An Example of Using ReSSA in Complex Geometry of Reinforced Tiered Slope

By

Dov Leshchinsky

Introduction

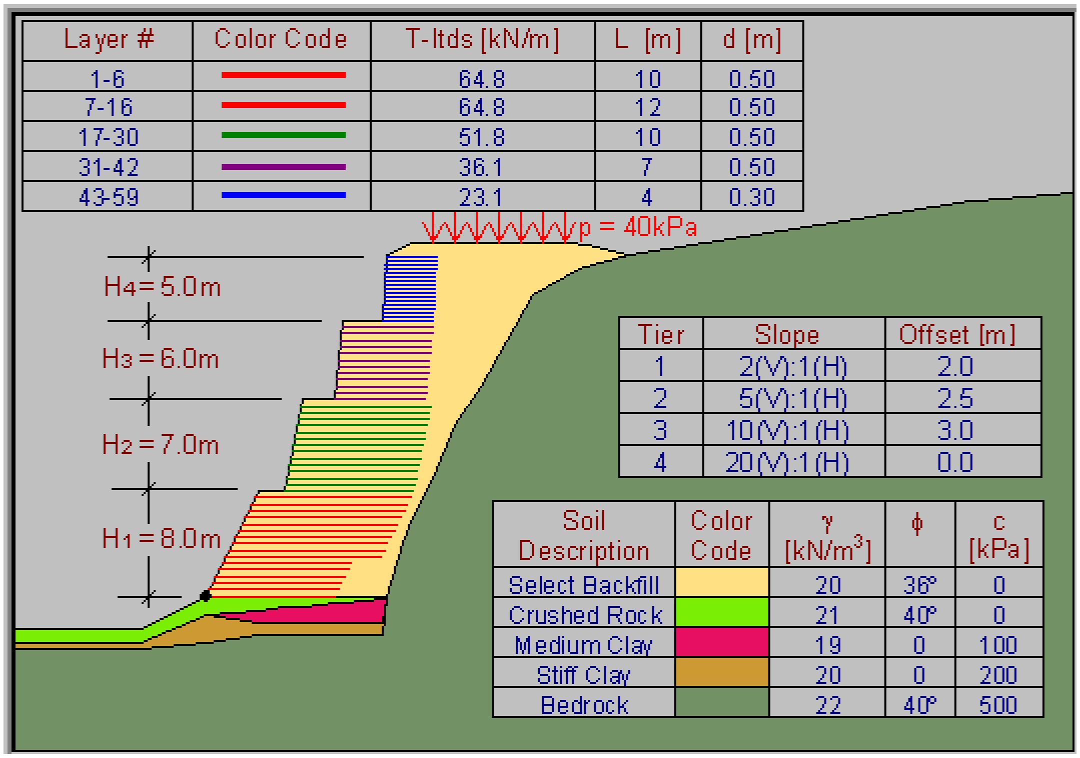
Geosynthetic reinforced soil structures in the last three decades have demonstrated safe performance while being economical. As the old saying goes, "with the food comes the appetite." That is, these reinforced structures are attractive and designers are tempted to use them in complex applications such as multi-tiered steep slopes and walls. These applications are driven by the fact that current design methods for the alternative single-tiered structure require geosynthetics with high long-term strength rendering uneconomical or unfeasible this alternative reinforced wall/slope. Multi-tiered structures alleviate the required high strength of reinforcement thus enabling the construction of reinforced slopes that are very high. In fact, multi-tiered reinforced earth slopes are aesthetically appealing structures. The purpose of this article is to show that pushing the design envelope can be done in a straightforward manner, extending conventional geotechnical principles and using suitable software to overcome involved and tedious computational processes.

Background

ReSSA uses two methods of stability analysis. The first is Bishop Method (Bishop, 1955), which is applicable to circular slip surfaces. Although this method does not strictly satisfy equilibrium, its results are surprisingly close to more sophisticated stability methods. Generally, circular failure mechanism is reasonable when the strength of soil strata changes gradually (e.g., may not be applicable when granular soil is underlain by soft clay in which case translational mechanism may prevail). The second method used in ReSSA is Spencer Method (Spencer, 1967). This method is considered rigorous since it explicitly satisfies equilibrium. The mechanism used in conjunction with Spencer's is two- and three-part wedge. The two-part wedge is utilized to assess the potential for direct sliding along each reinforcement layer. This analysis does not assume that the reinforced soil is a coherent mass but, rather, it considers the effects of reinforcement layers intersecting with the sliding surface. The designer can investigate potential failures by invoking three-part wedge mechanism, which can be degenerated to one- and two-part wedges as well. Consequently, the designer can investigate the adequacy of geosynthetic, layout and strength, to resist rotational failure through and away from the reinforcement, to analyze the potential for direct sliding along each layer (considering the resistance effects of other layers), and to assess translational mechanisms through and away from the reinforcement.

ReSSA allows the user to input soil strata containing up to 25 different soils, use of tension crack, varieties of surcharge loads, seismicity, and water pressure. Water pressure can be introduced via a phreatic surface or by using twenty lines each representing a different piezometric head. Invoking water pressure enables the designer to conduct effective stress analysis or mixed type of analysis; total stress ignores porewater pressures. Mixed analysis means that in predetermined layers of soil, the shear strength of soil will be calculated based on effective stresses (i.e., using drained shear strength parameters) while in others it will use strength based on total stress (i.e., undrained shear strength parameters). Mixed analysis can be useful in many cases where reinforcement is used; e.g., reinforced slope comprised of granular, free-draining soil over saturated clay in which case the clayey foundation will likely exhibit an undrained behavior at failure while the granular backfill will practically exhibit drained strength. As a result, ReSSA is capable of assessing the required reinforcement strength and layout, including pullout resistance, under effective or total stress conditions thus enabling the assessment of waterfront structures.

In computing the available strength along each geosynthetic layer, ReSSA considers pullout resistance at the reinforcement rear-end implementing user-prescribed factor of safety. However, in a sense, mechanism similar to pullout can occur also in the front-end of each layer. In this case, the soil may slide outwards relative to the anchored reinforcement. The geosynthetic strength feasible at its ‘front-end’ depends on the ‘connection’ strength at the face of the slope. To calculate the geosynthetic strength at points away from the slope face, the resistance developing along the soil-reinforcement interface is added to the connection strength, not to exceed the long-term allowable strength of the reinforcement. The user needs to specify the connection strength; for reinforcement that terminates at the face of the slope it would be zero, for wrap-around with sufficiently long re-embedment it would be the strength of the reinforcement, and for attached facia (e.g., blocks or gabions) it would be the actual connection strength. ReSSA calculates the strength distribution along each layer based on the given interaction parameters, connection strength, overburden pressure and specified pullout resistance factor of safety. In stability calculations ReSSA uses the strength value at the intersection with each analyzed slip surface, be it rotational or translational (two- or three-part wedge).



Layer #	Color Code	T-ltds [kN/m]	L [m]	d [m]
1-6	🟥	64.8	10	0.50
7-16	🟥	64.8	12	0.50
17-30	🟩	51.8	10	0.50
31-42	🟪	36.1	7	0.50
43-59	🟦	23.1	4	0.30

Tier	Slope	Offset [m]
1	2(V):1(H)	2.0
2	5(V):1(H)	2.5
3	10(V):1(H)	3.0
4	20(V):1(H)	0.0

Soil Description	Color Code	γ [kN/m^3]	ϕ	c [kPa]
Select Backfill	🟨	20	36°	0
Crushed Rock	🟩	21	40°	0
Medium Clay	🟥	19	0	100
Stiff Clay	🟫	20	0	200
Bedrock	🟩	22	40°	500

Figure 1. Details of example problem

Example Problem

The usefulness of a computer program is best demonstrated through an instructive example problem. Refer to Figure 1 for the details of the problem to be analyzed. As shown, the tiered slope next to existing bedrock needs to be designed. There are four tiers, starting with high but not as steep slope [H_1 = 8.0 m at 2(V):1(H)] and ending with essentially a wall [H_4=5.0 m at 20(V):1(H)]. The natural foundation is comprised of stiff clay topped with a seam of medium clay. The design calls for placement of an unreinforced crushed rock (generally, 1 m thick) as a base material which is also used for grading to create a sloping toe at 1(V):2(H), 2.5 m high. Four types of geosynthetics are specified at different lengths and spacing. A nominal surcharge load of 40 kPa is applied at the crest as shown.

