“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

Other lagging has also been used

Greenbag Road
Morgantown, WV
They transfer the load from the weak upper strata to the stable material below.

Lagging (in this application) not structural
Purpose:
*Aesthetics
Contain loose debris
Piles **MUST** Penetrate the Slip Surface

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

**Subsurface data is a MUST!**
Subsurface data is a MUST!

Driven to Refusal

Top of Rock

Slip surface BELOW Top of Rock
Pile Wall Failure
Rt. 857, Morgantown, WV (Cheat Lake Area)
Stable material below

Rock ?? Not always!

WV has a lot of Inter-bedded weak clay seams in shale SITE specific!
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!
RP #97 - Dr. M.A. Gabr

• Graduate Student

DOH Installing piles into rock
10 feet or L/3

Conservative Approach
RP #97 History

LTBASE Pile Program Curves
Developed by Dr. Gabr

EI₁, L₁
EI₂, L₂

Thesis: Develop a Soil Curve

Basic Premise

Fu
Unbalanced Force
Allowable deformation
Deformation
Unbalanced Force, Fu

Hyperbolic Shear - Stress
Shear - Strain Relationship

TOR

Unbalanced Force, Fu

VERY Theoretical!
RP #97 History

Test Site
Bridgeport, WV
Rt. 73/73
Bridgeport, WV Rt. 73/73 Landslide
Magnitude of Cracks
Dead Man
Custom built a frame to house the dial gauges.
Also strained gauged along its length
RP #97 Successes

• 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)
Slope Inclinometer

Innovative Application
What you are measuring with the instrument

\[ d_1 = L \times \sin \theta_1 \]
\[ d_2 = L \times \sin \theta_2 \]
\[ d_3 = L \times \sin \theta_3 \]
\[ d_n = L \times \sin \theta_n \]

*Important!
*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

Slip plane (soil movement)

Cumulative deflection

Incremental data
Data Collection

*Full Scale Performance Monitoring*

2 Sites: Green Bag Road
And Forest Ave

Full Scale Test Site
Tygart Lake
109 Piles in the wall
  - Embedded in Lacustrine Clay on a 1° batter
  - Total Pile Lengths = 30 Feet
  - ~7 ft. above centerline, ~2 ft. above G.S. in the back

Monitoring 3 piles in the wall
  # 29, 49 and 73

And 2 test piles 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
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.
Pile #49 and Test Pile #2 show the most movement.
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”

Test Pile #2

Pile #49
Slope Stability Analysis
Green Bag Road

Section Cut Near Test Pile #49
A retrogressive slip was indicated
Figure 3.3.4: Green Bag Road - Original Profile, Retrogressive Slide #1

- Assumed Critical Slip #1, FS=1.01
- Cohesion = 0
- Residual Friction Angle = 25 Degrees
Slope Stability Analysis - Green Bag Road

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

X Distance (feet) vs. Y Elevation (feet) for Profile 2. The graph shows the elevation changes along the profile with assumed critical slip #2, FS = 1.0.
Slope Stability Analysis - Green Bag Road

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

Profile 3
Slip 1
Slip 2
Assumed Critical Slip #3, FS = 0.95
Final Slope Stability Analysis on Green Bag Road

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

Analyzed
Model Developed does **NOT** work for this case

**BAD NEWS!**

Landslide force is grossly overestimated

Another procedure is needed
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

Plan View

- 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

Very LITTLE Movement

2.5 ft. above GS
15.4 feet to Top of rock

Looking at Wall
Forest Avenue – Results of Inclinometer Readings, < 0.1”

Forest Avenue - Test Hole #3 - PILE #4
A-Plane, L=25 Feet, 2.5 Feet Above GS
Cumulative at Top < 0.1 Inches

Note X - Scale

Forest Avenue - Test Hole #5 - PILE #12
A-Plane, L=25 Feet, 2.5 Feet Above GS
Cumulative at Top < 0.1 Inches
Forest Avenue – Results of Slope Stability Analysis

Figure 3.2.4: Forest Avenue - Profile and Critical Slip Surface

Model works beautifully for this case!

Will return to this site after the models are introduced
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**
5 Test Piles
4 Slope Indicators

1 Slope Indicator
2 Wells

1 Wells
2 Wells

5 Wells placed in a triangular grid – shallow and deep

Tygart Lake Test Site

PROFILE VIEW
Monitoring wells - Deep and Shallow

Perched Water Table Detected
5 Test Piles
4 Slope Indicators

1 Slope Indicator
2 Wells

1 Wells
2 Wells

*Should have put an indicator or two down slope

Lake

Wells placed in a triangular grid – shallow and deep
Tygart Lake Test Site

PLAN VIEW

Lodge

6 120 ft 2

240 ft 3

150 ft 1

1120 ft 3

2

6

Slope Indicators

Wells
Visual Observations
Near Test Hole # 1 and 5
Initial theory based on visual observations proven wrong.
Tygart Lake - Test Hole #1 - A-Plane

Note: Pipe bend 3-3-00

Deflection (inches)

Depth (feet)

