The Power of Software in Geosynthetic Reinforcement Applications: Part I

by

Dov Leshchinsky

The objective in designing geosynthetic reinforced soil structures is to determine the required long-term strength and layout of the reinforcement. The layout and strength are interrelated rendering many possible solutions with the same level of stability but not necessarily having the same economics. Computer program can offer a diagnostic tool that helps the designer to reach an optimal solution. This tool is called Safety Map and was formally presented by Baker and Leshchinsky ("Spatial Distributions of Safety Factors," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 127, No. 2, 2001,135-145). This color-coded map shows the distribution of the safety factor within the soil mass thus indicating where the margin of safety is substandard or where it is excessively high. It was implemented in program ReSSA(2.0), developed by ADAMA Engineering (www.GeoPrograms.com). This is a generic slope stability program that is ideally suited to accommodate geosynthetic reinforcement. The following example problem demonstrates the usefulness of the Safety Map.

Consider the problem of the stability of an embankment over soft soil at the end of construction. The embankment is 5 m high, 1(v):2(H) side slopes, made of granular soil having a unit weight of 22 kN per cubic meter and friction angle of 35 degrees. It is underlain by soft clay, 3 meter thick, having saturated unit weight of 19 kN per cubic meter and undrained apparent cohesion of 15 kN per square meter. There is a dense sand layer below the clay with saturated unit weight of 23 kN per cubic meter and friction angle of 40 degrees. As the end of construction is the least stable state, total stress stability analysis is carried. The acceptable minimum factor of safety is 1.30. To simplify the presentation, only the results of Bishop Analysis are reviewed (limited to circular arc failure surfaces). First, the stability of the unreinforced embankment considered – see Figure 1. Looking at the distribution of the safety factors within the slope, one can make at a glance the following diagnosis:

1. The critical slip circle is indeed captured and represents the minimum factor of safety. This is evident by the fact that its trace, ab, is located well within the "red" zone.
2. The red zone signifies the range within all safety factors are less than the minimum required of 1.30. It means that strengthening (e.g., reinforcement) is within this zone. However, the safety map was constructed based on one-sided potential failures – all circles considered are to the left. In this symmetrical problem failures to the right are equally feasible. Hence, a mirror image of the safety map is also valid implying that, practically, reinforcement is needed along the entire base of the embankment.
3. The red zone is rather large implying that conducting an analysis to locate just the critical slip circle is not very meaningful in a practical sense. The critical circle does not show the scope of the problem.
4. The red zone is dictated and limited by the depth of the soft clay. It implies that mechanical or chemical treatment of the clay layer or simply stage construction

could also be considered as possible solutions. Hence, an economical evaluation of alternative engineering remedies can be done objectively.

As can be seen, the safety map provides an insight into the state of stability of the structure much more than single surface (albeit the critical circle). It also implies possible remedies. Let us examine such a remedy: place a high strength geotextile at the interface between the embankment and the foundation. Placing a single layer, extending from toe to toe and having long term strength of 150 kN per meter, produces the safety map as shown in Figure 2. Note that the available strength along the geotextile is superimposed on the safety map. It shows the required pullout resistance length on either end. Clearly, for high strength reinforcement embedded under a slope requires significant length to allow the mobilization of the geotextile strength. The safety map implies the following:

1. The safety factor everywhere exceeds the required minimum of 1.30. The map shows that for a rather large zone the range of Fs is between 1.32 and 1.50 (i.e., typical economical range for Fs). Hence, the selected strength and length of the reinforcement is adequate.
2. The soft soil consolidates and gains strength with time. Therefore, the margin of safety against deep seated failure increases with time. However, the strength of the granular embankment remains constant. If the desired minimal factor of safety against failures within the embankment only is 1.50, then the red zone in near the slope shows an unsatisfactory range where Fs is between 1.32 and 1.50. The design implication is that placing short multiple reinforcement layers can resolve the problem. The designer can realize instantly the required length which must exceed the depth of the red zone. Selecting a relatively weak multilayer reinforcement can be easily done by a quick trial and error process.

The simple example problem demonstrates the power of software in design. The results are no longer restricted to the critical slip surface and its associated minimum factor of safety. Rather, the distribution of the safety factor within the soil mass is displayed. This presentation makes it easy to visualize the state of stability of the structure. Identifying zones with insufficient stability enable the designer to prescribe economically the remedy; e.g., the length and strength of the reinforcement. Conversely, if the remedy renders a structure that excessively stable (i.e., an “overkill”), the designer can easily optimize the remedy to yield a structure that is safe and economical.

It should be pointed out that the example was limited to Bishop Analysis. However, ReSSA can also use Spencer Analysis considering two- and three-part wedge mechanisms. The safety maps and their implication to design are particularly useful when multiple reinforcement layers are employed. Such an application will be demonstrated in a future article.

