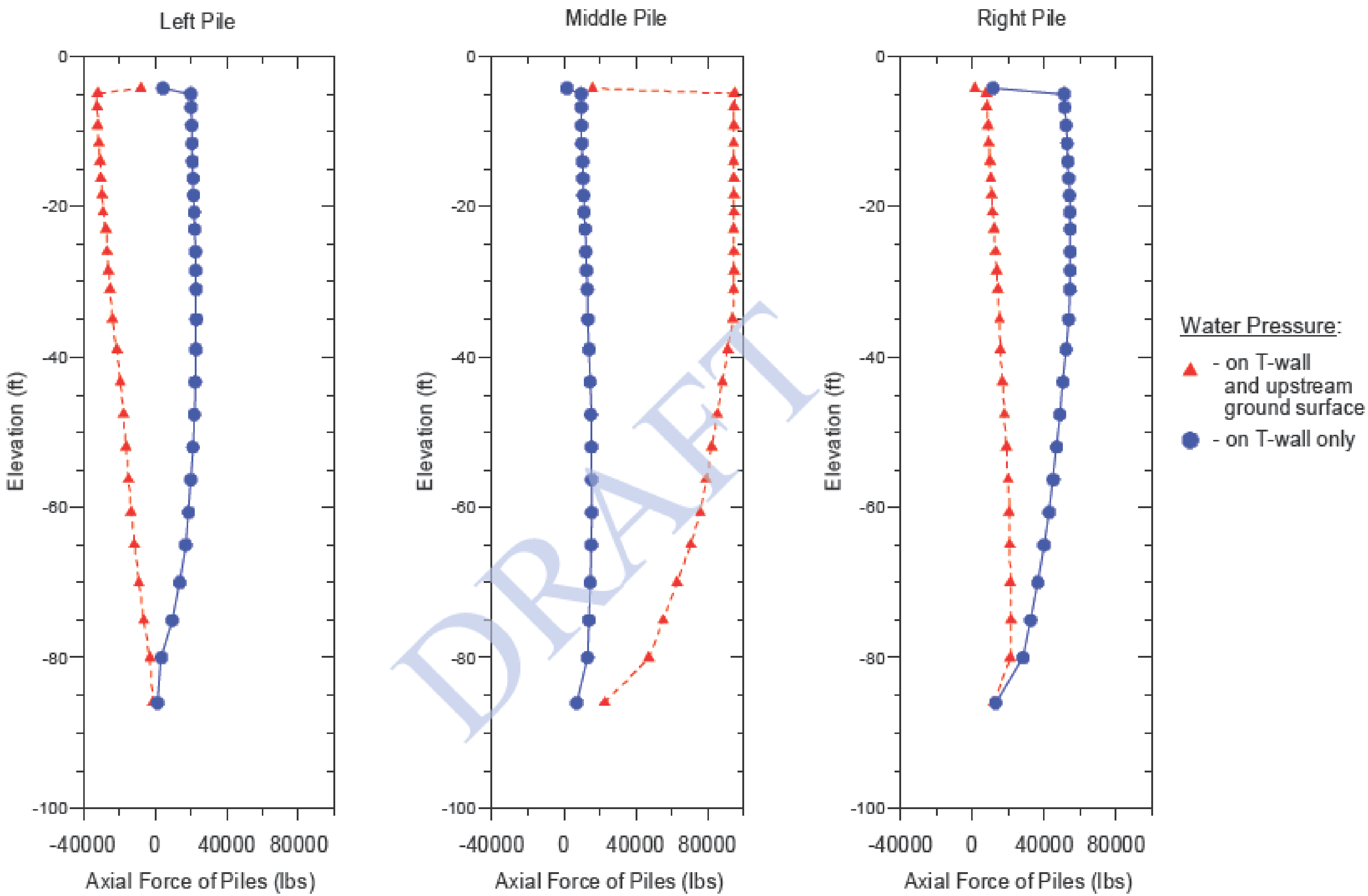
With and without sheet pile

Soil strength reduction

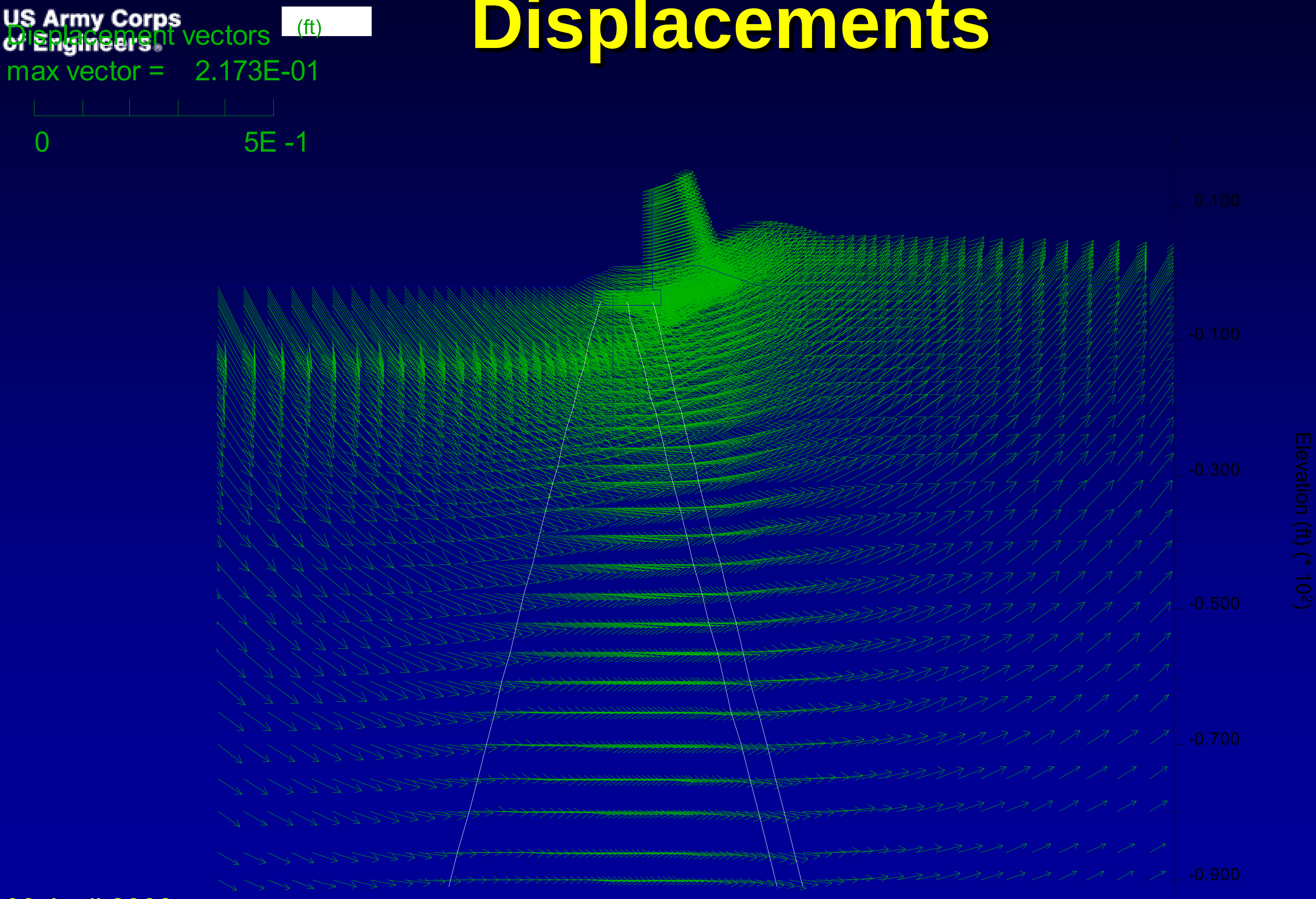
The two stage loading in GMX report revealed most deflections due to water load on the ground surface.



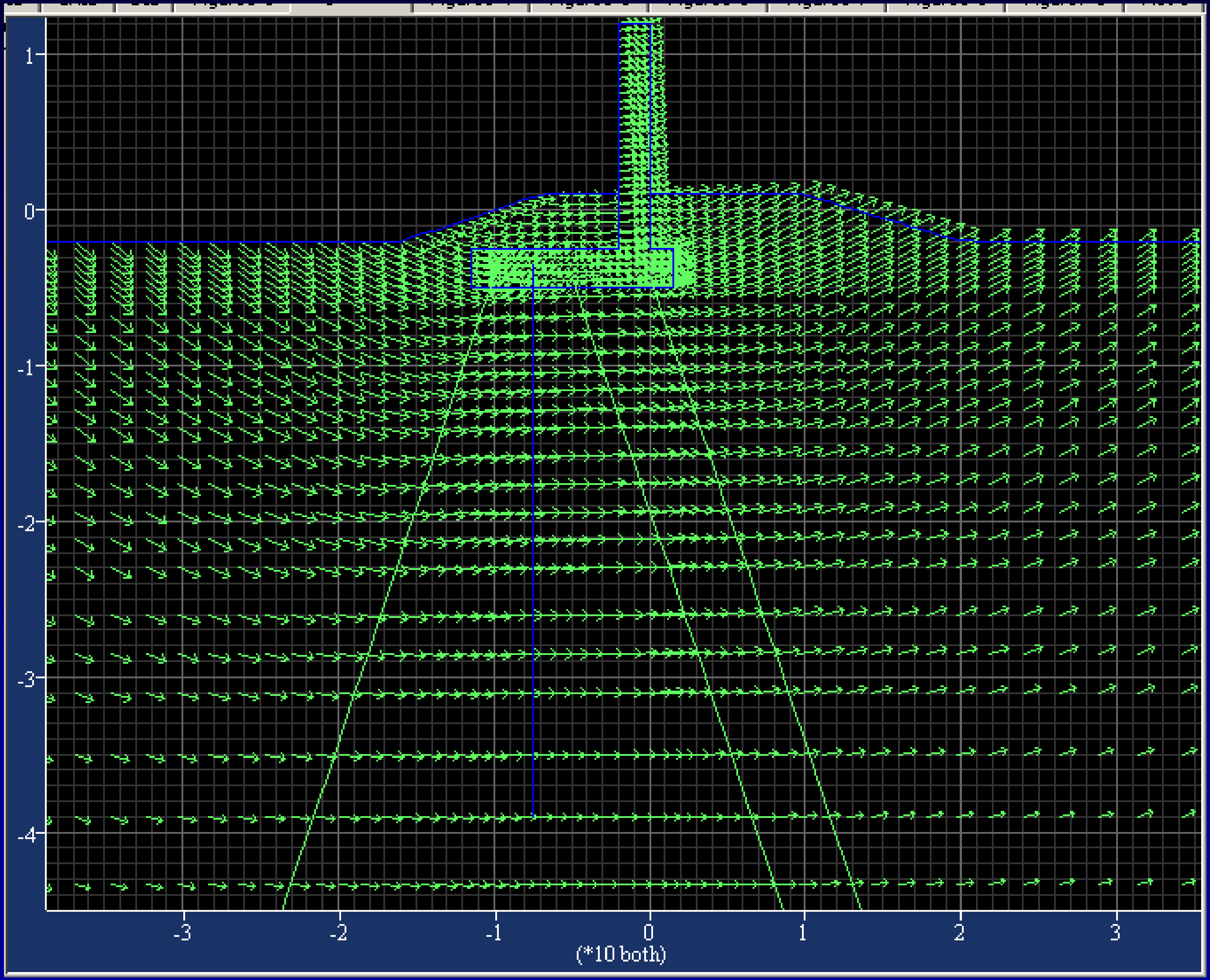

Left Pile
Middle Pile
Right Pile
0
-20
-40
-60
-80
-100
Elevation (ft)
0
0.2
0.4
0.6
Horizontal Displacement of Piles (ft)
Water Pressure:
- on T-wall and upstream ground surface
- on T-wall only
DRAFT


Left Pile
Middle Pile
Right Pile
Elevation (ft)
0
-20
-40
-60
-80
-100
-40000
0
40000
80000
Axial Force of Piles (lbs)
Water Pressure:
- on T-wall and upstream ground surface
- on T-wall only
DRAFT

Displacements



Displacements



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Axial Loads

Axial Force (lbs)

Structure	Max. Value
# 1 (Beam)	-1.131E+03

Left Pile

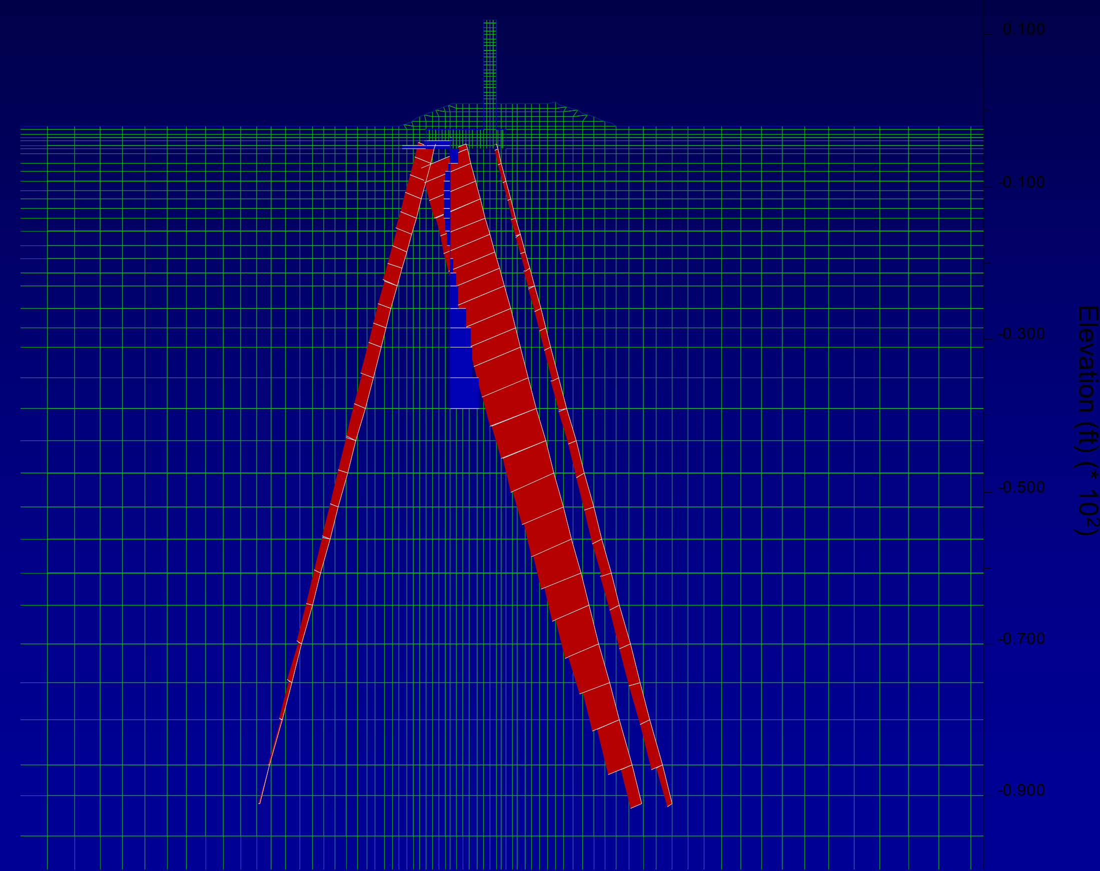
Structure	Max. Value
# 2 (Pile)	-3.222E+04
# 3 (Pile)	-3.076E+04
# 4 (Pile)	-2.745E+04
# 5 (Pile)	-2.674E+04
# 6 (Pile)	-2.507E+04
# 7 (Pile)	-2.139E+04
# 8 (Pile)	-1.147E+04
# 9 (Pile)	-8.916E+03
#10 (Pile)	-2.805E+03
#11 (Pile)	-1.036E+03

Middle Pile

Structure	Max. Value
#12 (Pile)	9.533E+04
#13 (Pile)	9.515E+04
#14 (Pile)	9.488E+04
#15 (Pile)	9.511E+04
#16 (Pile)	9.488E+04
#17 (Pile)	9.150E+04
#18 (Pile)	7.089E+04
#19 (Pile)	6.322E+04
#20 (Pile)	4.758E+04
#21 (Pile)	2.291E+04

Right Pile

Structure	Max. Value
#22 (Pile)	9.245E+03
#23 (Pile)	1.141E+04
#24 (Pile)	1.223E+04
#25 (Pile)	1.369E+04
#26 (Pile)	1.526E+04
#27 (Pile)	2.065E+04
#28 (Pile)	2.094E+04
#29 (Pile)	2.152E+04
#30 (Pile)	2.120E+04
#31 (Pile)	1.186E+04



Shear in Pile

Shear Forc (lbs)

Structure	Max. Value
# 1 (Beam)	-9.985E+03

Left Pile

# 2 (Pile)	-6.461E+03
# 3 (Pile)	2.530E+03
# 4 (Pile)	1.570E+03
# 5 (Pile)	2.625E+03
# 6 (Pile)	2.829E+03
# 7 (Pile)	-1.341E+03
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Right Pile

#22 (Pile)	-2.039E+03
#23 (Pile)	-9.497E+02
#24 (Pile)	5.790E+02
#25 (Pile)	1.848E+03
#26 (Pile)	2.132E+03
#27 (Pile)	-9.751E+02
#28 (Pile)	2.804E+02
#29 (Pile)	-3.577E+02
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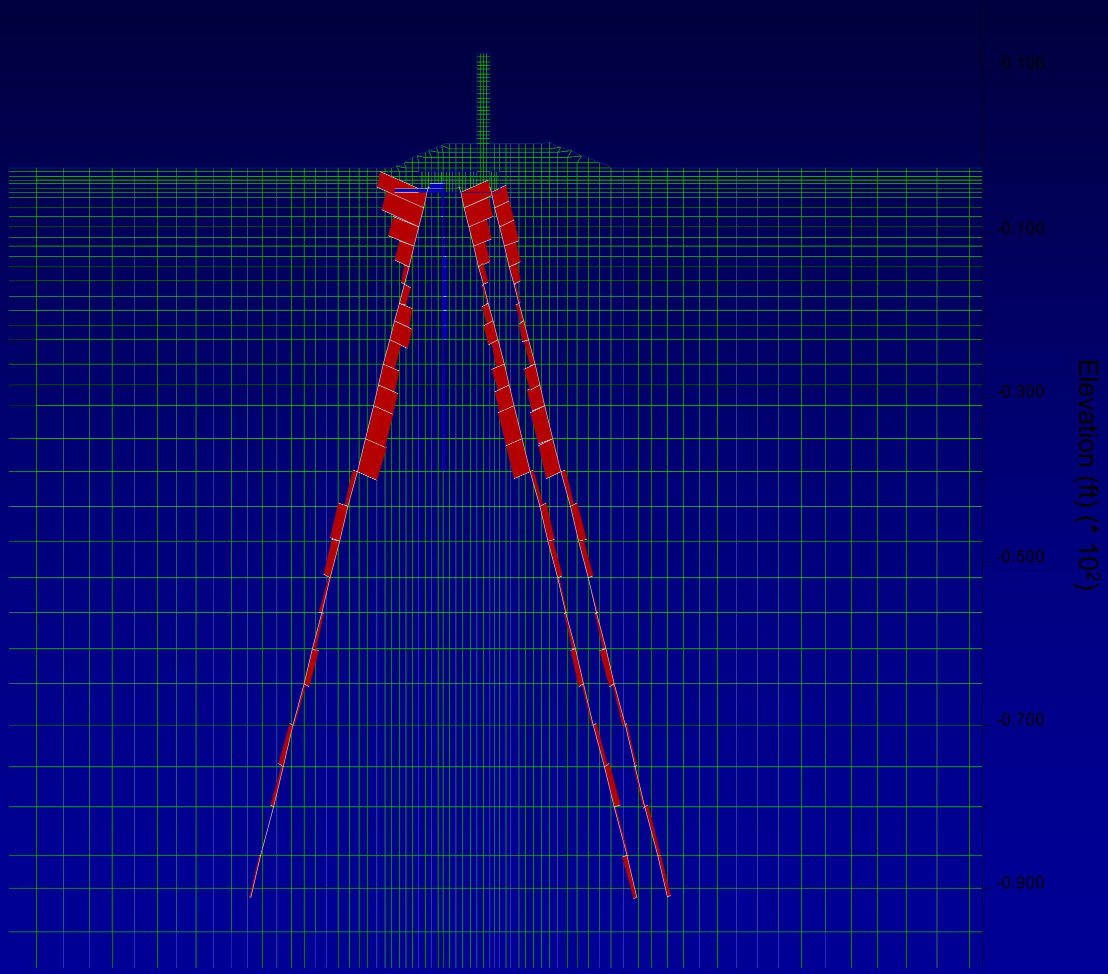
#31 (Pile)	-4.539E+02



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Moment in Pile

Moment (lb-ft)

Structure	Max. Value
# 1 (Beam)	8.055E+03

Left Pile

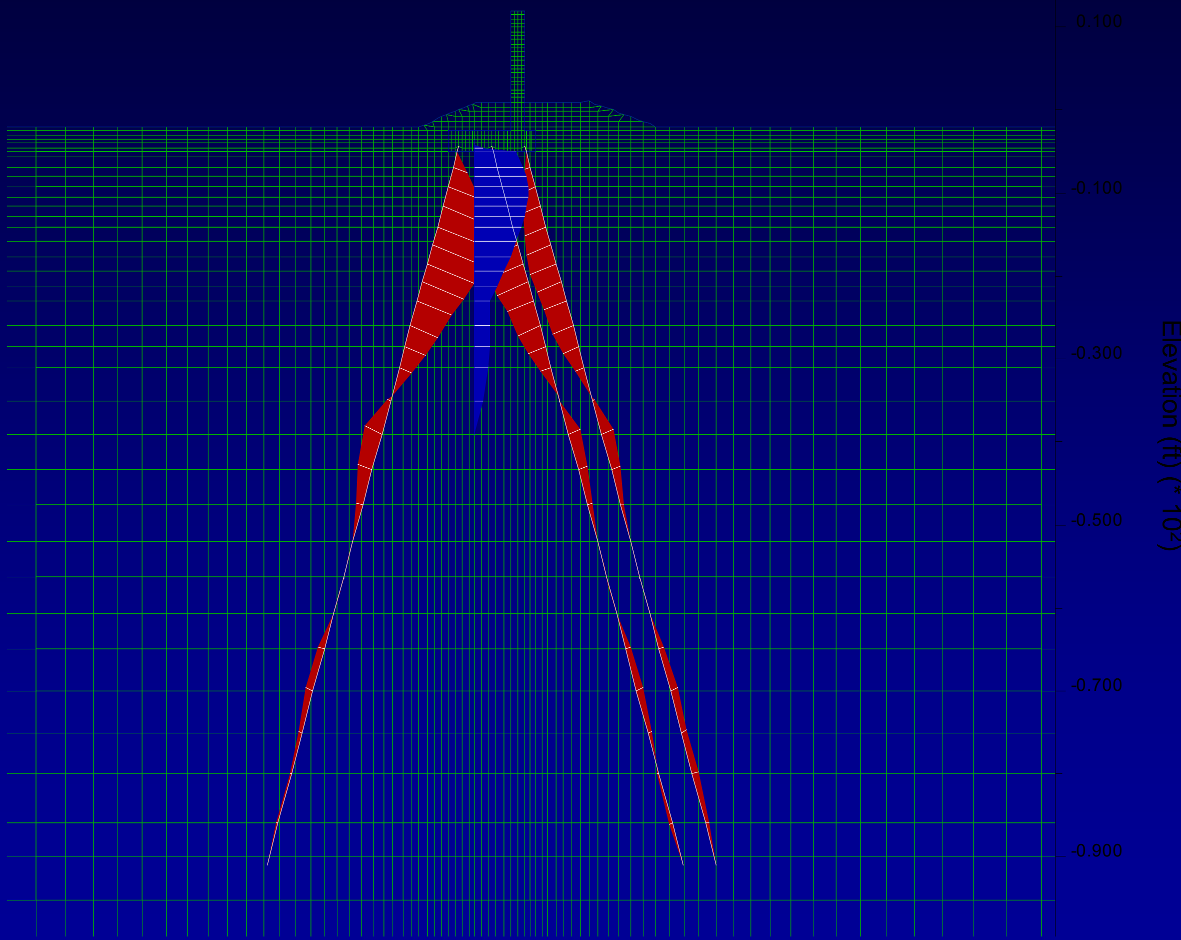
# 2 (Pile)	3.901E+04
# 3 (Pile)	4.014E+04
# 4 (Pile)	2.743E+04
# 5 (Pile)	2.246E+04
# 6 (Pile)	-1.389E+04
# 7 (Pile)	-1.389E+04
# 8 (Pile)	-5.986E+03
# 9 (Pile)	-5.986E+03
#10 (Pile)	-1.226E+03
#11 (Pile)	-1.226E+03

Middle Pile

#12 (Pile)	2.560E+04
#13 (Pile)	2.709E+04
#14 (Pile)	2.101E+04
#15 (Pile)	1.808E+04
#16 (Pile)	-1.003E+04
#17 (Pile)	-1.003E+04
#18 (Pile)	-5.547E+03
#19 (Pile)	-5.547E+03
#20 (Pile)	2.885E+03
#21 (Pile)	2.885E+03

Right Pile

#22 (Pile)	1.765E+04
#23 (Pile)	2.048E+04
#24 (Pile)	1.775E+04
#25 (Pile)	1.591E+04
#26 (Pile)	-1.017E+04
#27 (Pile)	-1.017E+04
#28 (Pile)	-5.754E+03
#29 (Pile)	-5.754E+03
#30 (Pile)	-5.142E+03
#31 (Pile)	-2.393E+03



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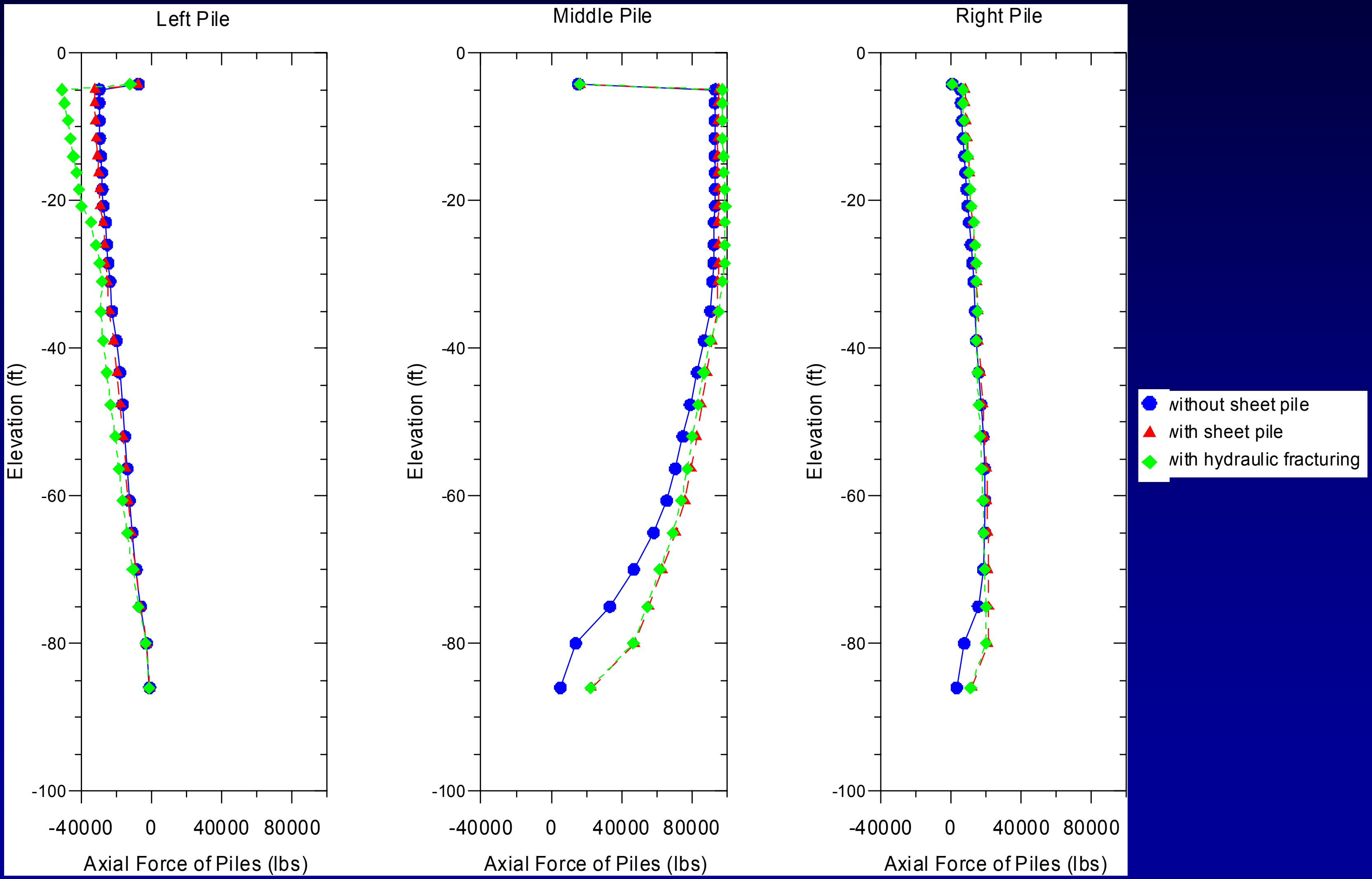
Without Sheet Pile



Investigations by Product Delivery Team

- FLAC 2D – using the GMX model
- Plaxis 2D and 3D
- UTexas4
- Group 7
- CPGA
- LPile and T-Z pile

Investigations with FLAC GMX model

20’ water load on wall

Short piles

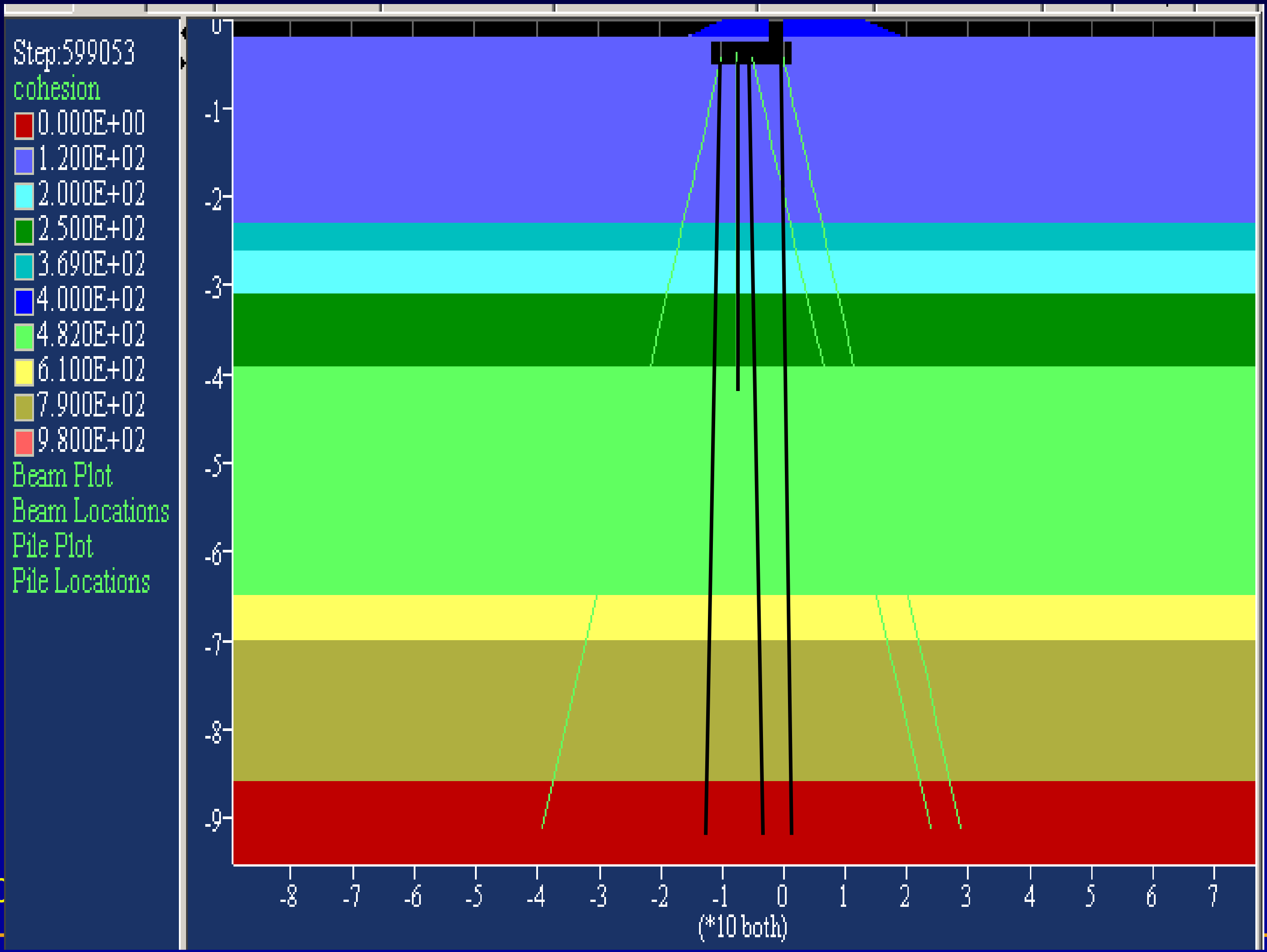
Vertical piles

Applied unbalanced load

Strength reduction factor (SRF)

Vertical piles

How does batter affect pile response?



Applied unbalanced load

- Load distributed along left H-Pile above critical failure surface.
- Load distributed along all piles above critical failure surface.
- Load distributed along full length of all piles.
- Load applied at structure.

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Strength reduction factor (SRF)

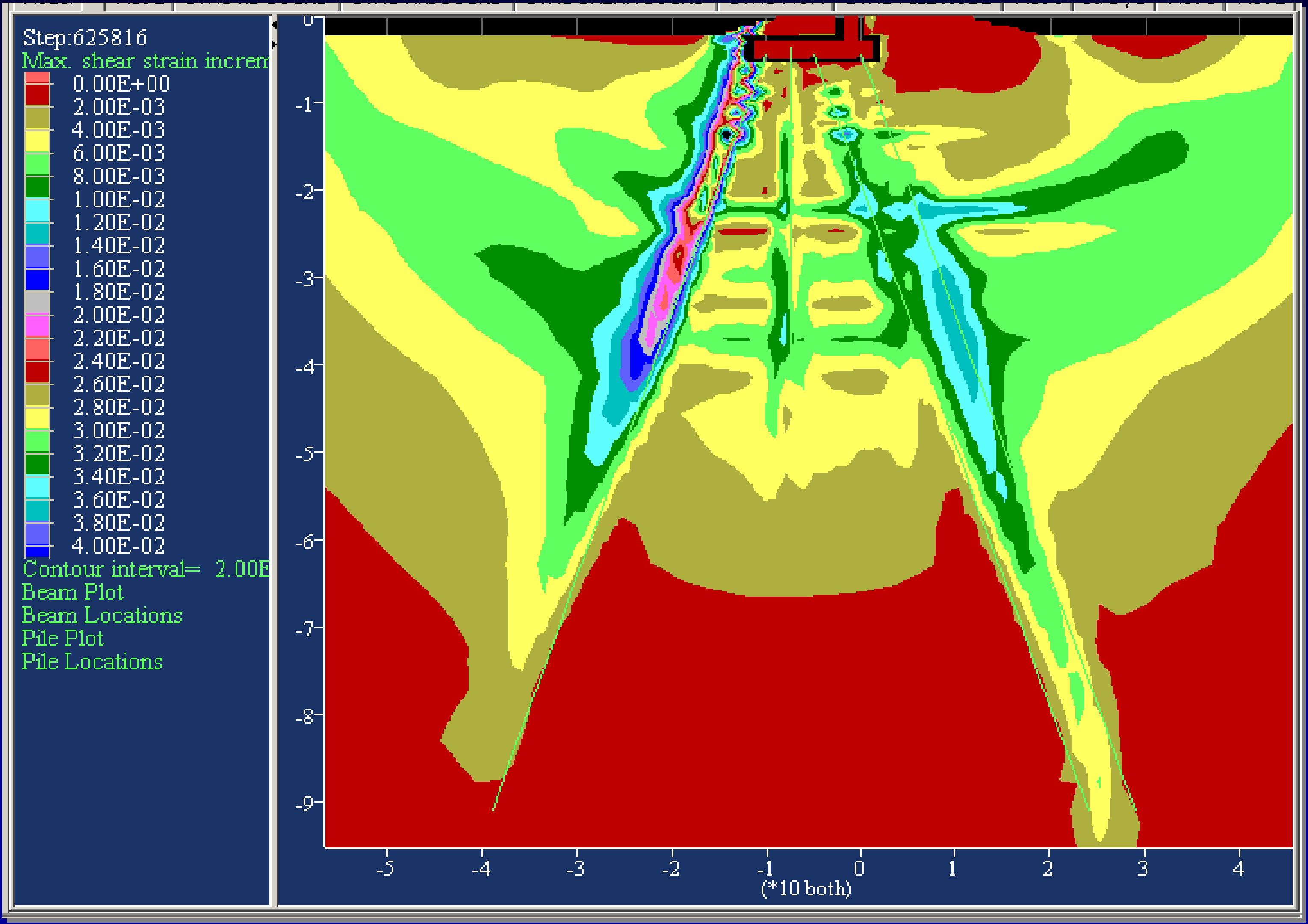
FLAC for slope stability

- Performs an automated strength reduction routine
- Matches FS from limit equilibrium analysis (UTexas4, Slide, SlopeW)

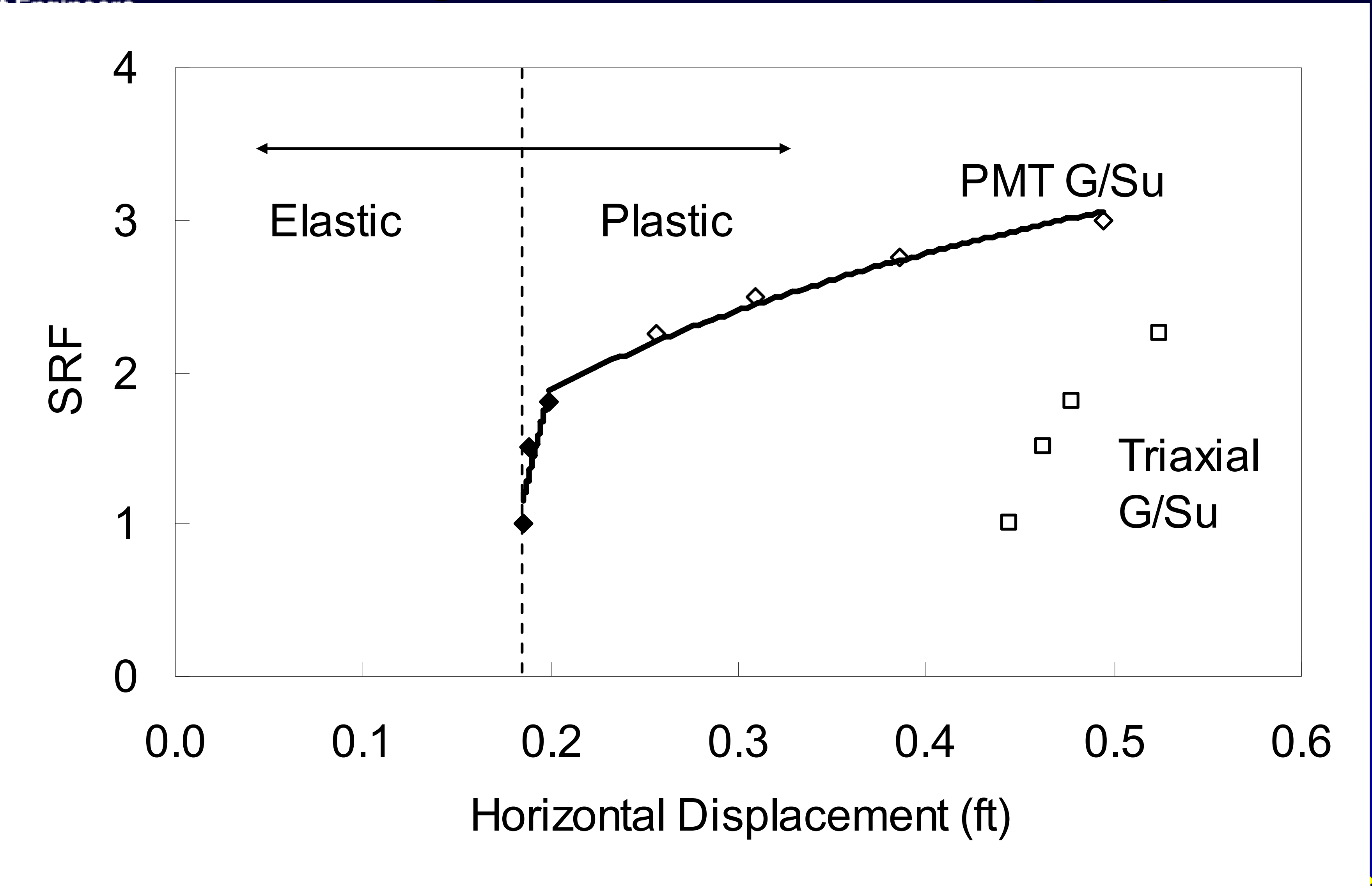
Questions about T-wall example

- Is the wall still stable with lower soil strengths?
- How does SRF compare to design method?
- How does presence of piles change failure mechanism?

Strength reduction factors (SRF = 2.75)



Strength reduction factors (SRF)



FLAC Analysis Conclusions

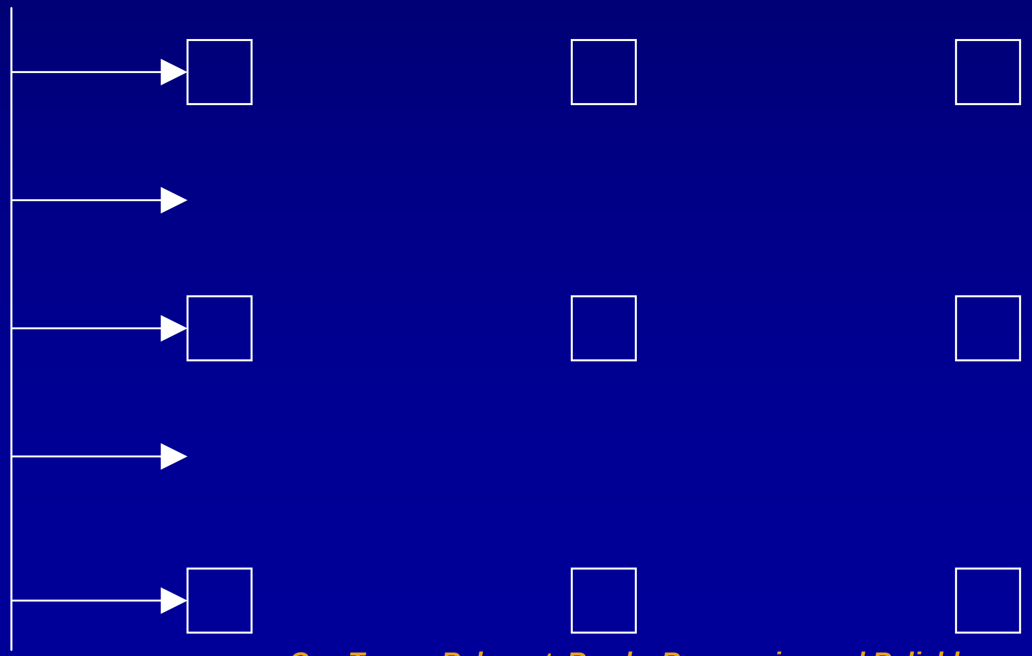
Presence of sheet pile did not affect pile loads or deflections

Battered H-pile much more effective than vertical

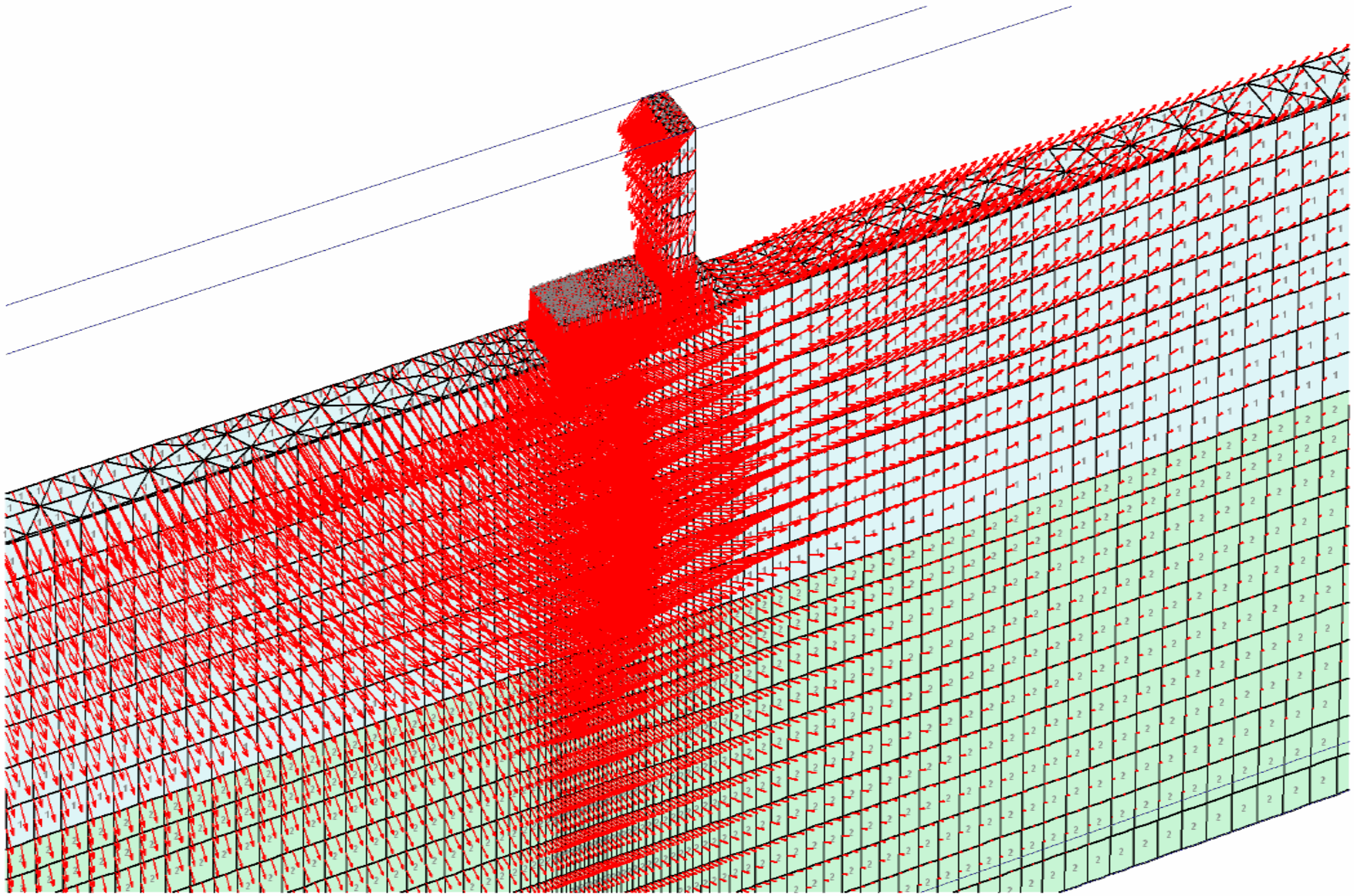
H-Piles and T-Wall are Effective in Stabilizing the Soil Mass

Investigations with Plaxis 3D

- **Flow of soil between piles**
- **Allowable pile spacing**
- **Load distribution between pile rows**



3-D Plaxis Model Displacements



Total displacements U_{Tot}

Extreme value = 209.04×10^{-3} ft

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Summary

- T-Walls are a complex SSI problem
- Numerical analyses illustrate SSI behavior
- Outside sources willing to supply FLAC model add great value to the report
- Goal is to determine practical methodology

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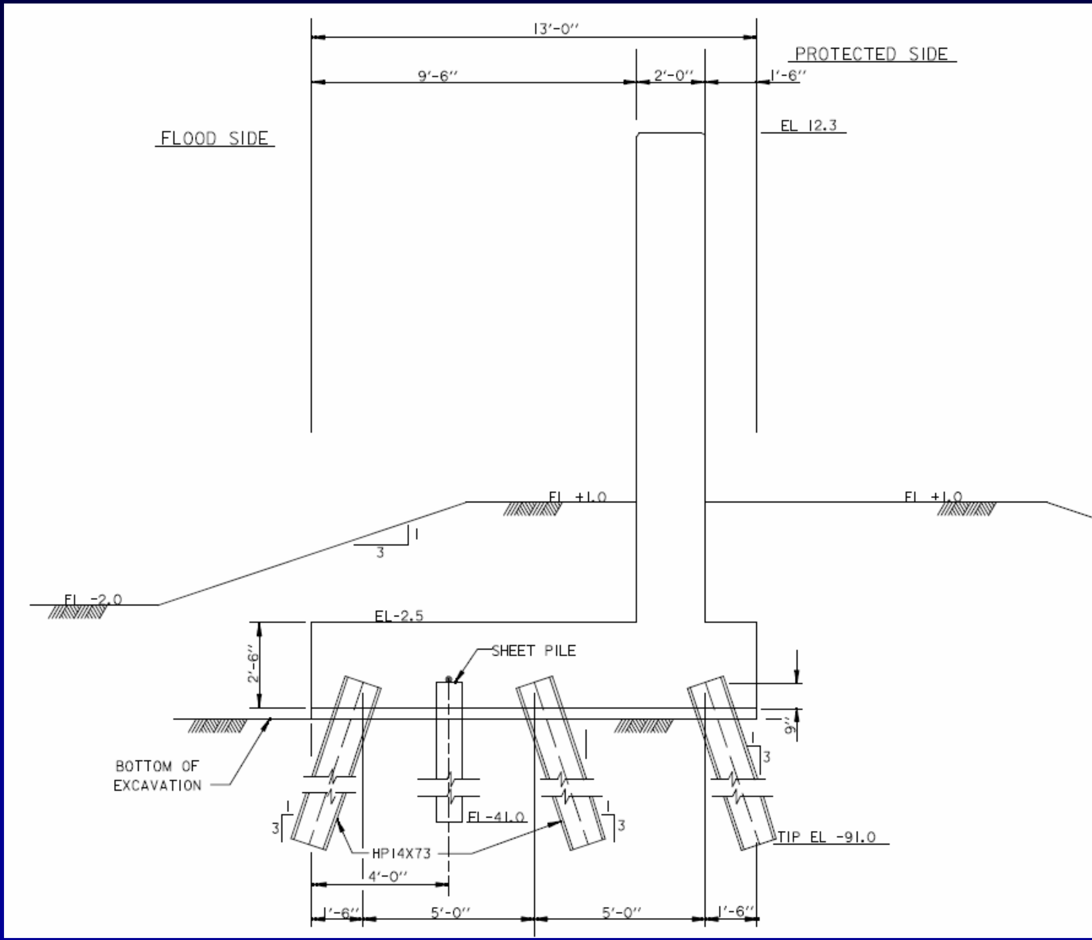
Method Development