The complexity of this example problem is twofold. The first difficulty is associated with assessing the internal and compound stability of multi-tiered reinforced slopes over a seam of medium clay. The second difficulty has to do with the thrust of the unreinforced soil, which is limited due to the proximity of the bedrock to the reinforcement. Such difficulties are occasionally encountered in reality where conventional designs are used though they are grossly oversimplified.

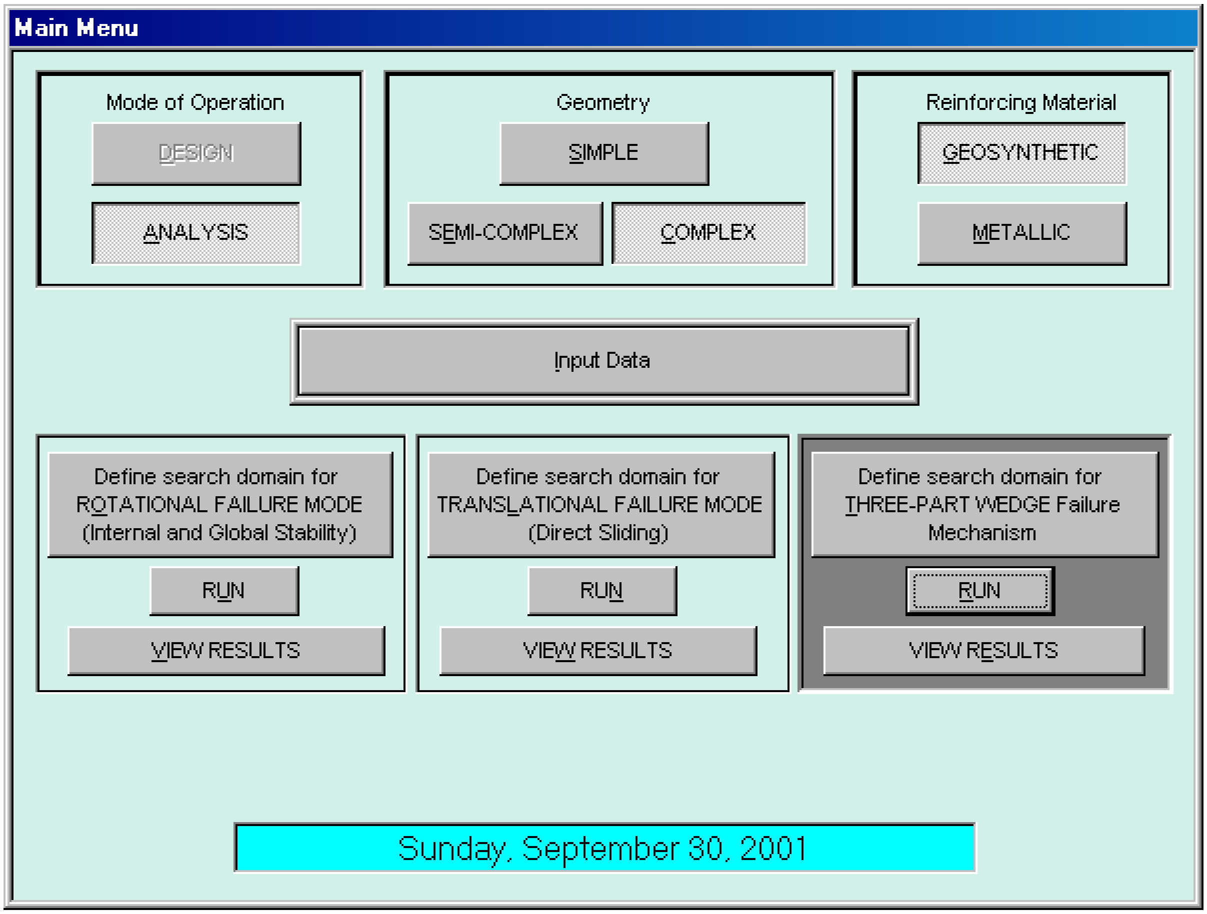


Figure 2. Main Menu in ReSSA (2.0)

Once ReSSA is activated, the Main Menu shown in Figure 2 appears. Note that it includes an option for inputting data for ‘Semi-Complex’ slopes. Semi-Complex structures in the context of ReSSA means up to 10 tiered slopes limited to three different types of soil. Input data is quick and simple. If a more complex problem is considered (e.g., Figure 1 which includes 5 different soils, each with its own irregular profile), one can use the Semi-Complex option to define the geometry of the tiered slopes and then switch to Complex geometry in Main Menu. Upon switching, ReSSA preserves all input data. The geometry format of Semi-Complex is translated to Complex (Figure 4) thus facilitating the input data process.

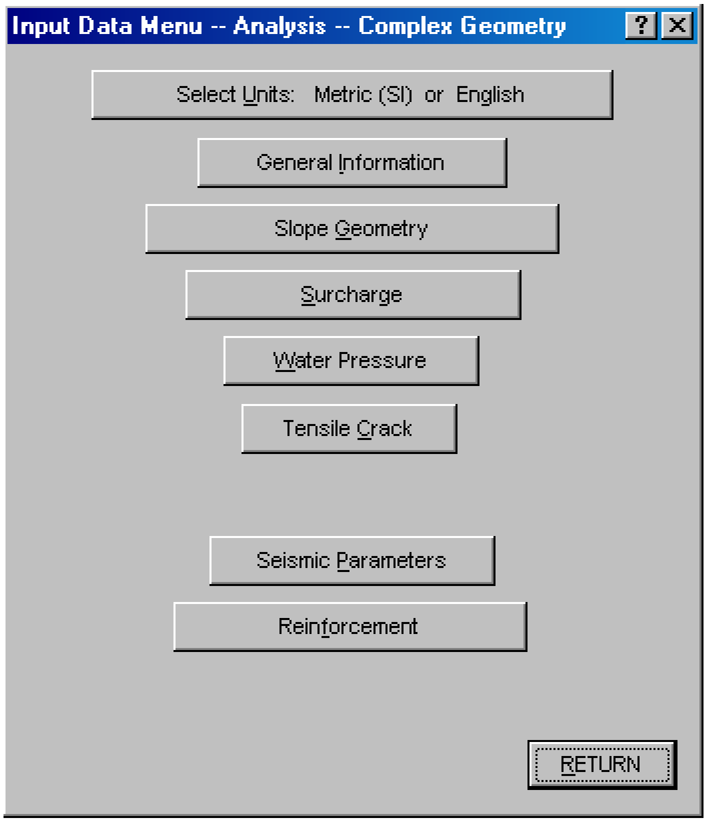
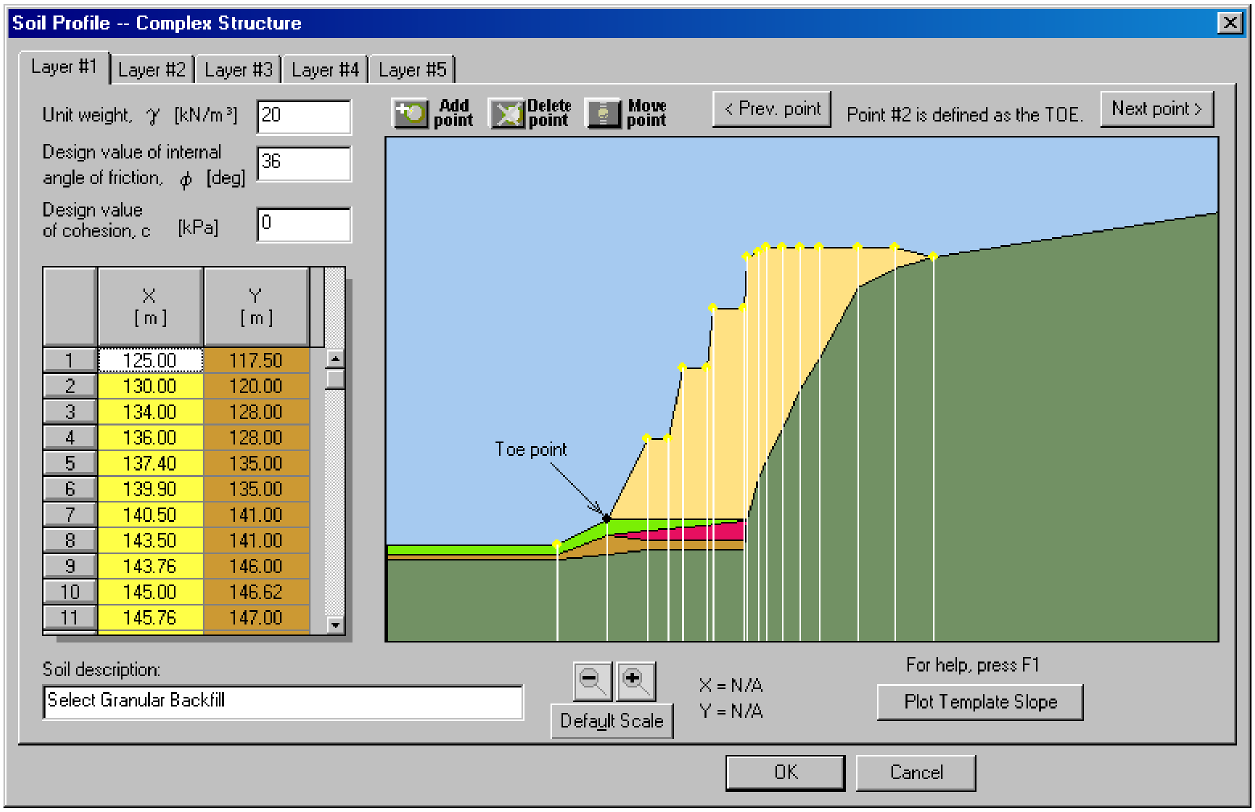


