

2009

WVDOH PSSLOPE MANUAL

West Virginia Department of Transportation

West Virginia Division of Highways

Engineering Division

1900 Kanawha Boulevard, East

Building 5, Room 317

Charleston, West Virginia 25305

(304) 558-2885

CHAPTER 1 - SLOPE STABILITY

A. PRELIMINARY STEPS

1. **The First Steps**: Before the data can be entered, is to prepare the cross section: Use the least number of straight line segments that will represent the cross section. You can often ignore some survey points if a single line segment is very close to two or more surveyed line segments. Each point where your line segments intersect or end is called a "point" and each line segment is called a "line." Use lines to show the ground surface, different soil zones and water table surface. Determine (and record on the cross section) the coordinates [offset or x, elevation or y] for the endpoints of all line segments, including those for the piezometric line, if any (Figure 1). Notice all boundaries have the same ending edge, extend the water surface to the same beginning and ending edge. No vertical or overhanging boundaries are allowed. The program always sets the starting point for the graph at xy=0,0. When preparing the cross section adjust the true values of the coordinates, if taken from a survey plotted in a cad program, and allow room for the slip plane. The program will set the graph at zero; if the true values of the coordinates are derived from a survey and entered, the program will plot the actual distance from zero, producing an impracticable graph.

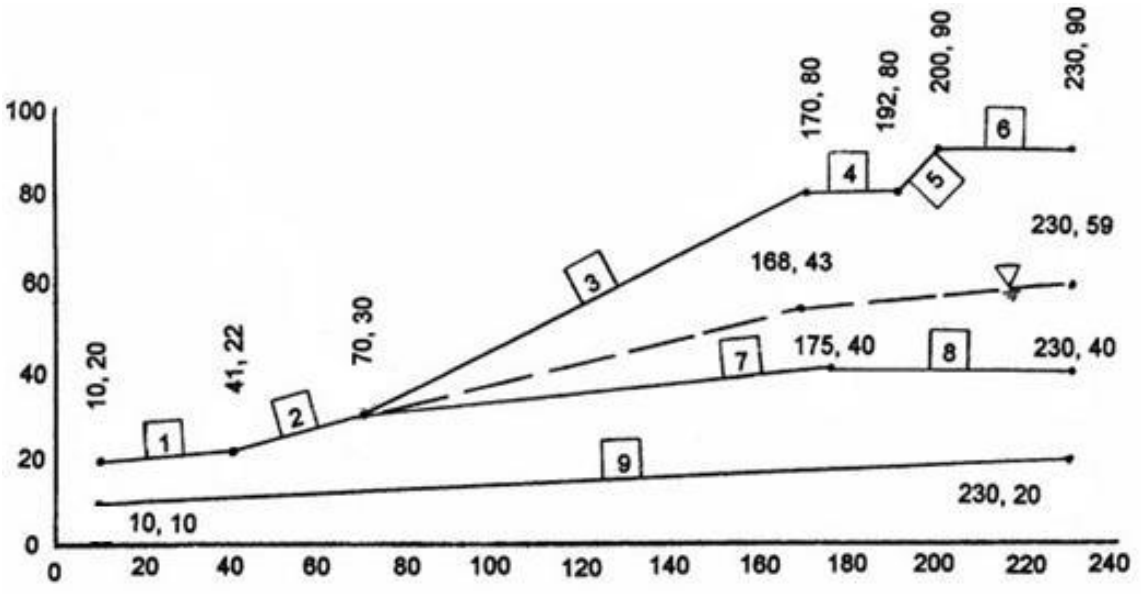


Figure 1: Flagged Section Showing, Lines, Piezometric Line, and Point Coordinates

2. **Prepare the Soils Data**: Plot the core boring stick plots on the cross section and determine the different soil types and boundaries. Number the soil (rock) zones on the cross section and record the properties of the soil in each zone (Figure 2). Unit weight, saturated unit weight, residual friction angle, peak friction angle, disturbed cohesion, and undisturbed cohesion are needed. The Rock Mass Rating (RMR) and the Standard Penetration Test (SPT) N value can also be used in the program.

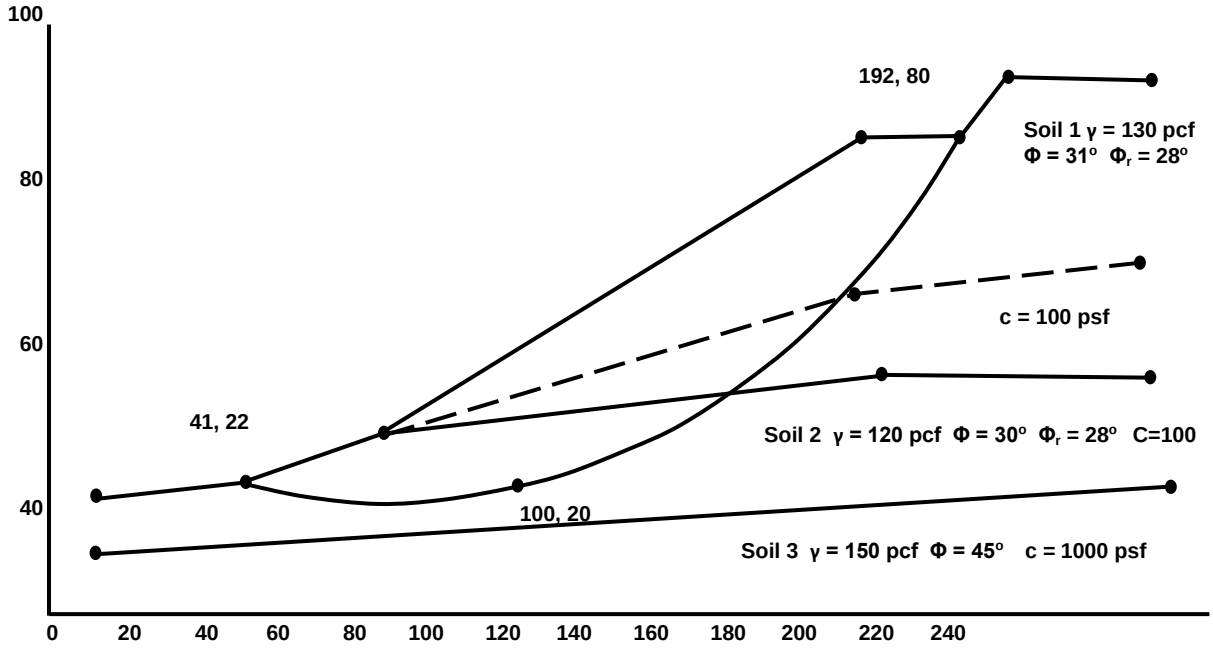


Figure 2: Cross Section (Slide Profile) Showing Typical Required Data

3. **Select Coordinates for the Failure Surface**: Use the scarp and toe plus any other criteria to determine or estimate the failure surface location. The program uses a circular failure surface. Use a CAD program or a compass and graph paper (this may require taping a piece of paper to your cross section) to find three points of the arc that fits the predicted failure surface (Figure 2). Alternatively, if a range for the initiation and ending point for the failure surface is entered the program will search for the worst failure surface out of the ten worst failure surfaces in the selected range. **[NOTE:** Make sure your circle does not intersect the ground surface in more than two points. You may have to change or ignore (eliminate from the analysis) some points or lines on the cross section, especially the slide scarp and lines above it.

B. INPUT

When entering data, refer to Figure 3 (Input Table)

1. Enter a title.

2. Enter a number for Number of Soil Types; this must be greater than zero, except when the "**Simple Wedge**" analysis is used, then the number of soils must be 2 (See page 13).

3. Change the SPT Hammer Efficiency if the hammer used has a different efficiency. The program internally adjusts the SPT blow-counts to the standard (N60) to determine the soil properties needed for soil-pile analysis. If the Auto Hammer is used adjust the efficiency to 80%.

4. Click the "Update Screen" button to generate the required rows for the number soils entered. After making changes to a table/section, and prior to selecting another table/section, or running the analysis, the screen **must** be updated.

5. Select the **Soil** type, there are four choices to choose from, three soils types and one rock. When selecting Soil type, it is important to understand how the program uses each type of soil in the calculations.

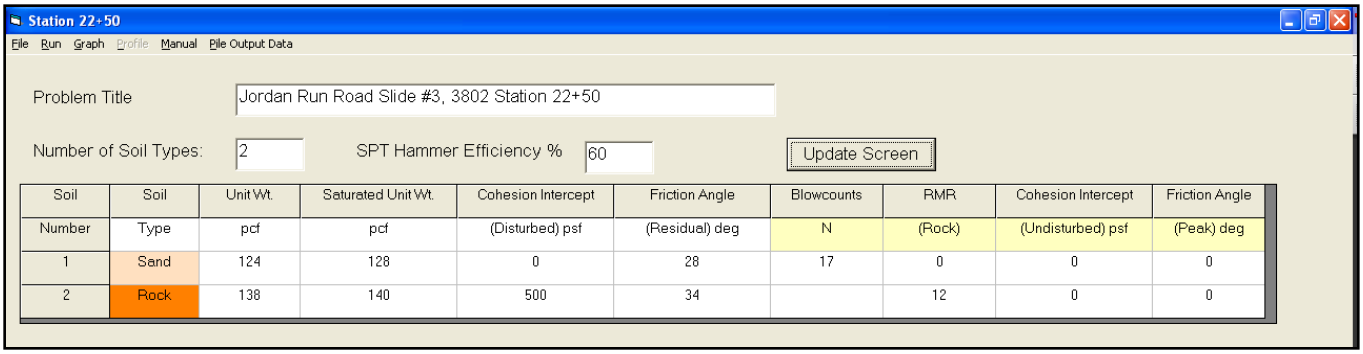
    a. **Sand**: This soil type lacks cohesion and is a pure friction soil; therefore the program ignores any values entered in the 8th column (Cohesion Intercept). This soil would be classified as pure sand.
    b. **Clay**: This soil type lacks friction and is pure cohesion soil; therefore the program ignores any values entered in the 9th (last) column **(Peak Friction Angle).** This soil would be classified as pure clay, undrained.
    c. **C-Phi**: This soil type is the typical soil found in West Virginia and contains both friction angle and cohesion soil properties. This selection will use both soil properties in the calculation. This soil should be selected unless it can be determined the soil is pure sand or clay.
    d. **Rock**: Used for bedrock of all types, including an intermediate geologic material (IGM) of extremely weathered rock.

6. Input the disturbed cohesion intercept and friction angle. Cohesion Interception **Disturbed** and Friction Angle **Residual** represent the soil strength parameters along the failure surface. These values are used in the slope stability analysis.

7. The last four columns of the soil property, **Blowcounts**, **RMR** (rock mass rating), **Cohesion Intercept**, **Friction Angle**, represent the data needed for the soil-pile analysis. These represent the soil strength parameters above and below the failure surface.

8. The program defaults to the columns labeled "**Blowcounts**" and "**RMR**", when running the soil-pile analysis. If values are entered into the Blowcounts (N Value), or Rock Mass Rating (RMR) column, the program ignores any value entered in the last two columns, Cohesion Intercept and Friction Angle, respectively.

9. Use the Enter Key or the mouse to move from one cell to the next, when entering data.



Soil Number	Soil Type	Unit Wt. pcf	Saturated Unit Wt. pcf	Cohesion Intercept (Disturbed) psf	Friction Angle (Residual) deg	Blowcounts N	RMR (Rock)	Cohesion Intercept (Undisturbed) psf	Friction Angle (Peak) deg
1	Sand	124	128	0	28	17	0	0	0
2	Rock	138	140	500	34		12	0	0

Figure 3: Soil Input Table

C. SOIL BOUNDARIES

1. There are three methods for inputting the soil boundaries and analyzing the slope stability. This section covers only the first of the three methods. When inputting data into this section refer to Figure 4.

   a. Existing Failure Surface
   b. Potential Failure Surface
   c. Simple Wedge Analysis

2. Before inputting the soil layer boundaries and selecting a method for analysis it is important to understand the difference in each method. The first two methods, "**Existing**" and "**Potential**" Failure Surface, both require a detailed input of boundaries, soil profile, water surface and slip plane. The third method, "**Simple Wedge Analysis**", which will be discussed later in detail, requires only the width of the wedge, height of wedge, depth of water table and depth to bedrock. No soil surface or water surface lines need to be entered for the simple wedge analysis (See page 13).

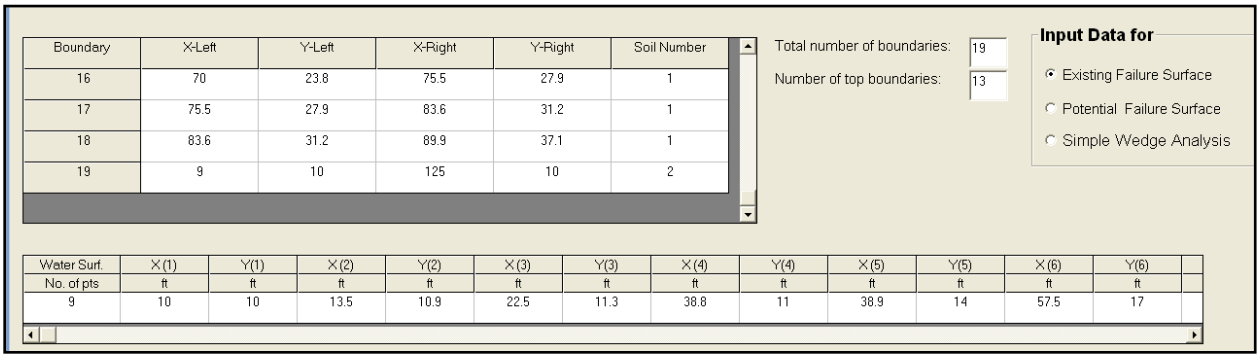
3. Input the "Total number of boundaries" and the "Number of top boundaries" and click "Update Screen".