- **Provide Overview of**
  - **How T-wall Design Procedure Was Developed so Designers Understand its Basis and Limitations**



Design Method Development

PDT as shown in early slide

Use existing tools and methods if possible

Replicate FLAC Results

Reasonable Design

Methods

Various Methods Tried – Reinforced Slope Concept

FLAC Models with Applied Lateral Load

Tried Applying Lateral Loads in Ensoft Group 7

- At Rest Pressure
- Unbalanced Load

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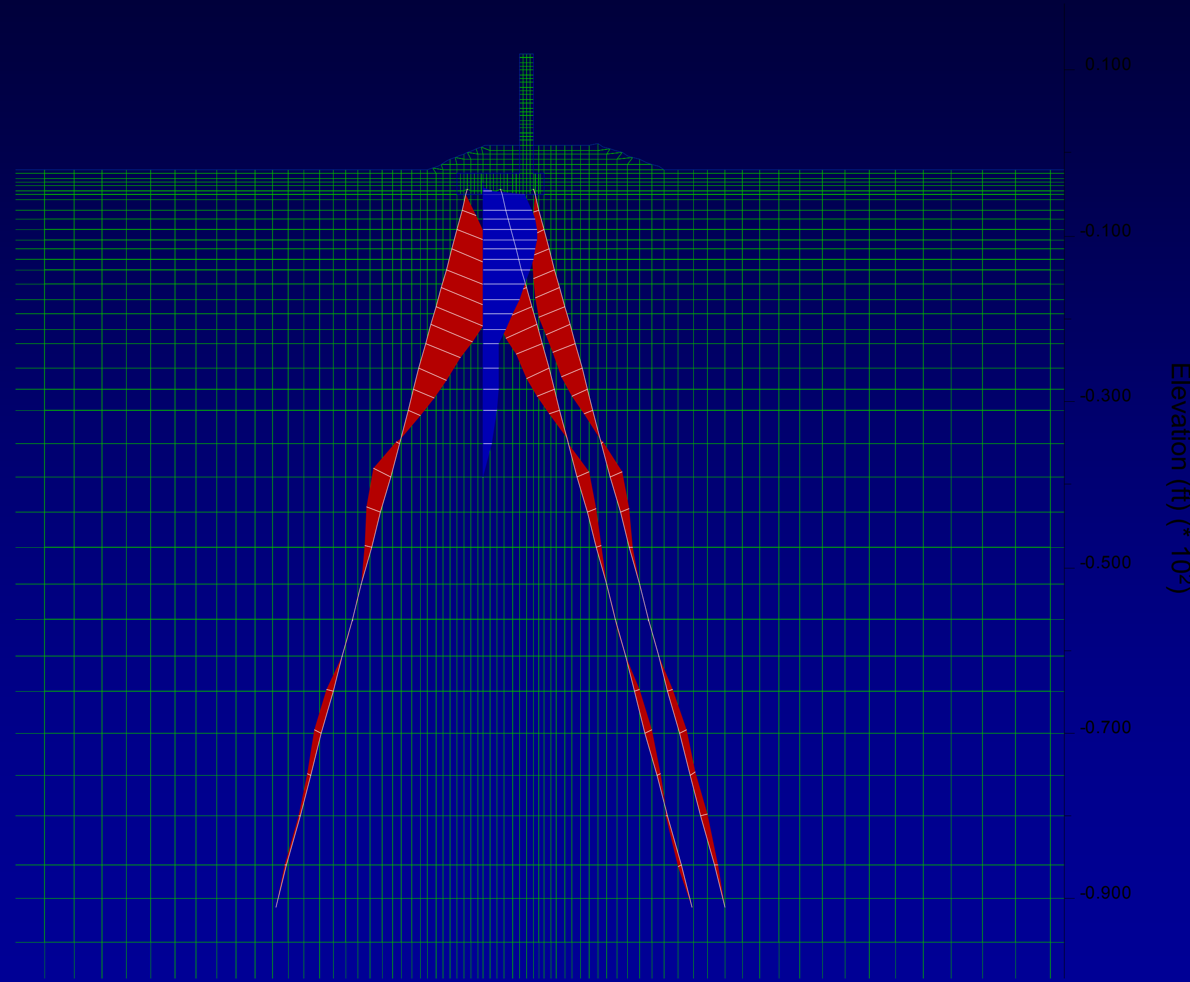

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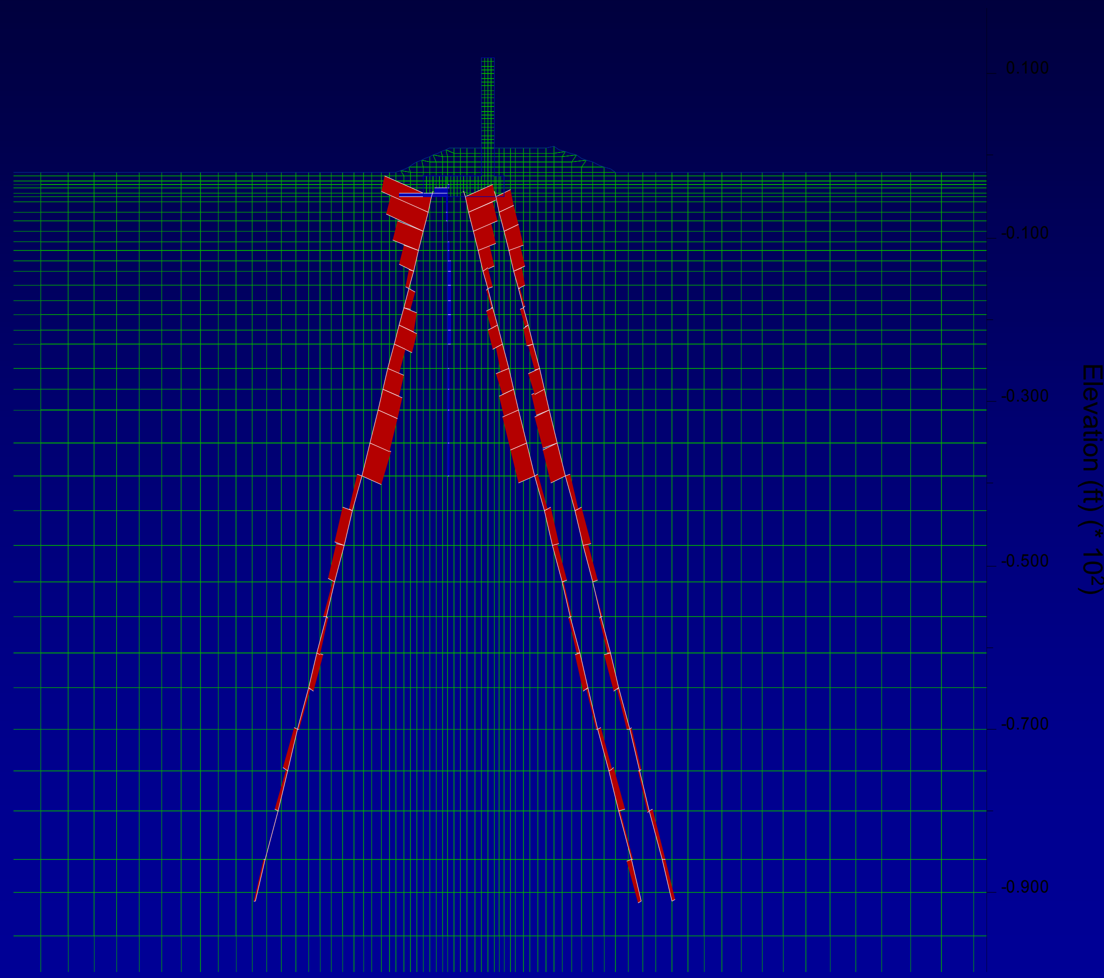

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Design Method

Group 7 Method

- Compute "Unbalanced" Load to Provide Factor of Safety
- Apply Unbalanced Force Directly to Piles
- No lateral soil resistance to critical failure surface
- "Normal" Loads on Wall itself
- Matched FLAC results.
- Pile Forces Computed Directly

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Method Development

Directly Second FLAC model (18’ Water Elevation) also had good correlation with Group 7 Method

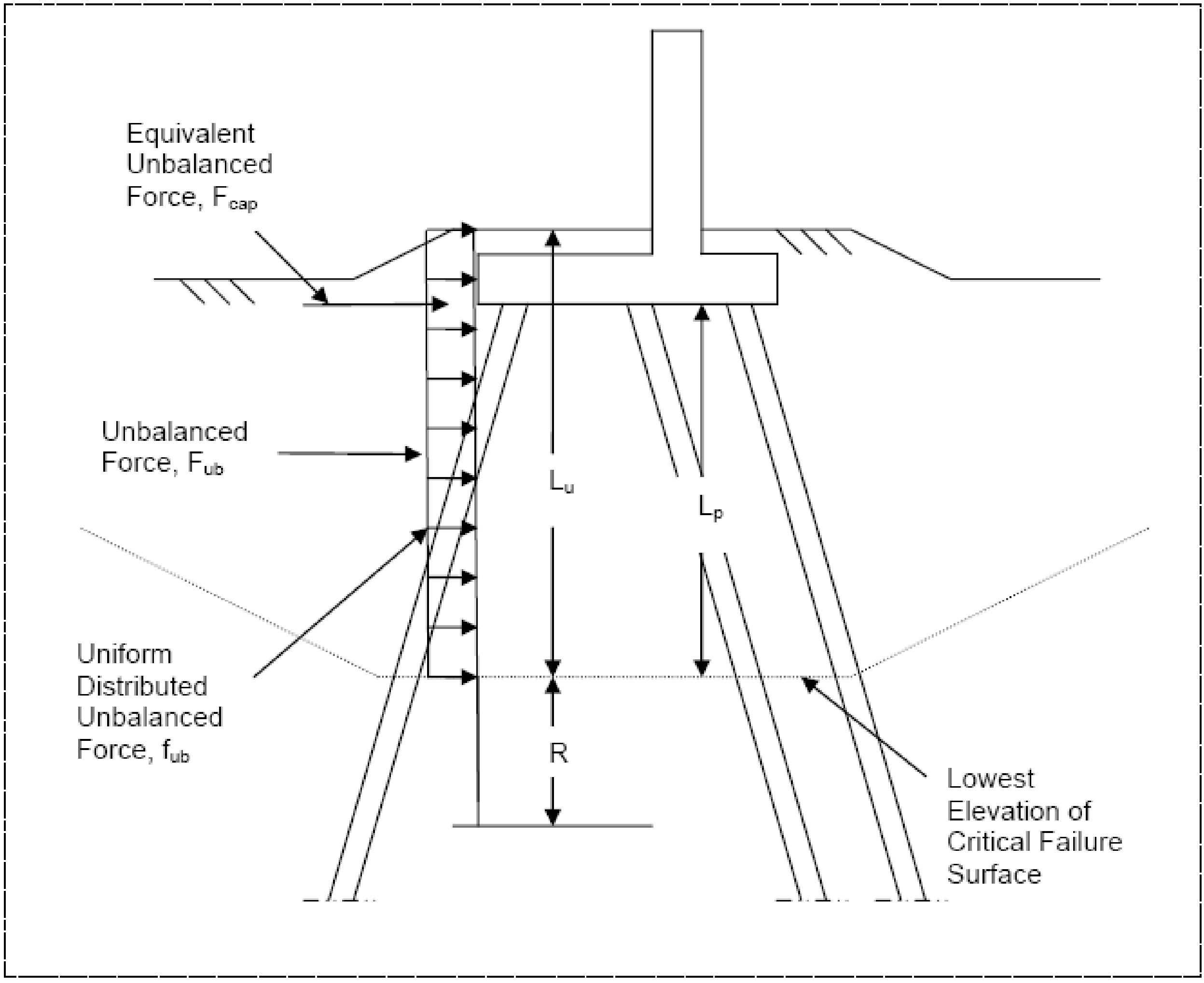
Pile Distribution (50% on Lead Pile) selected from FLAC results – axial loads not sensitive to this

CPGA approximation developed to help deal with the many load cases

CPGA Approximation

$$F_{cap} = F_{ub}\left[\frac{\left(\frac{L_p}{2}+R\right)}{\left(L_p+R\right)}\right]\frac{L_p}{L_u}$$

$$R = \sqrt[4]{\frac{EI}{Es}}$$



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Comparison, Axial Loads

	Deflection (in)	Axial Loading in Piles (kips)		
		Left	Middle	Right
Group 7, Pervious	0.52	-39.7	91.8	3.6
Group 7, Impervious	0.49	-35.4	89.6	10.7
CPGA, Pervious	0.46	-45.0	100.4	0.6
CPGA, Impervious	0.43	-41.0	97.9	7.8
FLAC	2.21	-32.5	95.7	6.7
Ex 1, Group 7, Pervious	0.53	-39.9	93.5	2.3
Ex 1, Group 7, Impervious	0.49	-35.8	91.5	9.2
Ex 1, CPGA, Pervious	0.66	-46.8	97.2	5.2
Ex 1, CPGA, Impervious	0.61	-42.3	94.4	12.5

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Comparison, Moments

	%	Max + Moment (kip-ft			Max - Moment (kip-ft		
		Left	Middle	Right	Left	Middle	Right
Group 7, Pervious	50	23.9	8.75	7.47	-20.6	-17.5	-19.7
Group 7, Impervious	50	24.3	9.17	7.98	-19.8	-16.5	-18.5
FLAC		41.5	28.5	21.6	-15.2	-10.8	-10.8
Ex 1, Group 7, Pervious	50	26.2	9.5	8.2	-21.5	-17.3	-18.9
Ex 1, Group 7, Impervious	50	26.5	9.9	8.6	-20.8	-16.5	-18.1
Ex 1, Group 7, Pervious	100	69.8	-	-	-36.8	-17.2	-19.1
Ex 1, Group 7, Impervious	100	70.3	-	-	-36.3	-16.1	-18.0

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Flow Through

Direct Transfer of Soil Movement to Piles

Ensure Piles Really Take All Load

Limited 3D model studies

Research – studies of lateral soil loading on piles and pile Groups has been studied numerous times

Method developed from these studies.

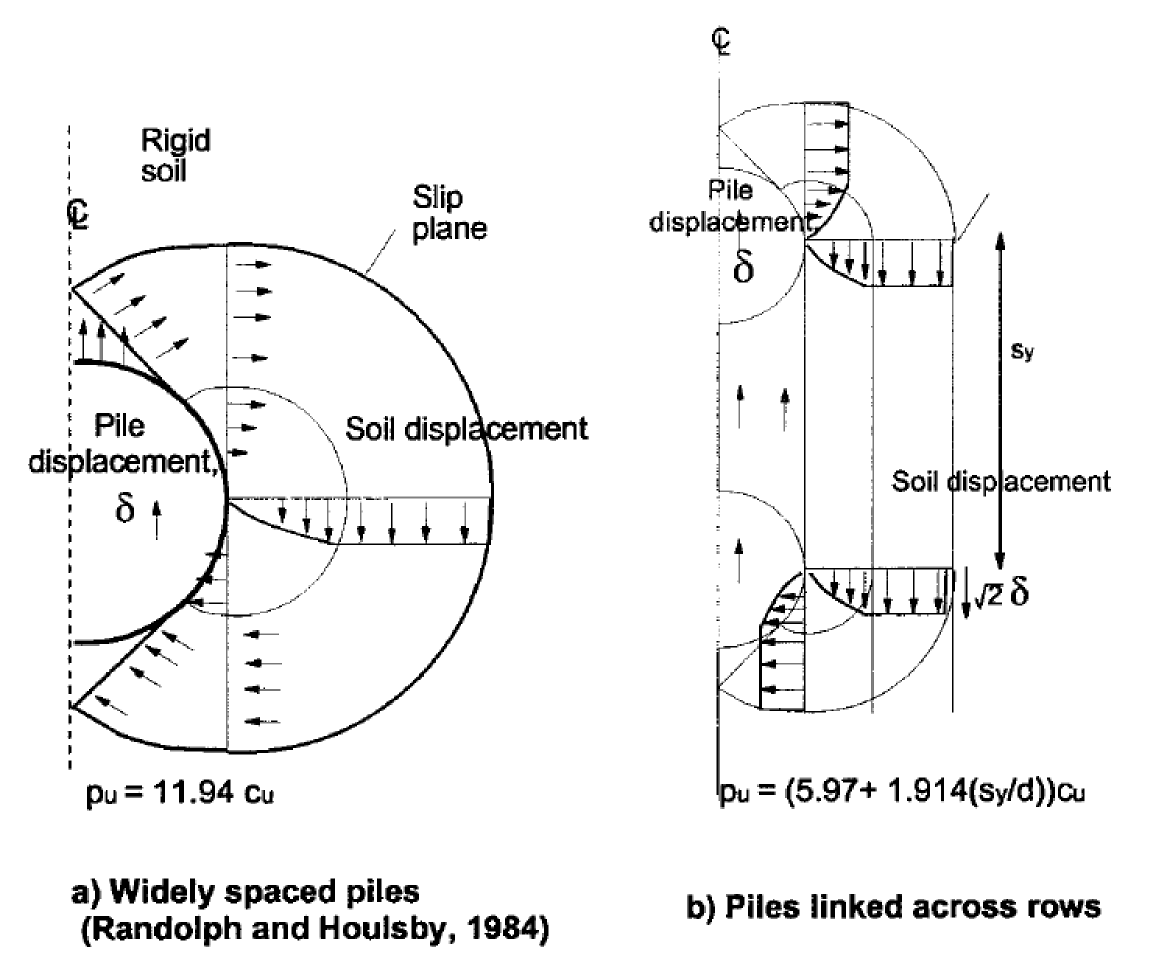
Flow Through

Check Flow Through, Type 1

Pile Lateral Capacity

Basic Capacity

$P_{ult} = 9Cu$



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Question?

Thank You

Comparison Between Spencer's Method And Method of Planes

by

Rich Varuso, P.E.

April 8, 2008

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Method of Planes Analysis (MOP)

Useful in Lower Mississippi River Alluvial Valley for:

- Highly stratified soft soils
- Moderately weak soils on a hard surface
- Or in a foundation with one or more weak zones

Method of Planes

Divides soil mass into three segments

- Active wedge
- Central block
- Passive wedge

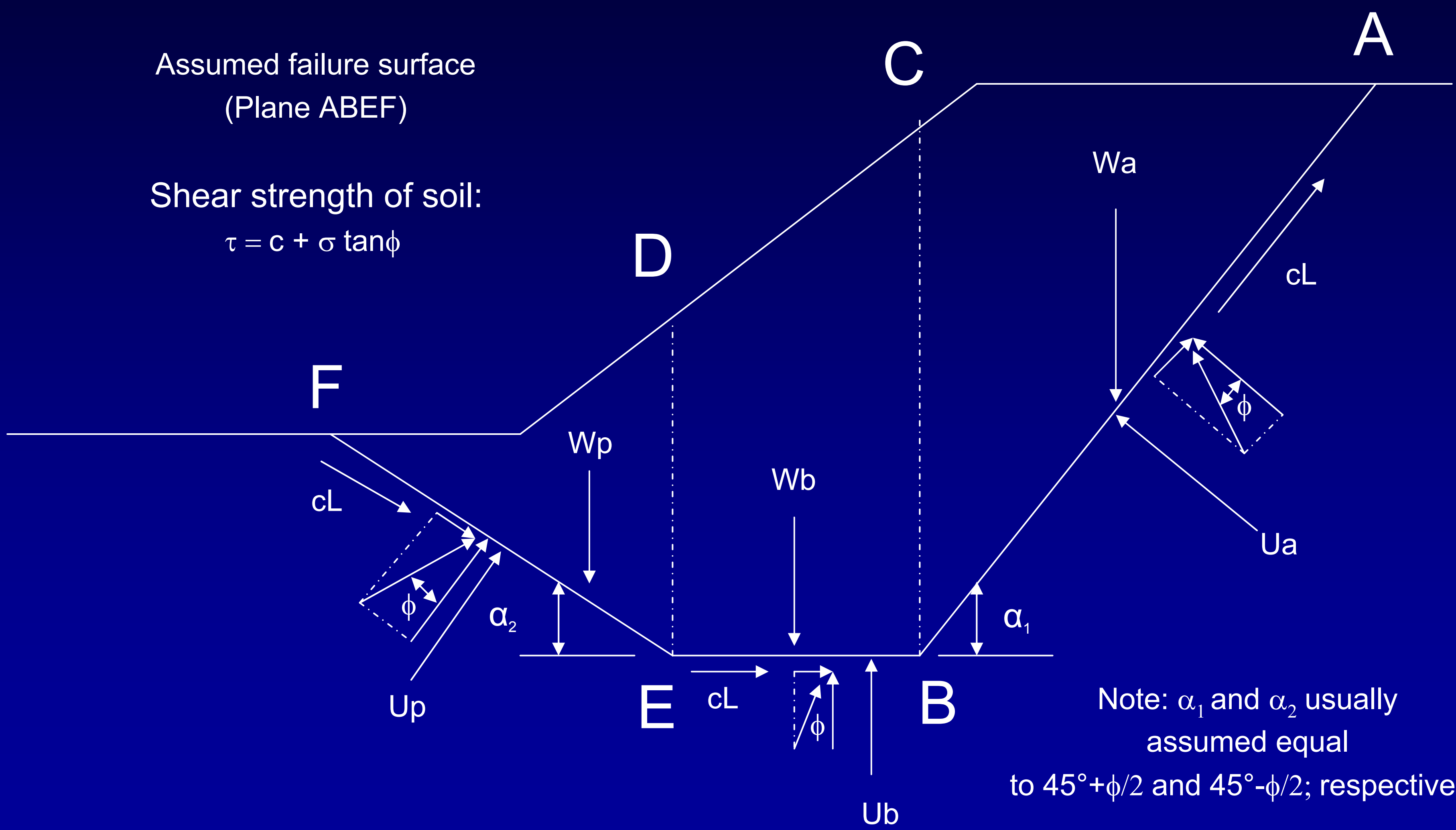
Wedges are treated as rigid bodies (according to Coulomb)

Method of Planes

Assumed failure surface
(Plane ABEF)

Shear strength of soil:

$\tau = c + \sigma \tan\phi$



Note: α_1 and α_2 usually assumed equal to 45°+$\phi/2$ and 45°-$\phi/2$; respectively.

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Method of Planes

$$FS = \frac{R_a + R_b + R_p}{D_a - D_p}$$

Da = Active Driving Force

Ra = Active Resistance

Rb = Central Block Resistance

Dp = Passive Driving Resistance

Rp = Passive Resistance

FW= Lateral Free Water Pressure

$$UL = (D_a – FW) – (R_a + R_b + R_p + D_p)$$

Spencer's Method

HSDRRSDG Table 3.1: "*Spencer method shall be used for circular and non-circular failure surfaces since it satisfies all conditions of static equilibrium and because its numerical stability is well suited for computer application.*"

Finding the shear-normal ratio that makes the two factors of safety equal, means that both moment and force equilibrium are satisfied.

Spencer's Method

Spencer (1967) developed two factor of safety equations; one with respect to moment equilibrium and another with respect to horizontal force equilibrium. He adopted a constant relationship between the interslice shear and normal forces, and through an iterative procedure altered the interslice shear to normal ratio until the two factors of safety were the same.

Finding the shear-normal ratio that makes the two factors of safety equal, means that both moment and force equilibrium are satisfied.

Spencer's Method

The GLE factor of safety equation with respect to moment equilibrium is:

$$F_m = \frac{\sum (c'\beta R + (N - u\beta)R \ \tan\phi')}{\sum Wx - \sum Nf \pm \sum Dd}$$

The factor of safety equation with respect to horizontal force equilibrium is:

$$F_f = \frac{\sum (c'\beta \cos\alpha + (N - u\beta) \tan\phi' \cos\alpha)}{\sum N \sin\alpha - \sum D \cos\omega}$$

The terms in the equations are:

c'	=	effective cohesion
ϕ'	=	effective angle of friction
u	=	pore-water pressure
N	=	slice base normal force
W	=	slice weight
D	=	line load
β, R, x, f, d, ω	=	geometric parameters
α	=	inclination of slice base

Spencer's Method

One of the key variables in both equations is N, the normal at the base of each slice. This equation is obtained by the summation of vertical forces, thus vertical force equilibrium is consequently satisfied. In equation form, the base normal is defined as:

$$N = \frac{W + (X_R - X_L) - \dfrac{c'\beta \sin\alpha + u\beta \sin\alpha \tan\phi'}{F}}{\cos\alpha + \dfrac{\sin\alpha \tan\phi'}{F}}$$

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Spencer's Method

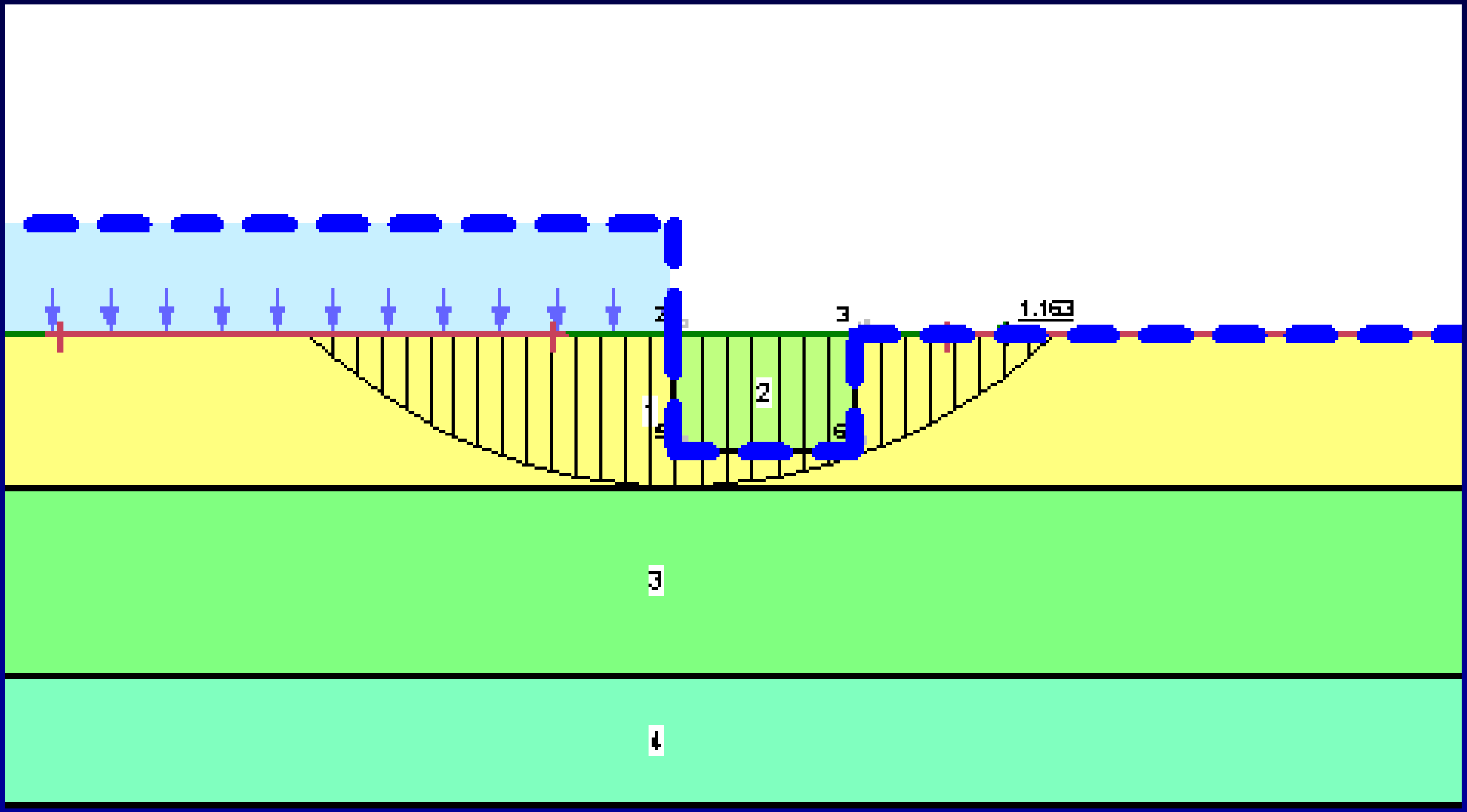
Determine the non-circular failure surface:

- **Sufficient analysis has been done to varying soil profiles to assure that the non-circular surfaces shall govern the stability assessment.**

- **Numerical modeling has indicated that soil displacement is nearly horizontal under the base of a pile-supported T-Wall.**

Spencer's Method

Unrealistic Slip Surface



Spencer's Method

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EM 1110-2-1902 requires verification of the results of computer analysis:

"All reports, except reconnaissance phase reports, that deal with critical embankments or slopes should include verification of the results of computer analyses. The verification should be commensurate with the level of risk associated with the structure and should include one or more of the following methods of analysis using:

(1) Graphical (force polygon) method.

(2) Spreadsheet calculations.

(3) Another slope stability computer program.

(4) Slope stability charts."

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Spencer's Method

Slope Stability Design Factors of Safety for T-Walls

Analysis Condition	Required Minimum Factor of Safety	
	Spencer's Method	MOP
Protected Side (SWL)	1.5	1.3
Protected Side (top of wall - TOW)	1.4	1.3
Floodside (low water)	1.4	1.3

Spencer's Method

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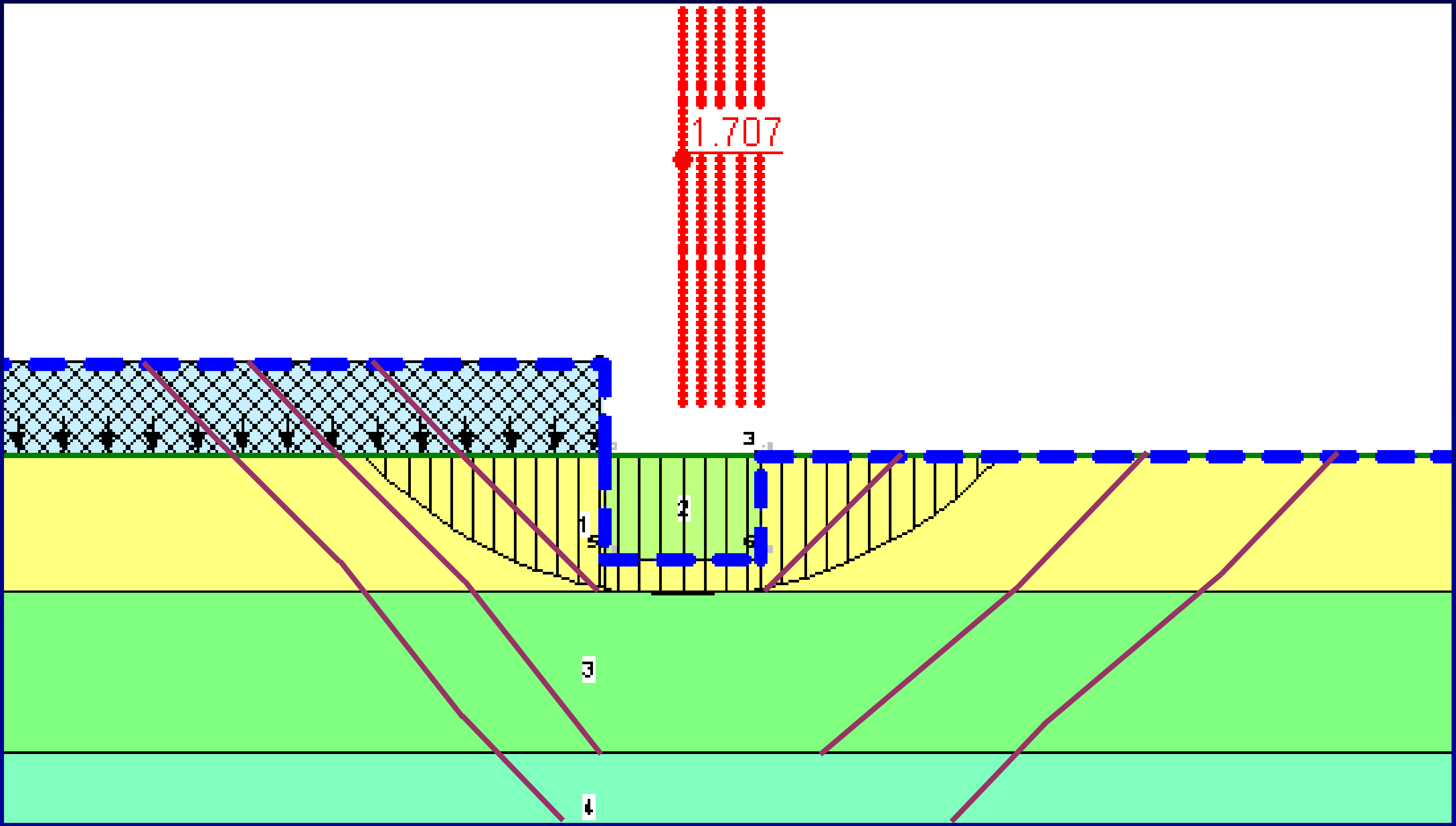
Stability Analysis using Method of Planes (MOP)

HSDRRSDG: ***"LMVD Method of Planes shall be used as a design check for verification that the HPS design satisfies historic district requirements. Analysis shall include a full search for the critical failure surface since it may vary from that found following the Spencer's Method."***

Spencer's Method

Spencer's Method compared to MOP



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Question?

Thank You

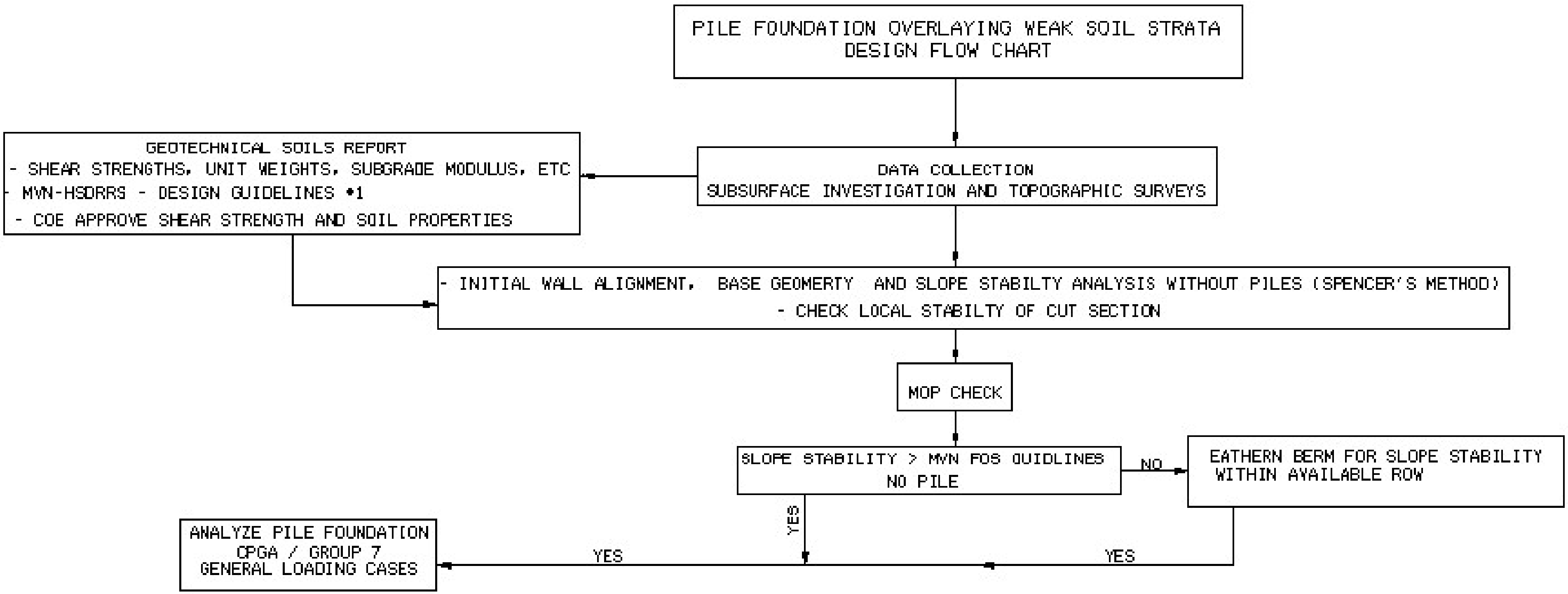
T-Wall Design Procedure for Unbalanced Load

by

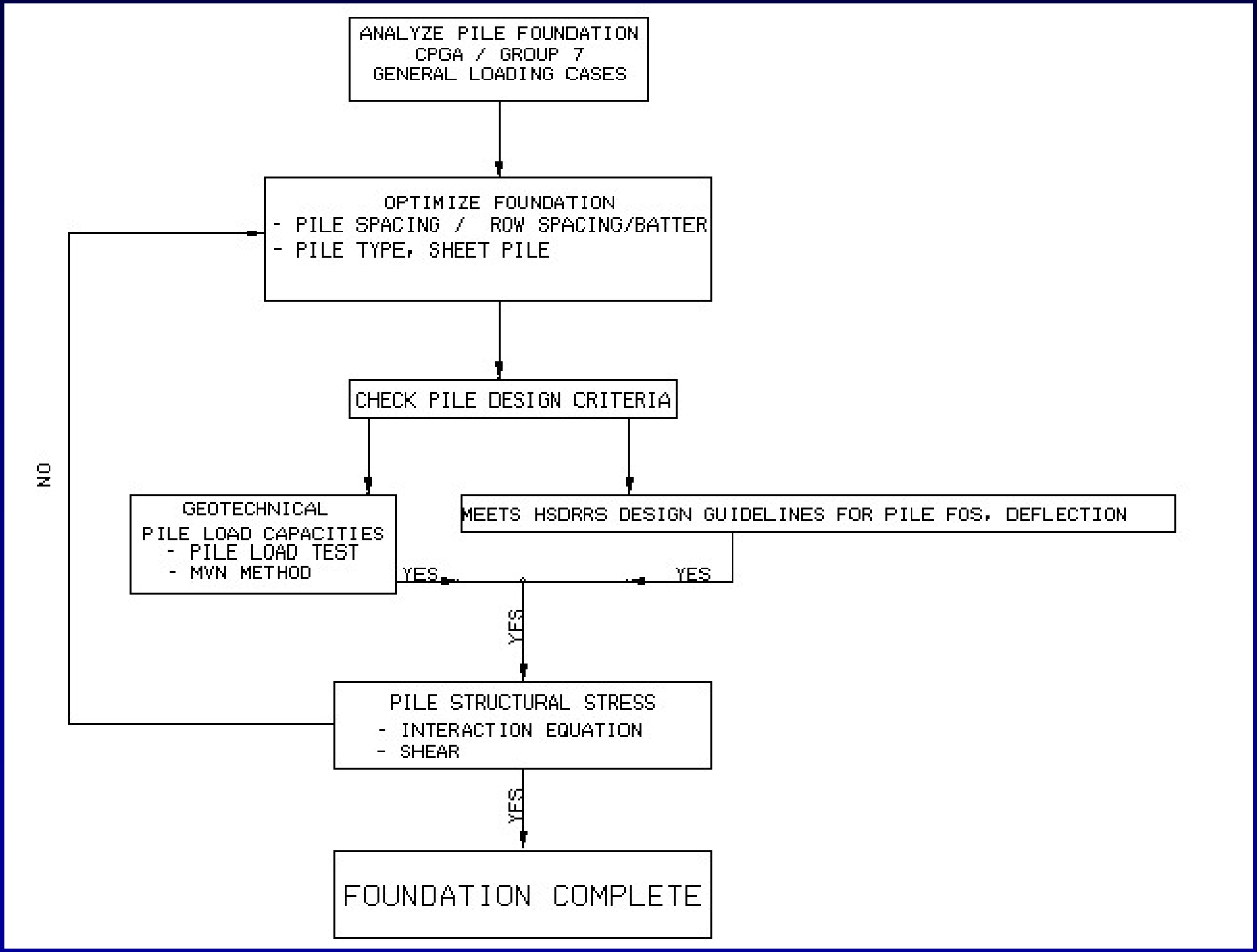
Mark Gonski, P.E.,
Kent Hokens, P.E.,
Neil Schwanz, P.E.,
Rob Werner and Brian Powell

April 8, 2008

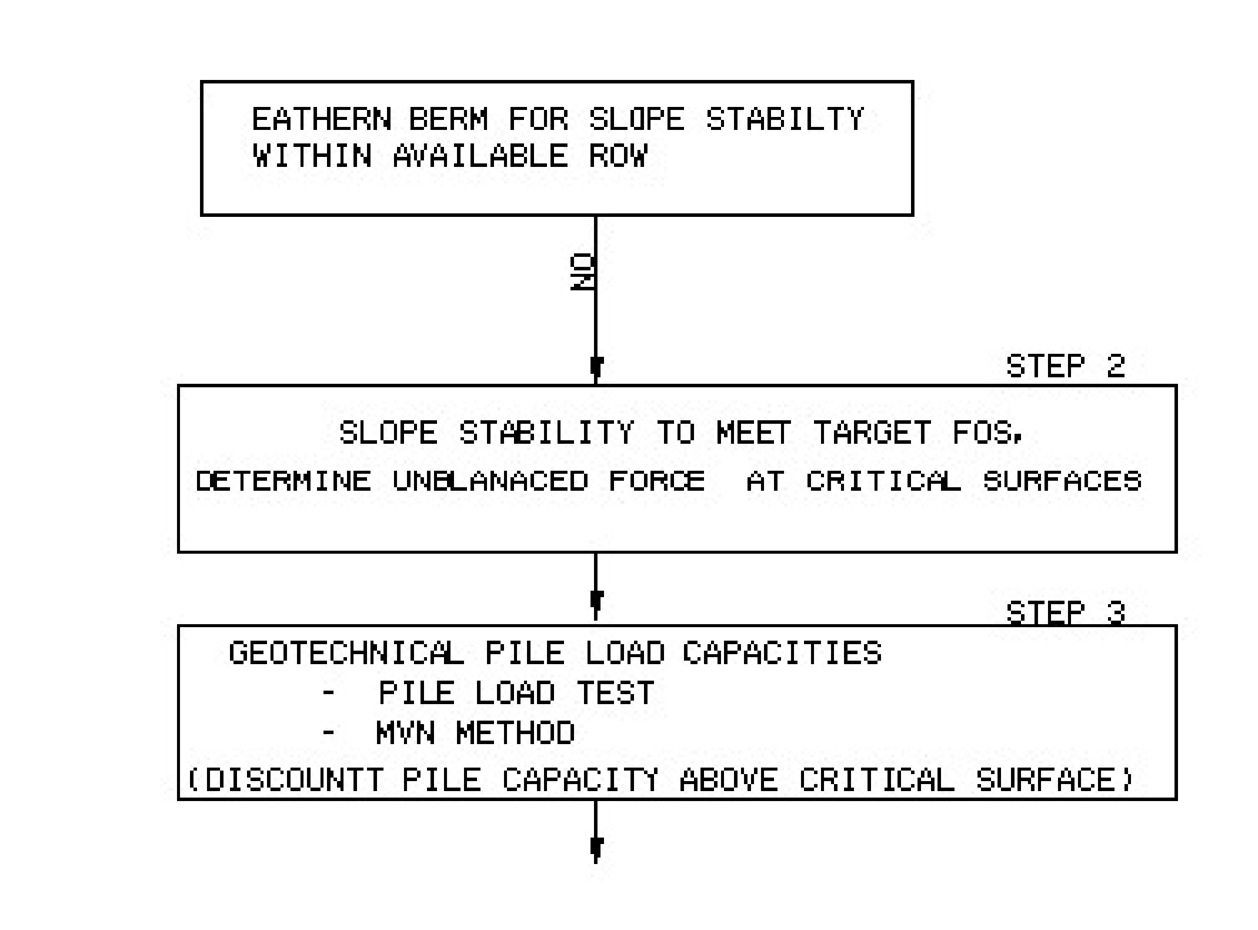
NEW METHODOLOGY
STEP 1



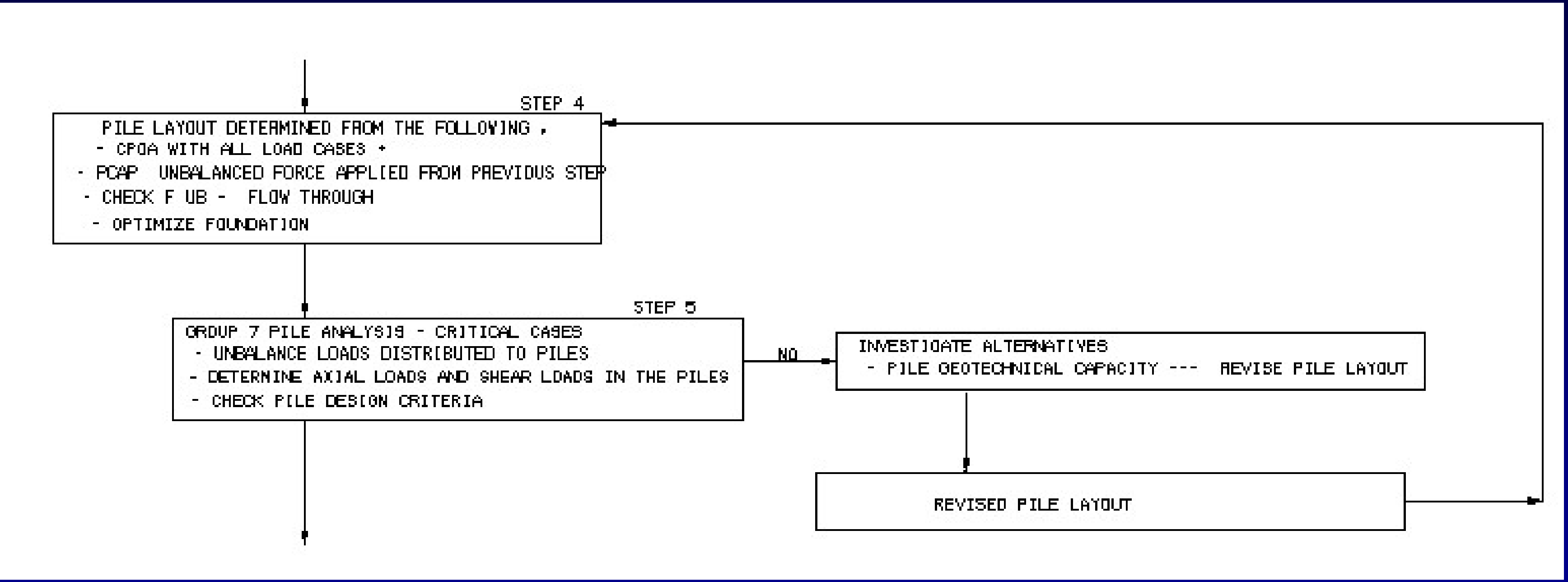
NEW METHODOLOGY STEP 1a



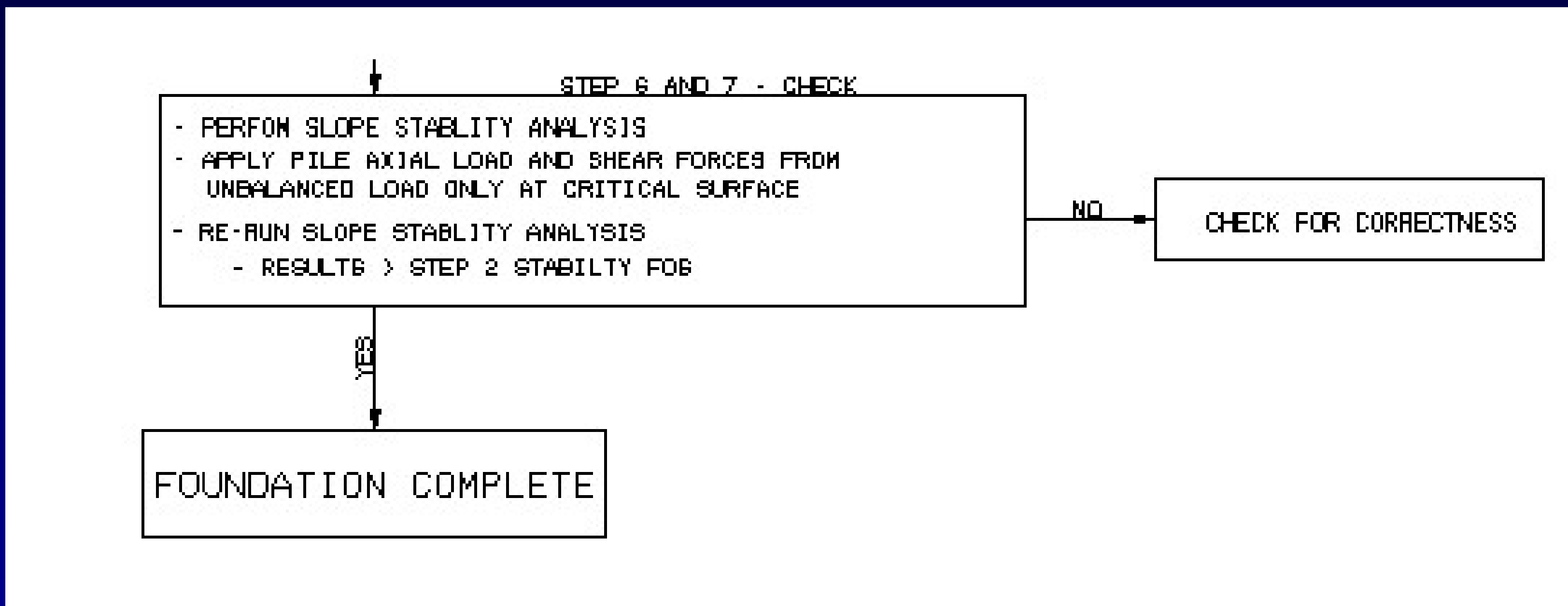
NEW METHODOLOGY
STEPS 2 & 3



NEW METHODOLOGY
STEPS 4 & 5



NEW METHODOLOGY
STEPS 6 & 7



NEW METHODOLOGY NOTES

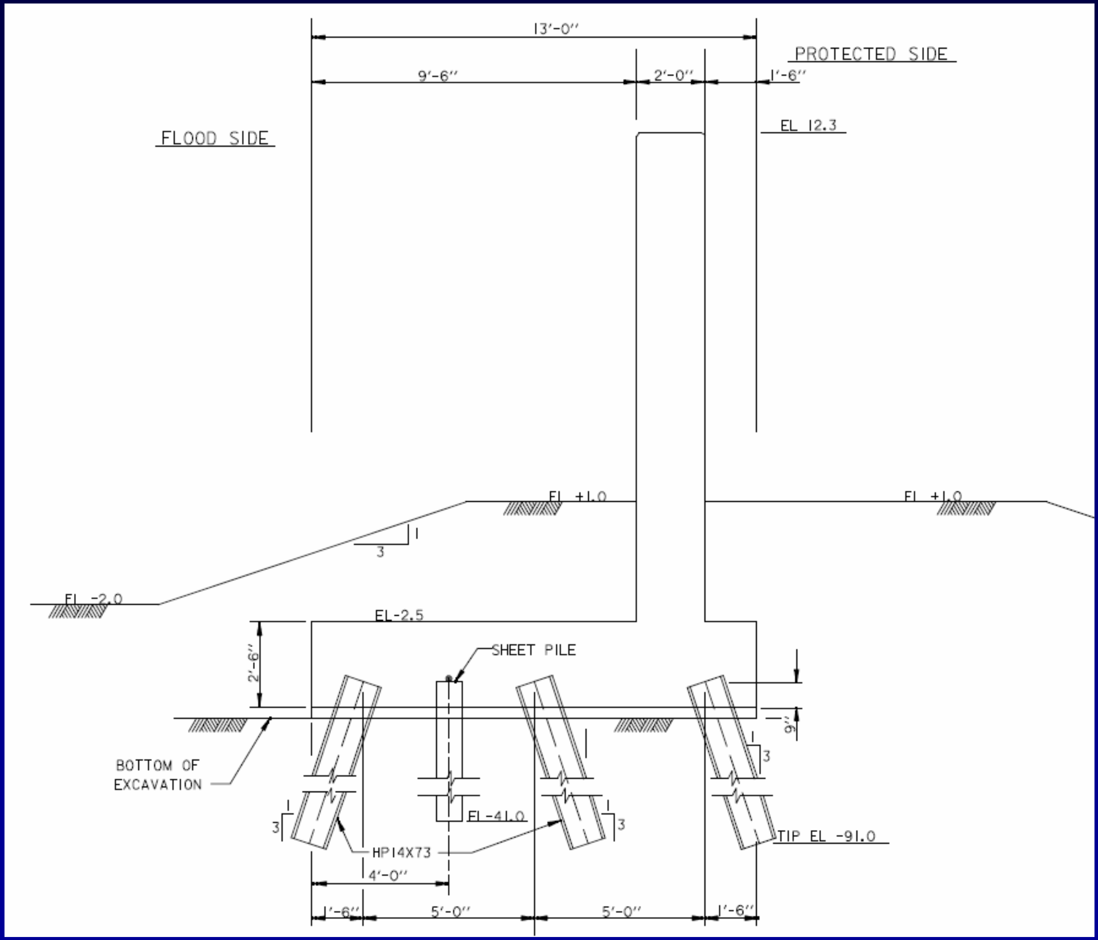
NOTES:

1. MVN - HURRICANE AND STORM DAMAGE RISK REDUCTION SYSTEM (HSDRRS) DESIGN GUIDELINES.
2. SPENCER'S ANALYSIS WILL BE USED FOR ALL SLOPE STABILITY DESIGN ANALYSIS.
3. MOP WILL ONLY BE USED FOR A DESIGN CHECK.
4. SHEET PILE - DESIGN FOR SEEPAGE, MINIMUM TIP BASED ON SOIL STRATUM.