Movement detected in Test Hole #1
August 1998

Movement detected in Test Hole #5
May 2003
5 years later
Test Hole #3 - Visual Observations
Test Hole #3 - Visual Observations

Assumed an deep angular slip

ONE deep slip initially detected
Complicated Slide S!
Inclinometer Observations

Test Hole #3
1 deep slip within the first year.
Two more detected 2 years later
Three distinct slip planes detected!
PLUS it was slipping on an angle as evidenced by movement in both the A and B direction.
Visible scarp, supports indicator data
TYGART LAKE

Test Holes #2 & 6
FIRST to move

Pipes Bent
Last Full Reading
July 1998

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

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

Plan View

TEST PILES

Lodge

5 - TOR
4 - L/6
3 - L/3

Test Piles

After 1 year

5

4

3

2

1

 Dam

Test Piles

1 - L/6
2 - L/3
*Installed 5 SMALL piles at this site on purpose – we wanted them to move!

HP 10 x 42

A-36 Carbon Grade Steel
Tygart Lake
TEST PILE
RESULTS

Near Test Hole #3
(3 slips)

Test Pile #2
NOT fixed at its base

**Very important**
Recall

Cumulative Deviation

\[ d_1 + d_2 + d_3 \]

\[ d_1 = L \times \sin\theta_1 \]
\[ d_2 = L \times \sin\theta_2 \]
\[ d_3 = L \times \sin\theta_3 \]
\[ d_n = L \times \sin\theta_n \]

*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
Tygart Lake - Test PILE #5 - A-Plane
Pile Top 2’ above GS
Near TB #2/6, L=24 Feet

Tygart Lake - Test PILE #4 - A-Plane
Cumulative at Pile Top 1.3 Inches
Near TB #2/6, L/6 ~ 5 Feet, L = 30 Feet

Tygart Lake - Test PILE #3 - A-Plane
Pile Top 2’ above GS
Near TB #2/6, L/3 ~ 13 Feet, L = 40 Feet

TEST PILE RESULTS
Near Test Holes 2 & 6
Model Development

After initial data collection

Considers a Landslide Based on an Impending Failure

Factor of Safety = 1.0
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
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.
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

$$N = W_i \cdot \sin(\alpha_i)$$

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

Blown up Pictorial

Driving Forces

Inter-slice forces

Resisting Force

\( W_i \)

\( N_i \)
Method of Slices

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

\[ T = W_i \sin (\alpha_i) \]

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

\[ S = cl + \sum (N_i \times \tan (\phi)) \]

Pore water pressures are considered by reducing N
Resisting Force: Shear Strength of Soil

\[ S = cl + \sum (N_i \times \tan(\phi)) \]
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

\[(\text{sum } T - \text{sum } (N-U) \times \tan \phi ) \times R\]
\[= P \times Y\]

(Driving – Resisting)

* Radius = What the pile must provide

Statics problem!

Inter slice forces are neglected
Solving for $P$

Rest is based on geometry

**Variables from slope stability analysis**

**X, Y Circle Center**

**R**

**P**

 DEFINE $X$
Distance from ground surface to bottom of slip

$Y = f (X)$
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.

Inclined ground surface
Resisting passive support is only included below the slip plane.
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
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

As given in LPILE by Reese et al. 1999
ACTUAL problem

Resulting driving force from a landslide

Does **NOT** act at the pile **TOP**
Passive Support \( \text{f (slip plane)} \) and location of pile.

**Critical Case**

Based on how the pile programs operate.

- Considers a load at the top.

- Pile analysis length: \( L' \)

- Passive Support \( \text{f (slip plane)} \) and location of pile.
Pile Problem

Analysis Ground Surface

L’
Pile analysis length

Actual ground surface geometry and pile length

Analysis ground surface on passive side
1. Excessive deflection at the pile top greater than 2”

2. Movement at the bottom indicating that fixity was not obtained:
   > 0.0004b

3. Moment developed > Moment allowable for pile size
Excessive deflection at the pile top > ~2 inches

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

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

IF deflection is STILL excessive after you increase the length and obtain fixity – increase section
2. Movement at the bottom indicating that fixity was not obtained:

> 0.0004b

i.e. Not socketed into a firm enough material
Fixity NOT obtained!
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

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

**Passive GS**

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**Figure 4.5.1: Example Problem #1 - Forest Avenue**

Blown Up View of Contributing Slices and Input Information

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**From stability analysis**

- Manual

**Passive GS**

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**Figure 4.5.1: Example Problem #1 - Forest Avenue**

Blown Up View of Contributing Slices and Input Information

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**Important Point - Point #1**

Locates the pile and includes a portion of a slice. One must manually calculate the X and Y coordinates of this point and the corresponding Y of the ground surface.