4. Input the boundary line segments in the <u>increasing offset direction to the right</u> and starting with the top layer and working down through the layers. Input line segments using an x and y coordinate for the start and end of each line segment.

5. When entering the line segments, it is required to define which soil type underlies which line segment by giving the soil a number corresponding to the soil type .

6. Enter the number of water surface points that make up the total number of line segments, do not forget the last ending point. For example, 9 line segments will require 10 points.

Enter the X and Y coordinates that make up the line segments. The program only accepts one water table surface.



Boundary	X-Left	Y-Left	X-Right	Y-Right	Soil Number
16	70	23.8	75.5	27.9	1
17	75.5	27.9	83.6	31.2	1
18	83.6	31.2	89.9	37.1	1
19	9	10	125	10	2

Total number of boundaries: 19
Number of top boundaries: 13

Input Data for
- Existing Failure Surface
- Potential Failure Surface
- Simple Wedge Analysis

Water Surf.	X(1)	Y(1)	X(2)	Y(2)	X(3)	Y(3)	X(4)	Y(4)	X(5)	Y(5)	X(6)	Y(6)
No. of pts	ft	ft	ft	ft	ft	ft	ft	ft	ft	ft	ft	ft
9	10	10	13.5	10.9	22.5	11.3	38.8	11	38.9	14	57.5	17

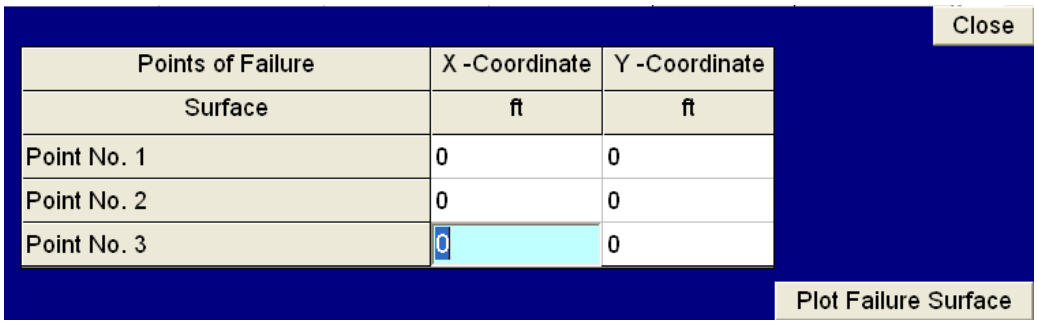
Figure 4: Input Table for Soil Surface and Water Table Surface Segments

7. It is possible to enter the data for either/both "Existing Failure Surface" or "Potential Failure Surface", on the same file and switch back and forth between the two methods. However, if, at anytime the "Simple Wedge Analysis" button is selected, all soil boundaries will be deleted and lost from the program. To switch back to one of the other methods, requires the boundary data to be re-entered. It is highly recommended to save the file after inputting the boundary data and prior to switching methods of analysis. It is good practice to save the file with the same name, with an additional term that would identify which analysis method is used with the file. When running several methods of analysis it can get confusing and data can easily be lost.

D. RUNNING STABILITY ANALYSIS:

Existing and Potential Failure Surface

1. **<u>Existing Failure Surface</u>**: This method requires inputting the slip surface, utilizing a three point method. This method requires determining the failure surface from the slope geometric cross section. These three points can be determined by the scarp, toe and depth to slip plane as indicated from the borings. This requires the x and y coordinates for the starting, ending and middle points, be entered in a table that opens when the button is selected (Figure 5). From this table, there is the option of viewing the plot, to determine, if adjustments need to be made to the failure surface and/or surface segments.



Close

Points of Failure Surface	X -Coordinate ft	Y -Coordinate ft
Point No. 1	0	0
Point No. 2	0	0
Point No. 3	0	0

Plot Failure Surface

Figure 5: Existing Failure Surface Input Box

If the table is closed without inputting data, the program will generate the following Warning Box (Figure 6)! Ignore this warning; it is just indicating there is not data to plot.



Figure 6: Warning Box

2. **<u>Potential Failure Surface</u>**: This method requires entering the slip surface by inputting the "Leftmost Initiation Point", "Rightmost Initiation Point", "Left Termination Limit", "Right Termination Limit" and the "Min. Elevation of Surface Development" (Figure 7). The table will open when the 2nd button is selected (Figure 4). This method is used when the exact failure surface is unknown or when searching for the most critical slip surface. It is also used when just analyzing a slope for stability, which has not failed. It is common to conduct a preliminary search for the critical slip surface first. It is usually found that most of the slip surfaces occur within a defined range. It is possible after the first run to more precisely define the search limits or force the critical surface to a predetermined location.

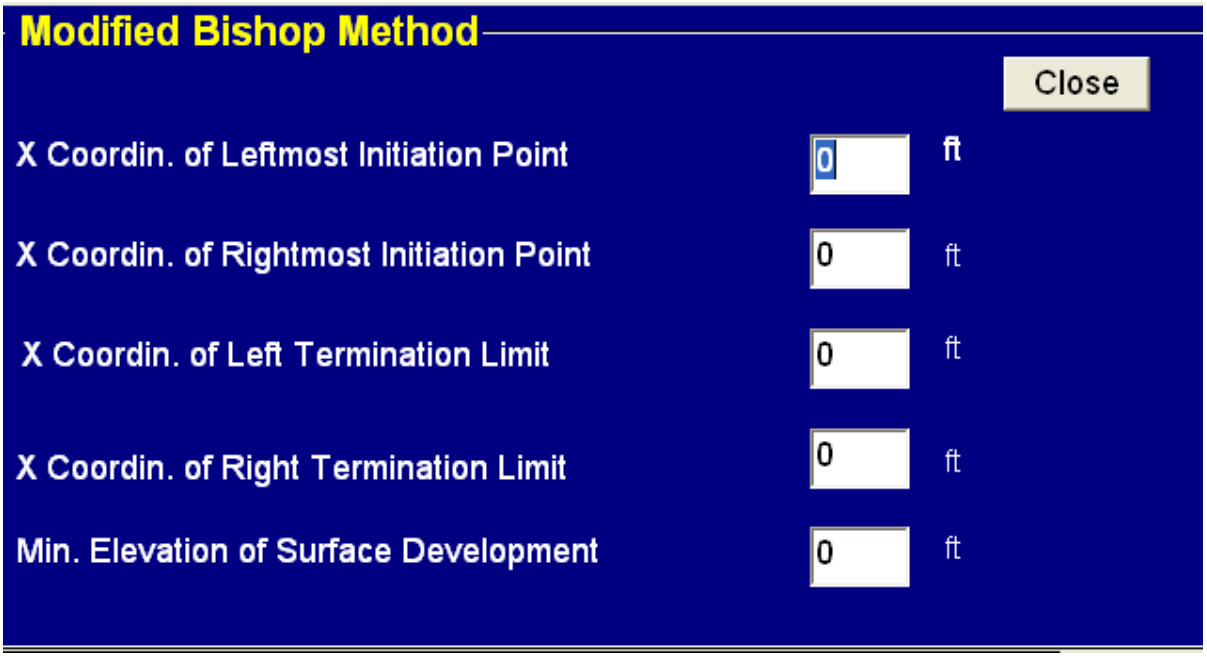


Figure 7: Potential Failure Surface Input Box

3. **The Stability Analysis Method**: The method used in the program is the "Modified Bishop Method" method of slices," which is the simplest method, and was used for many years for hand calculations. The factor of safety of a slide is 0.99, or for practical purposes 1.0.

4. **The Goal for the Initial Stability**: Analysis is to depict the slide mass and to establish the stability parameters (strength parameters and pore water pressure along the slip plane) to obtain a factor of safety of 1.0. The soil parameter values do not have to be exact; they need only be of the correct order of magnitude. This means that *the soil parameters must be reasonably correct*. If you are running the program for an existing slide, the factor of safety should be 1.0. If 1.0 factor of safety is not reached, adjust the strength parameters, the water table data, or both until a 1.0 is reached. Do not waste time making the slide factor of safety exactly 1.0, if the factor of safety rounds to 1.0 (i.e., is 0.96 to 1.04; use two decimal places only). Use subsequent stability analyses to evaluate soil parameters. We seek the "best" method to correct the slide. The best method may be the least expensive, the fastest, the easiest, or even the most aesthetic, depending on the circumstances. Albeit the programs best attribute is that of a Pile-Wall design, using the stability analysis section of the program does allow for other designs, such as a buttress, modifying the slope or relocating the road.

5. **Run the Stability Analysis**: At the top in the menu, select **Run, Slope Stability**. The following note will appear if all inputs were input correctly (Figure 8).

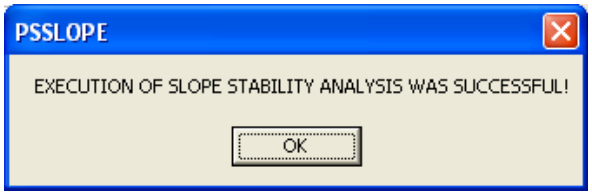


Figure 8: Notification Message of Successful Stability Analysis

6. **Common Input Errors**:
   a. Coordinates' value error:

      i. Mismatched line segments: Either the beginning or ending X or Y coordinate in a line segment does not match the previous or next line segment corresponding coordinate
      ii. Total number of boundaries and Top boundaries do not correspond to profile (Figure 11).

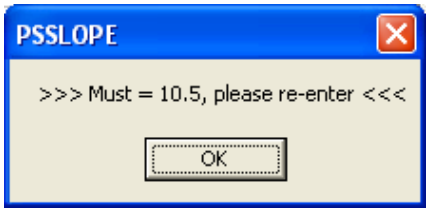


Figure 11: Error Message

b. Number of top boundaries exceeding total number of boundaries (Figure 12).

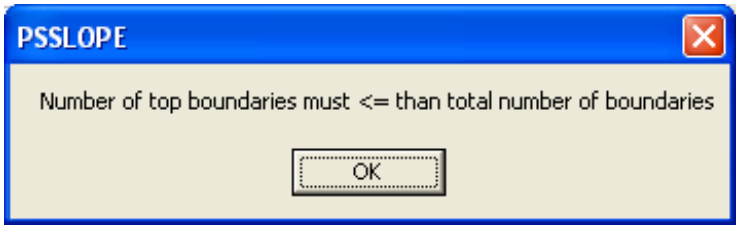


Figure 12: Error Message

c. Total number of boundaries exceeds the actual boundaries in the table (Figure 13). The program is expecting a value on the next line and to match the previous X value.



Figure 13: Error Message

d. Execution of program failure (Figure 14); This message can appear for a couple of reasons:
   i. Failure surface does not intersect the surface at two points or intersect in more than two points, For example, the failure surface jumps across a ditch.
   ii. A Negative number/s was input.



Figure 14: Error Message

e. The “Run-time error ‘#’ (Figure 15)

i. This is a common computer error message.
ii. Often this message is generated because the user has input an error that the programmer did not anticipate and the computer gets confused generates the message and then crashes.
iii. If this message is encountered please note the error message and contact the central office. The file (.stm) will need to be saved and sent to the office to correct the program.



Figure 15: Run-time error

f. The program will display a warning or error message for the first input error it encounters in the program. The error message, most likely points directly to the problem or it can indicate an error caused by an incorrect input in some other location. Check inputs carefully before making corrections. It is of the greatest importance to remember that the program will allow as many corrections to a section as needed, but the “Update Screen” must be selected prior to selecting another section for corrections or running an analysis.

7. **Viewing Results:** The program offers two methods to view the profile of the input parameters prior to running the stability analysis (this function is not available in the Simple Wedge Analysis). This function can be used to check the soil, water table and failure surfaces, and make adjustments prior to running the analysis (Figure 17).

a. In the “Existing Failure Surface” press the “Plot Failure Surface” button (Figure 16). This button is not available in the “Potential Failure Surface”.

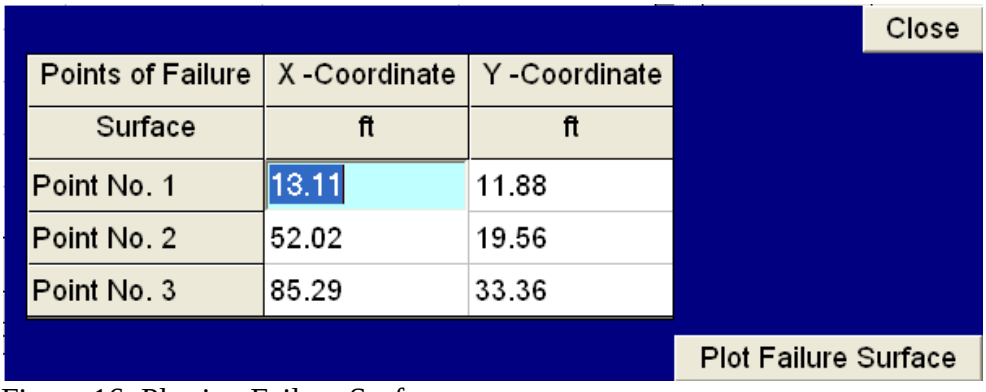


Figure 16: Plotting Failure Surface

A small sketch of the surface, water and slip plane boundaries will be generated (Figure 17).

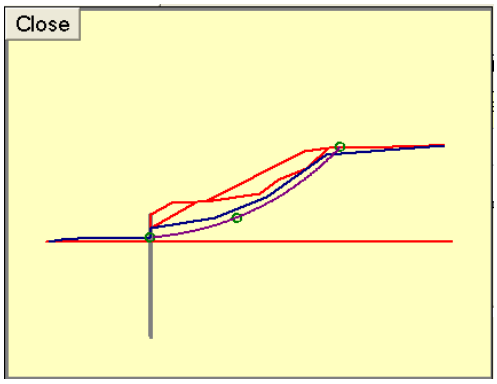


Figure 17: Preview

b. To view the preview sketch (Figure 17) in the "Potential Failure Surface", and in the "Existing Failure Surface", select "Profile" on the main menu bar at the top of the screen (Figure 18).