Purpose

Step by Step Design Method

Example No. 1 with SWL = El. +10 ft (target FS = 1.5)



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Steps Overview

1. **Check Factor of Safety**
   - UTexas4 Spencer Search Methodology
   - UT4 Results for Example 1
   - Slope/W Methodology and Results for Example 1
2. **Find Unbalanced Load**
3. **Compute Pile Capacities**
4. **Preliminary Design with CPGA – check flow through**
5. **Group 7 Analysis of critical cases**
6. **Find Reinforcement Forces**
7. **Check Global FOS with Reinforcement**

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UTexas4 Search Methodology

1. Problem Definition – Program Input
2. Trial Failure Surfaces
3. Solution Convergence
4. Automatic Searches

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UTexas4 – Program Input

1. **UTexas4 vs. Earlier Versions**
   1. Property Interpolation
   2. Weight of Free Water
2. **T-Wall Design Input**
   1. Soil Layers and Properties
   2. Piezometric Surface & Water Load (Unit Weight H_2O)
   3. Weight of Wall & Forces on Wall
3. **Analysis/Computation**
   1. Procedure (Spencer = Default)
   2. Trial Surface & Automatic Search Criteria

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UTexas4 – Trial Surfaces

1. **Circular Surface**
    1. Initial Trial Center & Radius
    2. Tangent, Radius & Point Modes
    3. "Stop" Command
2. **Non-Circular Surface**
    1. Initial 4-Point "Wedge" Surface (MOP = Guide)
    2. 0.7H Base Length Constraint (the 5th-Point)

UTexas4 - Solution Convergence

1. **A Unique Solution ?**
2. **Convergence Criteria**
   1. Force Imbalance
   2. Moment Imbalance
3. **What to Look For**
   1. Cautions and Warnings
   2. Sense of Inclination
   3. Number of Iterations and Convergence Trends
4. **Troubleshooting Suggestions**
   1. Work Near Origin (Moments are taken about 0,0)
   2. Trial FS > Expected FS (Default is 3.0)
   3. Reduce Trial Inclination (Default is 15 degrees)

UTexas4 - Automatic Searches

1. **Local vs. Global Min. FS**
2. **Local vs. Global Max. Unbalanced Load**
3. **Circular Search**
    1. Floating and Fixed Grid
4. **Non-Circular Search**
    1. Degree of Freedom (No. of Points and Shift Direction)
    2. Shift Distance
    3. Coarse to Fine - Recycling and Refining Output as Input
5. **Results**
    1. Non-Circular Typically More Critical than Circular
    2. FS Usually Decreases as No. Points Increases and Shift Distance Decreases
    3. Several Successive Runs are Required (Single-Stage)

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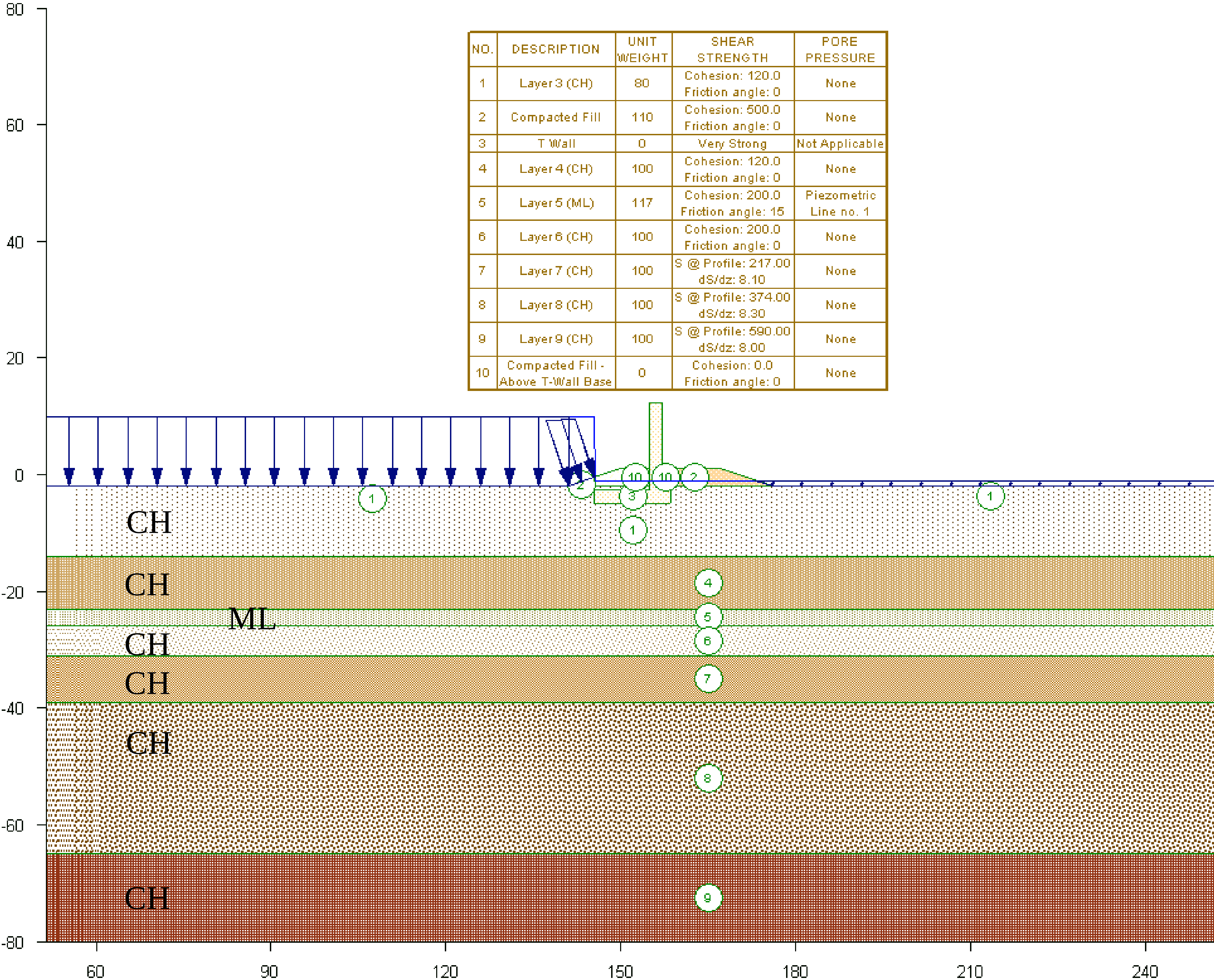
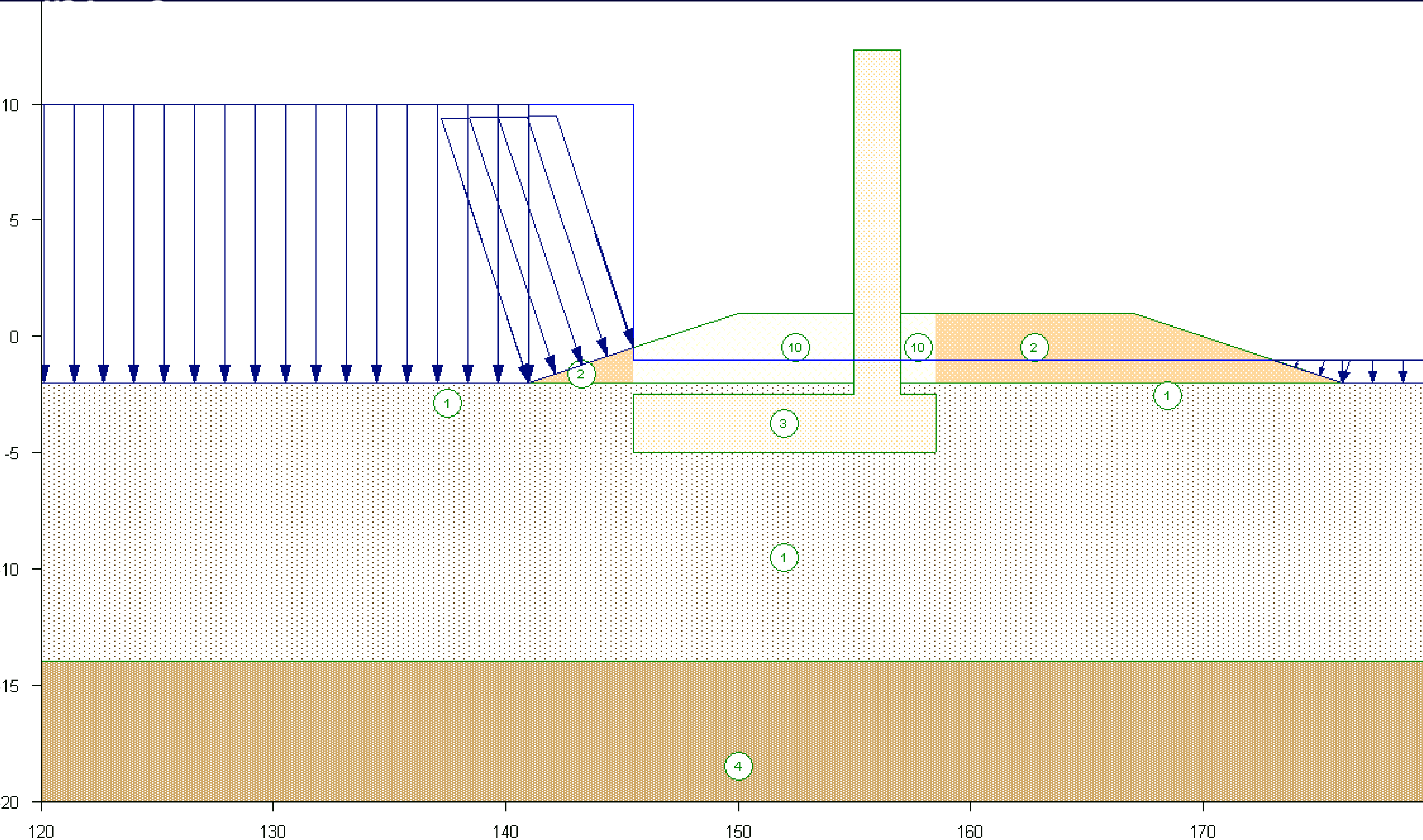
Steps 1 and 2 - UT4 Results

1. Spencer Procedure Model (UTexas4 or Slope/W)
2. Starting wall configuration
3. Establish stratigraphy and soil properties
4. Find failure surfaces that correspond to Lowest FS and Highest Unbalanced Load by evaluating several tangent elevations



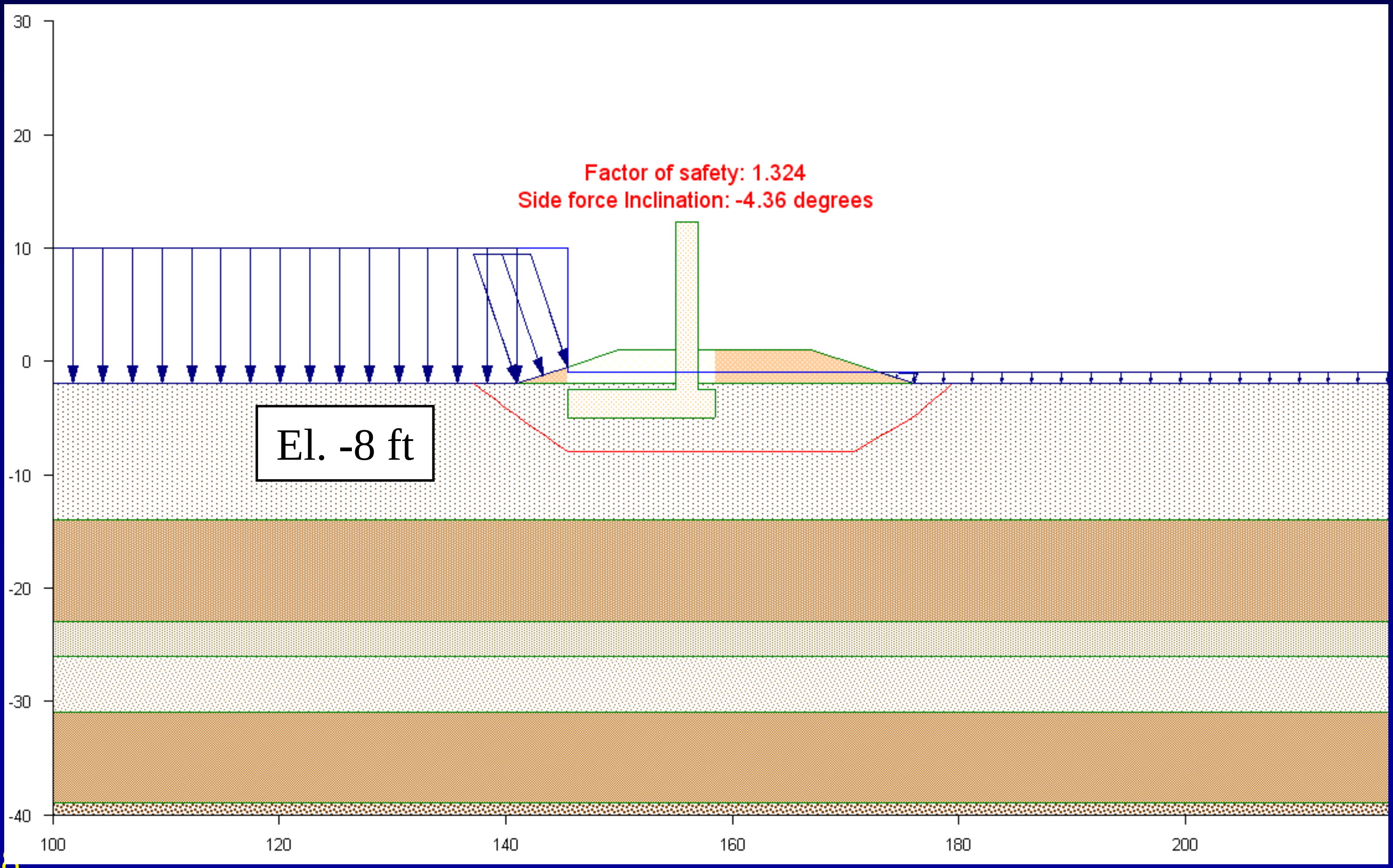
NO.	DESCRIPTION	UNIT WEIGHT	SHEAR STRENGTH	PORE PRESSURE
1	Layer 3 (CH)	80	Cohesion: 120.0 Friction angle: 0	None
2	Compacted Fill	110	Cohesion: 500.0 Friction angle: 0	None
3	T Wall	0	Very Strong	Not Applicable
4	Layer 4 (CH)	100	Cohesion: 120.0 Friction angle: 0	None
5	Layer 5 (ML)	117	Cohesion: 200.0 Friction angle: 15	Piezometric Line no. 1
6	Layer 6 (CH)	100	Cohesion: 200.0 Friction angle: 0	None
7	Layer 7 (CH)	100	S @ Profile: 217.00 dS/dz: 8.10	None
8	Layer 8 (CH)	100	S @ Profile: 374.00 dS/dz: 8.30	None
9	Layer 9 (CH)	100	S @ Profile: 590.00 dS/dz: 8.00	None
10	Compacted Fill - Above T-Wall Base	0	Cohesion: 0.0 Friction angle: 0	None



10
5
0
-5
-10
-15
-20
120
130
140
150
160
170
1
2
3
4
10

Step 1 (tangent elev. at -8 ft)

Check Global FOS using Spencer's Method



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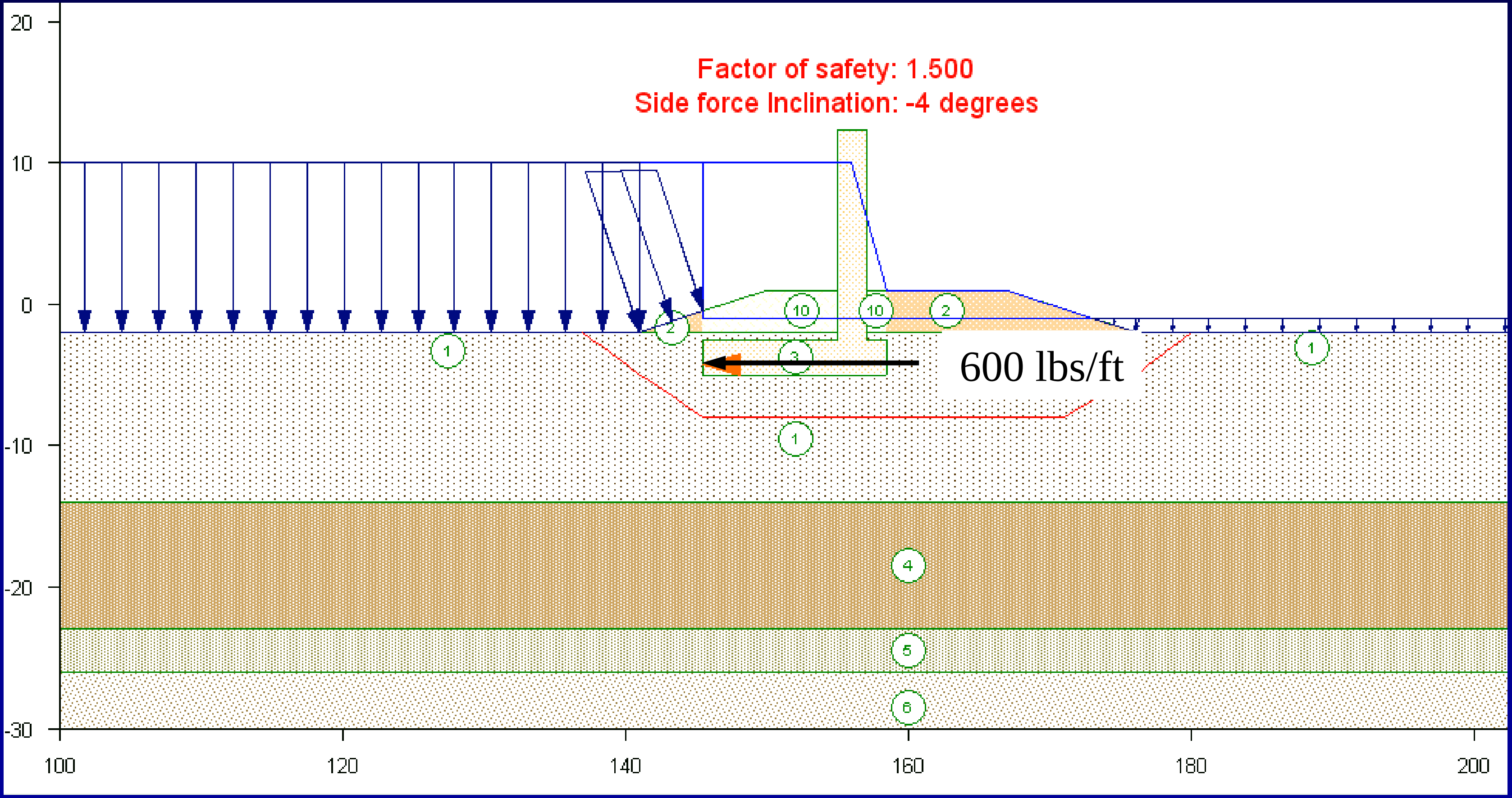
Step 2.1

- Search for highest unbalanced load
- Surface Defined as non-circular
  - Min of 0.7 H or Base Width
- Force located half way from ground surface at heel to elevation of critical failure surface
- Two cases SWL and TOW (only SWL shown)

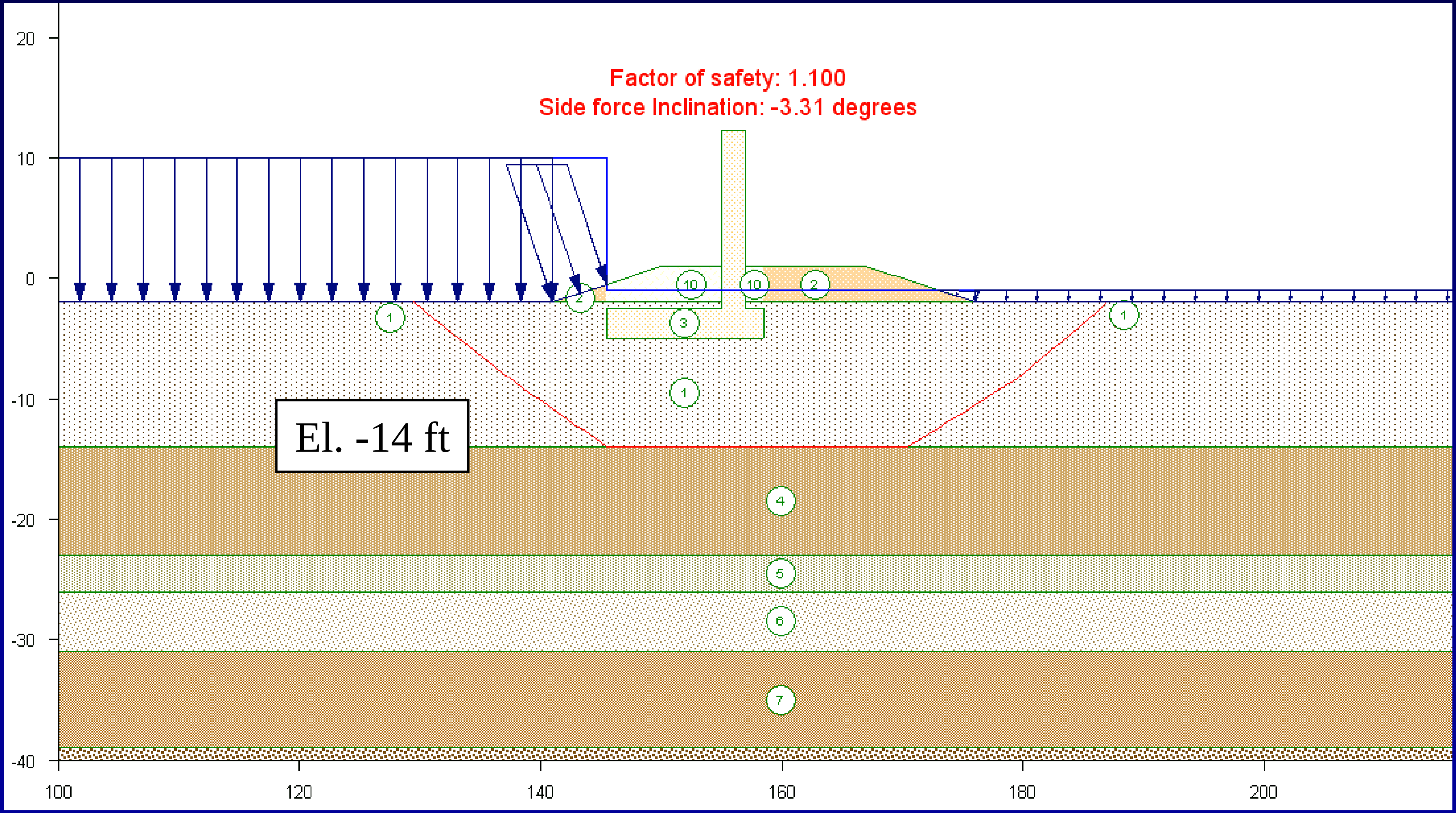
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



Step 1 (tangent elev. at -14 ft)

Check Global FOS using Spencer's Method



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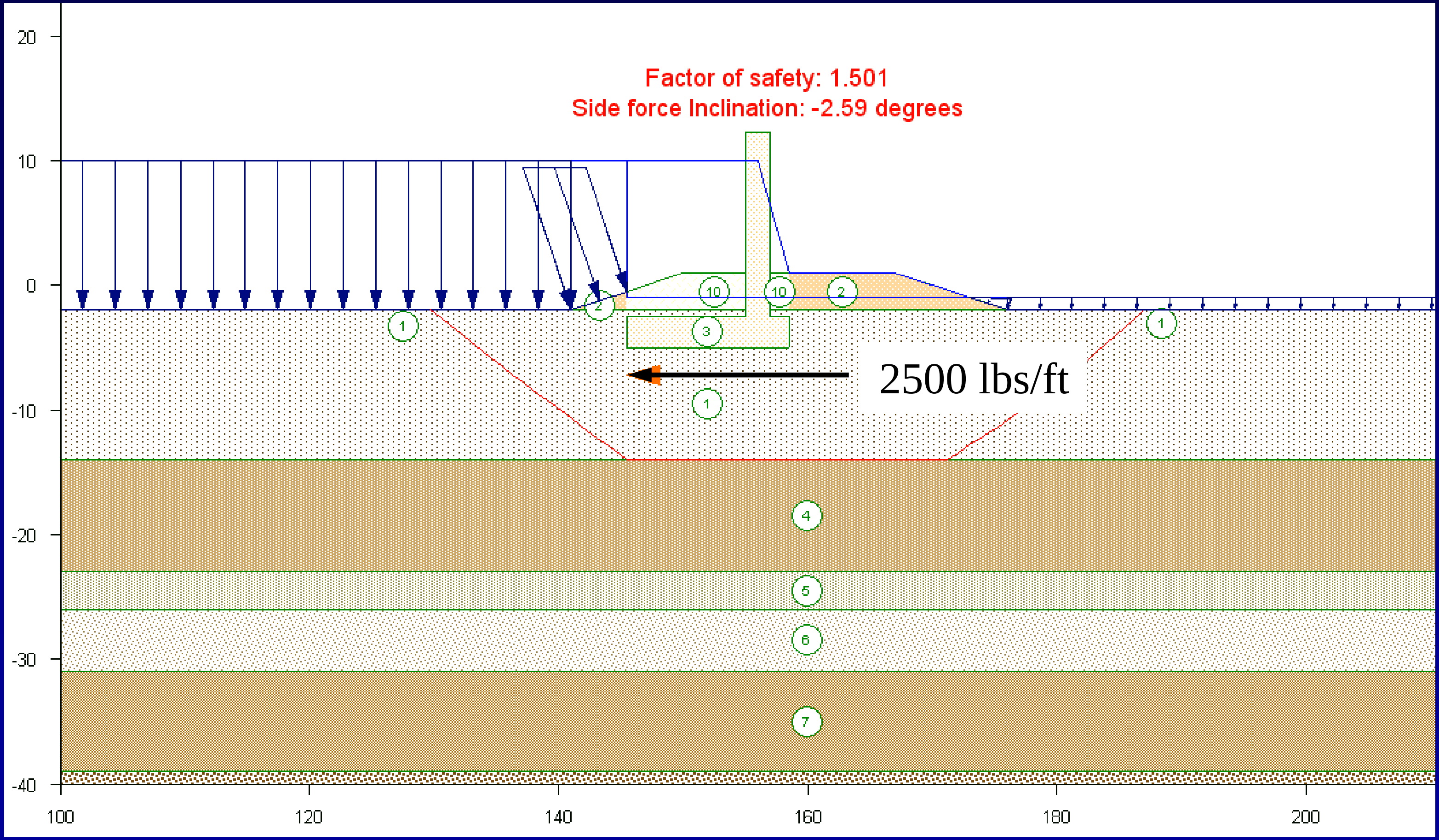
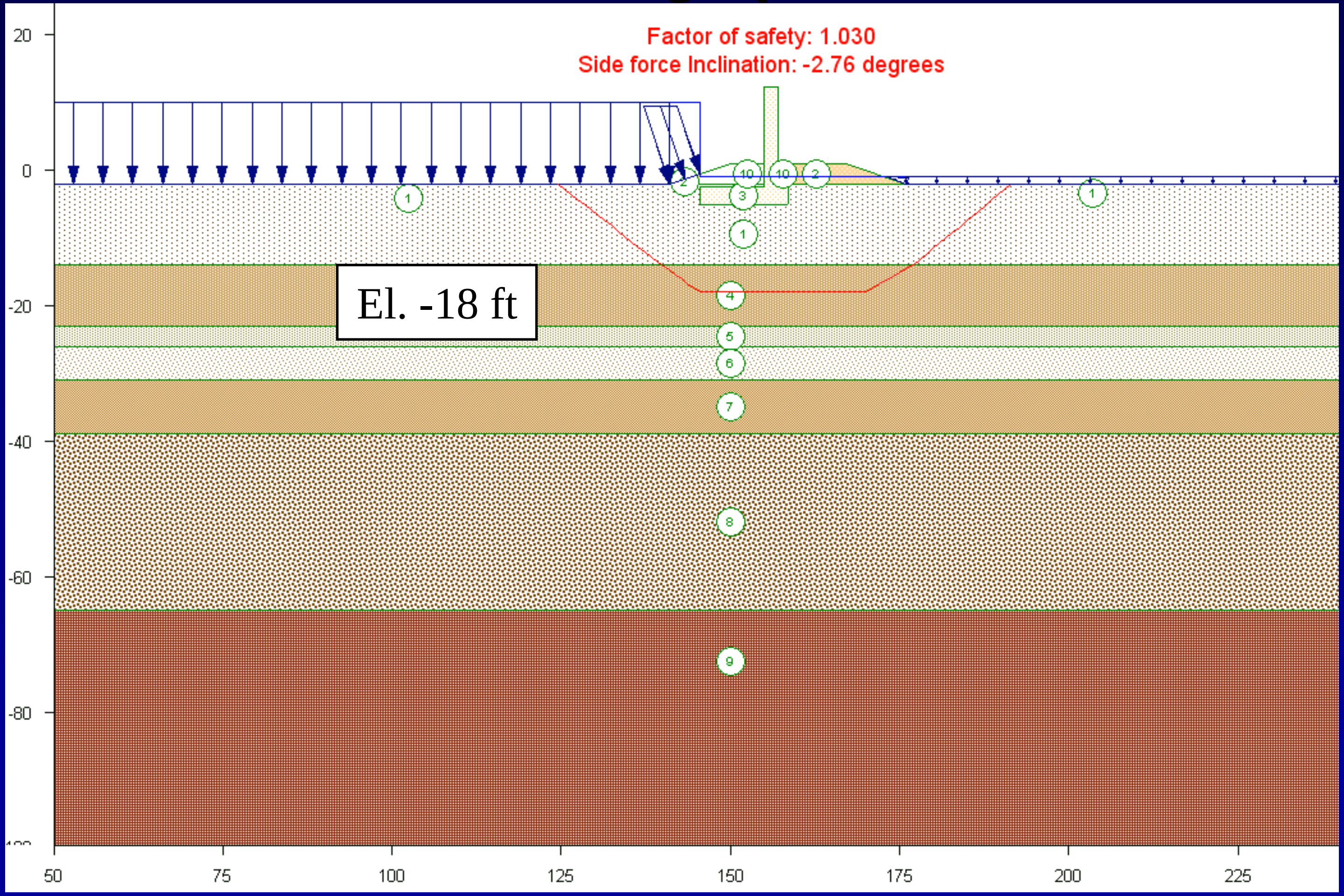
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



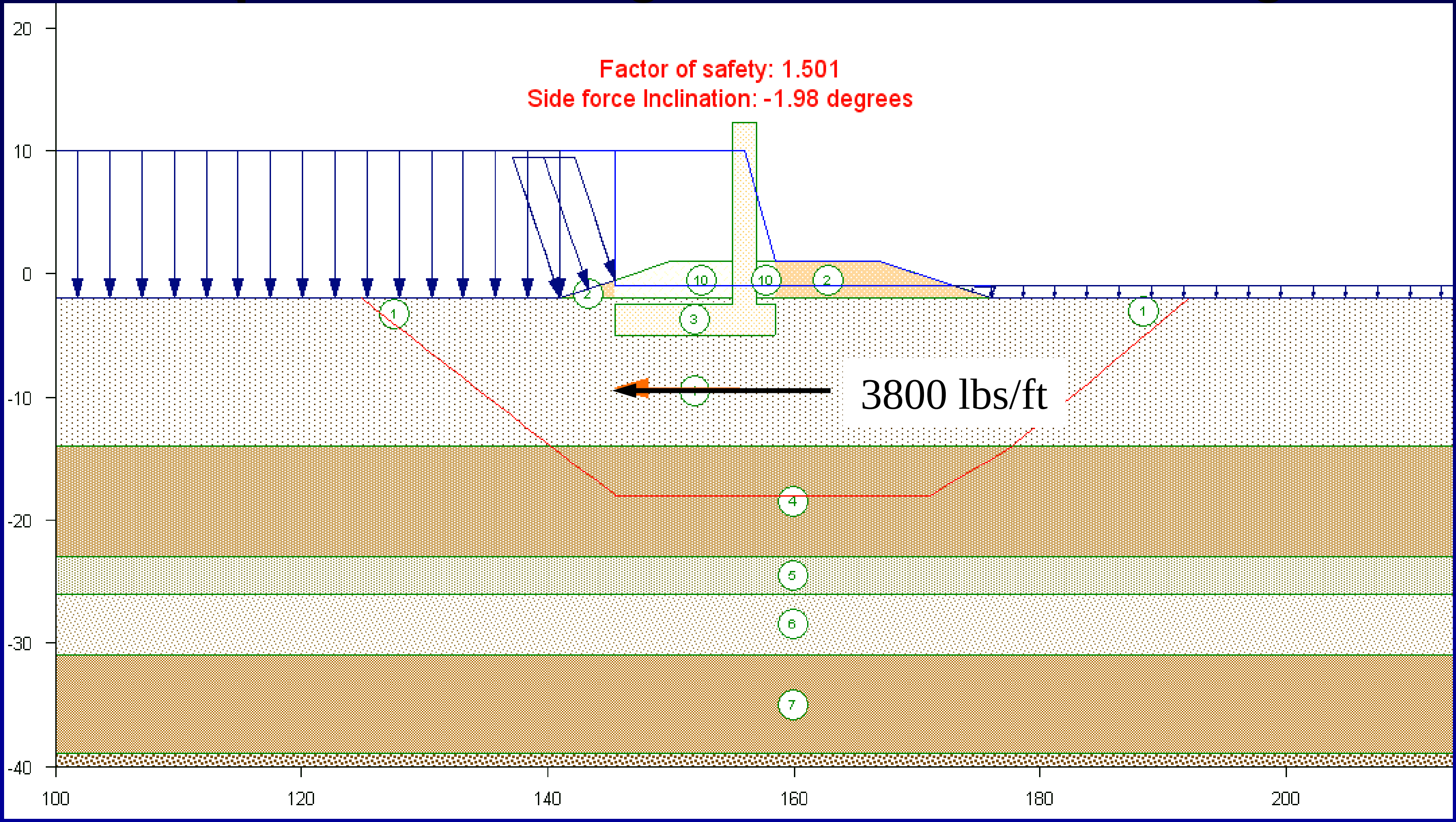
Step 1 (tangent elev. at -18 ft)

Check Global FOS using Spencer's Method



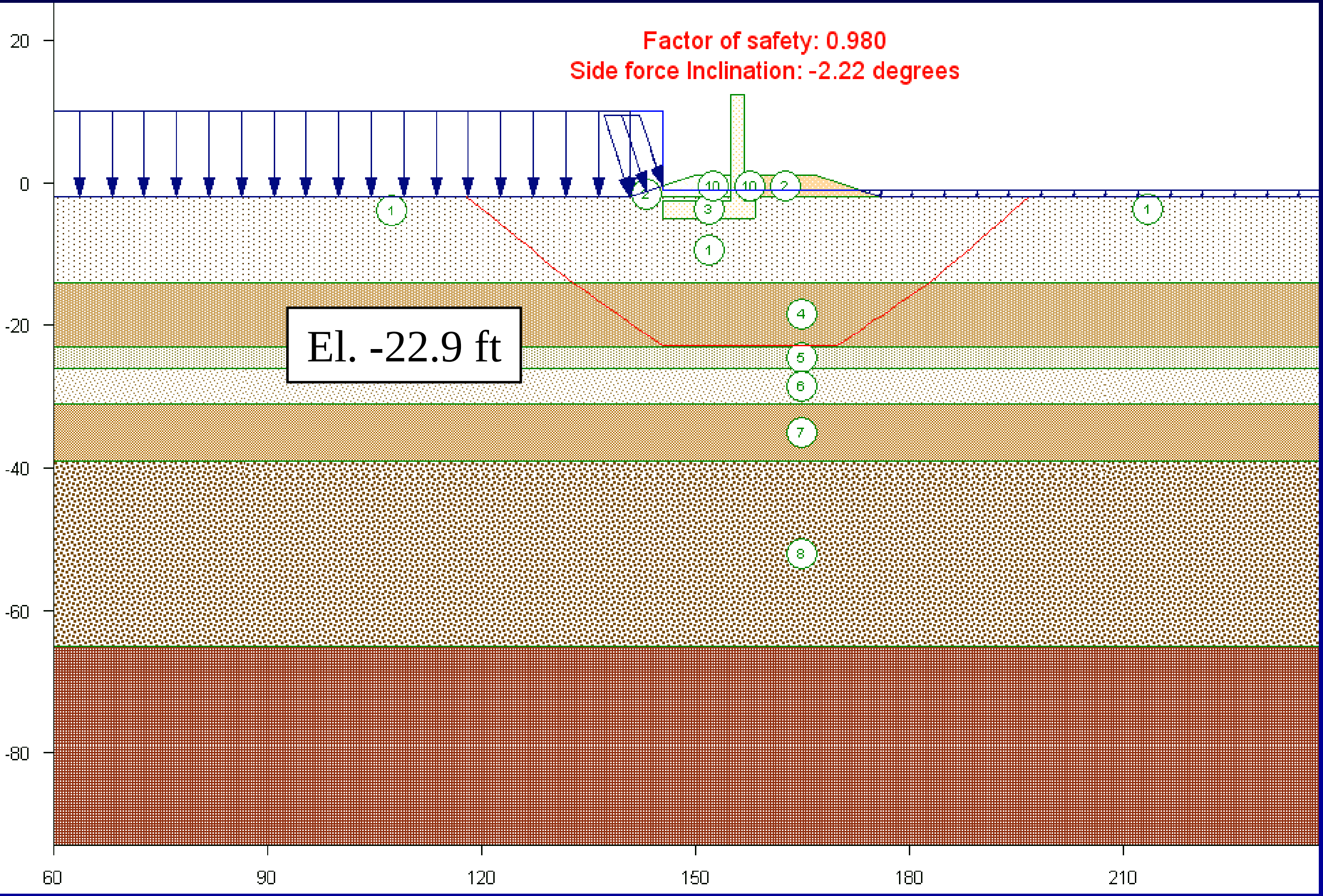
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



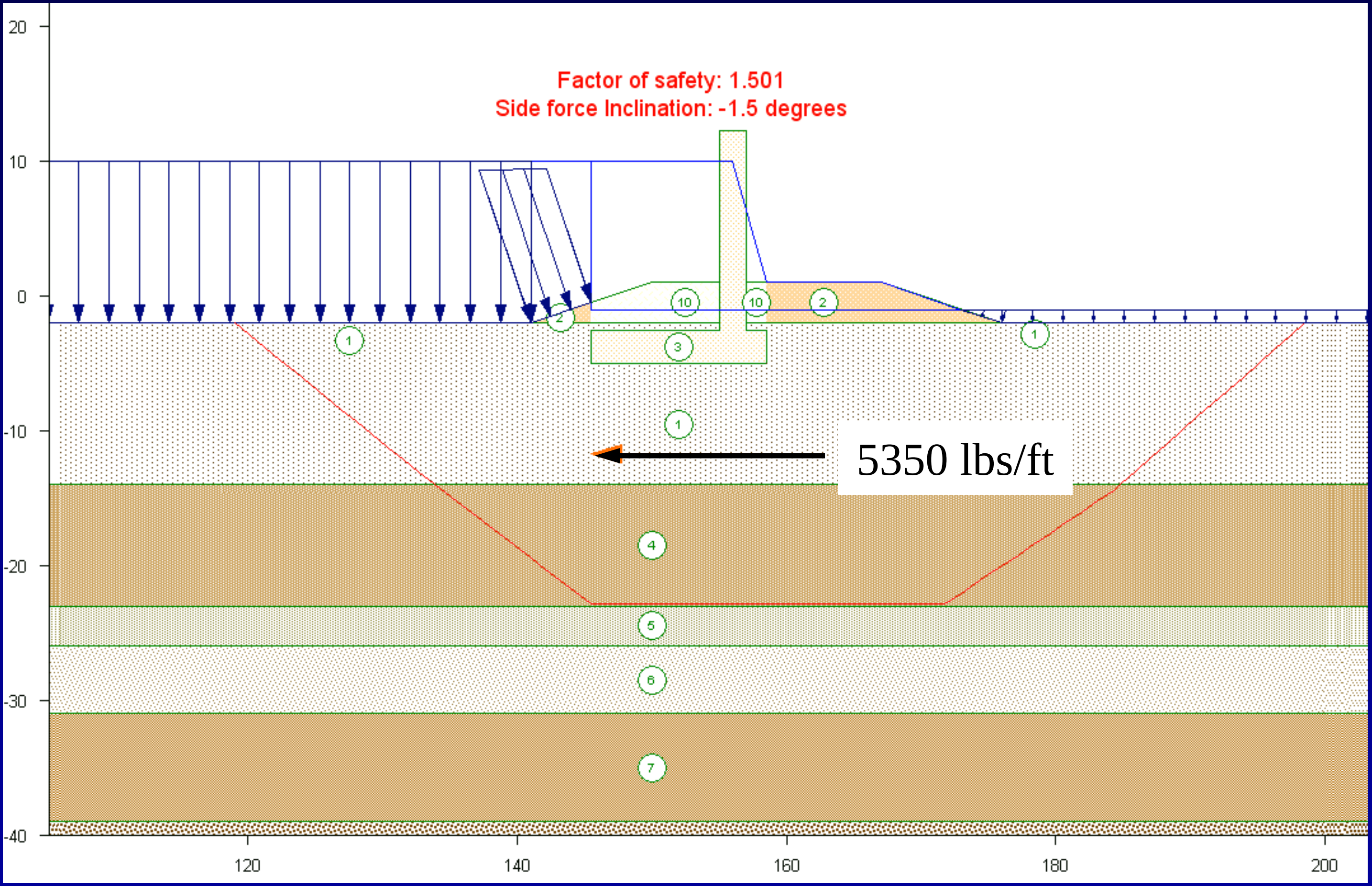
Step 1 (tangent elev. at -22.9 ft)

Check Global FOS using Spencer's Method



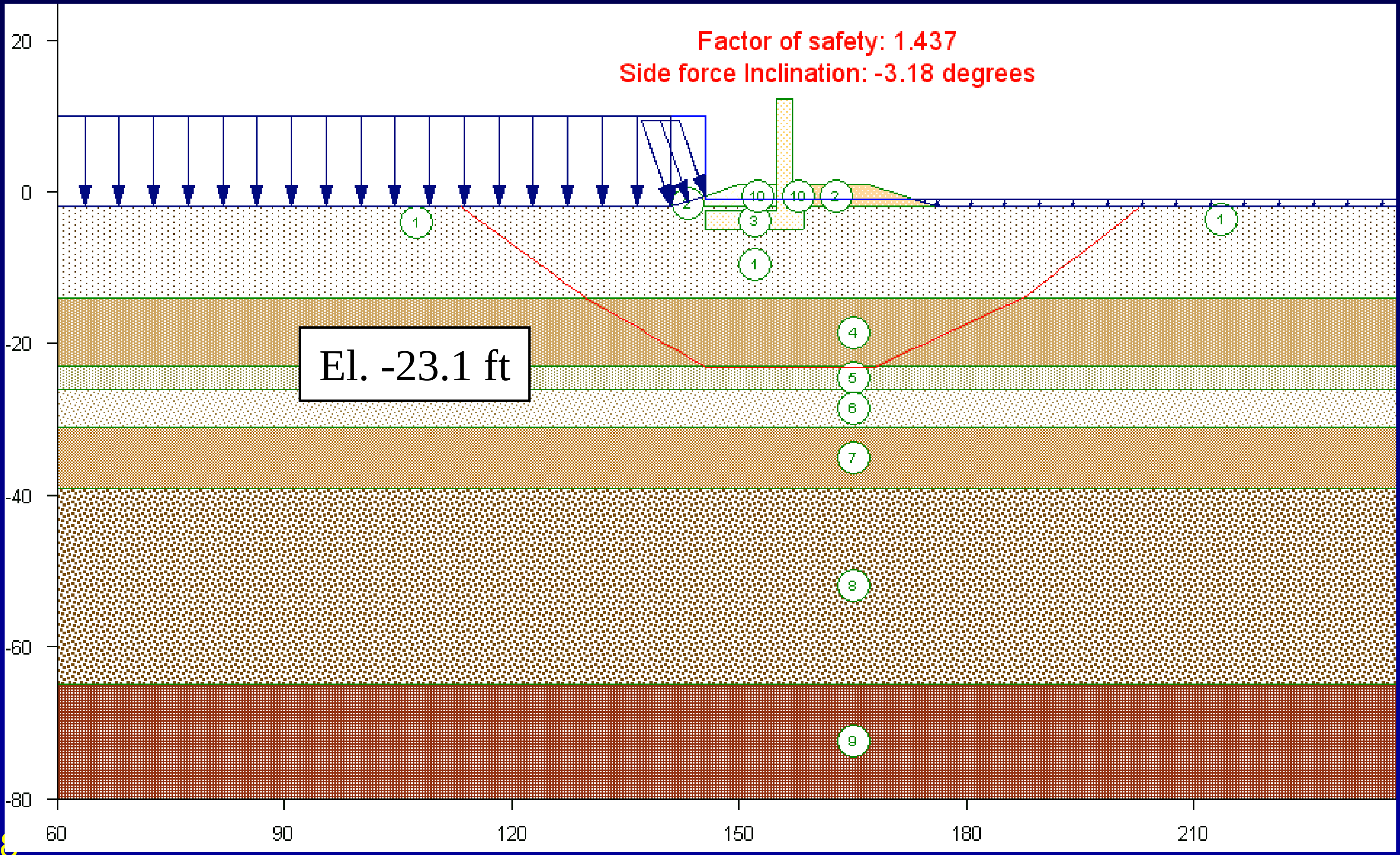
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