Figure 3. Input Data Menu

After clicking on Input Data in Main Menu, the Input Data Menu appears (Figure 3). This menu enables a convenient access to input data, one category at a time.



Unit weight, γ [kN/m³] 20

Design value of internal angle of friction, ϕ [deg] 36

Design value of cohesion, c [kPa] 0

Point #2 is defined as the TOE.

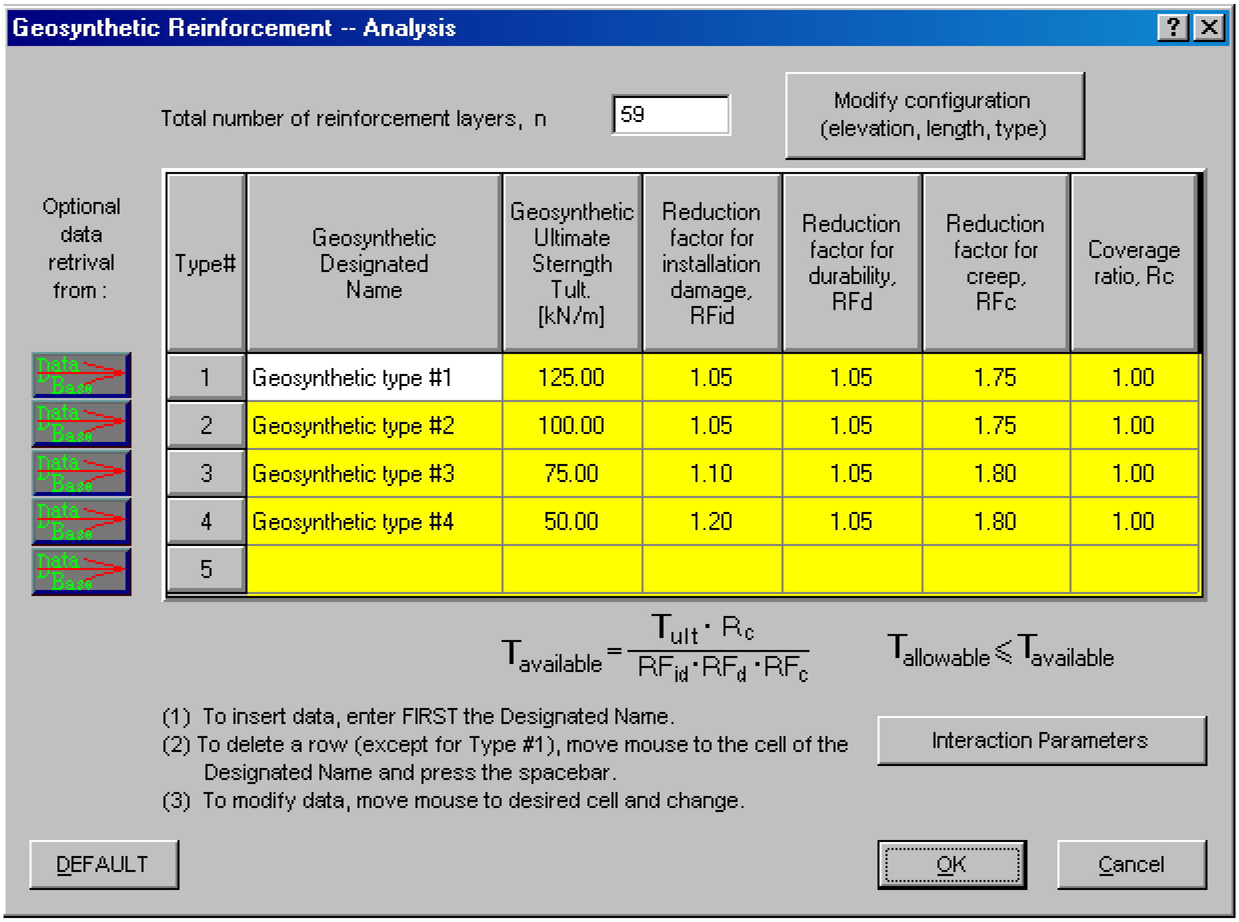
	X [m]	Y [m]
1	125.00	117.50
2	130.00	120.00
3	134.00	128.00
4	136.00	128.00
5	137.40	135.00
6	139.90	135.00
7	140.50	141.00
8	143.50	141.00
9	143.76	146.00
10	145.00	146.62
11	145.76	147.00

Soil description: Select Granular Backfill

X = N/A
Y = N/A

Figure 4. Dialog for entering the profile and properties of soils

Clicking on Slope Geometry access the dialogs for inputting the profile and properties of soils (Figure 4). Using first the Semi-Complex Geometry option generated most of the data in this dialog. The soil profile is described using vertical sections (up to 100). The coordinates of each layer intersecting each section can be input directly into the table (spreadsheet-like) or, for young engineers who are not familiar with the pre-PC era, by using mouse functions.



