August 4, 2005

WV DOH

RP #121

Experimental and Analytical Behavior of Slide Suppressors Embedded in Bedrock

"A design Model for Pile Walls Used to Stabilize Landslides"

By: Tia Maria Richardson, P.E.
Principal Investigator

Introduction

*Landslides are a common problem in WV

Pile Walls

*Are often used by the WV DOH as a soil reinforcement technique to remediate failed slopes

*They can be placed in lieu of traditional earth retaining structures

*The are particularly useful when space is limited

*Often referred to as “Slide Suppressors”

Slide Suppressors

Usually consist of pre-cast concrete panels supported by drilled or driven piers

Ron Rittenhouse/The Dominion Post

Hillside braces

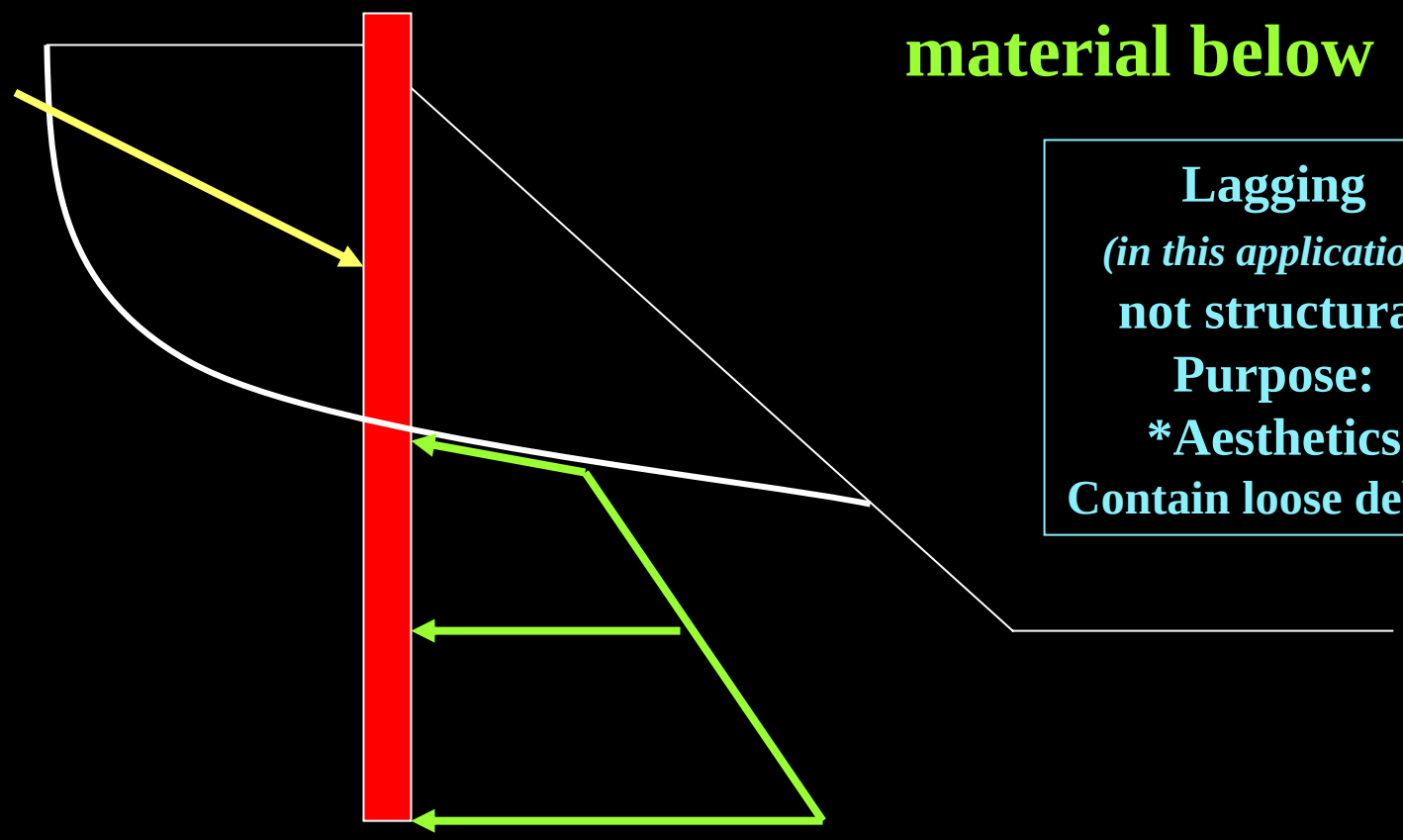
John Haynes (left), and Lane Mace, of BILCO Construction, Charleston, insert concrete slabs between pile driven steel beams on Green Bag Road near the intersection of Kingwood Pike. The beams are 35 feet in length with 25 feet driven into the ground. The work is part of a $248,000 project to shore up the hillside along the road in an effort to prevent flooding. The project is expected to take another three weeks.

Other lagging has also been used

Greenbag Road
Morgantown, WV

How do they work?

They <u>transfer the load</u> from the weak upper strata to the stable material below



Lagging
(in this application)
not structural
Purpose:
***Aesthetics**
Contain loose debris

To be Effective

Piles <u>MUST</u> Penetrate the Slip Surface

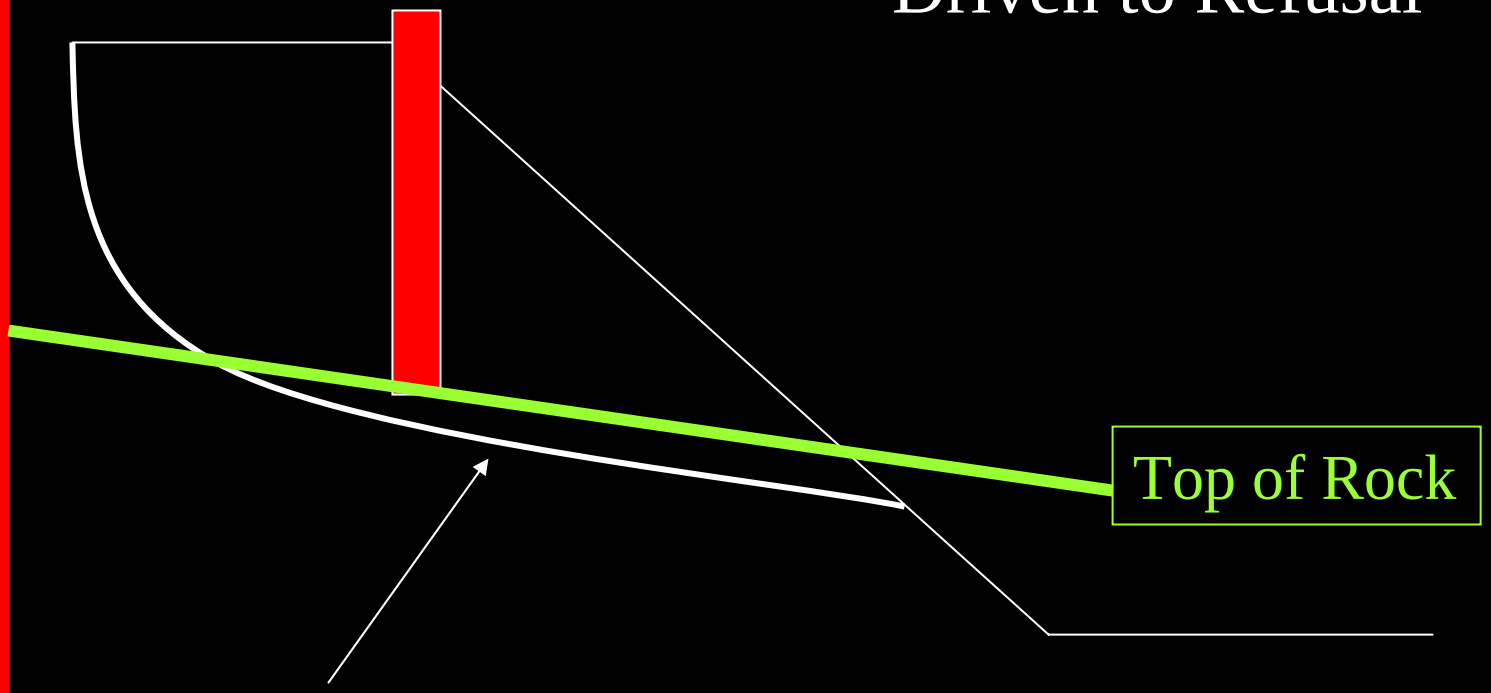
Must be **<u>embedded to fixity</u> -** into a stable material that is sufficiently strong to resist the landslide forces

Subsurface data is a MUST!

Must Penetrate the Slip Surface

Subsurface data is a MUST!

Driven to Refusal



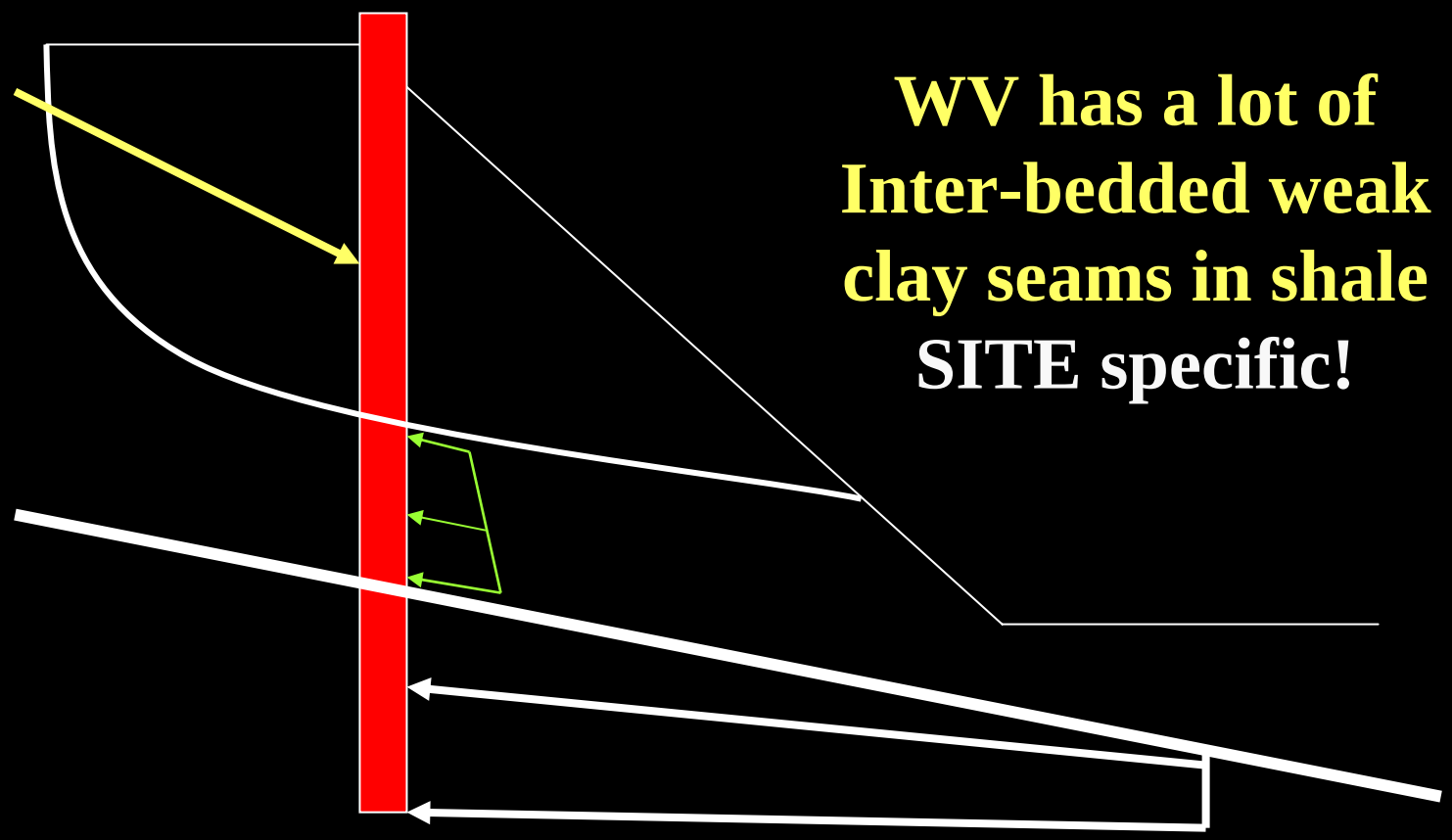
Slip surface BELOW Top of Rock

Pile Wall Failure
Rt. 857, Morgantown, WV (Cheat Lake Area)

Into a strong layer

Stable material below

Rock ?? Not always!



WV has a lot of Inter-bedded weak clay seams in shale

SITE specific!

Slide Suppressors

In a landslide situation

The Design & Analysis Requires Defining Two Main Variables:

1) The driving forces from the landslide
2) The passive resistance provided by placing the piles

WILL COME BACK TO THIS!

History

RP #97 - Dr. M.A. Gabr

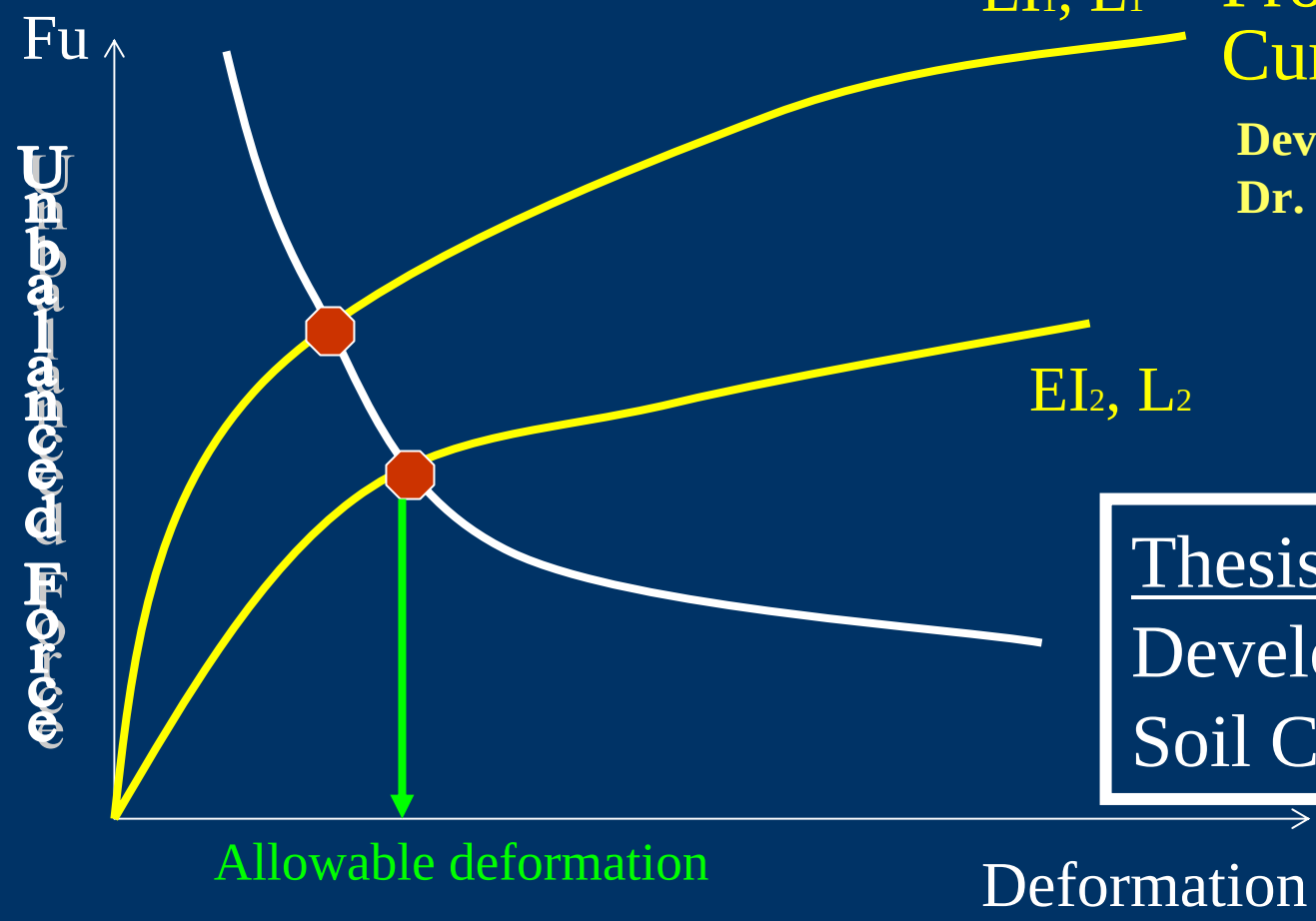
- Graduate Student

DOH Installing piles into rock
10 feet or L/3

Conservative Approach

RP #97 History

Basic Premise



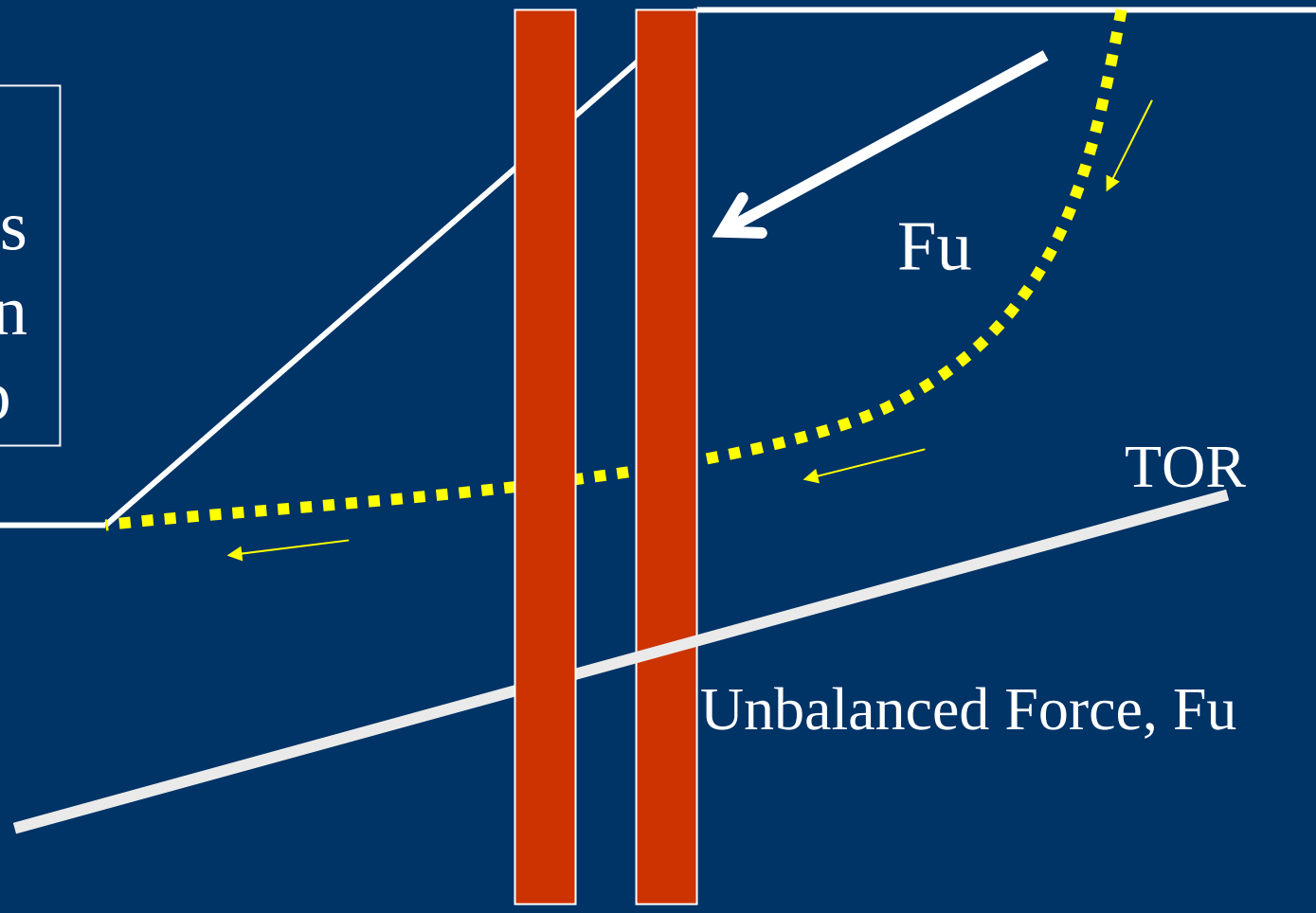
LTBASE Pile Program Curves

Developed by Dr. Gabr

Thesis: Develop a Soil Curve

RP #97 History

Hyperbolic
Shear - Stress
Shear - Strain
Relationship



VERY Theoretical!

RP #97 History

Test Site

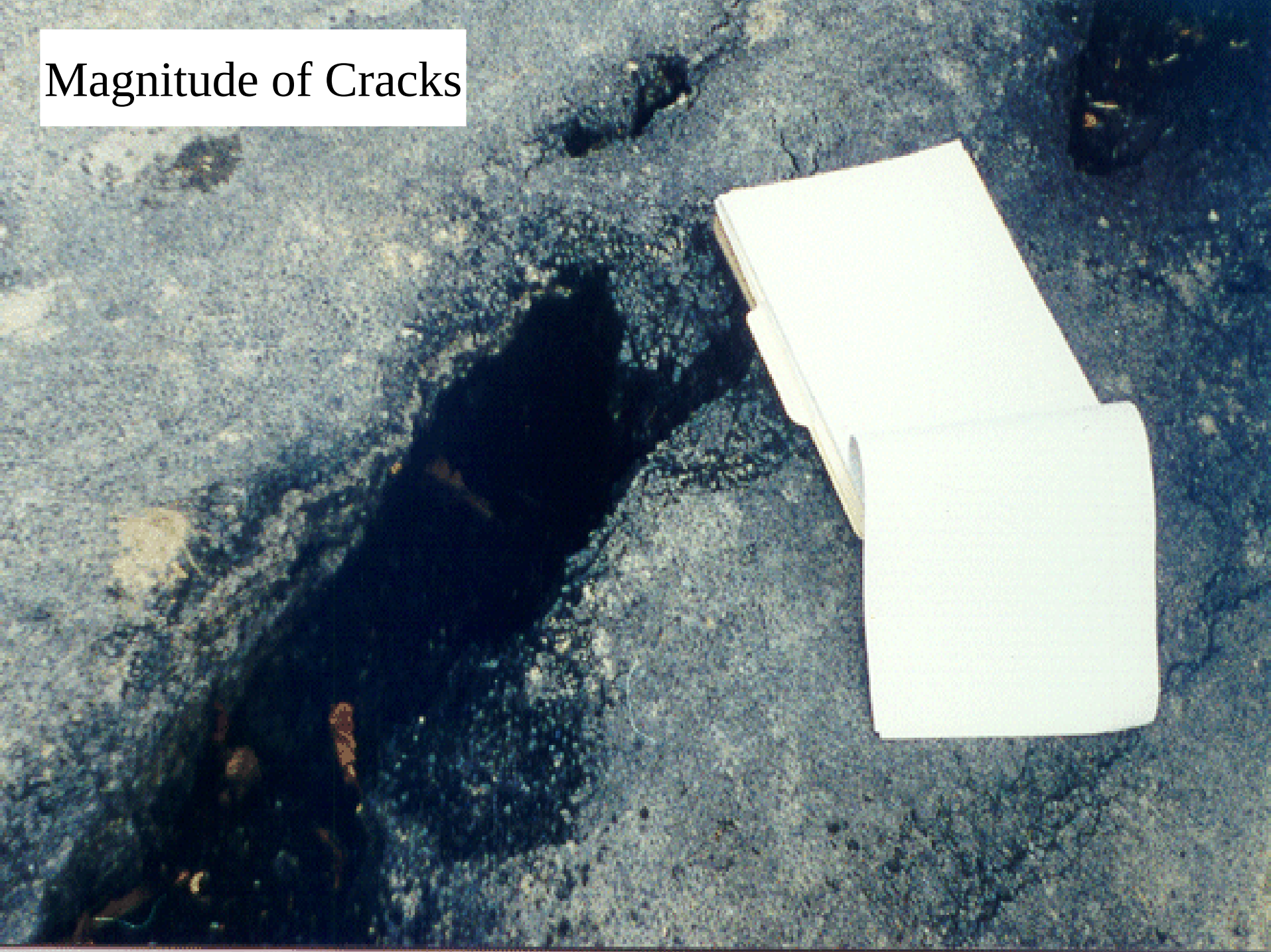
Bridgeport, WV

Rt. 73/73

Bridgeport, WV Rt. 73/73 Landslide


35
Road Closed!

Magnitude of Cracks




Dead
Man

Custom built a frame to house the dial gauges


Also strained gauged along its length

RP #97 Successes

Rt. 73/73 Test Site

- Validated LTBASE for a load at the top via strain gauges and dial gauges

- Demonstrated that after the point of fixity is reached - increased pile length does not reduce movements

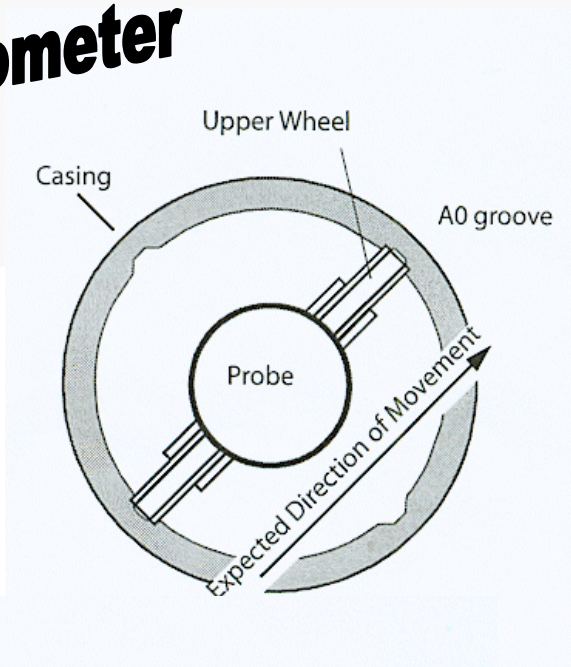
*Phase II: Demonstrated it actually increases bending moment & movement at the top