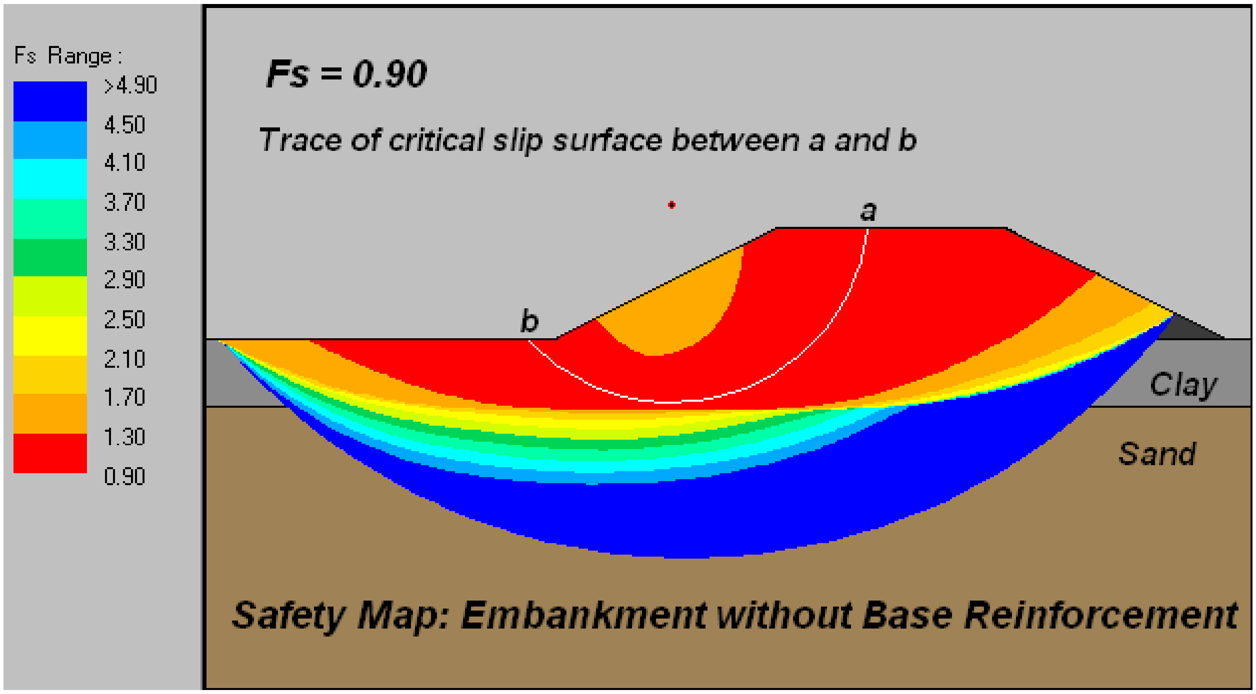

Figure 1. The basic problem of unreinforced embankment

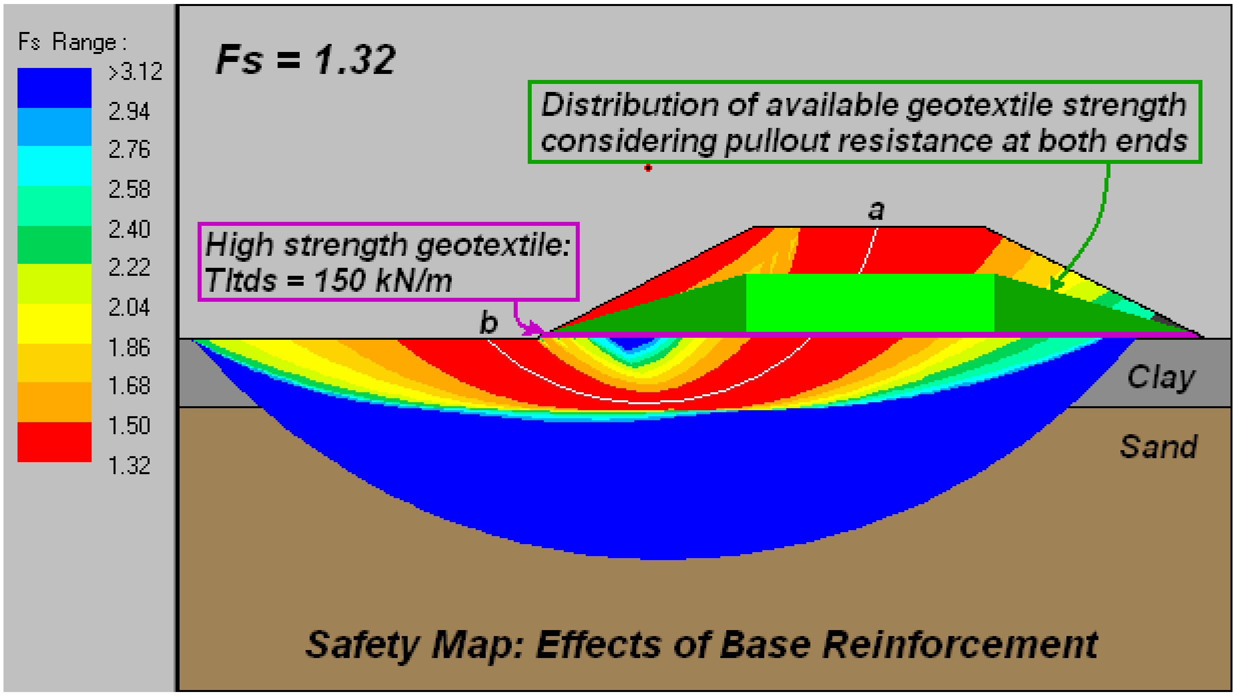

Figure 2. Effects of base reinforcement

The Power of Software in Geosynthetic Reinforcement Applications: Part II

by

Dov Leshchinsky

The objective in designing geosynthetic reinforced soil structures is to determine the required long-term strength and layout of the reinforcement. The layout and strength are interrelated rendering many possible solutions with the same level of stability but not necessarily having the same economics. Computer program can offer a diagnostic tool that helps the designer to reach an optimal solution. This tool is called Safety Map and was formally presented by Baker and Leshchinsky ("Spatial Distributions of Safety Factors," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127(2), 2001,135-145). This color-coded map shows the distribution of the safety factor within the soil mass thus indicating where the margin of safety is substandard or where it is excessively high. It was implemented in program ReSSA(2.0), developed by ADAMA Engineering (www.GeoPrograms.com). Part I of this series of articles demonstrated the use of Safety Maps in base reinforcement of embankment over soft soil. Part II demonstrates the application of the Safety Map in designing complex multitiered reinforced slopes/walls. It should be noted that the applicability of the computational framework used in ReSSA for multitiered structures was demonstrated by Leshchinsky and Han ("Geosynthetic Reinforced Multitiered Walls," *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, 130(12), 2004, 1225-1235).

Consider the problem of the stability of multitiered slope/wall augmented by bedrock as detailed in Figure 1. The objective is to determine the required layout and strength of reinforcement to ensure sufficient margin of safety efficiently. The slope of the lower tier is 2(v):1(h) while the top tier is at 20(v):1(h). According to FHWA, this is a case of tiered walls over tiered slopes and therefore, it should be analyzed using a slope stability analysis. Note that the foundation soil is comprised of a 2.5 m thick layer of residual soil, which after deformations rendered by the surcharge of 17 m high structure, will have its design strength dropped to 15 degrees. Also note that the bedrock creates a slender structure by limiting the depth of potential slip surfaces.

For granular unreinforced slopes, the critical slip surface coincides with the steepest slope surface. The corresponding factor of safety for our problem then is trivial. That is, its value equals to tan(phi)/tan(beta) where beta is the angle of the steepest slope. In our case the upper tier is the steepest; Fs=tan(34)/20=0.034. Figure 2 uses rotational failures combined with Bishop's analysis. It shows the location of the critical slip surface. By itself, this surface is of little value when designing for reinforcement. However, the red zone in the Safety Map in Figure 2 shows that, practically, most of the granular backfill needs to be reinforced as Fs<1.3 (where typically the minimum required Fs should equal or exceed 1.3). Clearly, the map is a diagnostic tool to assess the stability of the unreinforced slope indicating visually the zones within which the factor of safety is unsatisfactory.

As a first iteration in the design process, the reinforcement layout shown in Figure 1 is specified. The long term strength, Tltds, of reinforcement for the bottom tier is 80 kN/m;

for the second tier it is 50 kN/m; for the third tier it is 30 kN/m; and for the top tier, Tltds = 8 kN/m. Rerunning the reinforced problem using Bishop's analysis yields the Safety Map shown in Figure 3. The minimum factor of safety now is 1.29 (acceptable) and its corresponding critical surface is rather deep, naturally limited by the bedrock. The Safety Map implies the following:

3. The safety factor everywhere exceeds the required minimum of 1.3. The map shows that for a rather large zone the range of Fs is between 1.3 and 1.5 (i.e., typical economical range for Fs). Hence, the selected strength and length of the reinforcement is adequate to resist rotational failure economically.
4. The red zone extends into the residual soil and is restricted by the bedrock. Hence, though the red zone in Figure 3 indicates an economical selection of reinforcement, it also serves as a red flag for different potential failure mechanisms that can adapt to the given geology thus producing a more critical situation.

Figure 4 shows the Safety Map employing 2-part wedge failure mechanism combined with Spencer's stability analysis. Slip surfaces along the interface with the foundation, as well as along each reinforcement layer, are examined. The Safety Map implies the following:

1. The factor of safety for the initially assumed reinforcement is 0.9, much lower than the permissible value of 1.3. As can be seen, the critical slip surface propagates along the interface with the foundation (top of residual soil), extending beyond all reinforcement layers and limited by the bedrock.
2. The red zone signifies the range in which Fs is less than 1.3; i.e., unacceptable values. As seen in a glance, there are zones within each tier in which Fs is unacceptable (larger than 0.9 but less than 1.30).
3. Clearly, the reinforcement for the top tier must be stronger. It must be somewhat stronger for the tiers below as well.
4. While stronger reinforcement will improve stability against failures within the reinforced soil zones in all four tiers, it will not resolve the problem of failure around the reinforcement. Lengthening the reinforcement layers in the second and perhaps the third tier can solve this problem as reinforcement layers intersect the critical 2-part slip surface.

The lesson using the 2-part wedge mechanism combined with the initially assumed layout shows that one needs to increase both strength and length of reinforcement. The depth of the Safety Map suggests the extent to which the reinforcement should be lengthened; the existence of the red zone within the reinforced zone implies the need for increase in reinforcement strength. One can now lengthen and strengthen the reinforcement until the factor of safety is 1.3 and, for economical outcome, the red zone within the reinforced soil zone signifies Fs mostly between 1.3 and 1.5. Due to publication space limitations, this is not done here. However, Figure 3 demonstrates economical design (for rotational failures) and thus is instructive for the objective when using other mechanisms.

Figure 5 shows the Safety Map employing 3-part wedge failure mechanism combined with Spencer's stability analysis. Translational failure mechanisms within the 'red flag' zone, the foundation soil, are examined. The Safety Map implies the following:

1. The factor of safety for the initially assumed reinforcement is 0.7, much lower than the permissible value of 1.3. As can be seen, the critical slip surface propagates within the foundation, the residual soil, extending beyond all reinforcement layers and limited by the bedrock.
2. The red zone signifies the range in which Fs is less than 1.3; i.e., unacceptable values. As seen in a glance, there is one such zone. It extends between the rear segment of the reinforcement and the bedrock, as well as within the entire foundation soil zone.
3. The Safety Map implies that while increasing the strength of the reinforcement may narrow the red zone, it is not likely to eliminate it altogether. Lengthening of the reinforcement in the three upper tiers may help but not likely to render a safe and economical design.
4. The Safety Map indicates that the residual soil creates a zone which decreases stability significantly. A possible effective solution in this case could involve ground improvement such as replacement of the residual soil before construction of the tiered system starts. Replacement will also increase the resistance to direct sliding failure depicted by the critical 2-part wedge in Figure 4.

The Safety Map corresponding to the 3-part wedge mechanism implies that replacing the foundation residual soil may produce a good solution. Rerunning the problem with the foundation soil the same as the reinforced one (i.e., phi = 34 degrees), yields a factor of safety of 1.26 (approximately 1.3) for the 3-part wedge, an acceptable value. Rerunning the 2-part wedge results in the Safety Map shown in Figure 6. Clearly, the problem associated with the foundation soil is resolved also for the 2-part wedge (in fact, Fs along the foundation now is 1.37). The red zones in which Fs is less than 1.3 are within the second, third and fourth tiers. These zones indicate that slight increase in reinforcement strength is needed; length is OK. Furthermore, a slight increase in reinforcement strength in the three upper tiers is likely to produce a rather economical utilization of the reinforcement as the range of the safety factors will be mainly between 1.3 and 1.5.

The complex example problem demonstrates the power of software in design. The distribution of the safety factor within the soil mass enables the designer to guess an initial layout and strength of reinforcement. When used with various failure mechanisms the map indicates potential problems, not necessarily related to reinforcement. This diagnostic tool allows for a remedy that includes various alternatives. The designer can rationally optimize the remedy to yield a structure that is safe and economical.