**Points labeled Alpha 1 and 2:**

Are used to calculate the slope of the ground surface at the top of the passive soil resistance. Soils above the slip surface do not contribute to the passive resistance.
### Data Input

#### GENERAL INFORMATION
- **Project Name:** Forest Avenue
- **Section:** Critical
- **Operator:** Tia Richardson
- **Date:** 6/16/2003

#### 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 = \( \frac{R}{Y} \left( \text{Sum T} \right) - \left( \text{Sum (N - U)Tan (Phi)} \right) \)
  - Force P: 2,152.95
- Phi (radians) - no input req'd: 0.4887
- Center to Center Spacing of Piles - INPUT REQUIRED: 4

#### SOIL INPUT REQUIRED
- Unit Weight of Soil (pcf): 130
- Cohesion (psf): 0
- Residual Phi (degrees): 28

#### 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
- INPUT REQUIRED FOR PLOTTING, Pile Length:
  - 25

#### GWT Information - INPUT REQUIRED
- Required to calculate U = Pore Water Pressure
- Depth of GWT from Ground Surface, hw:
  - 5

#### 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

*See Note 3 on Page 2

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

<table>
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<tr>
<th>Point</th>
<th>X-Coordinate</th>
<th>Y-Coordinate</th>
<th>Slice (Radians)</th>
<th>Alpha (Degrees)</th>
<th>Y-Coordinate</th>
<th>Weight Driving Force</th>
<th>Normal Force</th>
<th>Y-top Ave</th>
<th>Y-bot Ave</th>
<th>Pore N-U Pressure</th>
<th>Hw</th>
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</tr>
</tbody>
</table>

**SUMMATIONS**

|                 | 3,894.43 | 4,790.73 | 607.33 |

**Note 1:** Delete rows below that which are not needed! Formulas will adjust accordingly.

**Note 2:** First entry point must be on line corresponding to Point 1.

**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.

---

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

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### Rock Line for Plotting purposes - Optional

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### Subroutine for Interpolation Only

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34.01 = Y
# Example #1 - SOIL MODEL SPREADSHEET - Page 2 of 3

**Data Input**

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<th>X-Coordinate</th>
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<th>Slice</th>
<th>Alpha Circle</th>
<th>Alpha Circle</th>
<th>Weight</th>
<th>Driving Force</th>
<th>Normal Force</th>
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**Note 4:** If H (Col M) is Negative, U is zero

**Note 5:** Can copy cells down if more rows are needed

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</tr>
<tr>
<td>4.75</td>
<td>276.8</td>
</tr>
<tr>
<td>4.75</td>
<td>-8 Y</td>
</tr>
<tr>
<td>8</td>
<td>272.05</td>
</tr>
</tbody>
</table>

34.01 = 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.
Figure 5.2.1: Example #1 - Forest Avenue - Pile Problem
Piles 4, 8 and 12

- **L' - Pile Analysis Length**
  \[ L' = L - 2/3X - H \text{ above actual GS} \]

- **Resultant Force Location**
  \[ P = 8,612 \text{ lbs per foot} \]

- **Alpha**
  \[ \alpha = 36^\circ \]

- **Actual Pile Lengths**
  - Pile #4 & 12 = 300"
  - Pile #8 = 360"

Note: Actual Pile Lenghts

Additional information added manually to better describe pile problem
Results
Forest Avenue
Figure 5.3.1.3: Comparison of Predicted Deflection Versus Measured Deflection
Forest Avenue

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

Horizontal Distance (feet)

Vertical Distance (feet)

- Ground Surface
- GWT
- TOR
- Critical Circle
- 40 Foot Pile
Figure 4.5.4: Example Problem #2 - Tygart Lake, Section B-B (Near TB # 2 & 6)
Blown up View of Contributing Slices

See Figure 4.5.1 for additional information
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

- **Analysis GS**
- Slope of Passive Resistance, 23.8 degrees
- **L'** - Pile Analysis Length
  \[ L' = L - \frac{2}{3}X - H \text{ above GS} \]
- **Top of Rock**
- **Actural GS**
- **Force P = 17,178 lbs/ft**
- Distance above Analysis
  \[ \frac{X}{3} = 3.03 \]

- **Actual L**
- **Passive Soil Zone**
- **Passive Rock**
Results

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

NOTE: Longest pile showed most movement
Figure 5.3.2.5: Tygart Lake Section B-B, Movement Comparisons, Pile #3
Figure 5.3.2.6: Tygart Lake Section B-B, Movement Comparisons, Pile 4 & 5

Deflection (Inches)

-1.00 0.00 1.00 2.00 3.00 4.00 5.00 6.00

Depth Beneath GS (Feet)

-1.00 0.00 1.00 2.00 3.00 4.00 5.00 6.00

Predicted

Measured

Pile 4 - Predicted
Pile 5 - Predicted
Pile 4 - Measured
Pile 5 - Measured
Figure 5.3.2.7: Tygart Lake, Section B-B, Moment Comparisons - Pile 3

Deflection (Inches)

Depth Beneath GS (Feet)

Pile 3 - Predicted
Pile 3 - Measured

Predicted
Measured
Figure 5.3.2.8: Tygart Lake, Section B-B, Moment Comparisons - Pile 4
Figure 5.3.2.9: Tygart Lake, Section B-B, Moment Comparisons - Pile #5

- Deflection (Inches)
- Depth Beneath GS (Feet)

- Pile 5 - Predicted
- Pile 5 - Measured
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

Very common
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 not a concern

*Site Specific*
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 close agreement at two full scale 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.
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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