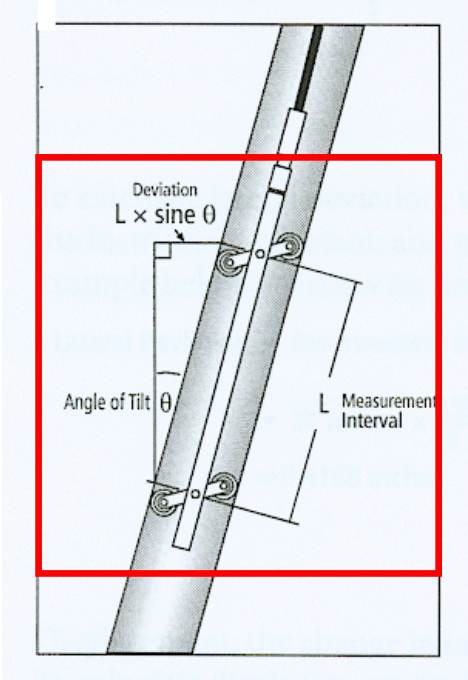

Inclinometer cut to size (or shorter)
Phase II

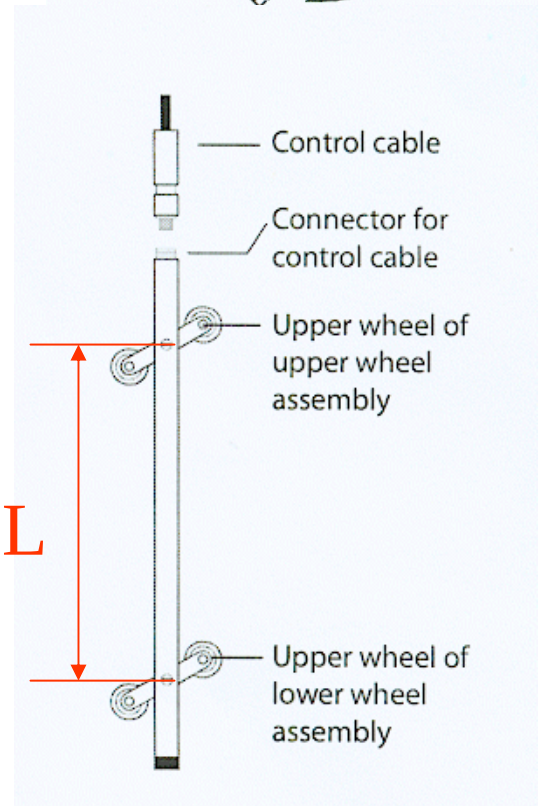

Phase I

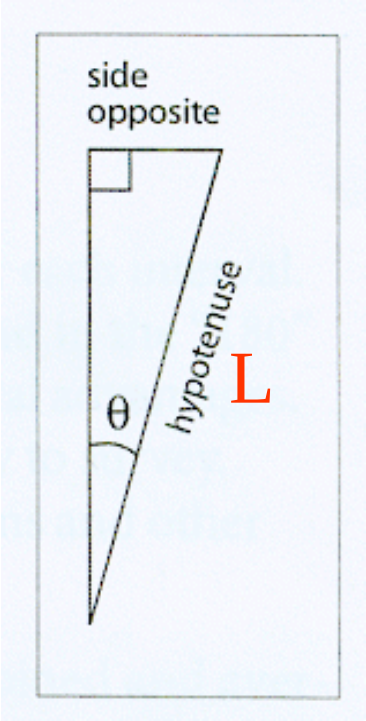
Slope Inclinometer

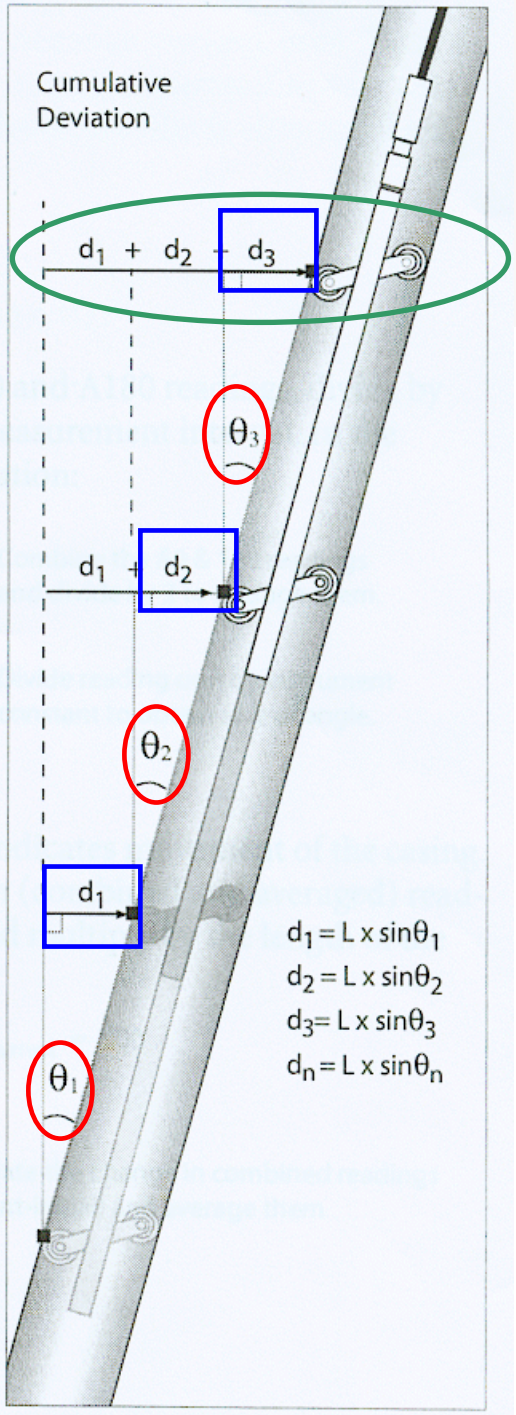
Innovative Application



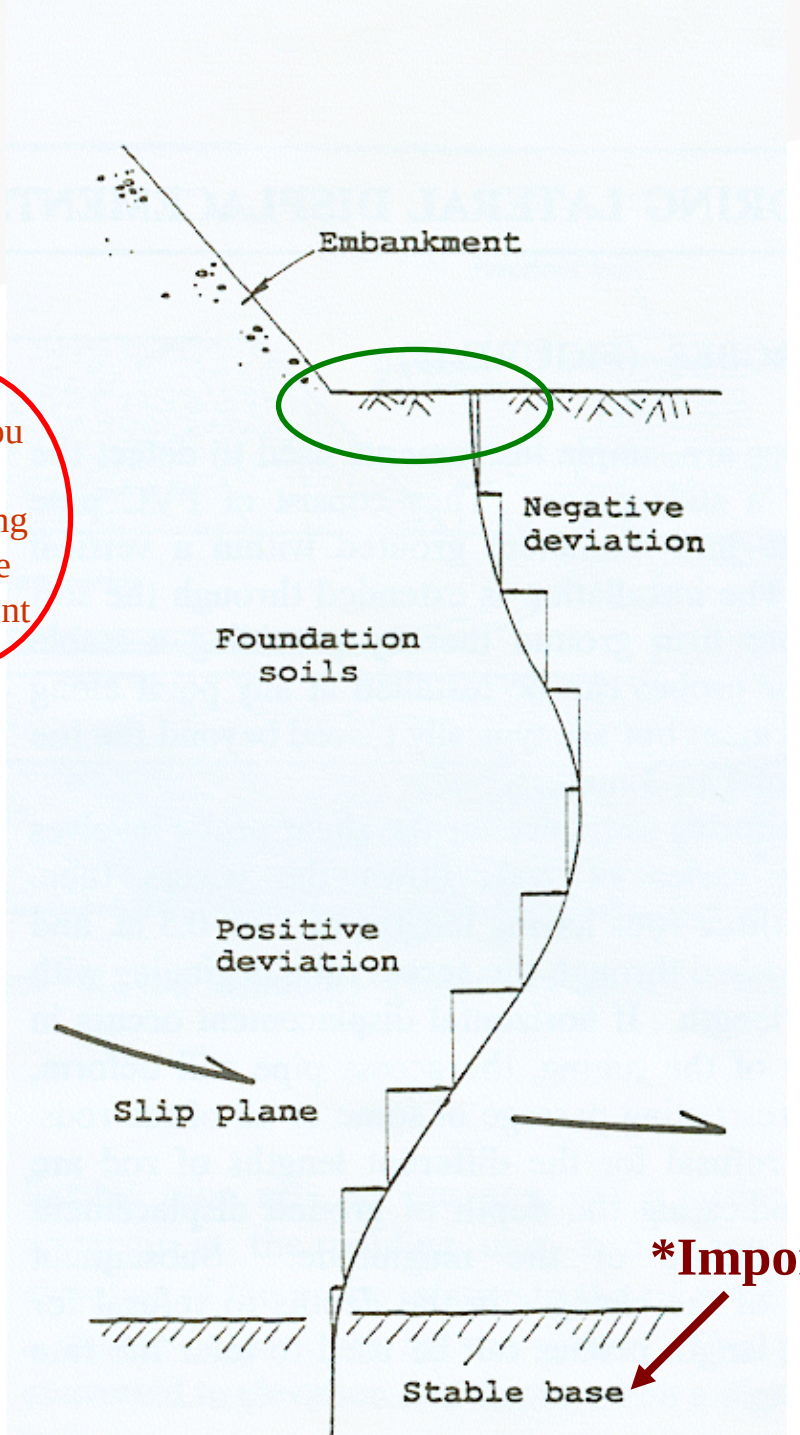




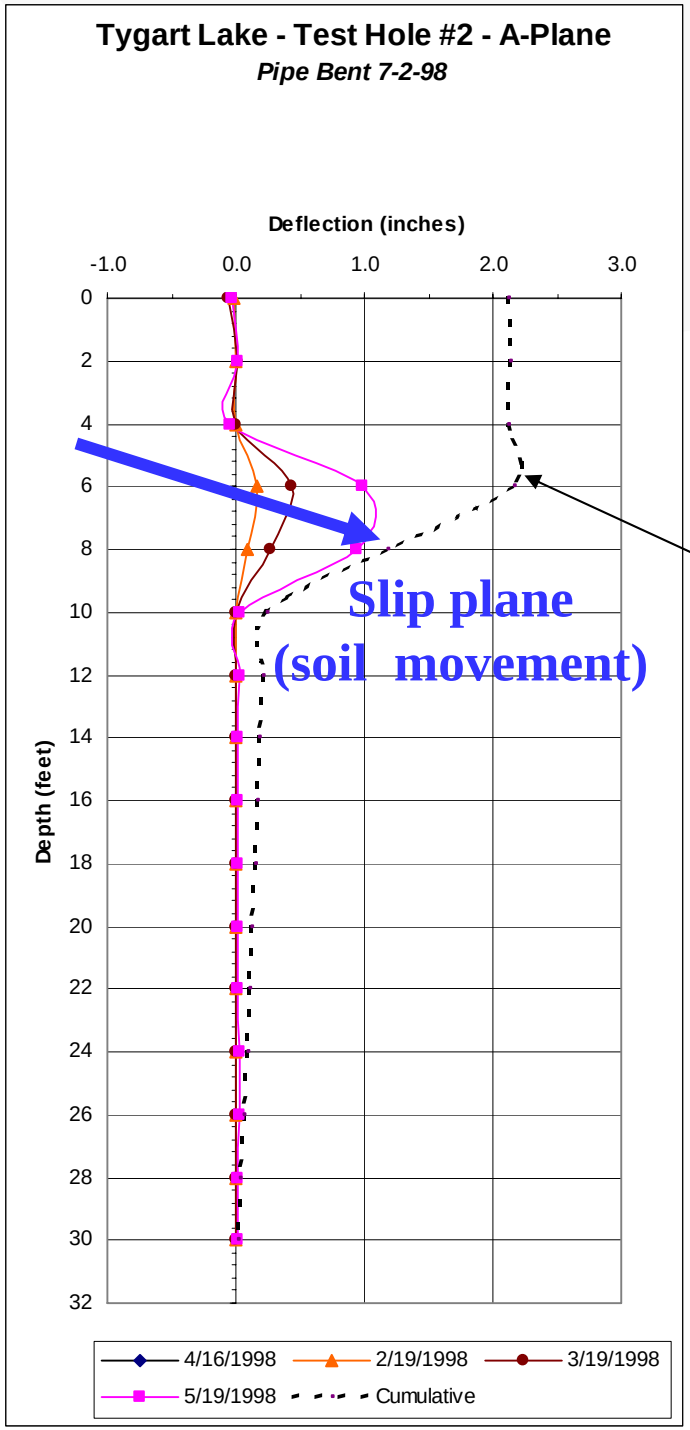




What you are measuring with the instrument



***Important !**

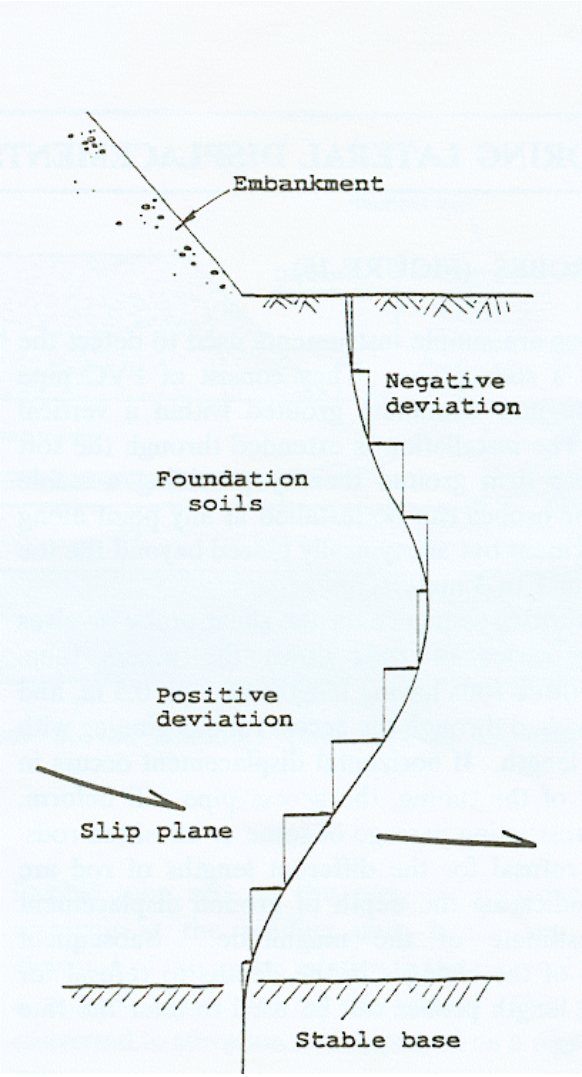


Cumulative deflection

Incremental data

***Keep in mind – the rigid piles will move different than flexible soil**

Will see both soil movement data and pile movement data throughout this presentation



Data Collection

***Full Scale Performance Monitoring**

2 Sites: Green Bag Road

And Forest Ave

Full Scale Test Site

Tygart Lake

Green Bag Road

WV DOH Site

- 109 Piles in the wall
  - Embedded in Lacustrine Clay on a 1^0 batter
  - Total Pile Lengths = 30 Feet
  - ~7 ft. above centerline, ~2 ft. above G.S. in the back
- Monitoring 3 piles <u>in the wall</u>

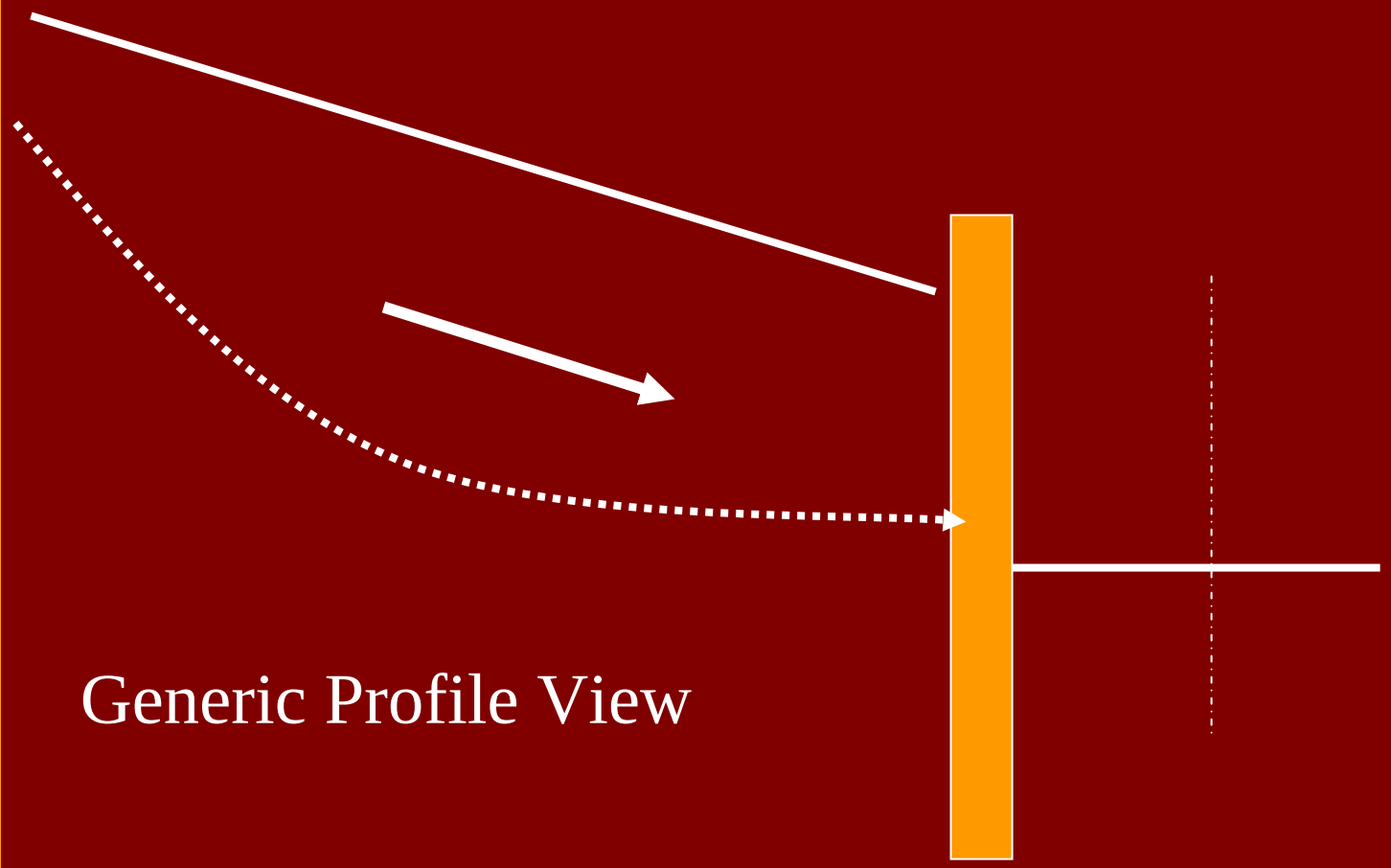
  # 29, 49 and 73
- And 2 <u>test piles</u> on end 25 - 30 feet long

GBR

Old pipe piles

Green Bag Road

Piles at toe of slope



Generic Profile View

Installation of Pile #29 Green Bag Road Morgantown, WV

Inclinometer Pipe

Position

Plane of maximum movement

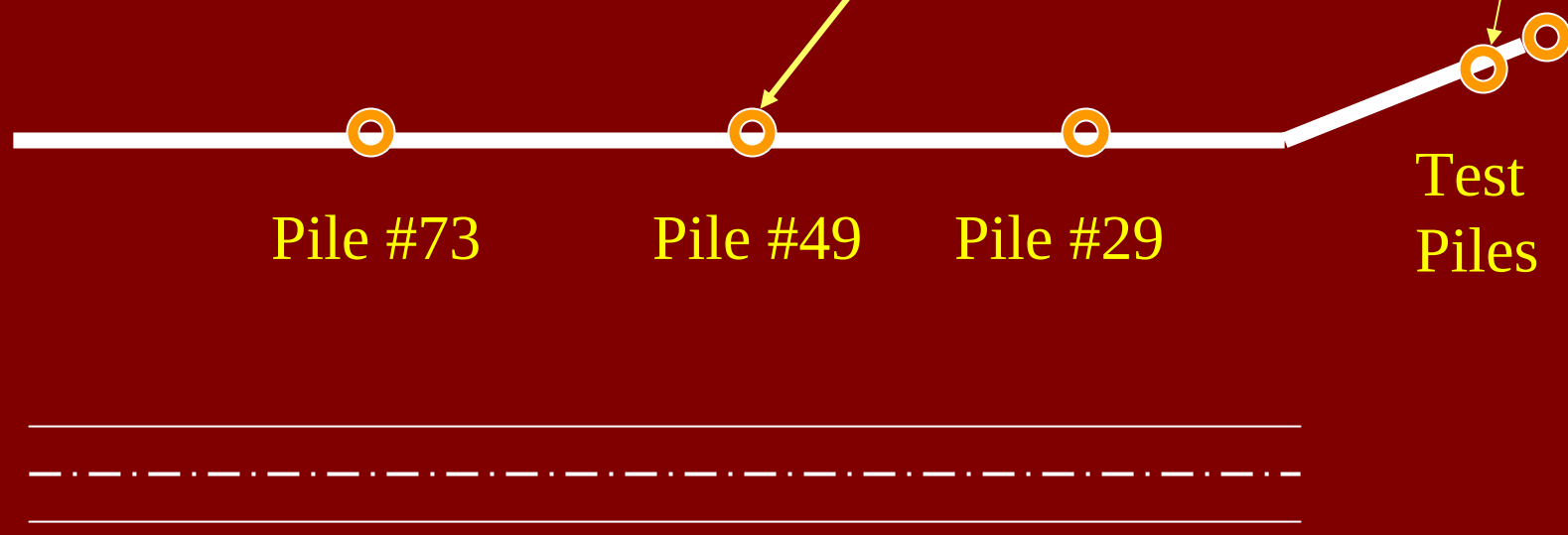
Ron Rittenhouse/The Dominion Post

Hillside braces

John Haynes (left), and Lane Mace, of BILCO Construction, Charleston, insert concrete slabs between pile driven steel beams on Green Bag Road near the intersection of Kingwood Pike. The beams are 35 feet in length with 25 feet driven into the ground. The work is part of a $248,000 project to shore up the hillside along the road in an effort to prevent flooding. The project is expected to take another three weeks.

Green Bag Road

Pile #49 and Test Pile #2 show the most movement

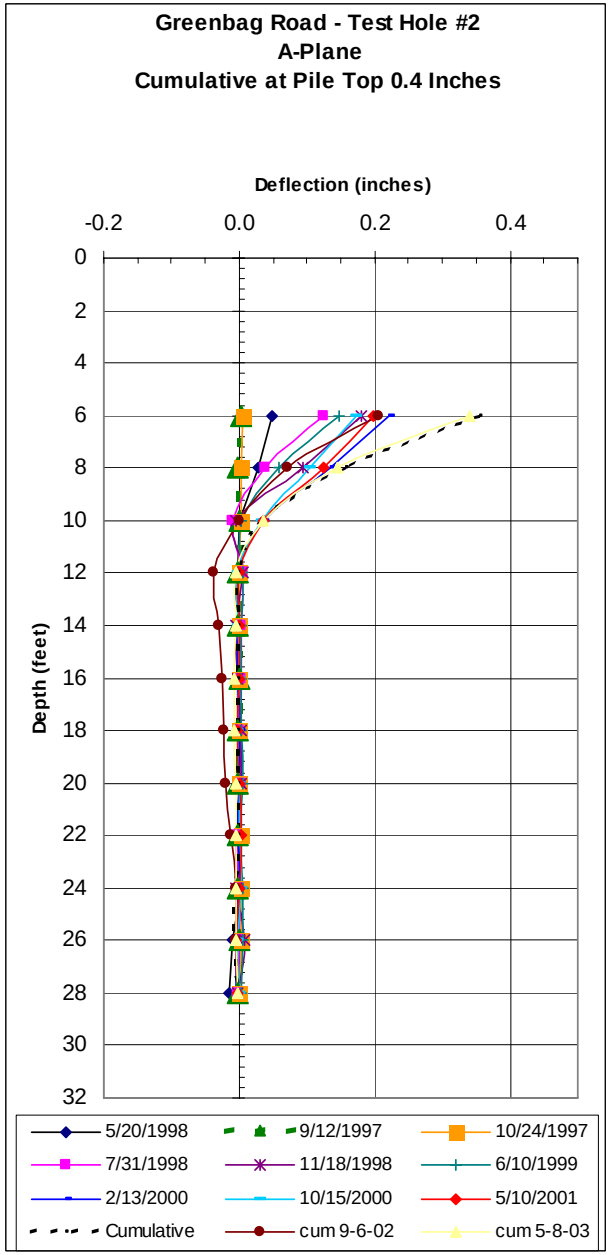


Pile Size

H 12x53

ASTM A-36 Carbon Grade Steel

Plan View



Test Pile #2

Green Bag Road

Maximum Movement

~ 0.6 Inches

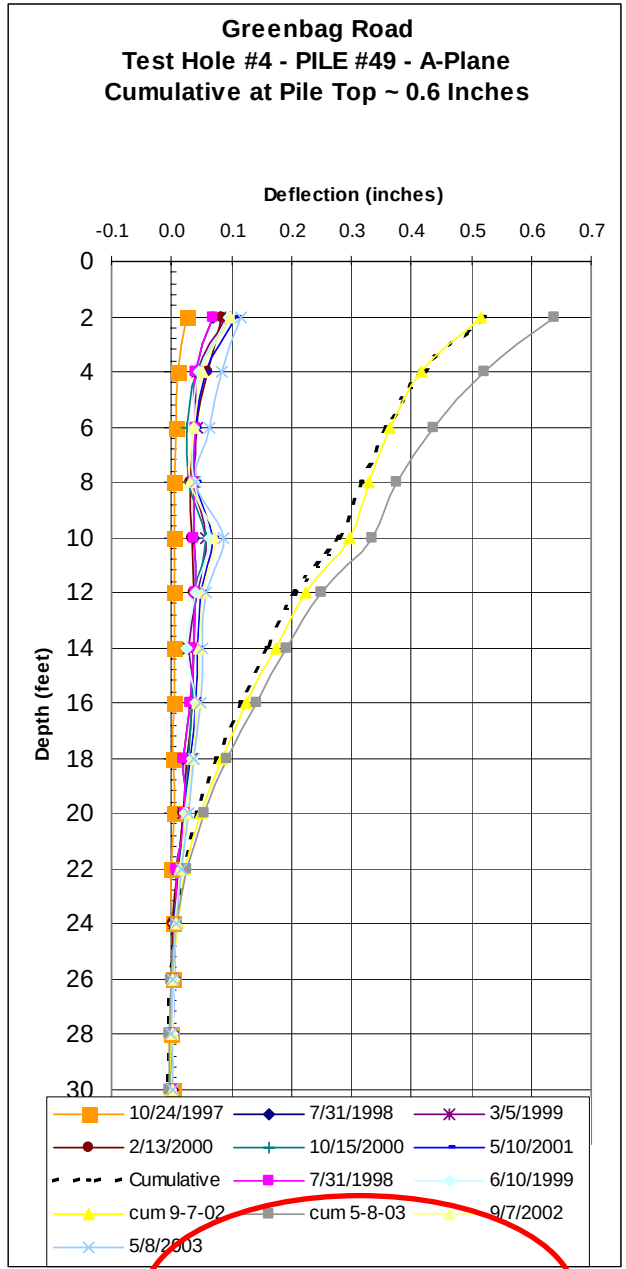
Pile #49

Near the center of the wall

Test Pile #2

~ 0.3 Inches

Rest < 0.1”



Pile #49

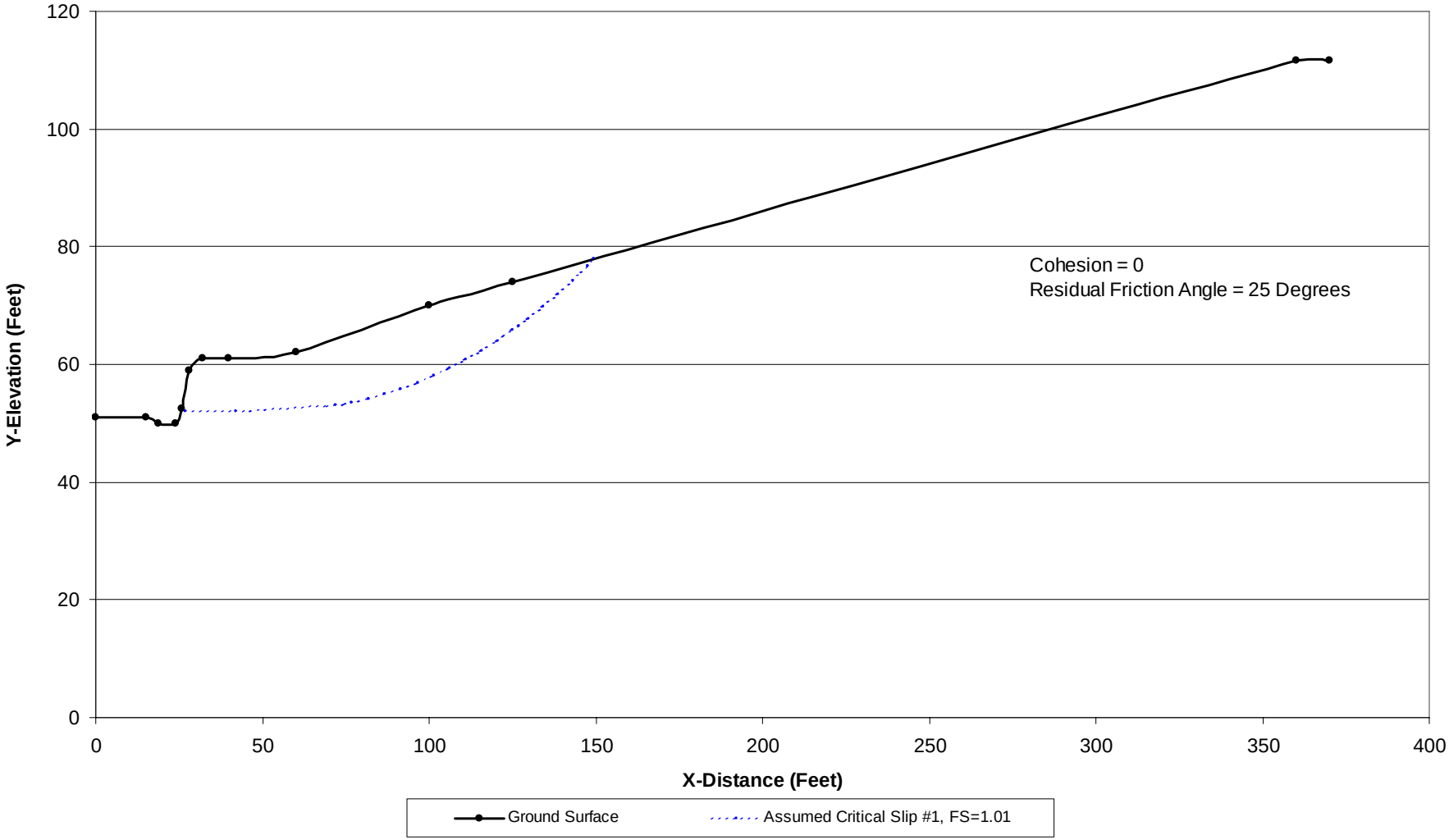
Slope Stability Analysis
Green Bag Road

Section Cut Near Test Pile #49

A retrogressive slip was indicated

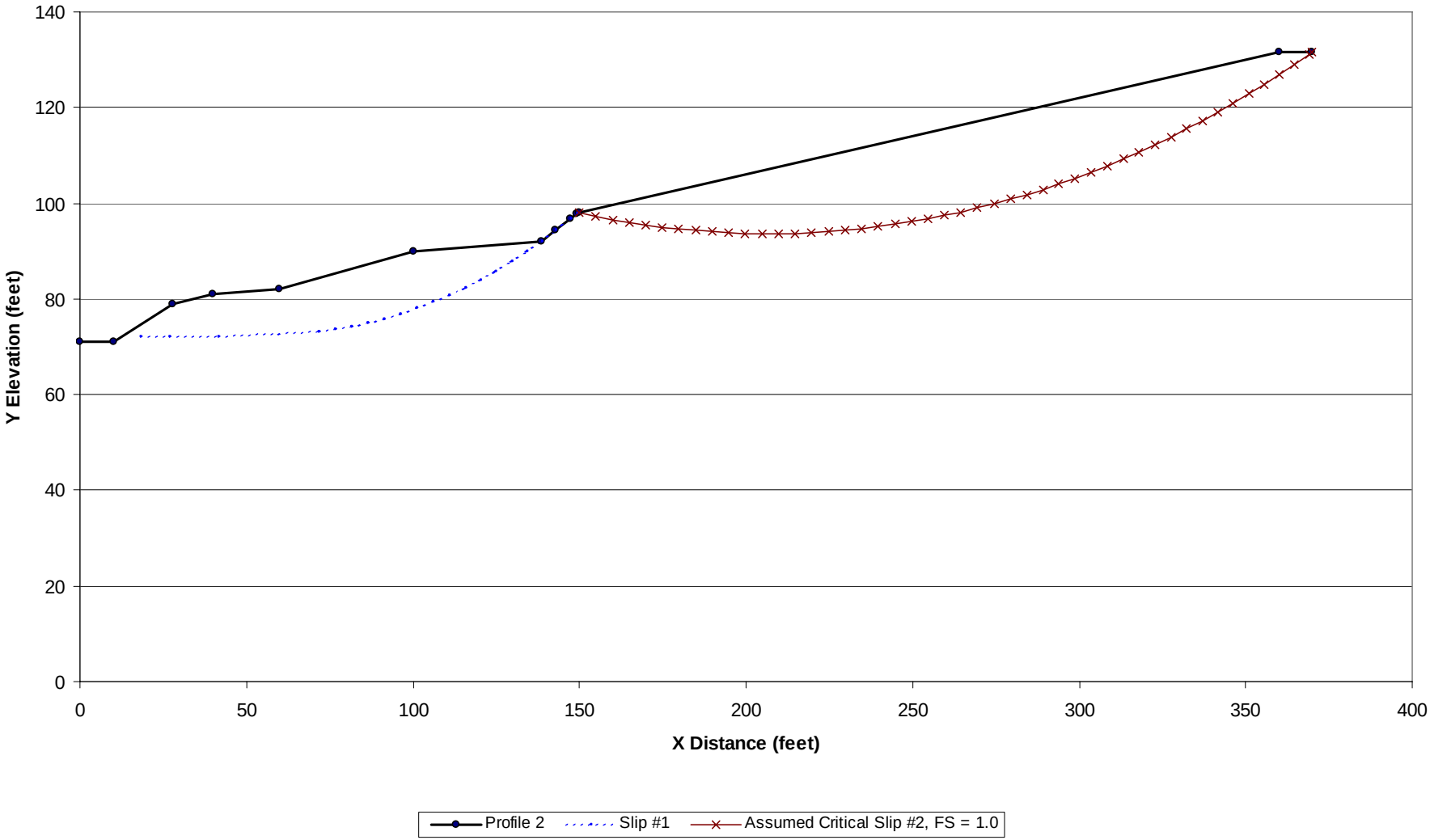
Slope Stability Analysis - Green Bag Road

Figure 3.3.4: Green Bag Road - Original Profile, Retrogressive Slide #1



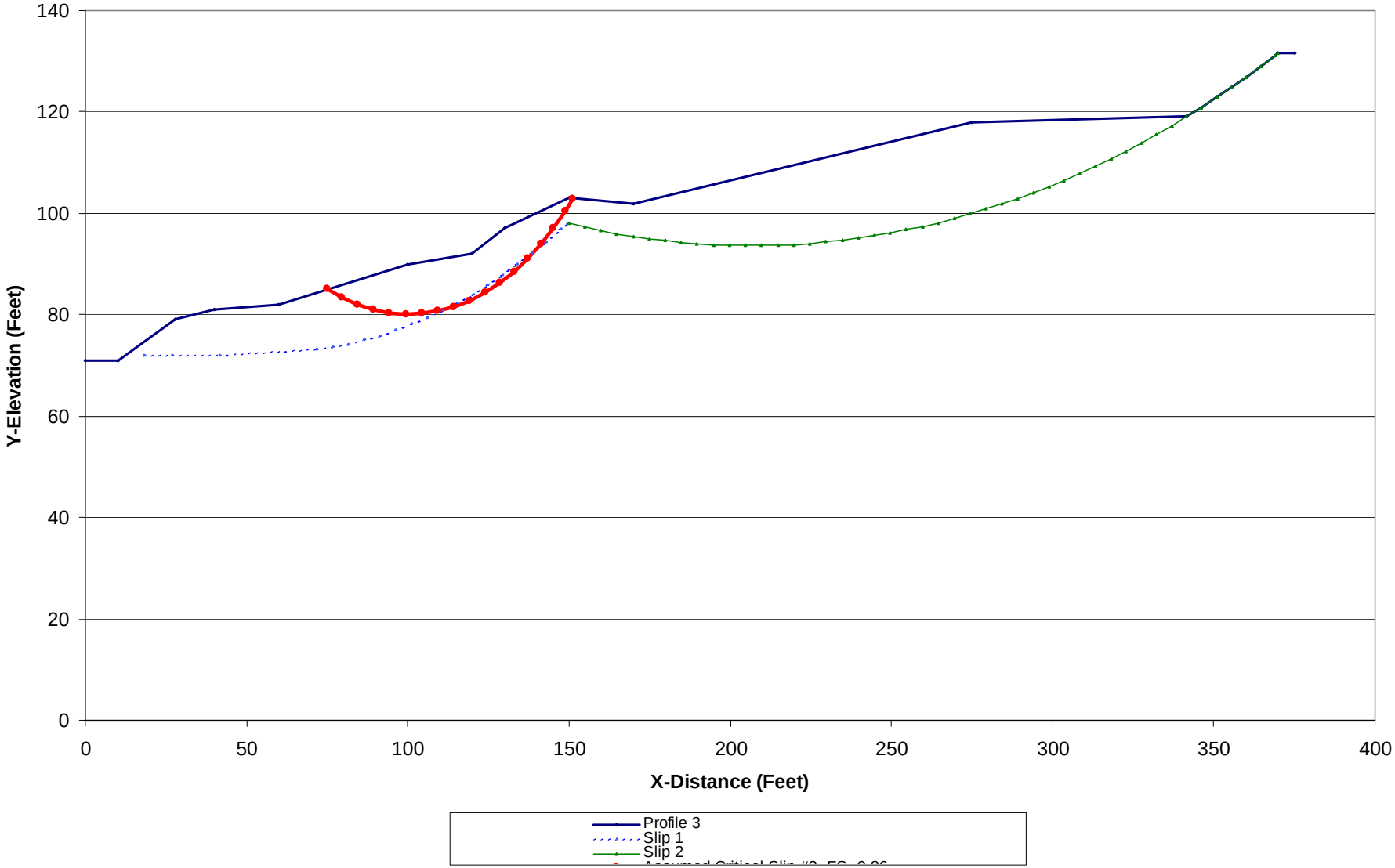
Slope Stability Analysis - Green Bag Road

Figure 3.3.5: Green Bag Road - Profile #2, Retrogressive Slide #2



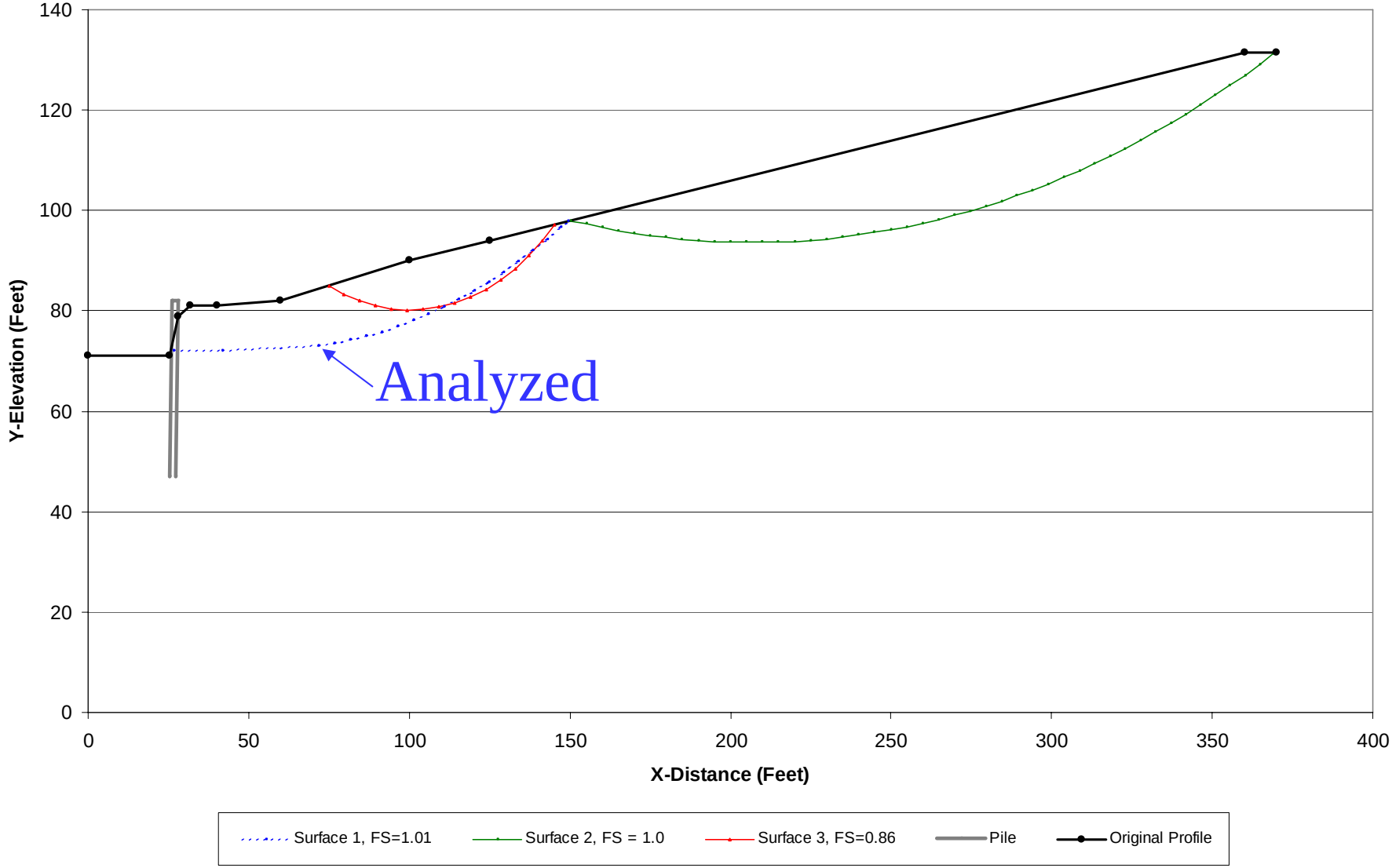
Slope Stability Analysis - Green Bag Road

Figure 3.3.6: Green Bag Road - Profile #3, Retrogressive Slide #3



Final Slope Stability Analysis on Green Bag Road

Figure 3.3.7: Green Bag Road - Original Profile, Pile Location and Summary of Slides



Green Bag Road

Model Developed does <u>NOT</u> work for this case

i.e. When the procedure is used for the slope

BAD NEWS!