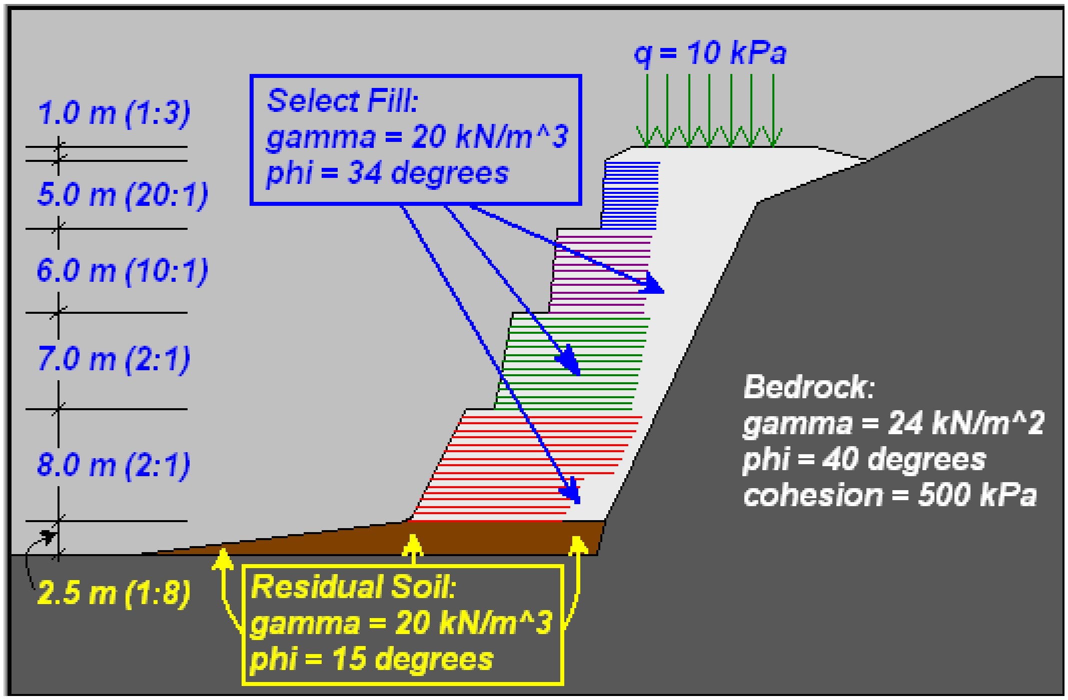

Figure 1. The basic problem of multitiered slope/wall

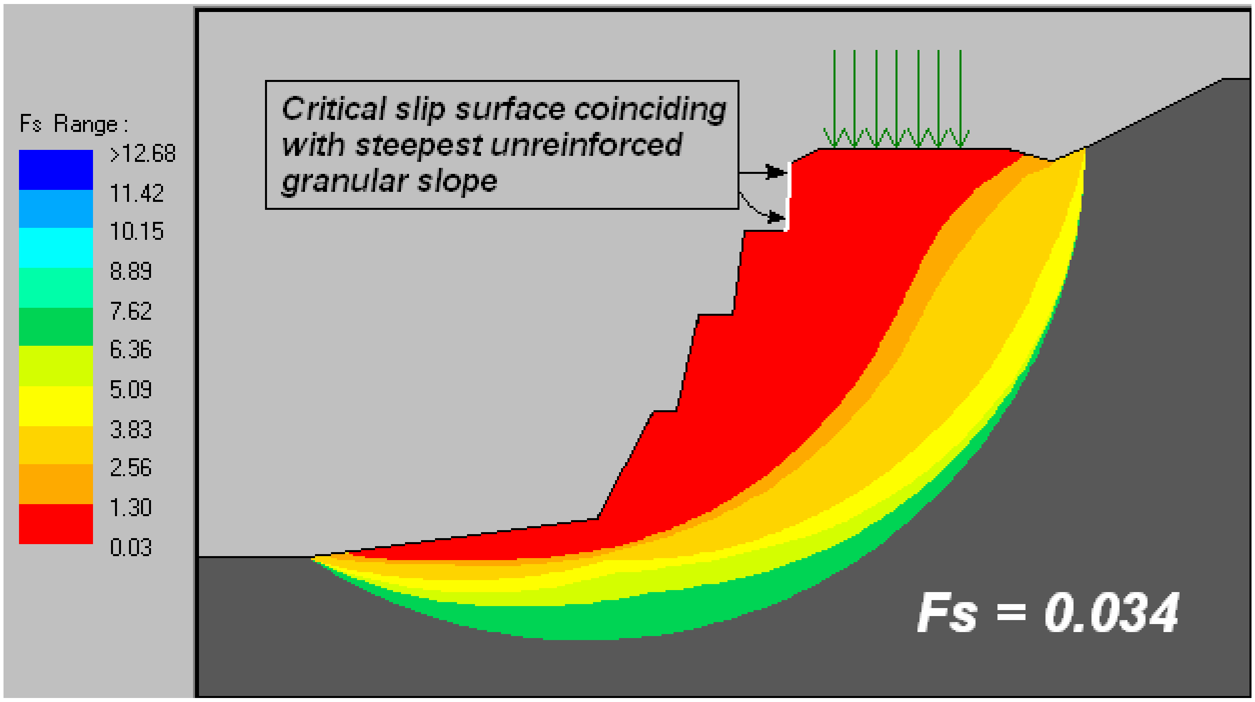

Figure 2. Safety Map for the unreinforced problem using circular slip surfaces combined with Bishop's analysis

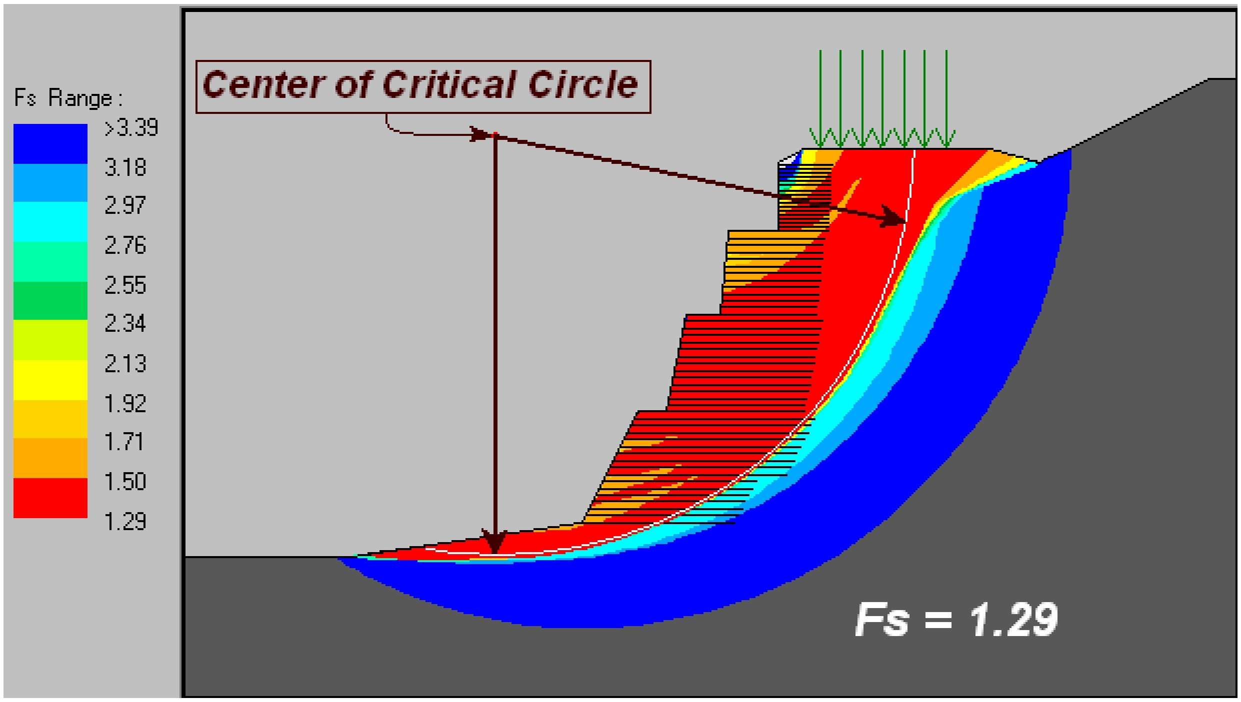

Figure 3. Safety Map for the reinforced problem using circular slip surfaces combined with Bishop's analysis

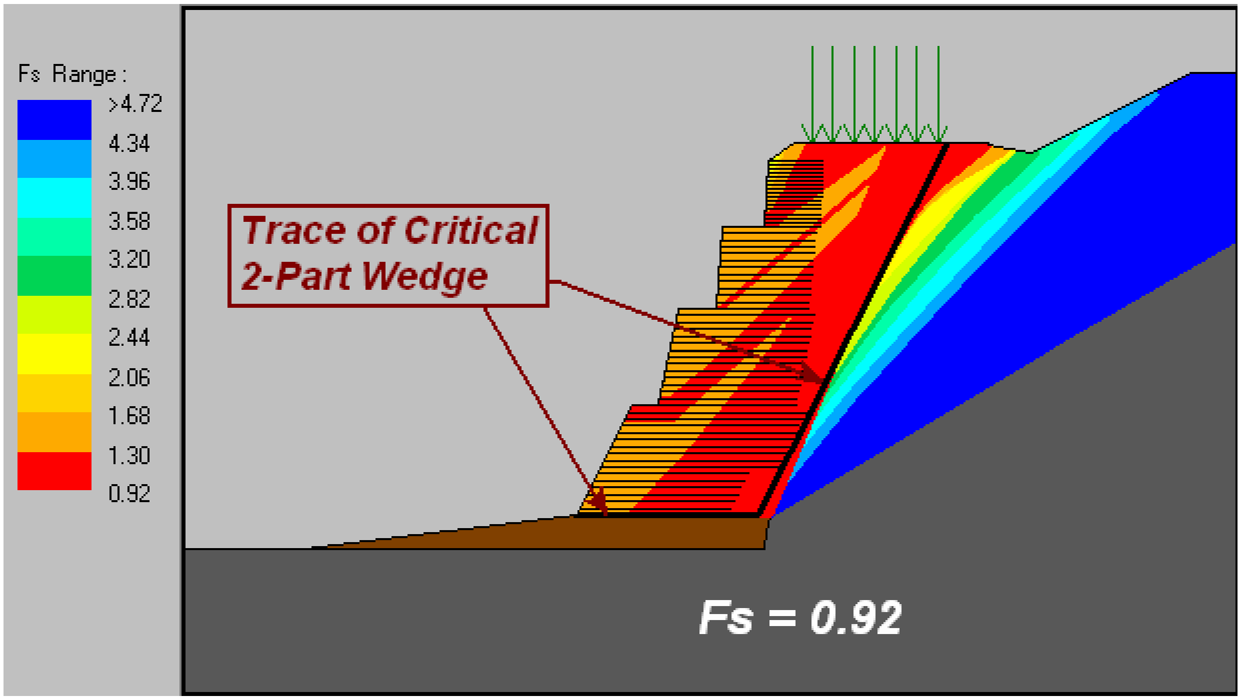

Figure 4. Safety Map for the reinforced problem using 2-part wedge surfaces combined with Spencer's analysis