Total number of reinforcement layers, n: 59

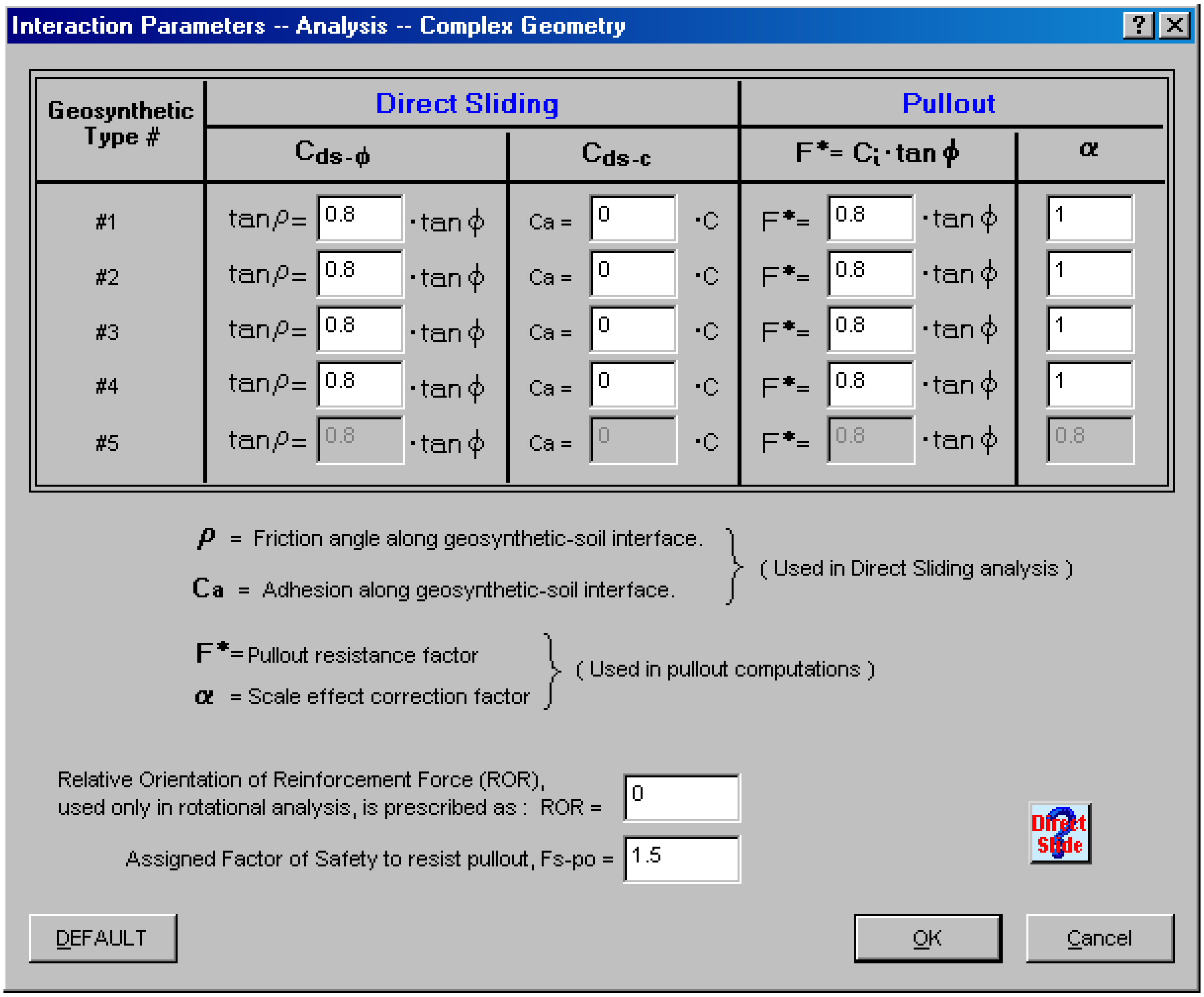
Type#	Geosynthetic Designated Name	Geosynthetic Ultimate Stength Tult. [kN/m]	Reduction factor for installation damage, RFid	Reduction factor for durability, RFd	Reduction factor for creep, RFc	Coverage ratio, Rc
1	Geosynthetic type #1	125.00	1.05	1.05	1.75	1.00
2	Geosynthetic type #2	100.00	1.05	1.05	1.75	1.00
3	Geosynthetic type #3	75.00	1.10	1.05	1.80	1.00
4	Geosynthetic type #4	50.00	1.20	1.05	1.80	1.00
5						

$$T_{available} = \frac{T_{ult} \cdot R_c}{RF_{id} \cdot RF_d \cdot RF_c} \qquad T_{allowable} \leqslant T_{available}$$

(1) To insert data, enter FIRST the Designated Name.
(2) To delete a row (except for Type #1), move mouse to the cell of the Designated Name and press the spacebar.
(3) To modify data, move mouse to desired cell and change.

Figure 5. Dialog for defining the geosynthetics strength properties

The dialog for entering the geosynthetic strength properties is depicted in Figure 5. In fact, ReSSA enables the user to select No Reinforcement (unreinforced slope stability analysis), Single Type of Reinforcement (quick input data including spacing and length), and Multiple Types of Reinforcement (which is the most versatile and is the option selected for the example problem). Note that up to five different geosynthetics can be considered in a problem. The designer specifies the ultimate strength, the reduction factors for installation damage, durability and creep, and the coverage ratio (less than one means use of non-continuous reinforcement). Alternatively, the data can be retrieved from a database, which may contain up to 100 different materials.



Geosynthetic Type #	Direct Sliding		Pullout	
	$C_{ds\text{-}\phi}$	$C_{ds\text{-}c}$	$F^* = C_i \cdot \tan\phi$	α
#1	$\tan\rho =$ 0.8 $\cdot\tan\phi$	Ca = 0 ·C	F*= 0.8 $\cdot\tan\phi$	1
#2	$\tan\rho =$ 0.8 $\cdot\tan\phi$	Ca = 0 ·C	F*= 0.8 $\cdot\tan\phi$	1
#3	$\tan\rho =$ 0.8 $\cdot\tan\phi$	Ca = 0 ·C	F*= 0.8 $\cdot\tan\phi$	1
#4	$\tan\rho =$ 0.8 $\cdot\tan\phi$	Ca = 0 ·C	F*= 0.8 $\cdot\tan\phi$	1
#5	$\tan\rho =$ 0.8 $\cdot\tan\phi$	Ca = 0 ·C	F*= 0.8 $\cdot\tan\phi$	0.8

ρ = Friction angle along geosynthetic-soil interface.
Ca = Adhesion along geosynthetic-soil interface.
(Used in Direct Sliding analysis)

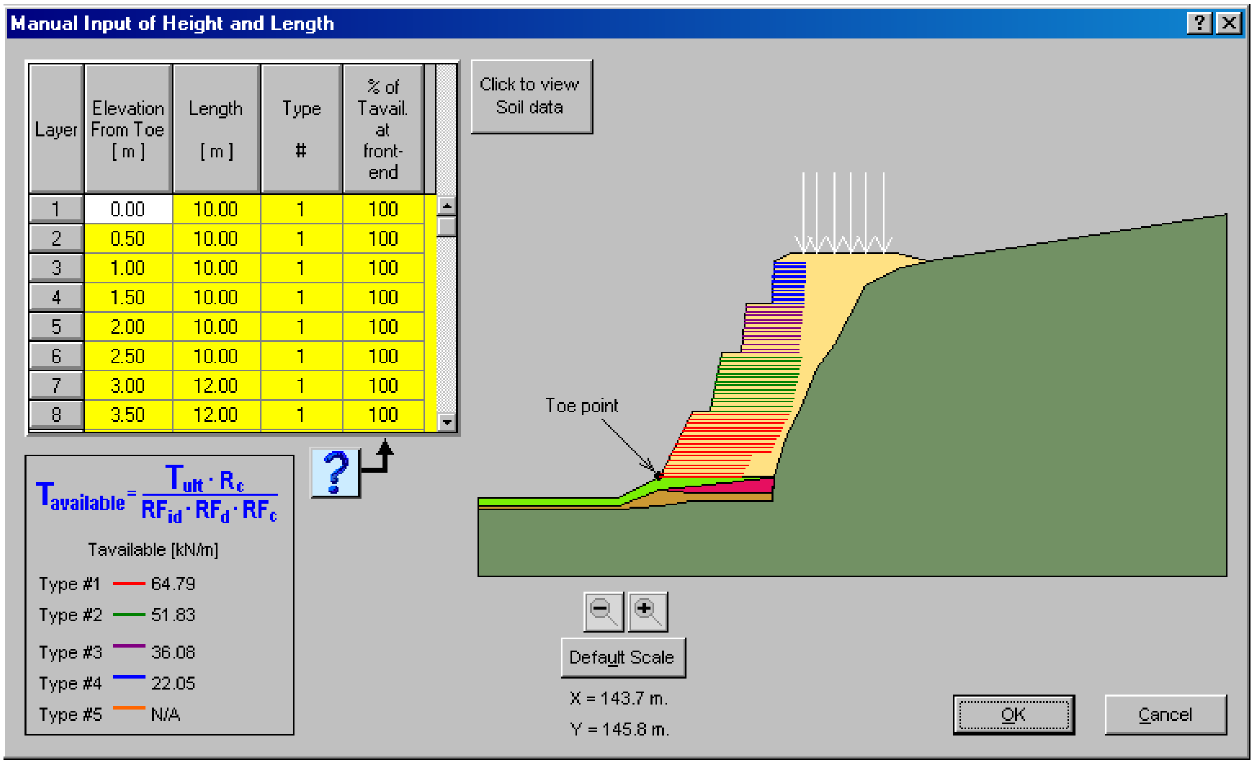
F*= Pullout resistance factor
α = Scale effect correction factor
(Used in pullout computations)

Relative Orientation of Reinforcement Force (ROR), used only in rotational analysis, is prescribed as : ROR = 0

Assigned Factor of Safety to resist pullout, Fs-po = 1.5

Figure 6. Input of Interaction Parameters

Clicking on the Interaction Parameters button opens the dialog shown in Figure 6. The parameters controlling the interfacial shear strength of each type of reinforcement are defined in this dialog. These parameters control the resistance to direct sliding as well as pullout. Furthermore, the factor of safety used for calculating pullout resistance needs to be input here; it affects the anchorage length needed to enable the reinforcement to develop its available strength at both its front- and rear-end.