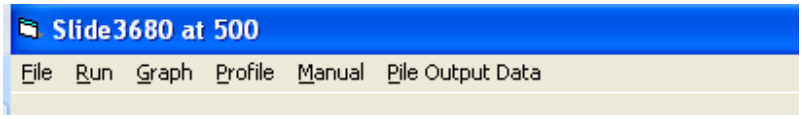


Figure 18: Profile on Main Menu Bar

c. Once the stability analysis has run successfully, the user has the option to view a graph/plot of the slide analysis, Figure 19. The graph displays the date and time, factor-of-safety (F.S.), water table, soil layers and slide name. If the mouse pointer is moved over the graph the X and Y coordinates are displayed on the lower border of the graph, the order of the coordinates are Y and X.

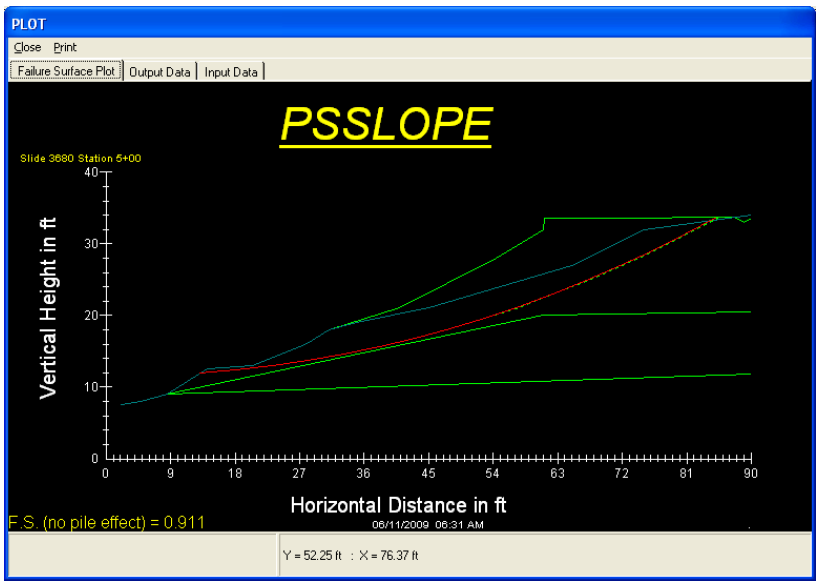


Figure 19: Stability Graph/Plot

In addition to the information displayed on the graph, other information can be printed or viewed on the additional two tabs:

i. Output Data: A couple of pages long, containing.
    1. All the input data
    2. Failure surface (17 points)
    3. Circle Center and Radius
    4. Data an forces along 32 slices
    5. Cannot be edited in this form

ii. Input Data
    1. All the input data in plain text form
    2. Can be edit, but not advisable

iii. Print
    1. Plot/Graph
        a. Monochrome
        b. Color (uses a lot of ink)
    2. Output data

g. Once a F.S. of 1.0 has been reached by back calculating the soil strength parameters and the user is confident in the modeling of the slip, it is highly recommended to adjust the soil layers to include the pile wall and correction. Often the installation of a pile wall requires rebuilding the road to include a 4 to 6 foot shoulder, and possibly a guardrail. This added weight could result in a greater driving force on the wall and should be modeled. When modeling the wall it is important to note that the piling cannot be input as a vertical line. Offset the top by 0.1-ft, uphill (remember that there must be "soil" under the line and not "air," so don't offset in the wrong direction). Remove any slide material below the piling that will be removed for construction and/or road clearing. This will be dependent upon the situation. The main objective is to model the correction as precisely as possible, eliminating any resisting forces and adding any additional driving forces. Run the analysis and ignore any change to the F.S. as a result of these changes.

CHAPTER 2 – PILE SIZING AND ANALYSIS

A. Pile Data Input

1. Select from the drop down menu the appropriate pile (Figure 20), the most common H and W sizes, for compact (Mp) and noncompact (My) piles are listed. Compact piles utilize the Plastic Moment and noncompact piles uses the Yield Moment.

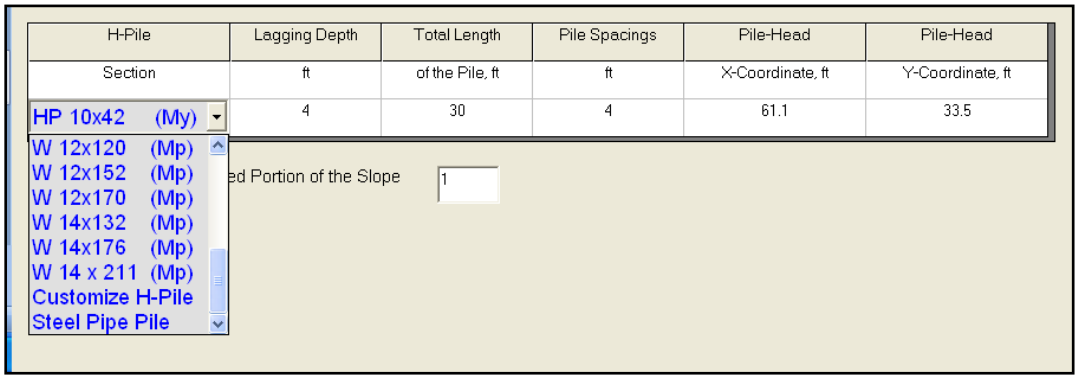


Figure 20: Pile Input Table

Another option is to enter a custom Pile size (Figure 21); some inputs can be obtained directly from the "Manual of Steel Construction" or any other official source. Others will have to be calculated as outlined below.

a. Flange Width: Column "Width (b_f)", from manual
b. Depth: Column "Depth (d)", from manual
c. EI: Modulus of Elasticity of Steel (E=29,000,000 psi) x Moment of Inertia (I), in the strong axis, (Elastic Properties column, Axis X-X, column I)
d. Unfactored Moment: 50,000 psi x S, in the strong direction (S=section modulus, (Elastic Properties column, Axis X-X, column S); or if $b_f/2t_f$ column under compact section criteria is less than 9.15, Z_x (plastic Module) can be used.

(ie...M=50,000 x Z_x)

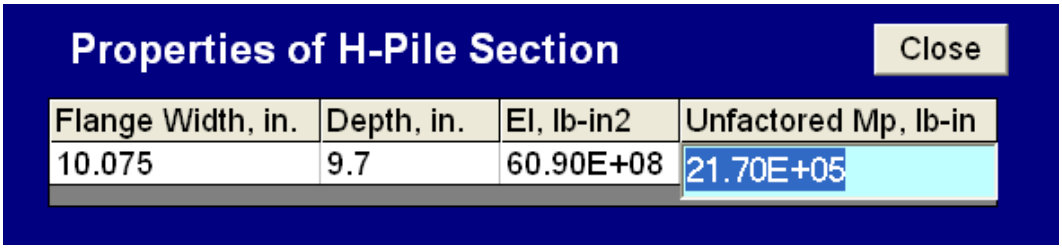


Figure 21: Custom H-Pile Input

Note that this input window is not limited to just H-Pile sections, other shapes can be used. Selection of the proper pile size will come with experience and will only need minor adjustment to achieve the proper performance and deflection. A good practice is to select a pile size a little larger than anticipated, and run the program to determine how much smaller to reduce the size by. Selecting a pile to small results in an output

message (Figure 22), the pile failed under the moment and produces no quantifying results in which to gage how much larger of a pile is needed.

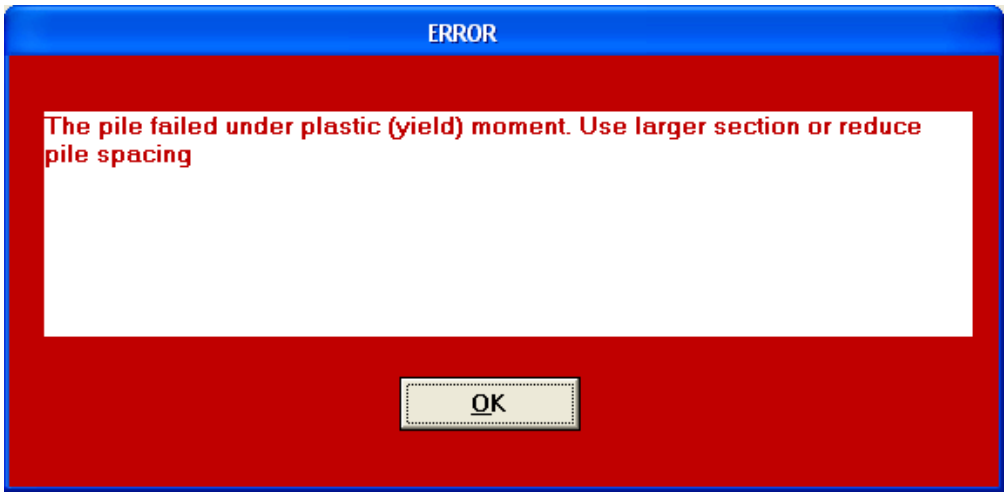


Figure 22: Pile Failure Warning Message.

2. Enter the desired "**Lagging Depth**"; keep in mind that the slope on the downhill side may continue to move. A good practice is to embed the lagging 2-ft into stable ground. The lagging cannot be extended beyond the failure surface.

3. Enter the estimated "**Total Length**" of the pile in feet. A good practice is to embed the pile 10-ft into bedrock. Although this is not always possible or practical.

4. Enter the '**Pile Spacing**", the standard spacing is 4-ft center-to-center of piles. This can be adjusted as the situation dictates.

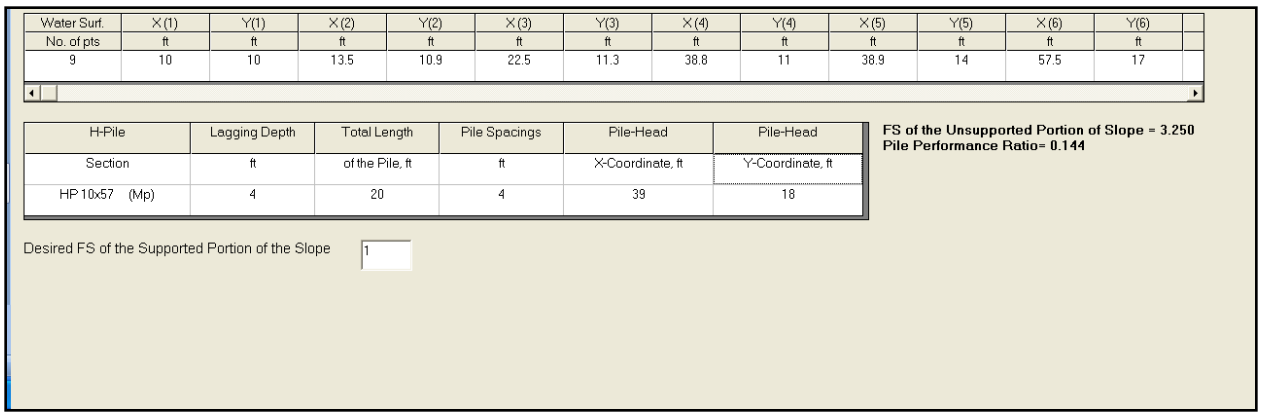
5. Enter the "**Pile Head**" X and Y coordinate; this must be the same coordinate as the top of the pile that was input in the soil boundaries.

6. Select the desired "**FS**", for the initial analysis, use FS of 1.0.

B. RUNNING PILE ANALYSIS

1. It is important to know and remember that the "**Slope Stability**" must be run prior to running the "**Slope with Piles**", ***EVERY TIME*** a change is made. If a change is made to ***ANY*** input data, then the slope stability must be run again. So it is highly recommended, as a practice to run the Slope Stability, and then run the Slope with Piles, every time. To run the program, select "Run the Slope with Piles".

2. Once the program has run successfully, pile performance information will be displayed on the main page, and the user has the option of viewing several files, and graphs. The Factor of Safety and Pile Performance Ratio will be displayed in the far lower right of the main page (Figure 23).



Water Surf.	X(1)	Y(1)	X(2)	Y(2)	X(3)	Y(3)	X(4)	Y(4)	X(5)	Y(5)	X(6)	Y(6)
No. of pts	ft	ft	ft	ft	ft	ft	ft	ft	ft	ft	ft	ft
9	10	10	13.5	10.9	22.5	11.3	38.8	11	38.9	14	57.5	17

H-Pile	Lagging Depth	Total Length	Pile Spacings	Pile-Head	Pile-Head
Section	ft	of the Pile, ft	ft	X-Coordinate, ft	Y-Coordinate, ft
HP 10x57 (Mp)	4	20	4	39	18

Figure 23: Pile Analysis Output

a. **FS of the Unsupported Portion of Slope**: This is the FS for the portion of the slide that is downhill from the pile wall, which is not supported by the pile wall. By stabilizing the upper portion of the slide, the driving force could be reduce or even eliminated, thereby stabilizing the lower portion. This information is of a concern, if there is something downhill of the slide that may be in jeopardy, such as structures, another road, railroad, etc.

b. **Pile Performance Ratio**: This is a percent of the factored pile strength that is being used. This information can be utilized several ways. When sizing the pile up or down, this percent can help in determining how much to adjust the pile size. It is import to remember that the final correction requires a factor of safety of 1.3 for general slides and 1.5 around structures (in accordance with LRFD). The higher FS will use a greater percent of the pile strength. Also if the pile is not long enough and rotates over (fence post), the performance ratio will be low. This number should always be used in conjunction with the deflection.