Step 1 (tangent elev. at -23.1 ft)

Check Global FOS using Spencer's Method



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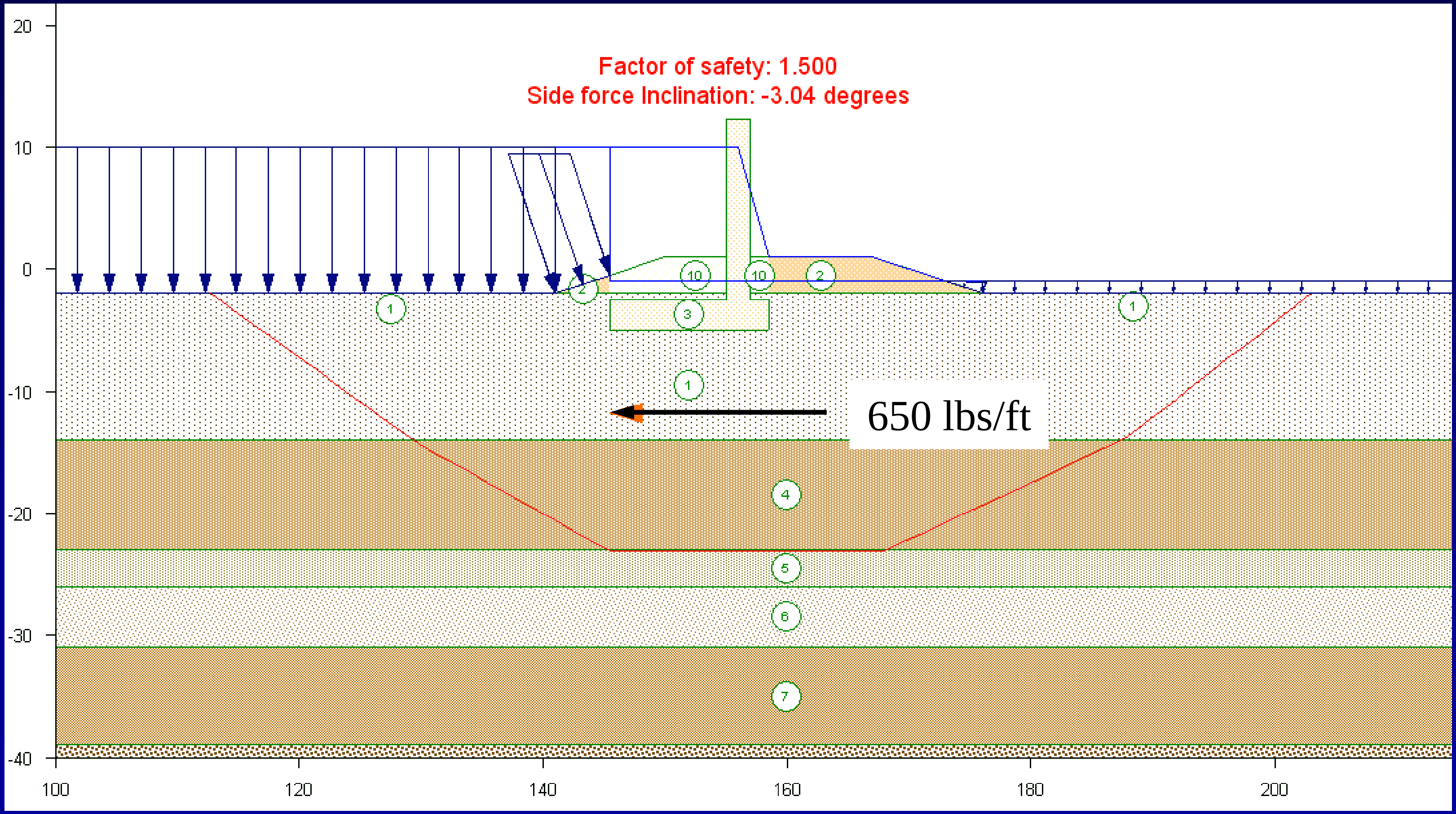
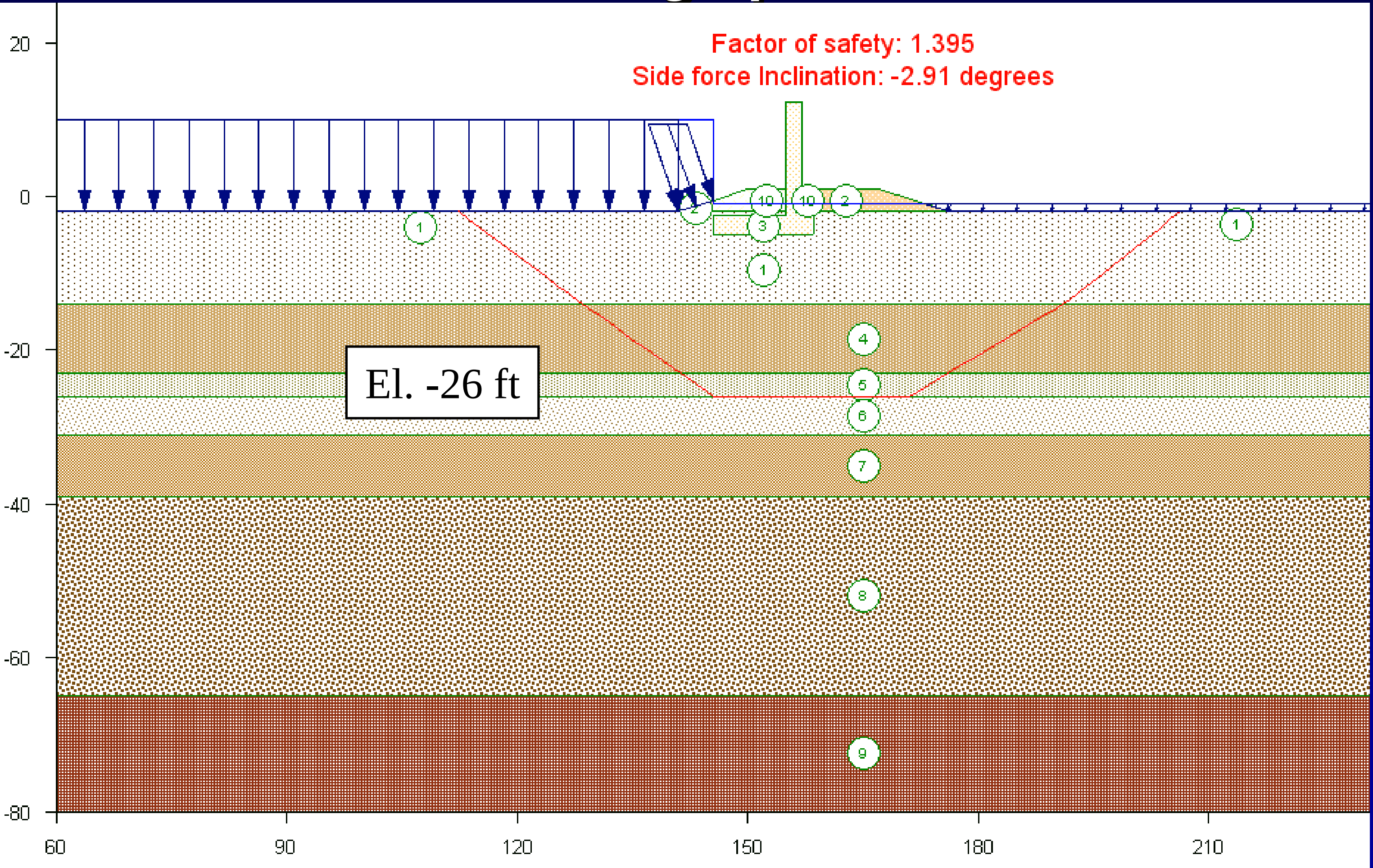
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



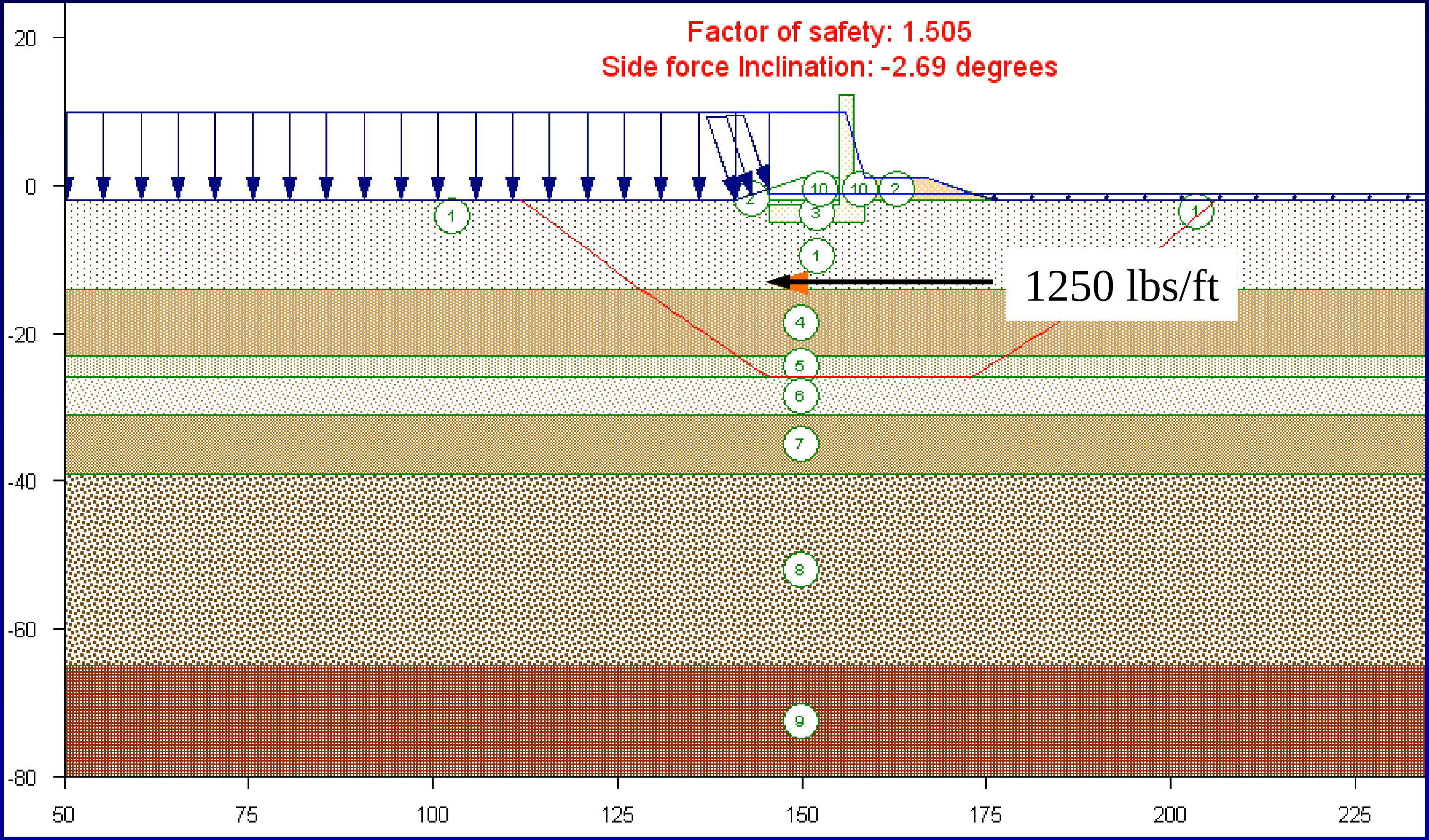
Step 1 (tangent elev. at -26 ft)

Check Global FOS using Spencer's Method



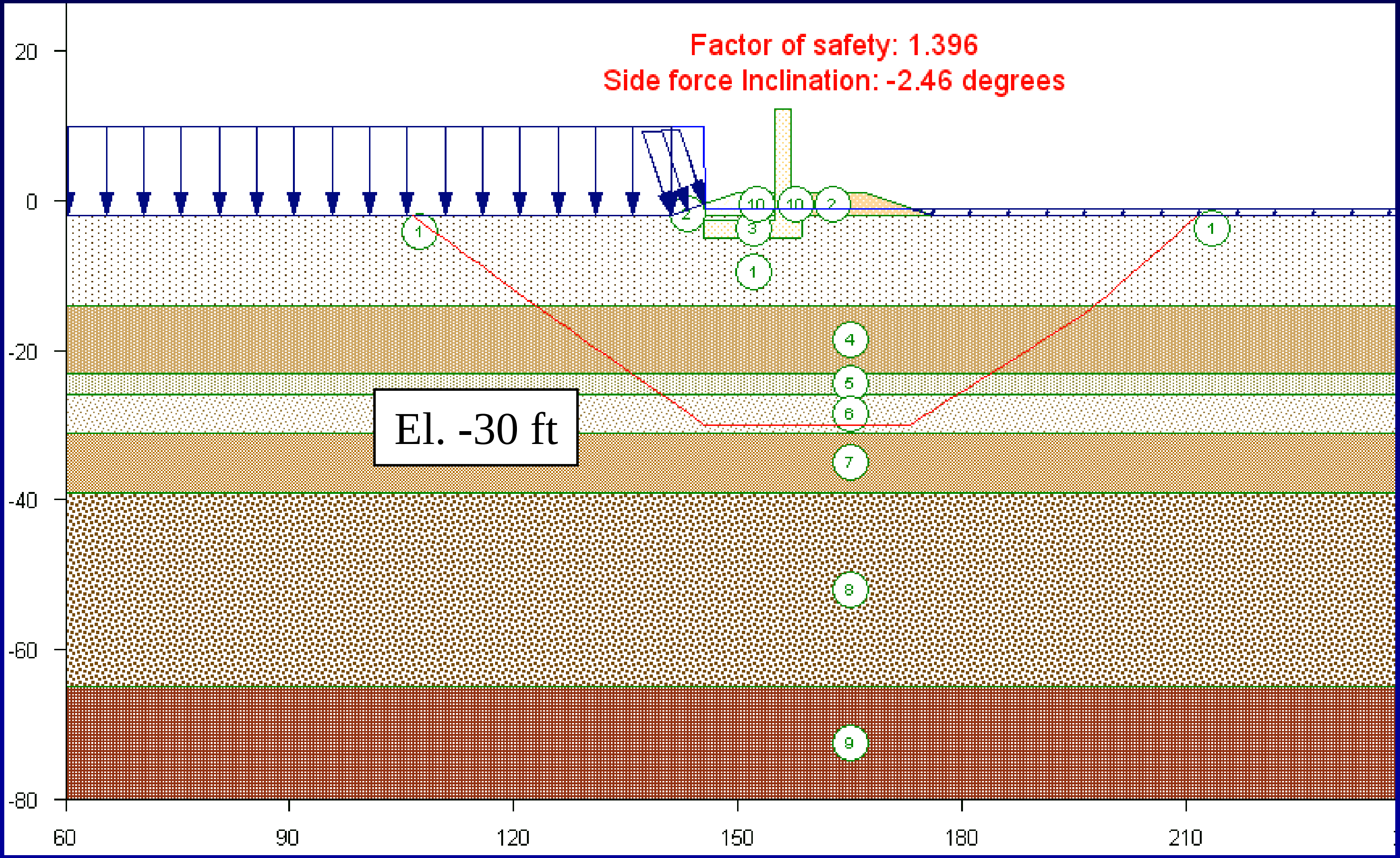
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



Step 1 (tangent elev. at -30 ft)

Check Global FOS using Spencer's Method



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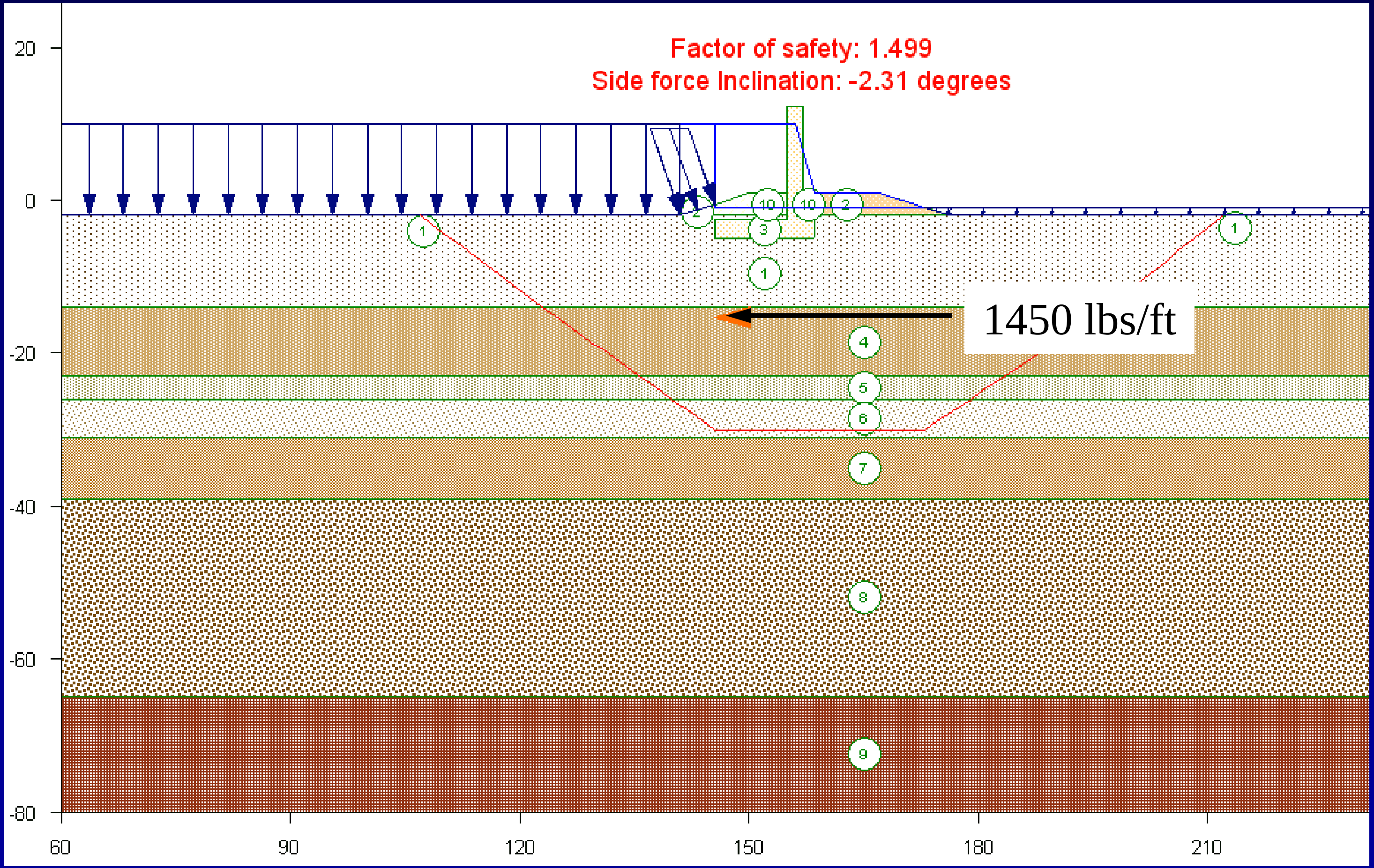
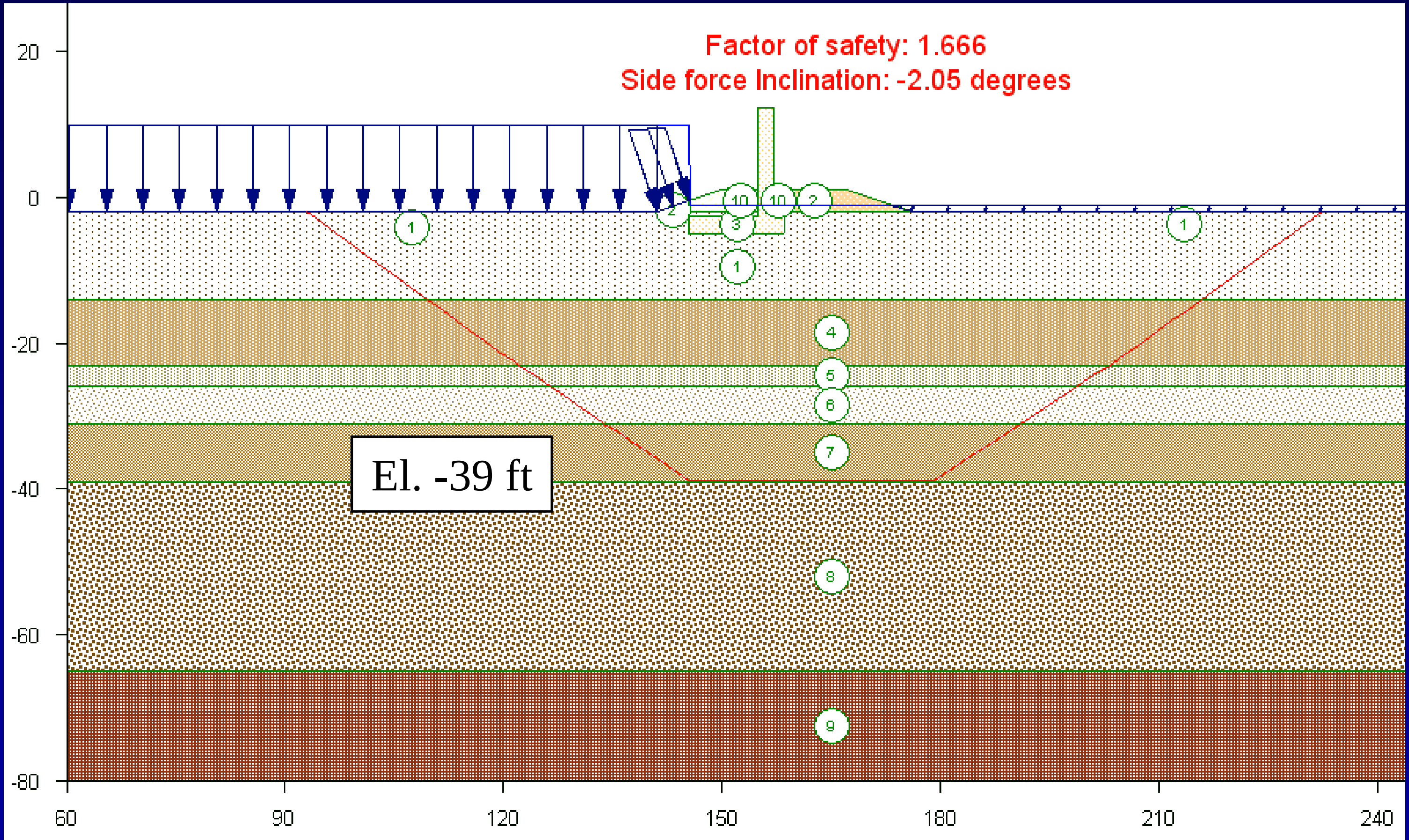
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



Step 1 (tangent elev. at -39 ft)

Check Global FOS using Spencer's Method



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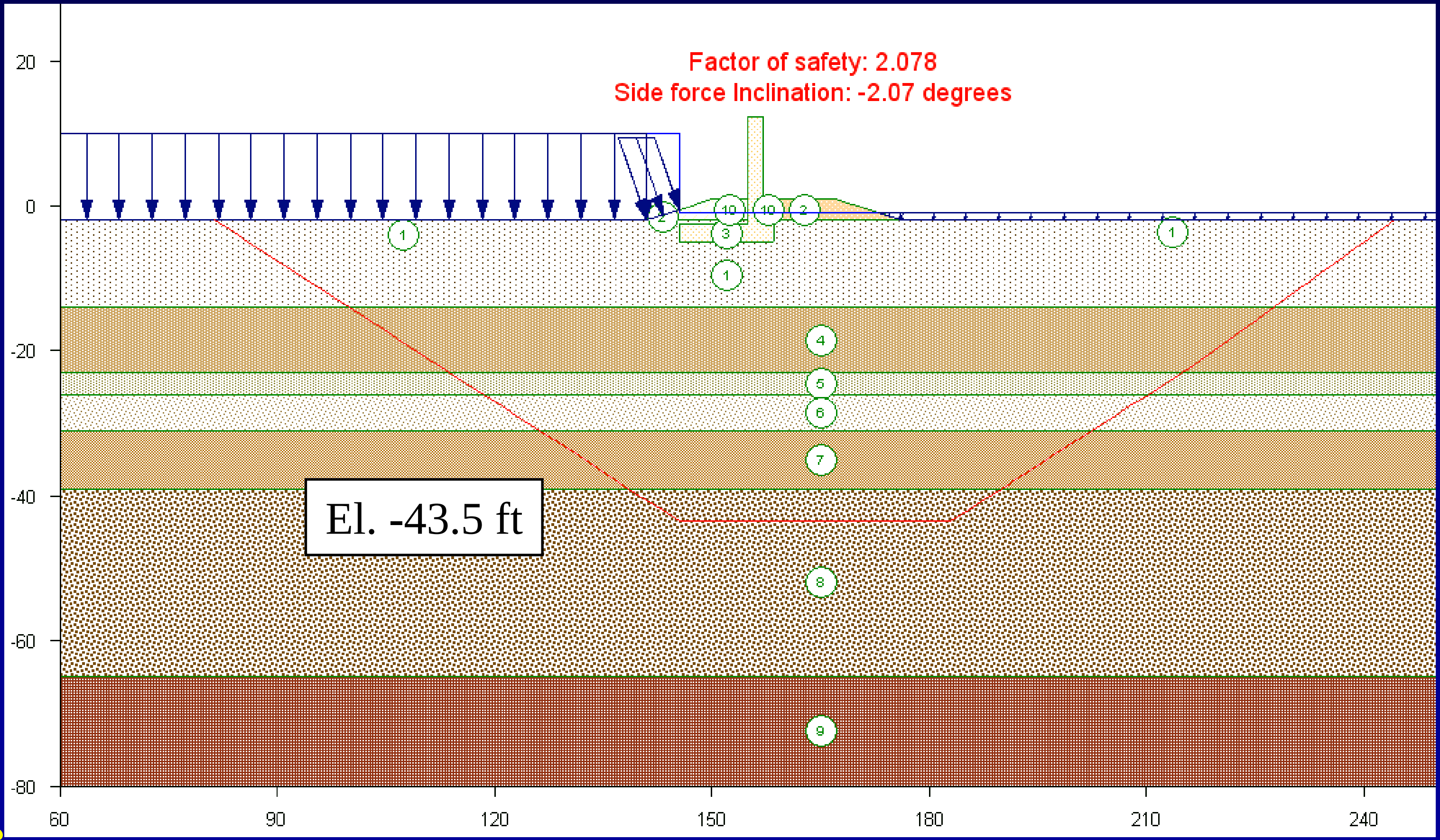
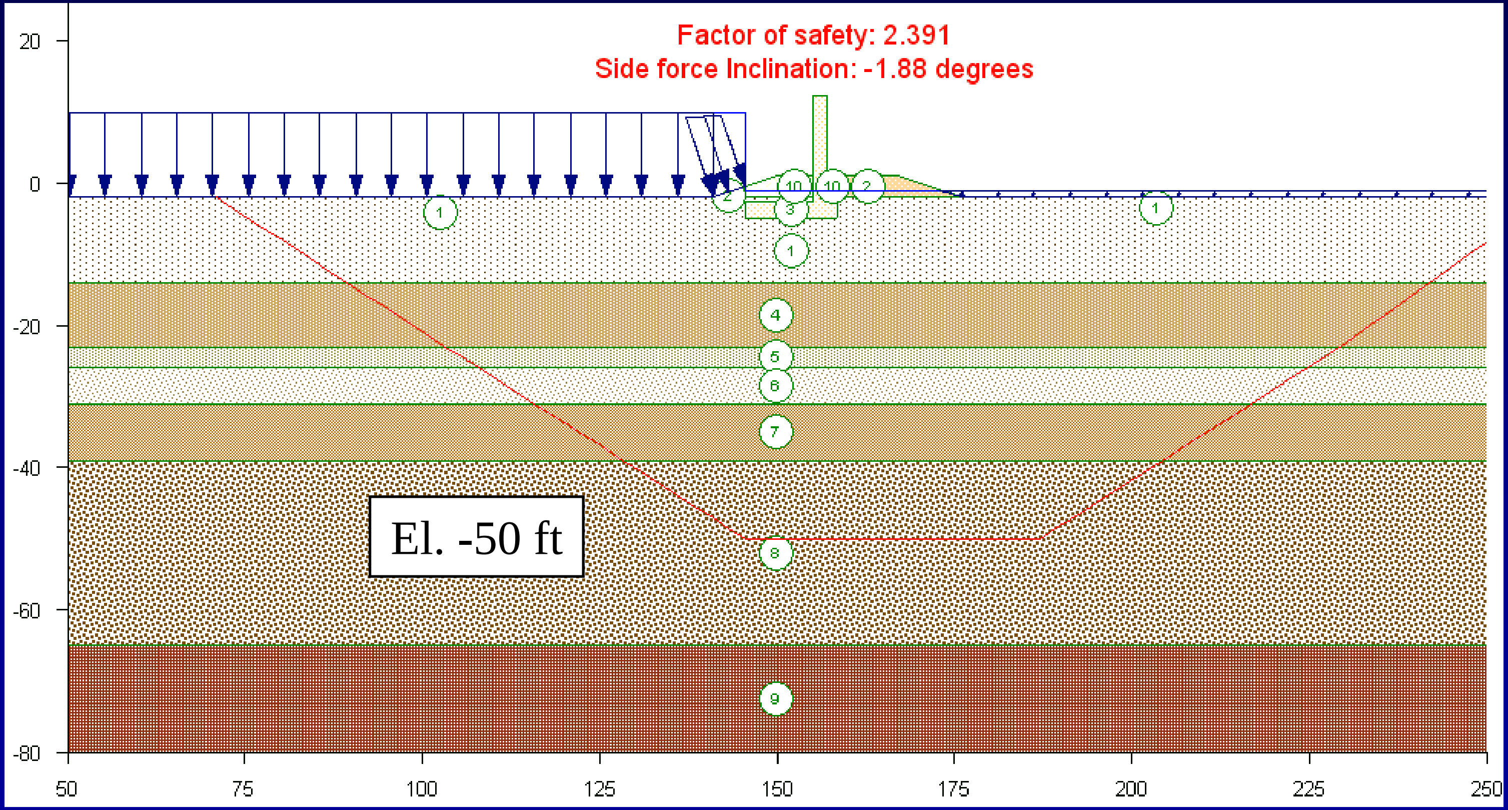
Step 1 (tangent elev. at -43.5 ft)

Check Global FOS using Spencer's Method



Step 1 (tangent elev. at -50 ft)

Check Global FOS using Spencer's Method



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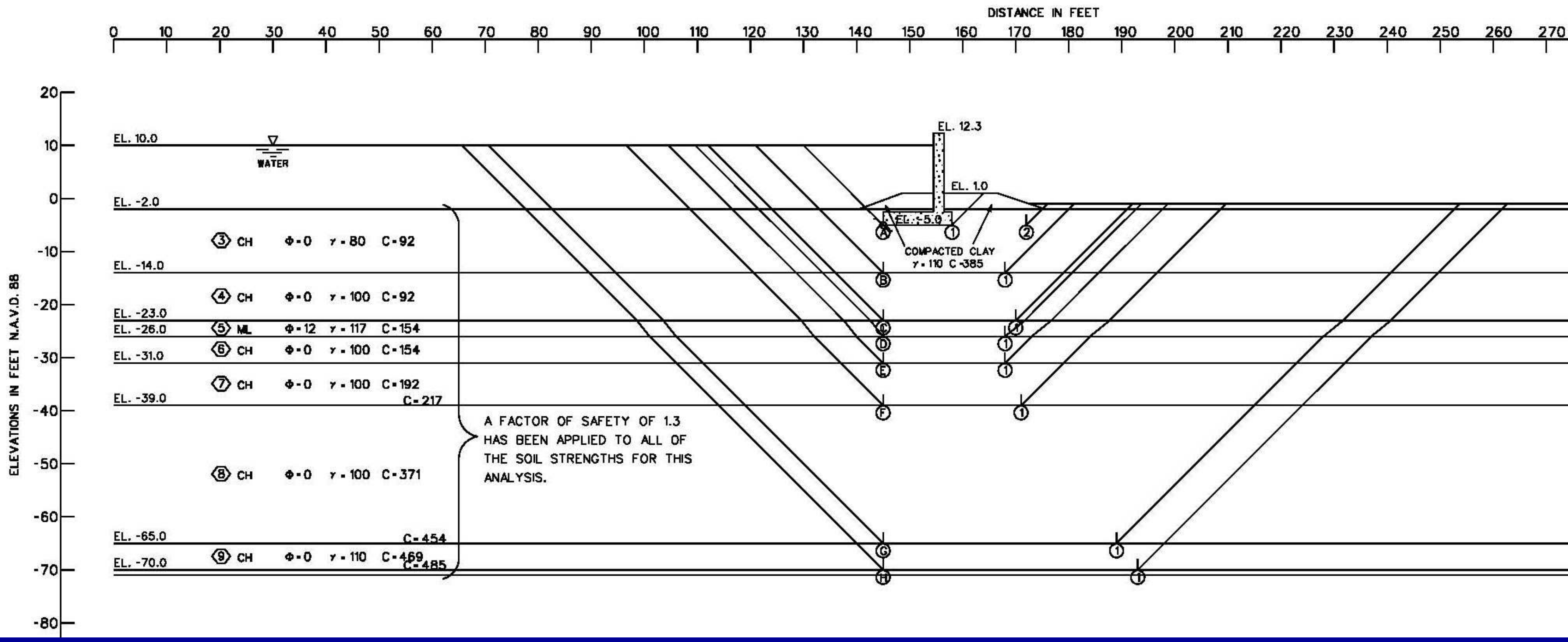
Step 2.2 Summary of Results

Neutral Block Tangent EL (ft)	Factor of Safety	Unbalanced Load (lbs/ft)
-8	1.32	600
-14	1.10	2500
-18	1.03	3800
-22.9	**0.98**	**5350**
-23.1	1.44	650
-26	1.40	1250
-30	1.40	1450
-39	1.67	-
-43.5	2.08	-
-50	2.31	-

Step 2.2

Check Failure Surfaces with MOP



Step 2.2

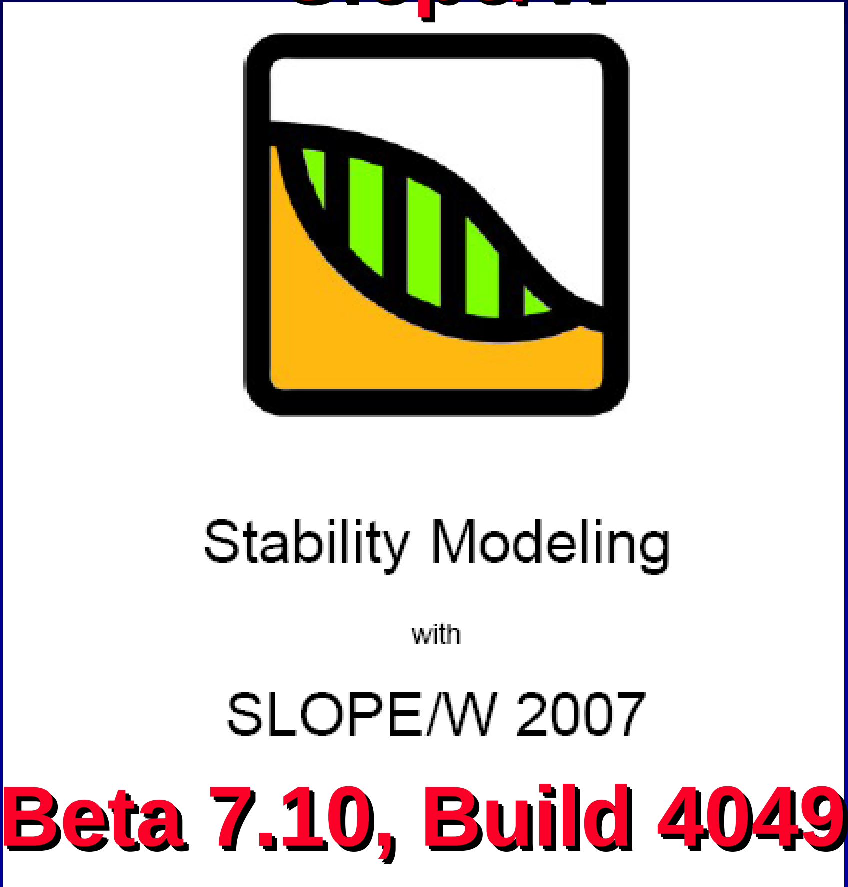
Check Failure Surfaces with MOP

Assumed Failure Surface			Resisting Forces			Driving Forces		Summation of Forces		Factor of Safety	$D_A - \Sigma R$	Free Water	Unbalanced Load
No.		Elev.	R_A	R_B	R_P	D_A	$-D_P$	Resisting	Driving				
Ⓐ	①	-5.0	858	0	2860	7057	1767	3718	5270	0.71	1552	4205	-2653
Ⓐ	②	-5.0	858	1288	648	7057	677	2794	6380	0.44	3586	4180	-594
Ⓑ	①	-14.0	2210	2116	2208	19222	7196	6534	12026	0.54	5492	4469	1023
Ⓒ	①	-23.0	3866	2300	3864	38662	20097	10030	18565	0.54	8535	4469	4066
Ⓓ	①	-26.0	5239	3542	6137	47001	26640	14918	20361	0.73	5443	4469	974
Ⓔ	①	-31.0	6804	3542	7557	63075	39350	17903	23725	0.75	5822	4469	1353
Ⓕ	①	-39.0	9876	5642	10608	93962	64275	26126	29687	0.88	3561	4469	-908
Ⓖ	①	-65.0	29167	19976	29900	238548	190798	79043	47750	1.66	-31293	4469	-35762
Ⓗ	①	-70.0	33857	23280	34590	274227	223039	91727	51188	1.79	-40539	4469	-45008

$D_A - \Sigma R = D_A - (R_A + R_B + R_P + D_P)$

Steps 1 & 2 Spencer's Analysis

Spencer's Procedure for T-Walls using Slope/W



Beta 7.10, Build 4049

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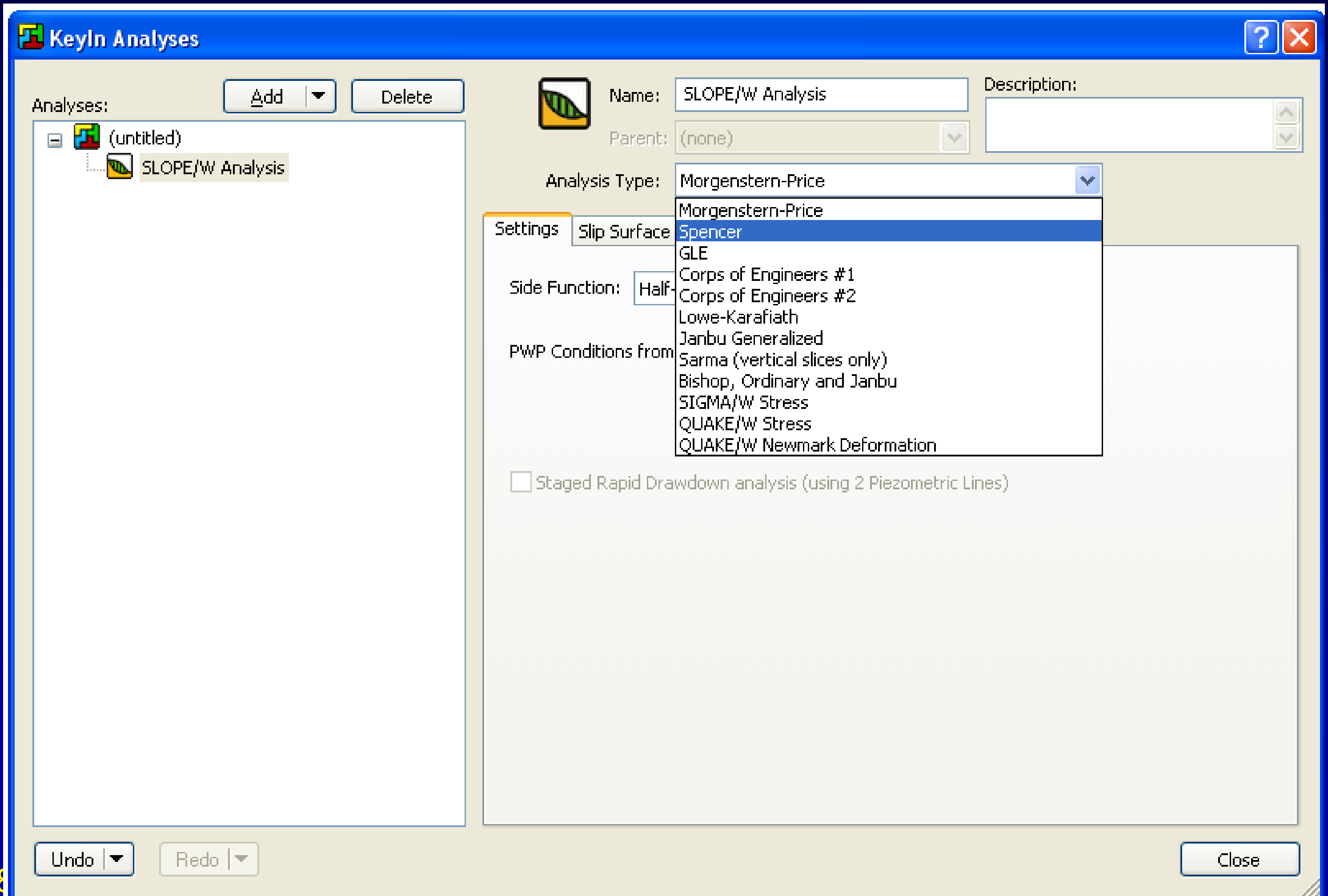
SLOPE/W Spencer’s Analysis

Slope/W Problem Setup



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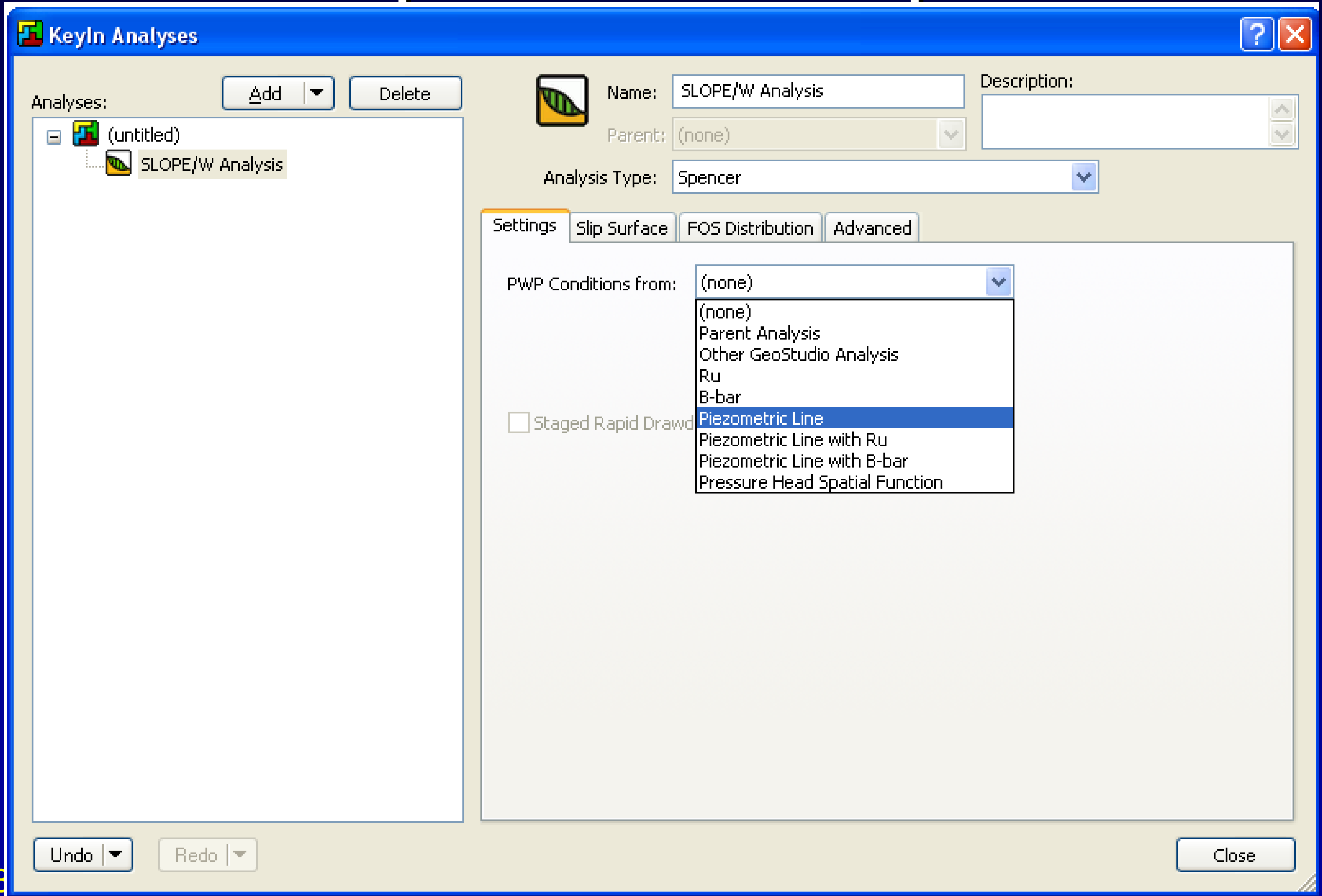
SLOPE/W Spencer's Analysis

Slope/W Problem Setup



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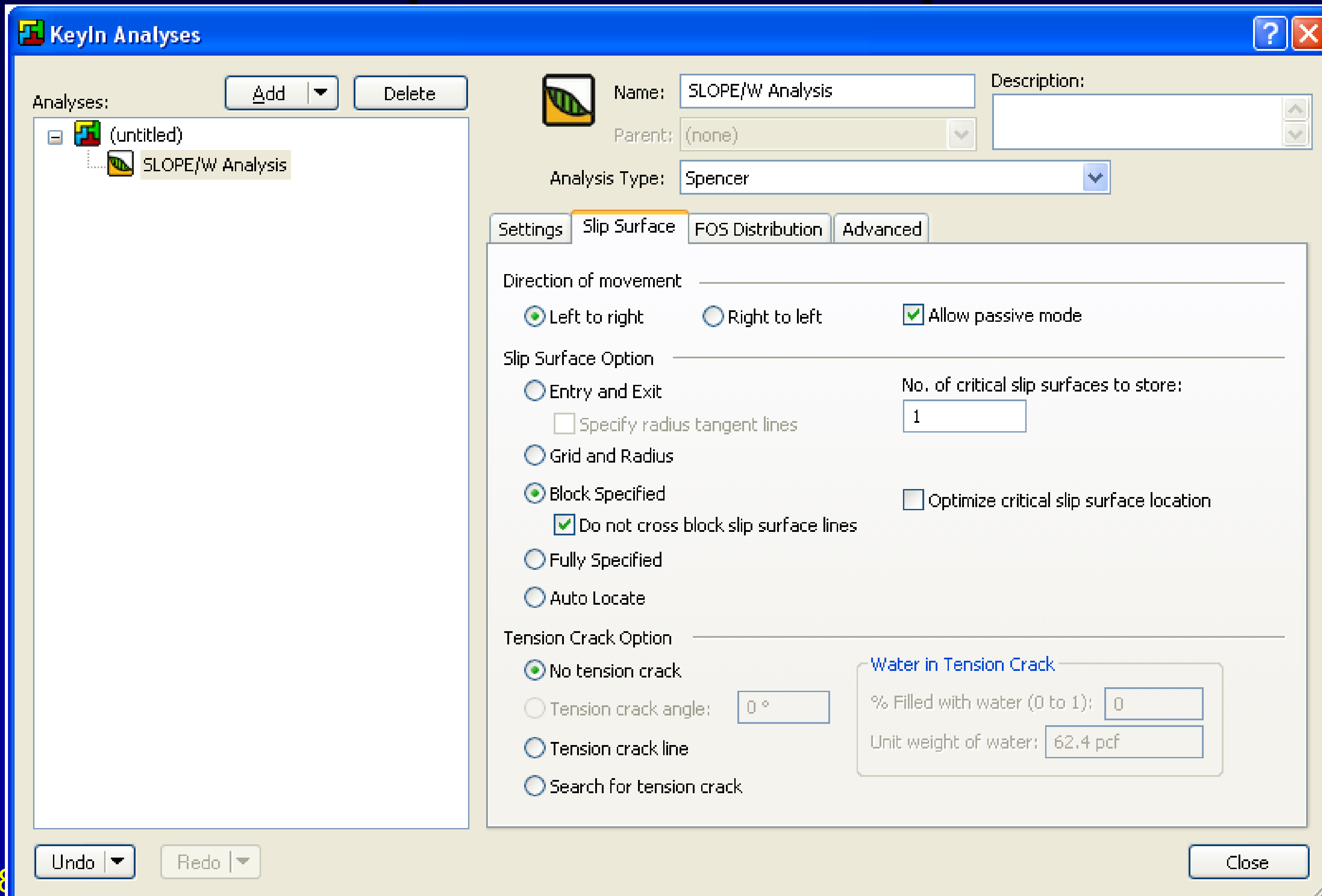
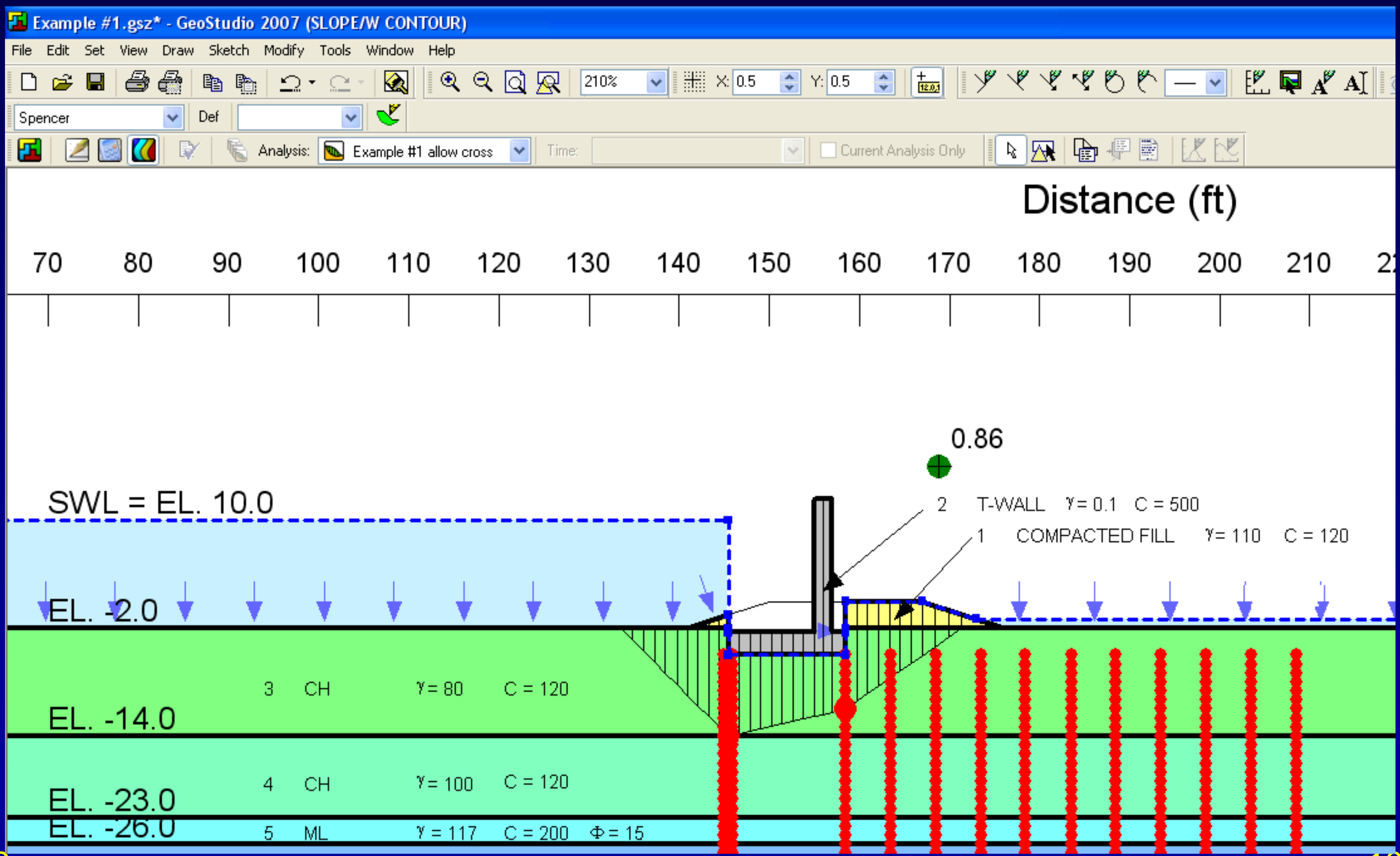
SLOPE/W Spencer's Analysis