Layer	Elevation From Toe [m]	Length [m]	Type #	% of Tavail. at front-end
1	0.00	10.00	1	100
2	0.50	10.00	1	100
3	1.00	10.00	1	100
4	1.50	10.00	1	100
5	2.00	10.00	1	100
6	2.50	10.00	1	100
7	3.00	12.00	1	100
8	3.50	12.00	1	100

$$T_{available} = \frac{T_{ult} \cdot R_c}{RF_{id} \cdot RF_d \cdot RF_c}$$

Tavailable [kN/m]

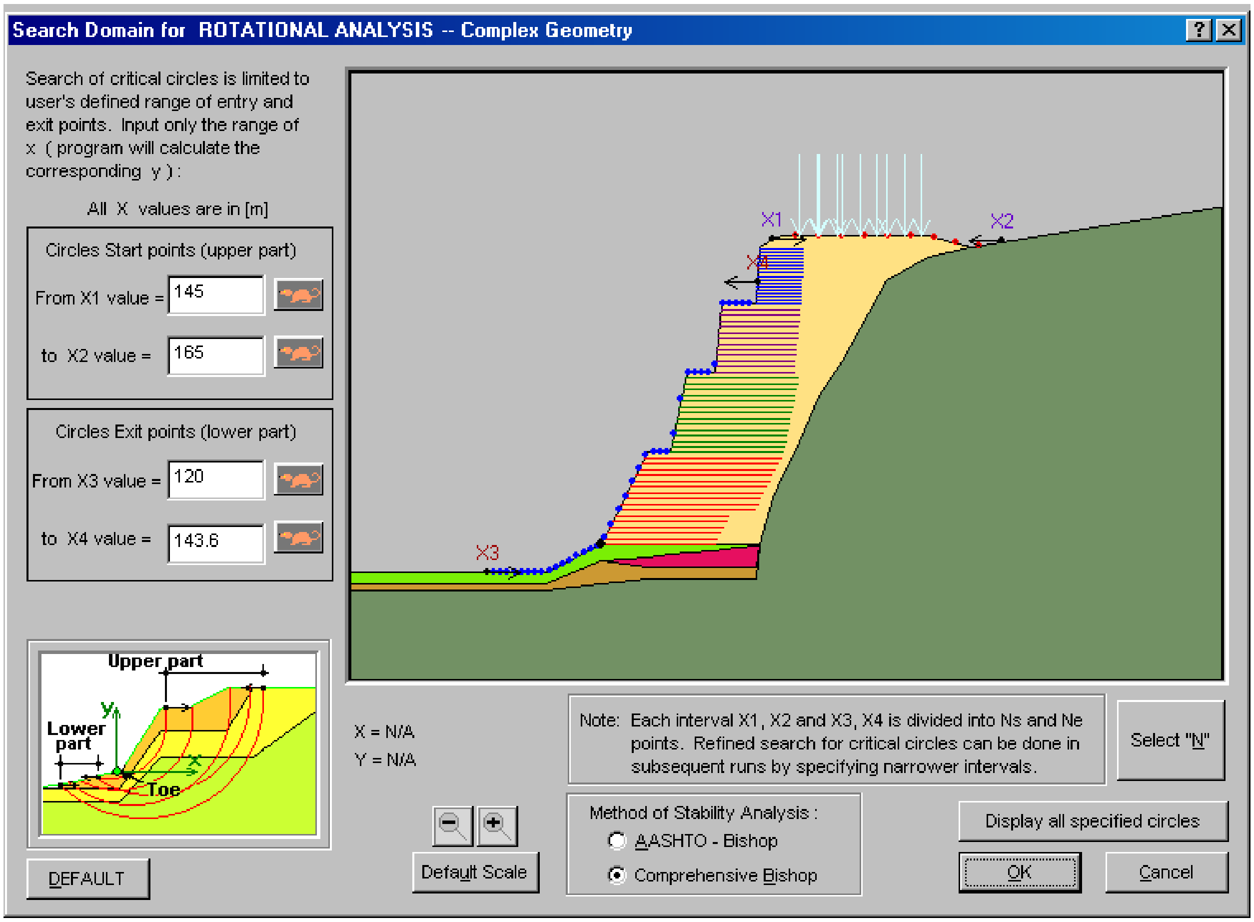
	Tavailable [kN/m]
Type #1	64.79
Type #2	51.83
Type #3	36.08
Type #4	22.05
Type #5	N/A

X = 143.7 m.
Y = 145.8 m.

Figure 7. Assigning reinforcement details to each geosynthetic layer

Returning to Figure 5 and then clicking on the button to Modify Configuration invokes the dialog shown in Figure 7. Using the spreadsheet-like table on the left, the designer can input the elevation, length, and type of each geosynthetic layer. The figure on the right adjusts automatically to the data. Note that the designer can also control the 'connection' strength of each geosynthetic layer as a percentage of its available strength; for the present problem it is assumed to be 100% for all layers.

Upon returning to the Main Menu, the designer is ready to conduct the various stability analyses. In principle, slope stability analysis is an optimization process in which the lowest factor of safety and its associated (critical) slip surface are sought. This means that a large number of slip surfaces have to be analyzed. There are automatic routines for conducting such a search; however, reinforced slopes may contain several minima of safety factors thus raising the concern that the genuine minimum may not necessarily be captured but rather a local minimum stopped the search. ReSSA allows the user to specify a search domain that controls the examined surfaces in a tangible fashion. It also allows for examination of the results to ascertain that indeed the genuine critical results have been identified.



Search Domain for ROTATIONAL ANALYSIS -- Complex Geometry

Search of critical circles is limited to user's defined range of entry and exit points. Input only the range of x (program will calculate the corresponding y):

All X values are in [m]

Circles Start points (upper part)

From X1 value = 145

to X2 value = 165

Circles Exit points (lower part)

From X3 value = 120

to X4 value = 143.6

X = N/A

Y = N/A

Note: Each interval X1, X2 and X3, X4 is divided into Ns and Ne points. Refined search for critical circles can be done in subsequent runs by specifying narrower intervals.

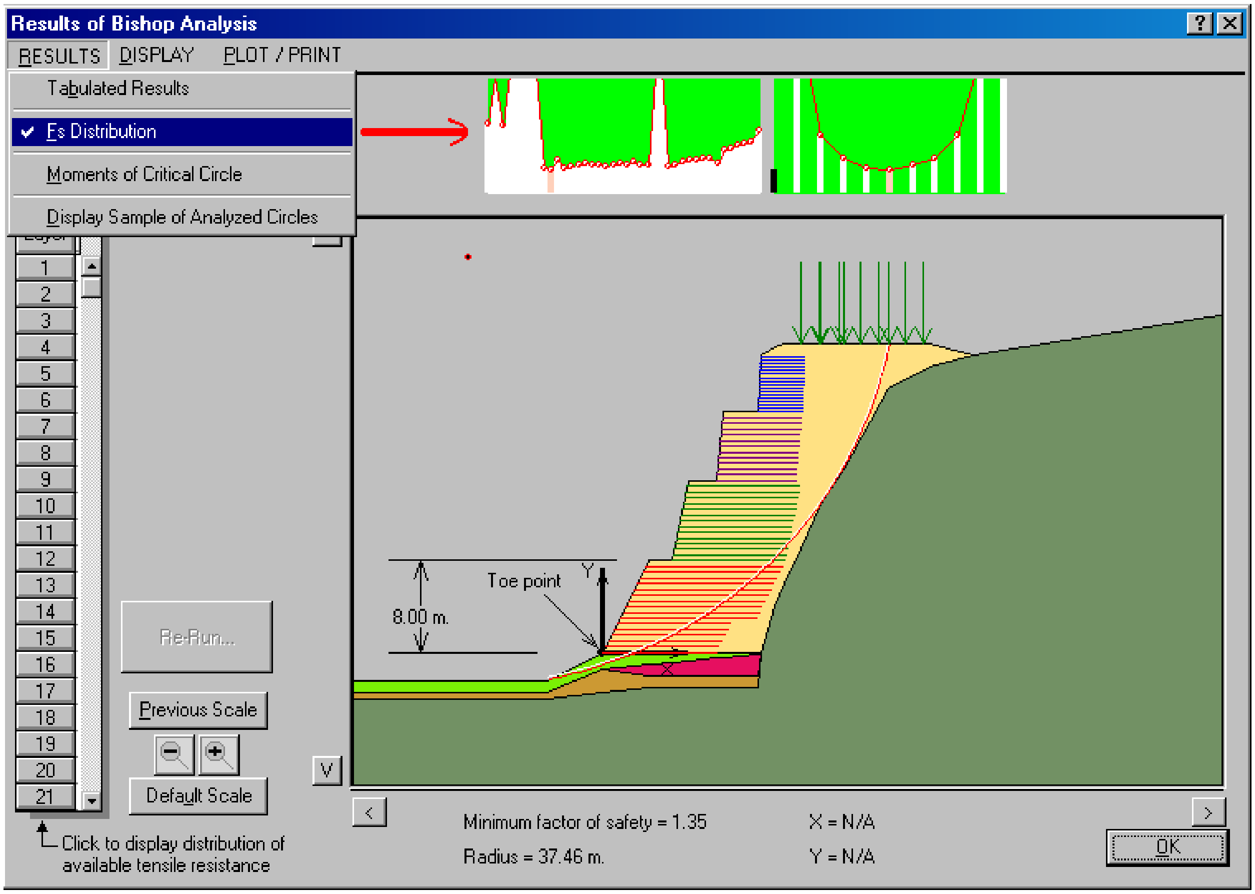
Method of Stability Analysis :