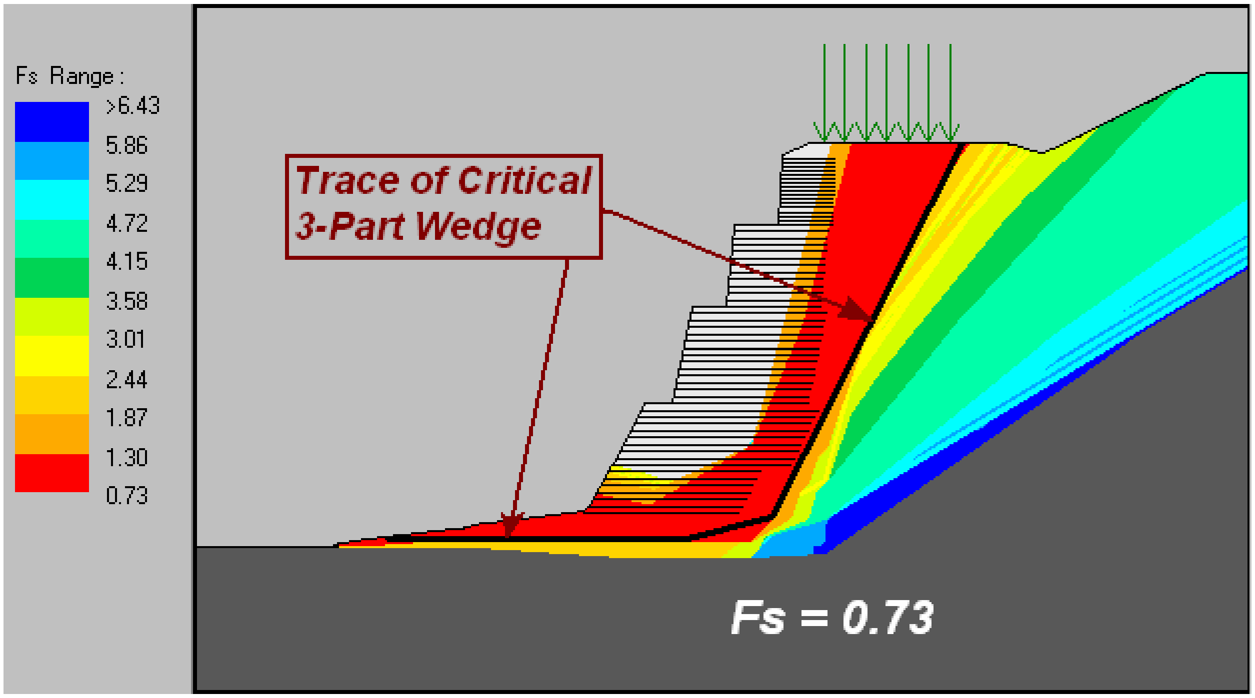

Figure 5. Safety Map for the reinforced problem using 3-part wedge surfaces combined with Spencer's analysis

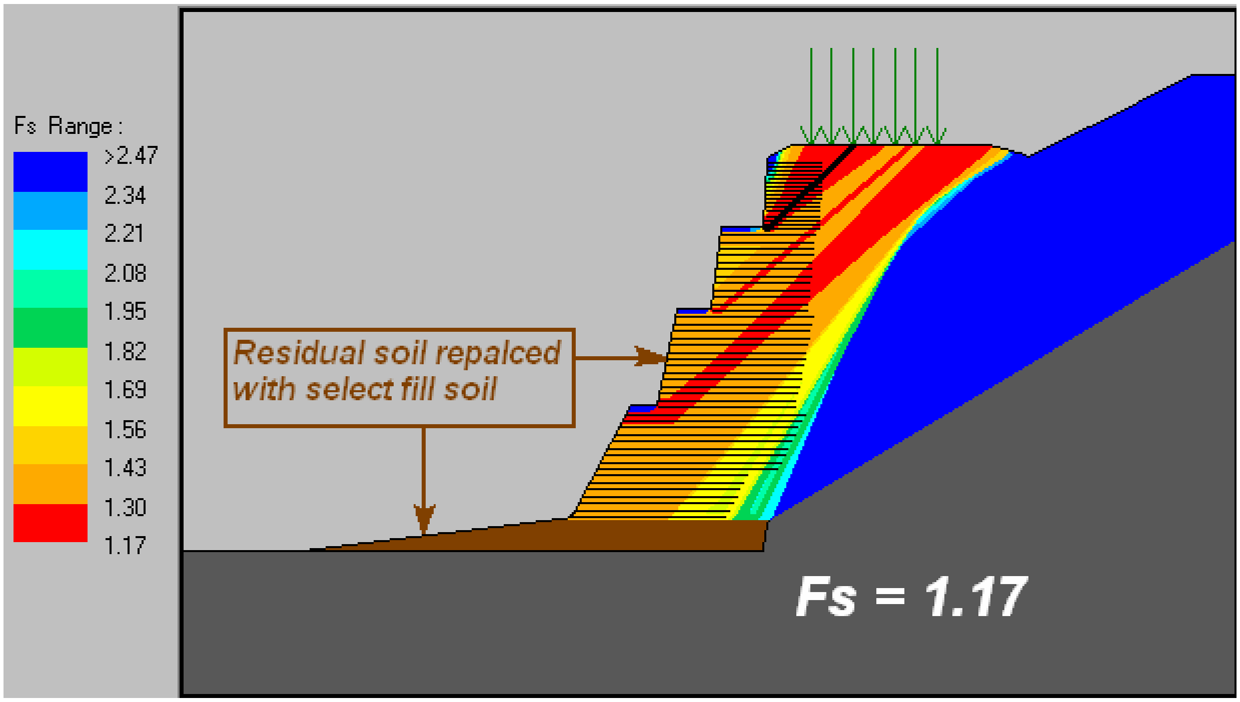

Figure 6. Effects of replacing the foundation soil with select fill (2-part wedge mechanism)

The Power of Software in Geosynthetic Reinforcement Applications: Part III

by

Dov Leshchinsky

The objective in designing geosynthetic reinforced soil structures is to determine the required long-term strength and layout of the reinforcement. The layout and strength are interrelated rendering many possible solutions with the same level of stability but not necessarily having the same economics. Computer program can offer a diagnostic tool that helps the designer to reach an optimal solution. This tool is called Safety Map and was formally presented by Baker and Leshchinsky ("Spatial Distributions of Safety Factors," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127(2), 2001,135-145). This color-coded map shows the distribution of the safety factor within the soil mass thus indicating where the margin of safety is substandard or where it is excessively high. It was implemented in program ReSSA(2.0), developed by ADAMA Engineering (www.GeoPrograms.com). Part I of this series of articles demonstrated the use of Safety Maps in base reinforcement of embankment over soft soil. Part II illustrated the application of the Safety Map in designing complex multitiered reinforced slopes/walls. Part III utilizes the Safety Map to show the effects of water on the required reinforcement strength and layout.

Consider the basic problem detailed in Figure 1. For simplicity, homogeneous soil profile is used. Note that a sloping toe, albeit mild, tends to decrease stability by enabling deep seated potential failures. Preventing such a mode of failure requires long and strong reinforcement. The objective is to determine the required layout and strength of reinforcement to ensure sufficient margin of safety efficiently. For brevity, the presentation in this article is limited to investigations using circular slip surfaces combined with Bishop's analysis. While such an approach might be acceptable in a preliminary design, one need to ascertain that, indeed, circular arcs represent the least stable failure mechanism.

For granular unreinforced slopes, the critical slip surface coincides with the steepest slope surface. The corresponding factor of safety for our problem is therefore trivial. That is, its value equals to tan(phi)/tan(beta) where beta is the angle of the steepest slope. In our case; Fs=tan(28)/2=0.27. Figure 2 uses rotational failures combined with Bishop's analysis to analyze the basic unreinforced problem. It confirms the benchmark value of Fs=0.27, showing the critical slip surface to coincide with the slope surface. By itself, this surface is of little value when designing for reinforcement. However, the red zone in the Safety Map in Figure 2 shows the unstable areas where Fs<1.3 (where typically the minimum required Fs should equal or exceed 1.3). Clearly, the map is a diagnostic tool to assess the stability of the unreinforced slope indicating visually the zones within which the factor of safety is unsatisfactory implying where the reinforcement is needed. As seen, the red zone extends below the toe; it is a result of the destabilizing effects of the sloping toe.