Slope/W Problem Setup



SLOPE/W Spencer's Analysis

Do not cross block slip surface lines



SLOPE/W Spencer's Analysis

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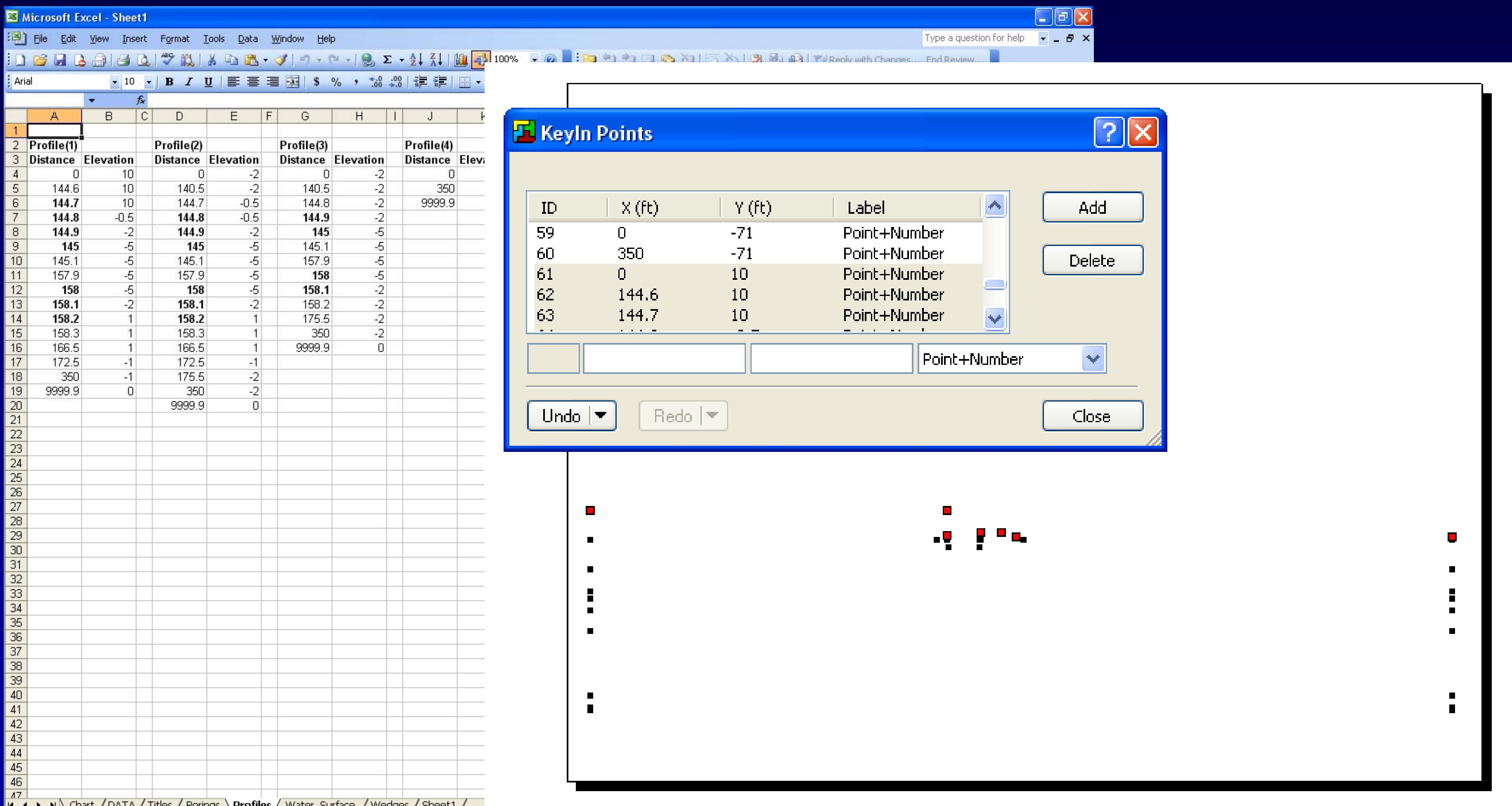
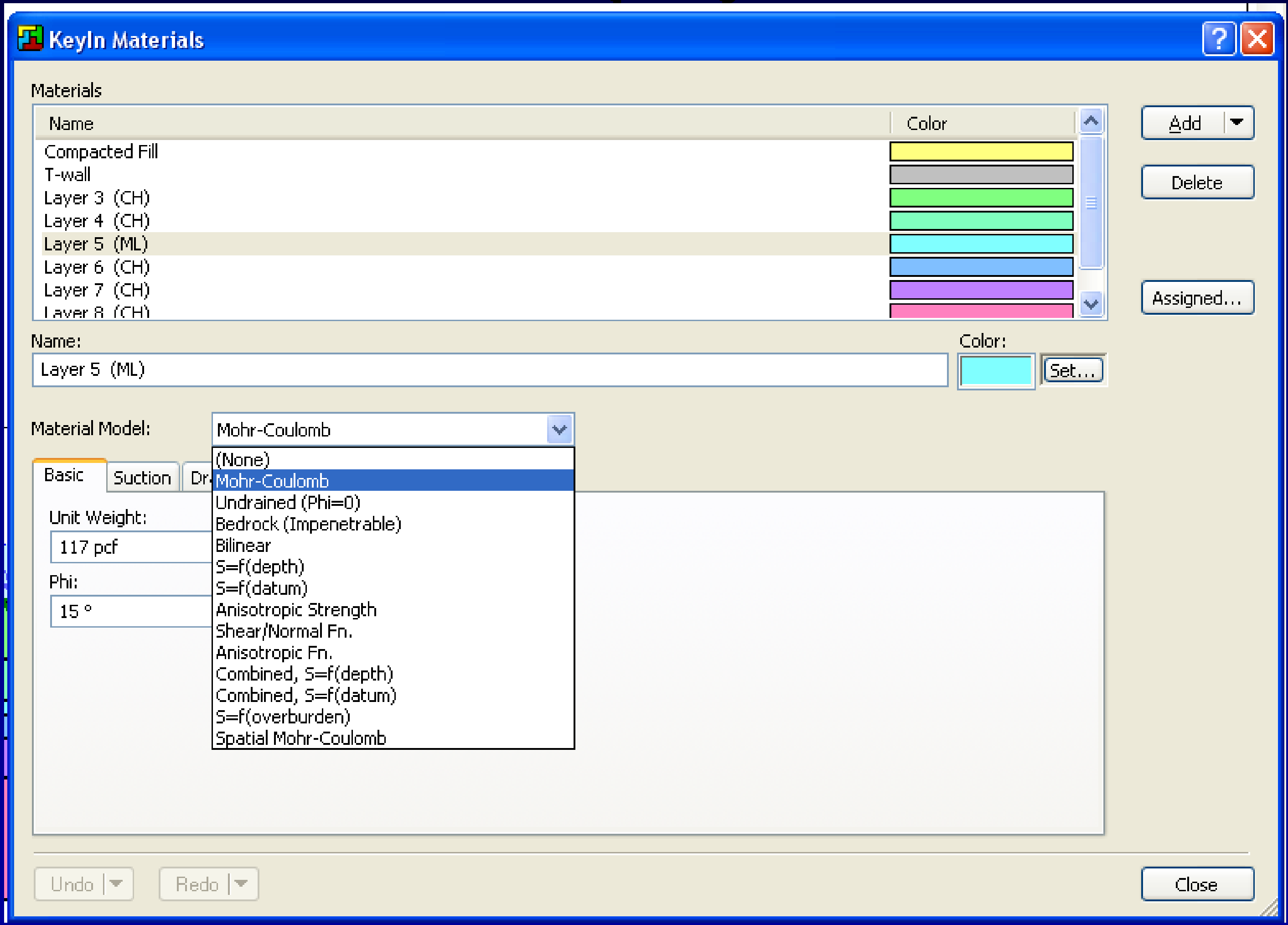
Create Profile – Paste MOP StabCheck.xls



Profile(1) Distance	Profile(1) Elevation	Profile(2) Distance	Profile(2) Elevation	Profile(3) Distance	Profile(3) Elevation	Profile(4) Distance
0	10	0	-2	0	-2	0
144.6	10	140.5	-2	140.5	-2	350
144.7	10	144.7	-0.5	144.8	-2	9999.9
144.8	-0.5	144.8	-0.5	144.9	-2	
144.9	-2	144.9	-2	145	-5	
145	-5	145	-5	145.1	-5	
145.1	-5	145.1	-5	157.9	-5	
157.9	-5	157.9	-5	158	-5	
158	-5	158	-5	158.1	-2	
158.1	-2	158.1	-2	158.2	-2	
158.2	1	158.2	1	175.5	-2	
158.3	1	158.3	1	350	-2	
166.5	1	166.5	1	9999.9	0	
172.5	-1	172.5	-1			
350	-1	175.5	-2			
9999.9	0	350	-2			
		9999.9	0			

SLOPE/W Spencer's Analysis

Material Property Models



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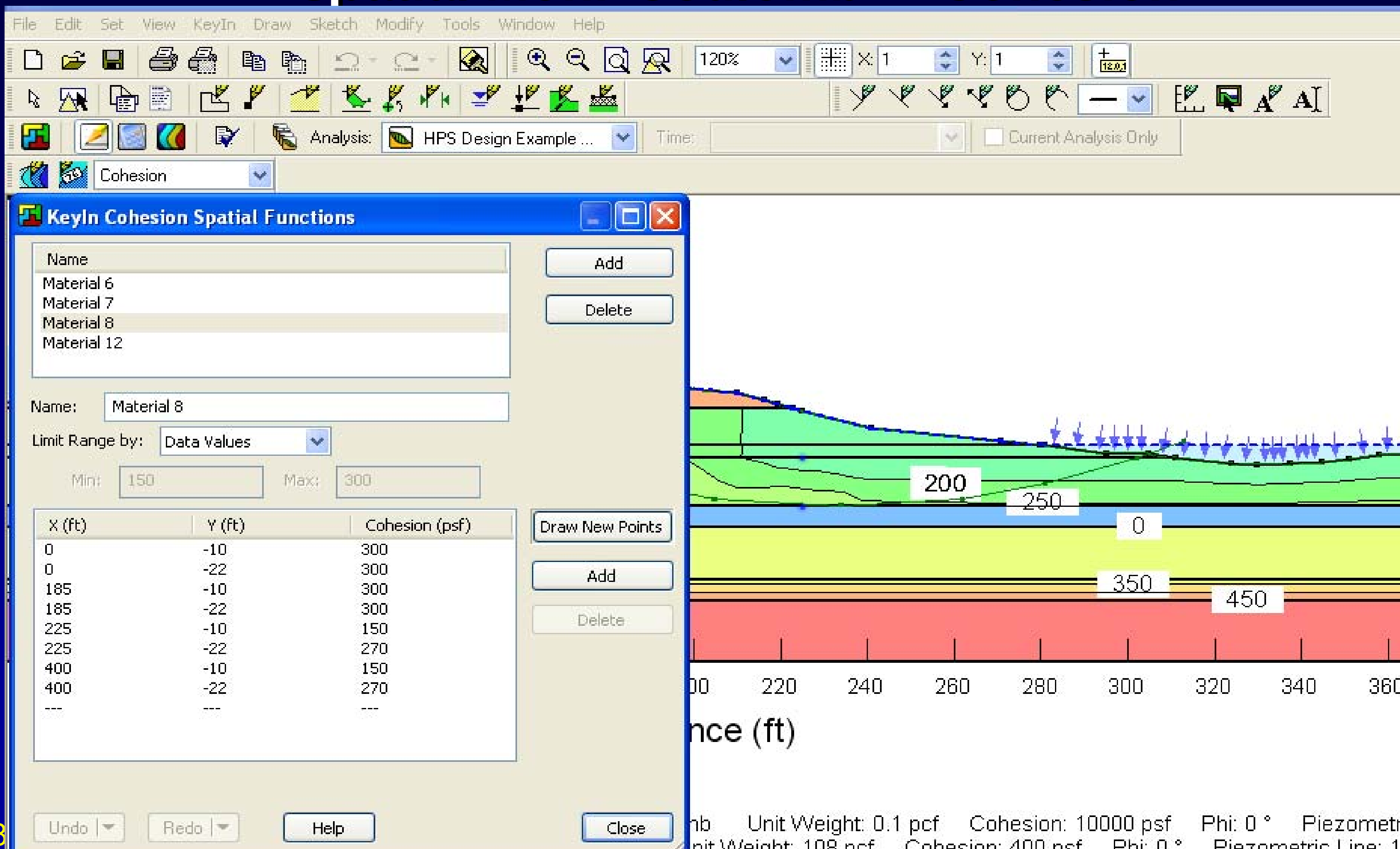
SLOPE/W Spencer's Analysis

Spatial Mohr-Coulomb - Cohesion



SLOPE/W Spencer's Analysis

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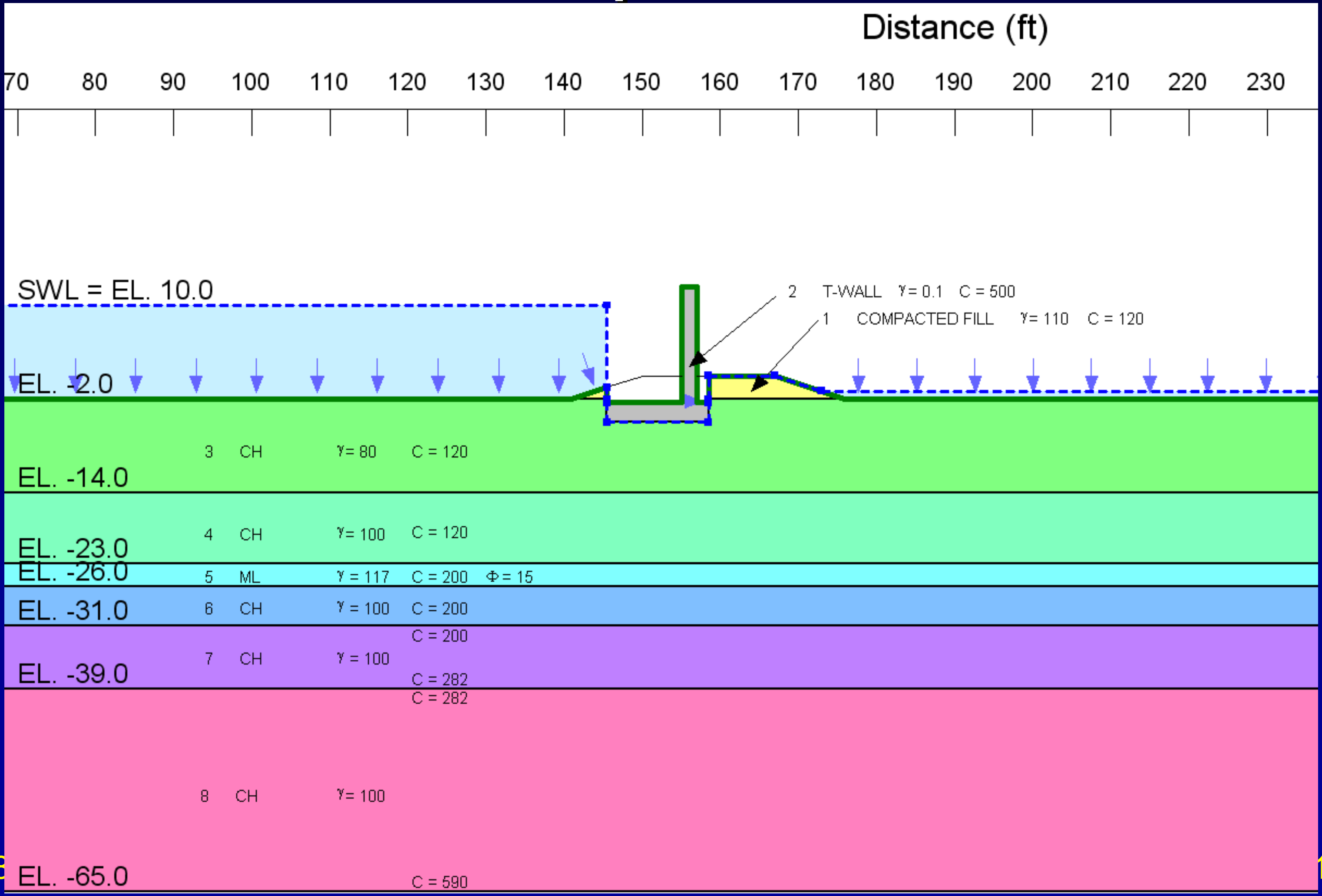
Example #1



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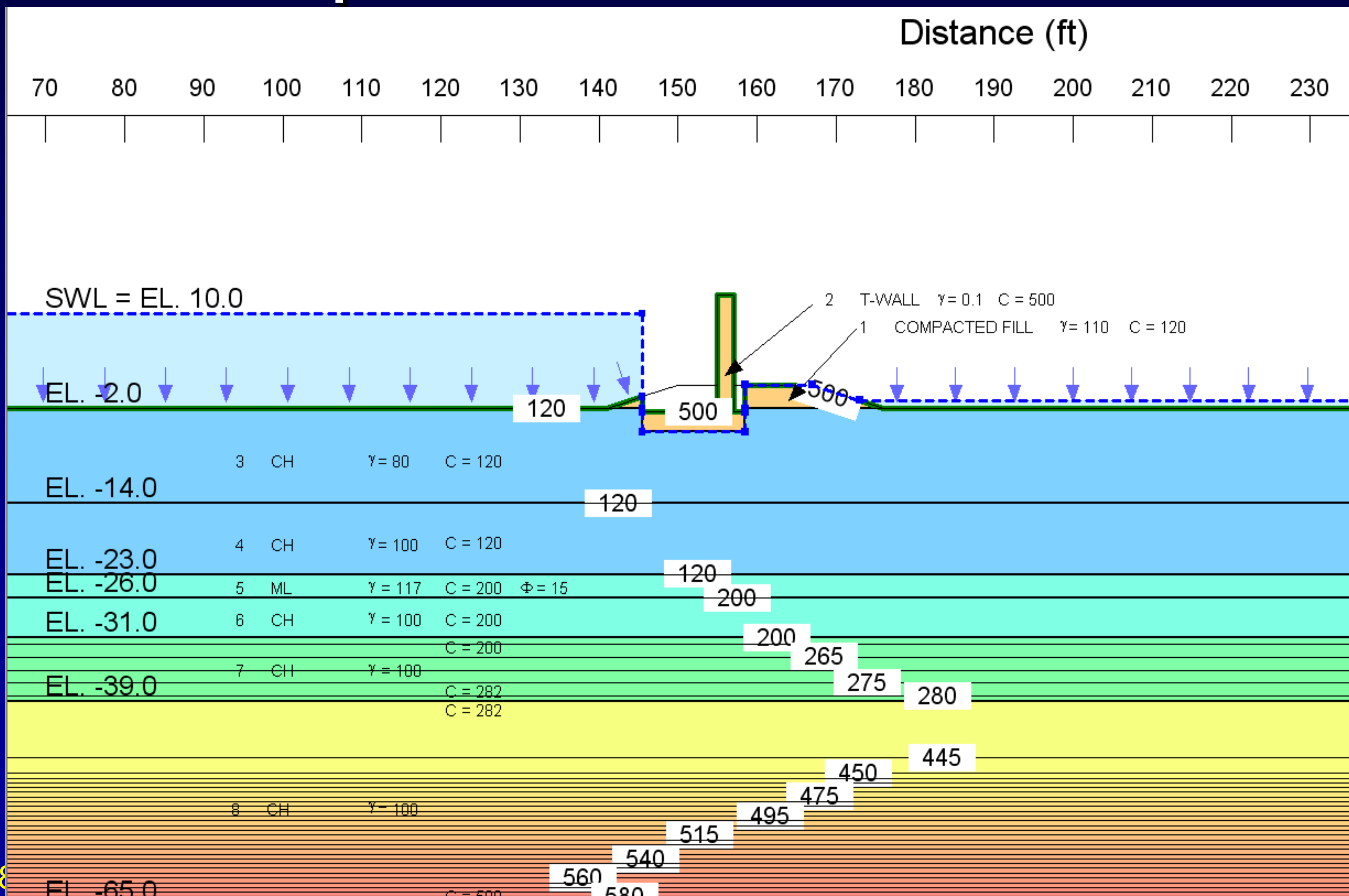
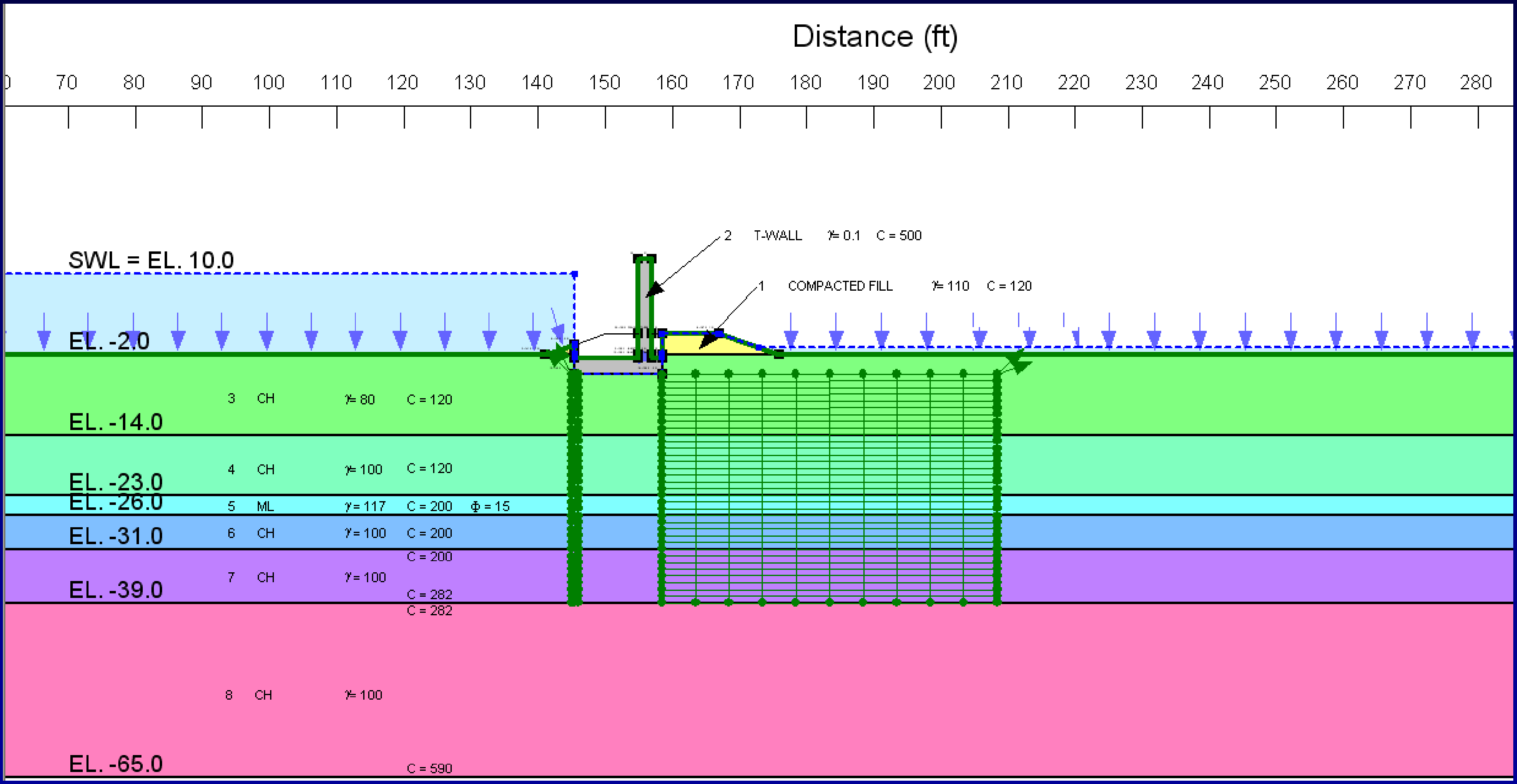
SLOPE/W Spencer's Analysis

Example #1 – Cohesion Contours



Step 1 Block Specified



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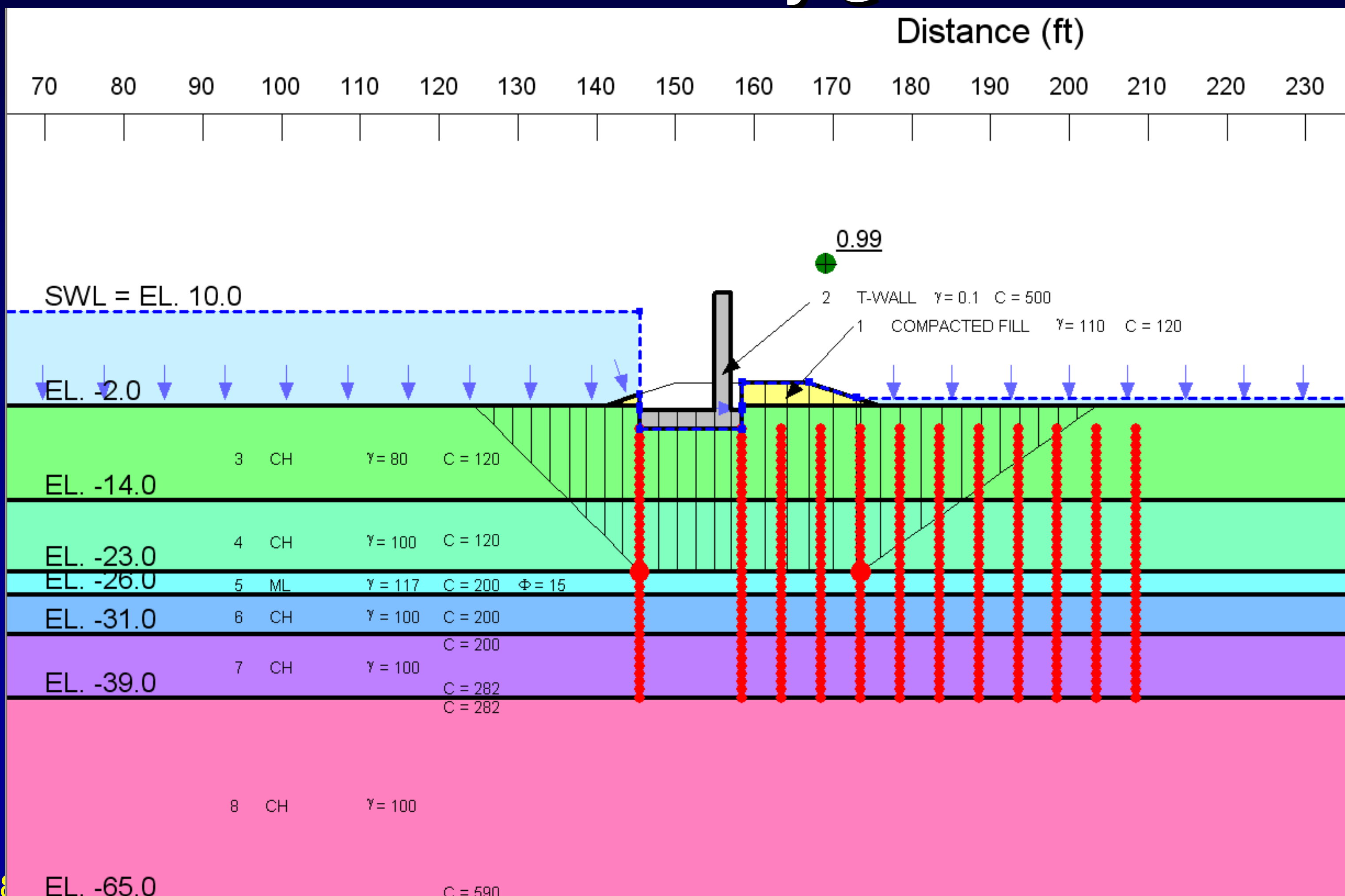
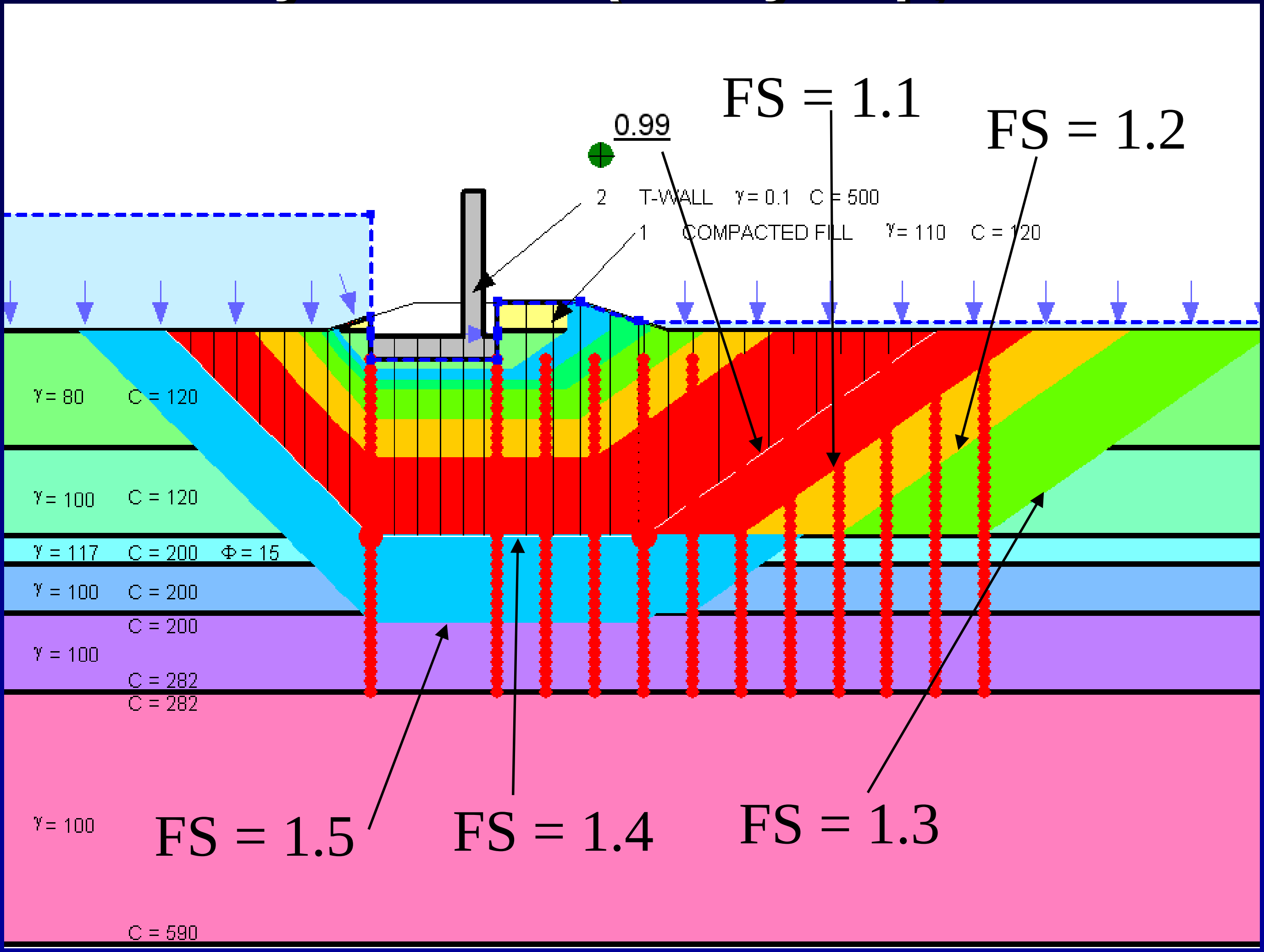
Step 1

Critical Factor of Safety @ EL. -23



Step 1

Factor of Safety Contours (Safety Map, Increment =0.1)



Step 1 (tangent elev. at -8 ft)

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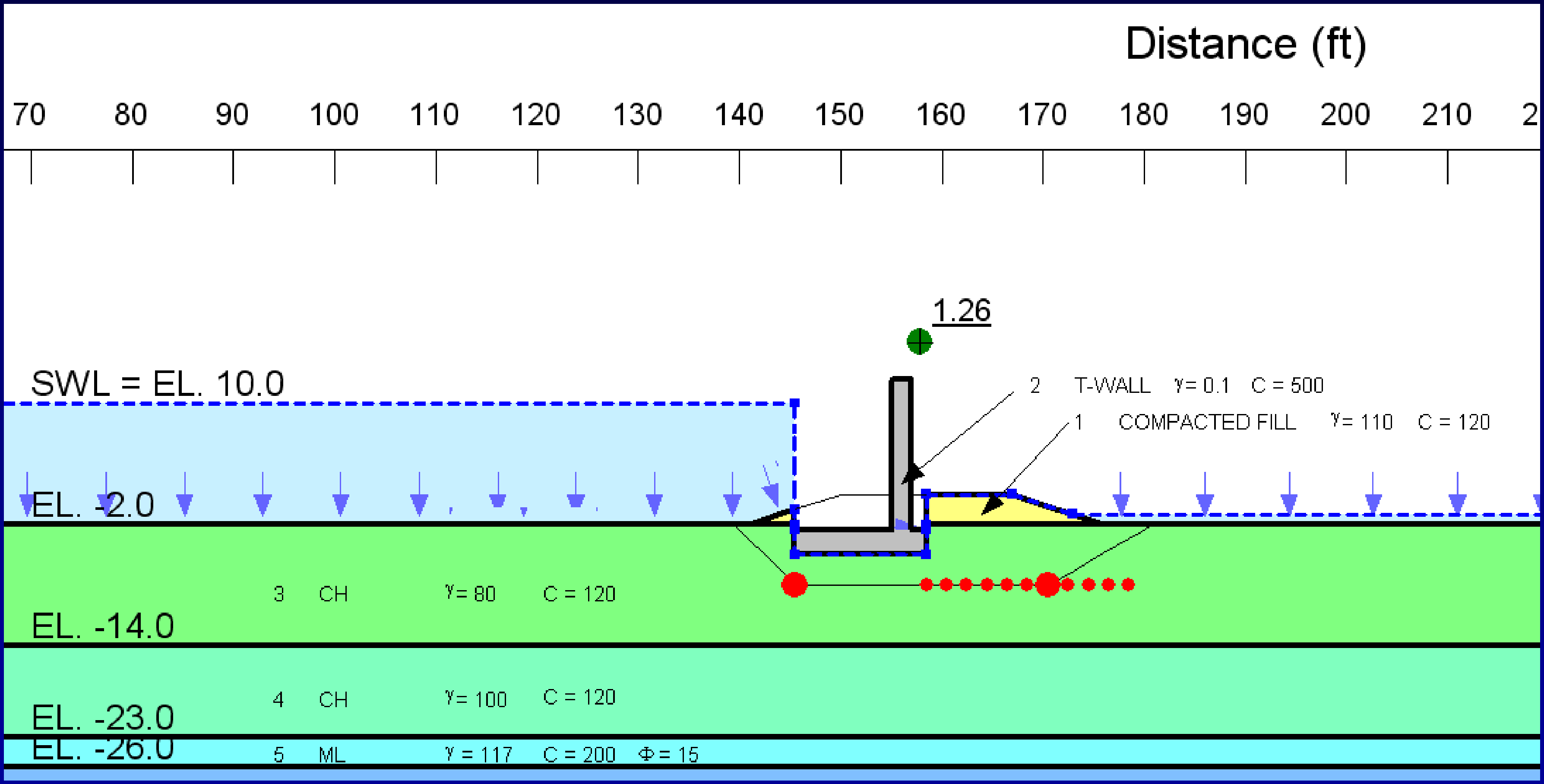
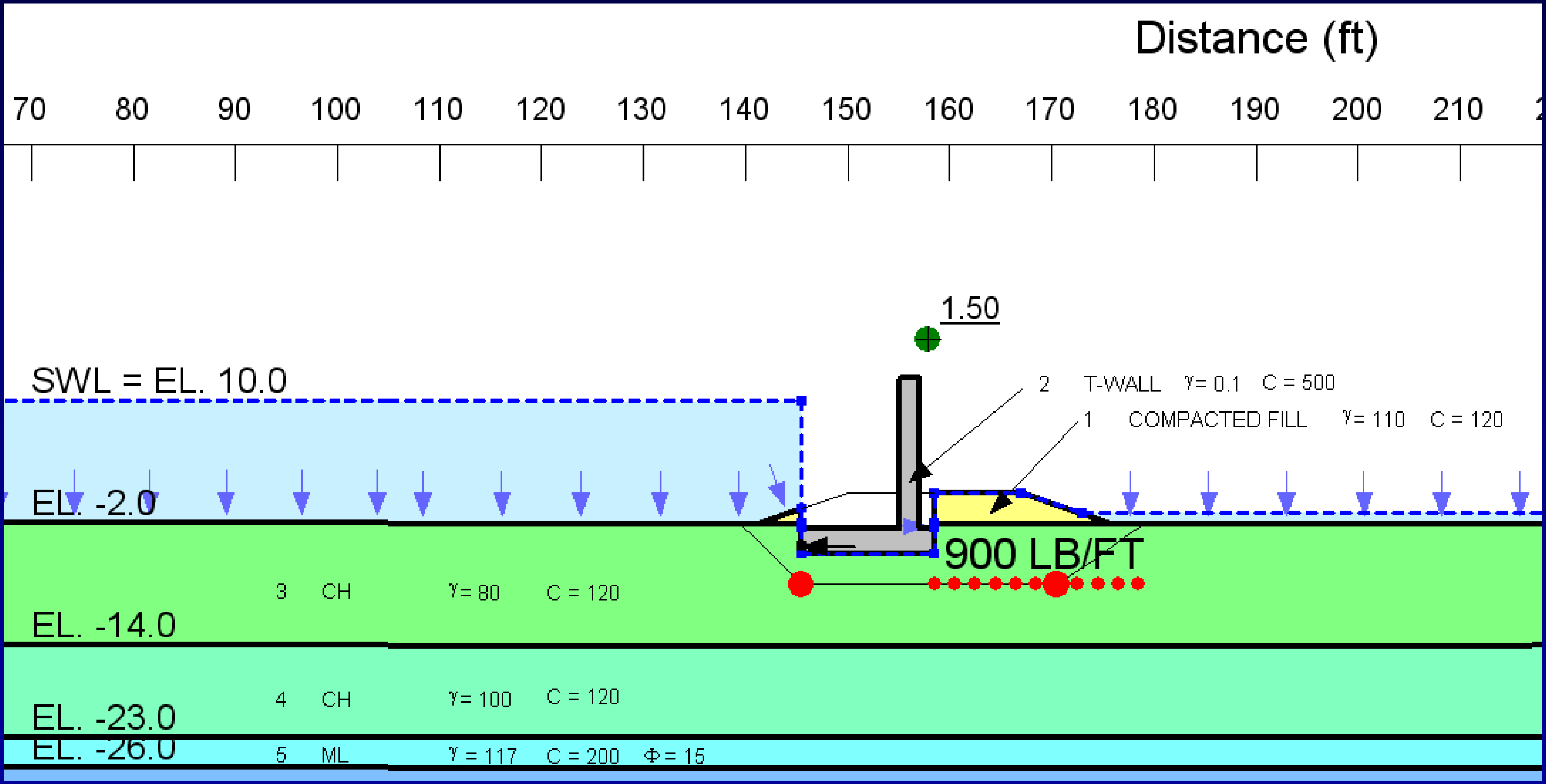
Check Global FOS using Spencer's Method



Step 2.1

Compute Stabilizing Force to Achieve Target FOS



Step 1 (tangent elev. at -14 ft)

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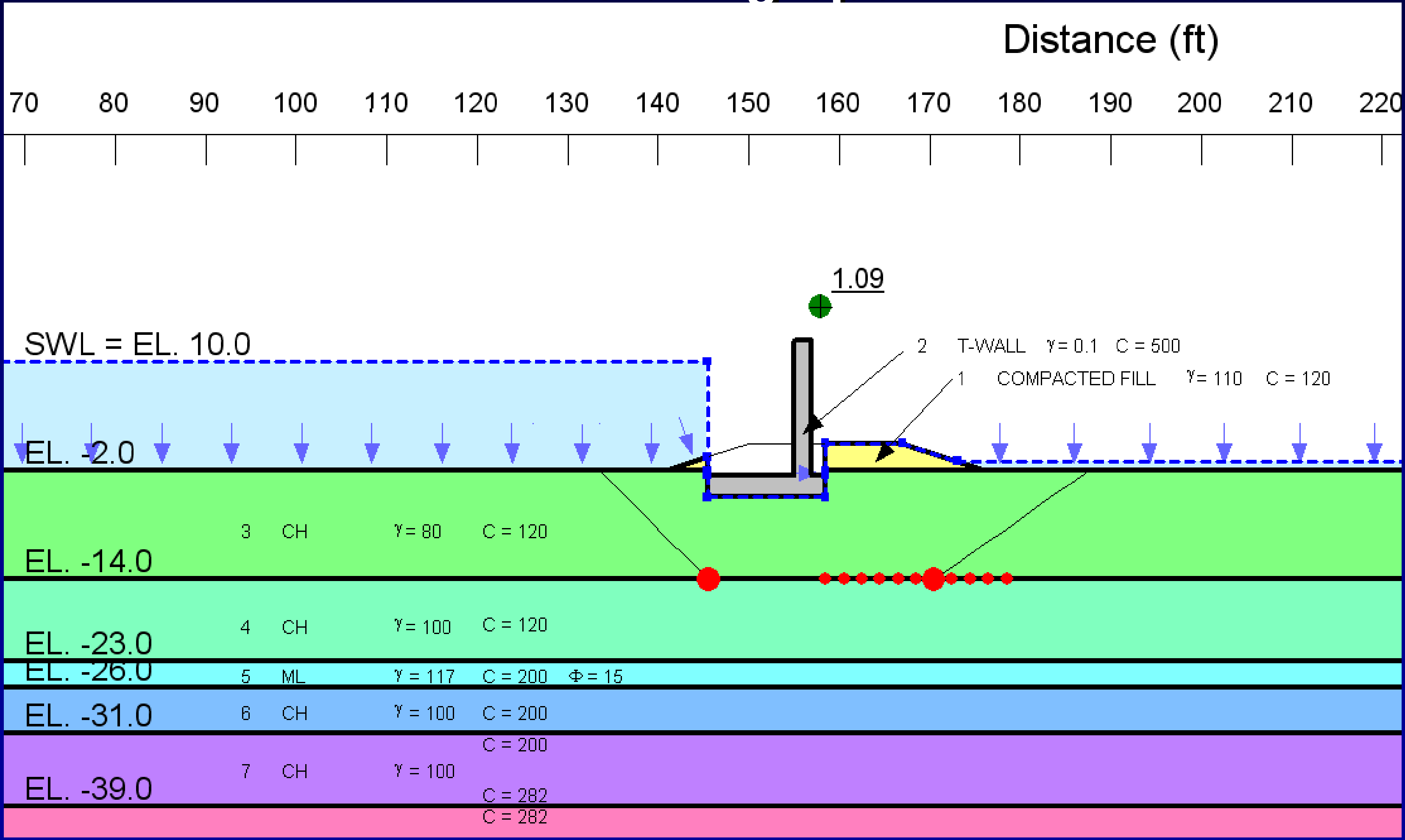
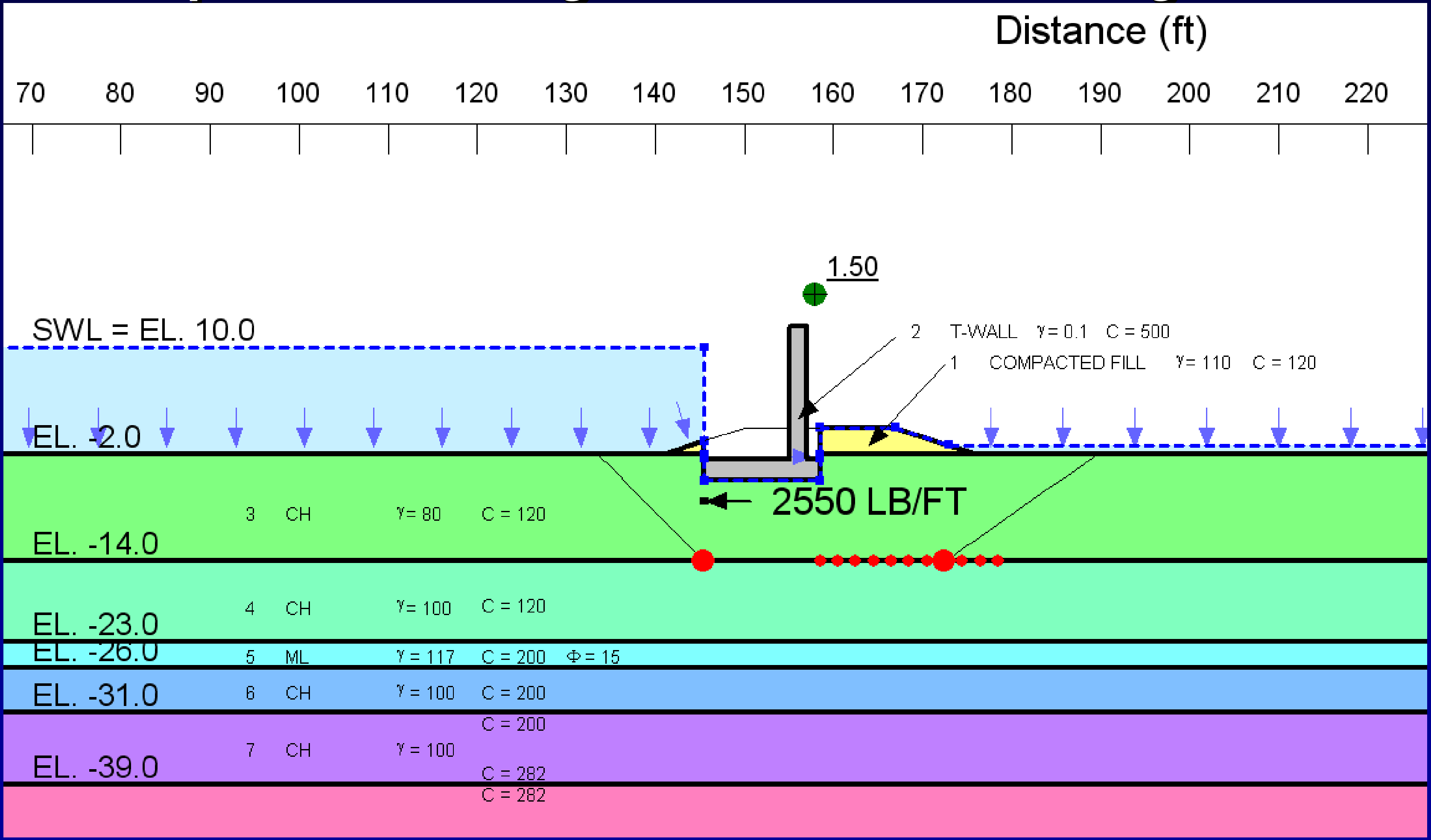
Check Global FOS using Spencer's Method