Landslide force is <u>grossly overestimated</u>

Another procedure is needed

Forest Avenue

Bilco

Triad

City Engineer
Terry Huff

City of Morgantown Site

16 piles in the wall - HP 12 x 74

Design L = 25 feet (some 30)

Design overkill - 40%L+ Embedded in bedrock

Monitoring 3 piles in the wall

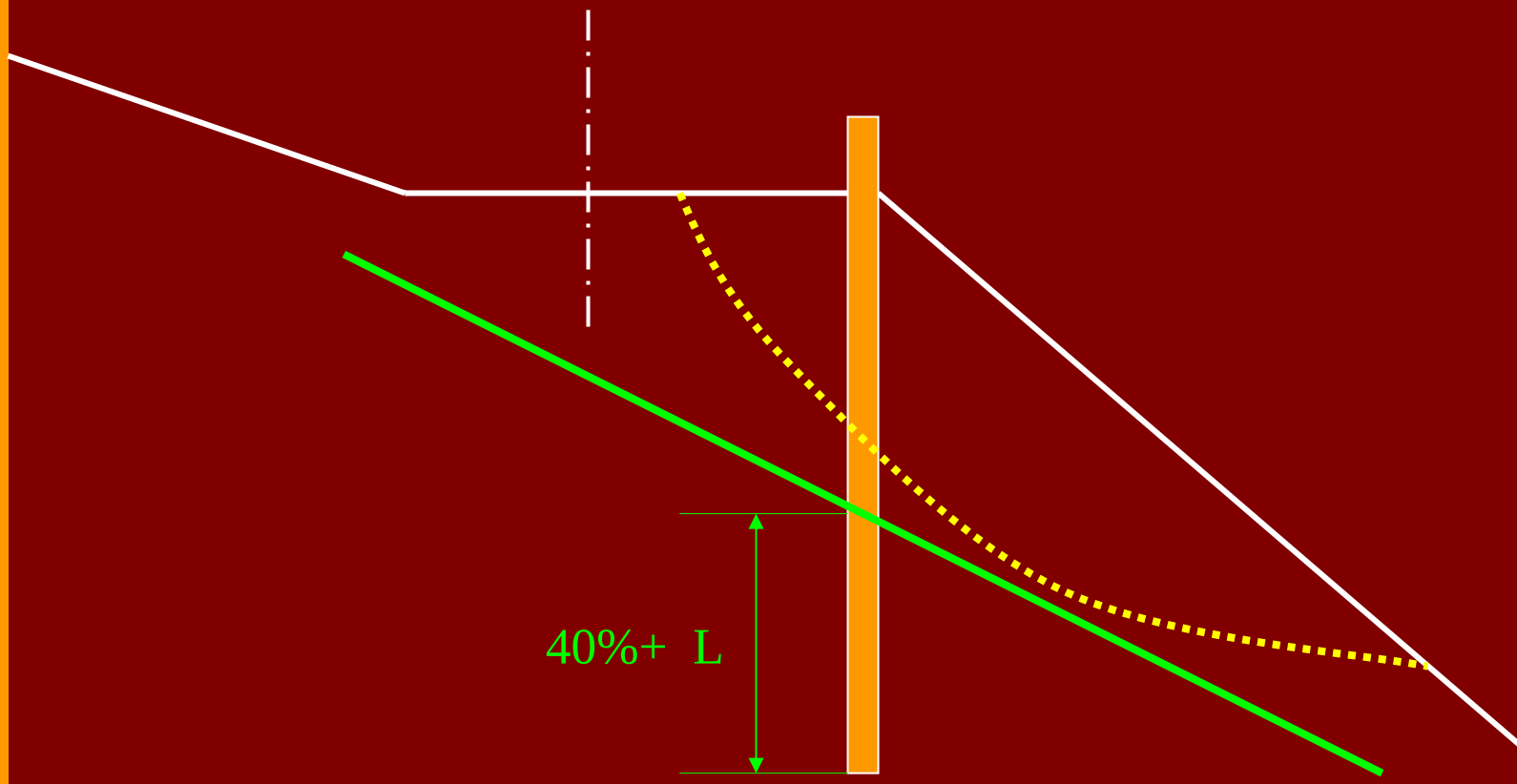
#4, 8 (30 ft.) and 12

Two test piles on the end

- NOT connected, 20 feet Long

Forest Avenue

Profile View



Forest Avenue

2.5 ft. above GS
15.4 feet to
Top of rock

Plan View

Very LITTLE Movement

Not Connected

Test Piles
4.6 ft.
in Rock

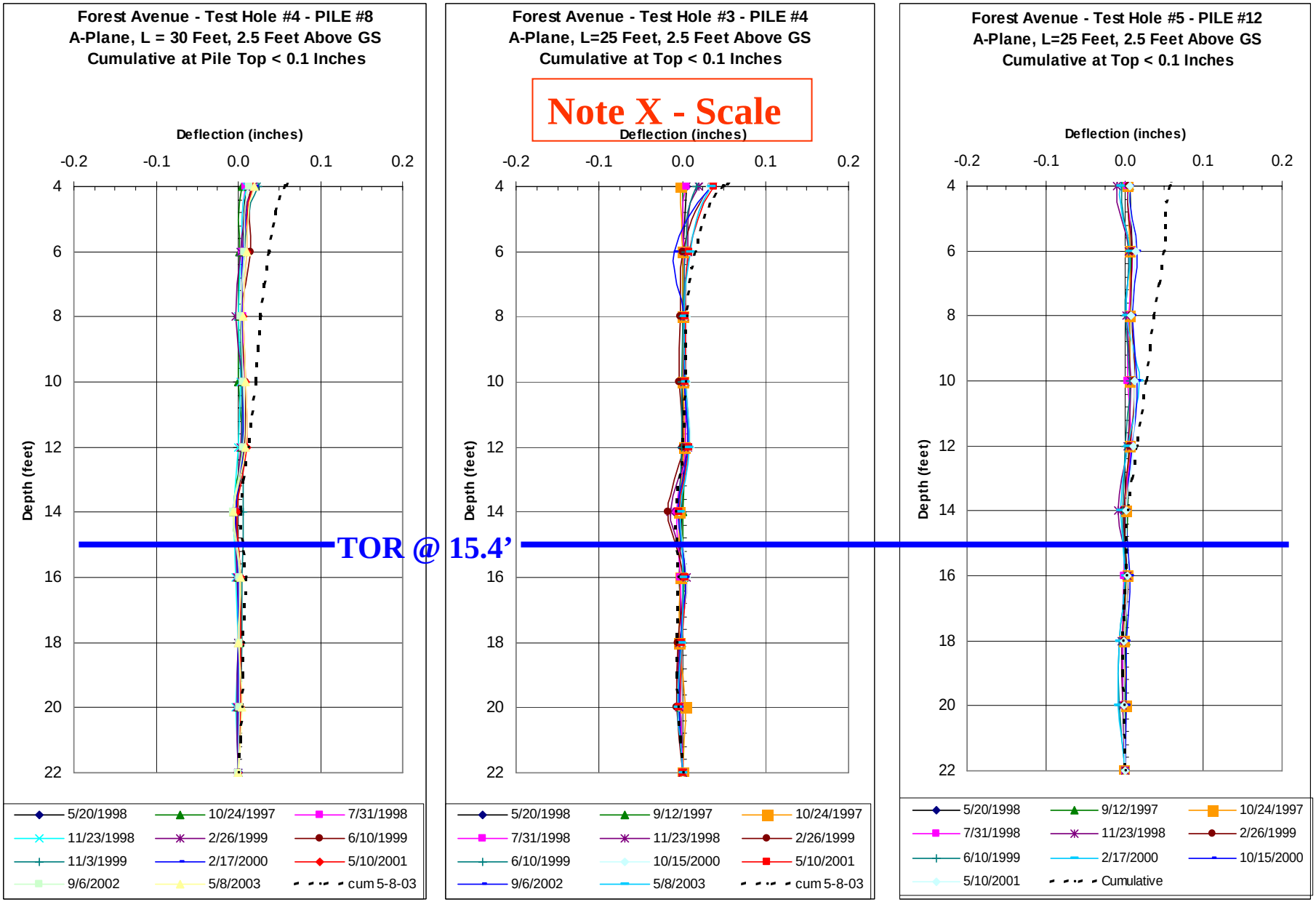
Pile #4
25 feet
7.1 ft.
in rock

Pile #8
30 feet
12.1 ft
in rock

Pile #12
25 feet
7.1 ft.
in rock

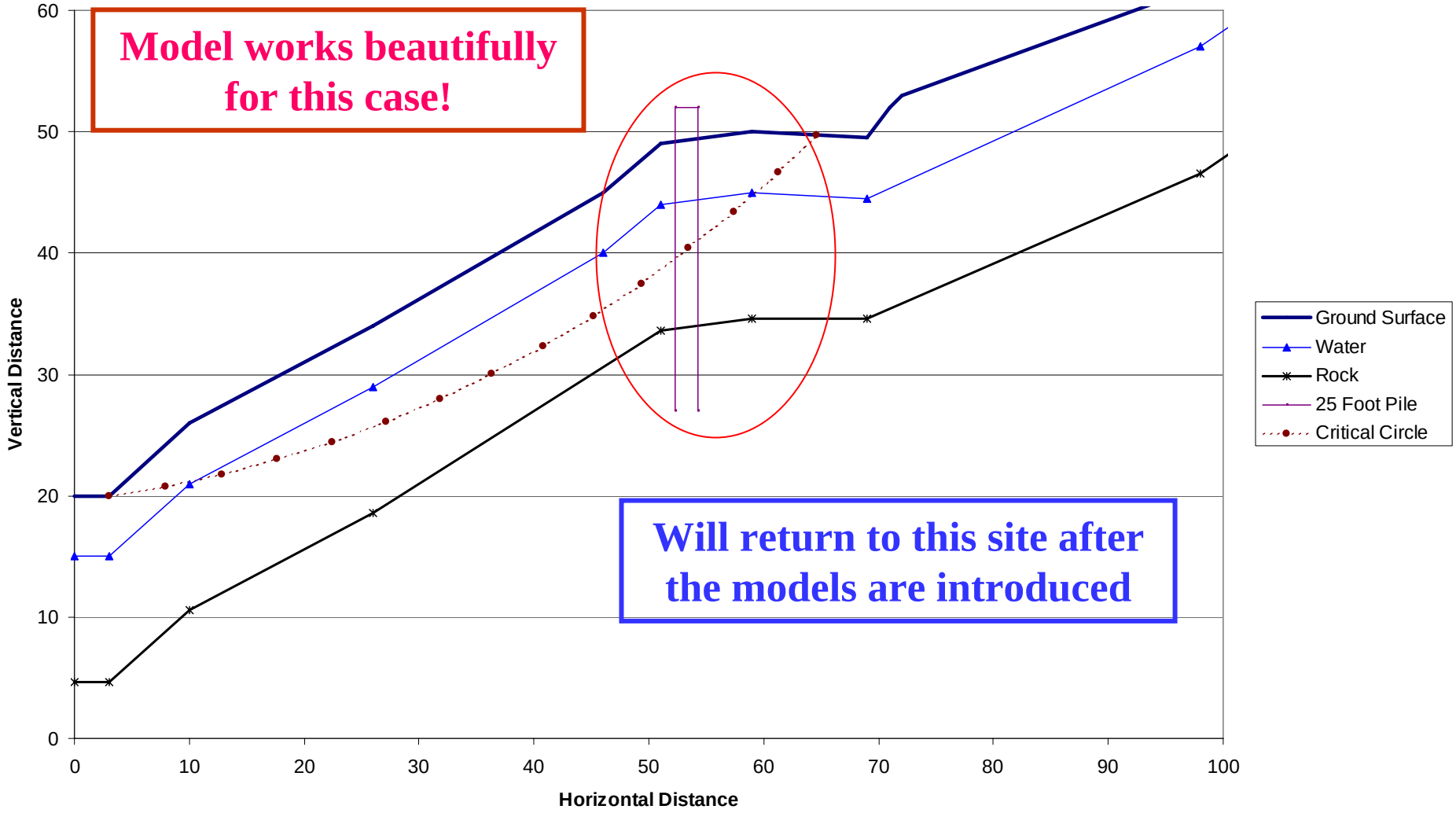
Looking at Wall

Forest Avenue – Results of Inclinometer Readings, < 0.1”



Forest Avenue – Results of Slope Stability Analysis

Figure 3.2.4: Forest Avenue - Profile and Critical Slip Surface



Tygart Lake

FULL Scale Test Site

State Park Office

US Army Corps of Engineers

District #4 DOH

Taylor County DOH

1. Subsurface Investigation

   Soil and Rock samples - 10 holes

   5 Slope Indicators holes

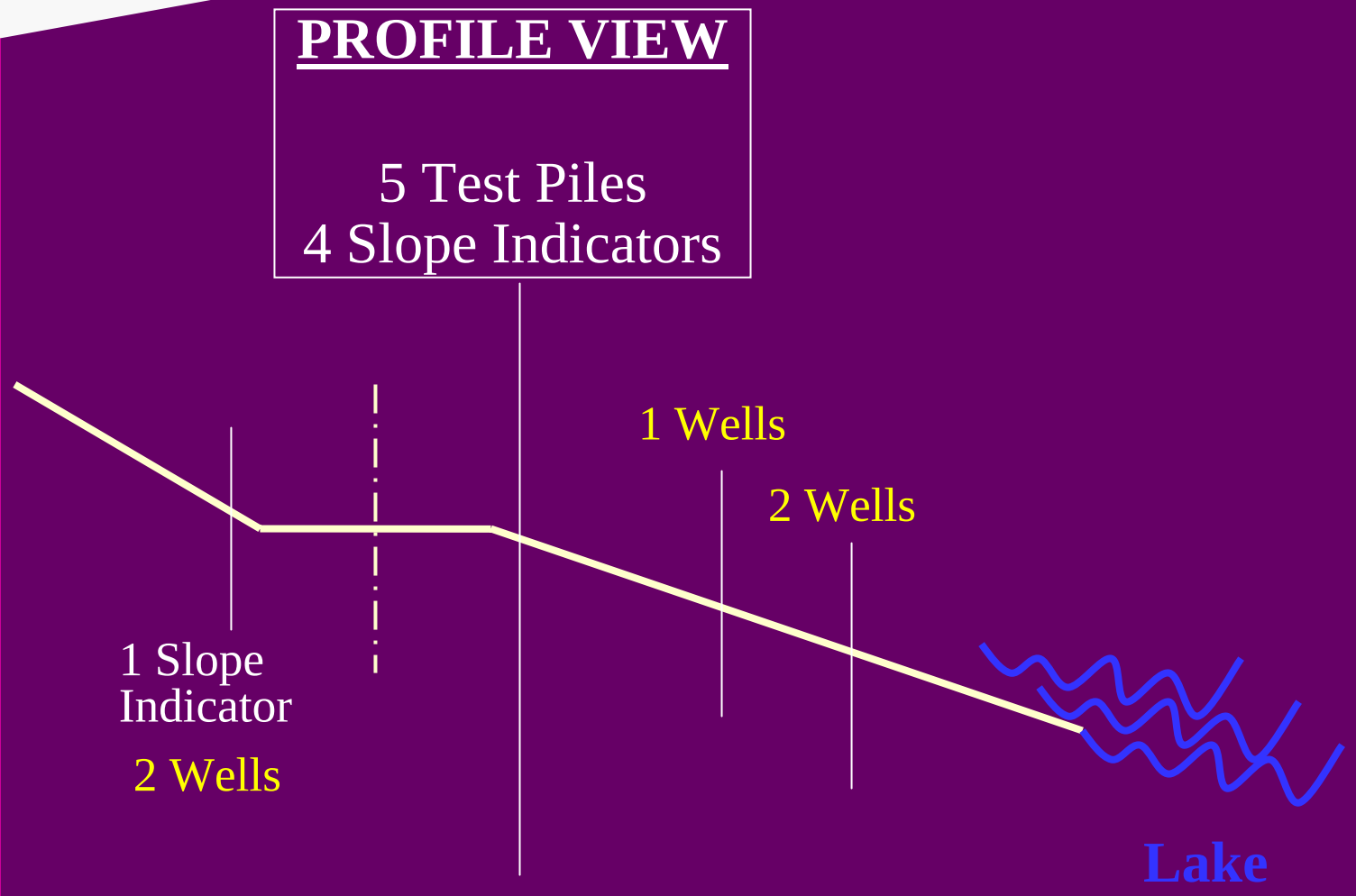
   5 Monitoring Wells - in a triangular grid

