STABILITY OF RECLAIMED ORE HEAPS WITH GEOMEMBRANE LINING SYSTEMS[1]

By

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Abstract. One of the required tasks in reclaiming an ore heap is to determine the long-term stability of the heap. The slope of the reclaimed heap must be fixed so that the desired factor of safety is obtained. The use of geomembranes in leach pad lining systems creates unique circumstances in that the leach pad lining system typically has lower shear strength than the surrounding materials. The lowest factor of safety is often obtained for the case where the shear surface passes along the geomembrane liner interface for some distance, and then up through the ore heap. Typical values of shear strength parameters for geomembrane materials were extracted from a database of laboratory test results from large-scale direct shear tests. Limit equilibrium stability analyses are summarized in a series of charts for typical ranges of strength and slope configurations. Two limit equilibrium methods are compared. The factor of safety obtained with Spencer's method was always greater than that obtained using the simplified Janbu method. For seismically active regions with an earthquake coefficient of 0.1, the static factor of safety necessary for a pseudo-static factor of safety greater than one was determined for a range in heap slopes.

Additional Key Words: geosynthetics, shear strength, stability charts

Introduction

A reclaimed ore heap should be graded so that it can remain in a stable condition indefinitely. When a geosynthetic material is used to line a heap leach pad, a weak interface is introduced which provides a lower resistance against slope failure. Sliding along the weaker interface must be evaluated in a stability analysis, and is most often the critical mode of failure for heap leach pads founded on competent subgrade.

For an accurate evaluation of ore heap stability, the material properties of the liner, subgrade, and ore materials must be determined. Material properties of various geomembrane to soil interfaces were compiled from a database of laboratory tests and are presented herein.

For preliminary stability analyses of an ore heap, a quick reference that provides the factor of safety for a proposed heap configuration has been developed in this paper. Results of stability analyses for the case of the ore heap sliding along the liner are presented in a series of charts for quick observation. Several different methods of stability analysis exist, and the factor of safety varies slightly with each different method. Two different limit equilibrium methods were utilized and compared in the development of the stability charts.

For heaps located in seismic zones, the stability of the ore heap can be evaluated using a pseudo-static procedure. A series of analyses were performed to determine the necessary static factor of safety required to obtain a factor of safety greater than one when a pseudo-static analysis is performed on the same heap configuration.

Stability Analyses for Reclaimed Ore Heaps

One step in the reclamation or design of ore heaps is to determine the maximum slope at which the ore heap can be graded while maintaining a minimum factor of safety against slope failure. The factor of safety against slope failure depends upon many factors which are discussed briefly within this paper.

There are two opposing details which present themselves in the design of leach pads. The first is that a leach pad liner is designed to achieve a low hydraulic conductivity. The materials with the lowest hydraulic conductivity inevitably have poor shear strength qualities. The second opposing detail is that the subgrade near the toe of the heap must be graded for drainage of the leach solution, which creates a steeper sliding surface on which the ore can slide.

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The majority of slope stability analyses are based on the concept of limit equilibrium. According to limit equilibrium theory, the slope is evaluated as though it is just on the verge of failure, and the shear strength necessary to "hold back" the slope is determined. The slope stability analysis consists of defining a two-dimensional cross section of the heap configuration, defining a likely shear failure surface, and calculating the factor of safety for the selected failure surface. The factor of safety can be defined as the ratio of the shear strength along the failure surface to the equilibrium shear stress along the same surface. The equilibrium shear stress, or "mobilized" shear strength, is therefore equal to the shear strength of the heap materials divided by the factor of safety.

Part of the stability analysis procedure is to search out the critical failure surface that produces the lowest factor of safety for the ore heap. A weaker shear plane results within the lining system, compared with the surrounding materials, due to the introduction of geomembranes into the leach pad lining system, which are utilized to achieve a required low hydraulic conductivity. The shear strength of soil against geomembranes is most often lower than that of the soil itself (Martin et al, 1984).

The majority of limit equilibrium slope stability methods employ a method of slices to analyze the factor of safety for a given slope. The number of unknown force vectors acting on each slice are such that the problem of slope stability becomes statically indeterminate. As a result, some simplifying assumptions must be made to make the problem determinate. Due to differences in assumptions, a variety of methods have been developed. Two methods were utilized in this study to evaluate ore heaps with geosynthetic liners, the simplified Janbu method (1956), and Spencer's method (1967).

In Janbu's Simplified method, overall force equilibrium is satisfied but not overall moment equilibrium. Janbu assumed that the inter-slice forces were equal to zero, and then applied a correction factor to account for them.

In Spencer's method, both overall force and moment equilibrium are satisfied. Spencer assumed that the inter-slice force vectors were parallel.

When there are unknown or suspected inaccuracies or variance in the material properties, the simplified Janbu method can be used to obtain more conservative results. The alternative procedure (preferred by the author) would be to obtain more accurate material properties and utilize Spencer's method of slices.