○ AASHTO - Bishop

● Comprehensive Bishop

Figure 8a. Specifying the search domain for circular slip surfaces

Clicking on the button to define the search domain for the rotational failure mode invokes the dialog shown in Figure 8a. Circles to be tested are defined by a set of points of entry and exit. ReSSA checks all possible circles between any pair of entry and exit points to identify the most critical circle. Note that the conventional approach is to specify centers and radii of circles; the traces of such slip circles are difficult to visualize thus possibly making the process less efficient. In Figure 8a, the points of entry are shown between X1 and X2; the exit points are between X3 and X4. These points can be defined by entering numbers in the respective cells or by using a mouse function (see left part of dialog).



Click to display distribution of available tensile resistance

Minimum factor of safety = 1.35

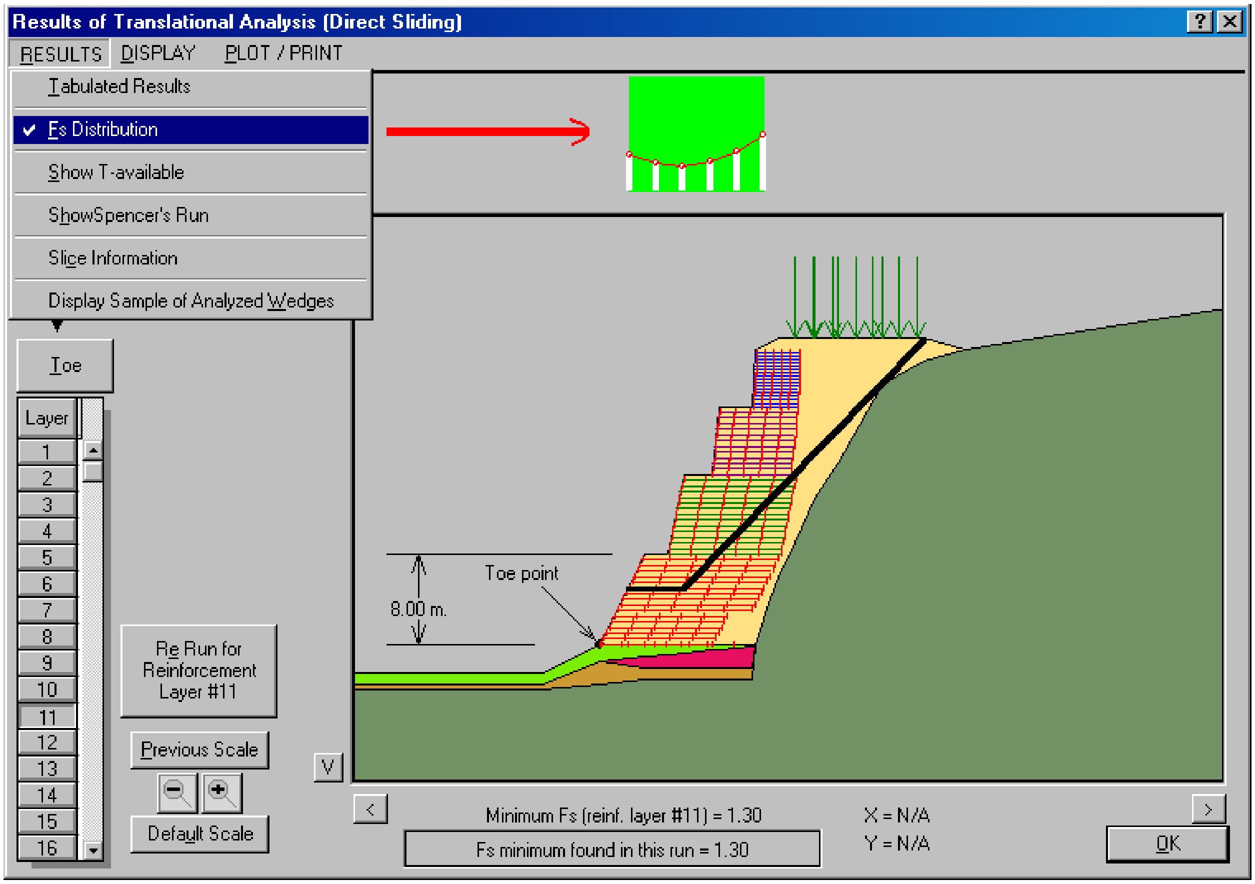
Radius = 37.46 m.

X = N/A

Y = N/A

Figure 8b. Critical slip circle based on specified search domain

After running Bishop analysis, the identified critical circle is displayed together with its corresponding factor of safety. Figure 8b shows these results and, in response to a selection from the dropdown menu (RESULT; see left upper corner), it includes the distribution of the minimal calculated safety factors for each specified points of entry and exit. The displayed distribution of safety factors (above the frame defining the problem) is plotted to scale, each point on the left or right corresponding to a specified point of entry or exit, respectively. Clearly, within the range of the specified search domain, the critical results were captured; the minimum factor of safety is 1.35 representing a circle that just touches the bedrock. Note that except for the sloping toe, the foundation soil in this case plays a minor role.