Step 2.1

Compute Stabilizing Force to Achieve Target FOS



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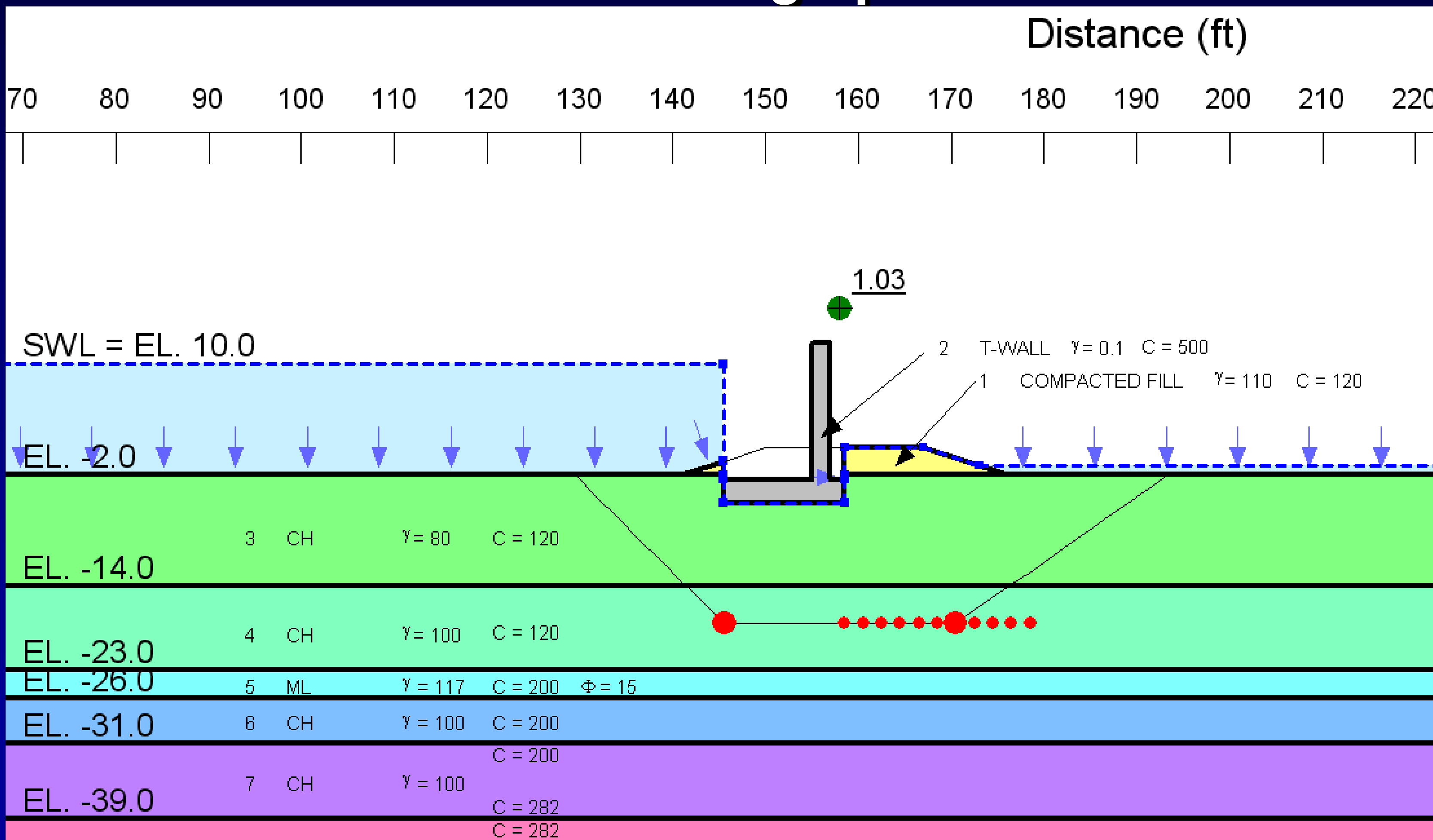
Step 1 (tangent elev. at -18 ft)

Check Global FOS using Spencer's Method



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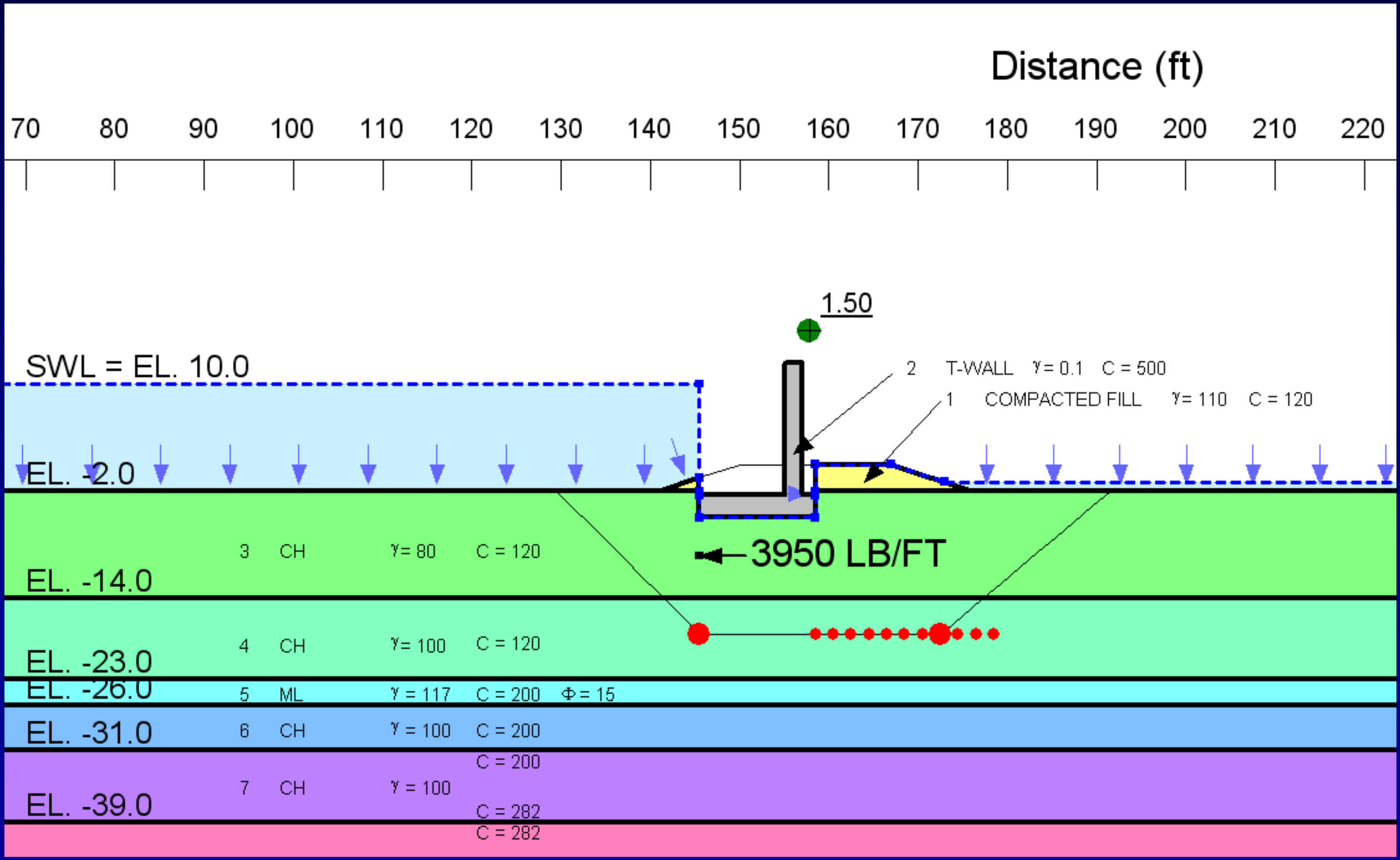
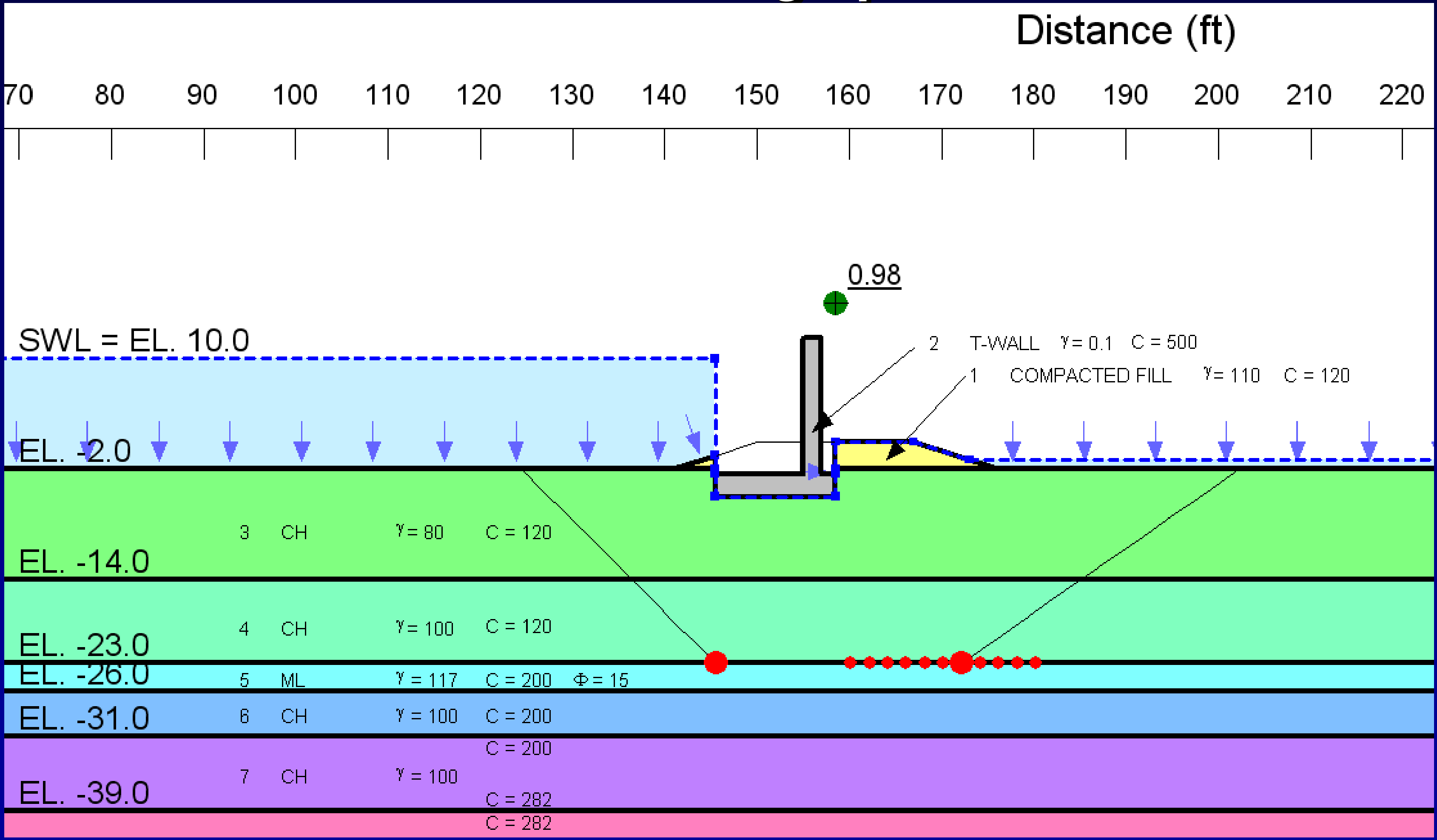
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



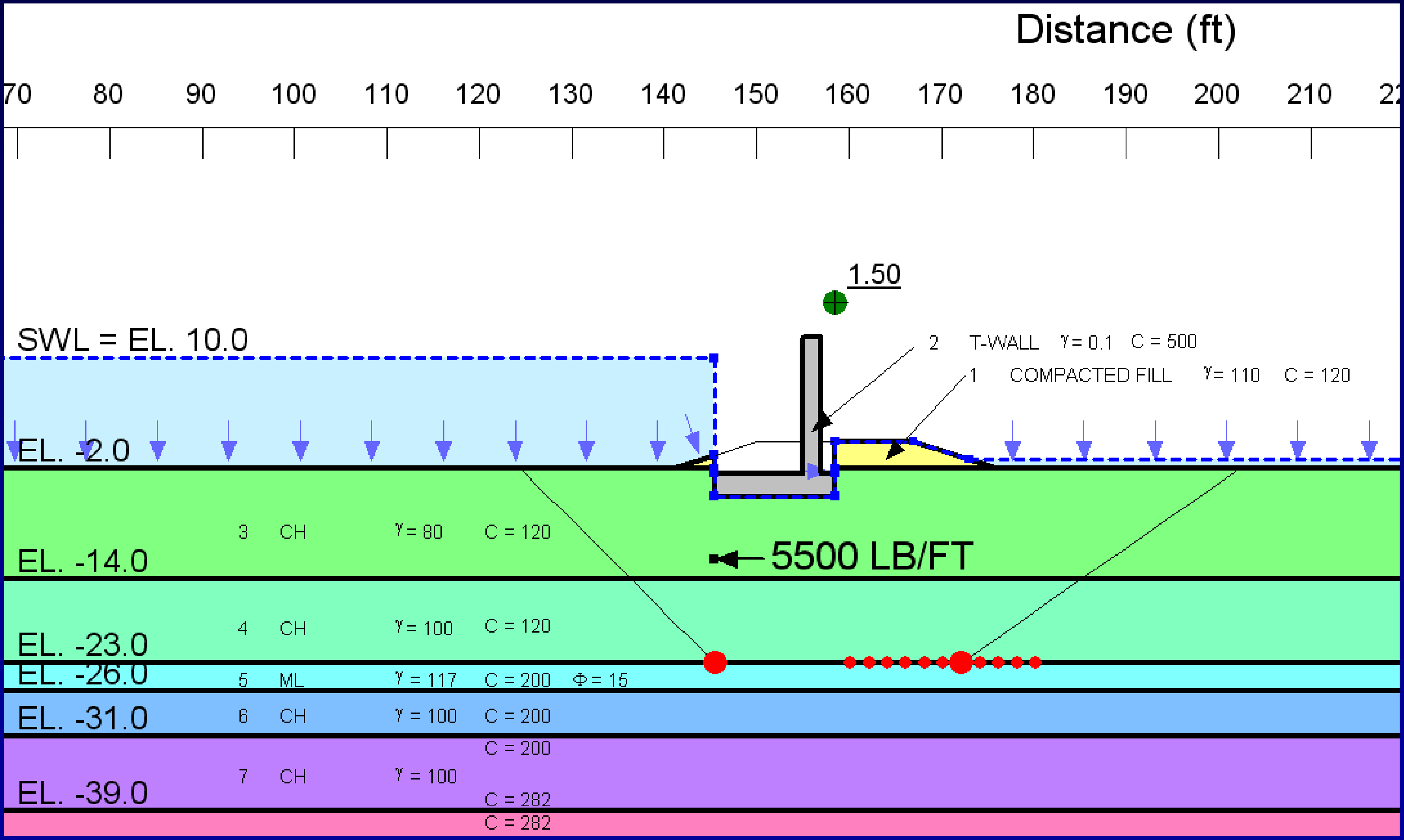
Step 1 (tangent elev. at -23 ft)

Check Global FOS using Spencer's Method



Step 2.1

Compute Stabilizing Force to Achieve Target FOS



Step 1 (tangent elev. at -23.1 ft)

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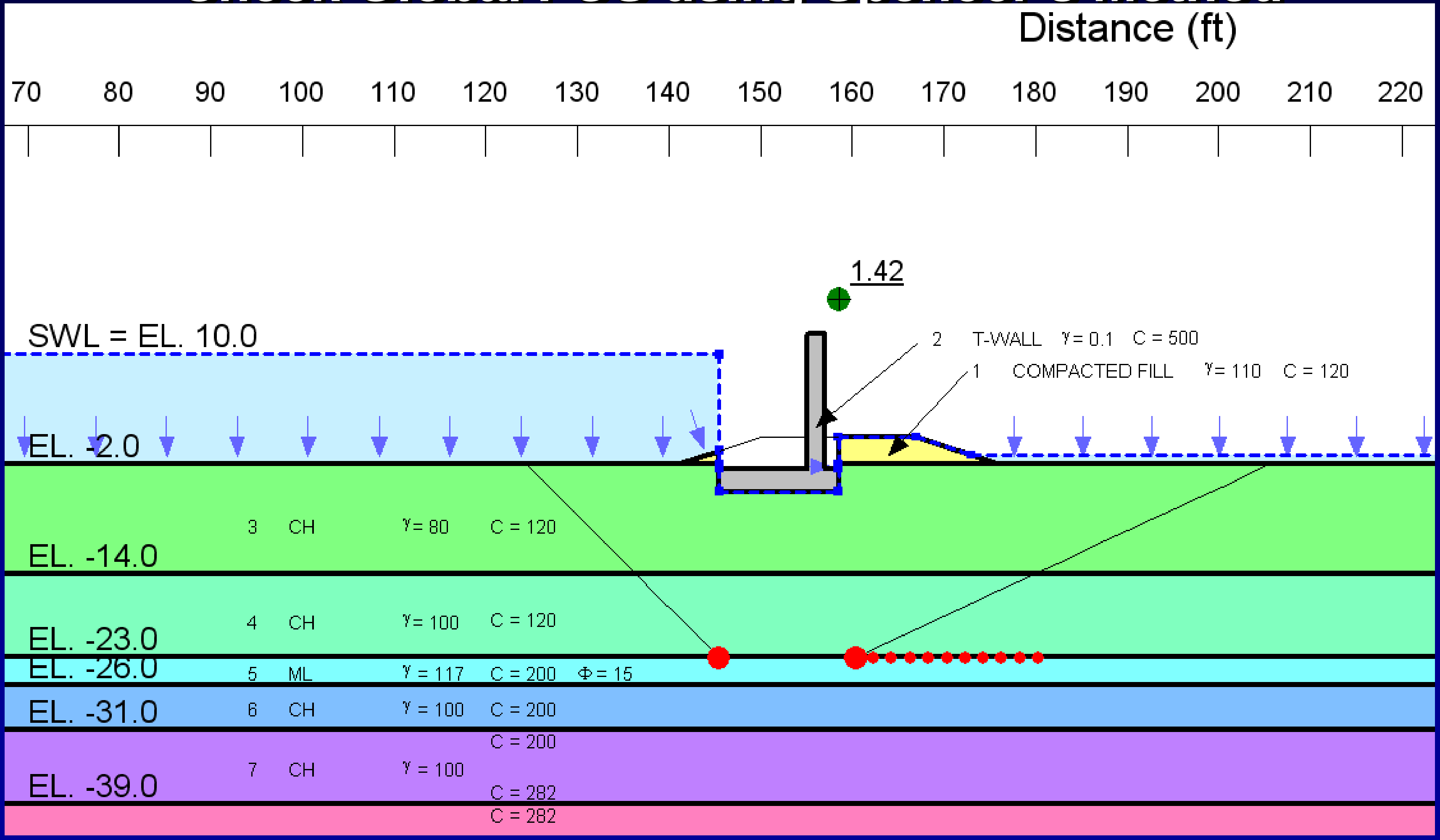
Check Global FOS using Spencer's Method



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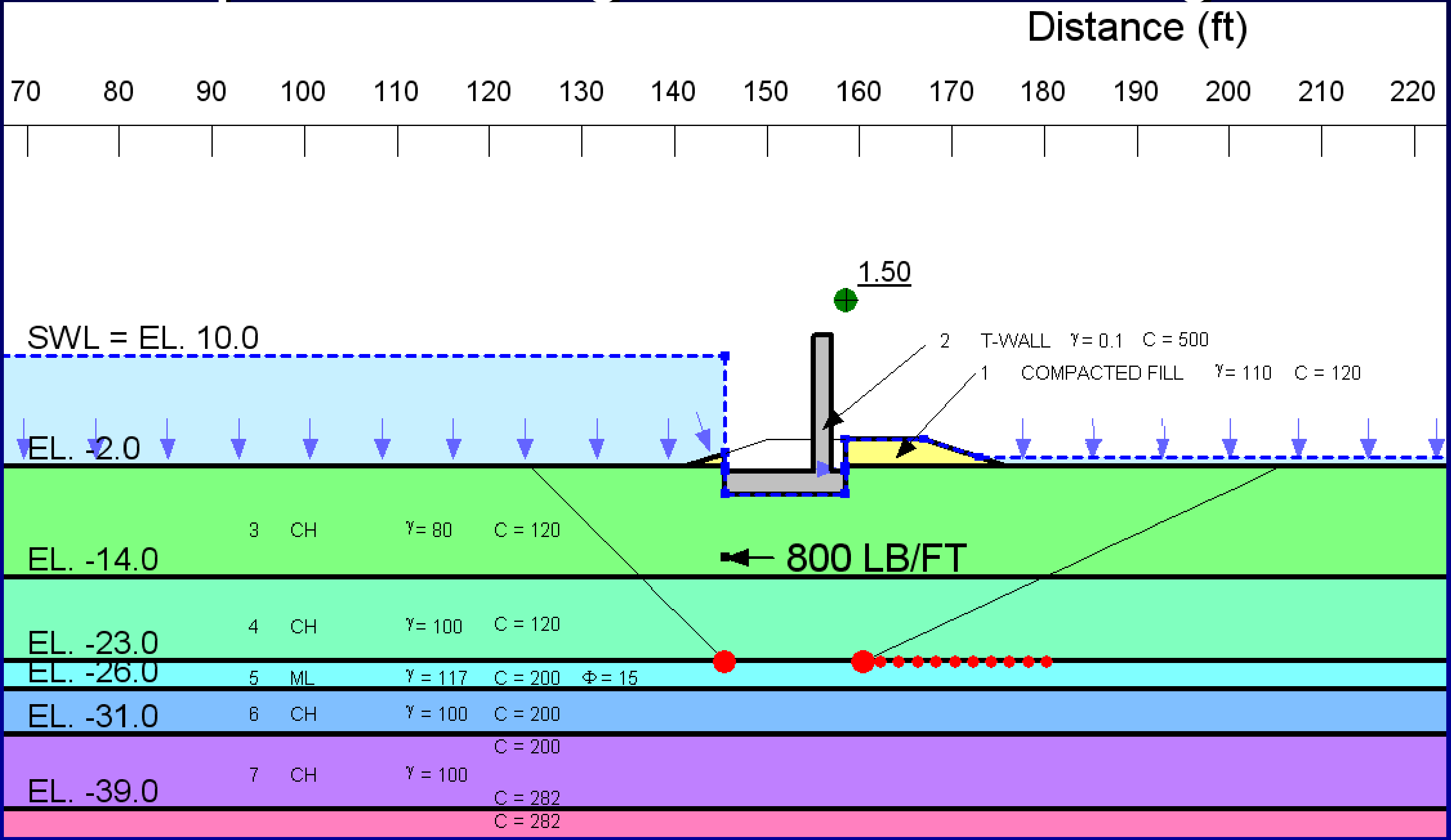
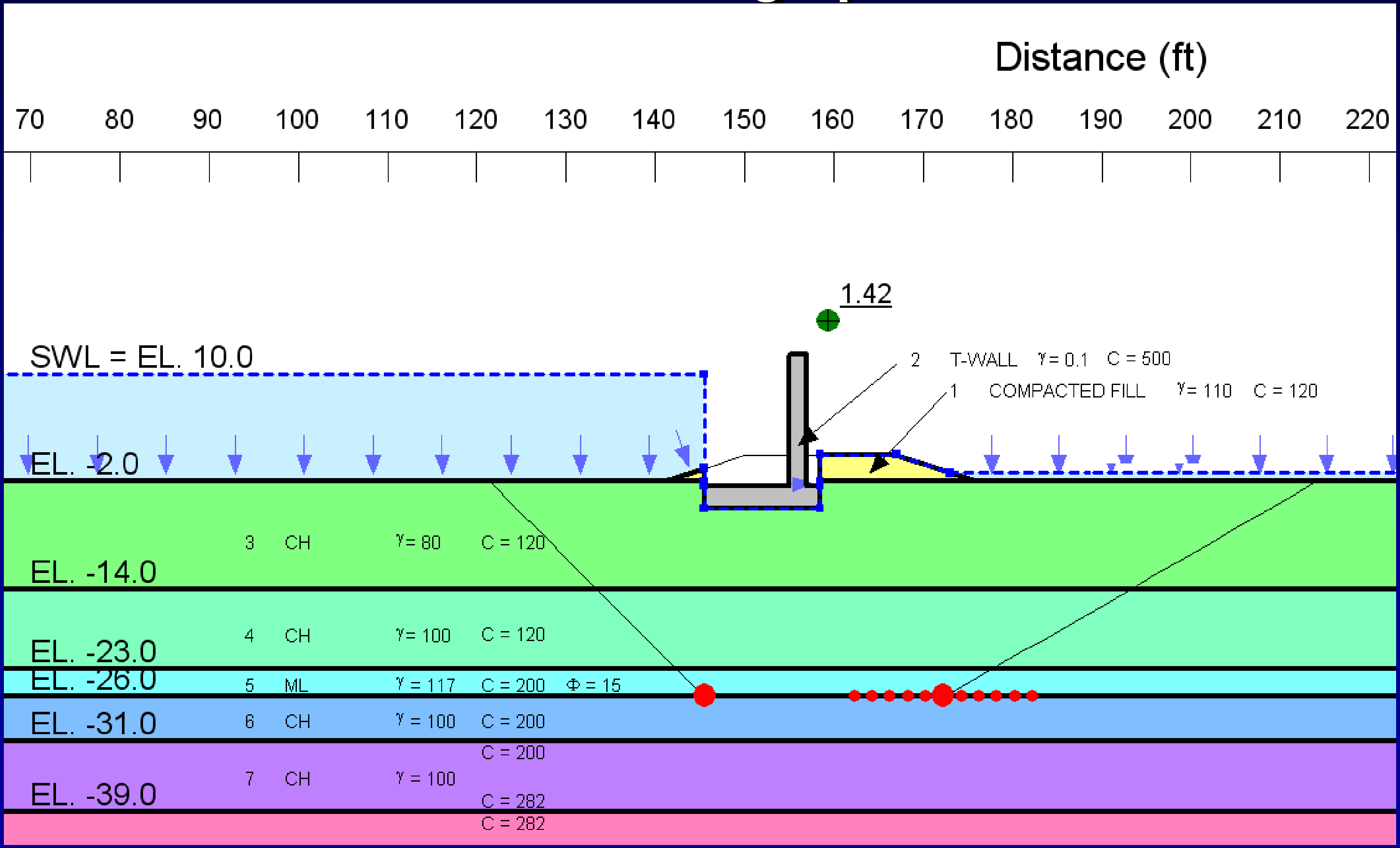
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



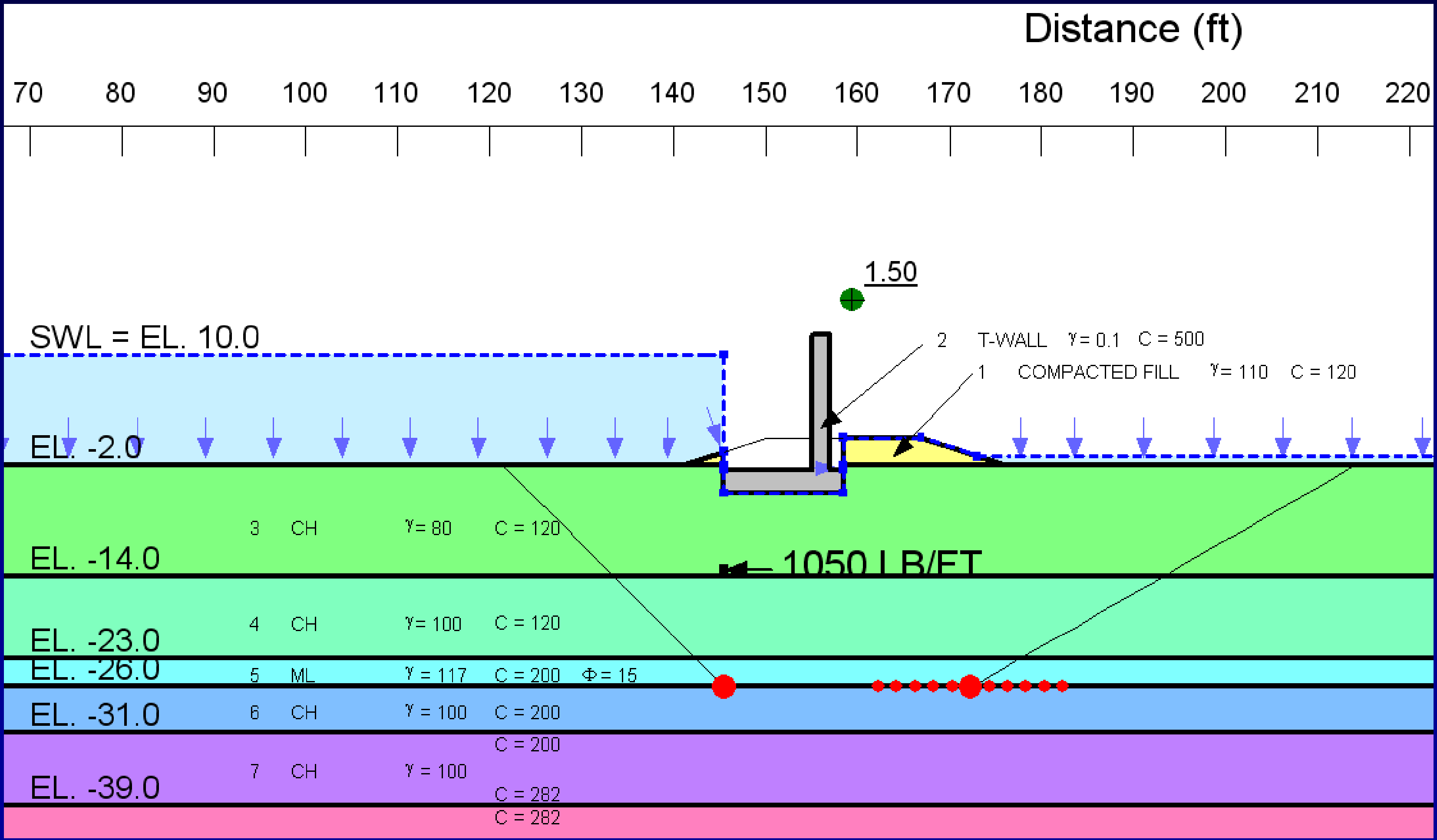
Step 1 (tangent elev. at -26.1 ft)

Check Global FOS using Spencer's Method



Step 2.1

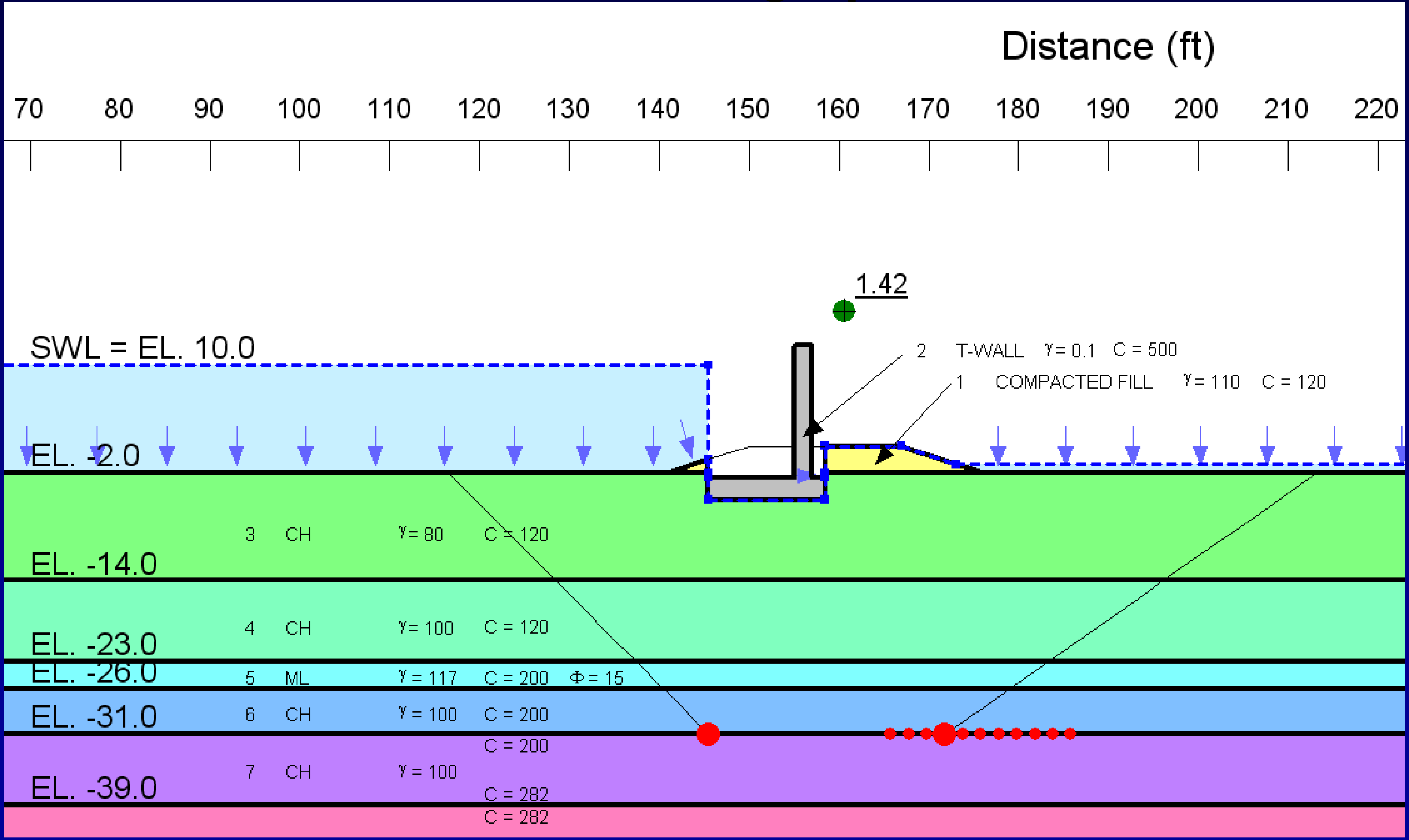
Compute Stabilizing Force to Achieve Target FOS



One Team: Relevant, Ready, Responsive and Reliable

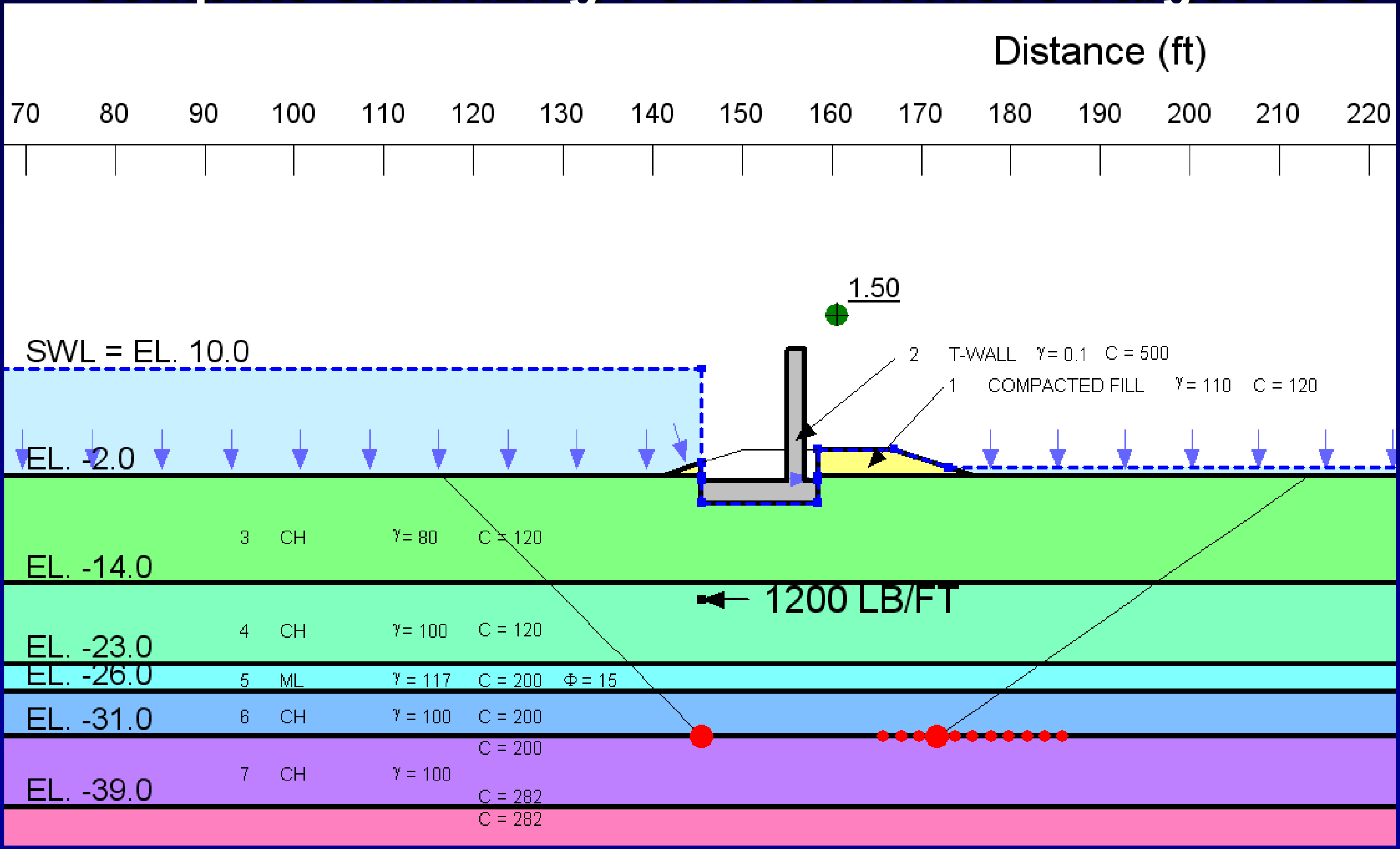
Step 1 (tangent elev. at -31 ft)

Check Global FOS using Spencer's Method



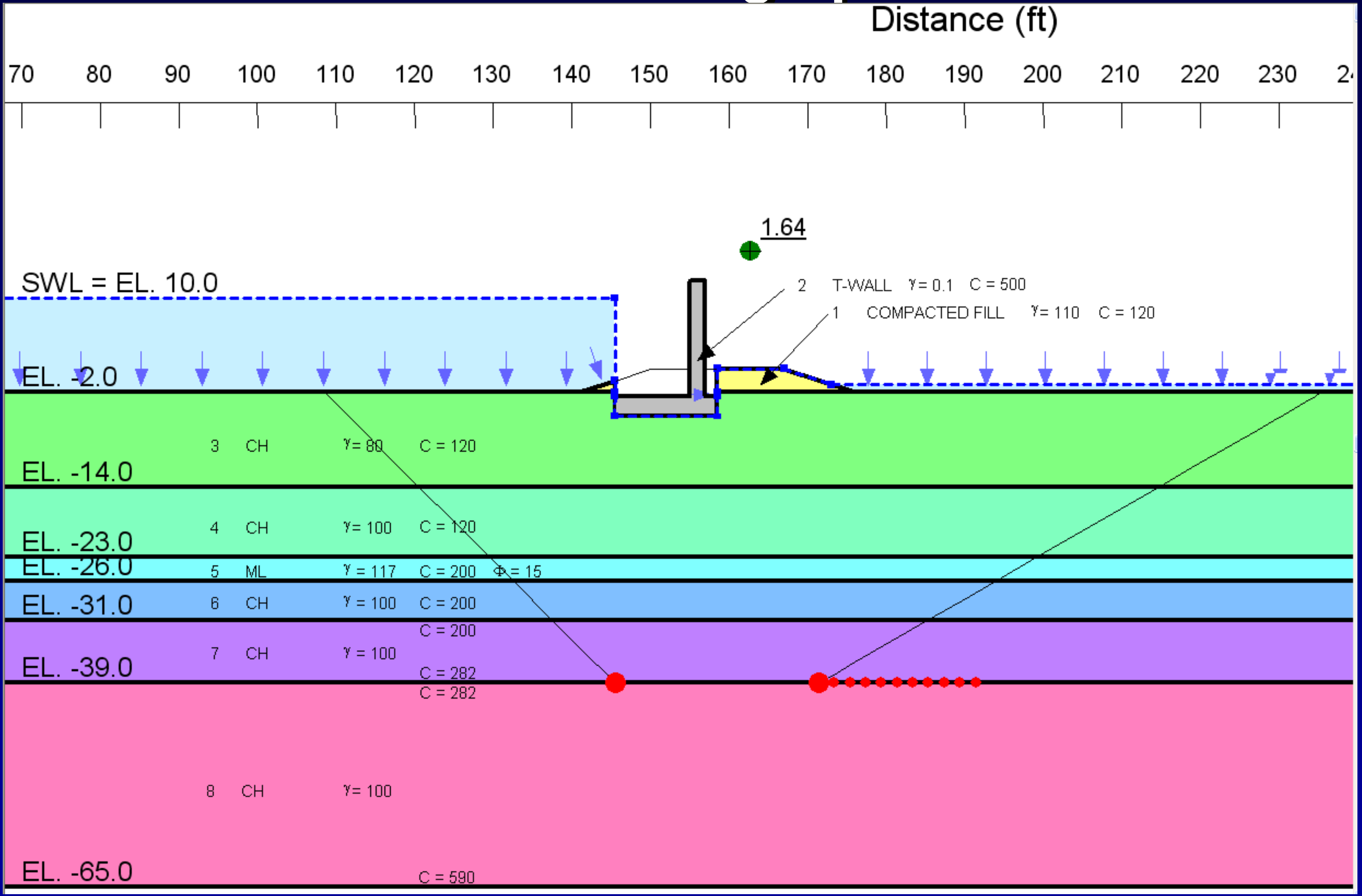
Step 2.1

Compute Stabilizing Force to Achieve Target FOS



Step 1 (tangent elev. at -39 ft)

Check Global FOS using Spencer's Method



Step 1 (tangent elev. at -43.5 ft)

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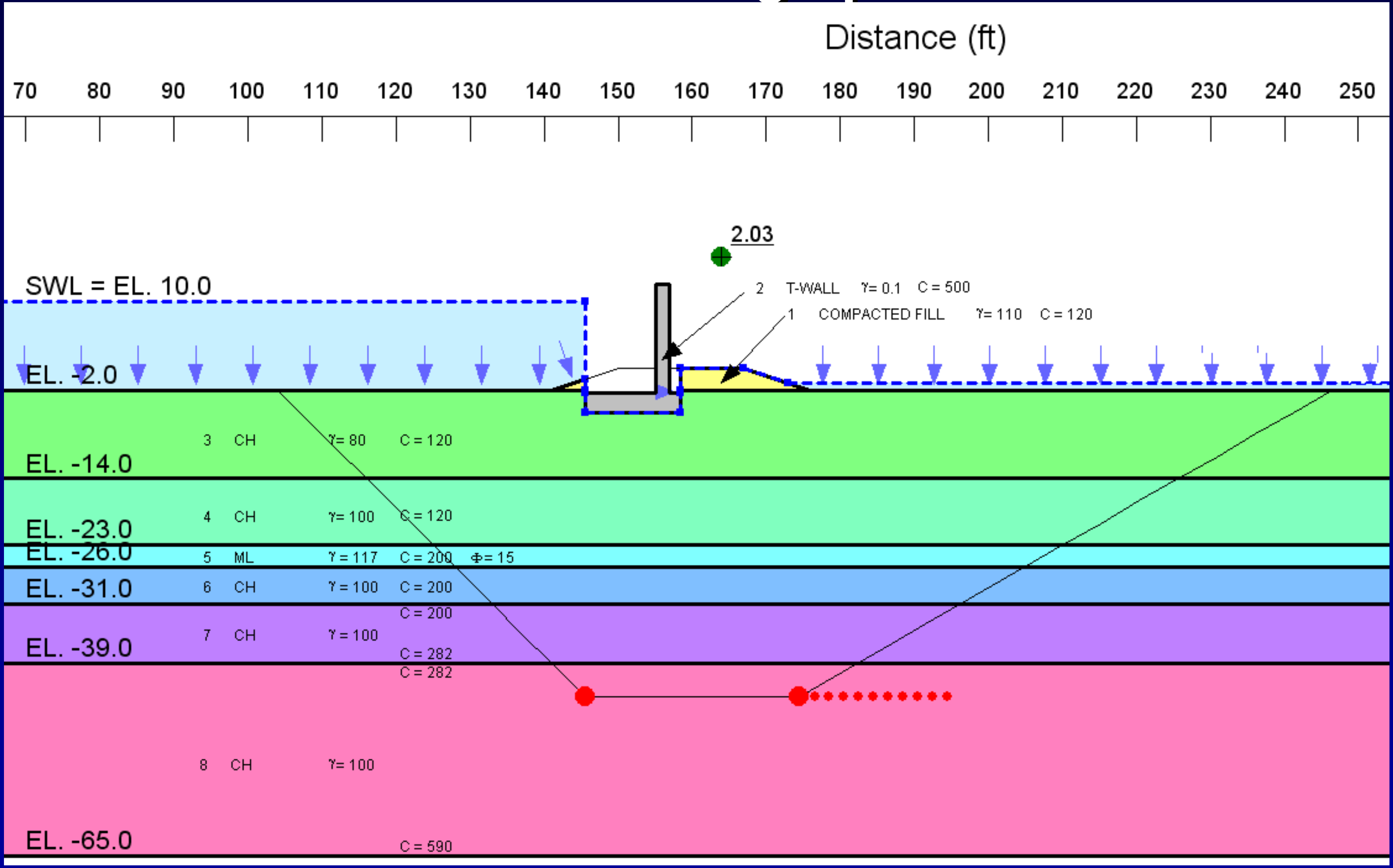
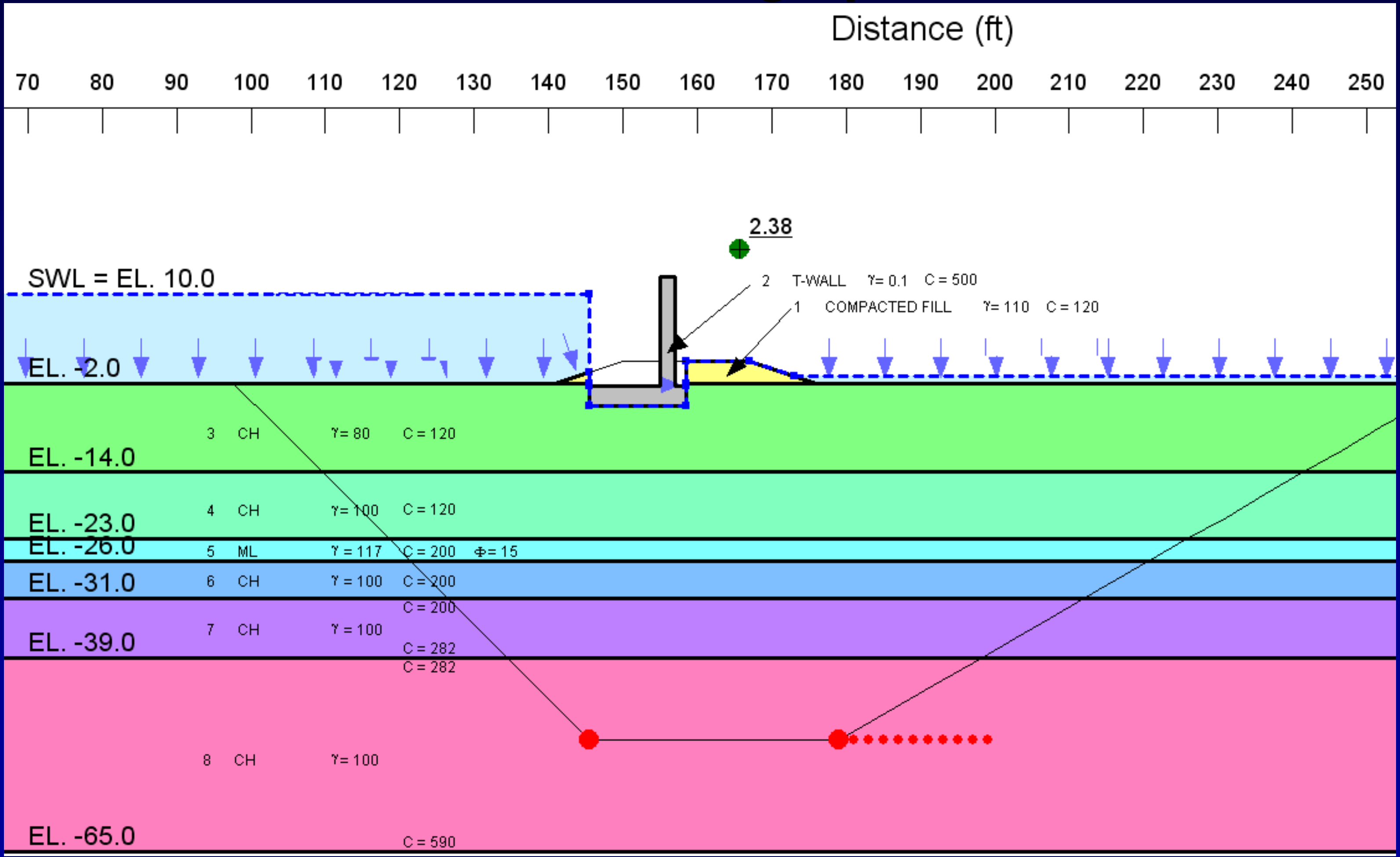
Check Global FOS using Spencer's Method