   3 deep, 2 shallow

2. Monitored slope for 1 year

   Good indication of the slip **PLANES**

Tygart Lake Test Site

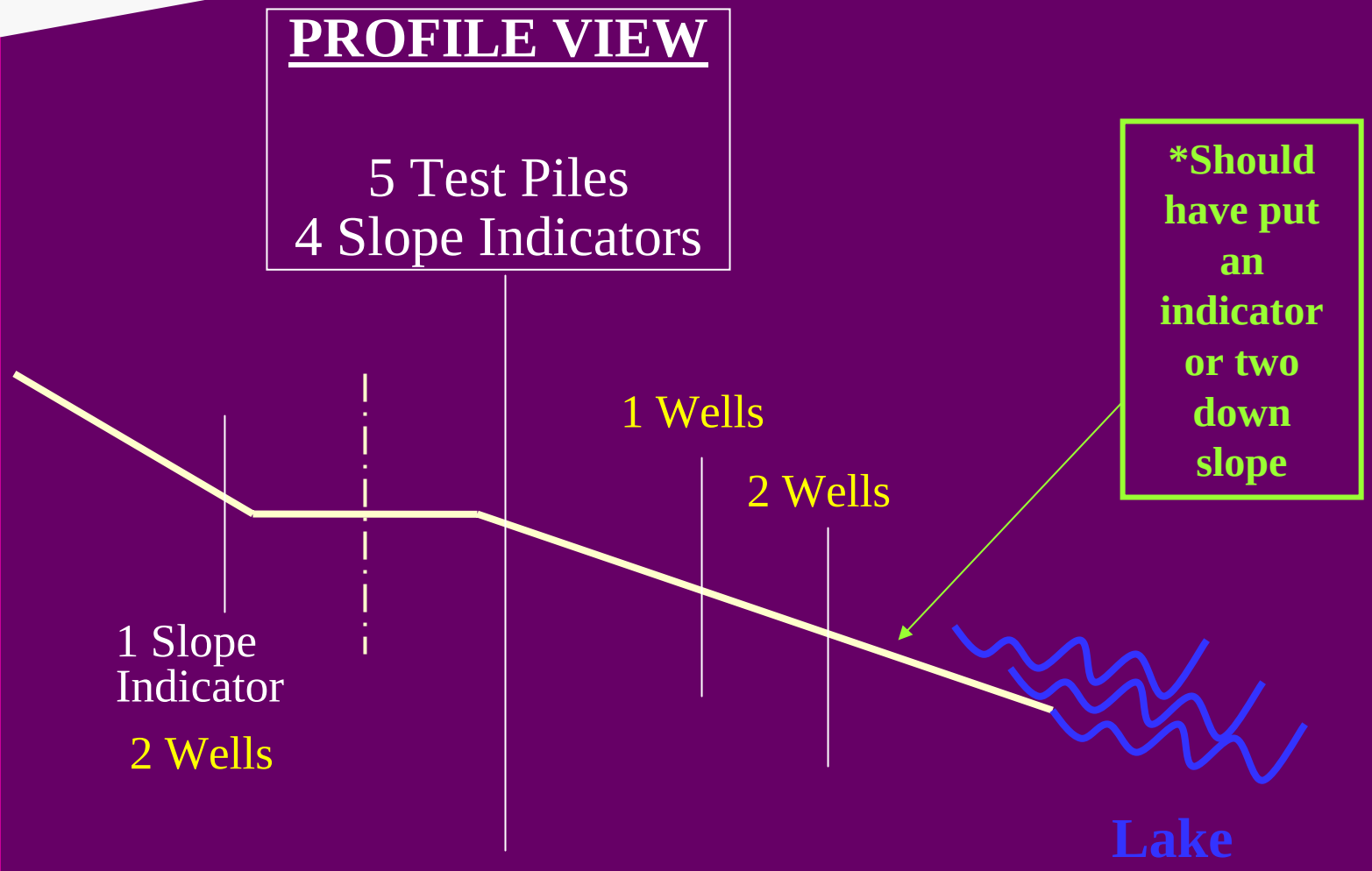


5 Wells placed in a triangular grid – shallow and deep

Monitoring wells - Deep and Shallow

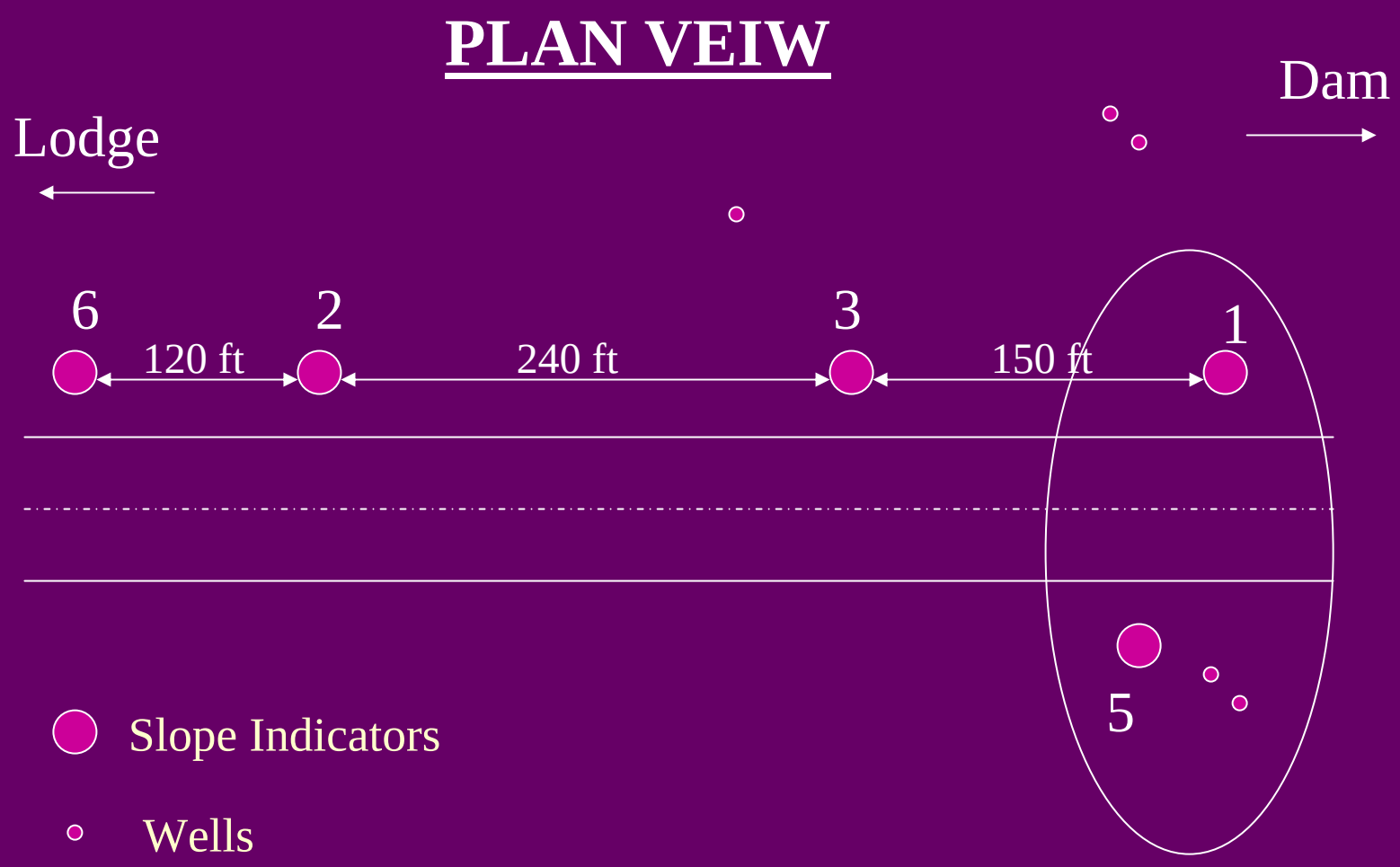
Perched Water Table Detected

Tygart Lake Test Site



Wells placed in a triangular grid – shallow and deep

Tygart Lake Test Site

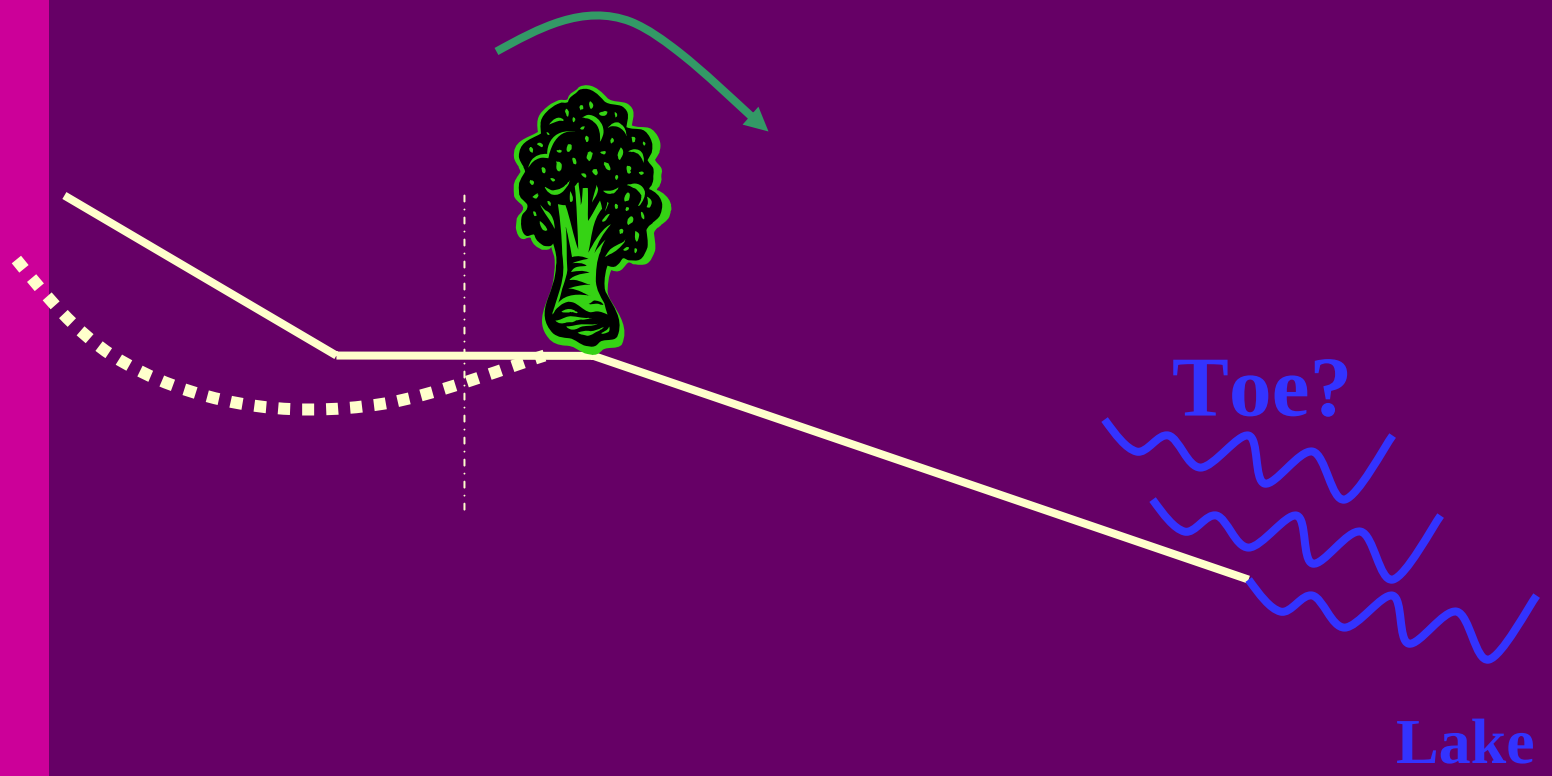


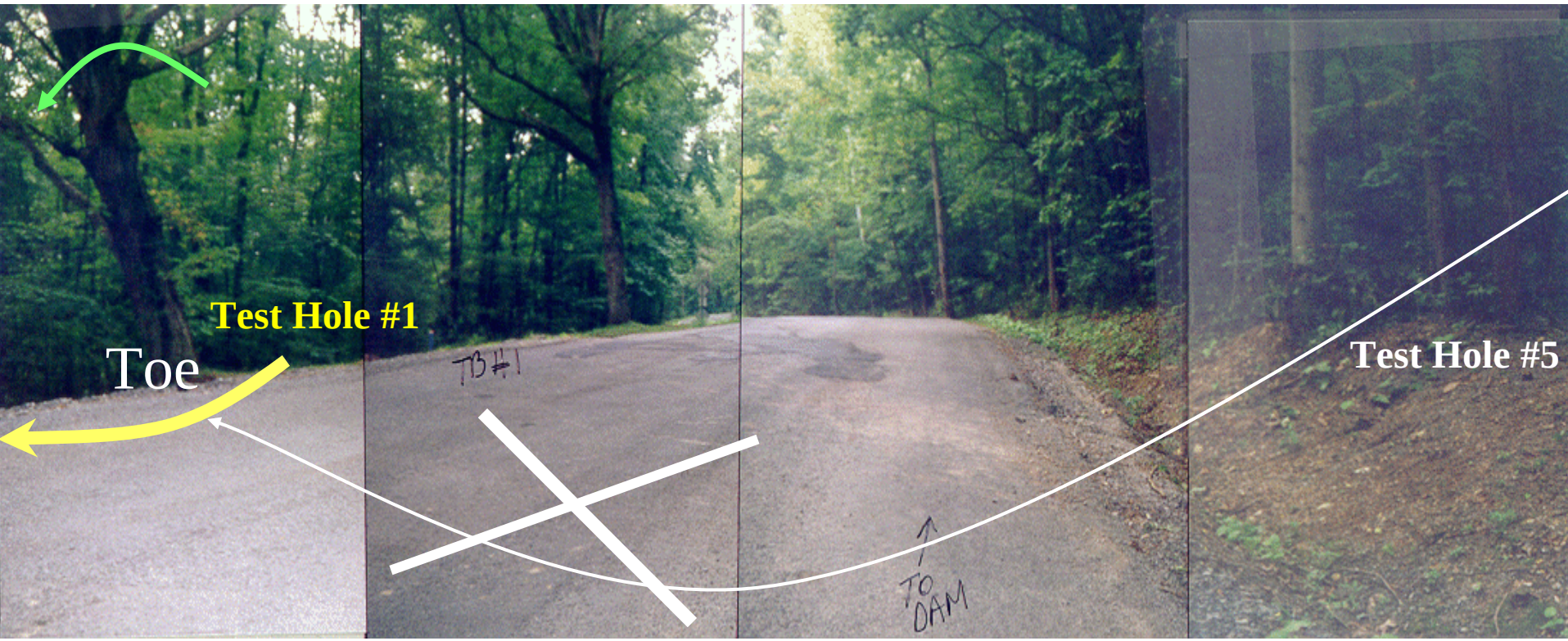
Tygart Lake Test Site

Profile View

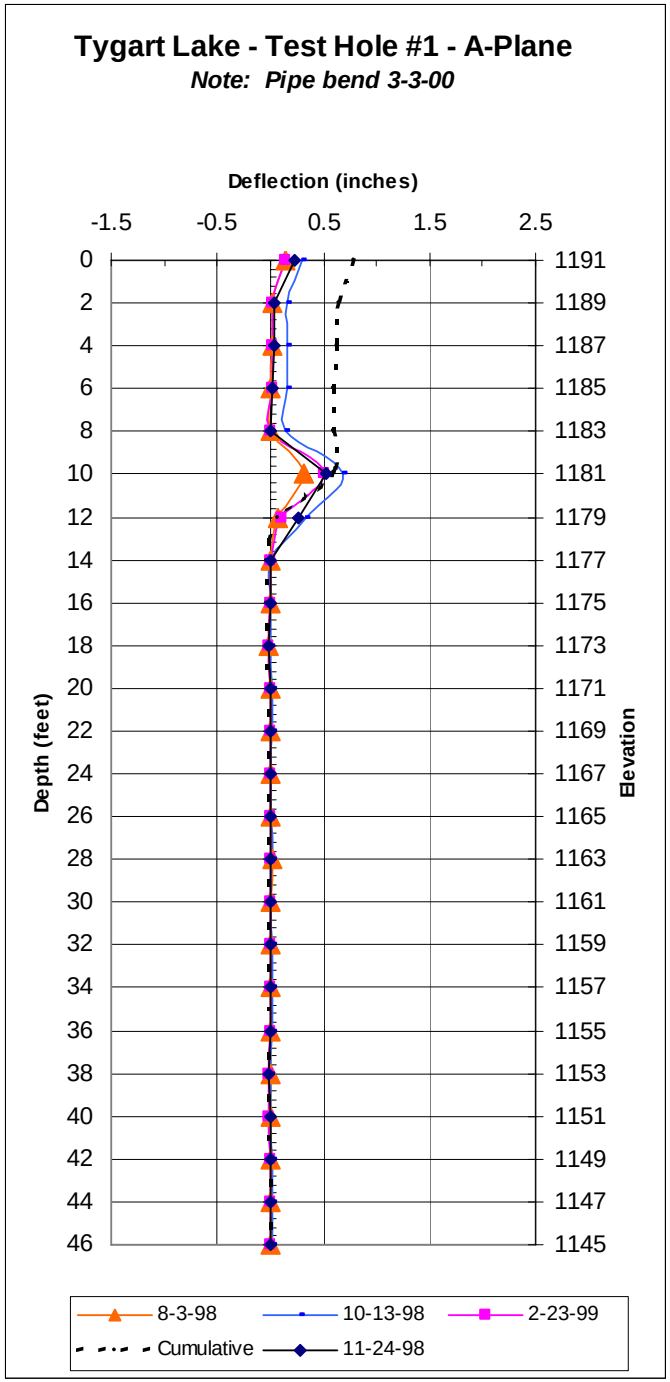
Visual Observations

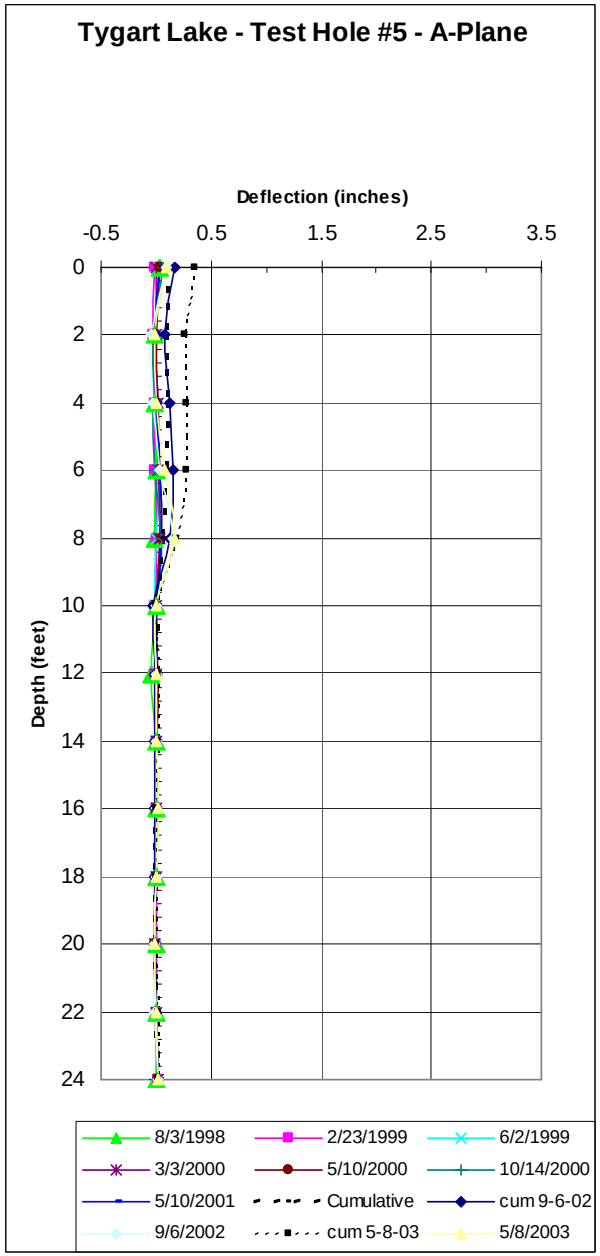
Near Test Hole # 1 and 5





Initial theory based on visual observations proven wrong





Movement detected in Test Hole #1

August 1998

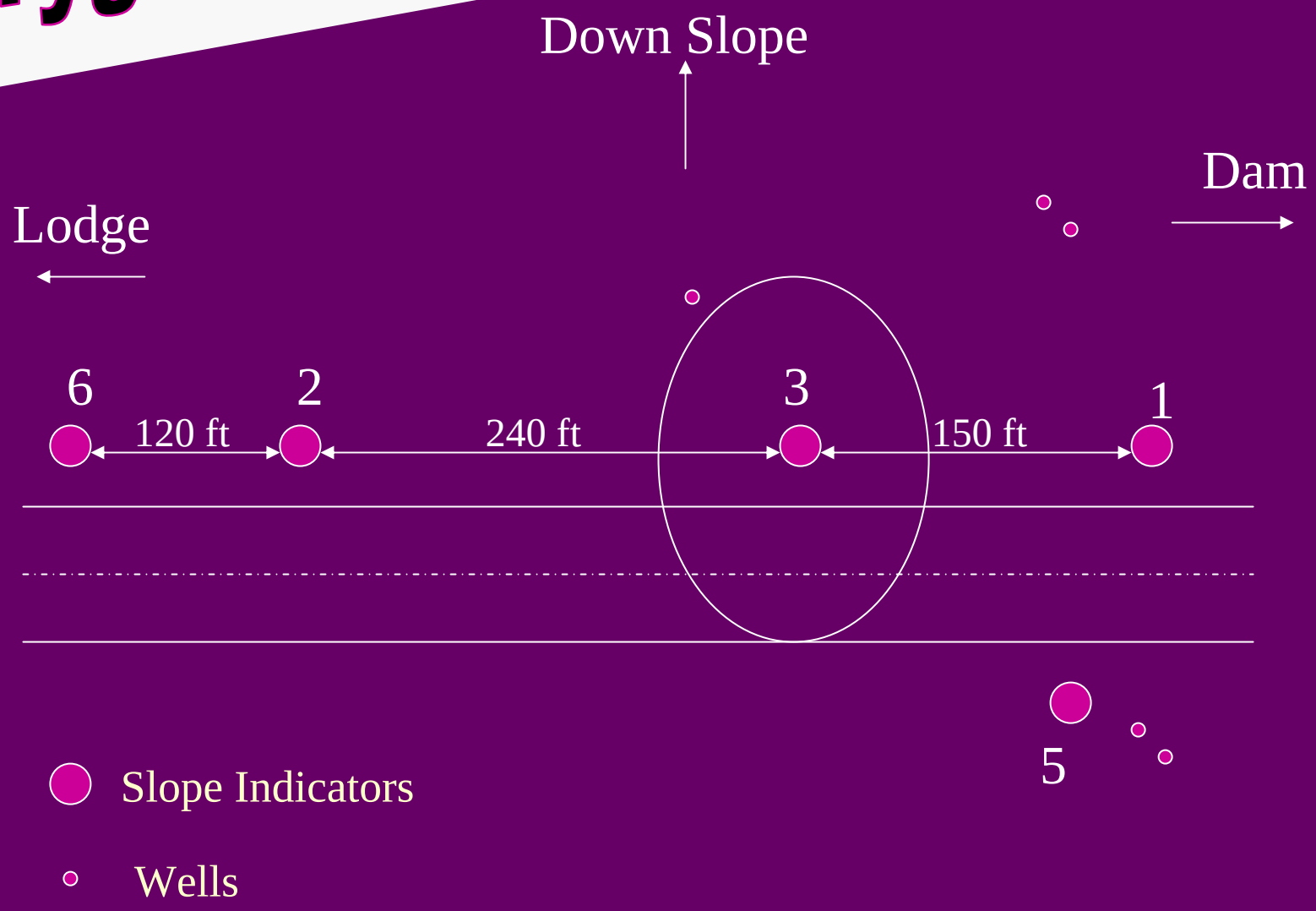
Movement detected in Test Hole #5

May 2003

5 years later

Tygart Lake Test Site

Plan View



Test Hole #3 - Visual Observations

Test Hole #3 - Visual Observations

Assumed an deep angular slip

ONE deep slip <u>initially</u> detected

Tygart Lake Test Site

Profile View

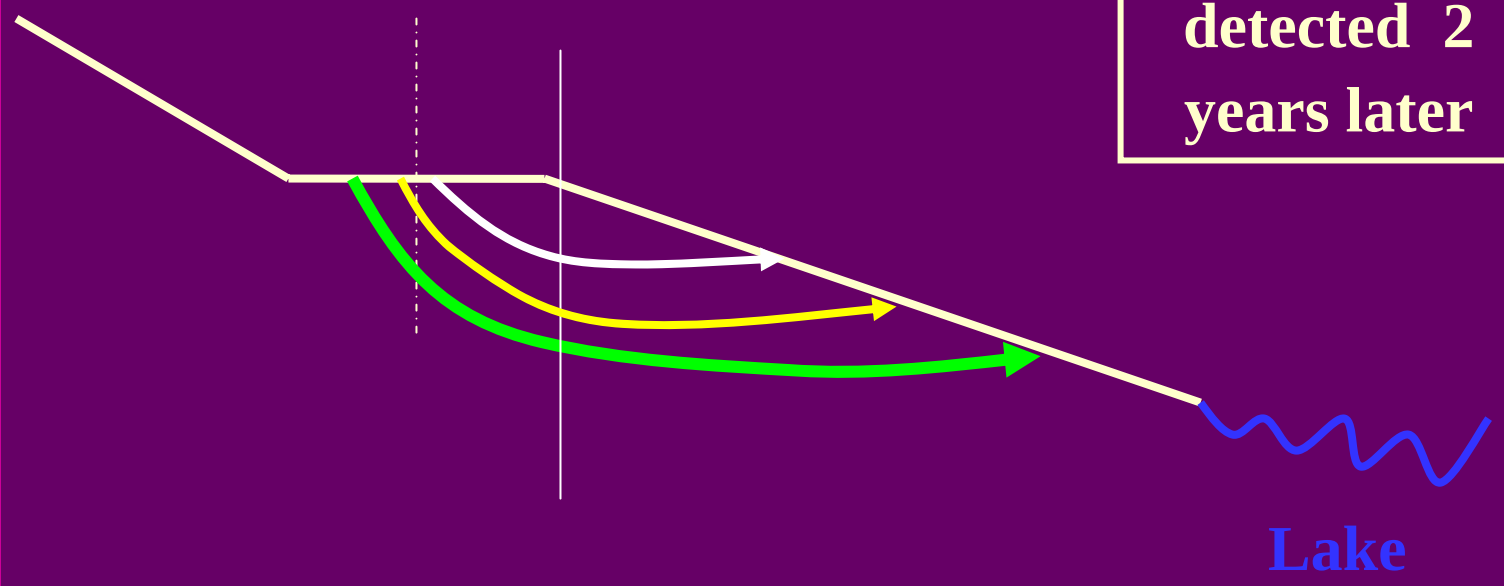
Complicated Slide S!

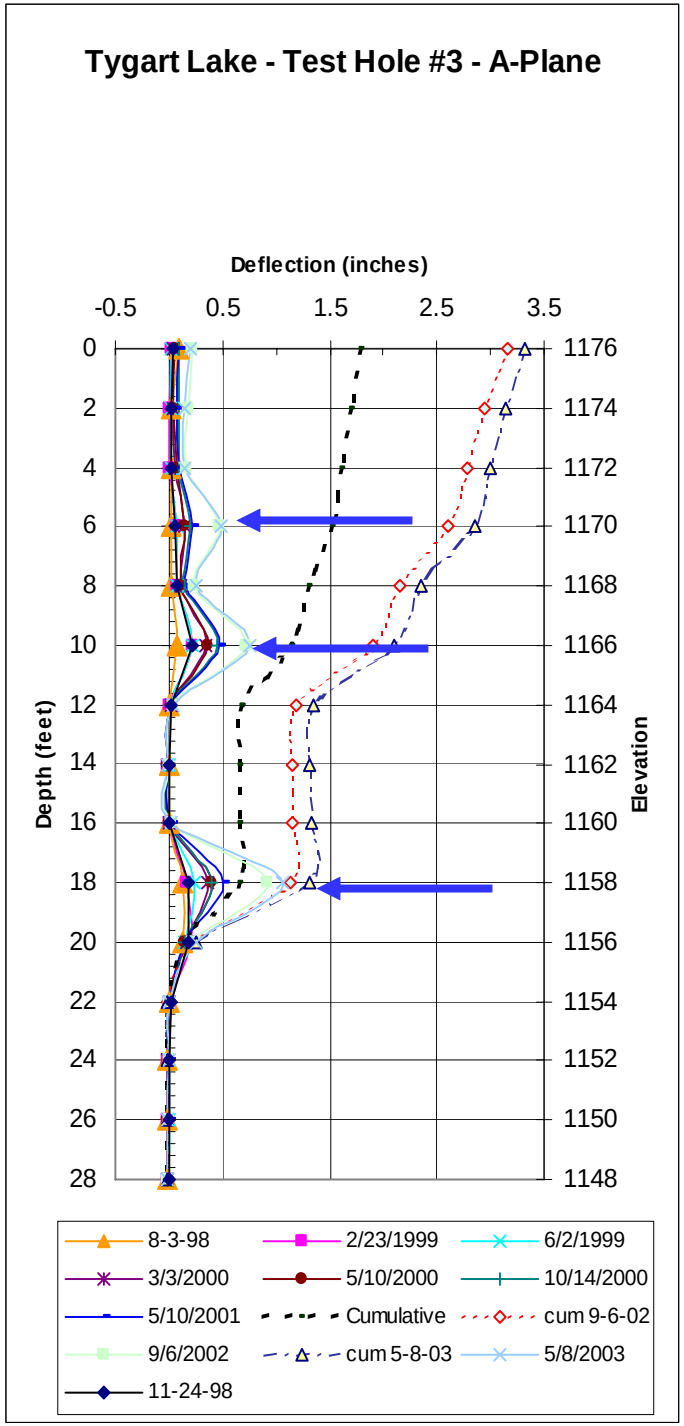
Inclinometer Observations

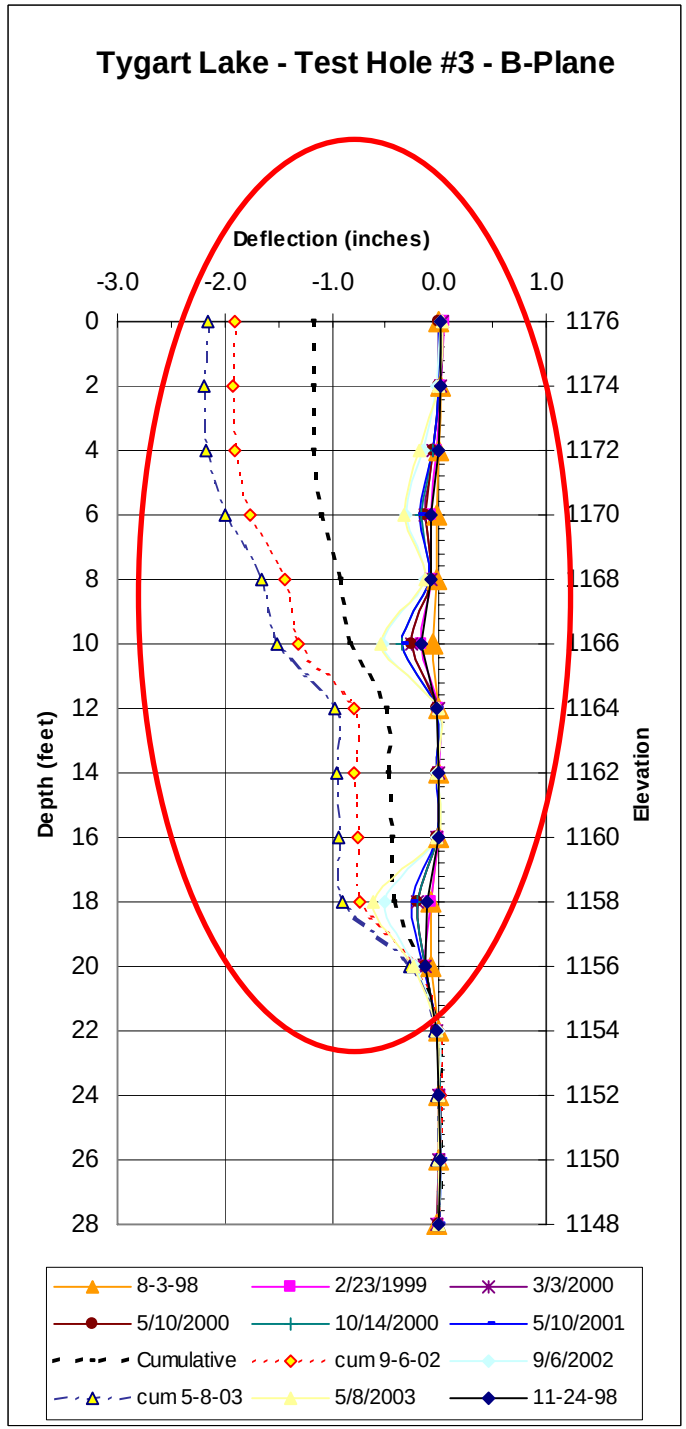
Test Hole #3

1 deep slip within the first year.

Two more detected 2 years later







Test Hole #3

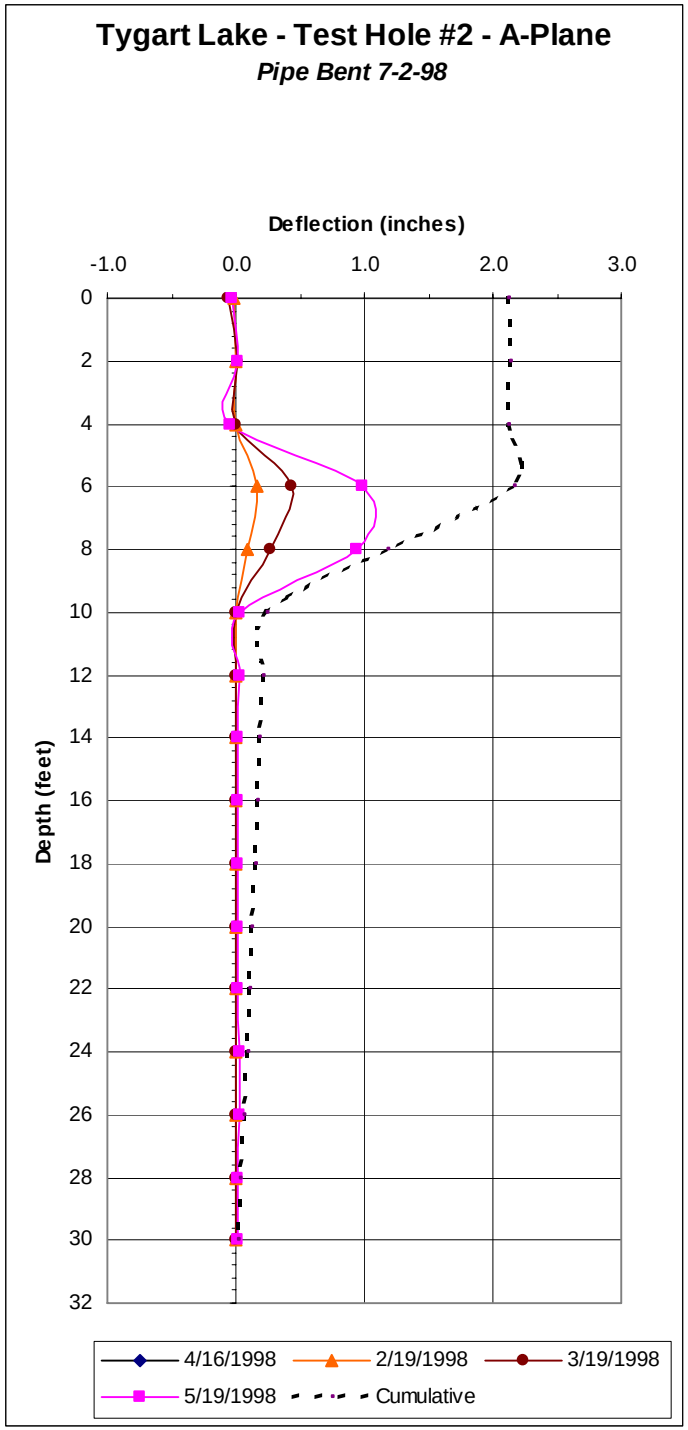
Three distinct slip planes detected!

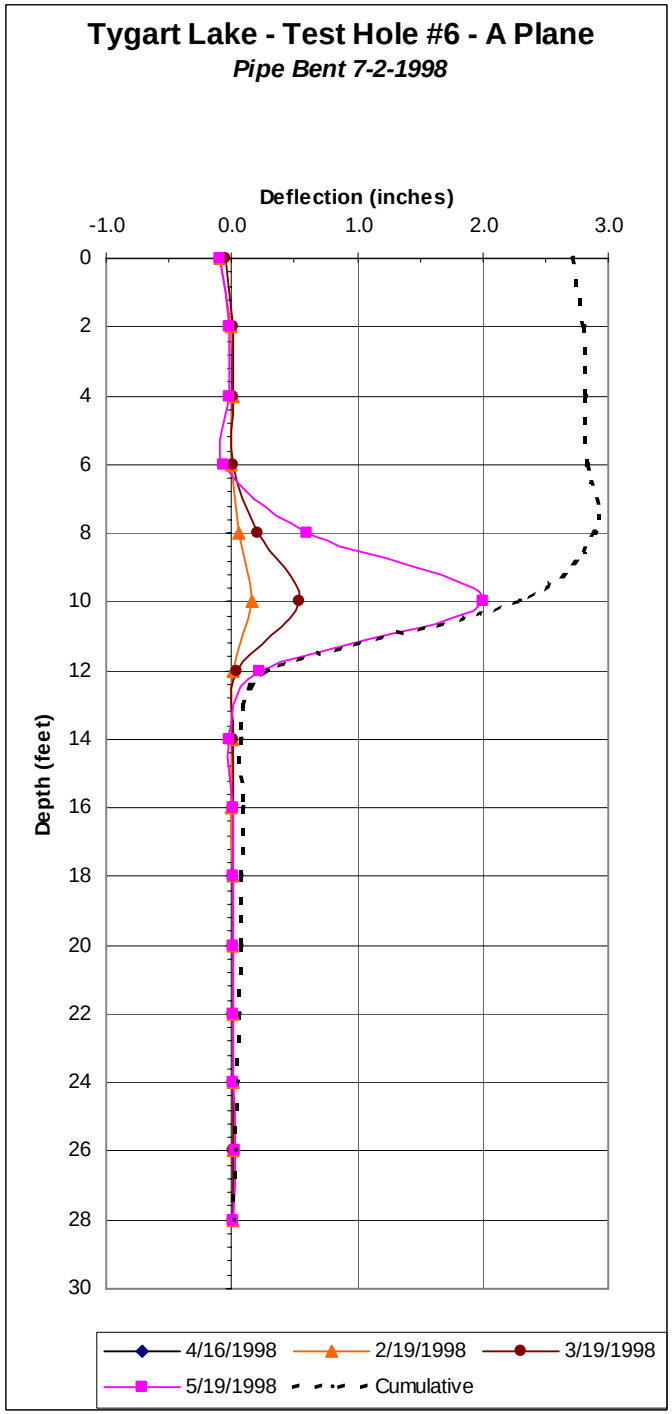
PLUS it was slipping on an angle as evidenced by movement in both the A and B direction

Tygart Lake Test Site

Plan View

Visible scarp, supports indicator data





TYGART LAKE

Test Holes #2 & 6
FIRST to move

Pipes Bent
Last Full Reading
July1998

Assumed same slip given the locations and time frames

Summary

After One (1) year:

TB # 2 & 6 Moved the most
(so much we couldn't monitor them anymore)

TB #3 Indicated one deep angular slip

No other significant movement

Test Piles were installed based on the results after ONE year

After Six (6) years:

TB#3 Showed signs of 3 independent slip planes

TB#1 Showed yet another independent surface

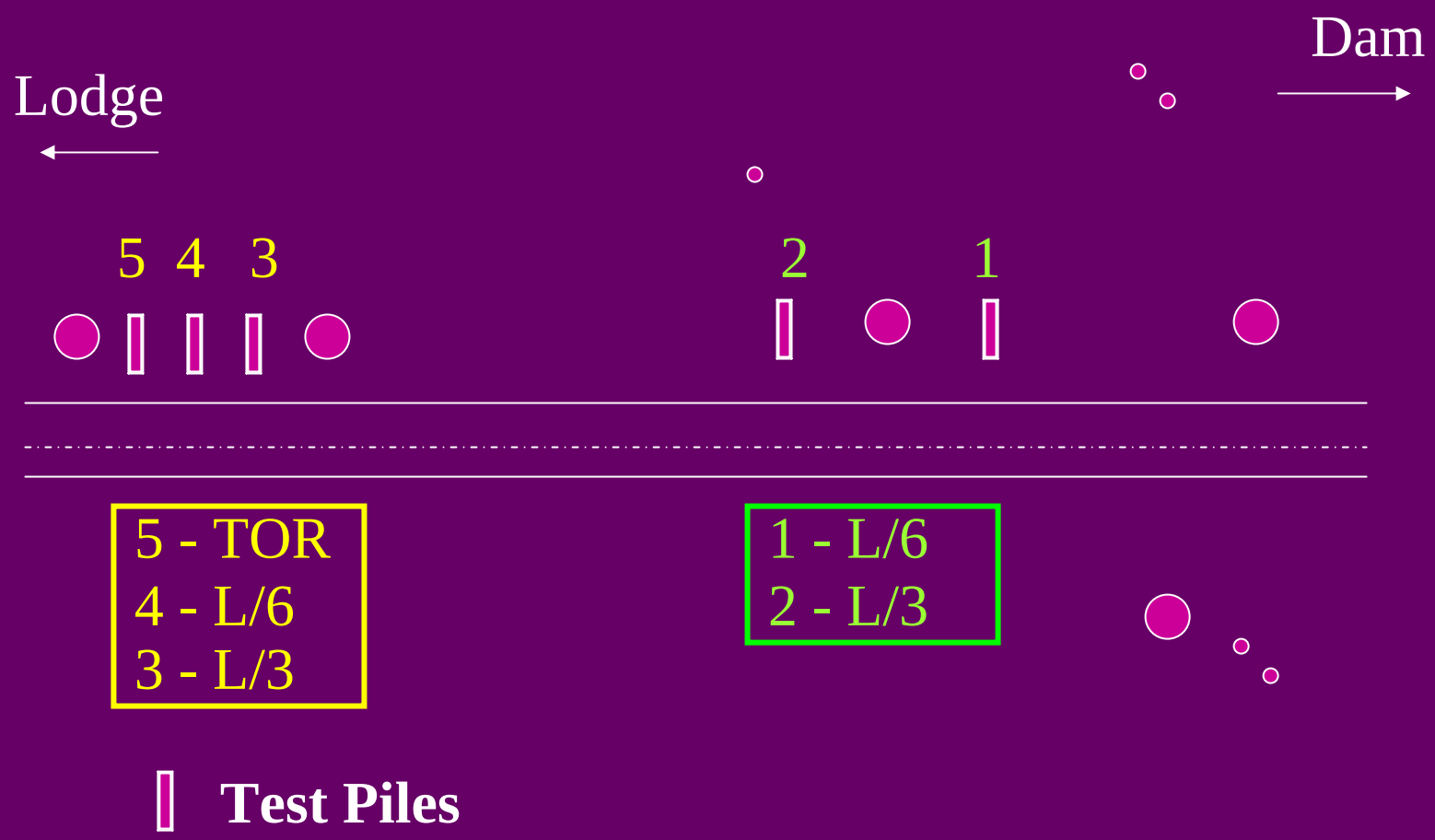
5 INDEPENDENT SLIP PLANES – 3 Sections

Tygart Lake Test Site

After 1 year

Plan View

TEST PILES

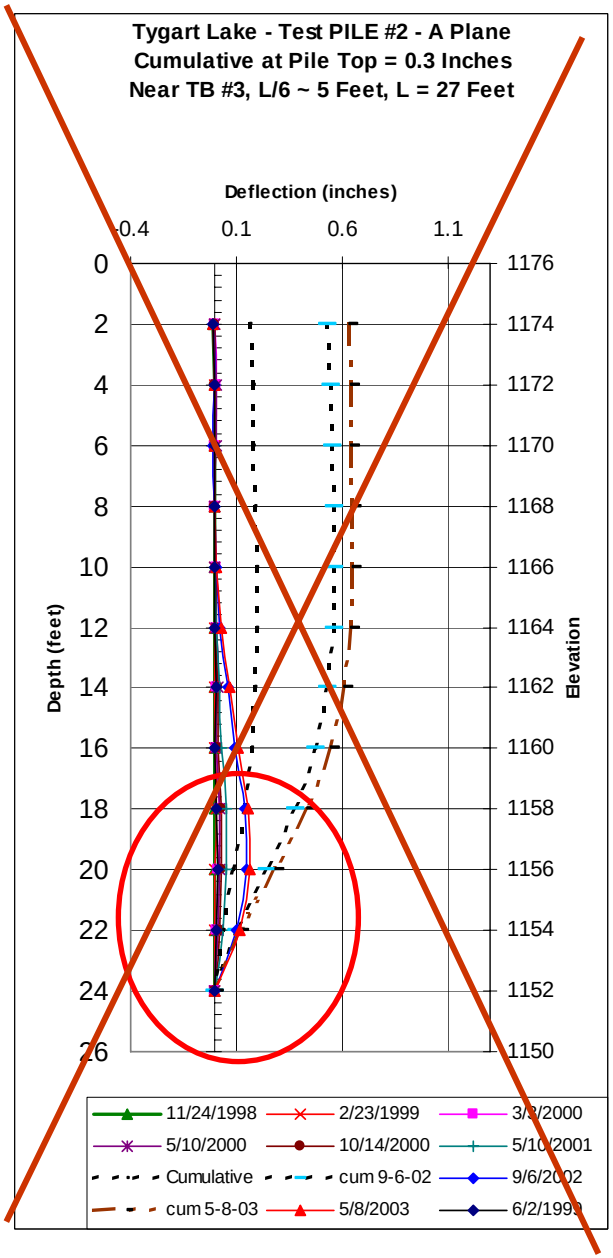


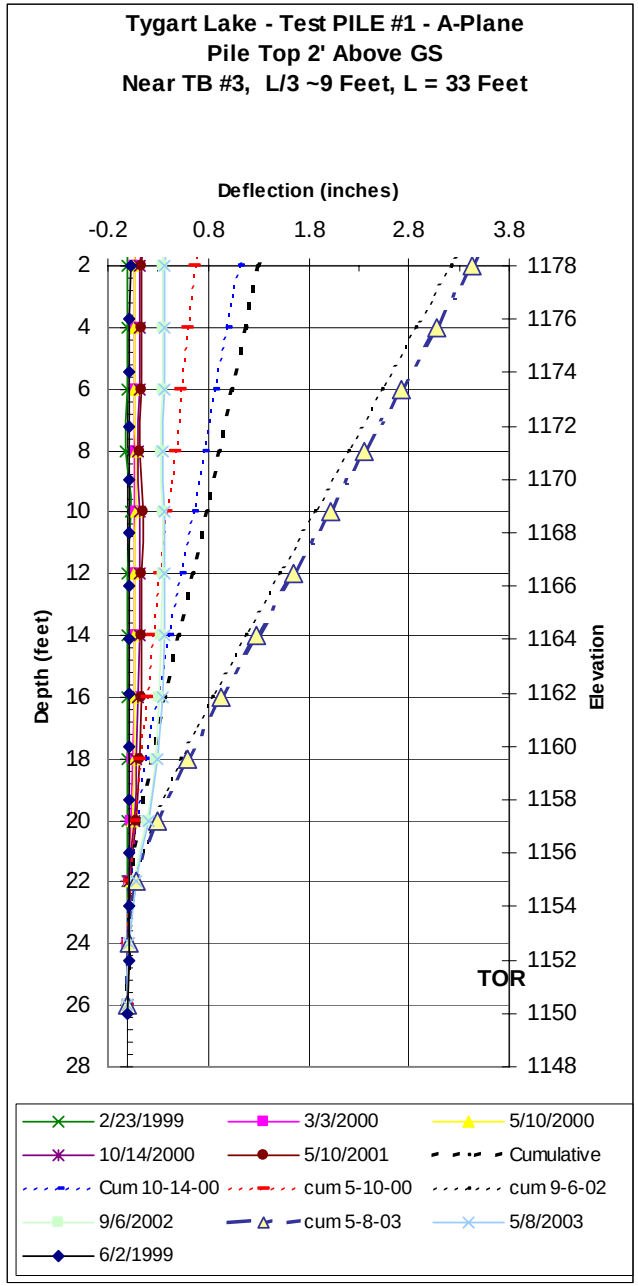
***Installed 5 SMALL piles at this site on purpose – we wanted them to move!**