3. **Graphing Results**: From the main menu select "Graph", then select "Pile Response" from the drop-down menu. The pile response is analysed utilizing four separate graphs: Deflection, Moment, Shear Force and Line Load. On the graph there is a tab for Graphic Control, this has no function with the program. Although it is still active and can be used to modify the overall look of the graph, it will tend to produce a graph that is not as usable. Once the graph has been manipulated with this function, it is not possible to return to the original graph. Do not fear, closing the program and restarting the program will restore the graph to the default.

a. Deflection: This graph displays the deflection of the pile, in feet, along the Y axis. Deflection is most critical when analysed at a factor of safety of 1.0 (Figure 24). The amount of deflection that is allowed is dependent on the situation. As a practice 4 inches is the maximum deflection for rural roads, 2.0 for major roads. Road type, slope steepness, shoulder width, and if a guardrail will be installed, all have a major impact on the maximum allowable deflection. If the shoulder is going to be paved up to the wall, less deflection is desirable. In addition to

deflection, this graph indicates if the length of the pile is adequate. It is important to get two points crossing fixity, using the final factor of safety of 1.3.

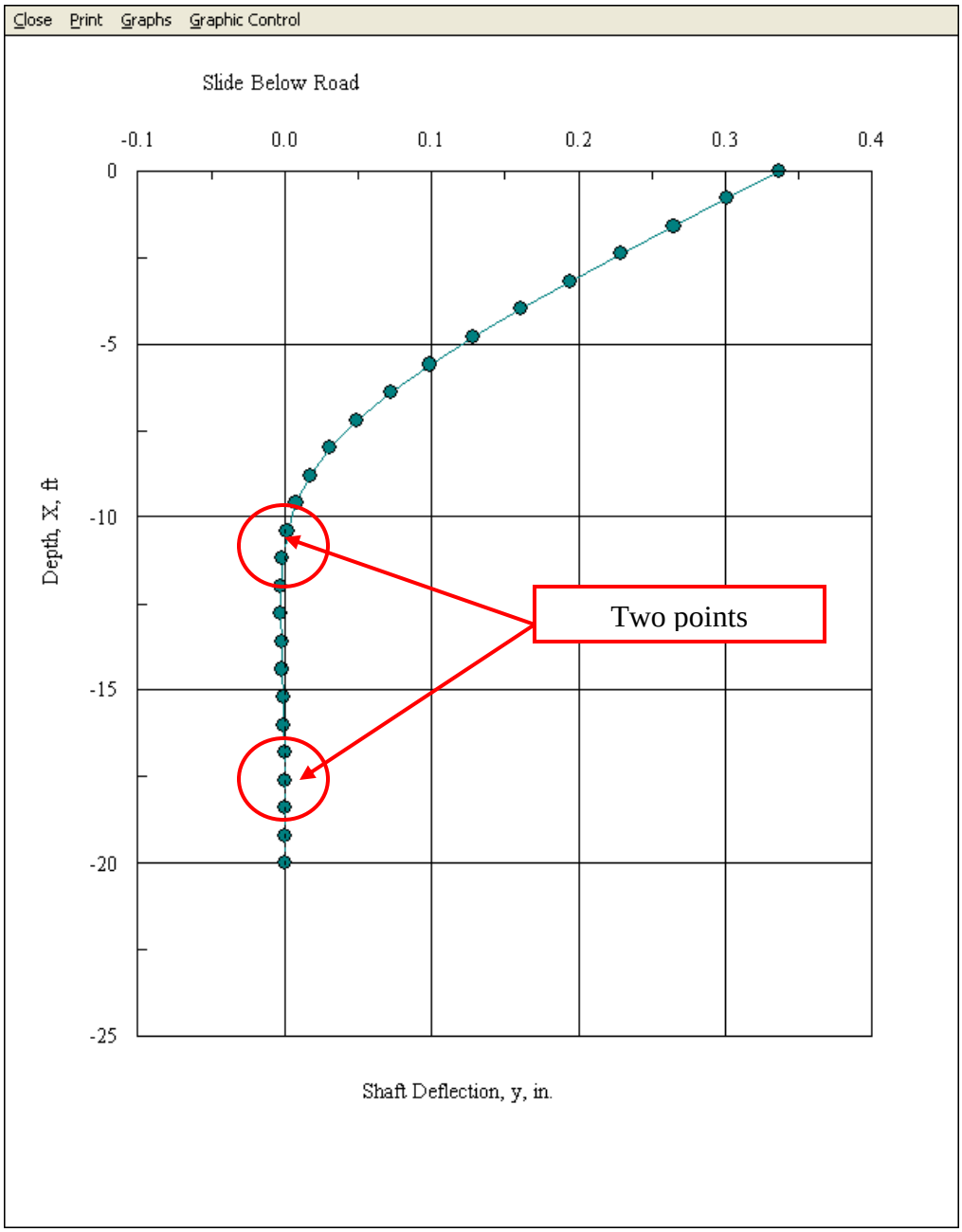


Figure 24: Deflection Graph

b. Bending Moment: The location and magnitude of the bending moment can be visualized (Figure 25). As a check, the moment in the flexure formula (moment/section modulus = fiber stress) can be used, to determine what section modulus to use if a different shape is desired.

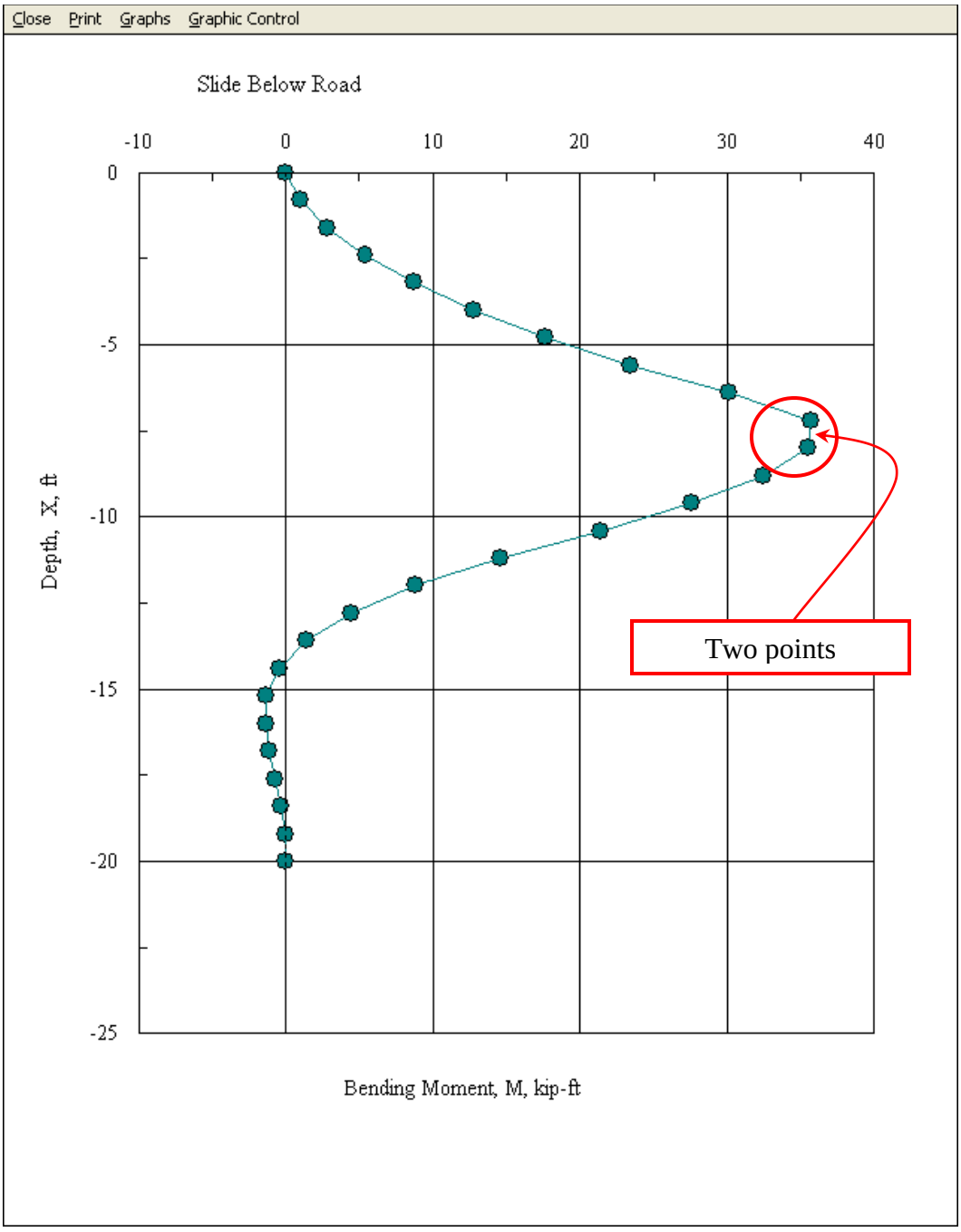


Figure 25: Bending Moment

c. Shear Force: The shear is built up within the pile by the slipping mass then shed into the more resistive layer below the slip surface. Shear is not a critical design state for steel piles (Figure 26).

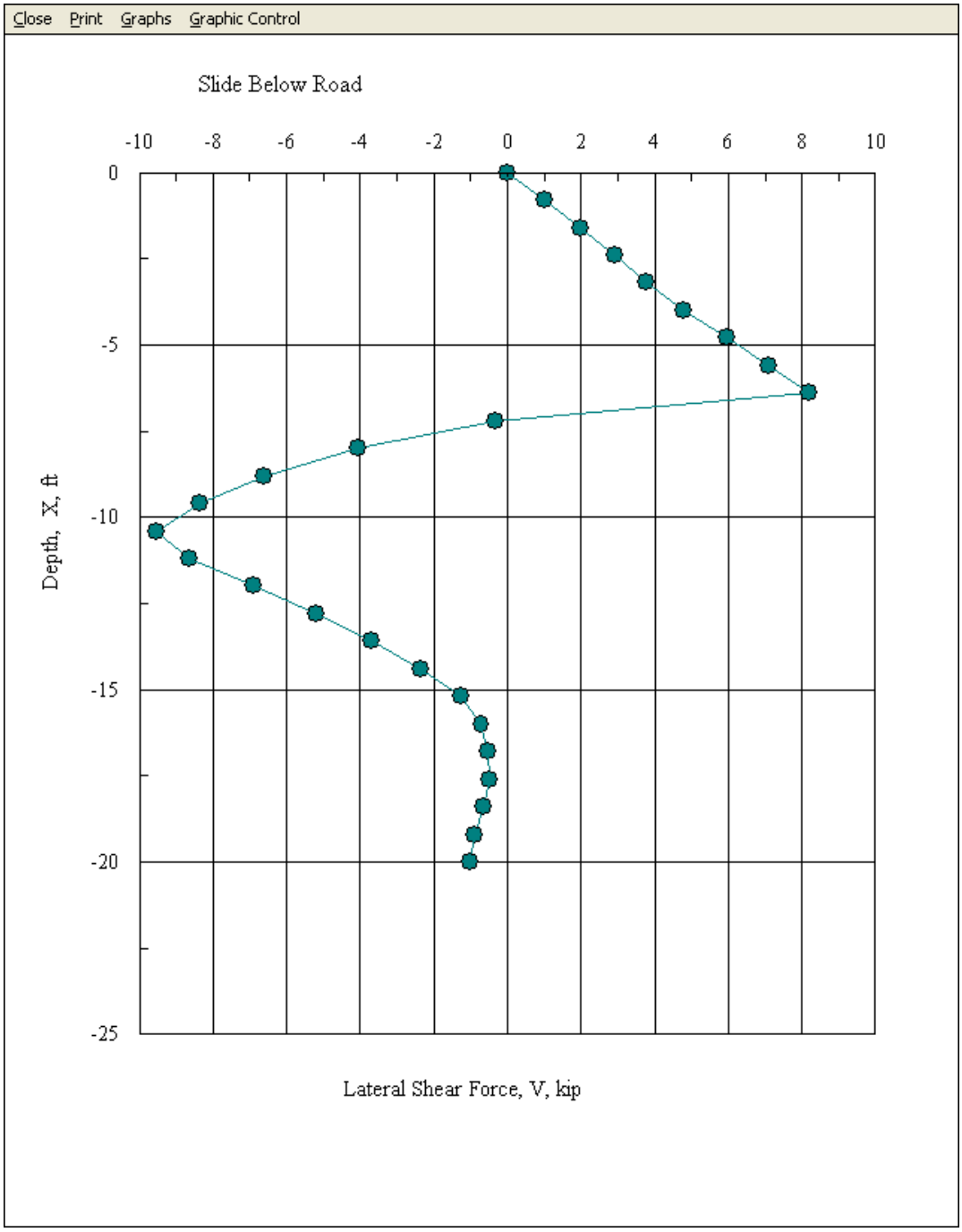


Figure 26: Shear Force

d. Line Load: The load per vertical inch of the pile that the soil or rock sees. To convert this load to stress, divide the force by the flange width. This is used to check the spike at the rock line to determine if the pressure exceeds the unconfined compressive strength of the rock mass (Figure 27).