Minimum Fs (reinf. layer #11) = 1.30

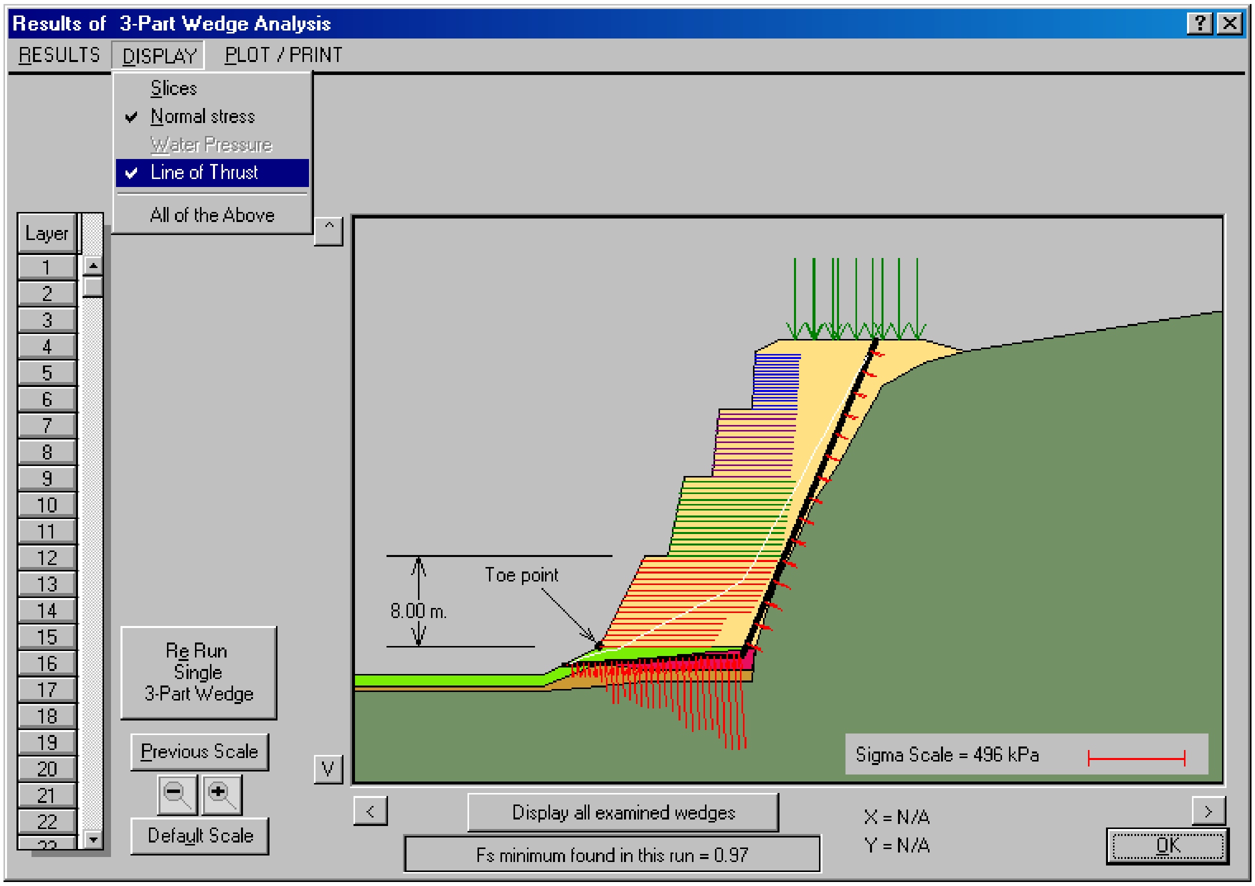
Fs minimum found in this run = 1.30

X = N/A

Y = N/A

Figure 9. Critical two-part wedge in direct sliding analysis

After defining the search domain for direct sliding analysis and running Spencer's, the screen shown in Figure 9 appears. The minimum factor of safety against direct sliding is 1.30 and it occurs along geosynthetic layer #11. There were 6 points along each layer for which two-part wedges were examined; upon clicking on the dropdown menu (RESULTS; see left upper corner), one can clearly see that the interwedge line is located in the front 1/3 of the layer. This observation is also obvious when looking at the trace of the critical two-part wedge. Note that the 'active' wedge is tangent to the bedrock meaning the rock plays a role in limiting the potential for direct sliding (same trend as with the rotational failure). Furthermore, the plane defining the active wedge intersects reinforcement layers and therefore, mobilizes their tensile resistance resulting in increased stability. The critical mechanism is contrary to the commonly assumed mechanism where the active wedge starts at the rear end of the reinforced zone. In fact, for the given problem this assumed mechanism seems to be unfeasible. The method utilized in ReSSA is a rational extension of slope stability analysis.


Results of 3-Part Wedge Analysis

Fs minimum found in this run = 0.97

Sigma Scale = 496 kPa

X = N/A

Y = N/A

Figure 10. Critical three-part wedge superimposed with the normal stress distribution and the thrust line

The three-part wedge mechanism can be defined for surfaces that may or may not intersect the reinforcement. Intersection of wedges with downward base inclination mobilizes the reinforcement tensile resistance thus increases stability. For the example problem, it appears that the seam of medium clay is critical (see Figure 10). It renders a minimal factor of safety of 0.97, certainly an unacceptable value. The active wedge is just between the rear end of the reinforcement and the rock; the base of the central wedge goes through the medium clay; the base of the passive wedge, having nearly the same inclination as the one of the central wedge, emerges at the sloping toe. By clicking on the dropdown menu (Figure 10), the normal stress distribution over the surface as well as the thrust line (white color) is superimposed on the sliding mass. Note that the thrust line connects the locations of resultants of interslice forces. Figure 10 indicates that although the design of reinforcement is adequate, failure may occur around the reinforcement through the weaker seam of clay. Good geotechnical practice requires the replacement of the clay seam with crushed rock (as part of grading). This would have resulted in a factor of safety in excess of 1.5; the critical three-part wedge then goes through the reinforced soil to emerge at the sloping toe. Alternatively, one could assume (optimistically) that the clayey seam would consolidate during construction thus exhibiting larger strength than that assumed in the analysis.

What If Scenarios?

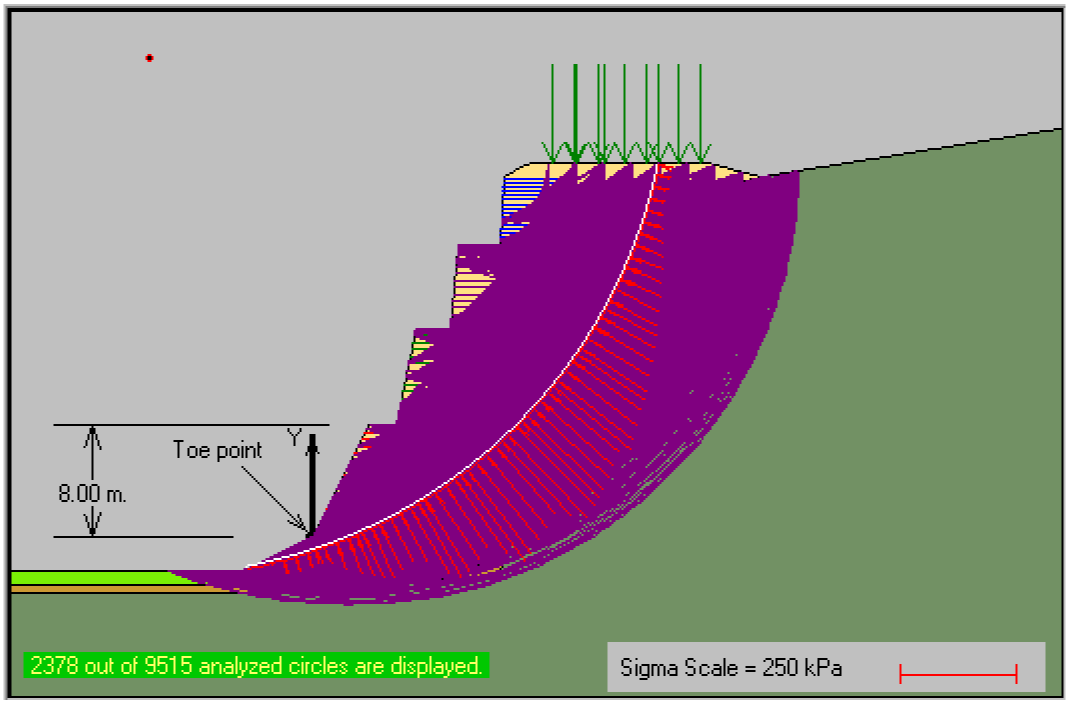
Any design process is dotted with ‘what if’ type of questions. Availability of software makes answering easier resulting in a rationally optimized design. The presented example problem may raise some ‘what if’ questions, a sample of which follows.

Q: How do I objectively check for ’reasonableness’ of results and what if they are not reasonable?
A: Limit equilibrium stability analysis is highly indeterminate problem. Hence, statical assumptions are needed to solve the problem. Such assumptions may render inadmissible results. In Bishop analysis this typically means negative normal stress over portions of the slip surface. In Spencer analysis it may mean negative normal stresses or, more likely, the thrust line is outside the sliding mass, which is physically impossible. ReSSA enables the user to view the normal stress distribution (Figures 10-11) as well as the thrust line (Figures 10, 12) thus providing an objective judgment tool. If the results represent an inadmissible solution, the user can introduce a tension crack or specify another slip surface until satisfactory results are obtained.

Q: What if in my search for critical results I did not cover the relevant zones within the given problem?
A: Upon clicking on a button in the dropdown menu (RESULTS), a large sample of all analyzed surfaces are displayed (e.g., Figures 11 and 12). The critical surface superimposed over the sample of analyzed surfaces gives a good and tangible indication whether the search covered extensively the relevant zones within the structure. If not, the user gets an idea which zones were not covered adequately (relative to the captured critical slip surface) and consequently, can redefine rationally the search domain.