The stability analyses completed for this paper were performed utilizing the computer program PCSTABL5 (Siegel, 1975). The computer program utilized the simplified Janbu and Spencer's methods of slices to calculate the factor of safety for non-circular shear failure surfaces. The critical shear surface was found interactively during program execution. Non-circular shear surfaces were made to shear along the geosynthetic liner interface for some distance, and then up through the ore. Depending on the subgrade properties or other varying features of the ore heap, the factors of safety determined for sliding of the ore heap along the geomembrane liner may not be the lowest factors of safety. Other forms of failure may produce the critical factor of safety, and must also be evaluated.

Material Properties

The stability of a given ore heap configuration is dependent upon the properties of the materials that exist within and below the heap. The material properties that must be defined are the shear strength and unit weight of each material. A typical ore heap stability model consists of three different materials: the ore, the lining system, and the subgrade. It is important that, wherever possible, samples of the exact materials existing within the heap should be tested in the laboratory to determine their material properties. The subgrade, lining, and ore materials should be tested to determine their shear strength and unit weight properties.

The shear strength, s, of the ore and liner interfaces can be expressed according to Mohr-Coulomb theory as:

$$s = c + \sigma \tan(\phi) \qquad (1)$$

where c is the cohesion or adhesion (shear strength when the confining pressure is zero), σ is the normal stress on the shear plane, and ϕ is the angle of internal friction (slope of the Mohr-Coulomb failure envelope).

For the purposes of this study, it was assumed that the subgrade beneath the ore heap is competent, with a strength significantly greater than the weakest interface within the lining system. Since the shear surface was forced to pass along the leach pad lining system and then up through the ore, the only material types requiring definition consisted of the ore material and the lining system components.

For long term conditions of a reclaimed ore heap, the stability should be analyzed in terms of effective stresses. The concept of effective stress refers to the use of shear strength parameters measured under drained conditions, with consideration of pore pressures for calculation of the normal stress on the shear plane. As part of the heap reclamation, the prevention of water head building up above the liner should be included in the closure design. Prevention of head buildup may be achieved by perforation the lining system to allow infiltration of water into the subgrade. In addition, a cover system which limits the amount of infiltration into the heap can be designed. The design should allow any water entering the heap to exit at the toe. Based on the assumption that some preventative measures are performed to limit water head buildup, the stability analyses performed for long term conditions did not include a phreatic surface within the heap.

The stress-strain curves for many soils or liner interfaces exhibit both a peak and residual shear strength. Strains may occur within the heap during the long period after heap closure which exceed the displacement coincident with the peak shear stress. To avoid a progressive type failure of the heap, the residual strengths of the materials should be used.

Ore Material Properties

The ore material can usually be considered as a homogeneous material. The shear strength of ore material is typically modeled with a friction angle between 30 to 45 degrees, although friction angles as high as 55 degrees can exist for the crushed ore materials. For long term stability analyses, the ore material should be modeled as a cohesionless material even if the ore contains a substantial amount of fine-grained material (Skempton, 1948). The stability charts developed as part of this study utilized a friction angle of 30 degrees for the ore, which in most cases will be conservative.

Although the unit weight of the heap materials enters into the stability equation, the stability of the ore heap is much more sensitive to the shear strength than to the unit weight of the ore material. The unit weight of ore typically varies between 100 to 120 pounds per cubic foot (pcf), depending on the depth within the heap and the manner in which it was placed on the heap leach pad. For this study, a unit weight of 110 pcf was used for the ore material.

Lining System Properties

The lining system can be modeled within the stability analyses as a layer of soil, typically with a thickness of 1 foot. The shear strength of the weakest interface or soil within the lining system is assigned to the equivalent soil layer. The critical shear failure surface is forced to pass through this equivalent soil layer to simulate shear along the weakest interface. The unit weight of the equivalent soil layer should be set equal to the overlying ore materials, although the stability results are not sensitive to this variable due to the small layer thickness compared to the heap.

The geosynthetic material used beneath the heap should be tested against the ore and/or subgrade materials in order to determine the lowest shear strength parameters to use for the liner in the stability analyses. It is important that geosynthetic materials identical to those used for construction are used in the testing program. The interface shear strength for the different geosynthetic material types can vary with the type of texturing, type of resin, or the manufacturer. Friction angles of soil and geomembrane interfaces are lowest for smoother, harder geomembranes, while rougher, softer geomembranes have relatively high friction values (Koerner, 1994). The interface shear strength should be tested utilizing a large scale direct shear device, in accordance with ASTM D5321. In the large scale direct shear test, the geosynthetic material to be tested is placed on the lower (fixed) portion of the box and the other material is forced to shear over it.

To aid in preliminary stability analyses of an ore heap, data from large scale direct shear tests were compiled for a variety of materials used in lining systems. In order to compare each shear test equally, the shear strength that was measured for each test was normalized to a specific cohesion, with the shear strength equalized at a normal pressure equivalent to the pressure exerted by approximately 90 feet of ore material, as shown in the example in Figure 1.