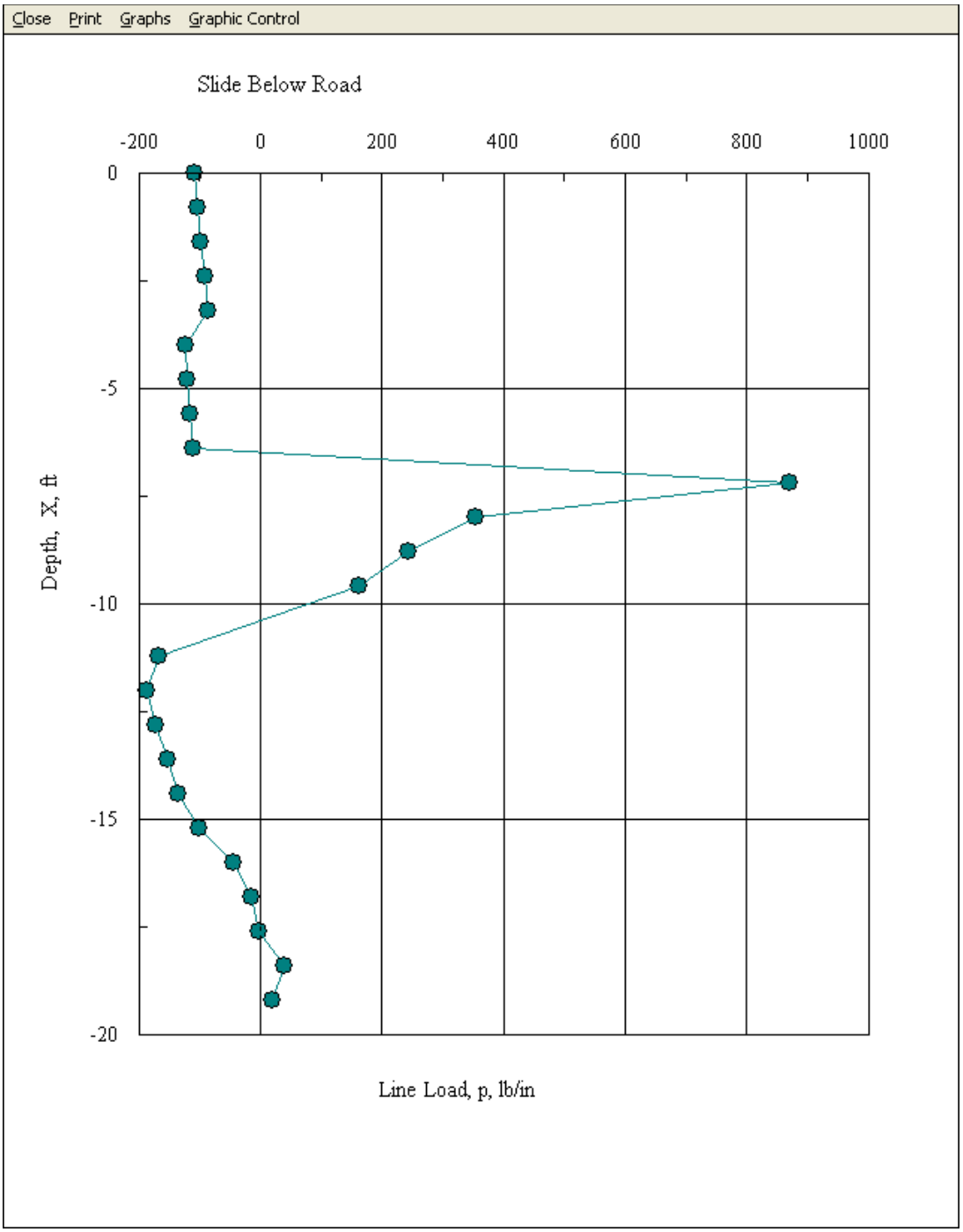


Figure 27: Line Load

e. Pile Size: Once the required pile size has been determined by checking the pile performance at a FS of 1.0 and 1.3, save the file, and print any files required.

4. In addition to graphs and plots the program generates two text files, Figure 28, 29 and 30. These files are output files generated and used as input files to parts of the program, they should be opened with caution. If needed, the user can obtain the exact deflection, and location and depth of the maximum moment. However as most things in Geotechnical Engineering, this level of accuracy is not really needed.

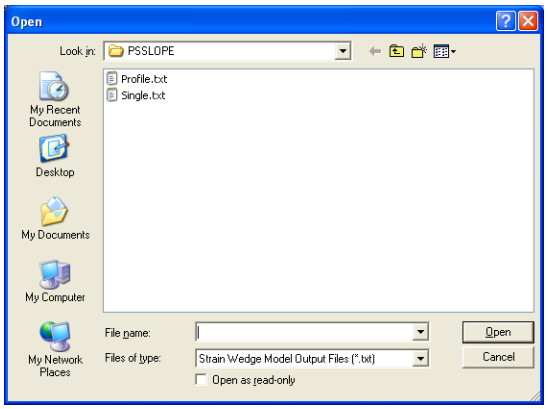


Figure 28: Output Text Files

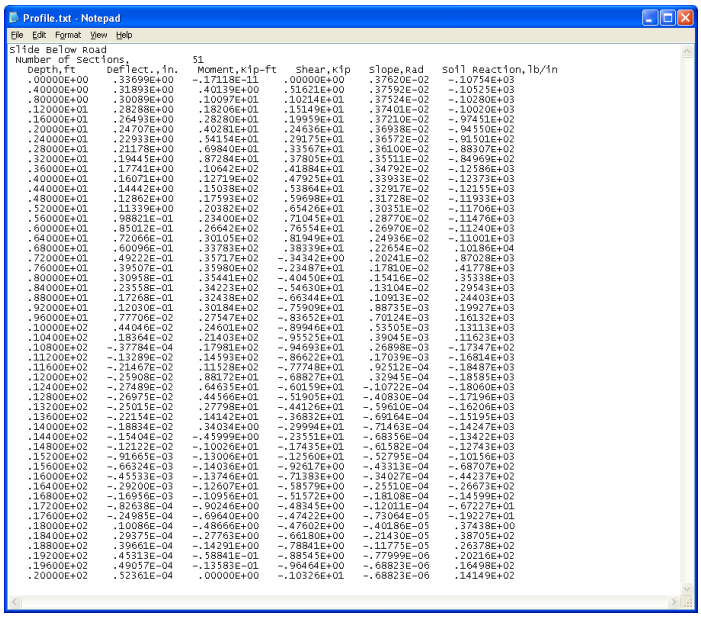


Figure 29: Profile Text File of Forces on the Pile

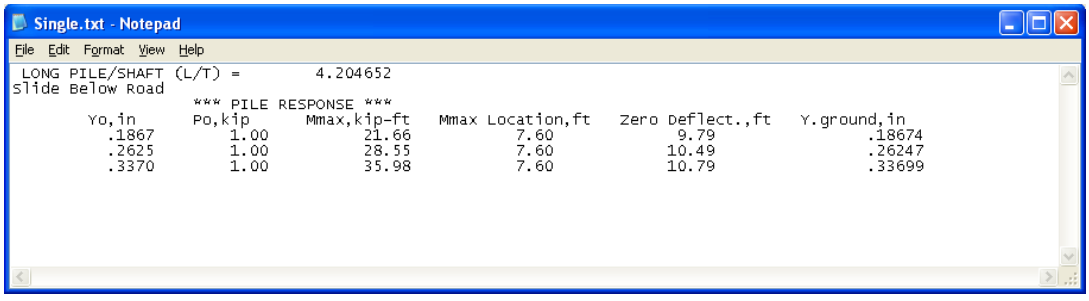


Figure 30:

C. SIMPLE WEDGE PROGRAM

1. **Simple Wedge Analysis**: This method of analysis is, as the name implies, a very simple method to model the slip as a simple wedge of soil applying a driving force to the pile. The program requires 2 soils, wedge of soil geometry, depth to water table, depth to bedrock, lagging depth, pile length, pile spacing and pile size (Figure 45). The second soil is assumed the bedrock, however it has the strength parameters entered.

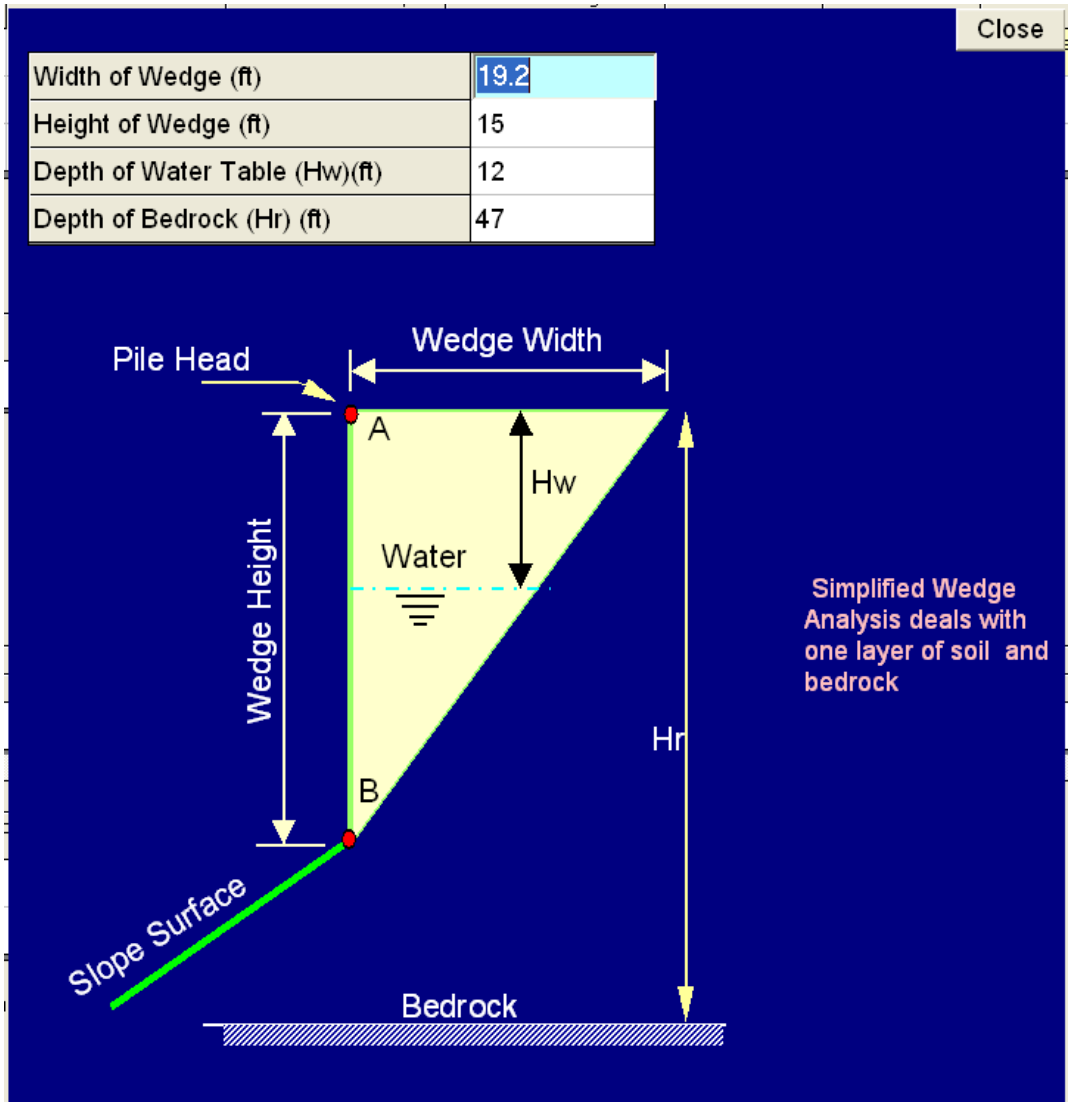


Figure 45: Simple Wedge Input

a. Soil Input - Enter the two soils as follows: One soil for the slip surface and surrounding area, and another to embed the pile into. Both soils can have the exact undisturbed and disturbed strength parameters, or they can be two entirely different soils/rock. The main point is the program requires 2 soils. The "Total number of boundaries", "Number of top boundaries", boundary coordinates and water table surface need not be entered. Next select the analysis button and enter the data into Figure 8.

b. Width of Wedge: Enter the "Width of the Wedge (ft)"; this is the horizontal distance from the top of the pile to the last break in the road. Adding extra width to the wedge is not advised, because this could have the opposite effect. The extra width can reduce the driving force. Caution is advised and the results can readily be checked, this will be discussed later.

c. Pile Height: Enter the "Height of Wedge (ft)"; this is the vertical distance from the top of the pile to the suspected slip surface.

d. Depth to Water Table: Input the estimated "Depth of Water Table (Hw) (ft).

e. Depth to Bedrock: Enter the "Depth of Bedrock (Hr) (ft), this is the second soil listed in Figure 1. The second soil does not necessarily have to be Rock or even a different soil type. If for example, the core borings show the same type of soil deeper then the estimated pile length, enter the second soil having the same strength properties as the first soil.

f. Pile Data: Enter the Pile size, Lagging Depth, Total Length and Pile Spacing.

g. FS: Enter the desired factor of safety. The program will be run at a FS of 1.0 and 1.3 for analysis, see page 13, "Running Pile Analysis

2. **Running the Program**: On the main menu tool bar select run, then "Slope with Piles" It is the only option.

3. **Viewing the Results**: The program only allows for the viewing of the pile response. The simple wedge diagram is the block analysis that is depicted on the input page.

4. **Pile Performance**: The pile performance is analyised by viewing the available graphs and the "Pile Performance Ratio", see page 13.

CHAPTER 3 – EXAMPLE PROBLEMS

A. Learning By Example

1. The following example problem is provided to show the user how to design a pile wall as a corrective measure. The user is encouraged to adjust the soil, rock and water table parameters (layering and soil properties) to produce a variety of results. The user is also highly encouraged to experiment with the different slope stability methods. An effort has been made to explain all steps in the analysis and design.

2. The program has been made as user friendly as practicable; this includes trying to "trap" common errors that the user may make. However, all of these errors cannot be anticipated, and error messages may arise that are incomprehensible.

B. A Note on Factors of Safety

1. **Service Limit State**: In the analysis a factor of safety of 1.0 is only used to determine an acceptable deflection. If a higher FS is used, the deflection becomes meaningless, since the pile/soil should be in equilibrium when deflection is assessed.

2. **Strength Limit State**: The factor of safety used by WVDOH for the design of ordinary soil slopes (cuts and embankments) is 1.25 for "Allowable Stress Design" and 1.30 for "Load Factor Design". Many designs have been developed by the WVDOH Engineering Division in the last few years with factors of safety 1.25. The lowest FS in the strength limit state is 1.1. This should only be used for extreme event limit states, such as end of construction or rapid draw-down. A factor of safety of 1.1 is considered at the edge of failure due to the accuracy of the method.

3. **Factor of Safety**: The use of reduced factors of safety for slide corrections requires judgment based on experience. Sliding cause's a reduction of soil strength from peak to residual, so strength can be lost between the times of design and construction. Further, ground water conditions can become worse than those existing at the time of original failure. Use good judgment or, if you lack experience, use a factor of safety of 1.3. With experience, factors of safety of 1.25 can be used, based on local experience.