Step 1 (tangent elev. at -50 ft)

Check Global FOS using Spencer's Method



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Step 2.2 Summary of Results

Neutral Block Tangent EL (ft)	Factor of Safety	Unbalanced Load (lbs/ft)
-8	1.26	900
-14	1.09	2550
-18	1.03	3950
-23	**0.98**	**5500**
-23.1	1.42	800
-26.1	1.42	1150
-31	1.42	1200
-39	1.64	-
-43.5	2.03	-
-50	2.38	-

3.1 – Axial Capacity

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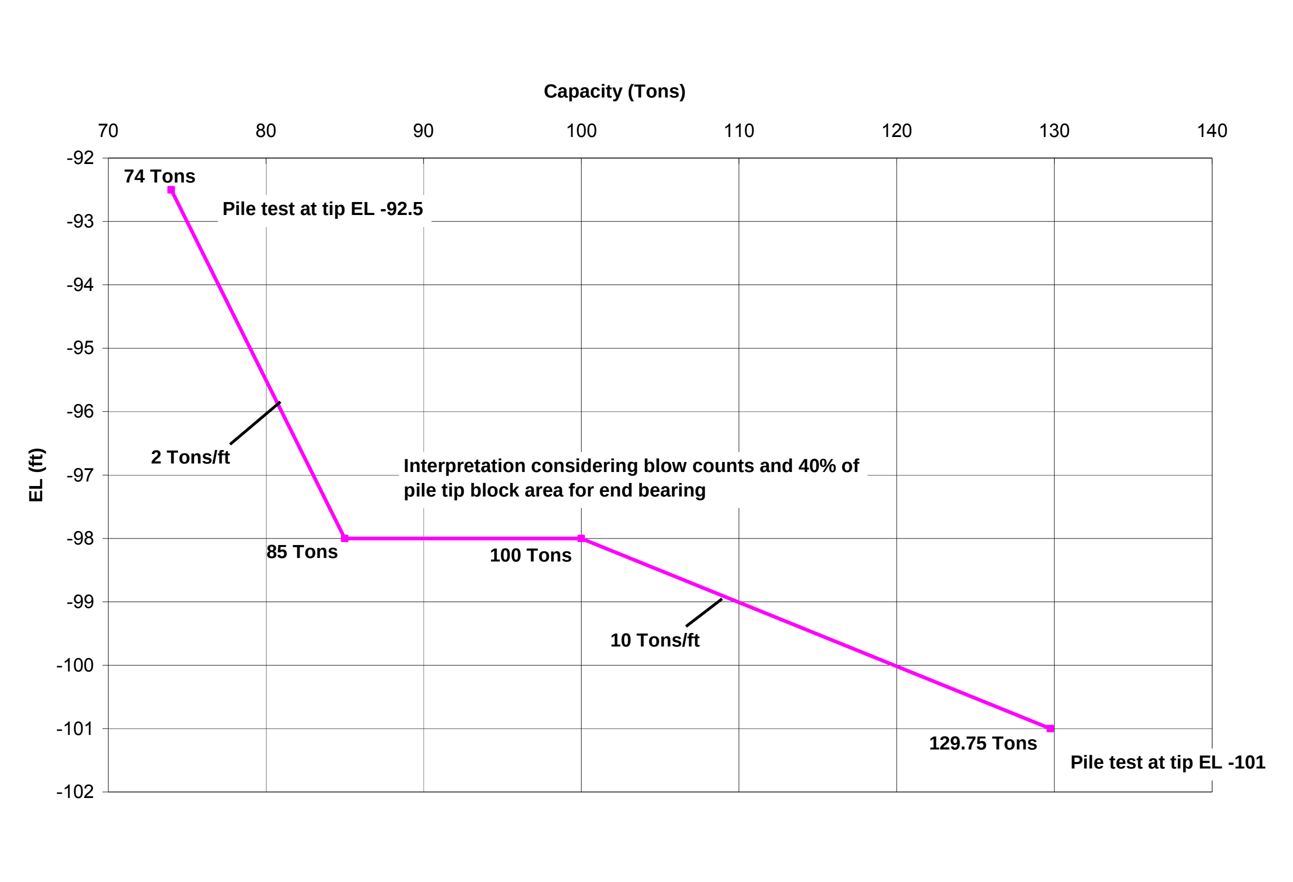
Compute axial capacity according to 3.3 of the HSDRS – based on EM 1110-2-2906 – None Above Failure Surface

Compression

Trial Pile Tip
El -92.5

Capacity FS =2

74 ton * 2 t/k /2
= 74 kips



3.1 – Axial Capacity

Tension

Trial Pile Tip El -92.5

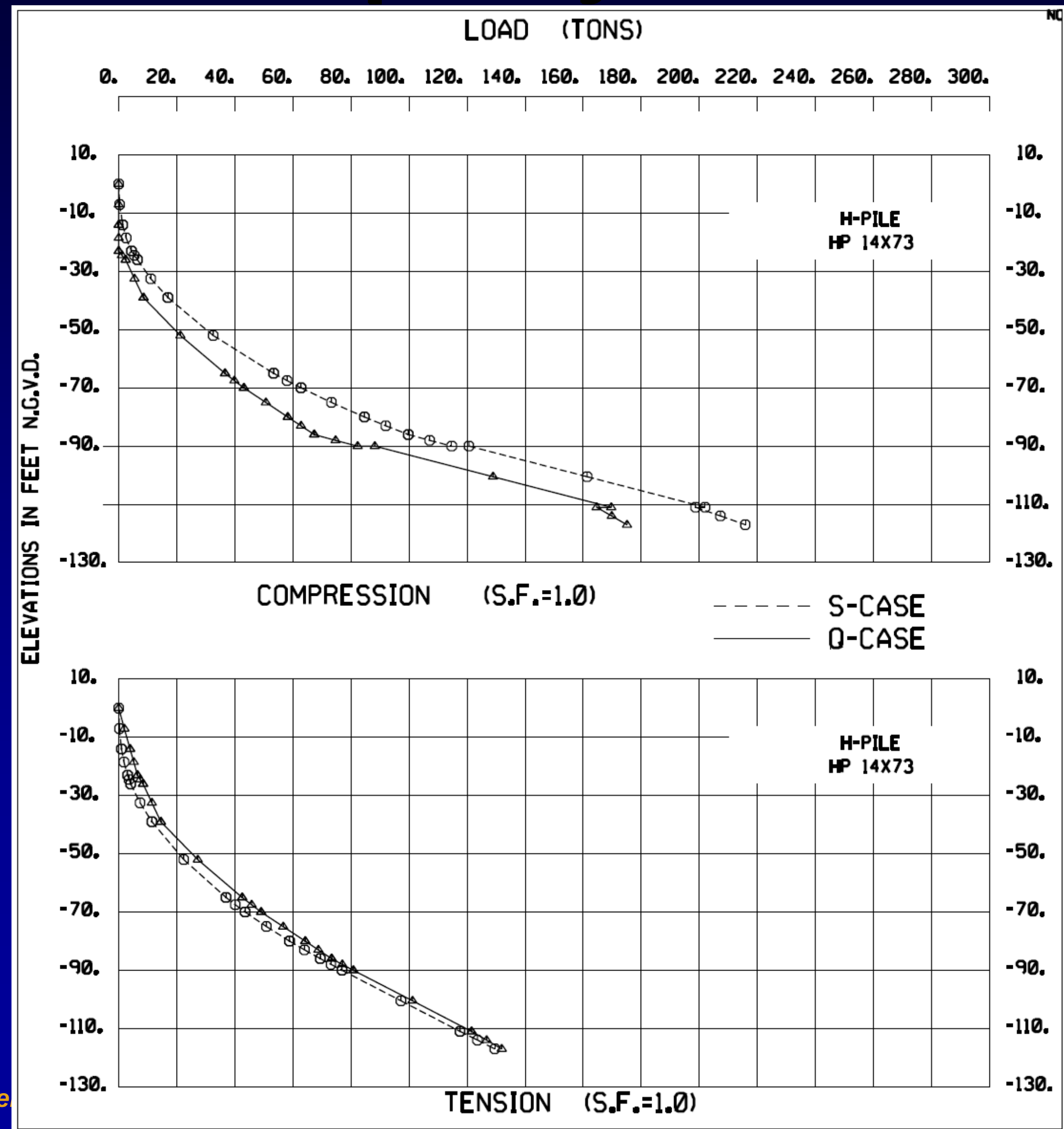
Ultimate = 81 tons

Capacity to -23 = 7 tons

Net Ultimate = 81 – 7 = 74 ton

FS = 3.0 – theoretical

Cap = 74 / 2t/k * 3.0 = 49 kip



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3.2 Lateral Capacity

Compute a lateral capacity at the elevation of the lowest failure surface with L-pile or COM624G

- Analyze with the top of the pile as a free head
- Add surcharge as thin layer with high unit weight
- Curve not Bilinear – carry to pile yield
- Factors of Safety for Calculated Loads (3.0)

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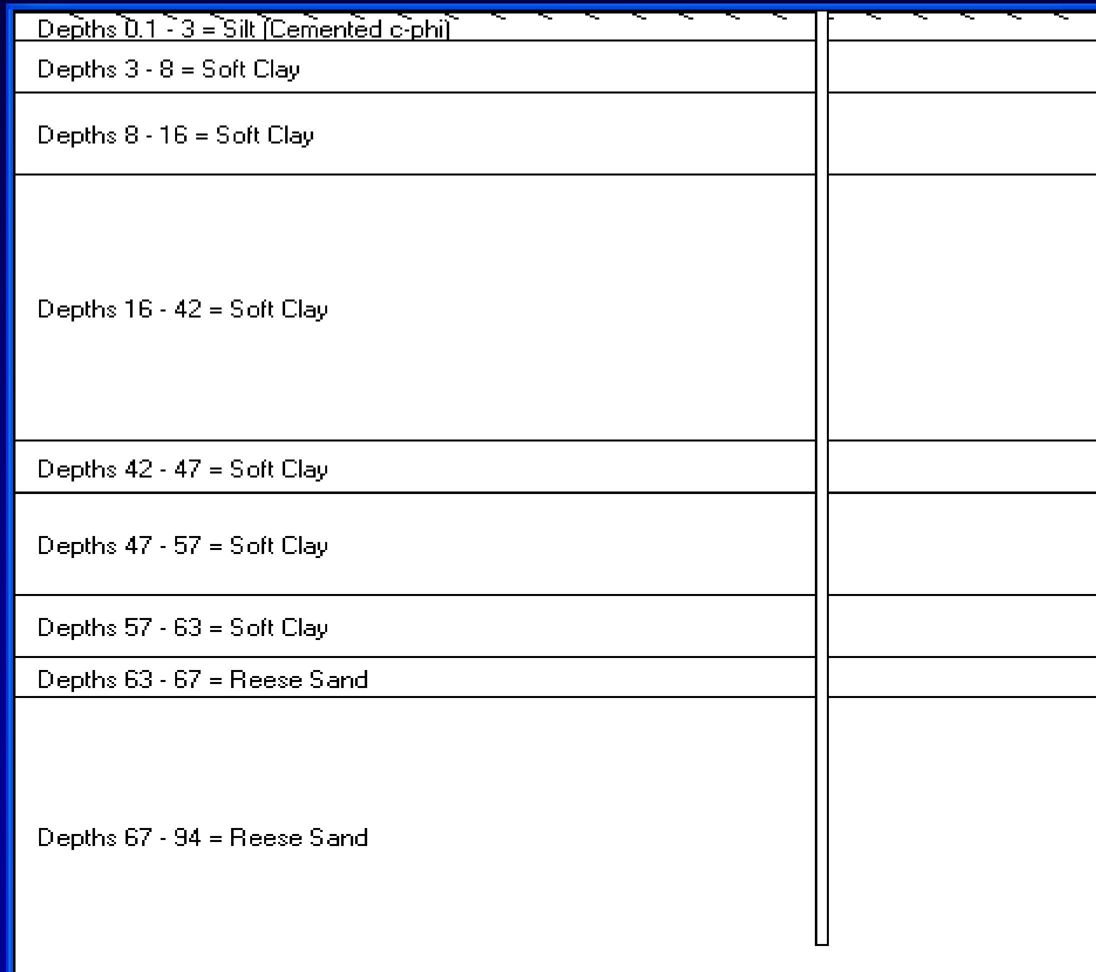
3.2

Compute Moment Capacity of HP 14x73

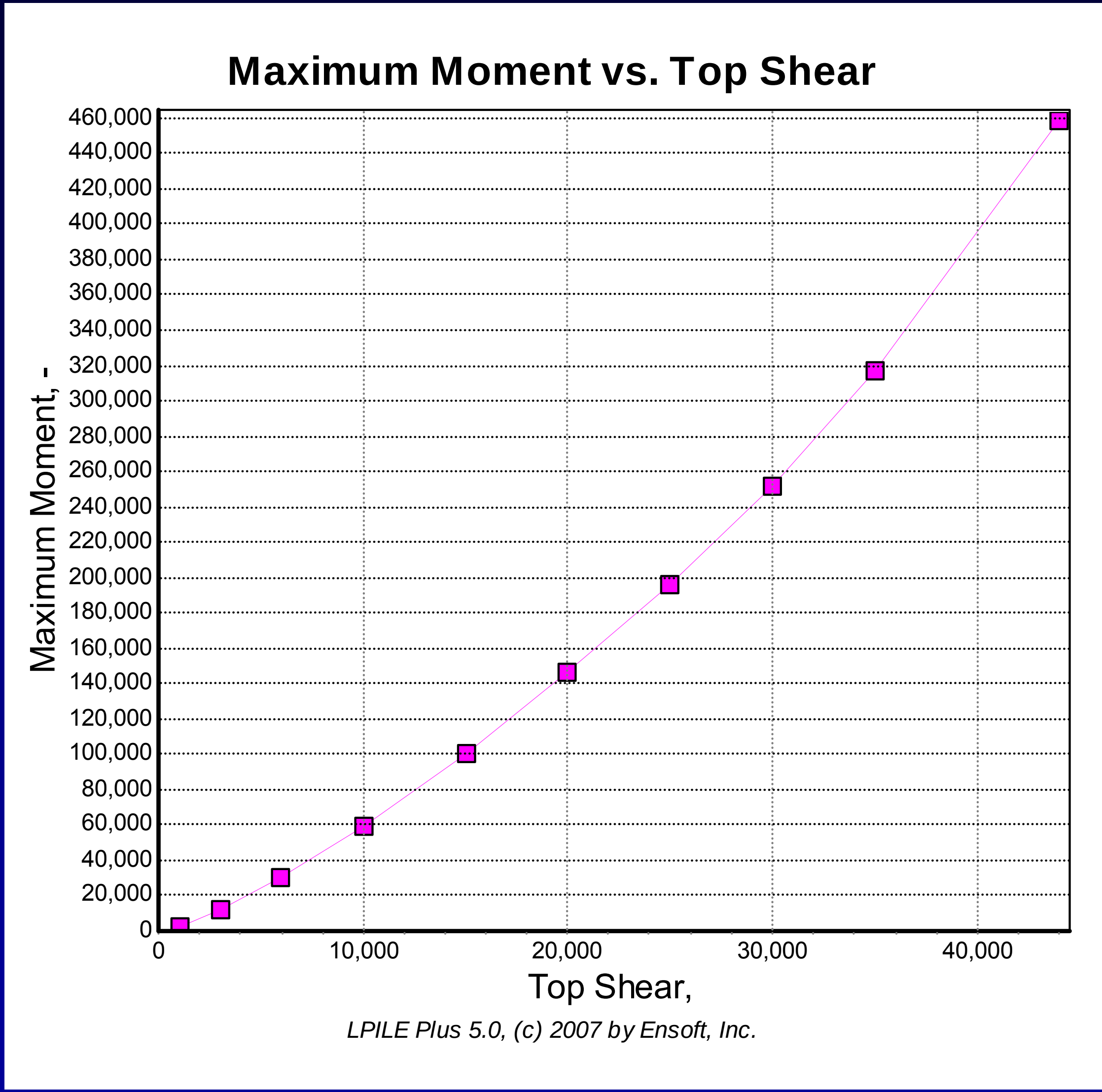
$F_y S_x = 50 \text{ ksi} \times 107 \text{ in}^3$

$= 5{,}350 \text{ lb-in}$

$= 456 \text{ kip–ft}$

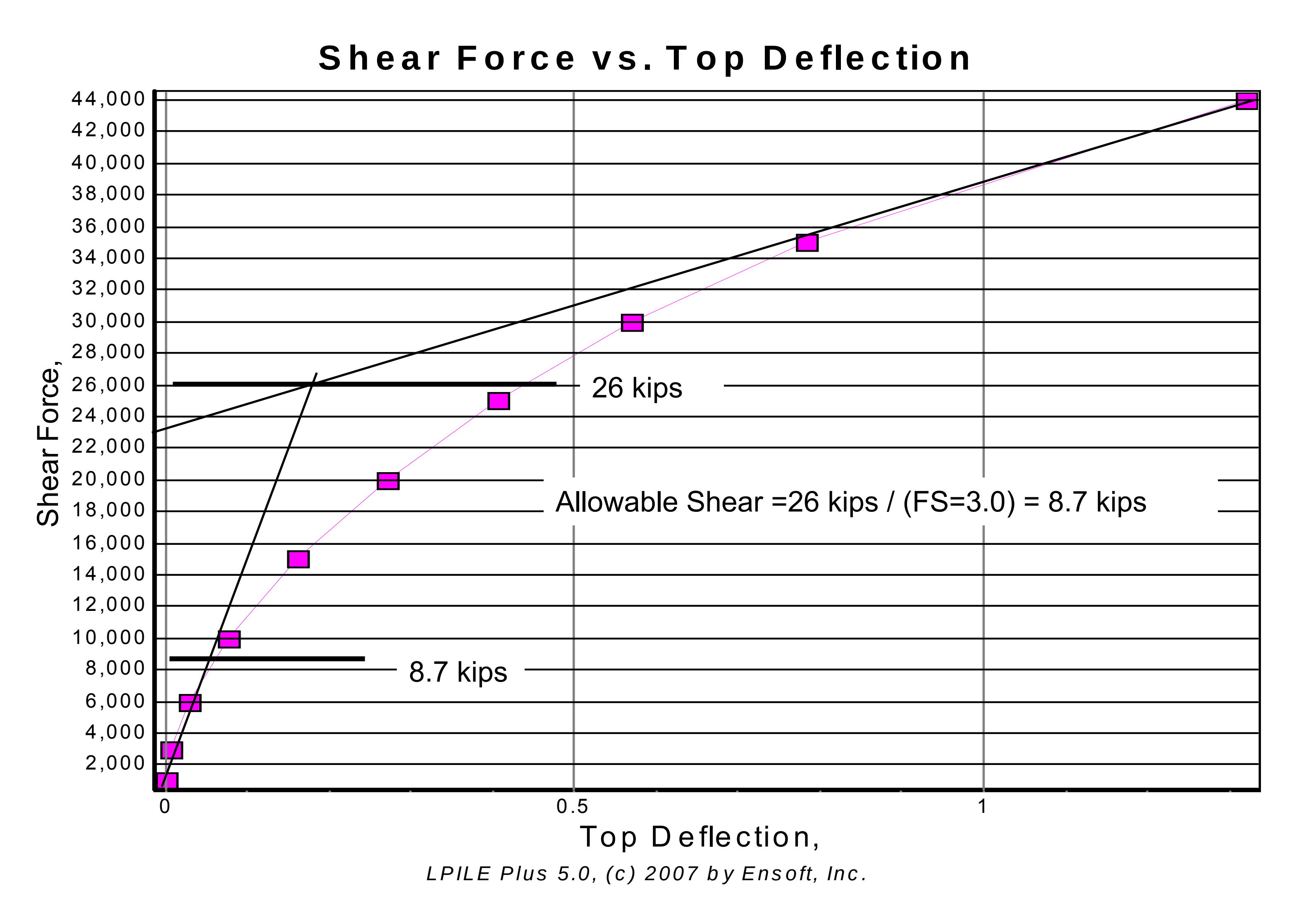


3.2



Maximum Moment vs. Top Shear
Maximum Moment, -
460,000
440,000
420,000
400,000
380,000
360,000
340,000
320,000
300,000
280,000
260,000
240,000
220,000
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10,000
20,000
30,000
40,000
Top Shear,
LPILE Plus 5.0, (c) 2007 by Ensoft, Inc.

Step 3



Shear Force vs. Top Deflection
Shear Force,
Top Deflection,
44,000
42,000
40,000
38,000
36,000
34,000
32,000
30,000
28,000
26,000
24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0.5
1
26 kips
Allowable Shear =26 kips / (FS=3.0) = 8.7 kips
8.7 kips
LPILE Plus 5.0, (c) 2007 by Ensoft, Inc.

$R = \sqrt{\frac{EI}{ES}}$

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Step 4

- **Preliminary Layout**
- **CPGA and compute Equivalent Force in Cap**
- **Normal Structural Loads above Base, Unbalanced Load Below Base**
- **CPGA Approximates Group – Not an Alternative to**
- **Load Cases as defined in HSDRS Design Criteria**
- **Check Flow through**

Step 4

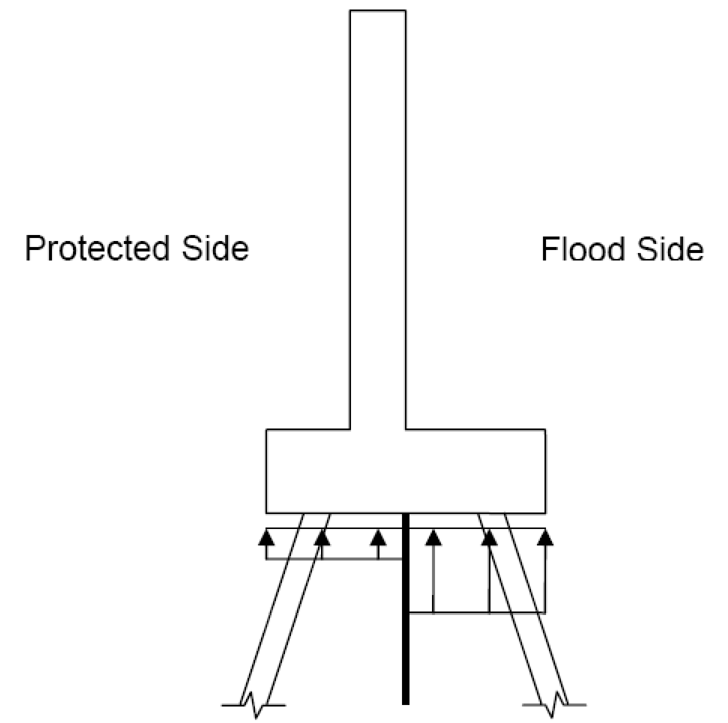


Figure 5.4 Impervious Sheet Pile Cut-off

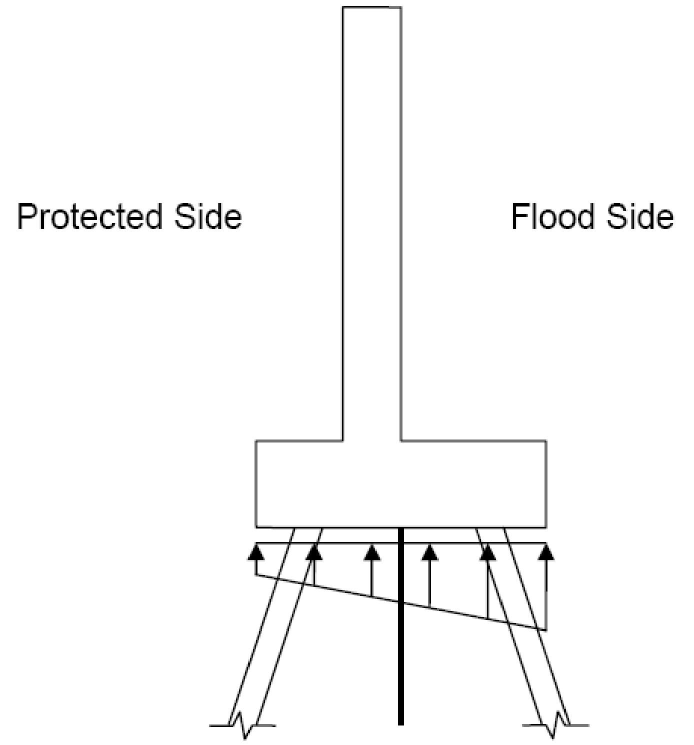


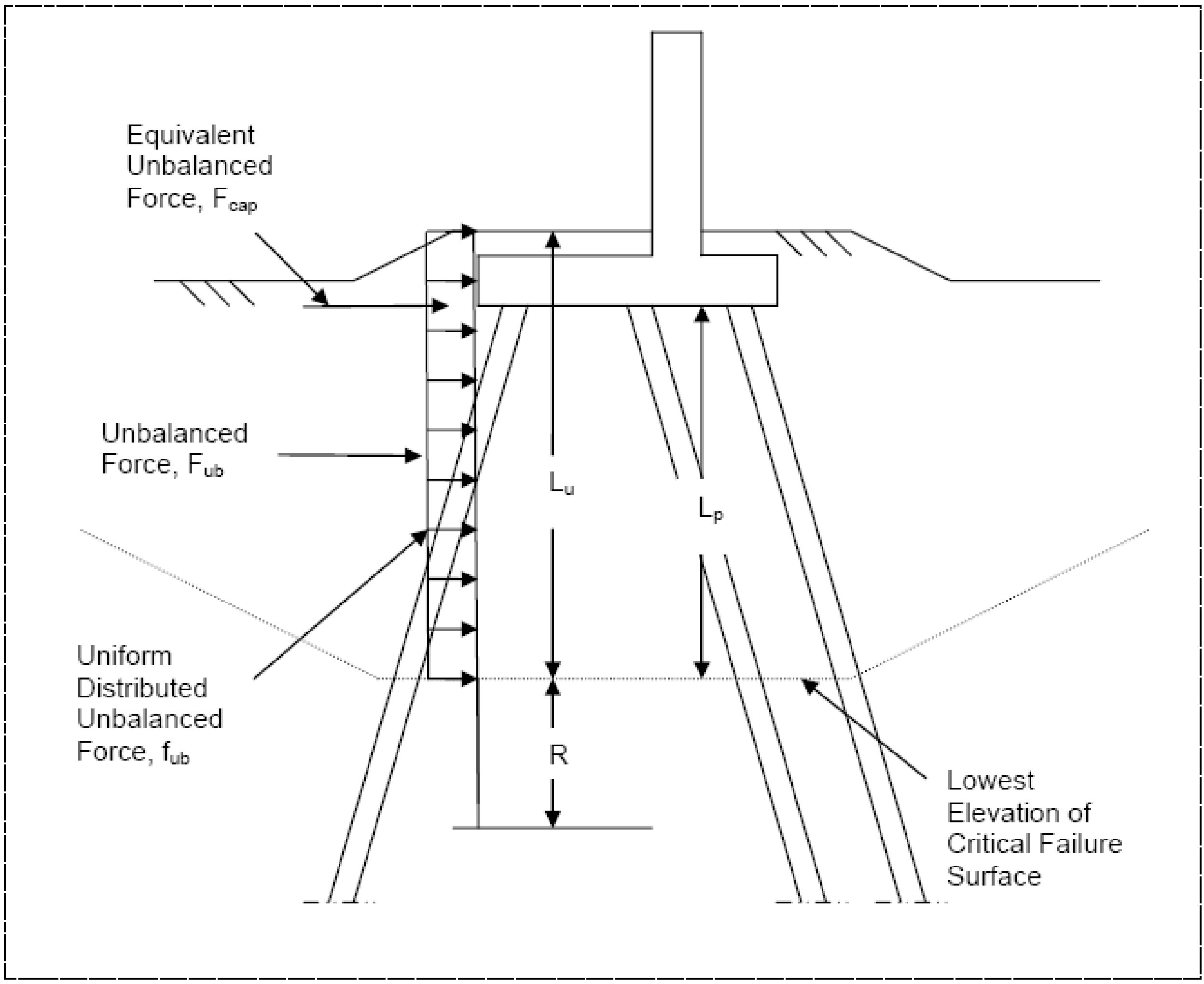
Figure 5.5 Pervious Sheet Pile Cut-off

4.1 Calculate Fcap

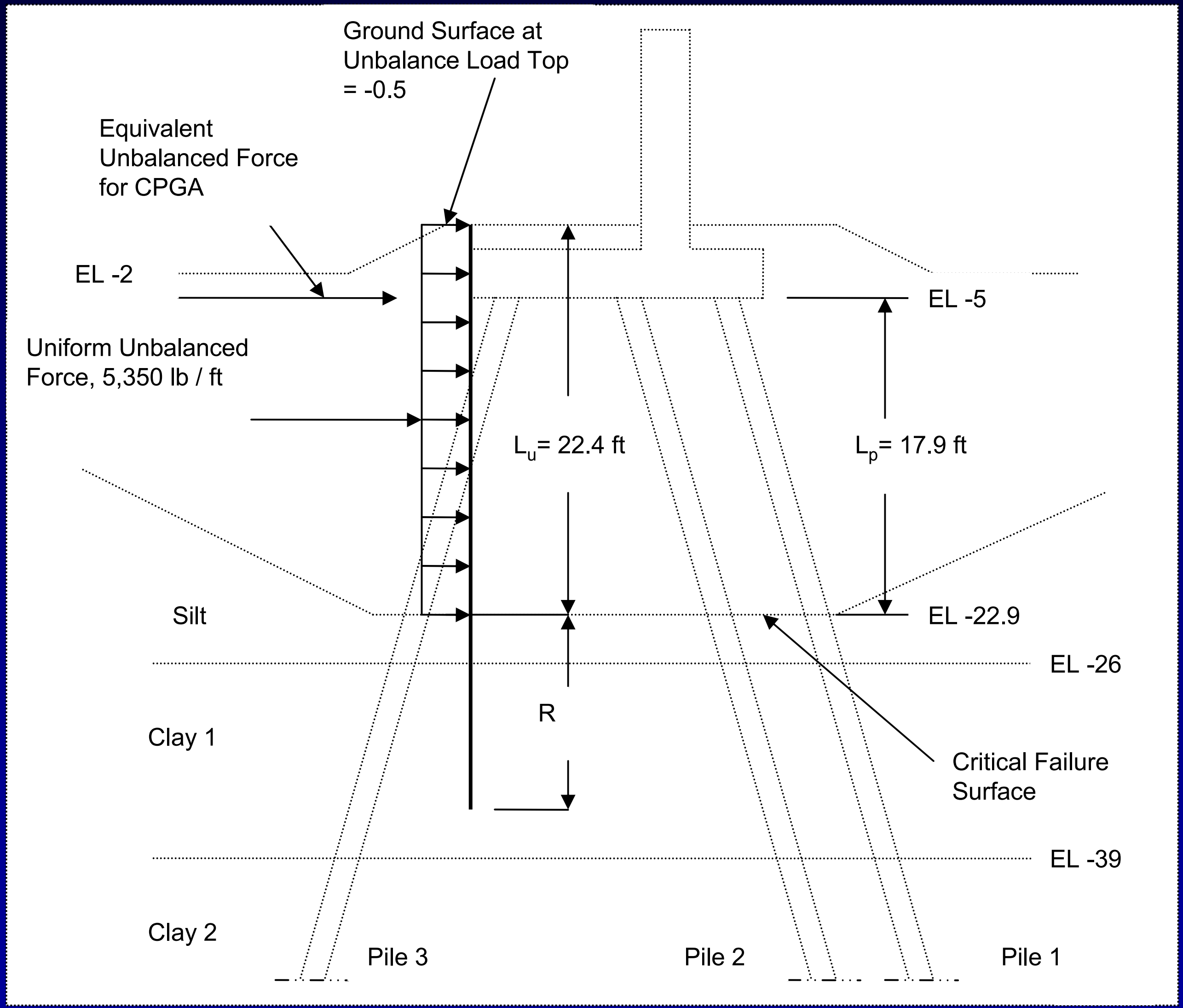
$$F_{cap} = F_{ub}\left[\frac{\left(\frac{L_p}{2}+R\right)}{\left(L_p+R\right)}\right]\frac{L_p}{L_u}$$

$$R = \sqrt[4]{\frac{EI}{Es}}$$

EI are Pile Properties
Es is below failure surface



4.1 Example



Ground Surface at
Unbalance Load Top
= -0.5
Equivalent
Unbalanced Force
for CPGA
EL -2
EL -5
Uniform Unbalanced
Force, 5,350 lb / ft
L_u= 22.4 ft
L_p= 17.9 ft
Silt
EL -22.9
EL -26
R
Clay 1
Critical Failure
Surface
EL -39
Clay 2
Pile 3
Pile 2
Pile 1

4.1 R and F_{cap}

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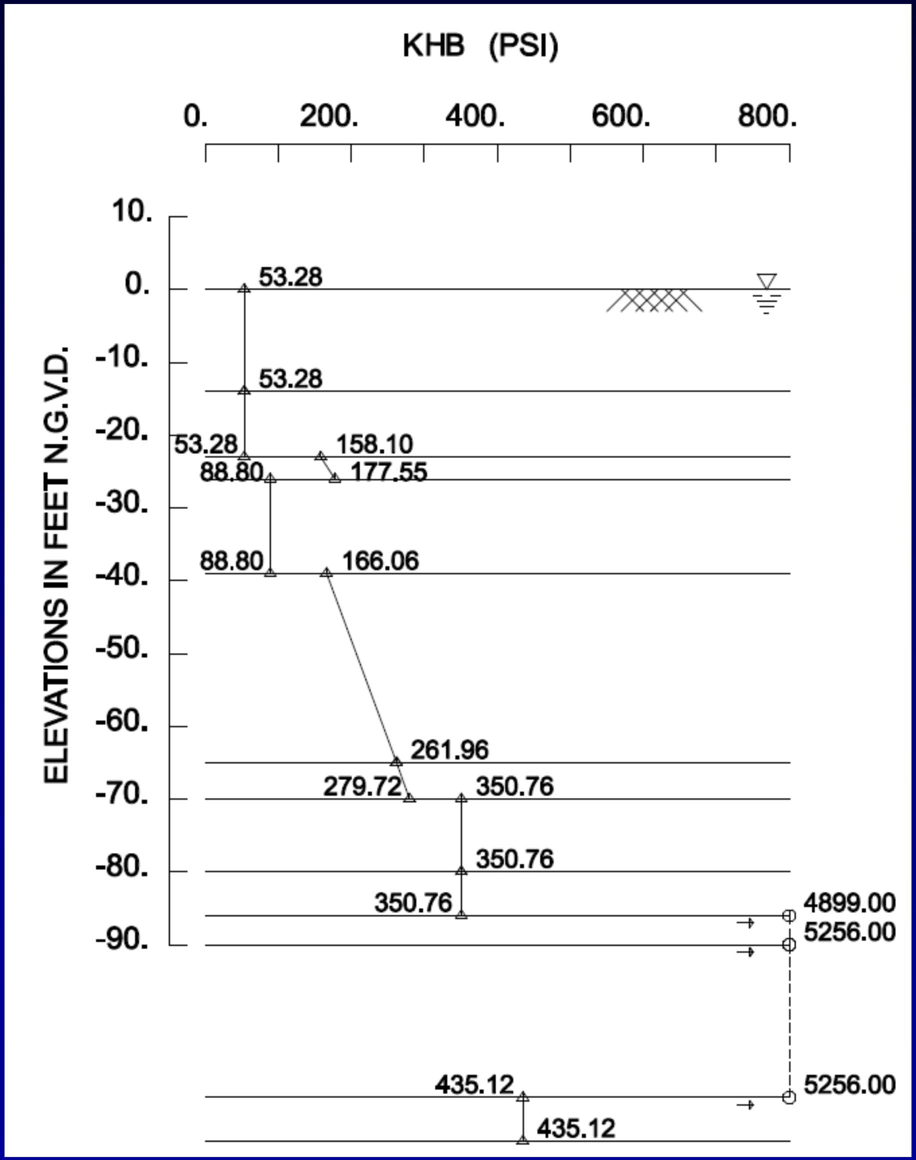
Piles

- HP 14x73.
- $I = 729\ in^4$
- $E = 29{,}000\ ksi$

Es for R (-22.9)

Average silt and upper clay

Es = 100 psi



$$R = \sqrt[4]{\frac{29{,}000{,}000\,psi \times 729in^4}{100\,psi}} = 120.6in = 10.05\,ft$$

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4.1 – R and F_{cap}

$$R = \sqrt[4]{\frac{29{,}000{,}000\,psi \times 729in^4}{100\,psi}} = 120.6in = 10\,ft$$

$$F_{cap} = F_{ub} \times \left(\frac{\frac{L_p}{2} + R}{L_P + R} \right) \frac{L_p}{L_u} = 5{,}350lb/\,ft \times \left(\frac{\frac{17.9\,ft}{2} + 10\,ft}{17.9\,ft + 10\,ft} \right) \frac{17.9}{22.4} = 2{,}904lb/\,ft$$

4.1 – Calculate Results

US Army Corps of Engineers / Saint Paul Distict	PROJECT TITLE: T-Wall Design Example	COMPUTED BY: KDH	DATE: 04/05/08	SHEET:
	SUBJECT TITLE: Water at El. 10', Pervious	CHECKED BY:	DATE:	

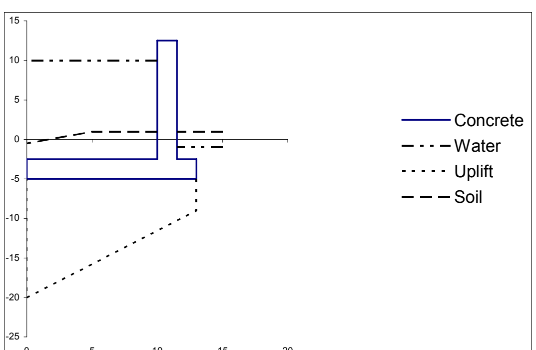
Input for CPGA pile analysis **Pervious Foundation Assumption**

Upstream Water Elevation	*10*	ft	Back Fill Soil Elevation	*1*	ft
Downstream Water Elevation	*-1*	ft	Front Fill Soil Elevation	*1*	ft
Wall Top Elevation	*12.5*	ft	Gamma Water	*0.0625*	kcf
Structure Bottom Elevation	*-5*	ft	Gamma Concrete	*0.15*	kcf
Base Width	*13*	ft	Gamma Sat. Backfill	*0.110*	kcf
Toe Width	*1.5*	ft	Distance to Backfill Break	*5.0*	ft
Wall Thickness	*1.5*	ft	Slope of Back Fill	*0.30*	
Base Thickness	*2.5*	ft	Soil Elevation at Heel	-0.50	ft

Vertical Forces								
Component	Height	x1	x2	Gamma	Force	Arm	Moment	
Stem Concrete	15	10	11.5	0.15	3.38	10.75	36.3	
Heel Concrete	2.5	0	11.5	0.15	4.31	5.75	24.8	
Toe Concrete	2.5	11.5	13	0.15	0.56	12.25	6.9	
Heel Water	9	0	10	0.0625	5.63	5	28.1	
Toe Water	1.5	11.5	13	0.0625	0.14	12.25	1.7	
Heel Soil	3.5	0	10	0.110	3.85	5	19.3	
-Triangle	1.50	0	5.0	-0.048	-0.18	1.67	-0.3	
Toe Soil	3.5	11.5	13	0.110	0.58	12.25	7.1	
Rect Uplift	-4	0	13	0.0625	-3.25	6.5	-21.1	
Tri Uplift	-11	0	13	0.0625	-4.47	4.3	-19.4	
Sum Vertical Forces					10.5		83.4	ft-k

Horizontal Forces								
Component	H1	H2	Gamma	Lat. Coeff.	Force	Arm	Moment	
Driving Water	10	-5	0.0625	1	7.03	5.00	35.16	
Resisting Water	-1	-5	0.0625	1	-0.50	1.33	-0.67	
Lateraral soil forces assumed equal and negligible								
Sum Horizontal Forces					6.53	5.28	34.49	ft-k

Total Structural Forces	Net Vert. Force	Arm	Moment	
About Heel	10.55	11.17	117.84	ft-k



Net Vertical Arm		
From Toe	1.83	ft

Moment About Toe
-19.3 ft-k

Model Width
5 ft

US Army Corps of Engineers / Saint Paul Distict	PROJECT TITLE: T-Wall Design Example	COMPUTED BY: KDH	DATE: 04/05/08	SHEET:
	SUBJECT TITLE: Water at El. 10', Pervious	CHECKED BY:	DATE:	

Calculation of Unbalanced Force

Unbalanced Force. F_{ub}	*5,350*	lb/ft	From UTexas Analysis
Elevation of Critical Surface	*-22.9*	ft	From UTexas Analysis
Length - Ground to Crit. Surface, L_u	22.4	ft	(assume failure surface is normal to pile)
Length - Base to Crit. Surface, L_p	18	ft	
Pile Moment of Inertia. I	*729*	in^4	HP14x73
Pile Modulus of Elasticity E	*29,000,000*	lb/in^2	
Soil Modulus of Subgrade Reaction, Es	*100*	lb/in^2	
Soil Stiffness Parameter, R	121	in	$(EI / Es)^{1/4}$
Equivalent Unbalanced Force, F_{cap}	2,906	lb/ft	$F_{ub} * (L_p/2 + R) / (L_p + R) (L_p/L_u)$

Step 4 CPGA Input

PX	-47.19	kips
PY		
PZ	52.73	kips
MX	0	
MY	-96.29	kip-ft
MZ	0	

Group Input - Steps 5 and 6

3 Pile Rows Parallel to Wall Face

Unbalanced Loading on Piles for Group Analysis

Total	100	lb/in	F_{ub} * Model Width /L_u
50%	50	lb/in	For Pile on Protected Sied
25%	25	lb/in	

Note: Applied to length of pile from bottom of cap to top of critical surface. 18

Step 5 Cap Loads for Group Analysis

PX	52,731	lb
PY	32,656	lb
PZ	0	lb
MX	0	
MY	0	
MZ	1,155,441	lb-in

Step 6 Cap Loads for Group Analysis of Unbalanced Load

Distance From Base to Ground Surface, Ds 4.50 ft

PX	0	lb	
PY	5,374	lb	F_{ub} * Model Width / L_u * Ds
PZ	0	lb	
MX	0		
MY	0		
MZ	-145,095	lb-in	-PZ * Ds/2

$E_s = \frac{(1.5-1.2)}{(1.5-1.0)}(100\,psi) = 40\%(100) = 40\,psi$

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4.2 - CPGA Es

Es = 0 (0.000001) for FS<1 (Ground Surface)

Es ratio from 0 to full theoretical Es for FS between 1 and Target FS

Example FS = 0.98 , Es Set to 0.000001

If the FS = 1.2, Target FS = 1.5, Es = 100 psi,

$$E_s = \frac{(1.5-1.2)}{(1.5-1.0)}(100\,psi) = 40\%(100) = 40\,psi$$

No distinction between leading and trailing rows

No cyclic reduction factors (won't matter much)

4.2 – Shallow Failure Surfaces

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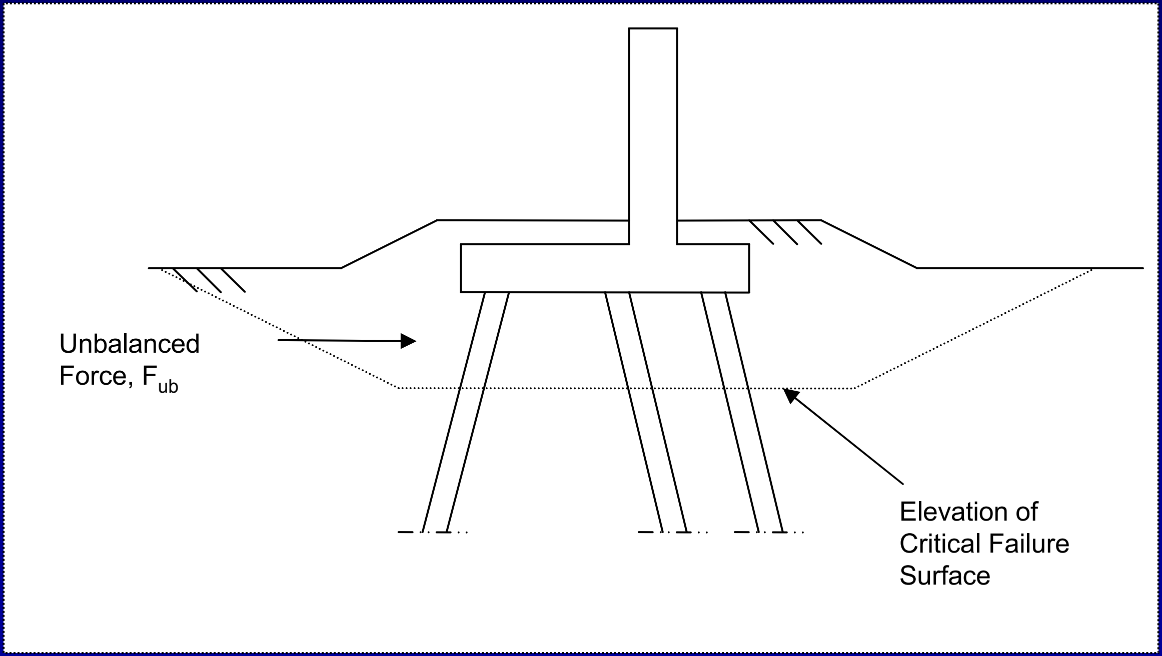
- Es= 0 Not so Good Approximation – not enough lateral support
- Won't Match Group Results
- Can Model Wall Suspended above failure surface



4.3 – Group Reduction

Group Reduction Factors - When Es is not 0

- Not required for Opposite Batters
- CPGA method is approximation
- Reduced Es reduces precision

Equations from Group Manual used

- More up-to-date than EM
- Similar to factors used in latest AASHTO

4.3 – Group Reduction

For loading perpendicular to the loading direction:

$$Rga = 0.64(s_a/b)^{0.34} \quad ; \text{ or } = 1.0 \text{ for } s_a/b > 3.75$$

Where:

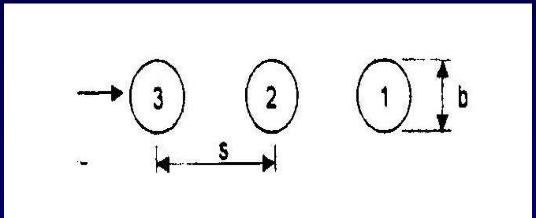
s_a = **spacing between piles perpendicular to the direction of loading (parallel to the wall face). Normally piles should be spaced no closer than 5 feet on center.**

b = **pile diameter or width**

4.3 – Group Reduction

For loading parallel to the loading direction:

For leading (flood side) piles:



$$Rgbl = 0.7(s_b/b)^{0.26} \quad ; \text{ or } = 1.0 \text{ for } s_b/b > 4.0$$

For trailing piles, the reduction factor, *Rgbt* is:

$$Rgbt = 0.48(s_b/b)^{0.3}; \text{ or } = 1.0 \text{ for } s_b/b > 7.0$$

Trailing Piles only follow piles with same batter

4.3 CPGA Analysis

LOAD CASE - 1 Pervious Uplift Assumption

PILE	F1	F2	F3	M1	M2	M3	ALF	CBF
	K	K	K	IN-K	IN-K	IN-K		
1	.0	.0	5.2	.0	-3.3	.0	.07	.02
2	.0	.0	97.2	.0	-3.0	.0	1.31	.31
3	.0	.0	-46.8	.0	3.1	.0	.96	.15

LOAD CASE - 2 Impervious Uplift Assumption

PILE	F1	F2	F3	M1	M2	M3	ALF	CBF
	K	K	K	IN-K	IN-K	IN-K		
1	.0	.0	12.5	.0	-3.0	.0	.17	.04
2	.0	.0	94.4	.0	-2.8	.0	1.28	.30
3	.0	.0	-42.3	.0	2.9	.0	.86	.14

PILE CAP DISPLACEMENTS

LOAD CASE	DX	DZ	R
	IN	IN	RAD
1	-.6619E+00	-.2626E+00	-.2868E-02
2	-.6125E+00	-.2266E+00	-.2549E-02

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4.4 Sheet pile

Sheet pile as required for seepage

Or Minimum 5’ Below Critical Failure Surface

Minimum Size - PZ -22 – No Analysis

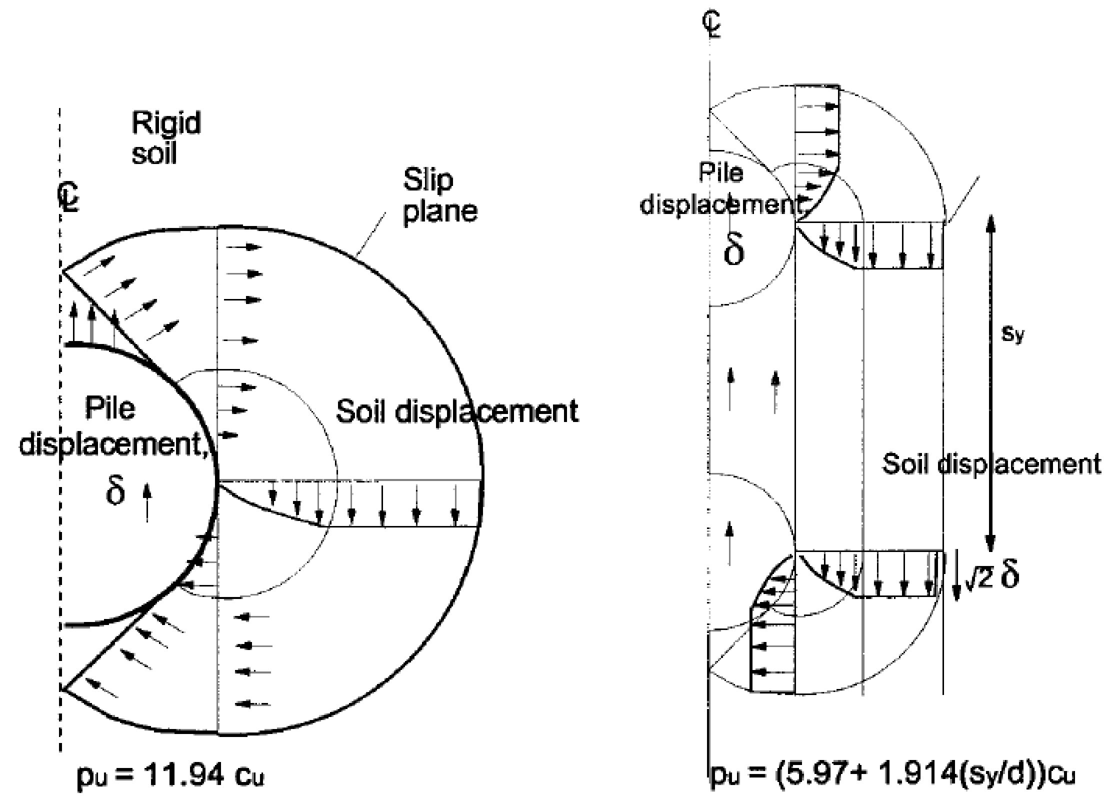
Example Tip Elevation = -23 - 5 = -28

4.5 Flow Through Check 1

Pile Lateral Capacity

Basic Capacity

$P_{ult} = 9Cu$



a) Widely spaced piles (Randolph and Houlsby, 1984)

b) Piles linked across rows

$\sum P_{all} = \frac{n \sum P_{ult}}{1.5}$

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4.5 Flow Through

Compute Capacity of Floodside Row

$$\sum P_{all} = \frac{n \sum P_{ult}}{1.5}$$

n = number of piles in row per monolith

ΣP_{ult} = summation of P_{ult} *over the height Lp*

$P_{ult} = \beta(9S_u b)$

S_u = soil shear strength

b = pile width

β = group reduction factor pile spacing parallel to the load (Defined in criteria)