HP 10 x 42

A-36 Carbon Grade Steel

Test Pile Installation at the Full Scale Tygart Lake Test Site

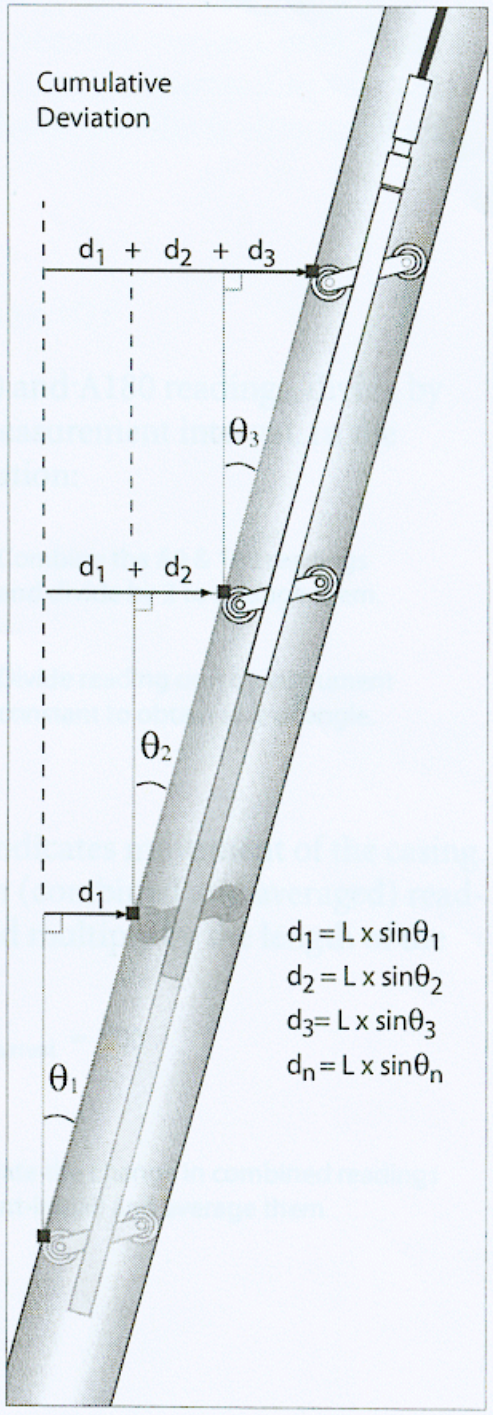




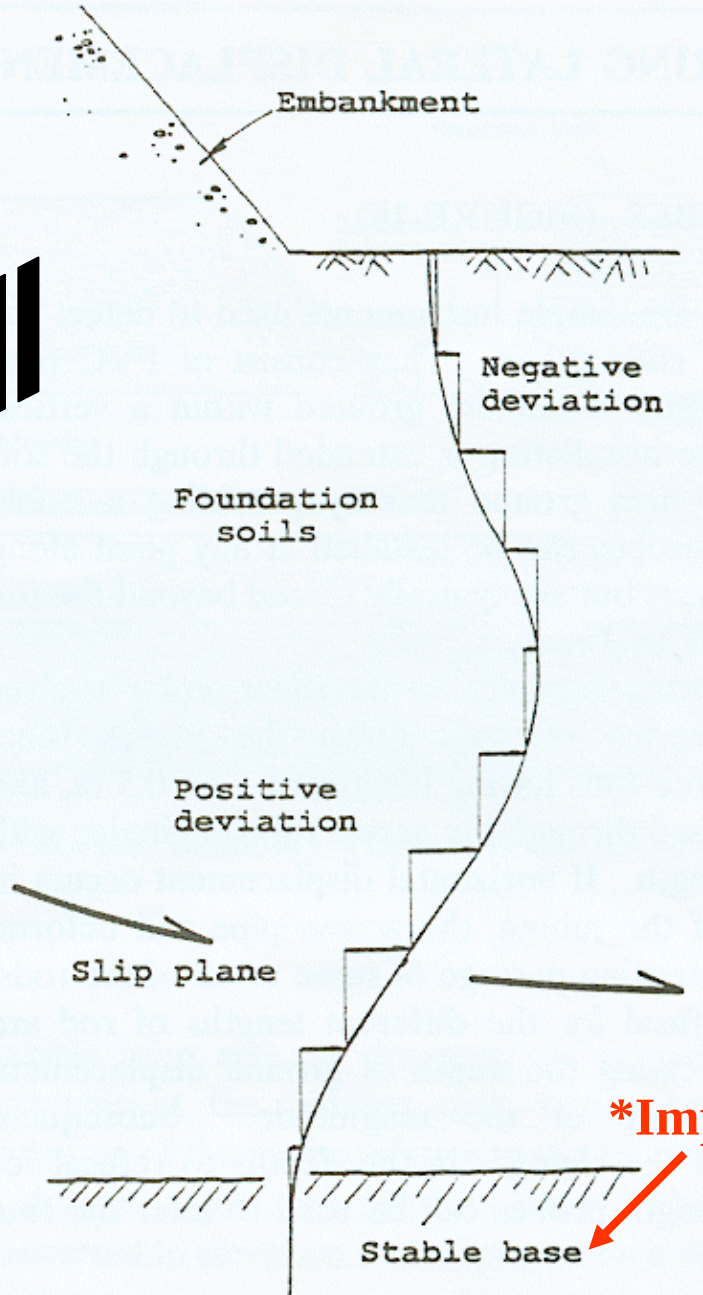
Tygart Lake
TEST PILE
RESULTS

Near Test Hole #3
(3 slips)

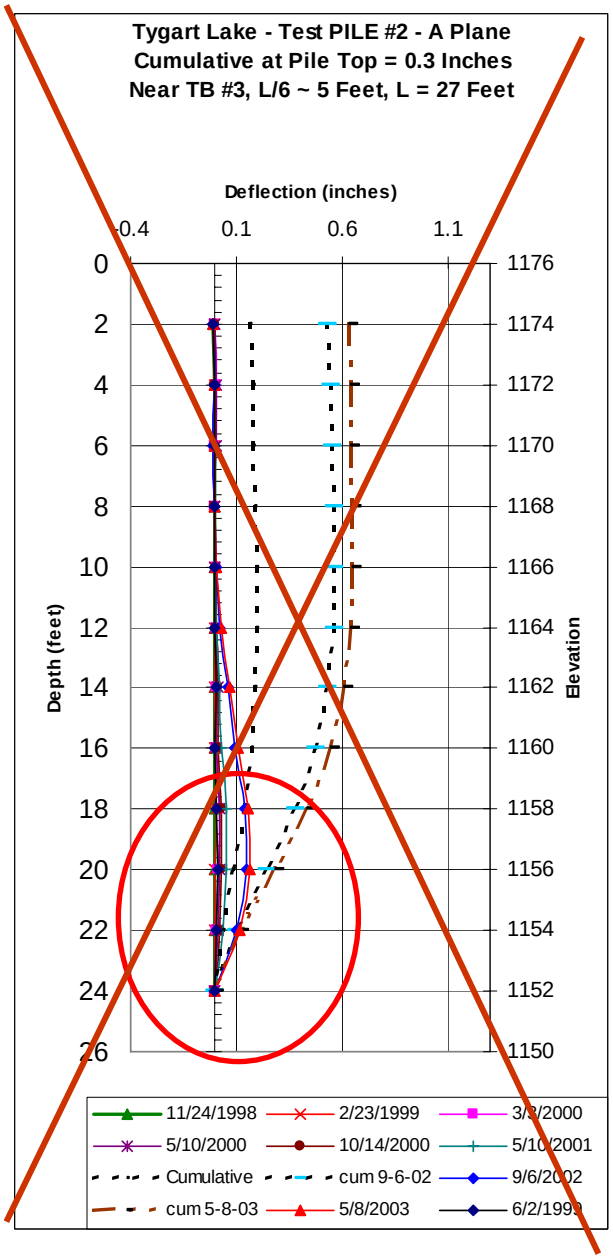
Test Pile #2
NOT fixed
at its base
**Very important

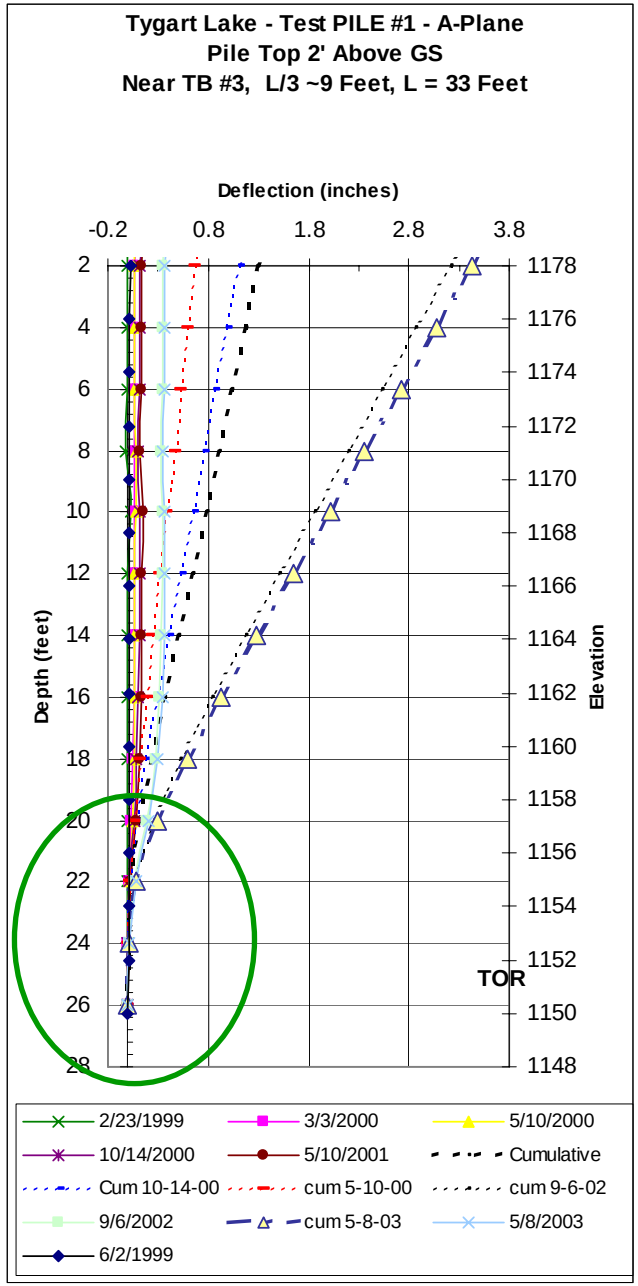


Recall



***Important !**





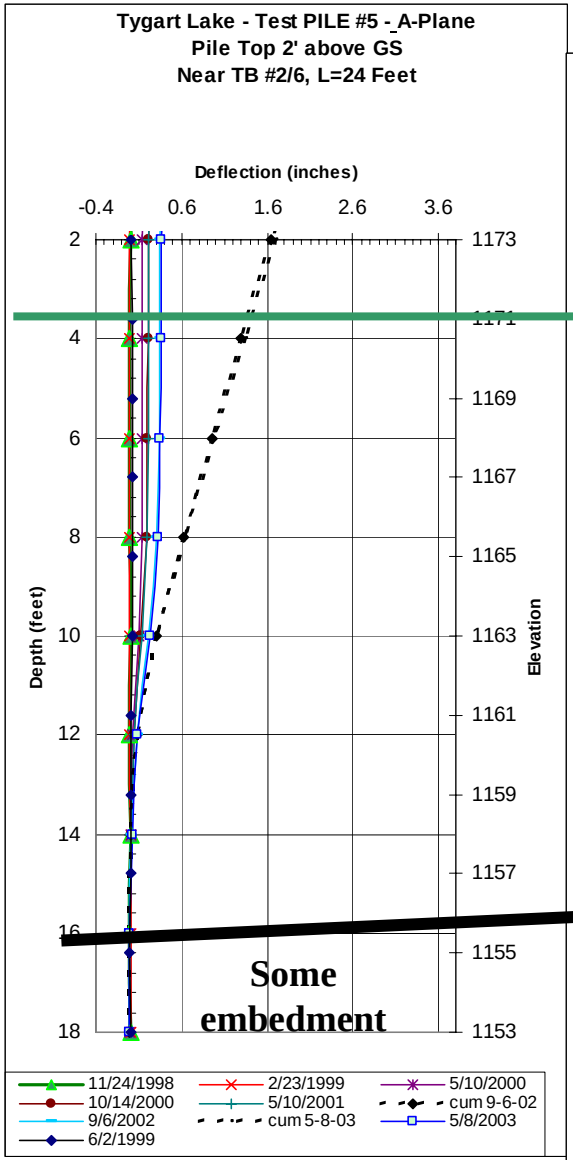
Tygart Lake
TEST PILE
RESULTS

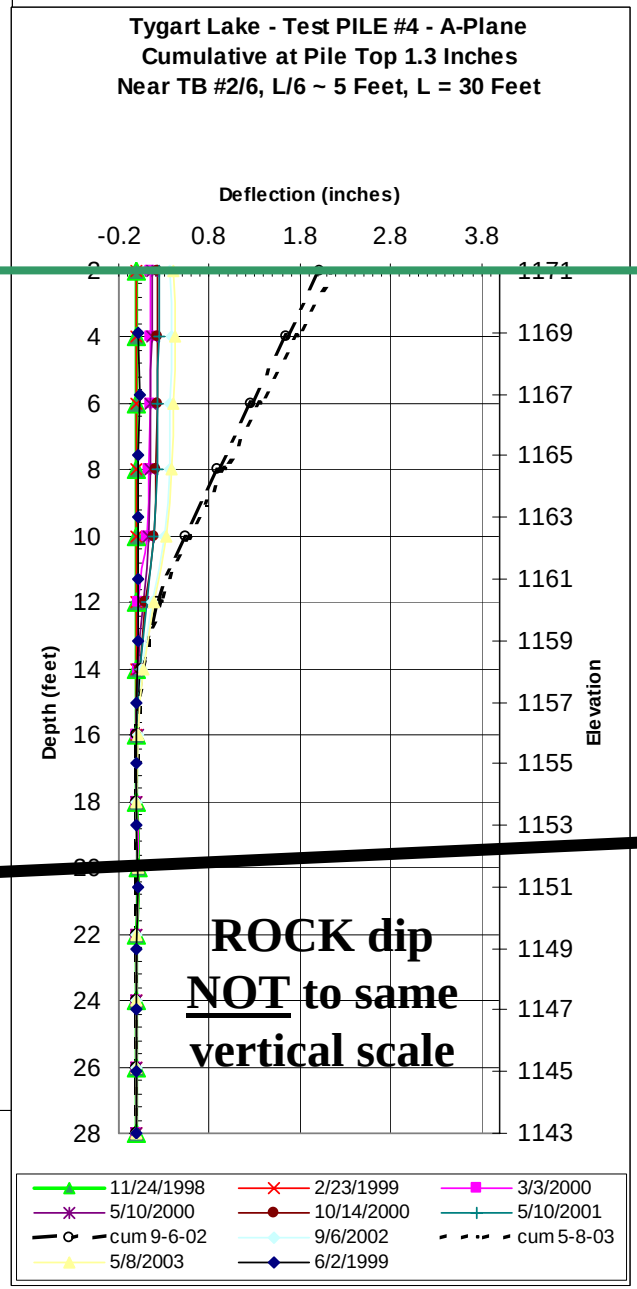
Near Test Hole #3
(3 slips)

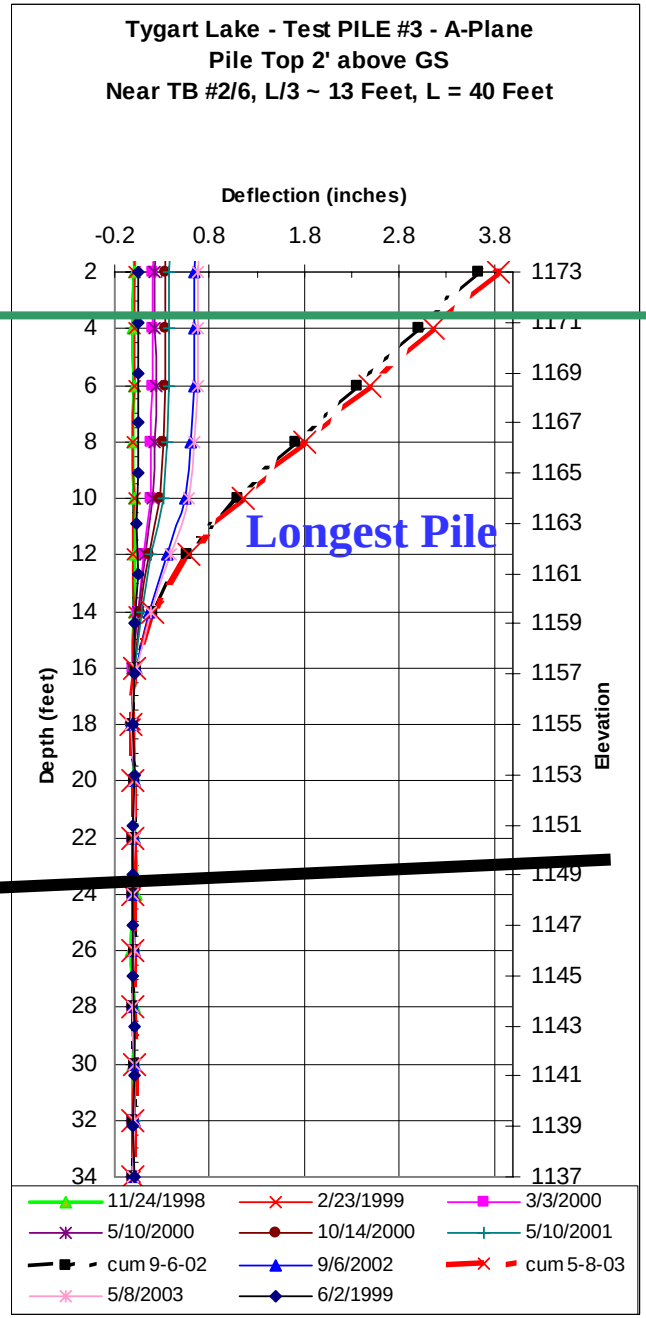
Test Pile #2
NOT fixed at its base

Very Important

Test Pile #1
Behaved as expected







TEST PILE RESULTS

Near Test Holes 2 & 6

Ground Surface

Model Development

After initial data collection

Considers a Landslide Based on an Impending Failure

Factor of Safety = 1.0

Design & Anaysis

Recall

Requires defining two main factors

1. **The force the piles must resist**

   Based on a landslide

2. **The passive resistance provided by the piles**

   Based on the location of the slip

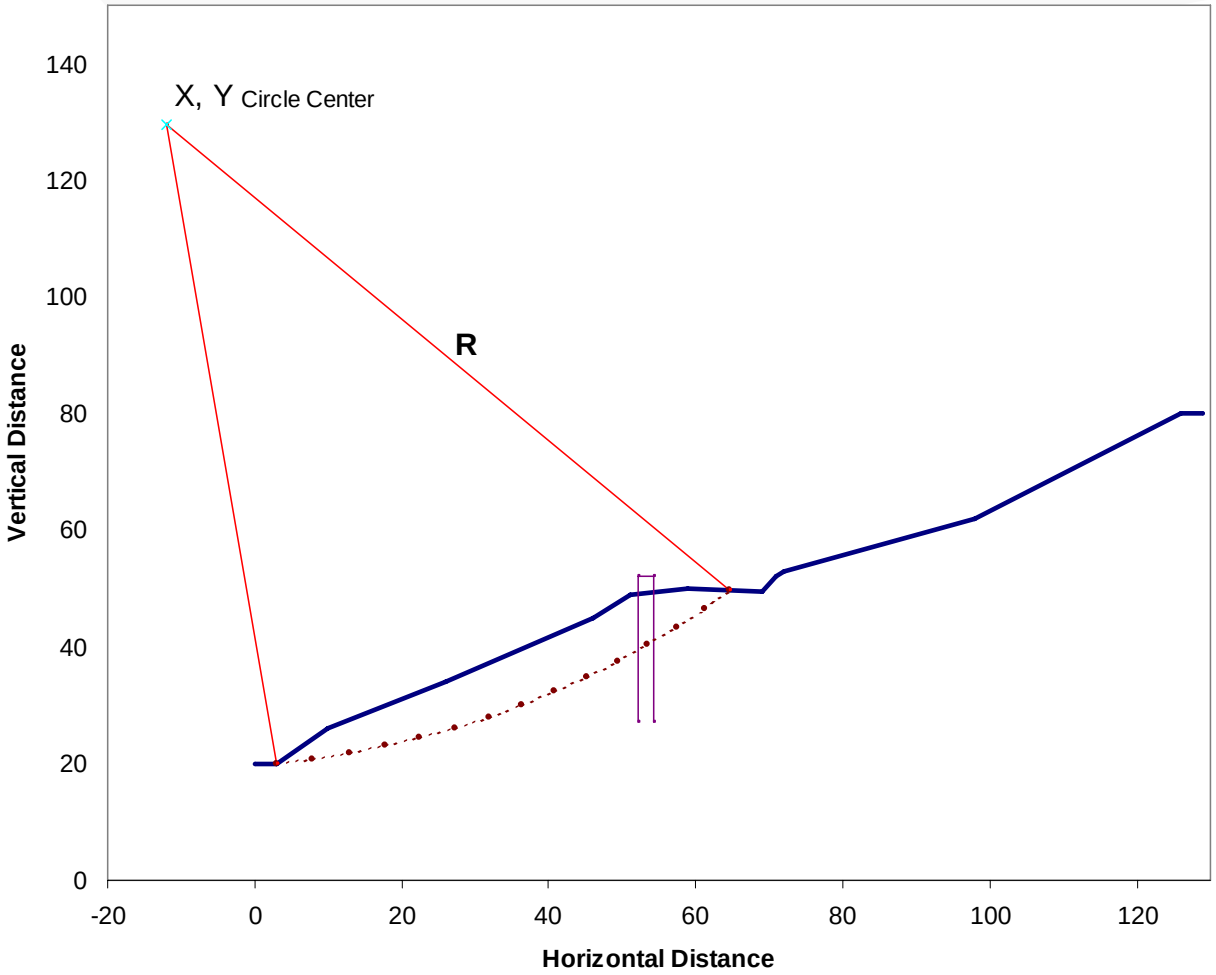
Driving Force

A slope stability analysis is first conducted to define the shape of the slip surface

A limit equilibrium analysis of a circular failure surface determined via the method of ordinary slices was selected

The program STABL was used

Knowledge of slope stability analysis required!



BASIC PREMIS

The surface of failure is represented by the arc of a circle

The soil within the circle rotates about the center of the circle

Method of Slices

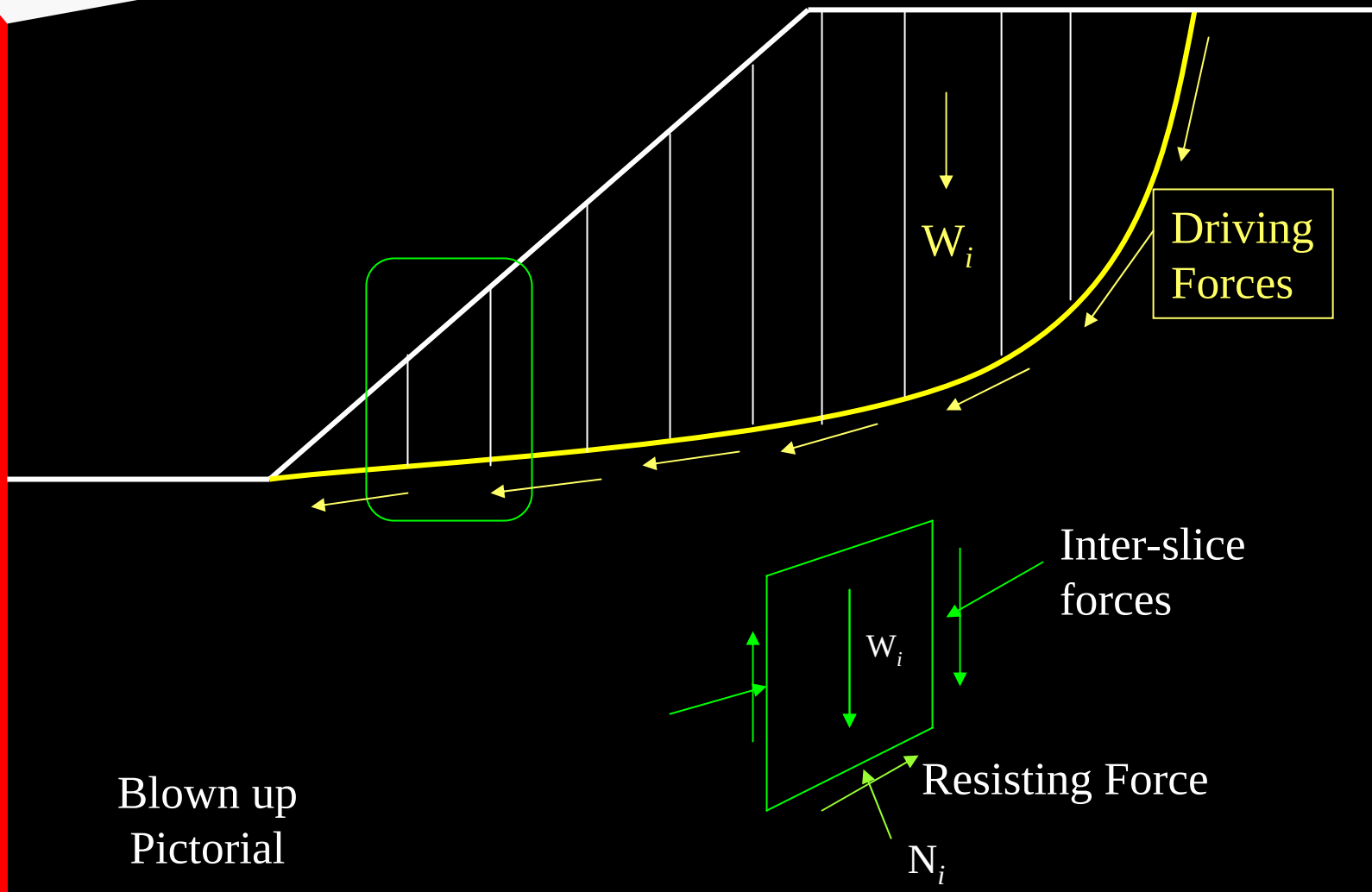
Depends on the distribution of Normal Stress, N, along a failure surface

$$N = W_i * \sin(\text{alpha}_i)$$

Is analyzed by discretizing the mass of the failed slope into *n* smaller slices

Each slice is treated as a unique sliding block and is affected by a general system of forces

Method of Slices



Method of Slices

The tangential vector **(driving force)** represents the slide-inducing forces

$$\boxed{\mathbf{T = W_i \sin(alpha_i)}}$$

The **resisting forces** consist of the soil cohesion, c, along the arc length, l, and the angle of internal friction, phi

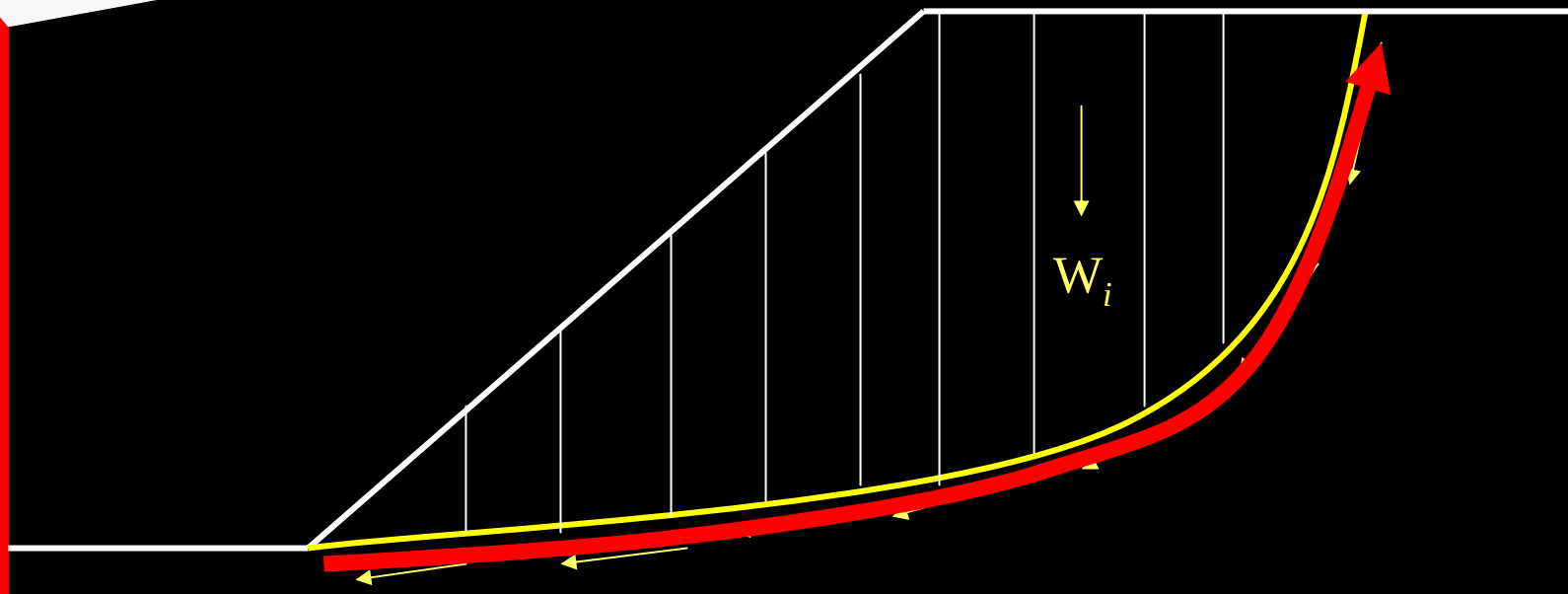
$$\boxed{S = cl + \text{sum}\left(N_i * \tan(phi) \right)}$$