Figure 3 shows the selected reinforcement layout following the Safety Map for the unreinforced slope in Figure 2. Ten equally spaced (0.5 m apart) layers of reinforcement, each 6.0 m long and having long-term strength, Tltds, of = 10 kN/m, are selected. Compared with Safety Map in Figure 2, such a guess looks reasonable. Rerunning the reinforced problem using Bishop's analysis yields the Safety Map shown in Figure 3. The minimum factor of safety now is 1.33 (acceptable) and its corresponding critical surface is marked as curve ab. The Safety Map implies the following:

5. The safety factor everywhere exceeds the required minimum of 1.3. The map shows that for a rather large zone (red zone), Fs is between 1.3 and 1.5, typical economical range for Fs.
6. The critical slip circle is within the reinforced soil zone. This means that the selected strength for the reinforcement is just about optimal. That is, stronger reinforcement will push back the critical surface and the red zone thus not utilizing the available strength of the reinforcement. The red zone, on the other hand, extends just beyond the reinforcement. This implies that shorter reinforcement could 'attract' a slip surface around the reinforcement. Hence, the uniform length of the reinforcement is also near optimum. The selected strength and length of the reinforcement is adequate to resist rotational failure economically. There is no guessing in this procedure – the Safety Map serves as a guide for the most efficient solution. Quickly and objectively.
7. The red zone extends deep into the foundation soil thus explaining the need for rather long and strong reinforcement. This is a consequence of the sloping toe. It also hints that any decrease in soil shear resistance (e.g., due to water seepage) could result in collapse as the mass that needs to be stabilized then is large.

Figure 4 shows the basic problem but now with water seeping through the slope as depicted by the upper flow line or phreatic line. Such a situation is of particular interest as failure of geotechnical structures, including reinforced soil, is often a result of seeping water. Simply, soil is a material that derives its strength from inter-particles friction. Presence of water in the voids produces uplift pressures and thus decreases the net inter-particles stresses resulting in a decrease of the soil frictional strength. In fact, this net pressure, called "effective stress", can drop by as much as half when saturated. Subsequently, the soil shear resistance can drop also by as much. Leaving the layout and strength as shown in Figure 3 for the seepage problem will result in factors of safety substantially smaller than one thus will result in failure.

Using the Safety Map for the seepage problem yields the strength and length of reinforcement as shown in Figure 5. That is, to obtain acceptable and economical layout, the long-term strength of the reinforcement is selected as Tltds = 23 kN/m and its length is selected as L= 12.0 m. The minimum Fs is 1.31, an acceptable value. The Safety Map implies the following:

5. The safety factor everywhere exceeds the required minimum of 1.3. The map shows that for a rather large zone (red zone), Fs is between 1.3 and 1.5, typical economical range for Fs.
6. The critical slip circle is within the reinforced soil zone. This means that the selected strength for the reinforcement is just about optimal. The red zone

extends just beyond the reinforcement. This implies that shorter reinforcement could 'attract' a slip surface around the reinforcement. Hence, the uniform length of the reinforcement is also near optimum. The selected strength and length of the reinforcement is adequate to resist rotational failure economically.

7. The presence of water deepens the extent of potential slip surfaces requiring stabilization of larger mass of soil.

Comparing Figures 5 and 3, one sees the impact of seeping water. For about the same optimized solution (as reflected by the Safety Maps), water requires double the length and more than double the strength of the reinforcement. This has clear economical implications. On the other hand, designing for dry conditions when in reality water will seep may create unpleasant surprise (which also has clear economical implications).

Realizing the destabilizing effects of water, it is interesting now to examine an engineered solution by introducing a control measure to divert the flow. Figure 6 shows the installation of a prefabricated geosynthetic drain which is located 8 m away from the face of the slope. This drain intercepts the seepage line basically recreating the free-draining surface of the slope deep inside the slope, where the geosynthetic drain is installed. The shallowest effective location for this drain (where the safety factors for surfaces around the reinforcement just meet the minimum requirements) was obtained using the Safety Map and its visualization power. Figure 7 presents the selected layout of reinforcement. The bottom layers 1 through 6 are L = 8.0 m long, having a long-term strength of Tltds = 15 kN/m. The top layers 7 through 10 are L = 6.0 m long and Tltds = 10 kN/m strong. The Safety Map in Figure 7 implies the following:

1. The safety factor everywhere exceeds the required minimum of 1.3. The map shows that for a rather large zone (red zone), Fs is between 1.3 and 1.5, typical economical range for Fs.
2. The critical slip circle is within the reinforced soil zone. This means that the selected strength for the reinforcement is just about optimal. The red zone extends just beyond the reinforcement. This implies that shorter reinforcement could 'attract' a slip surface around the reinforcement. The upper four layers are not needed in the rear. The selected strength and lengths of the reinforcement is adequate to resist rotational failure economically.

Clearly, the geosynthetic drain substantially reduced the required reinforcement when compared with the case where water was seeping at the face of the slope. Looking at Figure 7 and 5 one can realize the economics of using such a drain.

The example problem demonstrates the power of software in optimal design. The distribution of the safety factor within the soil mass enables the designer to guess an initial layout and strength of reinforcement. This diagnostic tool allows for a remedy that includes various alternatives. The designer can rationally optimize the remedy to yield a structure that is safe and economical.

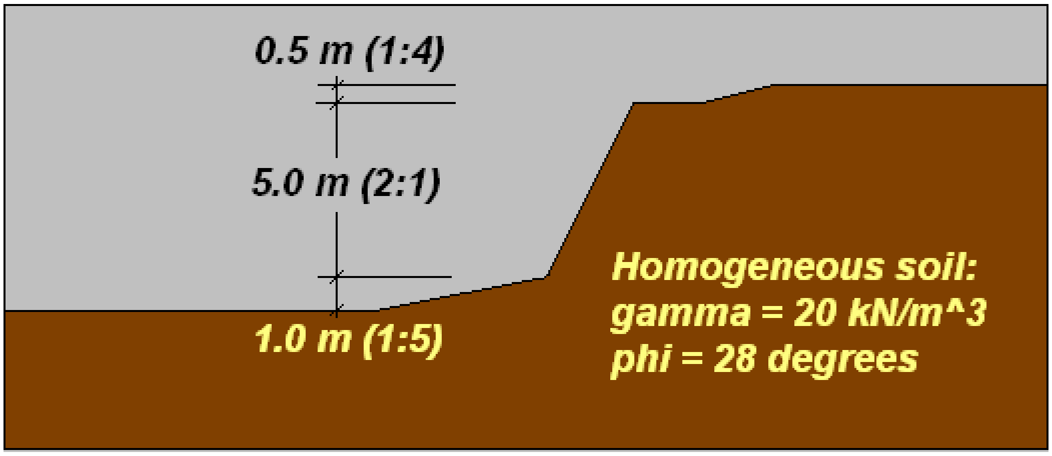

Figure 1. The basic dry problem

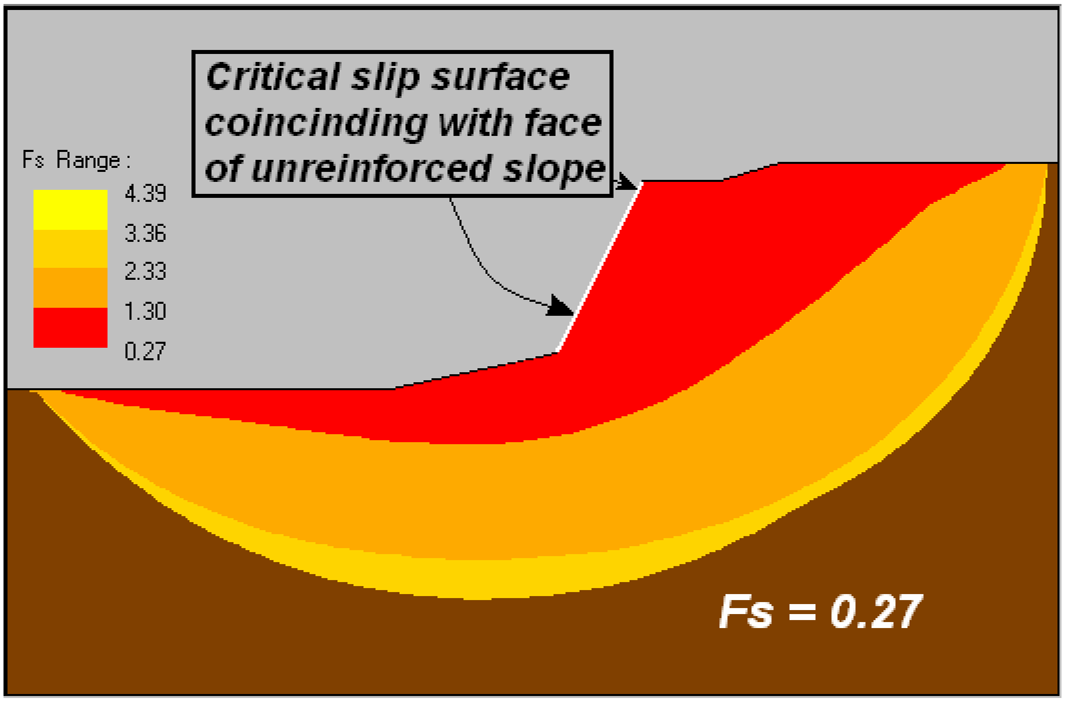

Figure 2. Safety Map for the unreinforced problem using circular slip surfaces combined with Bishop’s analysis