C. A Note on Failure Surfaces

1. **Failure Circle**: The failure circle must intersect the ground surface in two points (the end points of the circular arc). Otherwise an error message will appear. If the slide has a steep scarp or slope above the upper limit of the slip plane, the circle may intersect the ground surface *again* (for the third time). Hence, some superfluous lines above the slip plane must be eliminated. However, if a new circle is run to check the corrective design, *the eliminated lines may have to be added.*

2. On rare occasions, a circle through the toe of the slope can intersect a line below (for the third time) to give an error. It is good to check your circles before you run the program.

3. The maximum vertical depth of a slide rarely exceeds ¼ of the slope length of the slide; the maximum failure surface depth is always less than 0.3 times the length and averages about 0.17 times the length. These criteria do not apply to new embankments over soft, deep clay foundations.

D. Important Design Considerations

1. **Driving Forces**: The driving force to be resisted depends on the location of corrective measures within the slide and the slope configuration within the slide. For example, a piling correction near the top of the slide may only have to hold the top of the slide, not the entire slide. However, if we must fill on top of the slide (e.g., to rebuild the road surface), we need a piling wall (with lagging) to hold the top of the slide PLUS the new fill. We need to perform a new stability analysis on the slide and fill to obtain the force the piling must resist. To accomplish this, the soil surface profile will need to be modified to model the correction. So prior planning when selecting and entering the X and Y coordinates makes possible the remodeling of the correction, much easier and becomes a simple matter of entering new line segments at the end of the input table or change the value of a few points.

2. **Resisting Forces**:

   a. **Soil Strength**: Soil strength is defined by the parameters of the internal friction angle (phiϕ) and the cohesion intercept (c). Each type of soil will, in general, have different values for ϕ and c. Further, the same soil within and surrounding a slide mass will typically have different strength.

   b. Where to use different strength parameters? Use ϕ_r along the slip plane (disturbed) during the original analysis. Within the slide mass and below the slip plane (undisturbed), use peak values. Do not choose strength parameters over conservatively; this will require the ground water to be modeled higher to get the slide to fail.

   c. Ground Water: The pore water force (U) values reduce the effective normal forces, thereby reducing resisting forces. The exact U values are rarely known since this requires extensive and usually long term piezometric water level measurements. Even when such measurements are made, they may not reflect values at the time of failure. One of following three ground water conditions is normally encountered during corrective design.

      1. Ground water approximately known or partially known: Seepage is sometimes visible on the ground surface so that the uppermost elevation where the water emerges from the ground can be measured. On some of these occasions, the

water level at the time of failure will be at the ground surface for the full length of the slide, even though there is no visual evidence. Borings above the visible seepage may also show indications of the ground water level (when practical, have observation well installed). These conditions allow an approximate ground water level to be plotted on the design cross section. If only partial information is available, i.e., only visible surface seepage or only an indication of the water level in a boring, the water level must be estimated from this information. The estimated water level may be adjusted later if results of the stability analysis indicate that such adjustment is necessary.

2. Ground water unknown, but soil strength is known: Sometimes no reliable indications of ground water are available. If soil strength parameters are available, either from test results, N-Values, or from estimates, a stability analysis without ground water can be performed. Use a rough water level to estimate a trial water surface. Adjust the water surface to get F.S. =1.0. If strength parameters were estimated and water levels appear to be too high or too low, you can adjust the strength parameters (usually just ϕ_r with c = 0) so that the water level looks reasonable. Be careful adjusting the soil strength too much as piezometric levels can be above the ground surface when artesian pressures are encountered and at least some groundwater will be present.

3. Ground water and soil strength unknown: Emergency situations arise where corrective measures must be based solely on site observations. Surface soils are visible and surface indications of ground water may be visible, but strength parameters and water levels are quite problematic. Guesstimate strength parameters and water levels based on your observations, and run a stability analysis. Adjust the assumed values to obtain a 1.0 factor of safety. Design the correction using these values to estimate conditions outside the slide area. For example, if the ϕ_r is 23 degrees and use ϕ = 27 degrees and c = 100 psf for the soil under the slide. Adjust the embedment depth during piling installation if the soil under the slide is significantly different or if bedrock is encountered.

E. Example Problem

1. The number of soils used in the analysis will depend upon the information available. It is often easy to determine the number of soil zones from boring logs. For this example the soil parameters were derived from field observations and core borings they are depicted in figure 31 and 32. The core boring indicated three main soil layers and a depth to water, at the time of coring.

Core Boring Results				
Soil Type	**Blow Count (N)**	**Consistency**	**Moisture Content**	**Weathering**
Silty Clay	10	Stiff	Slightly Moist	
Sandy Clay	6	Med Stiff	Moist	
Sandstone	NA	Hard	Dry	Slightly Weathered

Figure 31: Core Boring Table

Estimated Soil Strength Properties							
Soil #	Soil Type	Unit Weight	Saturated Unit Weight	Cohesion Intercept Disturbed	Friction Angle Residual	Cohesion Intercept Undisturbed	F Friction Angle Peak
1	C-Phi	124	126	0	23	50	31
2	C-Phi	120	124	0	26	100	28
3	Rock	145	146	10000	36	10000	36

Figure 32: Soil Strength Parameters Table

2. Input the soil data in the program from Figure 31 and 32.

3. Determining the soil boundary coordinates is best accomplished through the use of a CAD program. Often the coordinates are derived from a professional survey, but if time is a limiting factor, the user can, with the aid of an assistant, produce a simple plan view and cross section, by utilizing a surveyors tape and Abney Level. In this example the soil boundaries and water surface coordinates have been determined and plotted on Figure 33 and entered into the Figure 35.

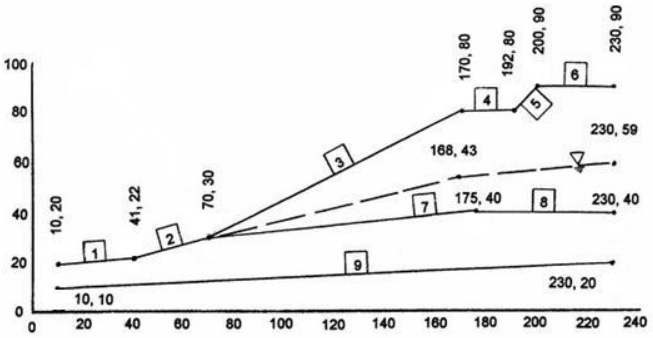


Figure 33: Surface Boundaries Coordinates

4. The soil types and corresponding soil number have been annotated on Figure 34.

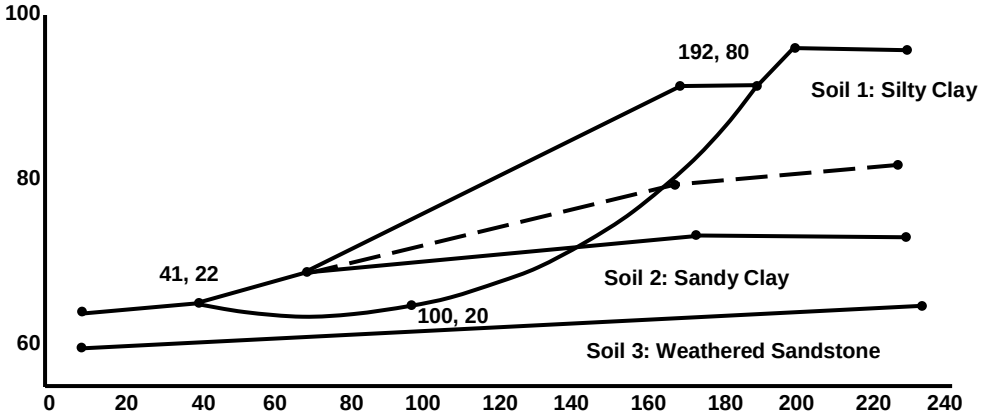


Figure 34: Soil Types

5. Input the "Total number of boundaries" and the "Number of top boundaries, and the soil layer boundary coordinates from Figure 35 the coordinate table, Figure 35.

SOIL SURFACE COORDINATES					
Total Number of Boundaries = **9**			Total of Top Boundaries = **6**		
Boundary	**X-Left**	**Y-Left**	**X-Right**	**Y-Right**	**Soil Num**
1	10	20	41	22	1
2	41	22	70	30	1
3	70	30	170	80	1
4	170	80	192	80	1
5	192	80	200	90	1
6	200	90	230	90	1
7	70	30	175	40	2
8	175	40	230	40	2
9	10	10	230	20	3

WATER SURFACE COORDINATES										
No. of Pts	X(1)	Y(1)	X(2)	Y(2)	X(3)	Y(3)	X(4)	Y(4)	X(5)	Y(5)
5	10	20	41	22	70	30	168	52	230	59

Figure 35: Soil and Water Surface Coordinate Table

6. Input the "Water Surface" coordinates from Figure 35.

7. Input the "Existing Failure Surface" from Figure 34, utilizing the 3 points.

8. Plot the failure surface; recall there are two methods for checking the failure surface. Adjust inputs as required, correcting any errors.

9. After making any necessary adjustments, run the “Slope Stability” analysis.

10. View the Graph of the Slope Stability analysis and check the factor of safety. The goal is to adjust the parameters to achieve a factor of safety of 1.0. At this point the graph should look similar to Figure 36.

    In this example the initial input of soil parameters were estimated low to produce a F.S. of less than 1.0, for demonstration purposes. For this example assume the water surface to be close to correct and adjust point Y(3) to read 30.

11. Adjust the soil parameters as required to obtain a F.S. of 1.0, rounded. The “Cohesion Intercept” and “Friction Angle” have the greatest effect. However, disturbed soil has little to no cohesion, so it is highly recommended to input “0” for cohesion. The friction angle is determined by the type of soil, which will have a close range of strength parameters. Try adjusting the friction angle and unit weight of the soil that is affected by the failure surface.

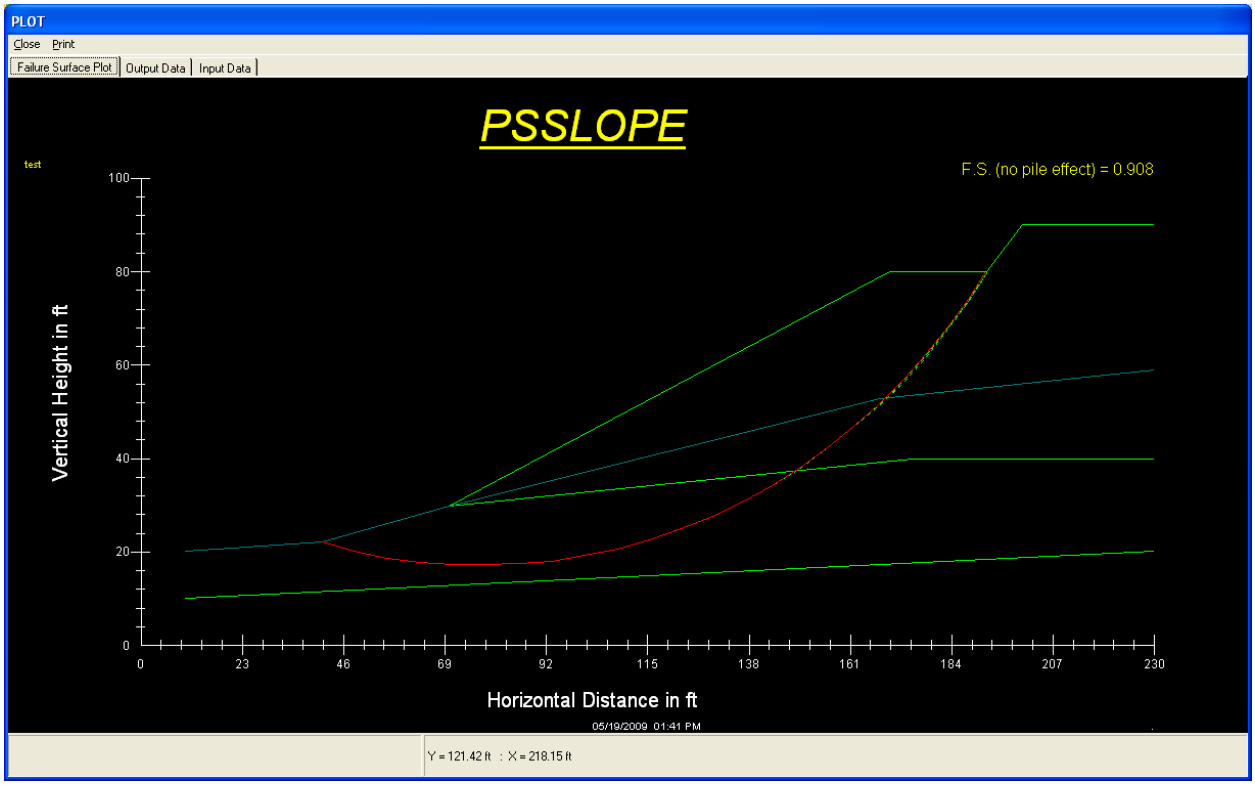


Figure 36: Slope Stability Analysis Graph

Adjust each item one at a time and check the graph, until proficiency is gained at predicting the desired results.

12. The inputs in Figure 37 will give the desired results of a F.S. of 1.0, rounded. Enter the inputs from the table below if a F.S. has not been achieved or the user

inputs differ greatly from those listed in the table. Having similar inputs will be important to obtaining similar pile size for the rest of the exercise.

Soil Strength Properties							
Soil #	Soil Type	Unit Weight	Saturated Unit Weight	Cohesion Intercept Disturbed	Friction Angle Residual	Cohesion Intercept Undisturbed	Friction Angle Peak
1	C-Phi	126	128	0	24	50	31
2	C-Phi	124	126	0	28	100	28
3	Rock	145	145	10000	36	10000	36

Figure 37: Inputs that Produce 1.0 Factor of Safety in Example Problem.