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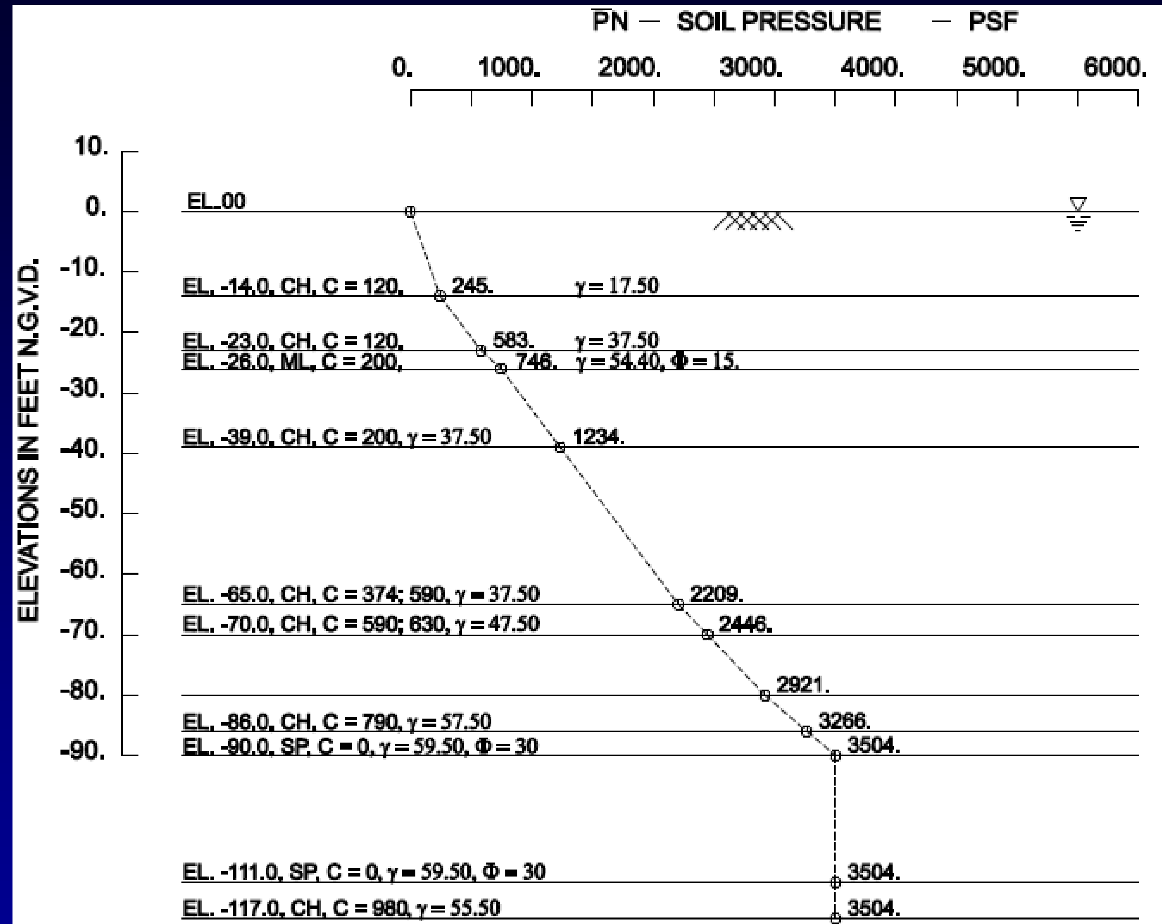
4.5

Soils under slab, S_u = 120 psf to failure surface

Pile width, b = 14”

Group reduction factor, not applicable (single row on flood side), Rf = 1



$$P_{ult} = 1.0(9)(120\,psf)\left(\frac{14in}{12\frac{in}{ft}}\right) = 1{,}260lb/\,ft$$

4.5

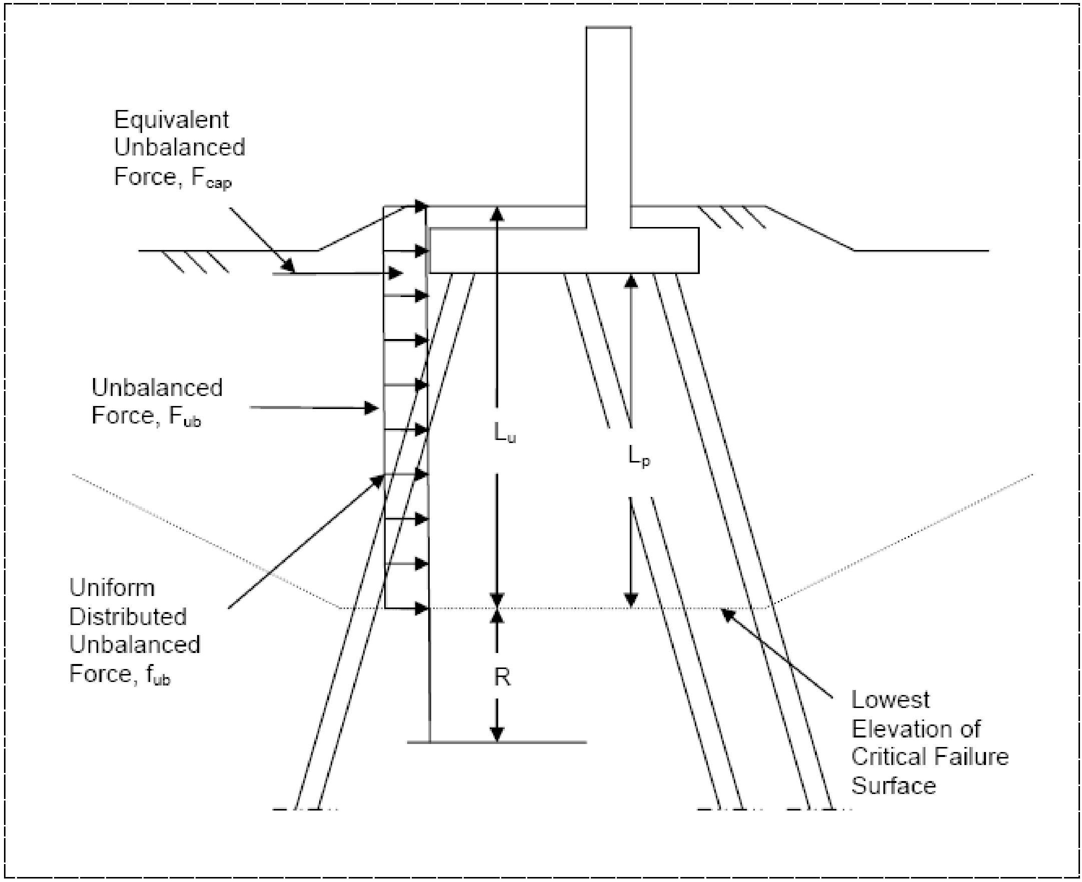
Capacity of Floodside Rows

ΣP_{ult} = summation of P_{ult} over the height L_p,

ΣPult = 1,260 lb/ft(17.9 ft)
= 22,554 lb

$$\sum P_{all} = \frac{n \sum P_{ult}}{1.5}$$

ΣPall = 1(22,554lb) /1.5
= 15,036 lb



$F_p = wf_{ub}L_p$

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4.5

Compute Unbalanced Load on Piles to check against ΣP_{all}

$$F_p = w f_{ub} L_p$$

w = Monolith width or Pile Spacing

$$f_{ub} = \frac{F_{ub}}{L_u}$$

F_{ub} = Total unbalanced force per foot from Step 2

L_u and L_p as defined in paragraph 4.1

4.5

F_{ub} = Total unbalanced force per foot from Step 2
= 5,350 lb/ft

L_u = 22.4 ft
L_p = 17.9 ft

f_{ub} = 5,350 lb/ft / 22.4 ft
= 239 lb/ft/ft

$$f_{ub} = \frac{F_{ub}}{L_u}$$

F_p = 5 ft x 239 lb/ft/ft x 17.9ft
= 21,391 lb

$$F_{up} = w f_{ub} L_p$$

4.5

If 50% of $F_p < \Sigma P_{all}$ then OK

If 50% of $F_p > \Sigma P_{all}$ then:

compute ΣP_{all} for all of the piles

If ΣP_{all} for all piles $> F_p$ then OK

If ΣP_{all} for all piles $< F_p$ then Redesign

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4.5

F_p = 21,391 lb

50% of F_p = 21,391 lb(0.50) = 10,695 lb

ΣPall = 15,036 lb > 10,695 lb

OK

4.6 Second Flow Through Check

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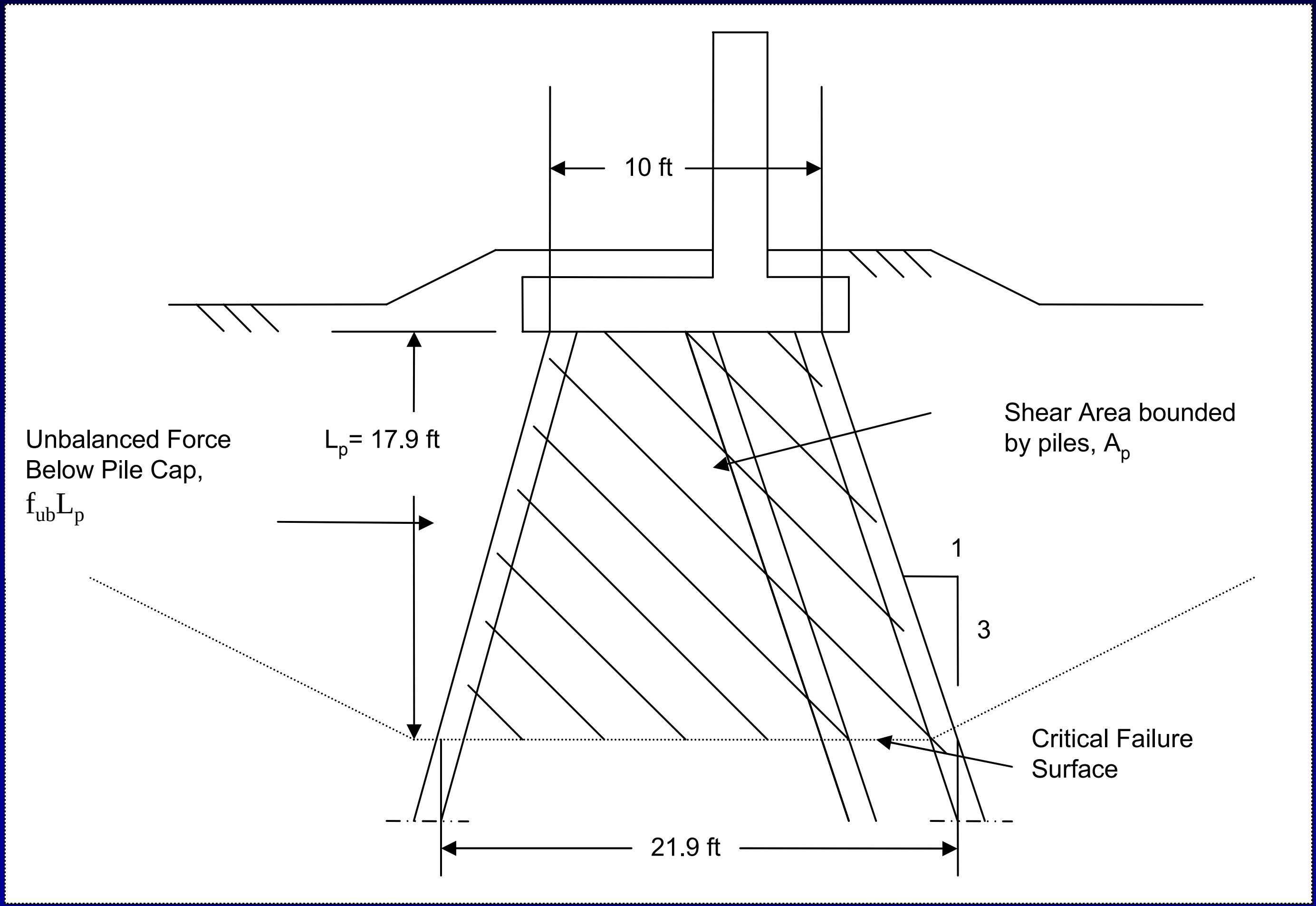
Shear Along Planes Bounded by Piles



$$A_p S_u \le 17.9\,ft\left(\frac{10\,ft + 21.9\,ft}{2}\right)(120\,psf) = 34,260\,lb$$

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4.6

$$f_{ub} L_p \le \frac{A_p S_u}{FS}\left[\frac{2}{(s_t - b)}\right]$$

$A_p S_u$ **= The area bounded by the bottom of the T-wall base, the critical failure surface, the upstream pile row and the downstream pile row multiplied by the shear strength of the soil within that area.**

For layered soils, the product of the area and Su for each layer is computed and added for a total ApSu. See Figure 3.

FS **= Target factor of safety used in Steps 1 and 2.**

= 1.5

$$f_{ub}L_p \le \frac{A_p S_u}{FS}\left[\frac{2}{(s_t - b)}\right]$$

4.6

$$f_{ub}L_p \le \frac{A_p S_u}{FS}\left[\frac{2}{(s_t - b)}\right]$$

s_t = the spacing of the piles transverse (perpendicular) to the unbalanced force

= 5 ft

***b* = pile width**

= 14 in

$f_{ub}L_p \le \frac{A_p S_u}{FS}\left[\frac{2}{(s_t - b)}\right]$

US Army Corps of Engineers

4.6

$$A_p S_u = 17.9\,ft\left(\frac{10\,ft + 21.9\,ft}{2}\right)(120\,psf) = 34{,}260\,lb$$

$$\frac{A_p S_u}{FS}\left[\frac{2}{(s_t - b)}\right] = \frac{34{,}260}{1.5}\left[\frac{2}{5 - \left(\frac{14}{12}\right)}\right] = 11{,}917$$

$$f_{ub}L_p \le \frac{A_p S_u}{FS}\left[\frac{2}{(s_t - b)}\right]$$

$f_{ub}L_p$ = (239 lb/ft)(17.9 ft) = 4,278 lb/ft

OK

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Step 5 Group 7 Analysis

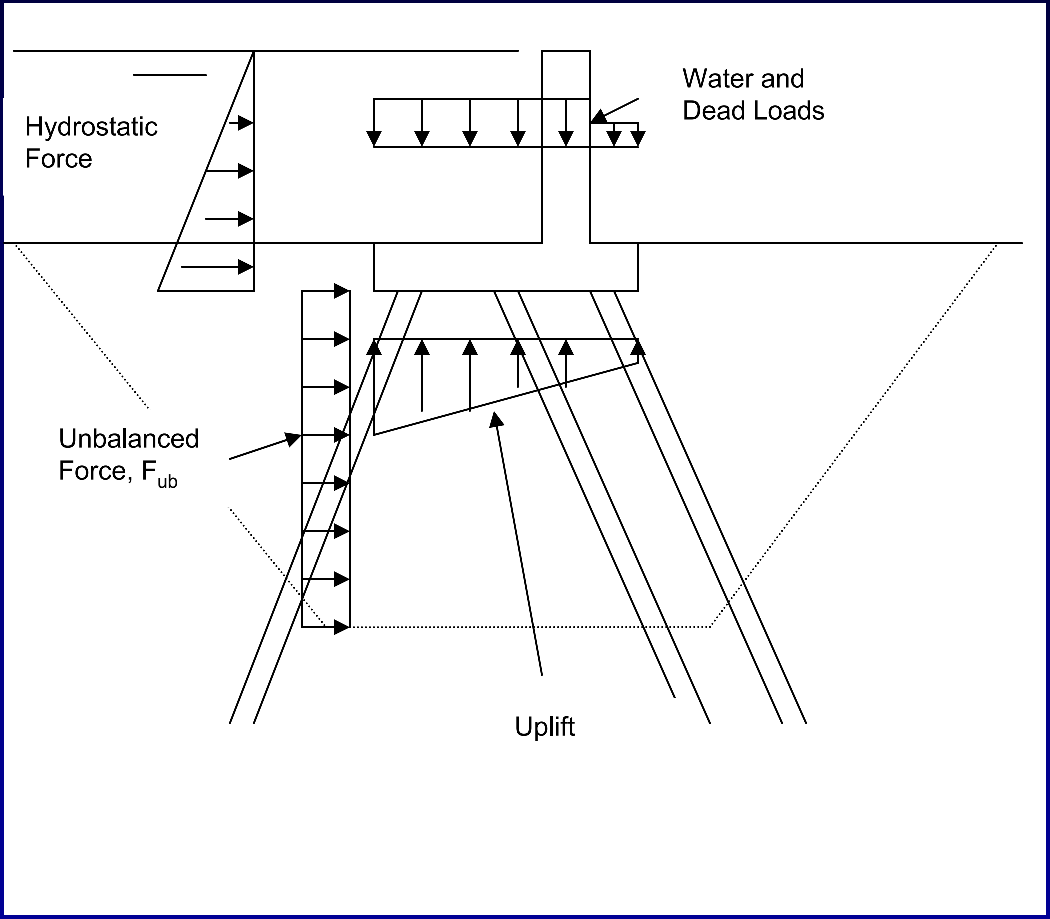
5.1

Only Critical Load Cases.

5.2

- Apply "Structural" loads at base and above to wall. (Water, Soil, Dead Loads).

- Unbalanced Load Applied Directly to Piles

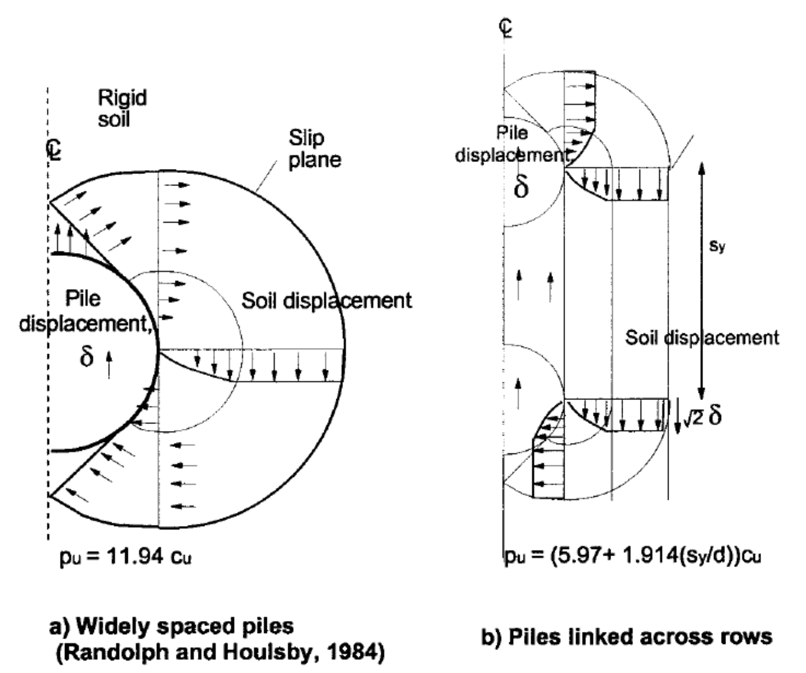


5.3

- **Look at flood side row with 50% Unbalance Force**
  - If $n\Sigma P_{ult} > 50\%\ F_p$ then 50% Unbalanced Force on Floodside row $0.5 f_{ub} s_t$ and the rest equally on remaining rows
  - If $n\Sigma P_{ult} < 50\%\ F_p$ then load = P_{ult} on Flood side row and the rest equally

    on remaining rows

  - P_{ult} Not P_{all}



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5.3

- Check if ($n\Sigma P_{ult}$) of the flood side pile row is greater than 50% F_p, (from 4.5)

.

- ($n\Sigma P_{ult}$) = 1 (22,554 lb) = 22,554 lb

- 50% F_p = (0.50)(21,391) = 10,696 lb

- Since $n\Sigma P_{ult}$ > 50% F_p, then 50% F_p will be applied to the flood side piles
  - uniform load $=0.5 f_{ub} s_t$
  - remaining 50% F_p will be applied equally to the remaining piles.

5.3

Distribute 50% of F_p onto the flood side (left) row of piles:

- **$0.5f_{ub}s_t = 0.5$ (239 lb/ft/ft)(5 ft)**
- **= 597.5 lb/ft = 50 lb/in**

The remainder is divided among the remaining piles.

- **Middle pile = 25 lb/in**
- **Right pile =25 lb/in**

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5.3

Check of Pile Stresses

100 % F_p applied to the flood side piles, < $n\Sigma P_{ult}$

Verify that 100% F_p does not exceed $n\Sigma P_{ult}$:

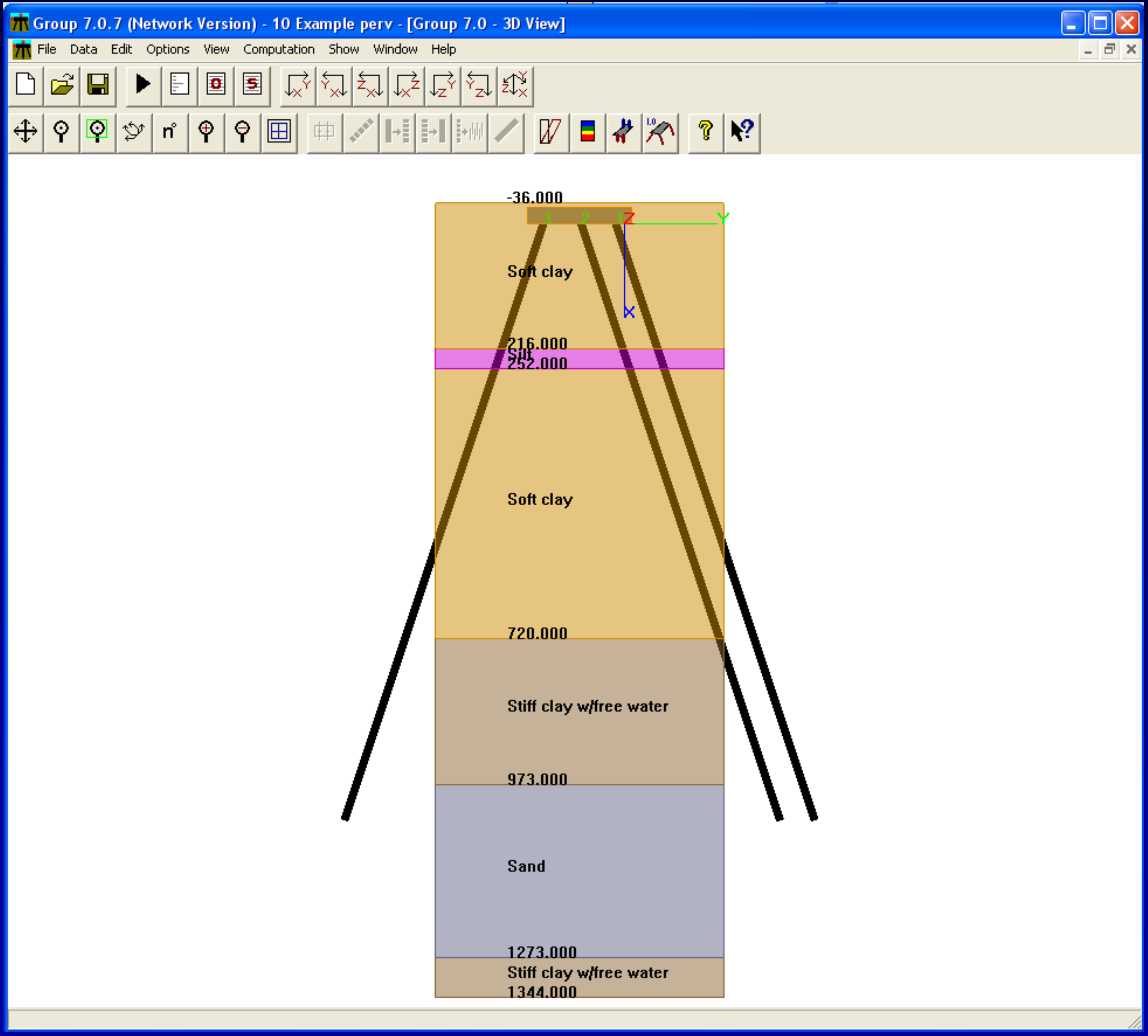
$$100\%F_p = 21,391 \text{ lb}$$

$$n\Sigma P_{ult} = 1\ (22{,}554 \text{ lb}) = 22{,}554 \text{ lb}$$

Since, 100% F_p < $n\Sigma P_{ult}$, 100% F_p distributed on the flood side piles

$f_{ub}s_t$ = (239 lb/ft/ft)(5 ft) = 1,195 lb/ft = 100 lb/in

5.5



Group 7.0.7 (Network Version) - 10 Example perv - [Group 7.0 - 3D View]
File Data Edit Options View Computation Show Window Help
-36.000
Soft clay
216.000
Silt
252.000
Soft clay
720.000
Stiff clay w/free water
973.000
Sand
1273.000
Stiff clay w/free water
1344.000

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5.6

Can use Group developed PY curves

Curves on piles from bottom of cap to lowest elevation of failure surface are adjusted to account for moving soil mass

Clay stiffness depends on C and e50

Sand stiffness depends on k and Phi

If FS < 1.0 then remove lateral resistance by making cohesion in soil layers very small (or k for sands)

IF FS >1.0 then ratio lateral resistance by ratio of factor of safety between 1.0 and target factor of safety – Multipy Cohesion (or k) by this percentage

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5.6

Our example

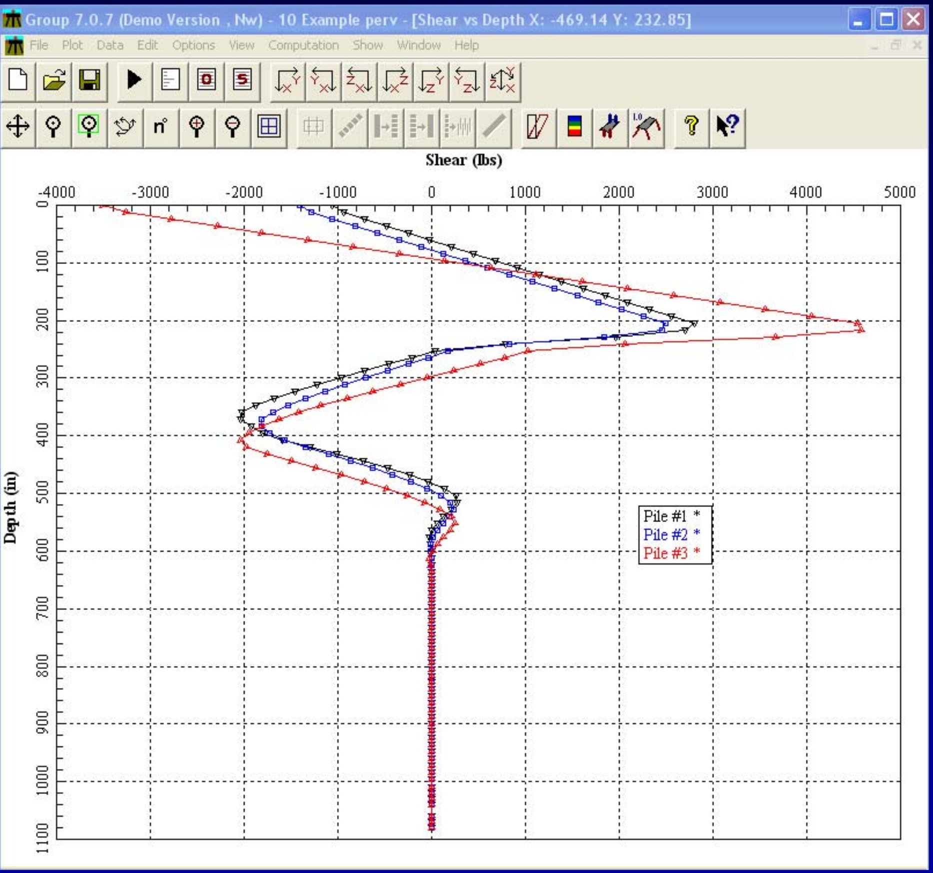
FS = 0.98

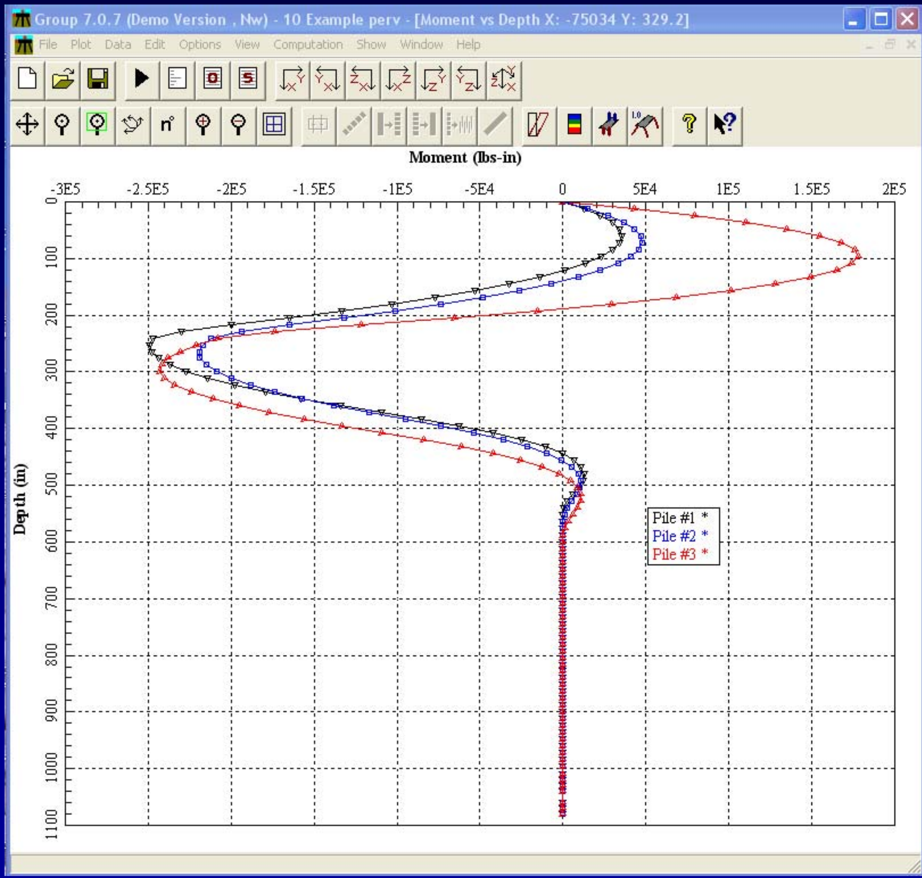
C = 0.0001

e50 does not need to be adjusted

K not used for Soft Clays

Step 5


Group 7.0.7 (Demo Version , Nw) - 10 Example perv - [Shear vs Depth X: -469.14 Y: 232.85]
File Plot Data Edit Options View Computation Show Window Help
Shear (lbs)
-4000 -3000 -2000 -1000 0 1000 2000 3000 4000 5000
Depth (in)
0 100 200 300 400 500 600 700 800 900 1000 1100
Pile #1 *
Pile #2 *
Pile #3 *


Group 7.0.7 (Demo Version , Nw) - 10 Example perv - [Moment vs Depth X: -75034 Y: 329.2]
File Plot Data Edit Options View Computation Show Window Help
Moment (lbs-in)
-3E5 -2.5E5 -2E5 -1.5E5 -1E5 -5E4 0 5E4 1E5 1.5E5 2E5
Depth (in)
0 100 200 300 400 500 600 700 800 900 1000 1100
Pile #1 *
Pile #2 *
Pile #3 *

5.6, 5.7

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- Compare output with allowables
- HSDRS Design Guides
- EM1110-2-2906
- Axial and Shear in Piles
  - Are compared with results from Step 3
  - Shear found at lowest critical surface elevation compared to capacity in Step 3

5.6, 5.7

Pervious Case – 50% on Floodside Pile

Pile	Axial (k)	Shear (k)	Max Moment (k-in)
1 Right	2.3 (C)	3.2	-227
2 Center	93.5 (C)	2.9	-207
3 Left	-39.9 (T)	5.2	314

Pervious Case – 100 % on Floodside Pile

Pile	Axial (k)	Shear (k)	Max Moment (k-in)
1 Right	1.3 (C)	1.8	-229
2 Center	98.6 (C)	1.6	-206
3 Left	-39.2 (T)	8.7	838

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5.6, 5.7

Impervious Case – 50% on Floodside Pile

Pile	Axial (k)	Shear (k)	Max Moment (k-in)
1 Right	9.2 (C)	3.1	-217
2 Center	91.5 (C)	2.9	-198
3 Left	-35.8 (T)	5.2	318

Impervious Case – 100 % on Floodside Pile

Pile	Axial (k)	Shear (k)	Max Moment (k-in)
1 Right	8.4 (C)	1.7	-216
2 Center	96.2 (C)	1.6	-193
3 Left	-34.9 (T)	8.7	843

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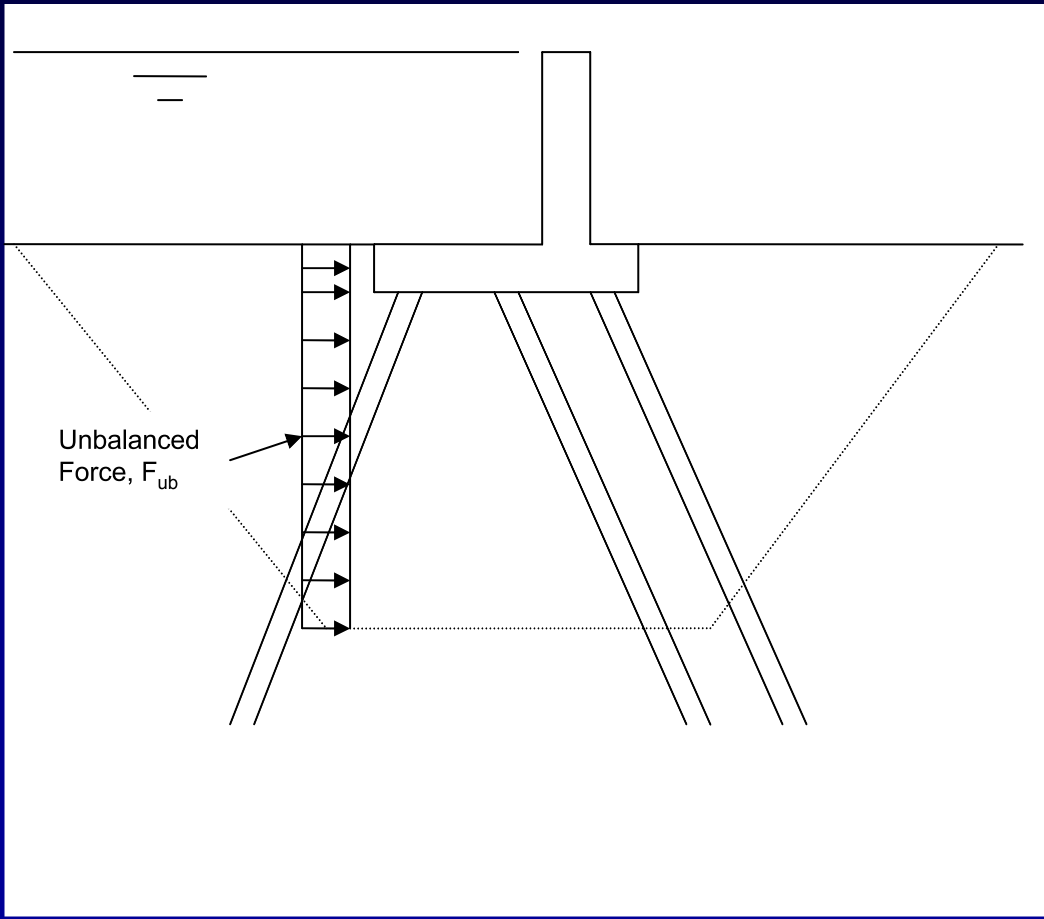
5.6, 5.7

Table Displacement of grouped pile foundation

Load Case	Load %	Horz (in)	Vert (in)
Pervious	50%	0.53	-0.21
Impervious	50%	0.49	-0.18
Pervious	100%	0.56	-0.22
Impervious	100%	0.52	-0.20

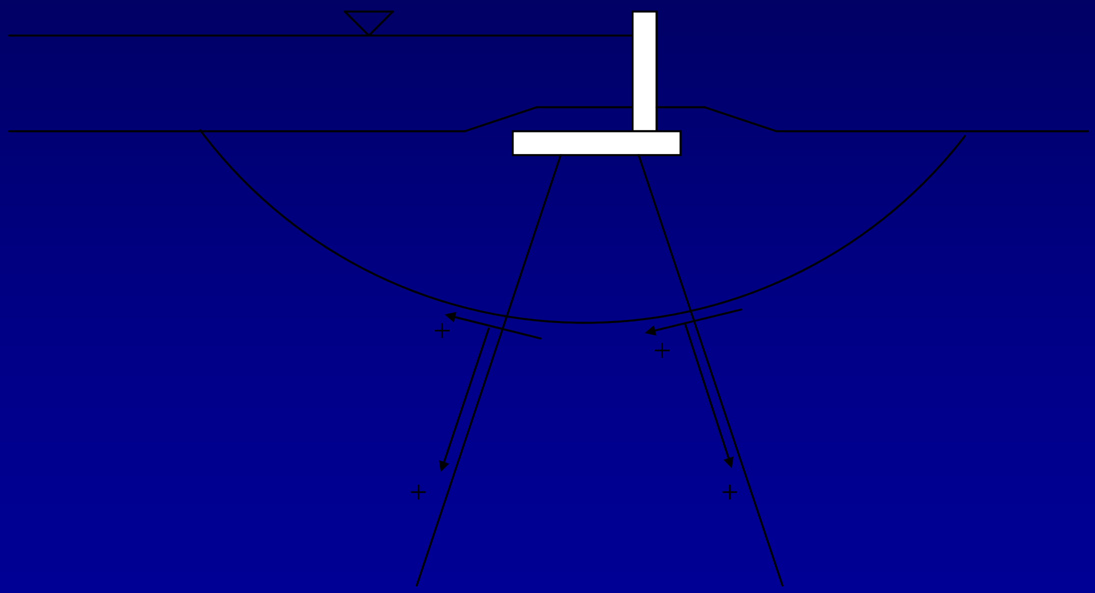
Step 6 (Optional)

NOT SHOWN



Step 7 (Optional) NOT COMPLETED

Global Stability Analysis with pile forces as reinforcement.



Question?

Thank You

Guidance on Long Structures And Trailing Structures

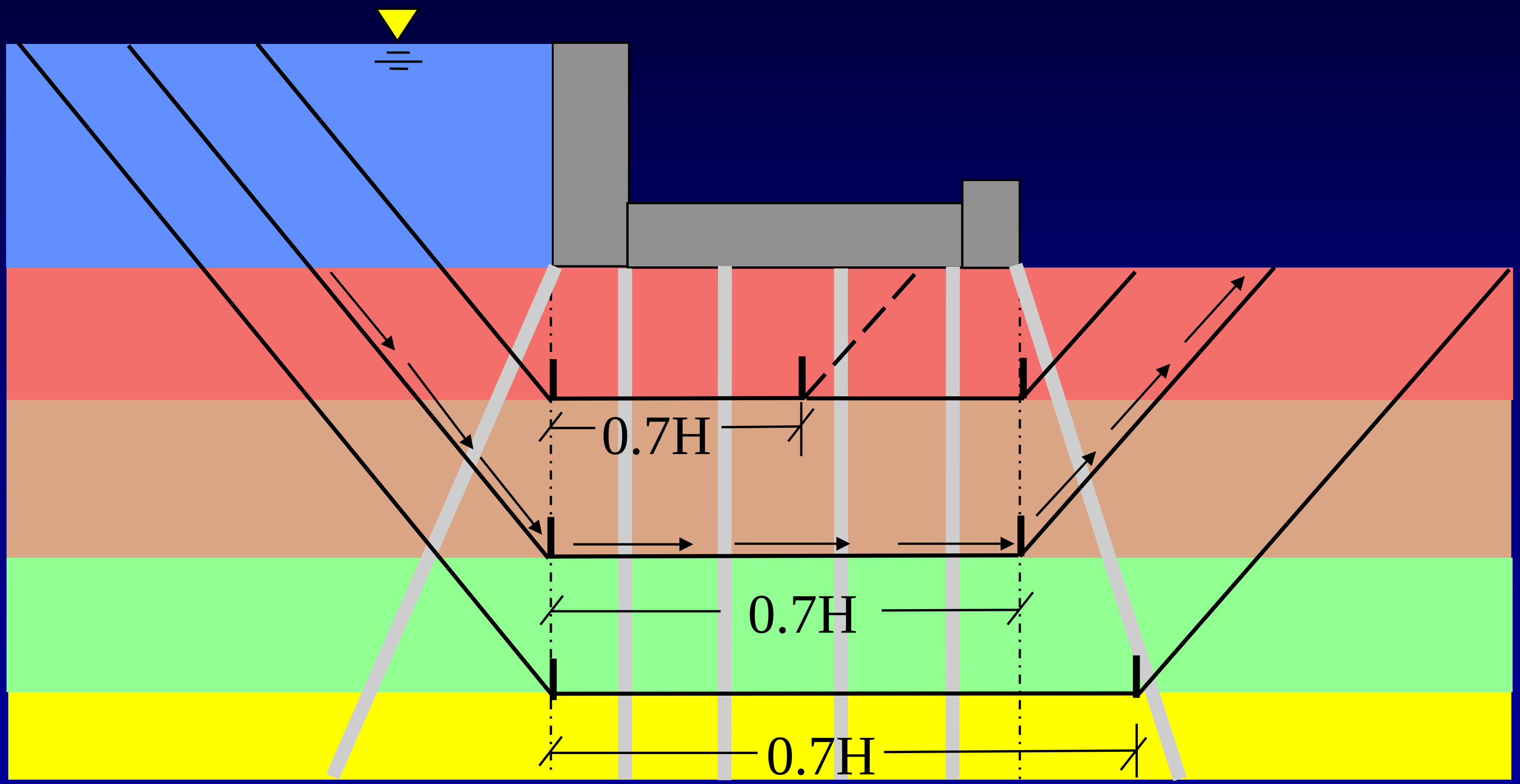
by

Rich Varuso, P.E.

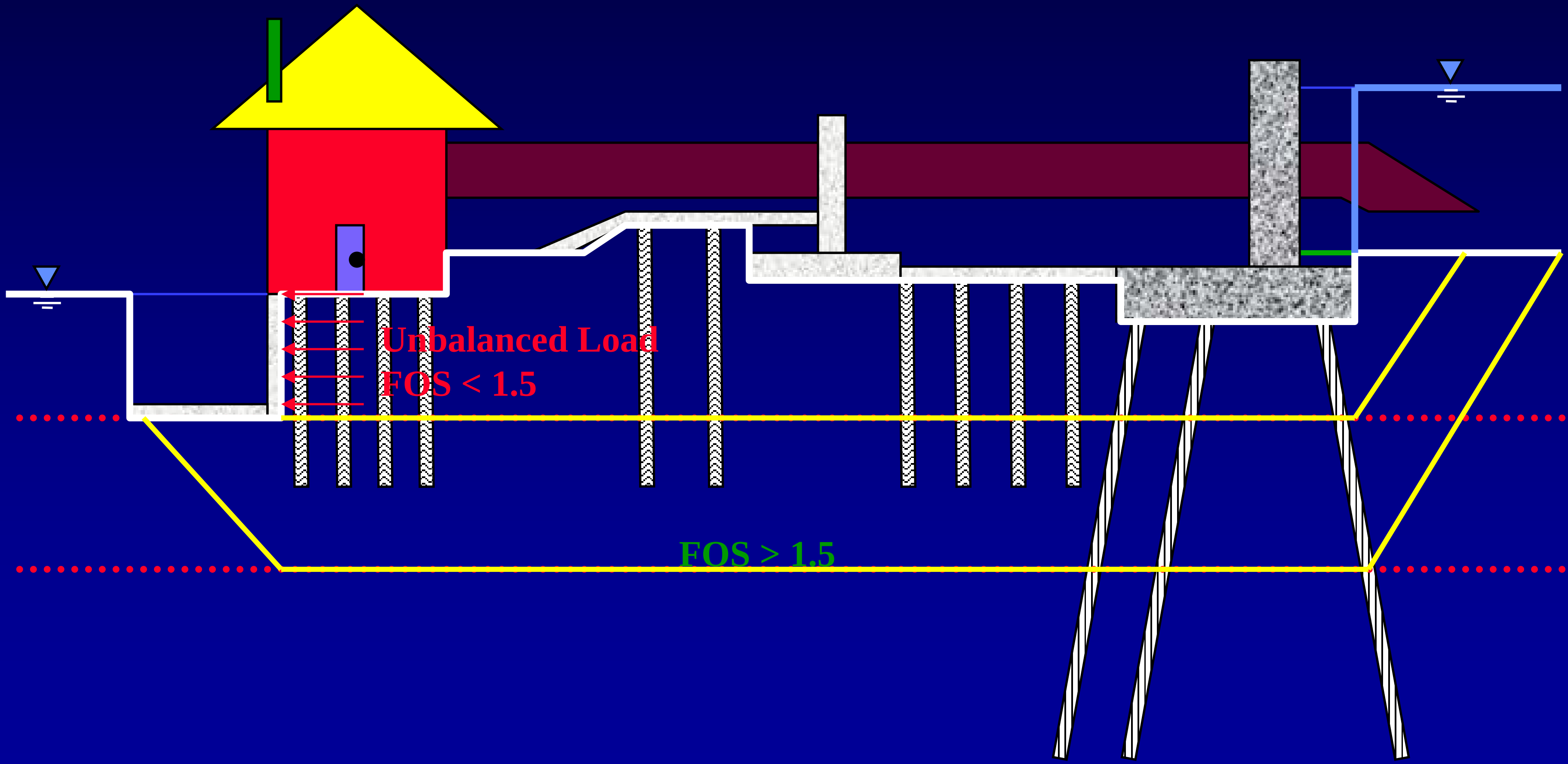
April 8, 2008

US Army Corps of Engineers

Long Structures



Adjacent Structures



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Question?

Thank You

Results of Ongoing Sensitivity Analysis

by

Bob Yokum, P.E.

April 8, 2008

On-going Sensitivity Analysis

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- Develop a systematic approach for selecting trial surfaces and managing search routines for UT4 and Slope W

- For 5 T-wall examples we compared MOP vs Spencers for both UT4 and Slope W (FOS and Unbalanced Load)

- For 5 T-wall examples we compared MOP vs Spencers using both UT4 and Slope W.

- We utilized the results from the new T-wall procedure to compare pile loads, pile stress and pile cap deflection for
  - **Steel H-piles**
  - **Concrete piles**
  - **Combination of steel and concrete piles**

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On-going Sensitivity Analysis

- We compared the effects of different pile spacing reduction factors.
    - **EM – 1110-2-2906**
    - **G-pile default values**

Analyzed the foundations with only the unbalanced load applied along the length of the pile.

- Analyzed the foundations with both the unbalanced load applied along the length of the pile and the super-structure loading.
- Plugged in the appropriate loads from G-pile into the stabilty analysis to determine the FOS for both cases listed above.

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Preliminary Findings/Results

- Variation in Pile Types
  - **Steel vs. Concrete**
  - **Mixed Foundations**
- Pile Spacing Reduction
  - **Lateral Deflections**
  - **Maximum Moments**
- Group Input Simplification
  - **Strata Unit Weights**
  - **Strata Shear Strengths**
  - **Soil Stiffness**

Preliminary Findings/Results

US Army Corps of Engineers

- Output Interpretation
  - Local Forces
  - Moments and Stresses Steel vs. Concrete
  - Input / Output Choices

- General Recommendations
  - Preliminary Foundation Design
  - Geotechnical Data Preparation and GROUP Input
  - Common Mistakes / Error Messages
  - You're Already Late

Preliminary Findings/Results

- Output Interpretation
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Q&A
Panel

Kent Hokens, P.E.
Neil Schwanz, P.E.
Mark Gonski, P.E.
Richard Pinner, P.E.
Rob Werner
Bob Yokum, P.E.

April 8, 2008