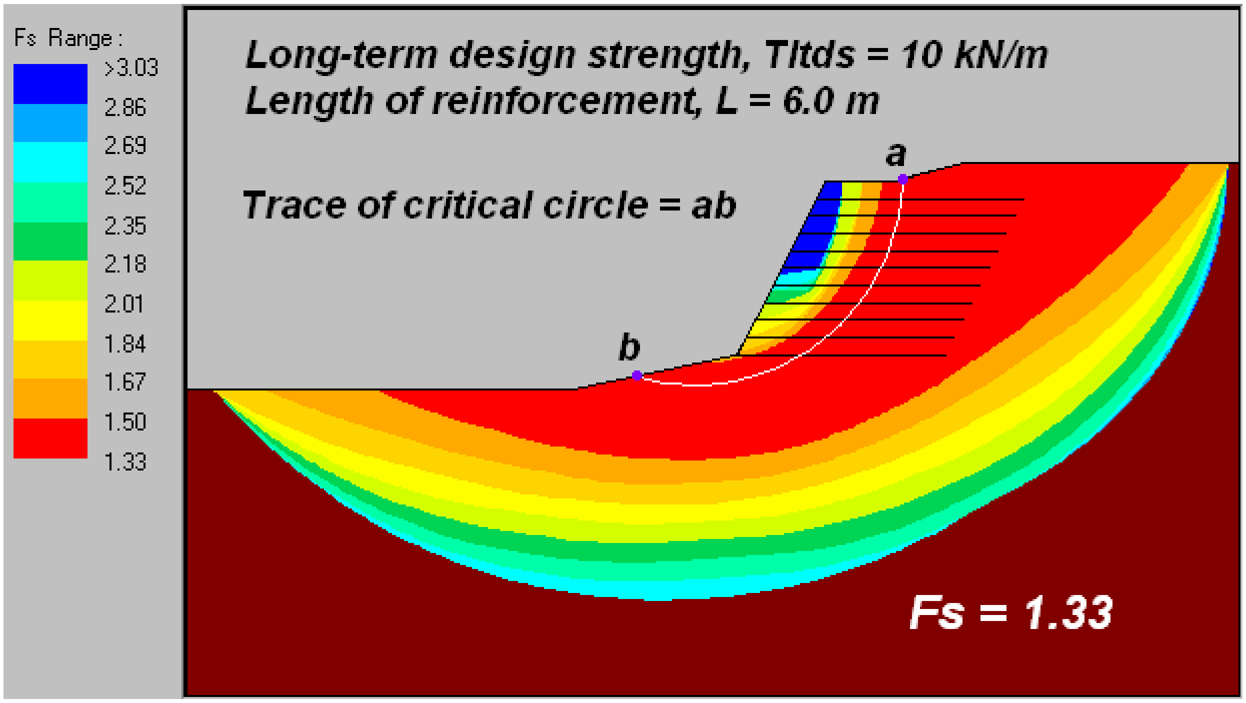

Figure 3. Safety Map for the reinforced problem using circular slip surfaces combined with Bishop's analysis

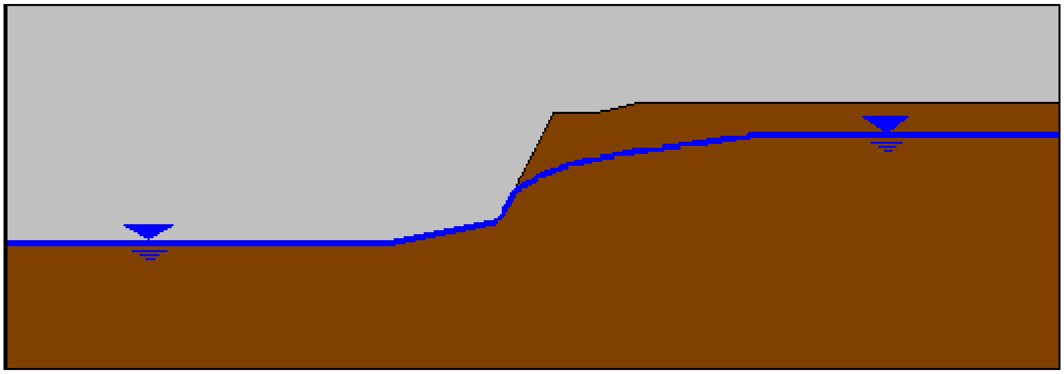

Figure 4. The basic problem with water seeping through the face

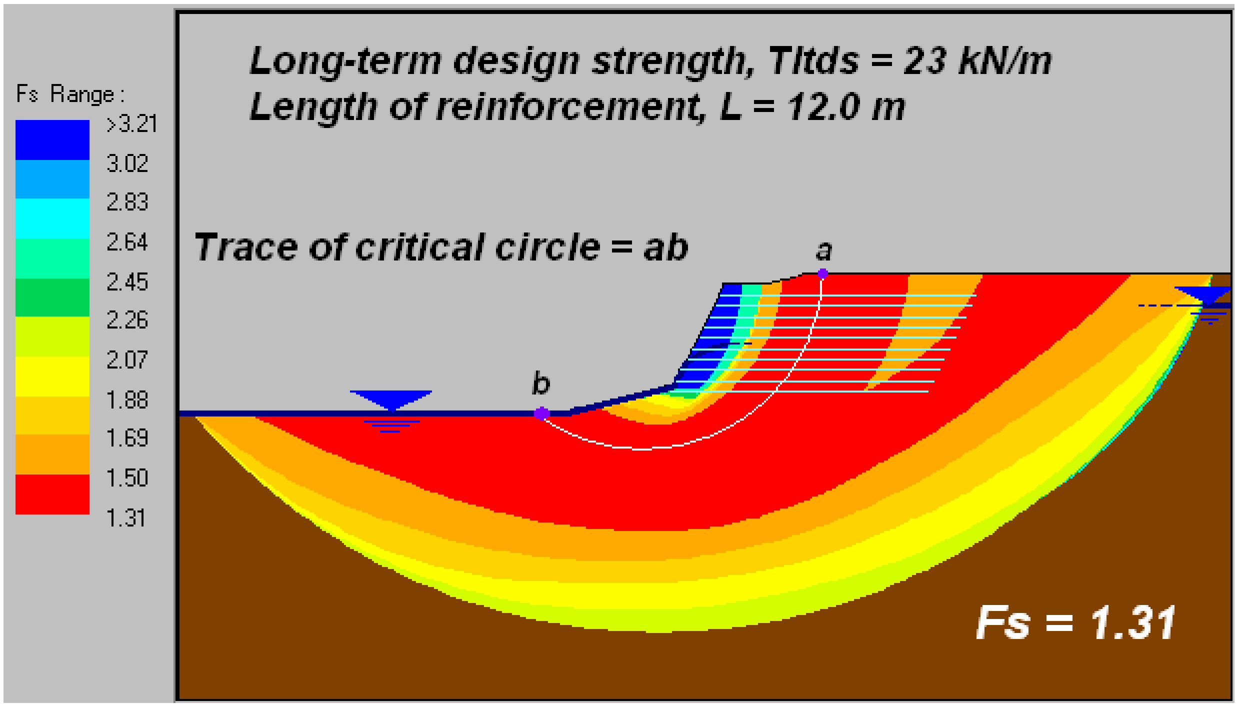

Figure 5. Safety Map considering water seepage through the face using circular slip surfaces combined with Bishop's analysis

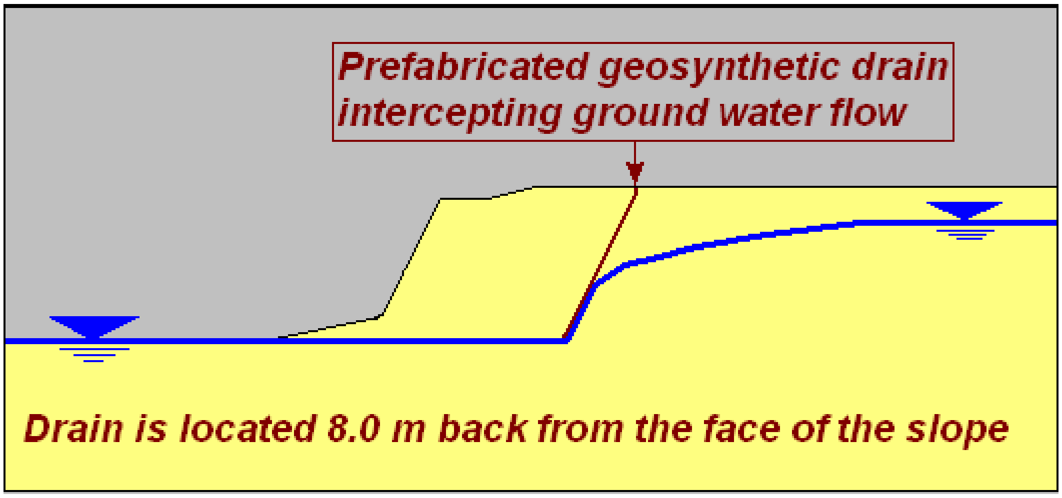

Figure 6. The basic problem with water seepage intercepted by prefabricated geosynthetic drain