Pore water pressures are considered by reducing N

Shear Strengh VS Resistance

Factor of Safety

Resisting to Sliding

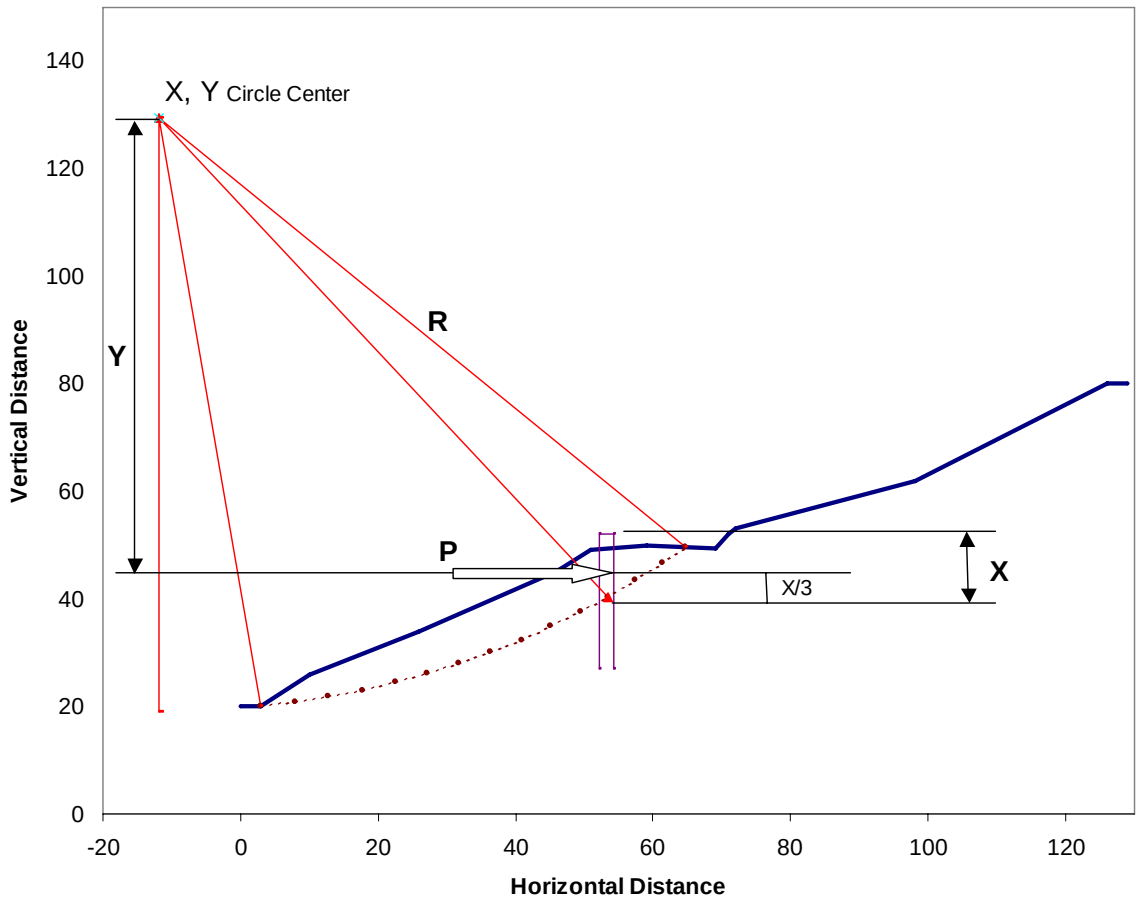


Resisting Force: Shear Strength of Soil

$$S = cl + \text{sum}\ (\ N_i * \tan(\text{phi})\ )$$

Basic geometry of analyzing a landslide with a circular failure surface

Figure 4.2.3: Pictorial of the Development of the Model Force
Forest Avenue - Profile and Critical Slip Surface



(sum T - sum (N-U) * tan phi) * R

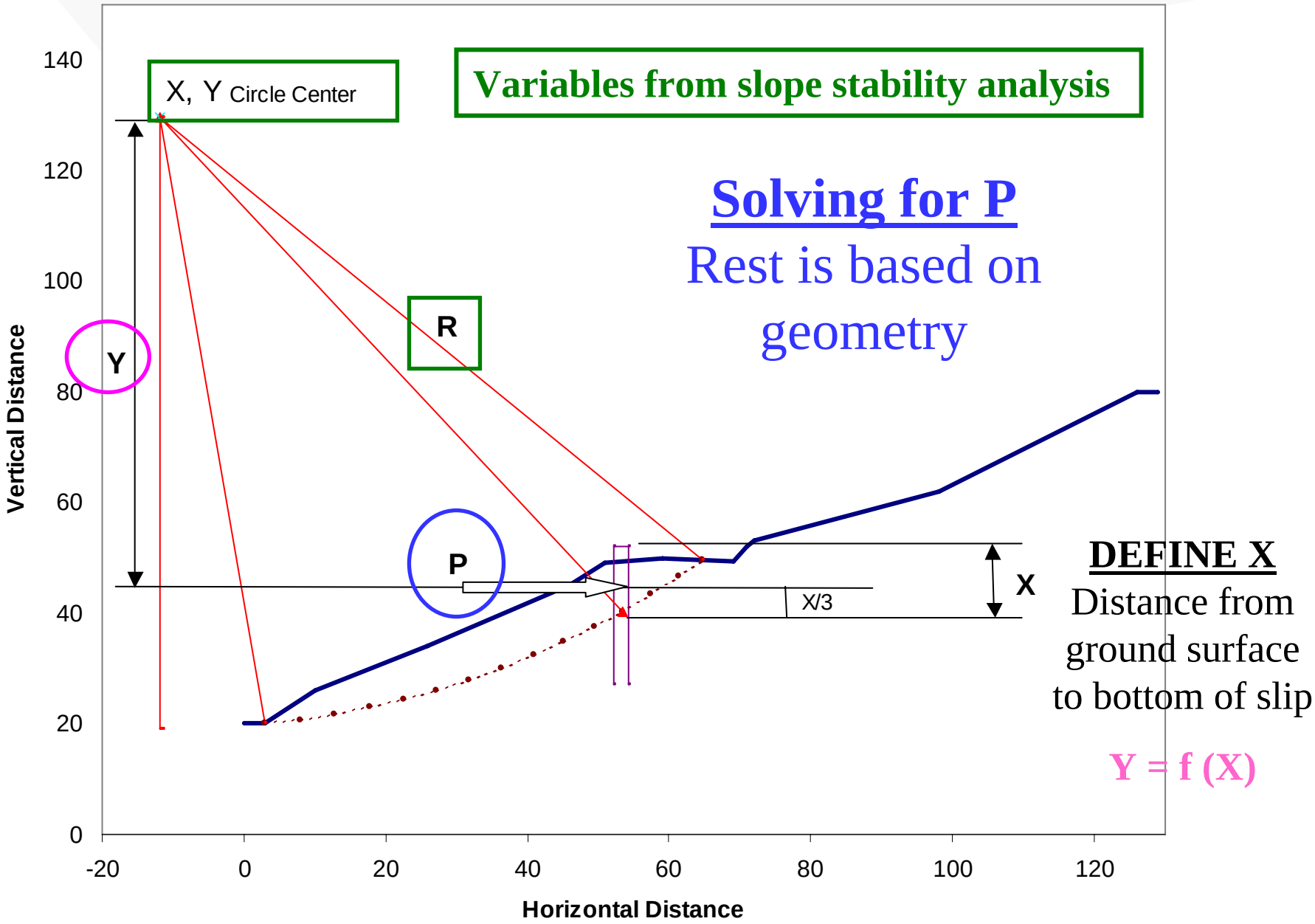
= P * Y

(Driving – Resisting) * Radius = What the pile must provide

Statics problem!

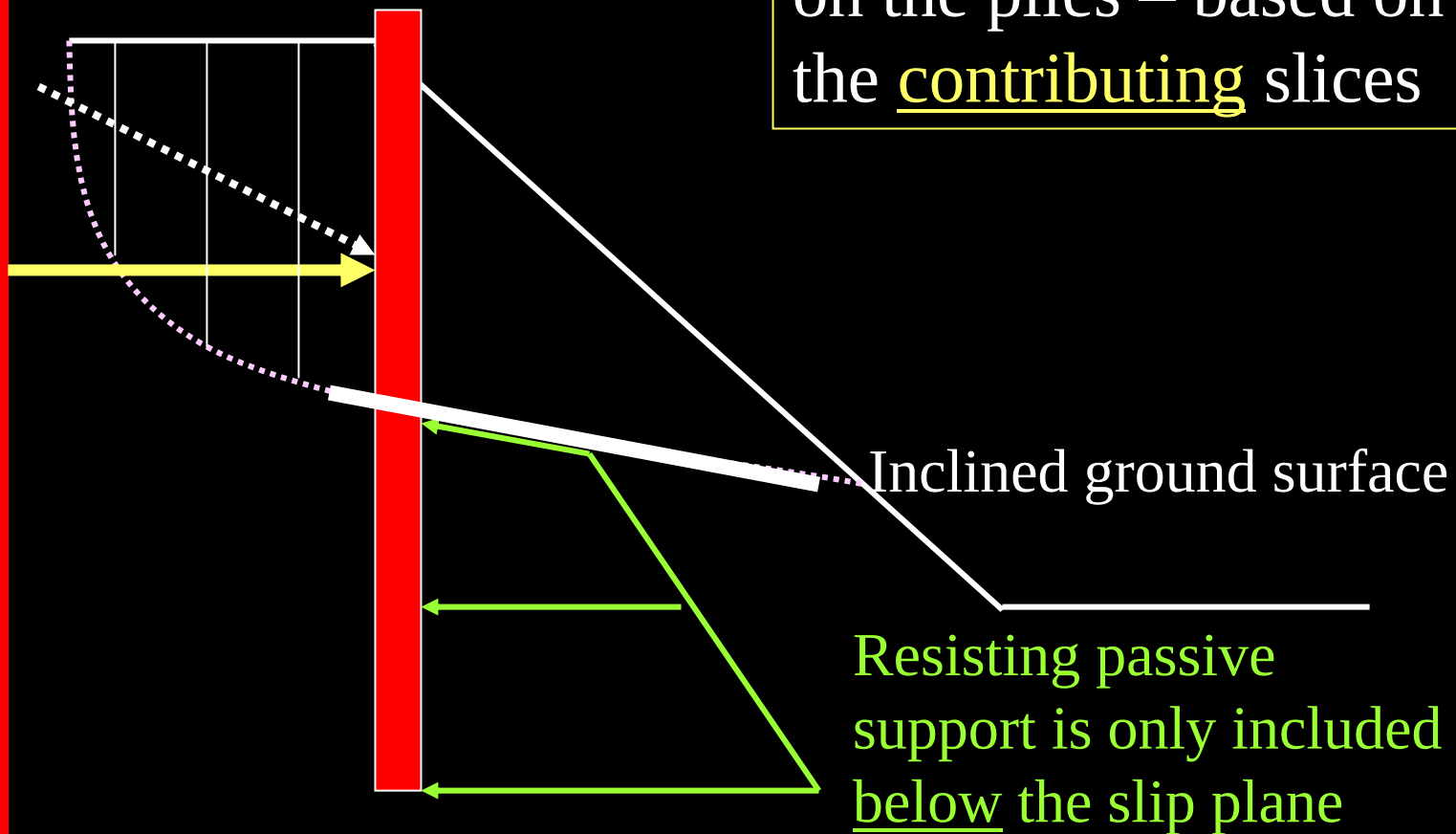
Inter slice forces are neglected

Figure 4.2.3: **Pictorial of the Development of the Model Force**
Forest Avenue - Profile and Critical Slip Surface



Basic Premise

Spreadsheet designed to calculate total force on the piles – based on the contributing slices



Note:

It was determined in Phase I (RP #97) that the vertical component did not contribute

Design & Anaysis

Requires defining two main factors

1. **The force the piles must resist**

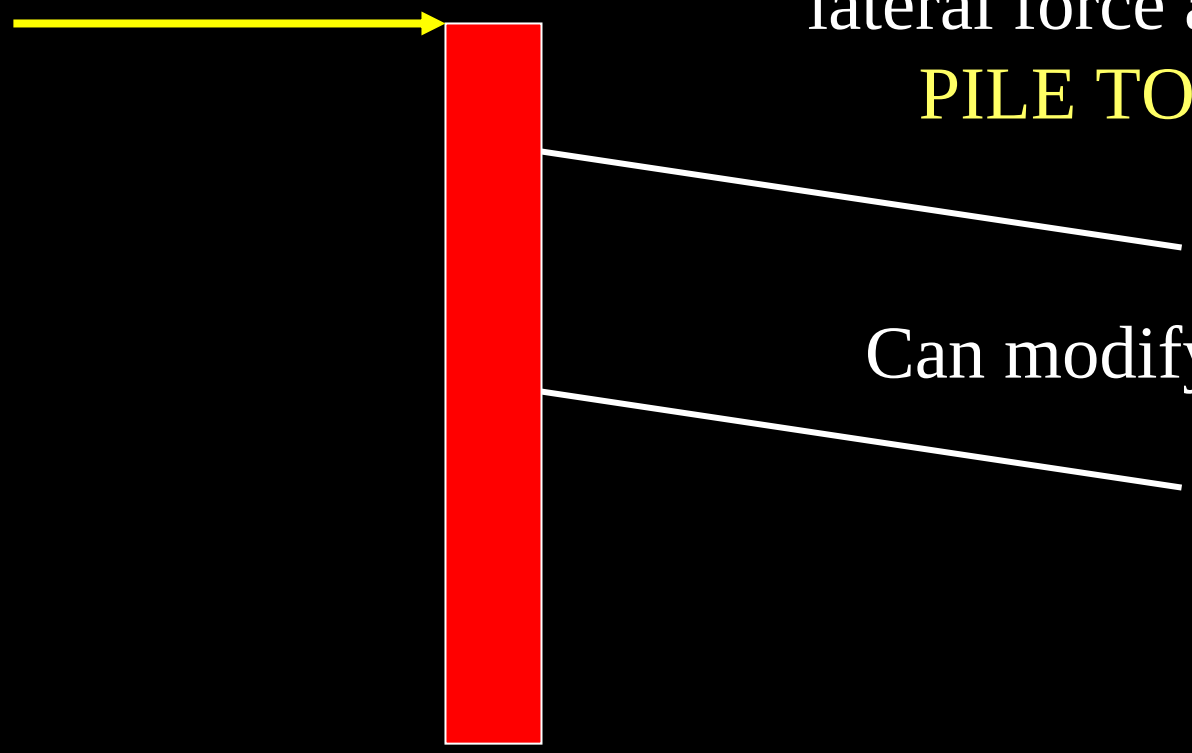
   Based on a landslide

2. **The passive resistance provided by the piles**

   Based on the location of the slip

Pile Code Problem

Laterally loaded Pile Programs – Consider a lateral force at the PILE TOP

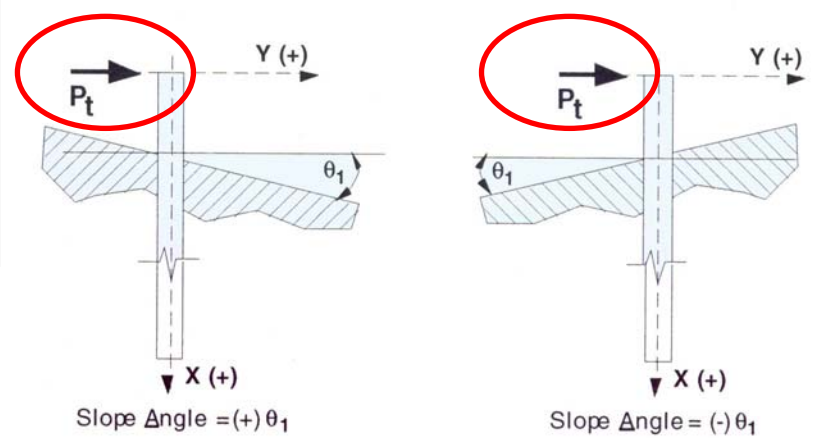


Can modify GS

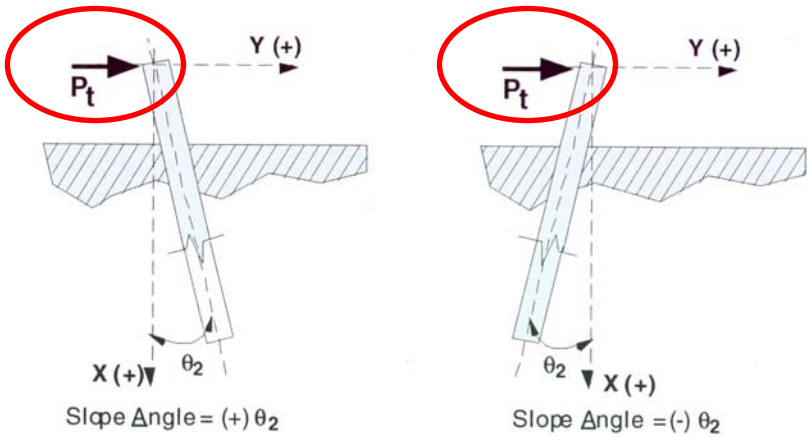
Pile Programs

Model Lateral force at the pile **TOP**

Variable ground surface and/or batter



Sign convention for input of Slope Angle to account for sloping grounds



Sign convention for input of Slope Angle to account for pile batter

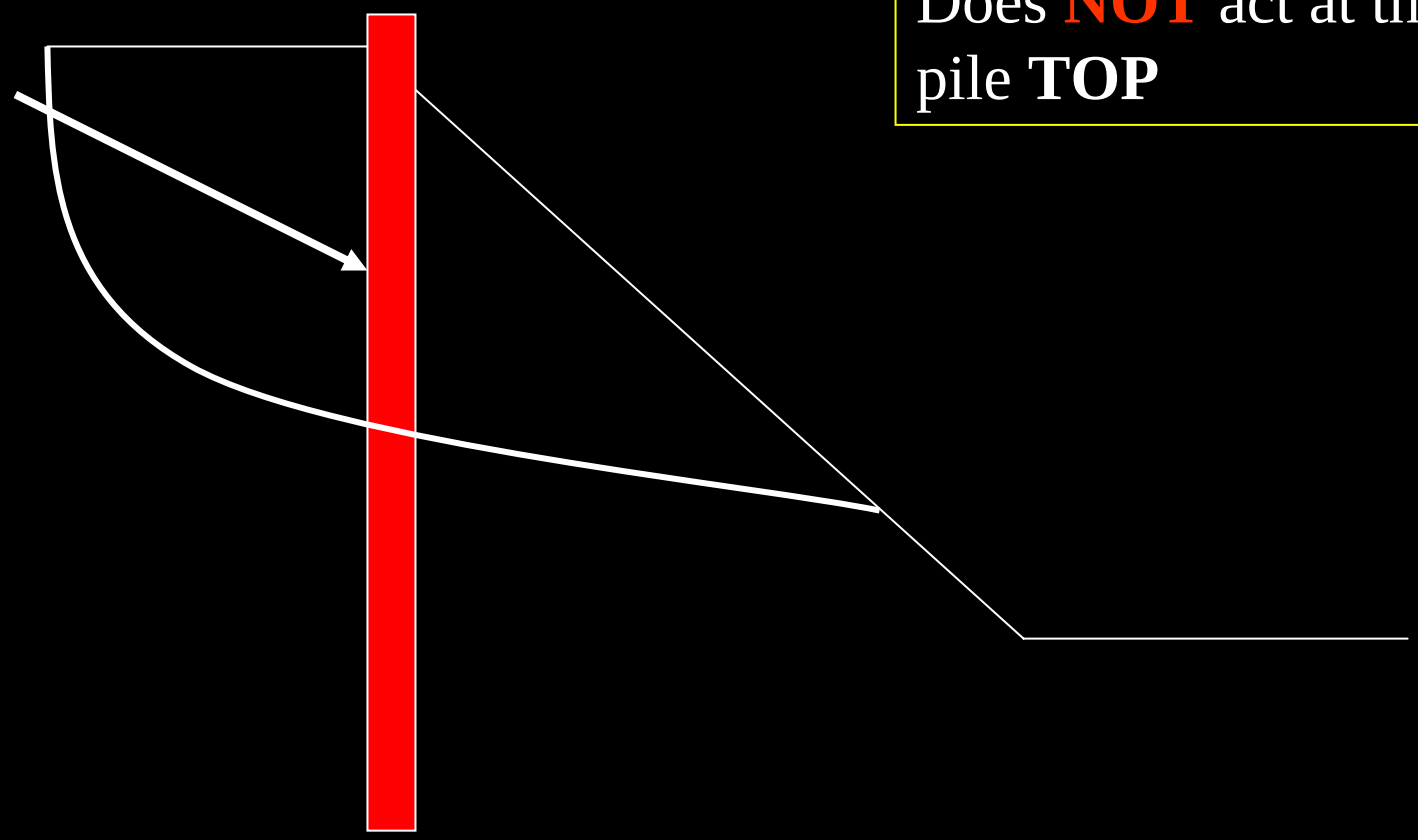
As given in LPILE by

Reese et al. 1999

ACTUAL problem

Resulting driving force from a landslide

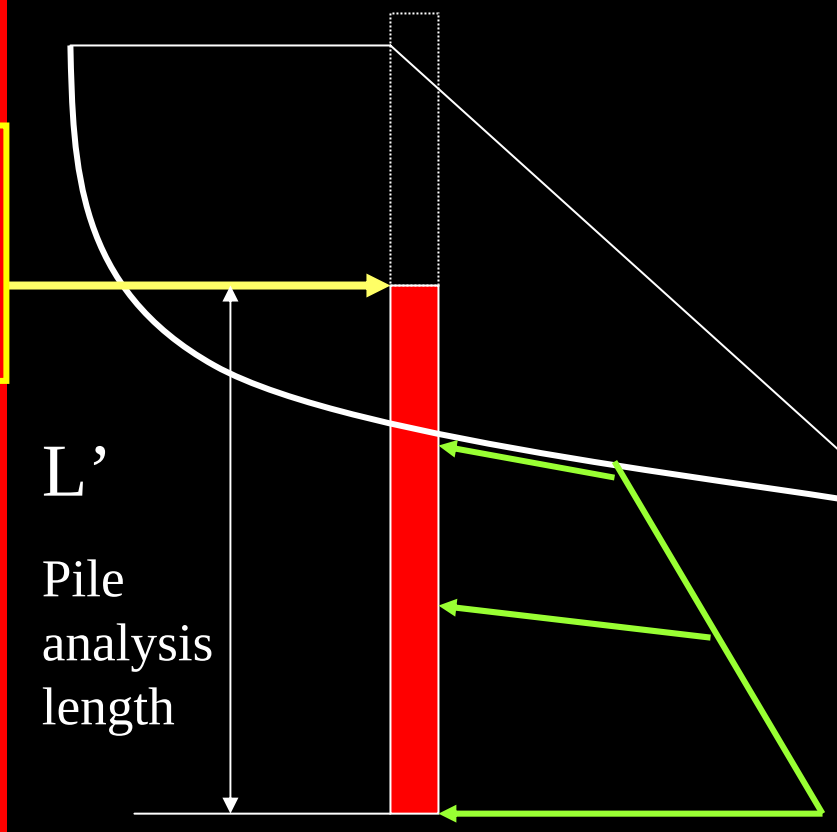
Does **NOT** act at the pile **TOP**



Pile Analysis

Critical Case Based on how the pile programs operate

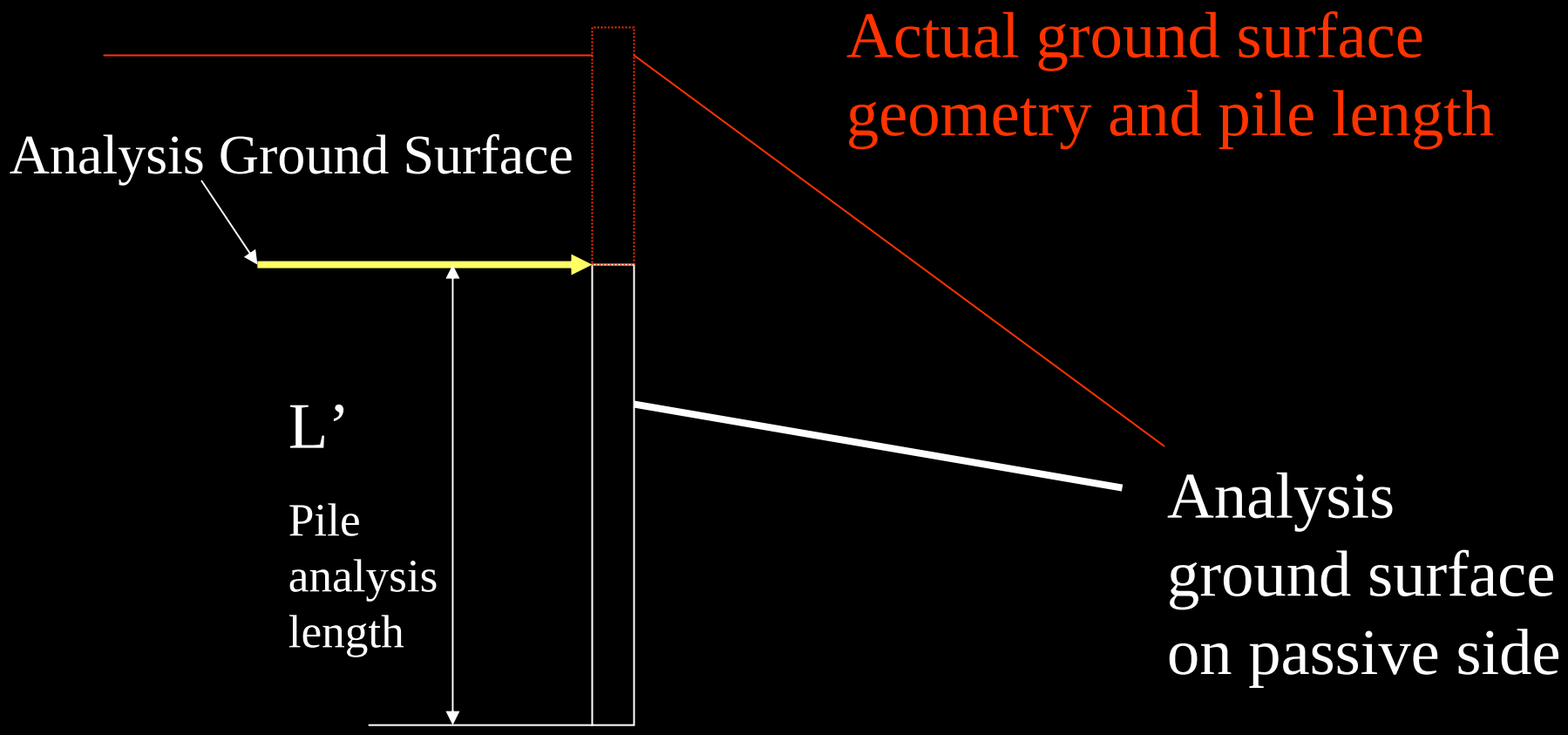
Considers a load at the top



Passive Support

f (slip plane) and location of pile

Pile Problem



Failure Criteria

Pile Analysis

1. Excessive deflection at the pile top

   greater than 2”

2. Movement at the bottom indicating that fixity was <u>not</u> obtained:

   > 0.0004b

3. Moment developed > Moment allowable for pile size

Failure Criteria 1

Excessive deflection at the pile top > ~2 inches

A. No movement at base – Implies excessive bending. Pile section is not BIG enough

Failure 3

B. Movement detected in the base – Implies fixity was not obtained. Increase the pile length and reexamine the results.

Failure 2

IF deflection is STILL excessive after you increase the length and obtain fixity – increase section

Failure Criteria 2

Pile Analysis

2. Movement at the bottom indicating that fixity was <u>not</u> obtained:

   $> 0.0004b$

i.e. Not socketed into a firm enough material

Fixity NOT obtained!