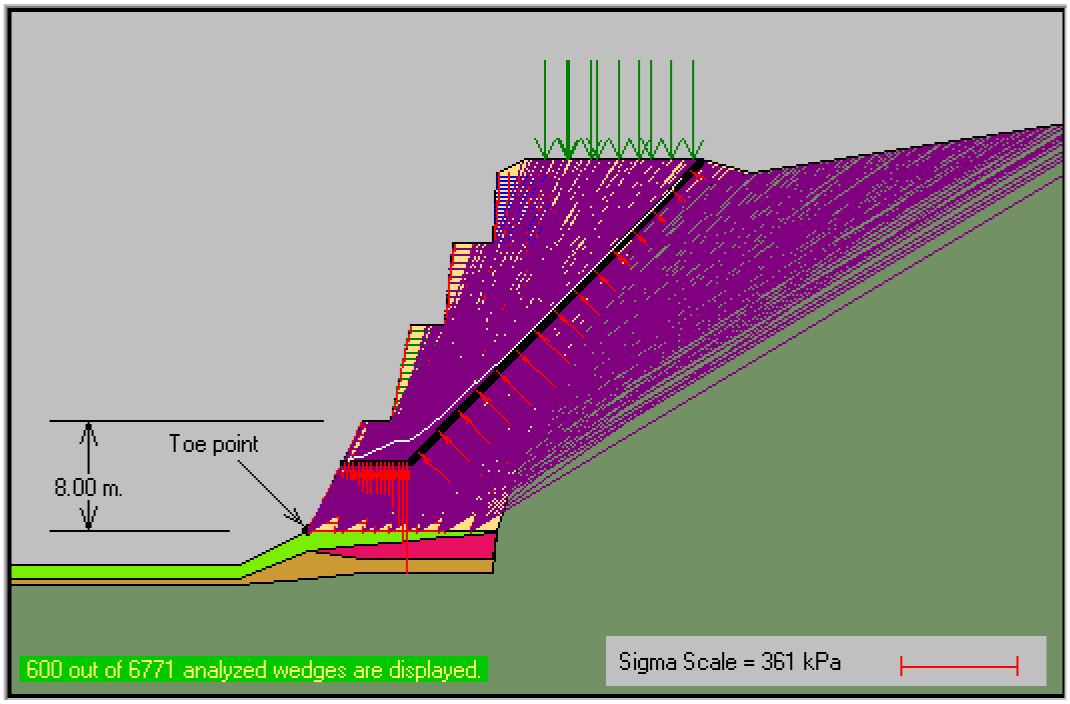
Q: What if the connection strength is not 100% as assumed in the problem?
A: Extremely significant drop in connection strength may allow for a surficial failure. ReSSA can identify surficial failures provided the search domain is properly defined. In such a case, the two-part wedge will degenerate into a single (active) wedge. Furthermore, the circular arc will practically degenerate into a planar segment (i.e., circle with pole far away from the slope) also describing, in essence, a single wedge. A drop of 50% in connection strength for the lower two tiers in the example problem resulted in nearly the same factors of safety as the 100% strength. Figure 13 shows the available strength distribution along a layer in each the first and second tier; in this case the prescribed connection strength for the lower two tiers was 0% (but surficial failures were not investigated). Very little connection strength is needed to resist surficial instability and a trace of cohesion may render this strength unnecessary.

Q: What if the seam of medium clay had been replaced with crushed rock?
A: The critical three-part wedge location would shift and the factor of safety would be in excess of 1.5. Always beware of weak soil seams (or planes of weakness introduced by geosynthetics such geomembranes).



2378 out of 9515 analyzed circles are displayed.

Figure 11. Normal stress distribution over the critical circle superimposed over a sample of analyzed circles



600 out of 6771 analyzed wedges are displayed.

Figure 12. Normal stress distribution over the critical two-part wedge superimposed over a sample of analyzed wedges

Q: What if the offset of the tiers was smaller and/or the reinforcement used stronger (in the context of direct siding)?
A: Figure 9 shows that the active wedge in direct sliding interests many layers of reinforcement. Hence, stronger reinforcement would have increased the factor of safety against direct sliding (this is not the case with direct sliding analysis that looks at the reinforced soil as a coherent mass). The mass subjected to direct sliding immediately below the offsets is decreased. As a result, the resistances to direct sliding derived from friction along layers below decrease. It is possible then that the critical two-part wedge will relocate to be under the offset although this may result in the active wedge intersecting larger number of reinforcement layers. The end result will depend on the given problem.

Q: What if closer spacing was used? What if Coverage Ratio (Rc) of less than 1.0 was used?
A: Closer spacing means that weaker reinforcement can be used to generate the same stability. Its required length, however, will remain nearly the same. If stronger reinforcement is used, the spacing may be increased; however, this may pose a constructability problem. Alternatively, strips of reinforcement, rather then full coverage, can be used so as to produce the same available strength using less material. Final decision about closer spacing or Rc needs to consider the economic consequences.

Q: What if the rock was ignored in analysis?
A: The bedrock effectively limits the extent of slip surfaces and therefore it renders much shorter and weaker reinforcement as compared with ignoring the bedrock. That is, ignoring the bedrock has clear economical consequences; overly conservative and expensive structure.

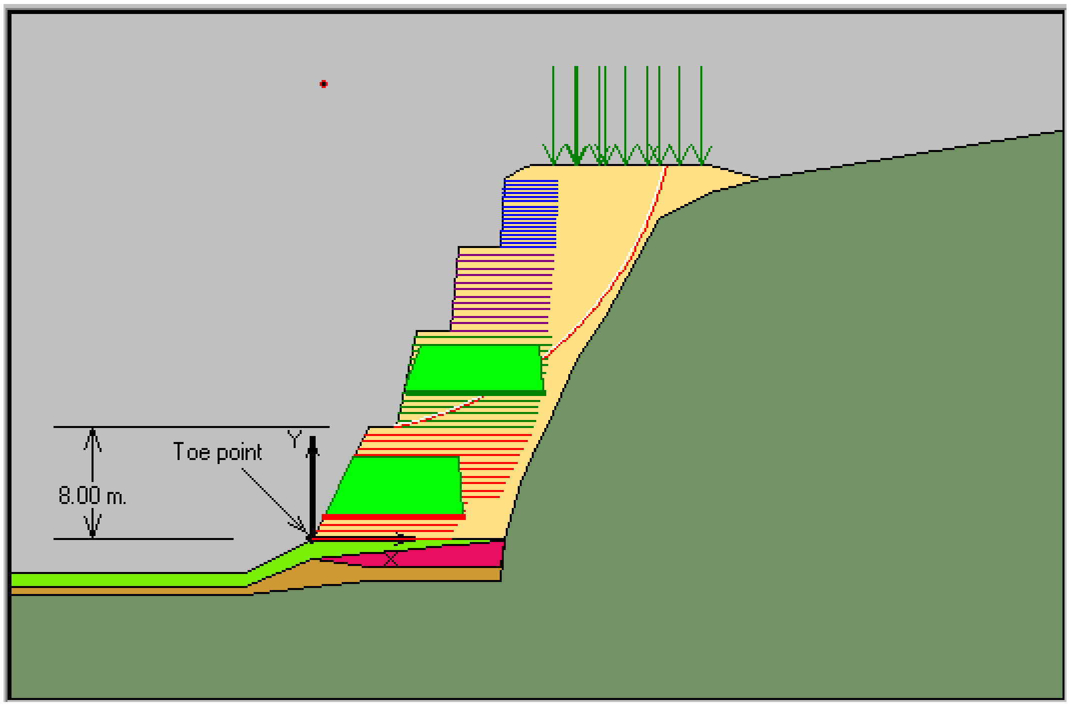


Figure 13. Schematic of tensile resistance distribution along layers in the lower two tiers where connection strength was changed to zero

Concluding Remarks

The economics and availability of 'made to order' manufactured geosynthetics make them attractive in soil reinforcement applications. Consequently, geosynthetics are increasingly being used in sophisticated and complex reinforcement applications. To enable ever increasing complicated uses, however, versatile designer-oriented software must be part of the design process. Acceptability of such software by designers is greatly facilitated if it expands current geotechnical practice to include the geosynthetics effects in a tangible fashion.

Presented is an instructive example problem through which some of the capabilities of recently developed software, program ReSSA (2.0), are demonstrated. The software allows for optimization of complex design while using conventional slope stability analysis.

References

Bishop A. W. (1955), "The use of the slip circle in stability analysis of slopes," *Geotechnique* 5, pp. 7-17.

Spencer, A. (1967), "A method of analysis for stability of embankments using parallel inter-slice forces," *Geotechnique* 17, pp. 11-26.