The output graph should look similar to the graph in Figure 38.

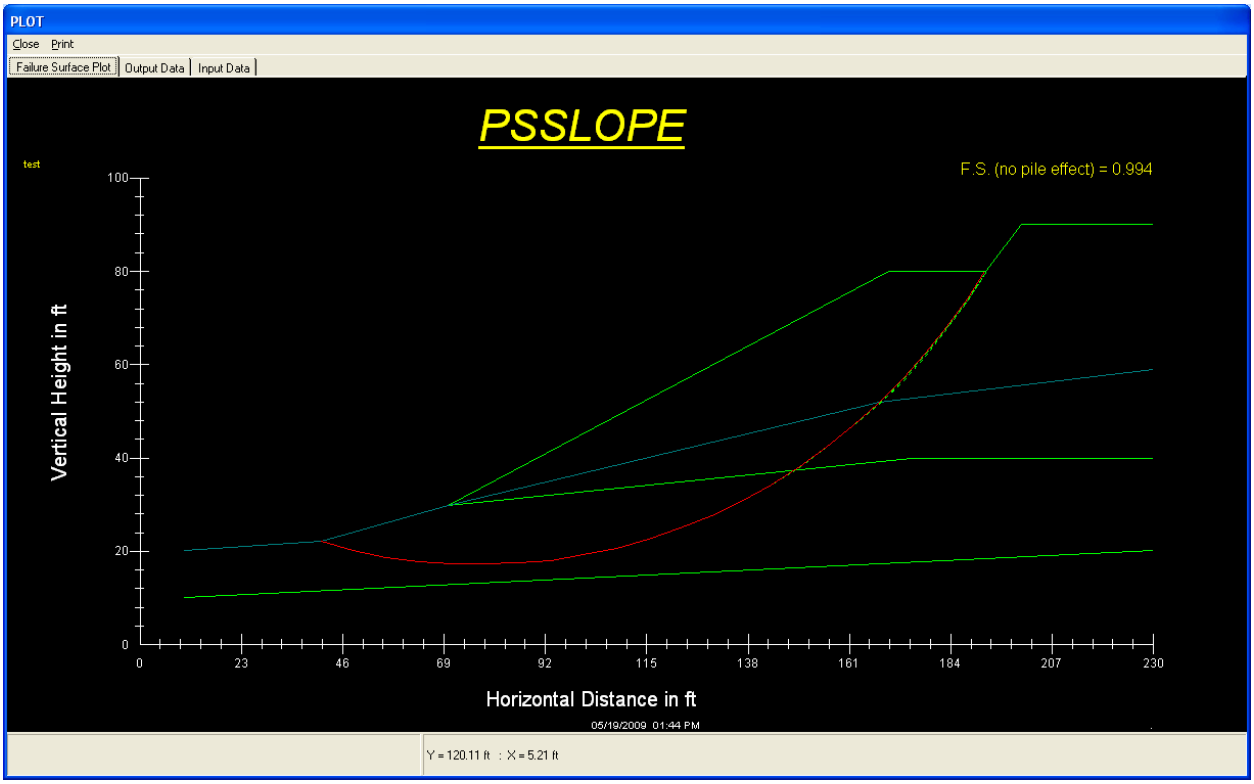


Figure 38: Stability Analysis Graph

13. Once the soil parameters have been adjusted to produce a factor of safety of 1.0 (rounded). Input the soil boundary coordinates (Figure 39) to model the pile wall correction: do not make adjustments to the disturbed soil strength parameters at this time. It is important to remember that the pile wall head needs to be battered slightly, for modeling purpose only. Only the cells highlighted in yellow have been changed. This adjustment will raise the soil boundary up, causing the slip surface to terminate below the surface. Adjust the slip surface to account for the extra soil (Figure 39).

SOIL SURFACE COORDINATES					
Total Number of Boundaries = **9**			Total of Top Boundaries = **6**		
Boundary	**X-Left**	**Y-Left**	**X-Right**	**Y-Right**	**Soil Num**
1	10	20	41	22	1
2	41	22	70	30	1
3	70	30	170	80	1
4	170	80	181.5	80	1
5	181.5	80	182	90	1
6	182	90	230	90	1
7	70	30	175	40	2
8	175	40	230	40	2
9	10	10	230	20	3
Slip Surface Adjustment		Point 3	X= 200		Y=90

Figure 39: Soil Surface Coordinates for pile wall correction

14. Run the stability analysis for the slope and view the graph (Figure 40) for any errors. Ignore the factor of safety.

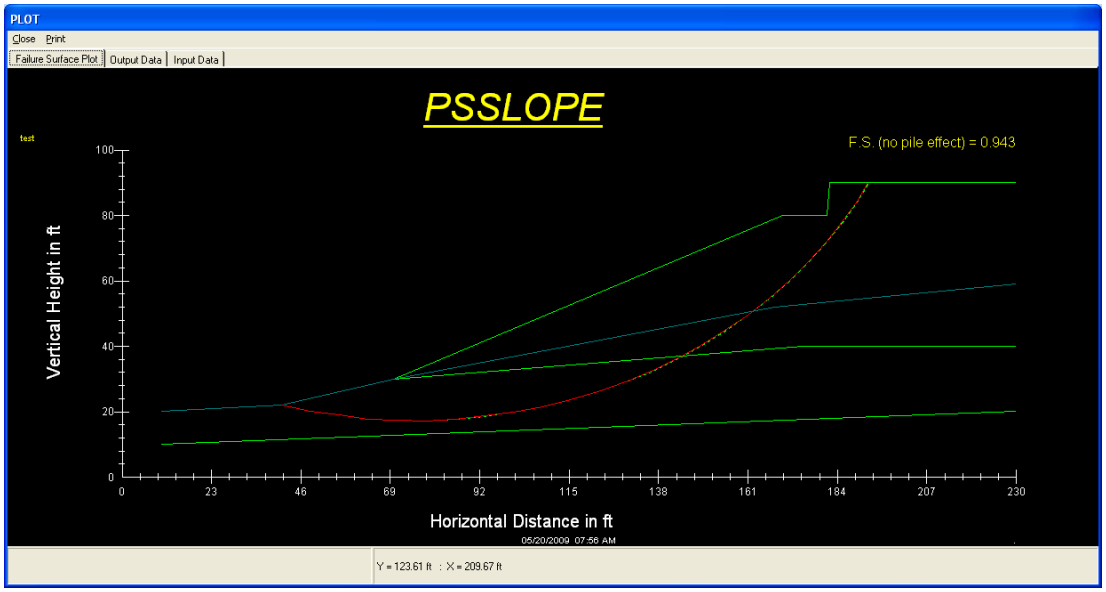


Figure 40: Slope Stability Graph

15. Input the undisturbed soil strength parameters from Figure 37, if not already accomplished.

16. Input the Pile analysis information from Figure 41 and run the "Stability with Pile". It is a good practice to size the pile larger than the anticipated size. However for demonstration purpose the initial input will be smaller than the

required size. The initial analysis should be done with the "Desired FS of the Supported Portion of the Slope" set to 1.0.

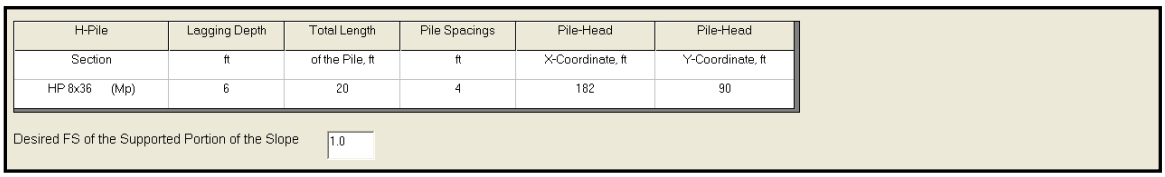


Figure 41: Pile Inputs

17. Because the selected pile was too short, the program generated the following warning, Figure 42

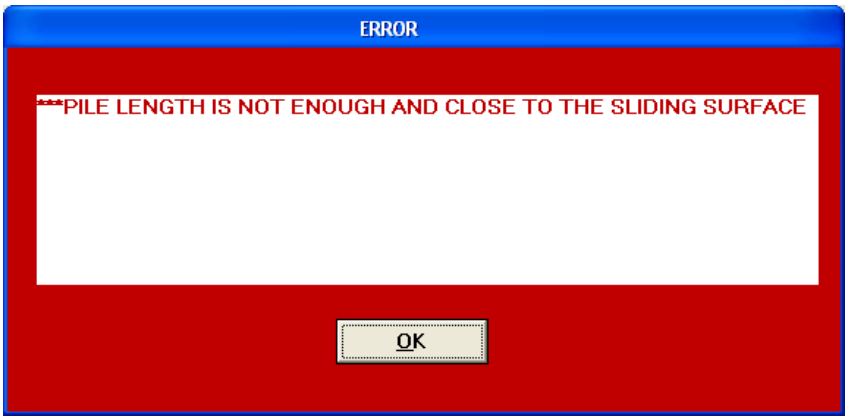


Figure 42 Pile Length Error Box

Check ok: The program will generate another error message, "Check data for zero value" (Figure 43). Click the ok button; this is normal because the short pile length caused a division by zero error.

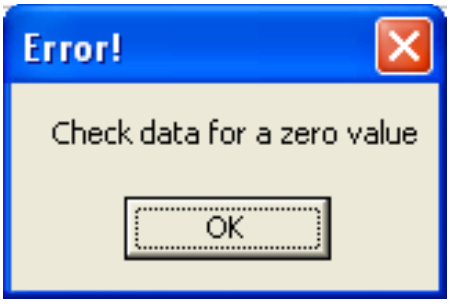


Figure 43: Error Message

18. Adjust the pile length to 30-ft, and run the slope stability and slope with piles programs again. The "Pile Performance Ratio" and "FS of the Unsupported Portion of Slope" is now displayed to the left of the input table. Check the stability graph and note the pile wall is now present on the graph, but was not used in the calculations of the slope stability.

19. Close the graph and view the pile response, deflection graph, Figure 44.

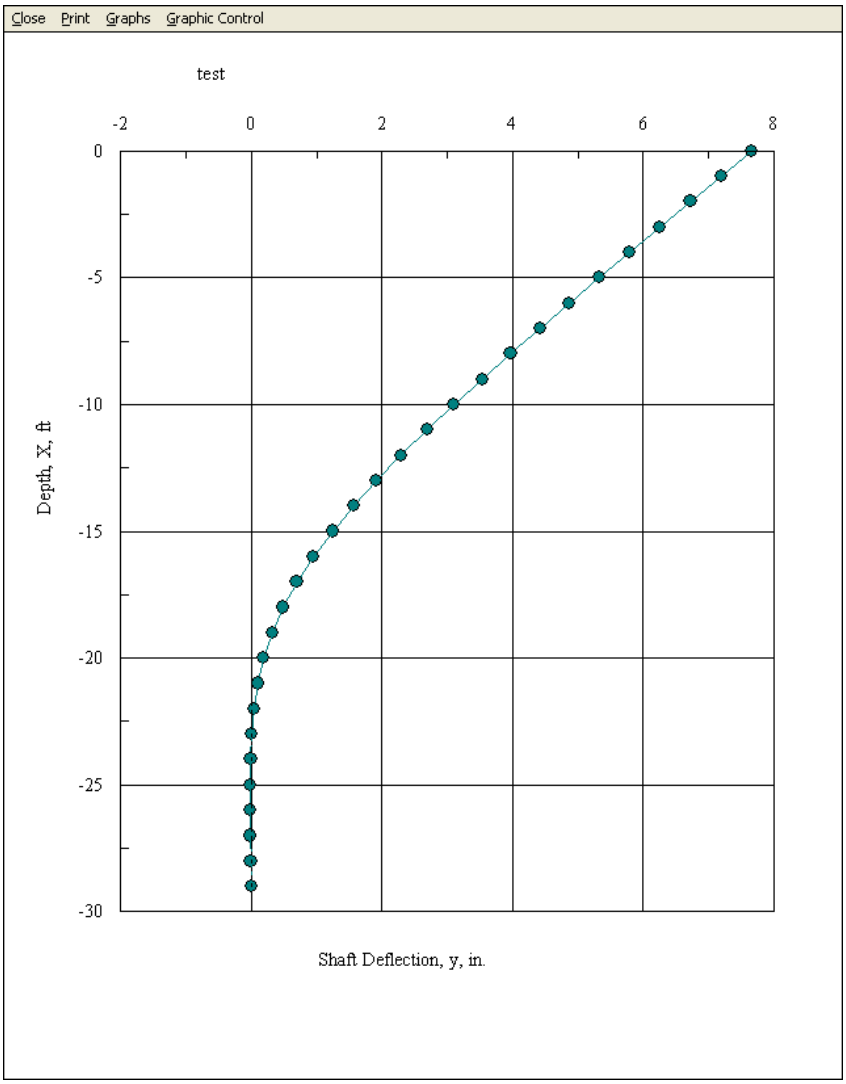


Figure 44: Graph of Pile Deflection

20. The pile has two points on the zero line (nodes); this indicates under these conditions the pile has fixity and the length is long enough. The deflection is almost 8 inches; this is excessive for a FS of 1.0.

    a. The desired deflection is less than 4 inches for rural roads and less than 2 inches for major roads.
    b. The pile size needs to be increased.
    c. For a major road, and this amount of deflection, the pile size should be increased to approximately HP 12X63, however, for demonstration purposes, increase the pile size to HP 10X42 and run both analyses.

21. The deflection is slightly greater than 4 inches. Increase the pile size to HP 10X57 and run the analyses again.

a. The deflection is less than 4 inches.
b. The performance ratio is 33%.

22. Increase the FS to 1.3 and run the program.
    a. The pile performance is 55%.
    b. The pile deflection is not critical at a FS of 1.3; however the pile does not have two points of fixity, indicating the pile length is too short.