Failure Criteria 3

Pile Analysis

Moment developed > Moment allowable for pile size

East Point - Bridgeport

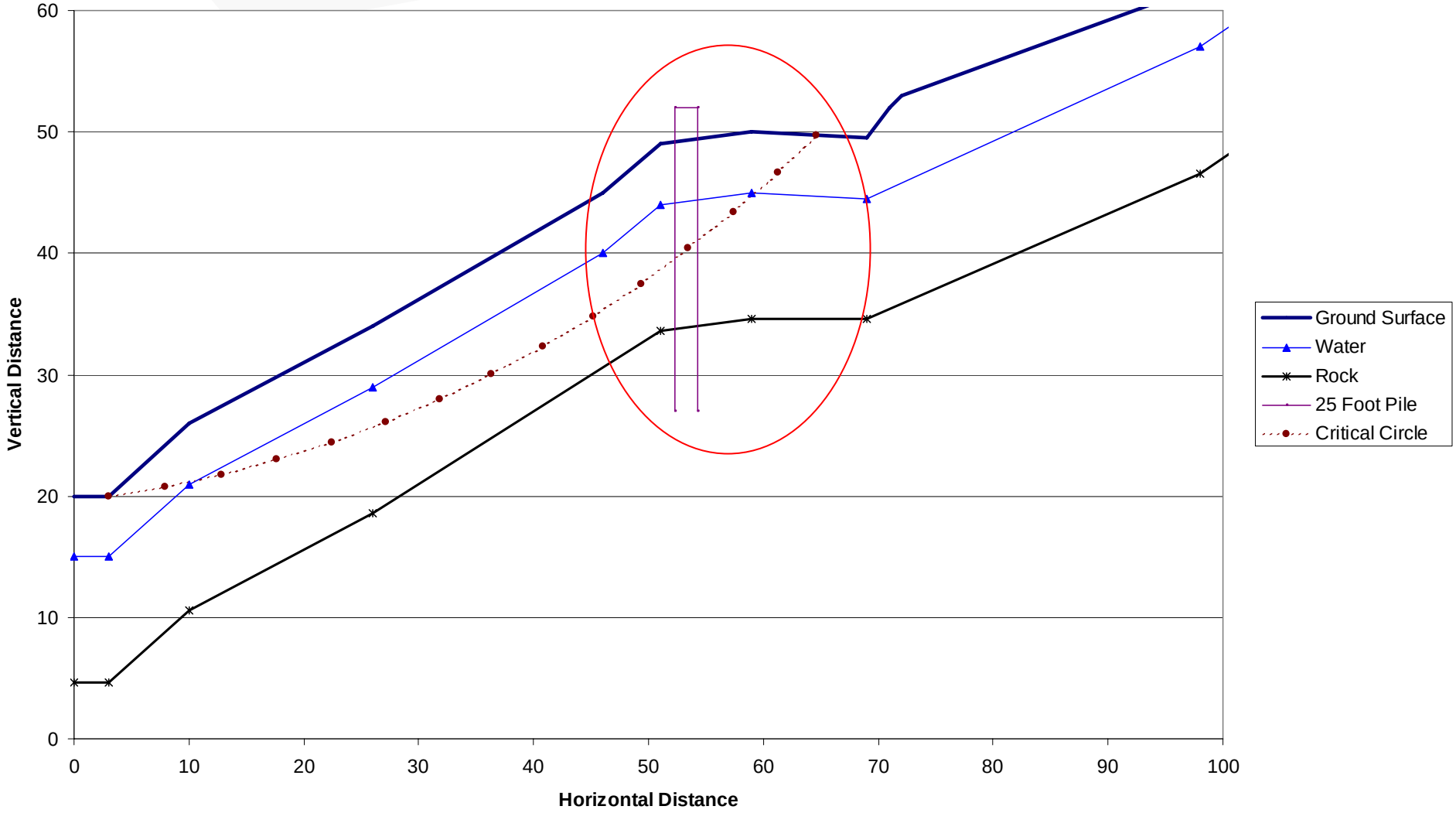
Select a larger Pile SECTION

Two Application Examples

Forest Avenue

Tygart Lake

Figure 3.2.4: Forest Avenue - Profile and Critical Slip Surface



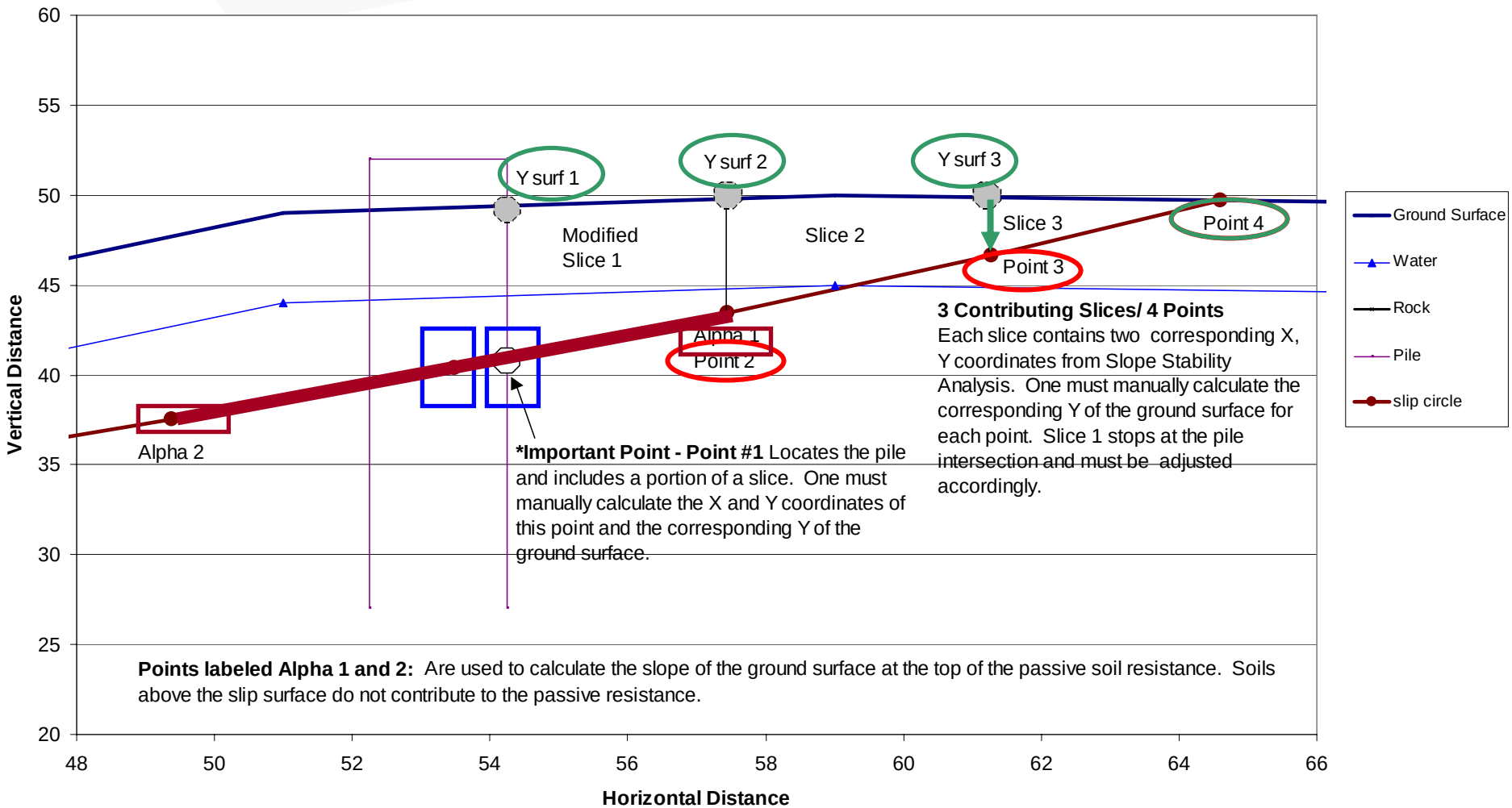
From stability analysis

Manual

Passive GS

GS corresponding to each X, Y on circle (manual)

Figure 4.5.1: Example Problem #1 - Forest Avenue
Blown Up View of Contributing Slices and Input Information



Example #1 - SOIL MODEL SPREADSHEET - Page 1 of 3

Data Input

GENERAL INFORMATION

Project Name:	Forest Avenue
Section:	Critical
Operator:	Tia Richardson
Date:	6/16/2003

Input

SOIL INPUT REQUIRED

Unit Weight of Soil (pcf):	130
Cohesion (psf):	0
Residual Phi (degrees):	28
Phi (radians) - no input req'd	0.4887

CRITICAL FAILURE SURFACE - INPUT REQUIRED

(From Slope Stability Analysis)

X Coordinate - (Center of circle):	-11.9
Y Coordinate - (Center of Circle):	129.5
Radius of Circle:	110.5

GWT Information - INPUT REQUIRED

Required to calculate U = Pore Water Pressure

Depth of GWT from Ground Surface, hw	5

*See Note 3 on Page 2

ALPHA Information to determine slope of passive resistance

X and Y coordinates of 2 points, one on each side of the pile

X1	49.38	Y1	37.51	ALPHA (Radians)	0.63
X2	57.45	Y2	43.42	ALPHA (Degrees)	36.2

FORCE DEVELOPMENT - Automatically Calculates

Distance from Ground Surface to Slip at intersection of pile and slip (Variable X)	8.44
X/3	2.81
Y Coordinate of X/3	43.78
Distance from X/3 to Radius (Variable Y)	85.72
Force P = R/Y ((Sum T) - (Sum (N - U)*Tan (Phi))	
Force P	**2,152.95**
Center to Center Spacing of Piles - INPUT REQUIRED	4
TOTAL FORCE P (lbs/ft)	**8,612**

INPUT REQUIRED FOR PLOTTING, Pile Length 25

Pile Location (assumes 2 ft. above GS)		Force P	
X	Y	X	Y
54.25	51.41	54.25	43.78
54.25	26.41	64.25	43.78

Note: For plotting purposes, adjust cell L39 as needed to show horizontal line of force P

Example #1 - SOIL MODEL SPREADSHEET - Page 2 of 3

Data Input

Point	INPUT REQUIRED X-Coordinate Circle Contibuting Slices	INPUT REQUIRED Y-Coordinate Circle Contibuting Slices	Slice Width B	Alpha of Slice (Radians)	Alpha of Slice (Degrees)	INPUT REQ'D Y-Coordinate of Ground Surface	Weight of Slice	Driving Force (Tangential)	Normal Force	*See Notes 3, 4 and 5 Pore Water Calculations Y-top ave	Y-bot ave	H Ave for Pore Pressure Hw	U	Slice Test N-U tan Phi
1	54.25	40.97				49.41								
2	57.45	43.42	3.2	0.653	37.439	49.81	3,084.64	1,875.19	2,449.22	49.61	42.20	2.42	607.33	979
3	61.27	46.65	3.82	0.702	40.216	49.89	2,391.13	1,543.89	1,825.90	49.85	45.04	-0.18		971
4	64.60	49.72	3.33	0.745	42.674	49.72	701.30	475.35	515.61	49.81	48.19	-3.38		274
SUMMATIONS								3,894.43	4,790.73				607.33	

Note 1: Delete rows below that which are not needed! Formulas will adjust accordingly
First entry point must be on line corresponding to to Point 1
Note 2: Can copy cells down if more rows are needed

Note 3: Adjust H of GWT in each cell if GWT is NOT equal distance from Surface (as input on page #1 - Cell E38)
Note 4: If H (Col M) is Negative, U is zero
Note 5: Check Slice test in Col O and P, if negative, U is zero

Rock Line for Plotting purposes - Optional
(Input Required)

X	Y
54.25	34.01
59	34.6
69	34.6

Sub routine for Interpolation Only

X	Y	
51	33.6	
54.25	Y	
59	34.6	
8	1	
4.75	Y2 - Y	
4.75	276.8	-8 Y
8	272.05	
34.01	= Y	

Water Line for Plotting purposes - Optional
(Input Required)

X	Y

Example #1 - SOIL MODEL SPREADSHEET - Page 2 of 3

Data Input

Point	INPUT REQUIRED X-Coordinate Circle Contibuting Slices	INPUT REQUIRED Y-Coordinate Circle Contibuting Slices	Slice Width B	Alpha of Slice (Radians)	Alpha of Slice (Degrees)	INPUT REQ'D Y-Coordinate of Ground Surface	Weight of Slice	Driving Force (Tangential)	Normal Force	*See Notes 3, 4 and 5 Pore Water Calculations Y-top ave	Y-bot ave	H Ave for Pore Pressure Hw	U	Slice Test N-U tan Phi
1	54.25	40.97				49.41								
2	57.45	43.42	3.2	0.653	37.439	49.81	3,084.64	1,875.19	2,449.22	49.61	42.20	2.42	607.33	979
3	61.27	46.65	3.82	0.702	40.216	49.89	2,391.13	1,543.89	1,825.90	49.85	45.04	-0.18		971
4	64.60	49.72	3.33	0.745	42.674	49.72	701.30	475.35	515.61	49.81	48.19	-3.38		274
SUMMATIONS								3,894.43	4,790.73				607.33	

No Reduction

Note 1: Delete rows below that which are not needed! Formulas will adjust accordingly
First entry point must be on line corresponding to to Point 1
Note 2: Can copy cells down if more rows are needed

Note 3: Adjust H of GWT in each cell if GWT is NOT equal distance from Surface (as input on page #1 - Cell E38)
Note 4: If H (Col M) is Negative, U is zero
Note 5: Check Slice test in Col O and P, if negative, U is zero

Rock Line for Plotting purposes - Optional
(Input Required)

X	Y
54.25	34.01
59	34.6
69	34.6

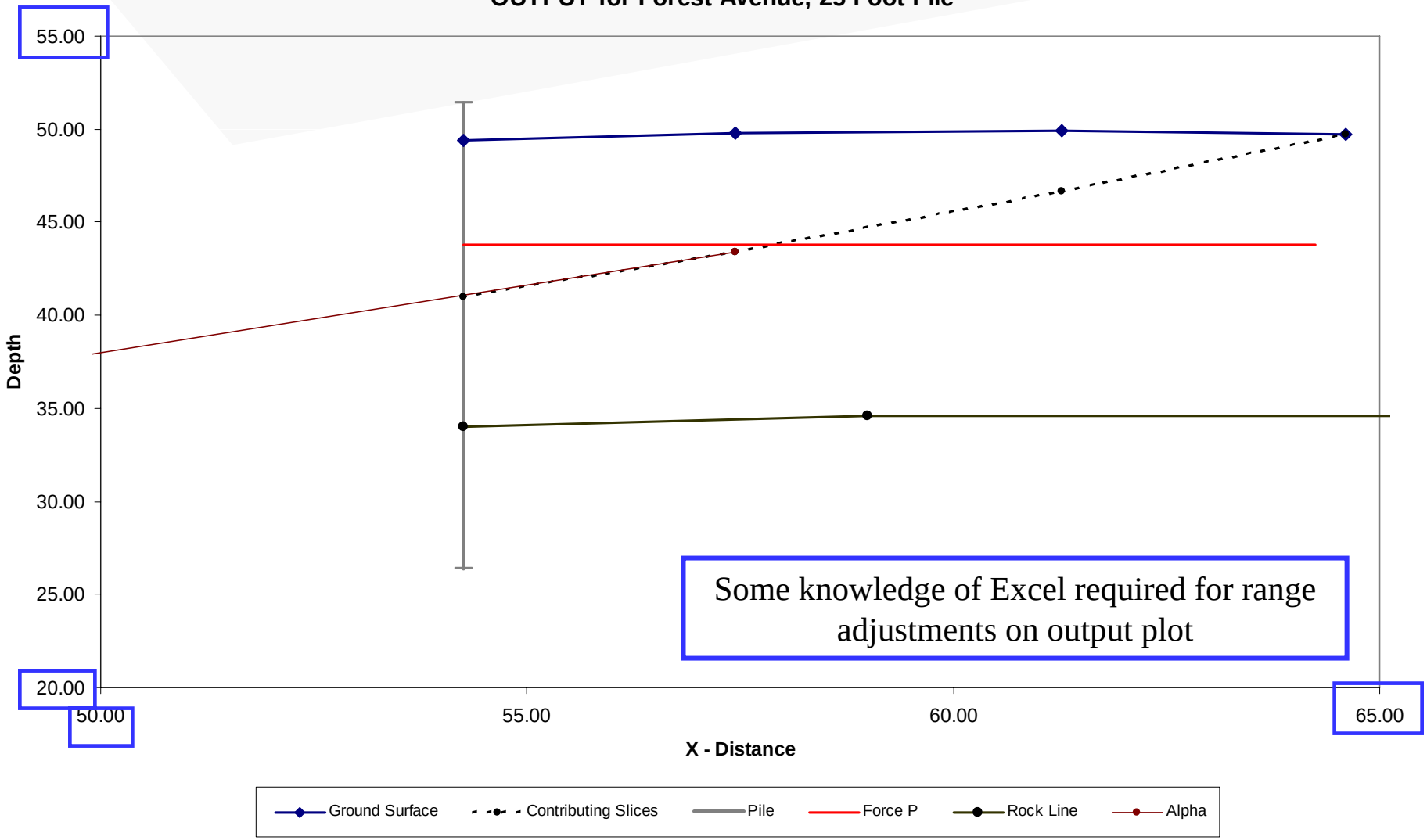
Sub routine for Interpolation Only

X	Y		
51	33.6		
54.25	Y		
59	34.6		
8	1		
4.75	Y2 - Y		
4.75	276.8	-8	Y
8	272.05		
34.01	= Y		

Water Line for Plotting purposes - Optional
(Input Required)

X	Y

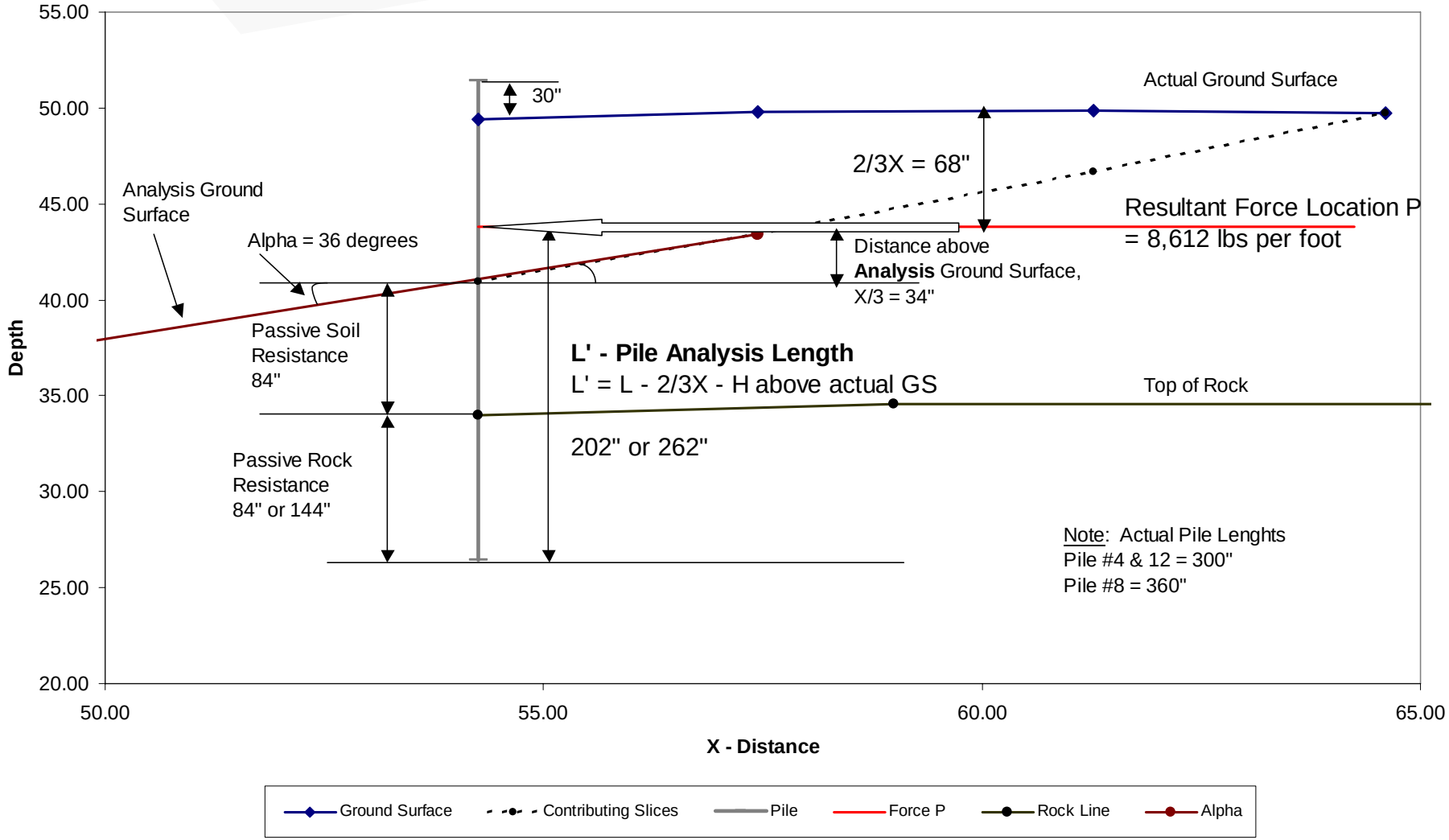
Figure 4.5.2: Example #1 - Soil Model Spreadsheet - Page 3 of 3
OUTPUT for Forest Avenue, 25 Foot Pile



Some knowledge of Excel required for range adjustments on output plot

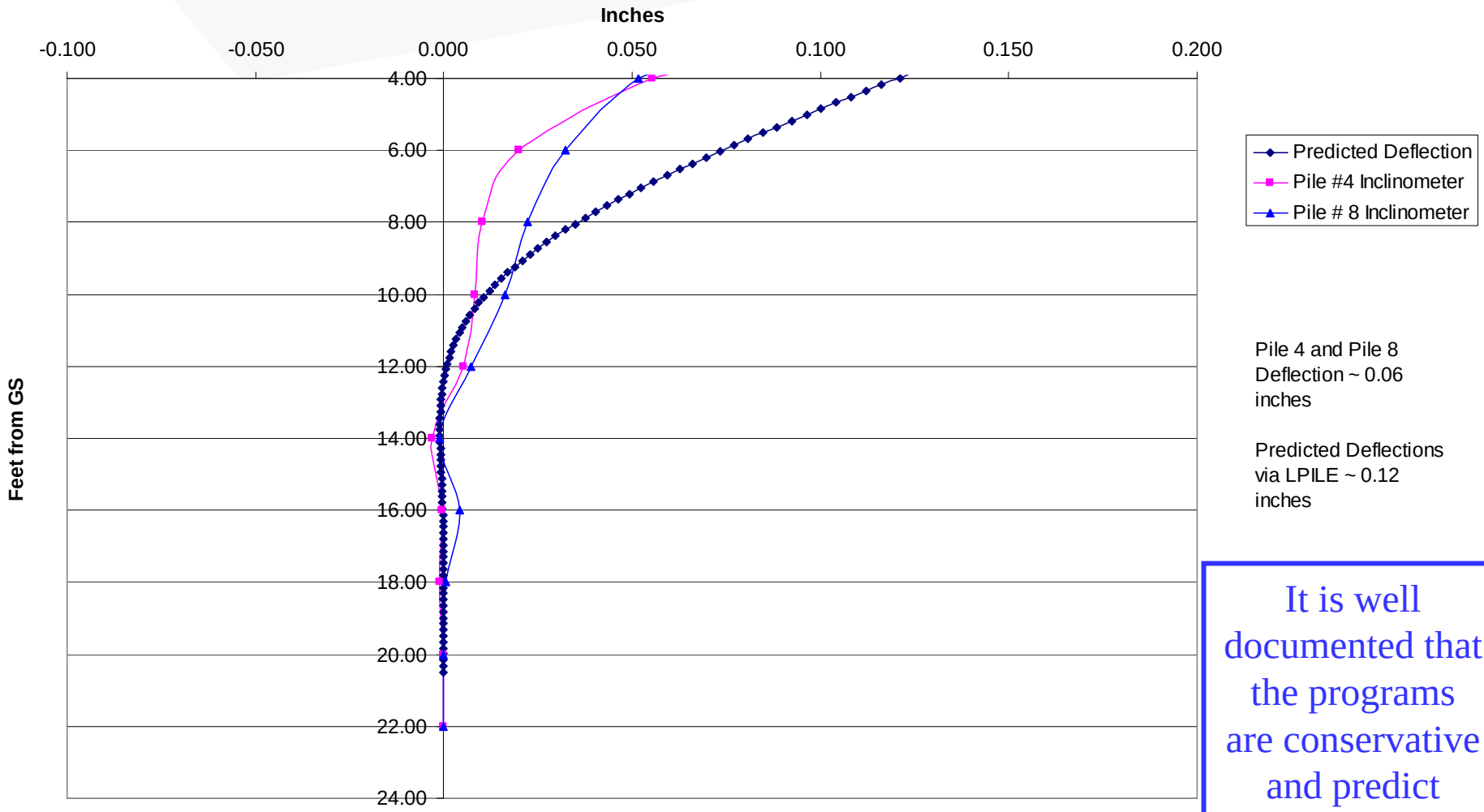
Additional information added manually to better describe pile problem

Figure 5.2.1: Example #1 - Forest Avenue - Pile Problem
Piles 4, 8 and 12



Results
Forest Avenue

Figure 5.3.1.3: Comparison of Predicted Deflection Versus Measured Deflection
Forest Avenue



Pile 4 and Pile 8 Deflection ~ 0.06 inches

Predicted Deflections via LPILE ~ 0.12 inches

It is well documented that the programs are conservative and predict more movement

Example #2

Tygart Lake

Figure 3.4.4: Tygart Lake, Section B-B (Near TB # 2 & 6)
Profile and Critical Slip

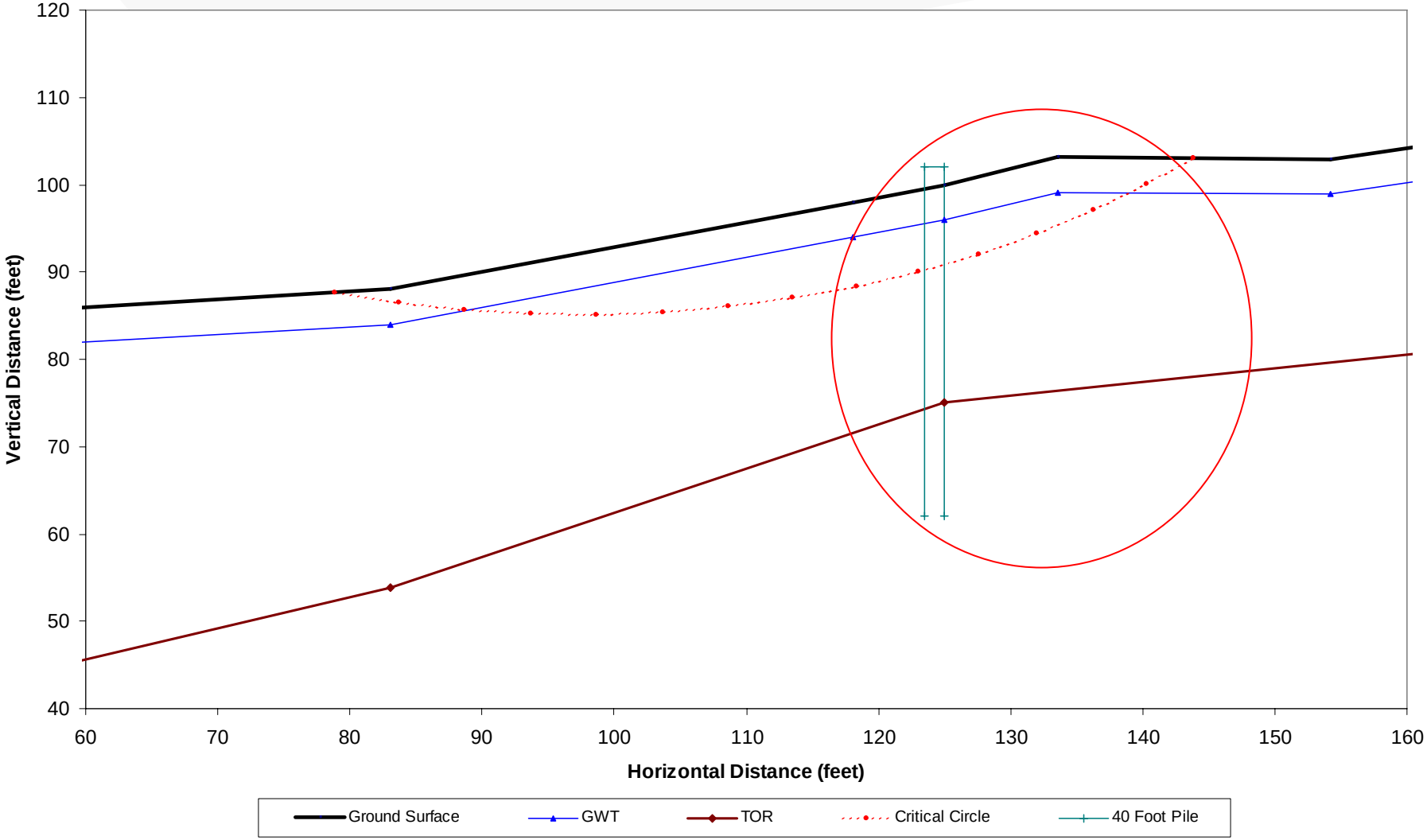


Figure 4.5.4: Example Problem #2 - Tygart Lake, Section B-B (Near TB # 2 & 6)
Blown up View of Contributing Slices

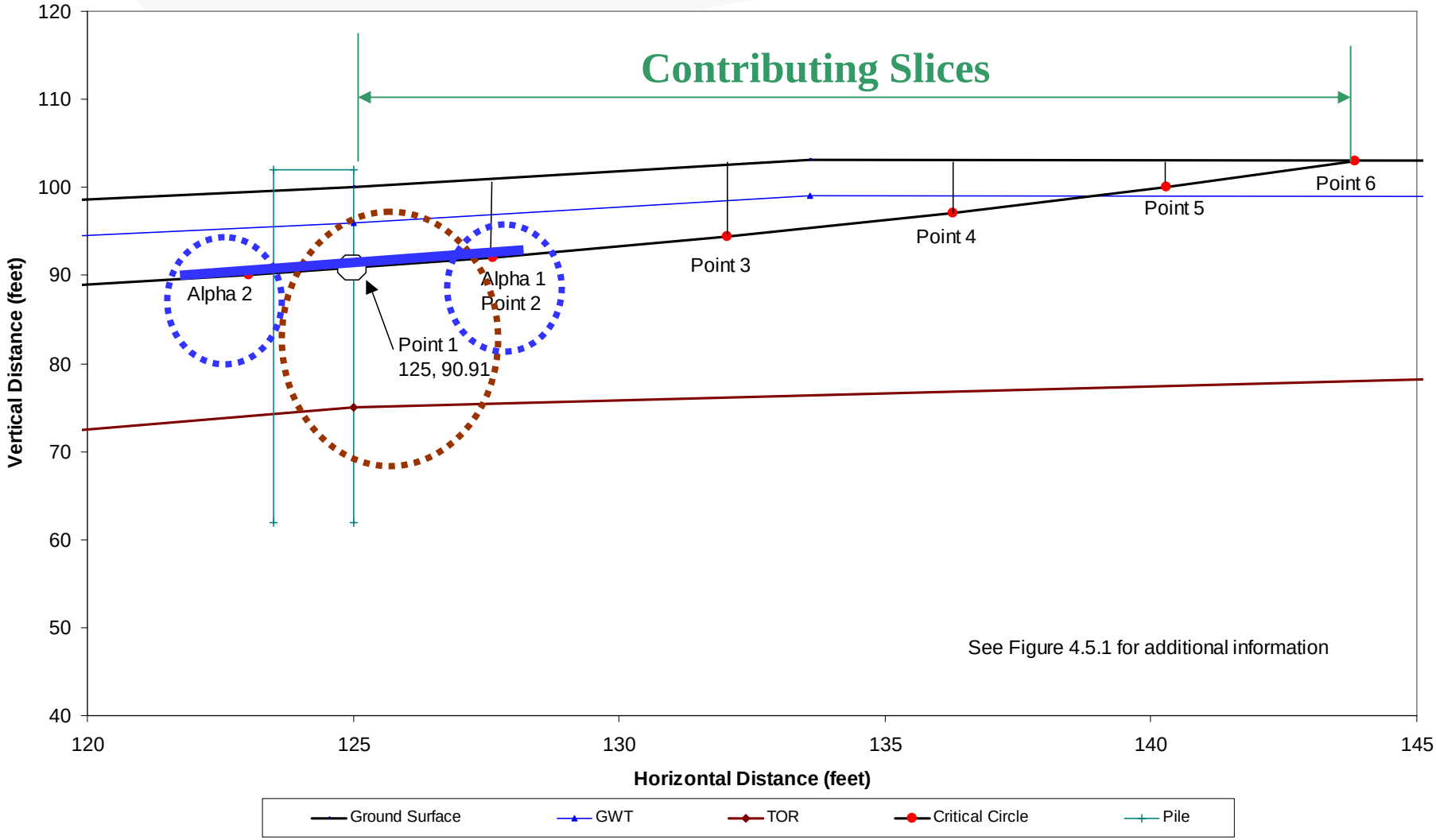


Figure 4.5.5: Example #2 - Soil Model Spreadsheet - Page 3 of 3
Output for Tygart Lake - Section B-B, 30 Foot Pile