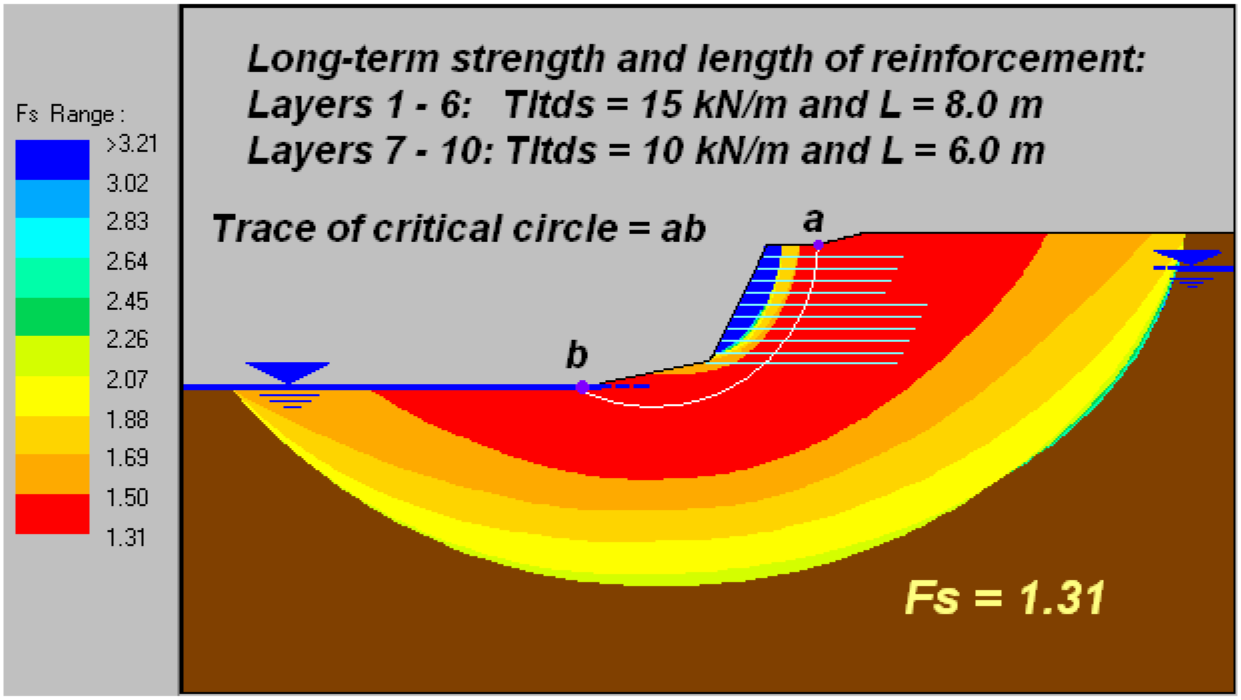

Figure 7. Safety Map considering water seepage and the effects of the drain interceptor using circular slip surfaces combined with Bishop's analysis

The Power of Software in Geosynthetic Reinforcement Applications: Part IV

by

Dov Leshchinsky

The objective in designing geosynthetic reinforced soil structures is to determine the required long-term strength and layout of the reinforcement. The layout and strength are interrelated rendering many possible solutions with the same level of stability but not necessarily having the same economics. Computer program can offer a diagnostic tool that helps the designer to reach an optimal solution. This tool is called Safety Map and was formally presented by Baker and Leshchinsky ("Spatial Distributions of Safety Factors," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127(2), 2001,135-145). This color-coded map shows the distribution of the safety factor within the soil mass thus indicating where the margin of safety is substandard or where it is excessively high. It was implemented in program ReSSA(2.0), developed by ADAMA Engineering (www.GeoPrograms.com). Part I of this series of articles demonstrated the use of Safety Maps in base reinforcement of embankment over soft soil. Part II illustrated the application of the Safety Map in designing complex multitiered reinforced slopes/walls. Part III used the Safety Map to show the effects of water on the required reinforcement strength and layout and thus optimize it. Utilizing the Safety Map approach, Part IV shows the effects of seismicity, employing a pseudostatic approach, on the required reinforcement.

Consider the problem detailed in Figure 1. Under static conditions (no seismicity) and for granular unreinforced slope, the factor of safety equals to tan(phi)/tan(beta) where beta is the angle of the steepest slope. In our case; Fs= tan(36)/0.5 =1.45 where the critical slip surface coincides with the slope surface. Figure 1 uses rotational failures combined with Bishop's analysis to analyze the unreinforced static problem. It confirms the benchmark value of Fs=1.45, showing the critical slip surface to coincide with the slope surface. It also shows the Safety Map. Basically, the zone within which the factor of safety is less than 1.5 is very shallow. For all practical purposes, this slope is stable without reinforcement.

Figure 2 shows the Safety Map for a seismic coefficient of Cs = 0.40/2 = 0.20. Note that the 0.40 represents the maximum ground acceleration. Use of its half value for design in stability analysis of reinforced (and unreinforced) slopes is permissible per FHWA in recognition of the conservative nature of pseudostatic analysis. It can be verified that for seismic analysis of granular slope, Fs = tan(phi)/tan(beta+theta) where theta is equal to arctan(Cs). In our case beta=26.6 degrees, theta=11.3 degrees, and therefore, Fs=tan(36)/(tan(26.6+11.3)=0.93. Similar to the static case, the critical slip surface coincides with the slope surface. Figure 2 confirms these known solutions. However, the minimum Fs by itself is of little value as there is a large zone within which the safety factor is unacceptably too low. The Safety Map in Figure 2 shows the red zone within which Fs<1.3. This zone needs to be stabilized. It is not a shallow zone as it penetrates the foundation implying possible deep seated failure.

Figure 2 reveals that a perfectly stable slope under static conditions might not be stable under seismic conditions. Multiple geosynthetic reinforcement can help. This reinforcement will be dormant under static conditions; however, during an earthquake its strength will be mobilized to keep the slope stable. Hence, concerns about creep (i.e., deformation under sustained load) are not of concern and the ultimate strength of the geosynthetic can be reduced only by construction damage and durability, normally two small factors.

Figures 3 and 4 show the Safety Maps for rotational slip surfaces and translational (2-part wedge) slip surfaces. It is presented for reinforcement layers which are 5.0 m long as implied by the Safety Map for the unreinforced seismic problem in Figure 2. The required strength of the reinforcement is Ts=3 kN/m (about 200 lb/ft), a very small value considering that no reduction for creep is considered. Both Safety Maps have the red zone signifying the range of Fs from its minimal acceptable value (1.3) to 1.5. The Safety Maps imply the following:

8. The safety factor everywhere exceeds the required minimum of 1.3. The maps show that for both, rotational and translational modes of potential failures, a rather large zone (zone defined by red color), Fs is between 1.3 and 1.5, typical economical range for Fs.
9. The red zone in either case is significantly within the reinforced soil zone. This means that the selected strength for the reinforcement is near optimal. That is, stronger reinforcement will push back the red zone thus not mobilizing much the available strength of the reinforcement. The red zone, on the other hand, extends just beyond the reinforcement. This implies that shorter reinforcement could ‘attract’ a slip surface around the reinforcement. Hence, the uniform length of the reinforcement is also near optimum. The selected strength and length of the reinforcement is adequate to resist failure economically. There is no guessing in this procedure – the Safety Map serves as a guide for the most efficient solution. Quickly and objectively.

The example problem demonstrates the power of software in optimal design. The distribution of the safety factor within the soil mass enables the designer to guess an initial layout and strength of reinforcement. The designer can rationally optimize the remedy to yield a structure that is safe and economical. The example problem is interesting in a sense that the slope is sufficiently stable under static conditions but might not be stable under earthquake loading. Hence, the reinforcement is active only during an earthquake event (that exceeds a certain magnitude); otherwise it is dormant. It required strength is typically very low. Consequently, the use of such reinforcement in construction in seismic areas could pay off over time.

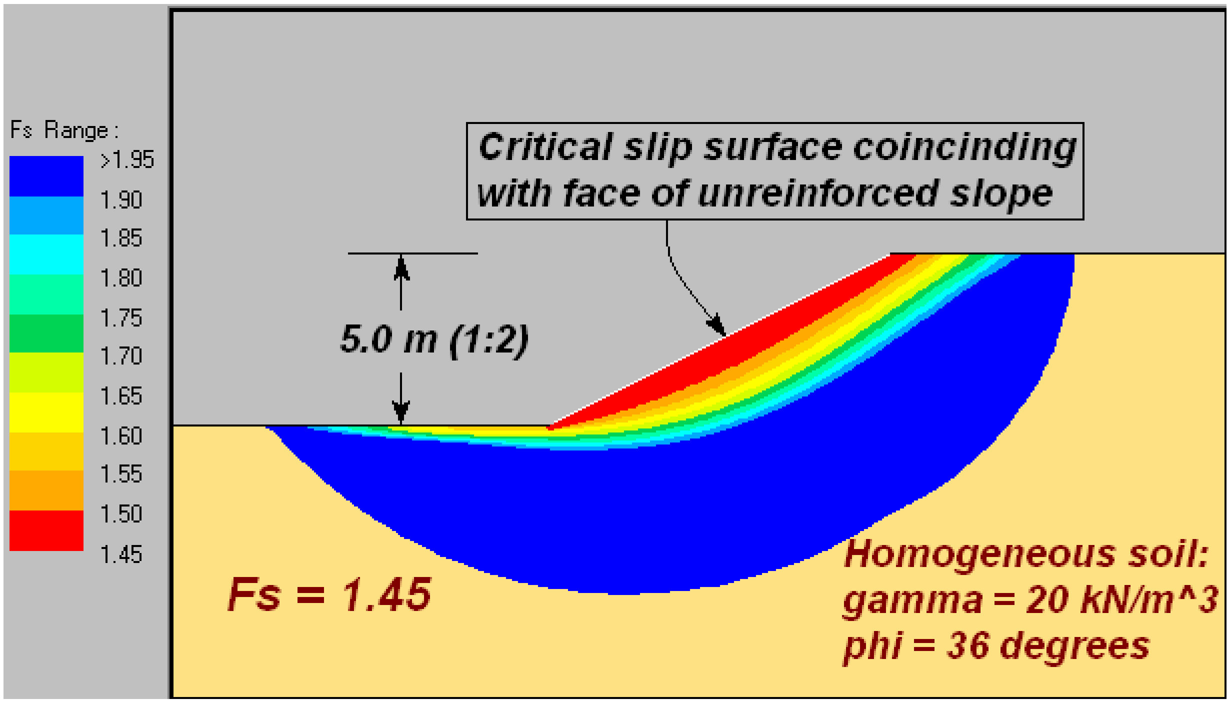

Figure 1. Safety Map for the static unreinforced problem using circular slip surfaces combined with Bishop's analysis