23. Increase the pile length to 35 feet and check the fixity at a FS of 1.3, and the deflection at a FS of 1.0.
    a. The deflection is less than 4.0 inches.
    b. The pile has two nodes.
    c. If this were a major road the deflection limit may be limited to less than 2 inches.
    d. This would require an increase in pile size.

24. Increase the pile size to HP 12X63 and check the response at a FS of 1.0 and 1.3.
    a. Deflection is less than 2 inch
    b. The pile has two nodes
    c. The pile performance is 44%

25. The "FS of the Unsupported Portion of Slope" is less than 1.0. It is anticipated the slope below the pile will continue to move. So place the lagging deep enough to count for the loss of material. If structure and/or road are below the slip, then the unsupported portion of the slope may need to be addressed.

F. Error and Warning Messages

1. General input error (Figure 45): This could be caused by several reasons
    a. Soil strength parameter missing: C=-Phi requires both cohesion and a friction angle. However the program will accept a Zero for cohesion, but not friction angle.
    b. Other inputs could cause this problem if a zero is placed in the cell.

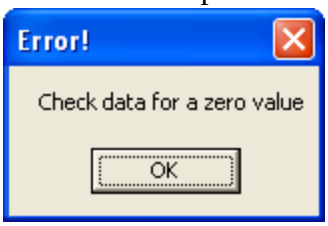


Figure 45: General input error

2. Boundary Input Warning (Figure 46): This box is generated for a couple of errors.
    a. A coordinate in a surface boundary does not correspond to a previously entered coordinate, OR.
    b. Total number of boundaries and top boundaries do not match the input of boundary data: The number of top boundaries is too great.

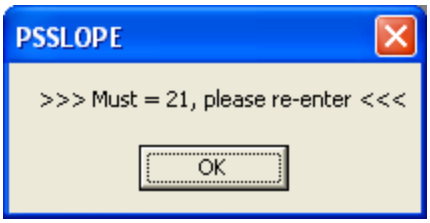


Figure 46: Input Warning

3. Top Boundary Warning (Figure 47): This message is self explanatory.

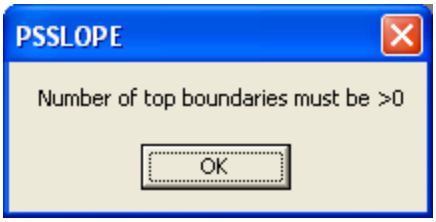


Figure 47: Top Boundary Warning

4. Water Surface Points Warning (Figure 48):
    a. The number points listed exceed the number of points entered or

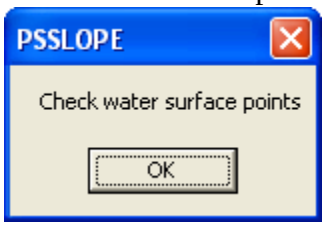


Figure 48: Water Surface Points Warning

5. Failure Surface Point Coordinates Warning (Figure 49):
    a. This error can difficult at times to locate
    b. Recheck all three points against CAD file.
    c. Common errors include, but not limited to
        i. Intersecting surface boundary more than twice
        ii. Not crossing surface boundary twice.



Figure 49: Slip Surface Coordinates Error

6. Number of Top Boundaries (Figure 50): This message is self explanatory.
    a. The number of boundaries on the top surface exceeds the total number of boundaries
    b. Check the number of total boundaries and
    c. Check the number of top boundaries.

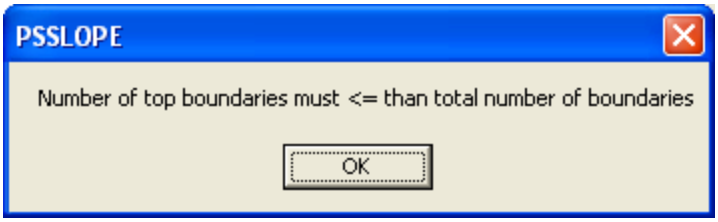


Figure 50: Number of Boundaries Warning

7. Surface Boundary Error (Figure 51): This message can occur for a couple of reasons.
    a. The right coordinate exceed the left coordinate.
    b. The "Total number of boundaries" exceeds the actual coordinates.
    c. The program is expecting coordinates on the last line.



Figure 51: Surface Boundary Error

8. General Stability Program Run Failure (Figure 52): This message can appear for a couple of reasons:
    a. Failure surface does not intersect the surface at two points or intersect in more than two points.
    b. A Negative number exist in the data.
        i. Negative numbers are not allowed



Figure 52: Stability Analysis Program Failure to Run

9. Lagging Depth Warning (Figure 53): This message is self explanatory.
    a. Lagging is set to deep, extends to or beyond the failure surface.



Figure 53: Lagging Depth Warning

10. Pile Spacing Error (Figure 54): This message is self explanatory.
    a. Enter a value for pile spacing (whole number).

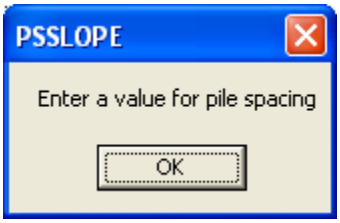


Figure 54: Pile Spacing Value Error

11. Concave Failure Surface Warning (Figure 55): This message is self explanatory.
    a. Check all three points for error
        i. Error is most likely is with the middle point.



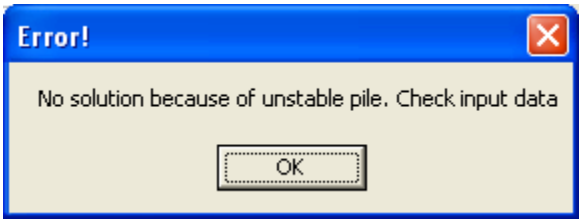
Figure 55: Concave Failure Surface

12. Slope Stability Warning (Figure 56): This message is self explanatory.
    a. The pile location needs to be moved, or
    b. The soil strength parameters need to be adjusted, or
    c. Water surface needs to be adjusted, or
    d. All of the above.



Figure 56: Stable Slope

13. No Solution
    a. Sdfg



14. Run Time Error (Figure 57): General input error.
    a. Run-time error "Number", are specific input and programming errors.
    b. They can occur from a large list of problems.
        i. Input error not anticipated in the programming or
        ii. Programming errors.
        iii. Program crash or error in loading (typical computer headache)
    c. They are difficult to diagnose
    d. Close program, restart program and rerun file.
        i. Sometimes a reboot of the computer is required.
    e. Check all input data
    f. Start another file and reenter the data
        i. The file may have become corrupted.
    g. Contact Head Office
    h. Write down the error and send email to Head Office.

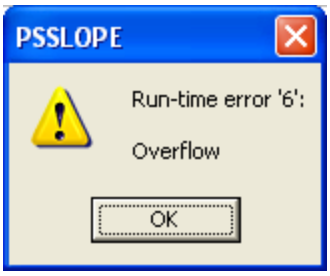


Figure 57: Run-time error

15. Pile to Soil Interaction Error (Figure 58): Soil strength is too low to accommodate the forces applied by the pile wall. The soil is yielding and flowing around the pile.
    a. Check soil parameters and adjust as necessary OR
    b. Adjust pile spacing to allow the soil wedge to interact with piles.

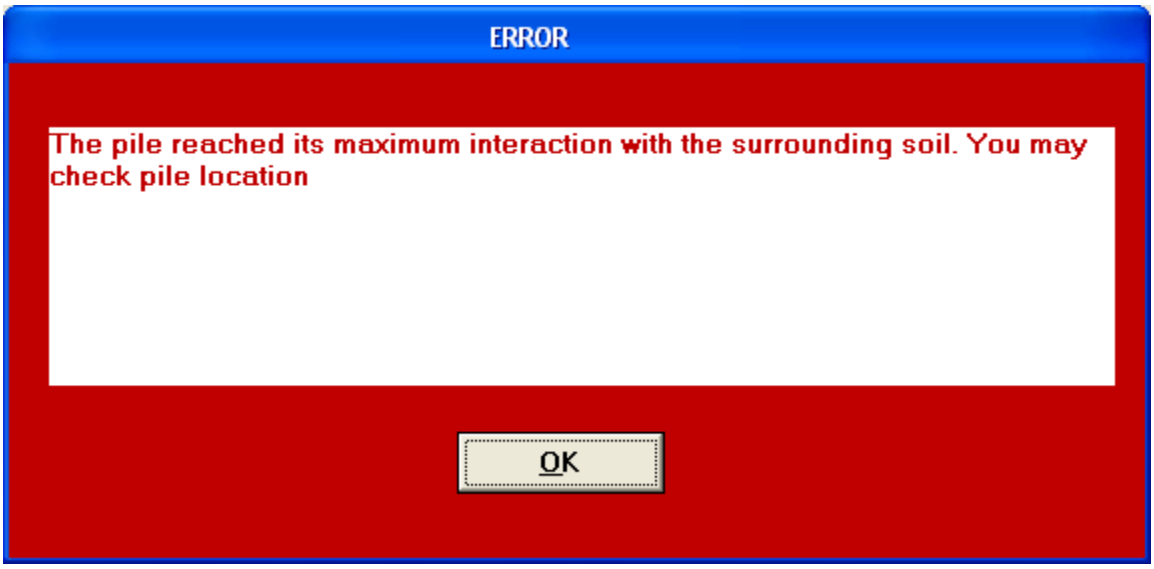


Figure 58: Pile to Soil Interaction

16. Pile Length Error (Figure 59): Tip of pile is not fixed in the soil below.
    a. Check pile length or
    b. Check failure surface.

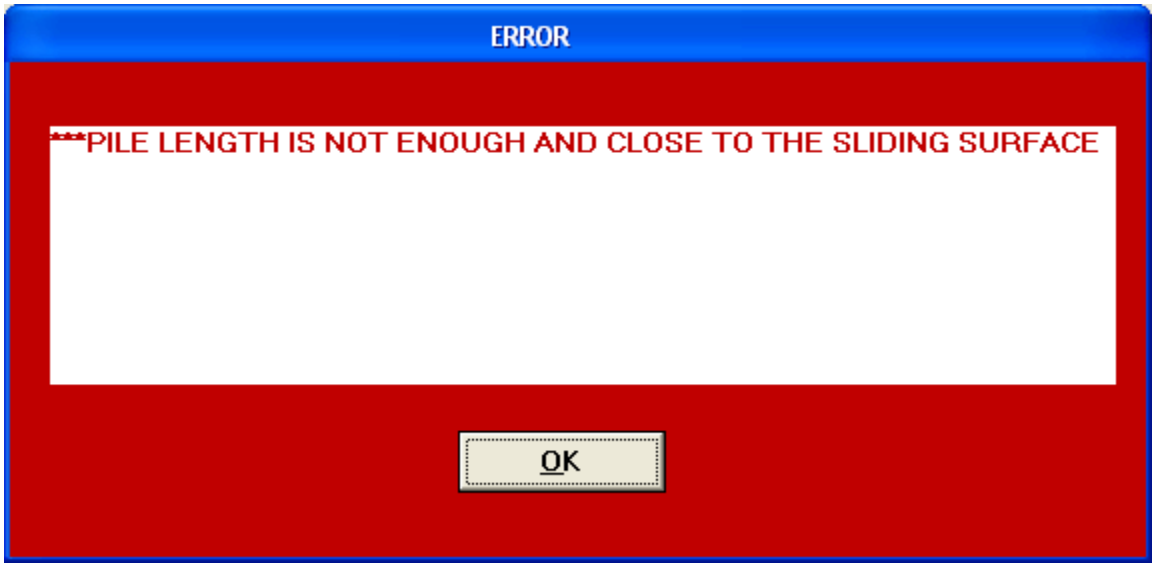


Figure 59: Pile Length

17. Pile Failure (Figure 60): The pile has failed due to excessive forces for the selected pile size.
    a. Select a larger pile size OR
    b. Reduce pile spacing OR
    c. Recheck stability analysis and failure surface for errors.

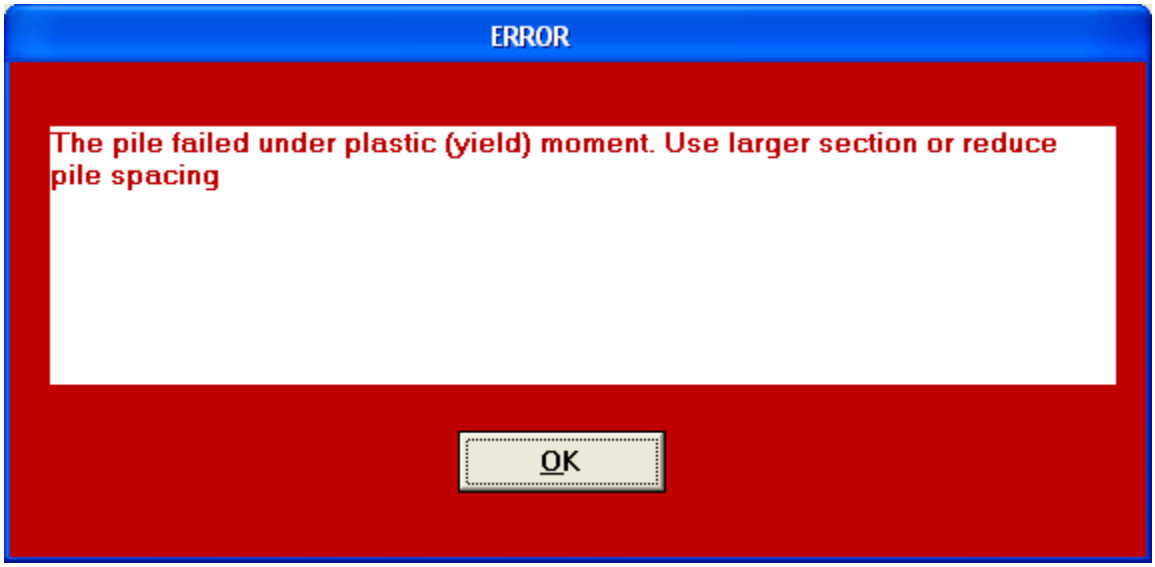


Figure 60: Pile Failure