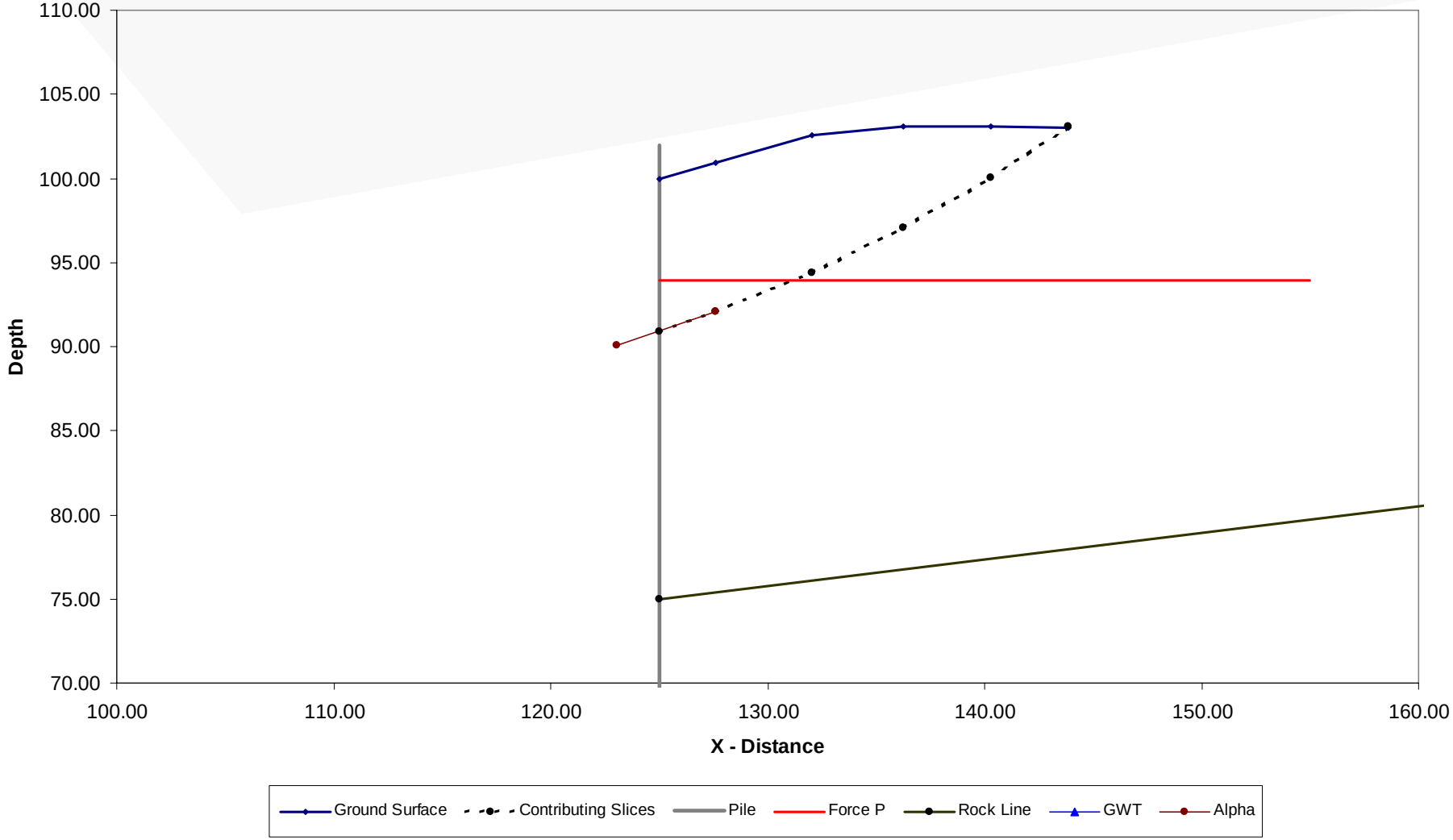
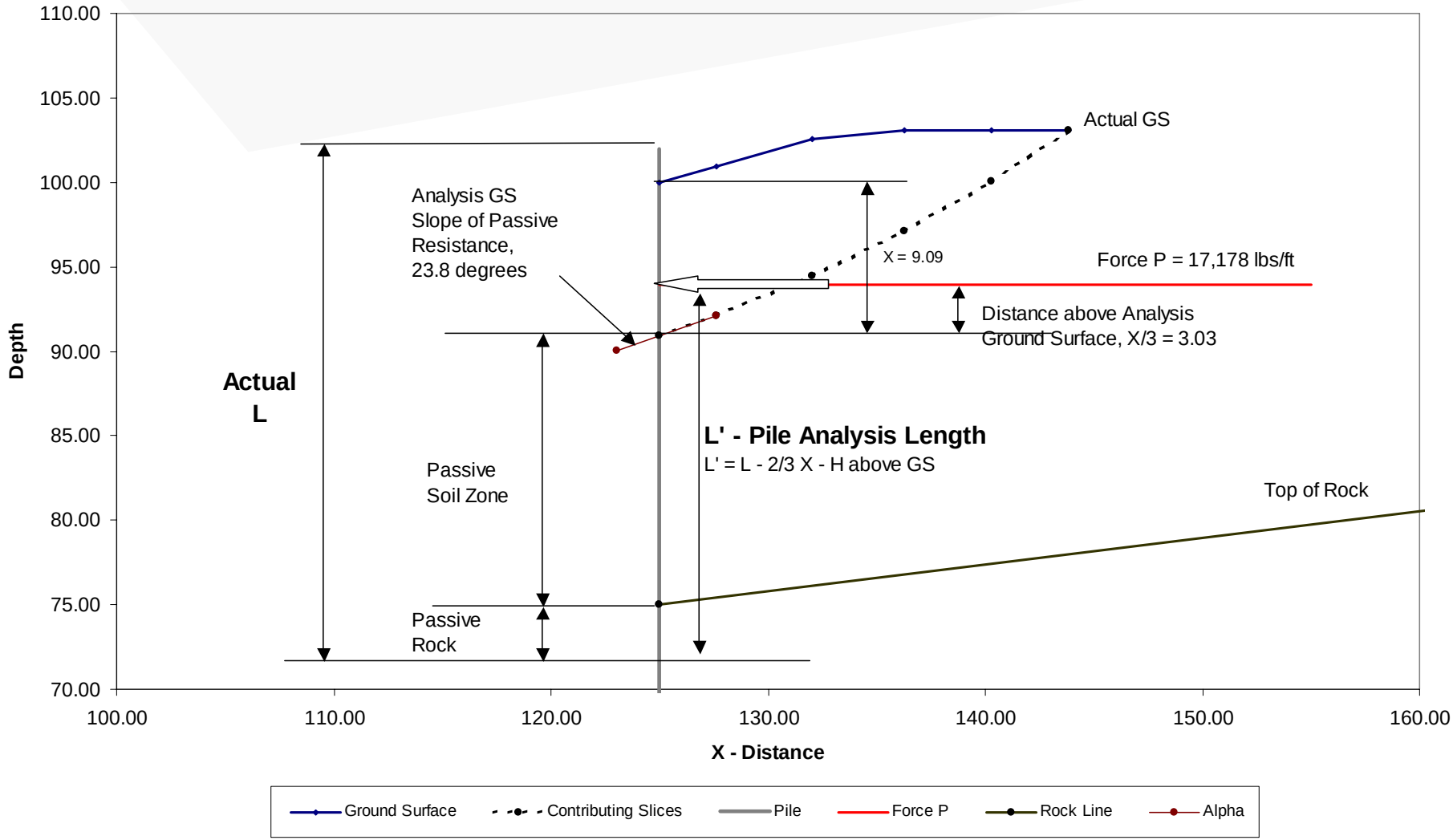


Figure 4.5.6: Example #2 - Soil Model Spreadsheet on Tygart Lake - Section B-B
Added Information to clarify model output to help define the pile problem - 30 Foot Pile



Results

Tygart Lake

Figure 5.3.2.4: Tygart Lake, Section B-B, Measured Deflections

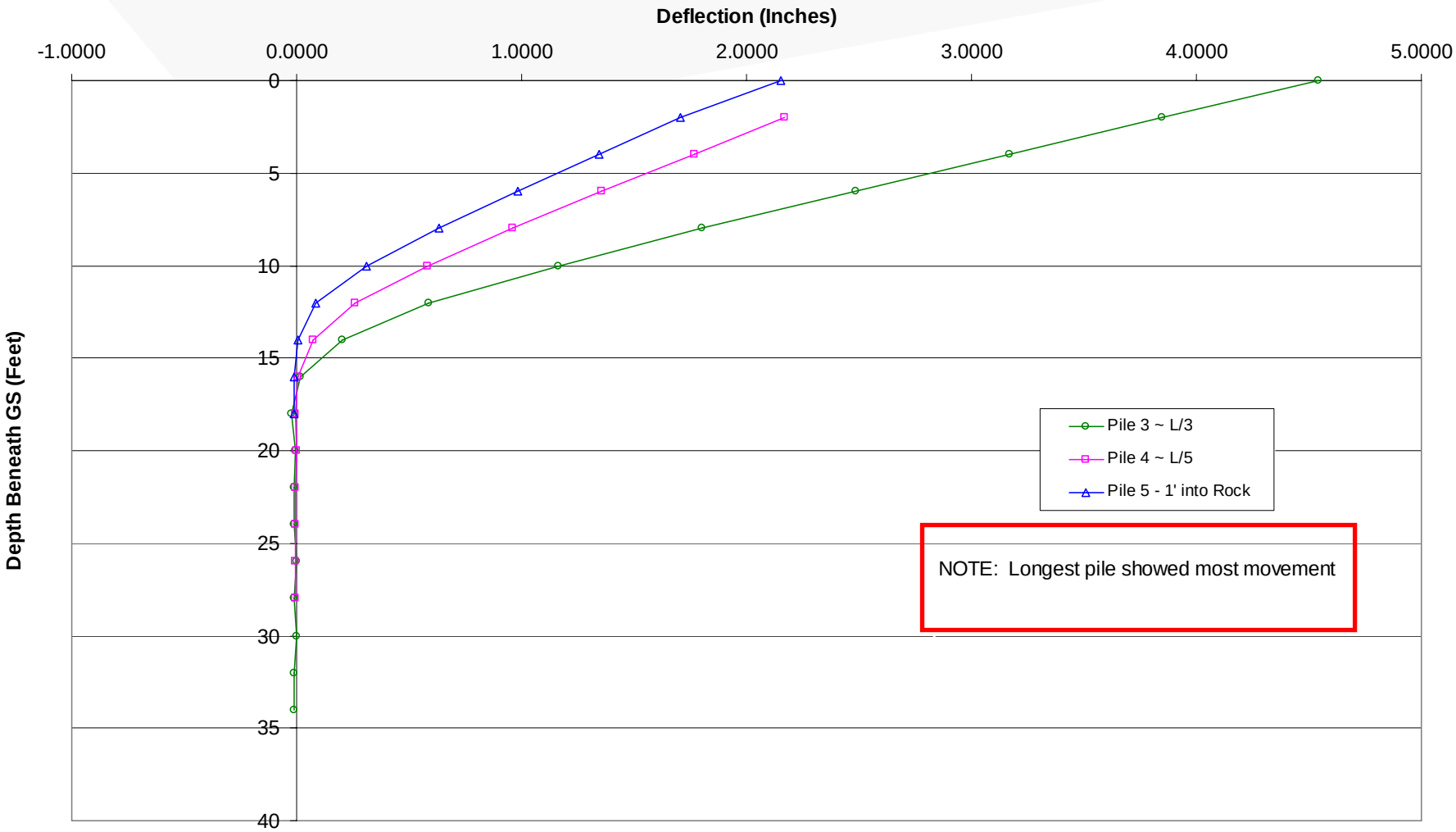


Figure 5.3.2.5: Tygart Lake Section B-B, Movement Compairsons, Pile #3

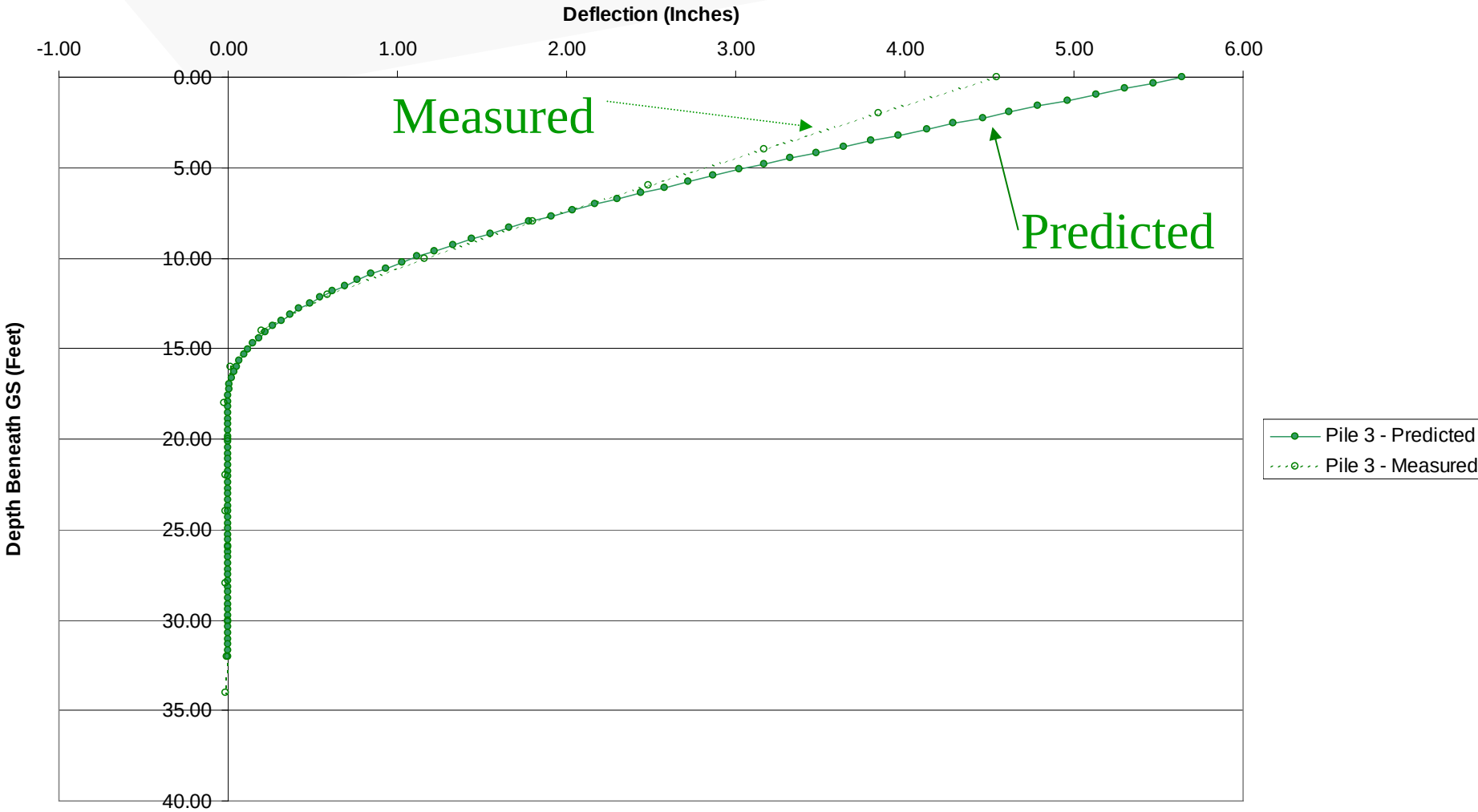


Figure 5.3.2.6: Tygart Lake Section B-B, Movement Compairsons, Pile 4 & 5

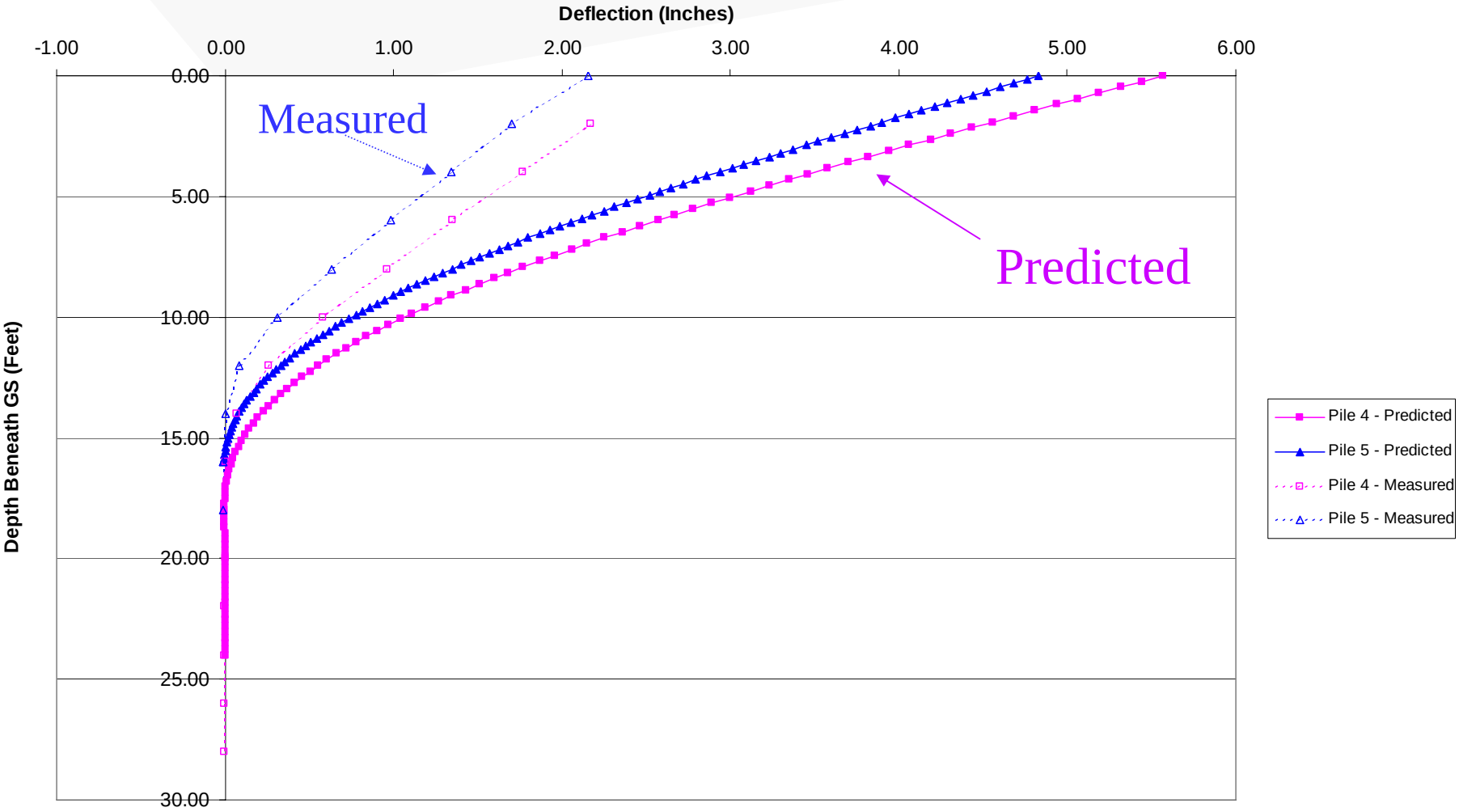


Figure 5.3.2.7: Tygart Lake, Section B-B, Moment Compairsons - Pile 3

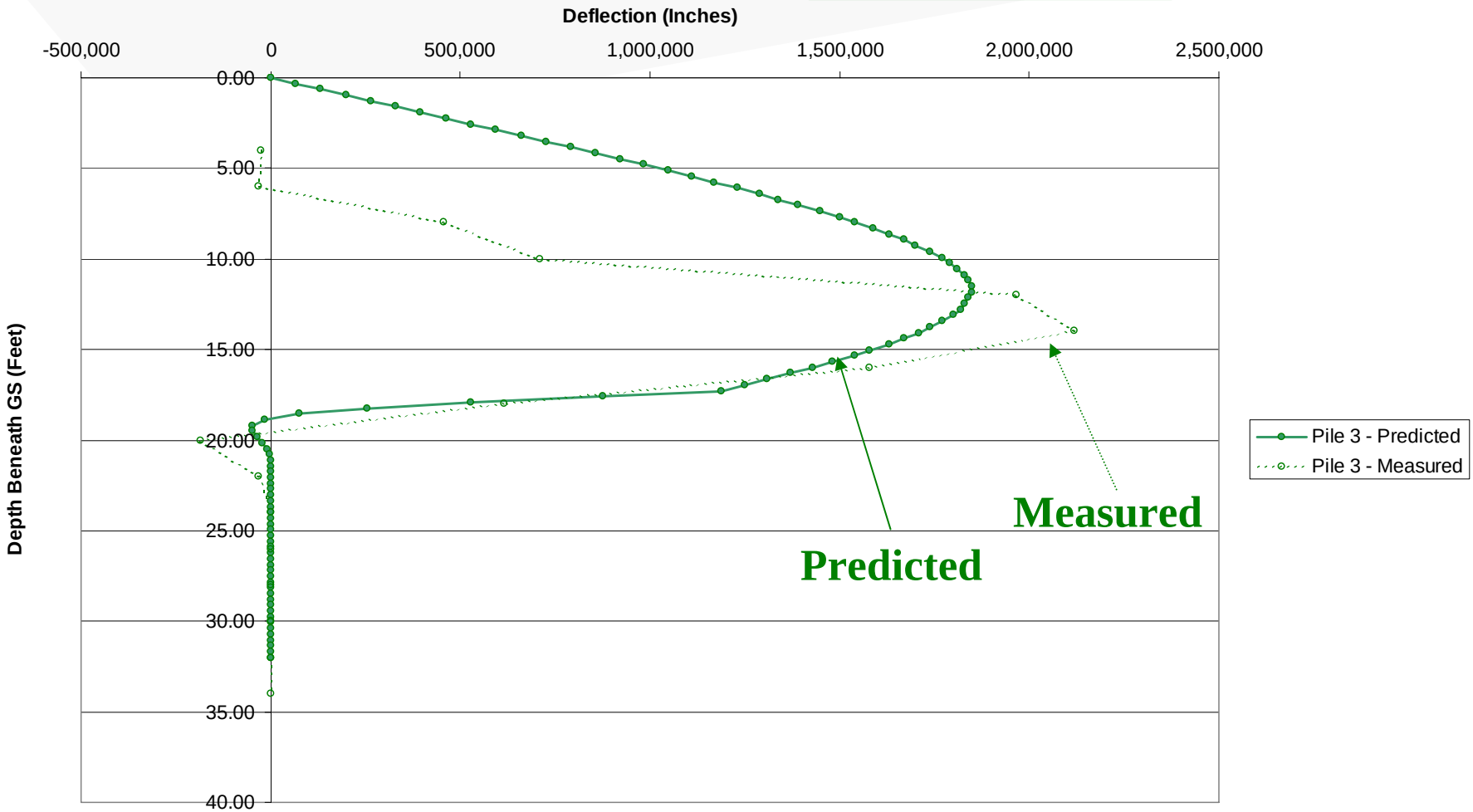


Figure 5.3.2.8: Tygart Lake, Section B-B, Moment Compairsons - Pile 4

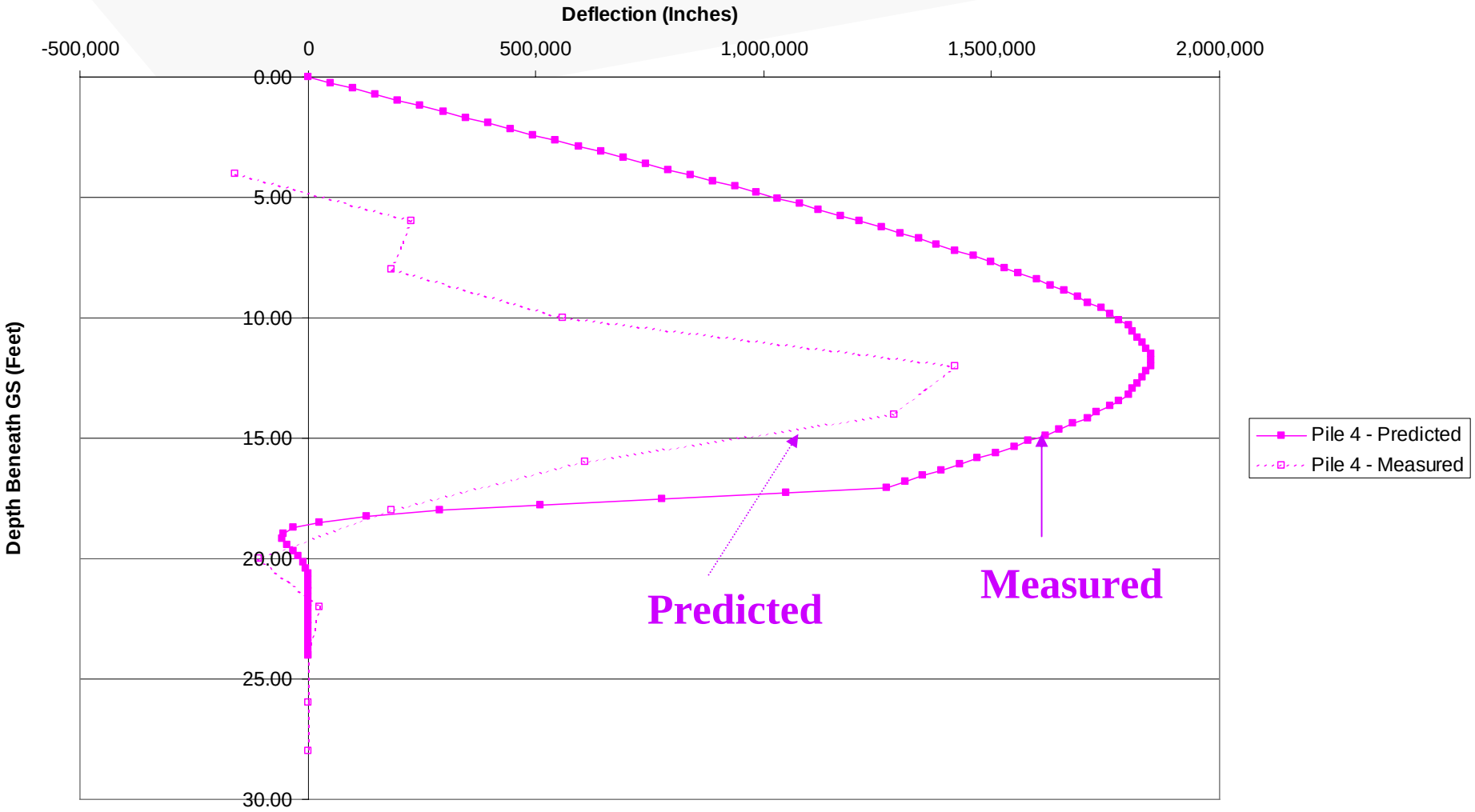
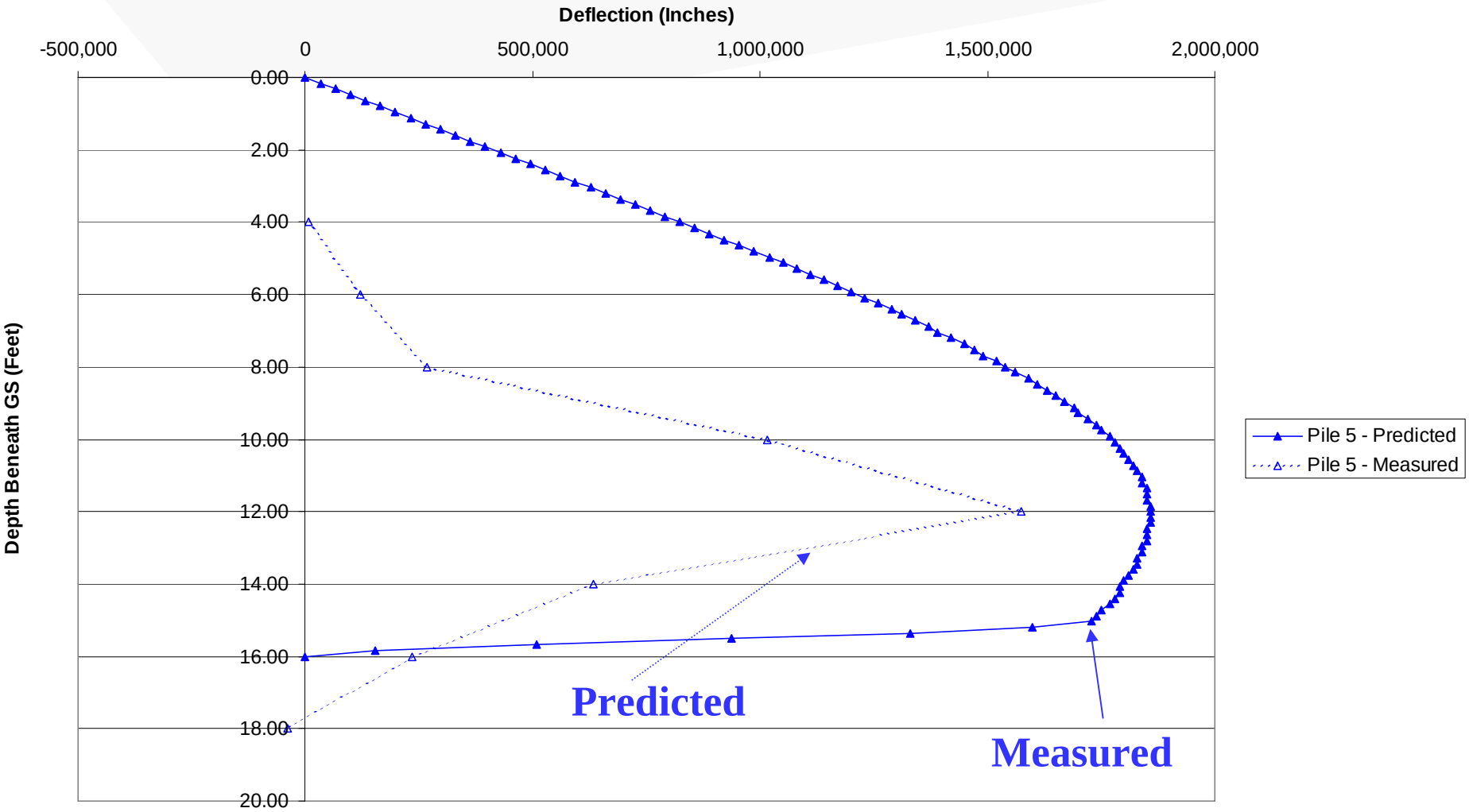
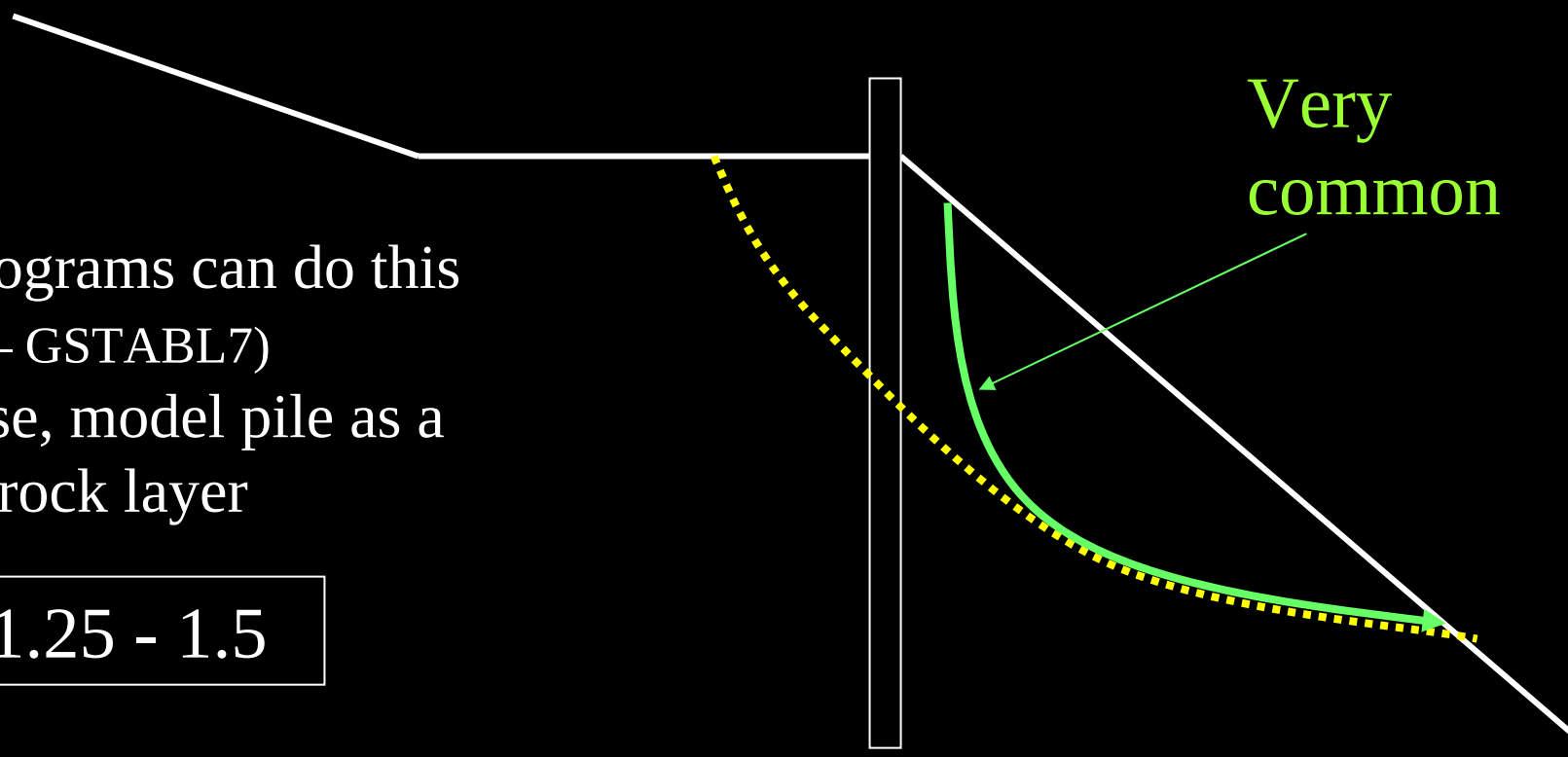


Figure 5.3.2.9: Tygart Lake, Section B-B, Moment Compairsons - Pile #5



Final Stability Check

Run stability with the pile in place



Some programs can do this
(Gregory – GSTABL7)
Otherwise, model pile as a strong a rock layer

FS > 1.25 - 1.5

Options

1. Move the pile:
   Find the optimal location in the slope
2. Add another row of piles

Most WV DOH Applications
Want to save the road and the down slope materials are <u>not</u> a concern

Site Specific

Conclusions

Proposed Model is suitable for predicting landslide forces acting on piles when:

The piles are placed near the top of the slope

Only one slip is occurring

Demonstrated <u>close</u> agreement at <u>two full scale</u> sites:

Forest Avenue – One Section

Tygart Lake - Two Sections

Conclusions

Same general trends observed as those found by other researchers:

Pile programs predict more movement than that which actually occurs in the field

The two pile programs used (LTBASE and LPILE) produced similar results.

LPILE has graphing advantages and rock options that LPILE does not

Limitations

Model overestimates the landslide forces when the piles are placed near the toe of the slope - Green Bag Road

Another method needed

Subsurface Data is paramount to the success

Use indicators on large projects!

At least drill test holes

Take samples and run lab tests

Limitations

Ones ability to define the critical slip surface is important.

*It predicts the force on the piles and the amount of passive resistance to include in the pile analysis

***Using a deeper seated slip is more conservative**

Ones ability to use a slope stability program, run a laterally loaded pile program and function in Excel or other spreadsheet is important.

Limitations

The behavior of rock at a particular site can be dictated by cracks, fissures, etc.

There exists a limited amount of experimental data on rock in the literature

And, only for loads applied at the top to failure

Not full-scale working conditions

Questions?

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