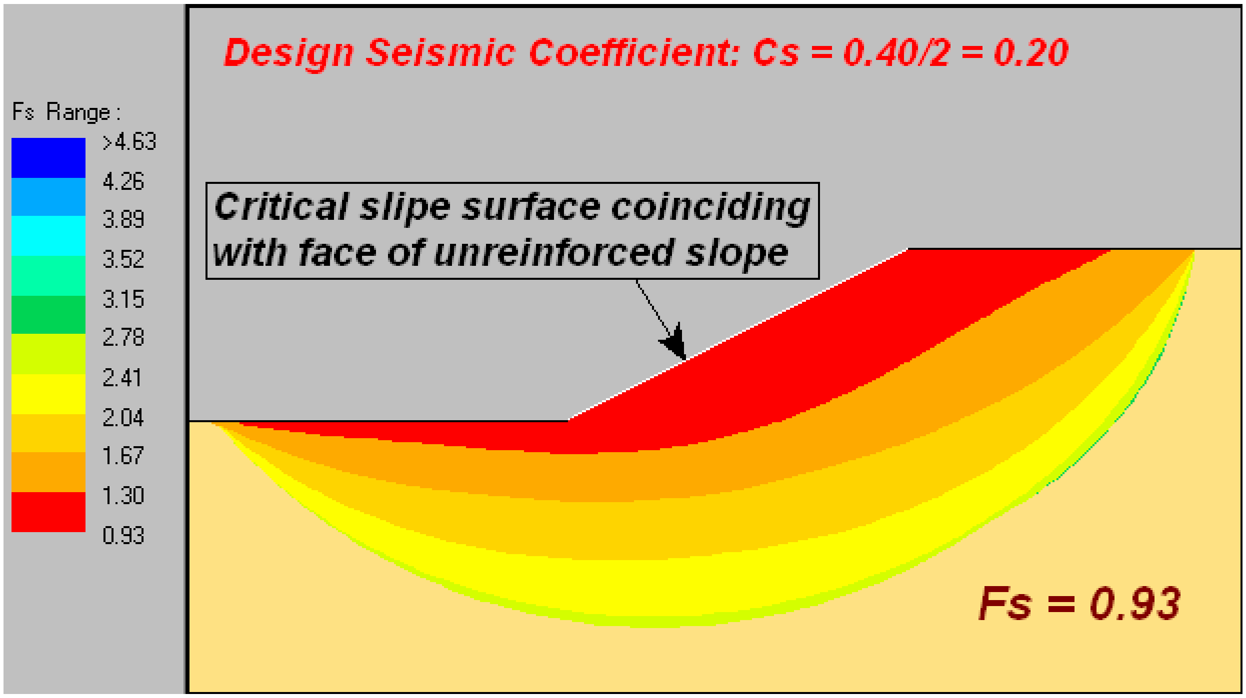

Figure 2. Safety Map for the seismic unreinforced problem using circular slip surfaces combined with Bishop's analysis

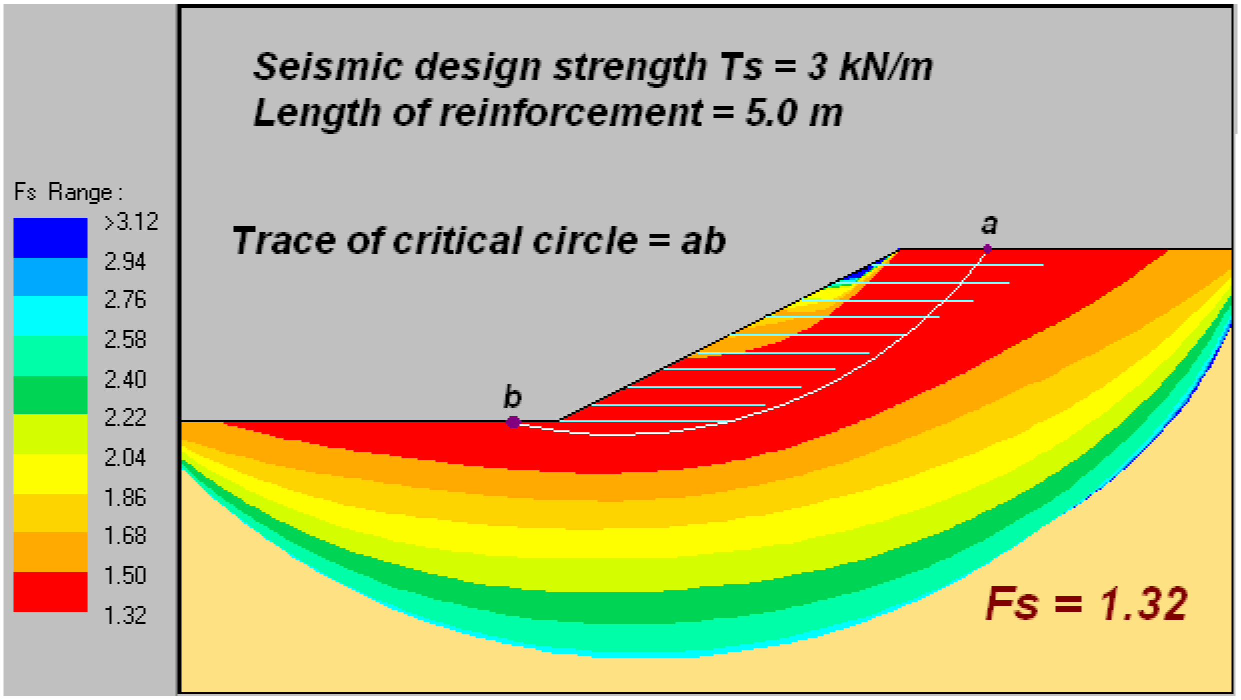

Figure 3. Safety Map for the seismic reinforced problem using circular slip surfaces combined with Bishop's analysis

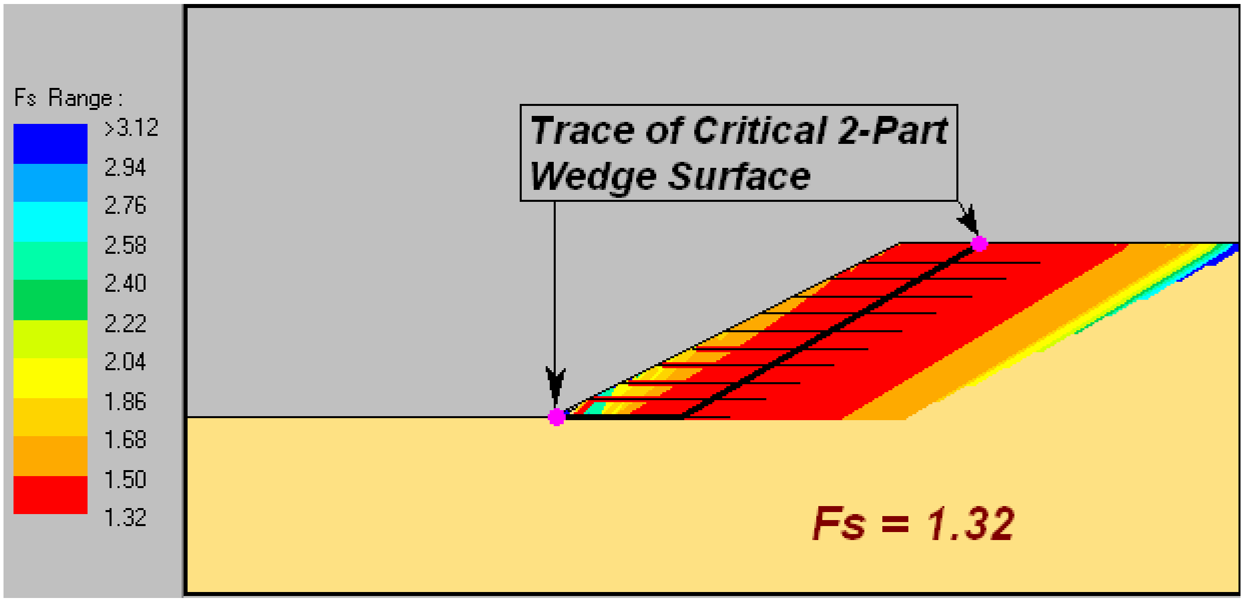

Figure 4. Safety Map for the seismic reinforced problem using 2-part wedge surfaces combined with Spencer's analysis