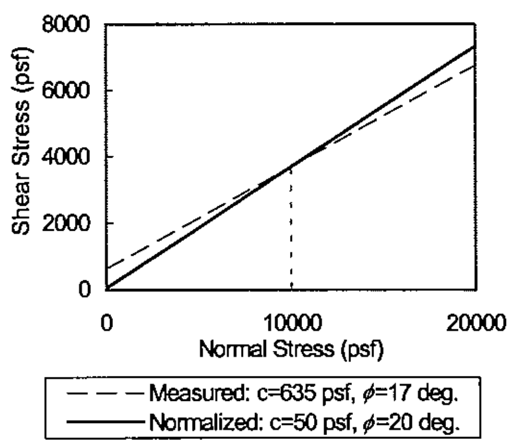

Figure 1. Normalization of measured shear strength parameters by rotating failure envelope.

The average cohesion measured for the interfaces with textured geosynthetic material was higher than that for smooth material. The average cohesion value for the interface tests with textured liner was 400 psf, while the average cohesion value for tests with smooth liner was 100 psf. For normalizing the friction angles, a cohesion of 50 psf and 200 psf was used for smooth and textured geomembranes, respectively, equal to one-half of the average values. The resulting normalized friction angles for the various soil and geomembrane materials are summarized in Table 1.

Although geomembranes were considered exclusively in this paper, the stability charts may also be used for lining systems that utilize other geosynthetic materials such as geotextiles or geocomposite clay liners. The shear strength of geotextiles to soil tends to be in the same order as the angle of shearing resistance of the soil (Williams, 1987). For geotextiles to smooth geomembrane, however, very low friction angles may result. Also, if the soil material that is part of the lining system is a weak clay such as montmorillonite, the strength of the lining system may be controlled by the shear strength of the clay itself. The friction angle of montmorillonite clay materials can be as low as 5 degrees (Olson, 1974). Special consideration is required for geosynthetic clay liners that utilize montmorillonite. In many cases, alternative stabilizing methods may be required beyond simply decreasing the slope of the ore heap.

Table 1. Summary of large scale direct shear tests with geomembrane to soil.

Smooth Liner				
	Average	High	Low	No. of Tests
c – LLDPE (psf)	110	360	0	32
c – HDPE (psf)	101	550	0	17
ϕ, Clay / HDPE (°)	11	15	8	9
ϕ, Sand / HDPE (°)	18	24	9	15
ϕ, Gravel/HDPE (°)	26	32	23	6
Textured Liner				
	Average	High	Low	No. of Tests
c – LLDPE (psf)	156	2510	0	84
c – HDPE (psf)	433	620	0	13
ϕ, Clay / HDPE (°)	21	41	5	42
ϕ, Sand / HDPE (°)	30	36	15	34
ϕ, Gravel/HDPE (°)	29	36	20	6

Stability Charts

The slope stability charts included in this paper were developed to reduce a multi-dimensional problem into a two-dimensional graphic display. The following parameters are required in order to perform a stability analysis of an ore heap with a geomembrane liner:

- F = factor of safety
- H = height of embankment (toe to crest),
- ϕ_{gi} = internal friction angle of geosynthetic interface,
- c_{gi} = adhesion of geosynthetic interface,
- ϕ_{ore} = internal friction angle of ore,
- c_{ore} = cohesion of ore,
- β = slope of ore heap, and
- α = slope of leach pad subgrade.

The height of the embankment, shear strength of the ore, and the adhesion of the geosynthetic to soil, were held constant for each chart. In order to reduce the amount of graphs required, the slope of the ore heap and leach pad subgrade were combined into one parameter, a slope factor, λ. The equation for the slope factor which combined the subgrade slope with the slope of the ore heap varied for different combinations of constant variables, and is printed above each chart.

Based on the typical values of liner interface shear strength described above, a range of internal friction angles for the lining system from 5 to 25 degrees was evaluated. Two different adhesion values for the geosynthetic interface were evaluated, 50 psf and 200 psf. An adhesion of 50 psf should be used for smooth geomembranes, and an adhesion of 200 psf should be used for textured geomembranes.

The height of the heap was varied in the stability analyses from 20 feet to 300 feet. The rate of change in the factor of safety was greatest for changes in heap height from 20 feet to 100 feet, and less of a change was noted for increasing the heap height from 100 to 300 feet.

The ore was modeled in all of the stability analyses as a cohesionless material, with an internal friction angle of 30 degrees. This will provide conservative results in most cases, since average ore shear strength parameters are typically around 35 degrees.

With the heap height, ore shear strength, and adhesion of the geosynthetic to soil held constant, the factor of safety was a function of the slope factor, λ, and the friction angle of the geosynthetic interface, as shown in the example of Figure 2. A power type curve was fit to the data points for each friction angle. Each data point used to create the curves represents the results of a stability analysis completed with the computer program PCSTABL5, utilizing either Spencer's or the simplified Janbu method of slices. The degree of error was relatively small for factors of safety between 1.0 and 2.5. Beyond these values, the factor of safety may deviate from the correct value by as much as one-tenth.

Using the best fit curves for each friction angle that was evaluated, stability charts were developed, and are presented in Figure 3 and Figure 4 for Spencer's and simplified Janbu methods respectively. The three charts on the left hand side of each figure should be used in the case where textured geomembranes were used in the lining system for the interface under consideration. The three charts on the right should be used for smooth geomembrane interfaces.

Factors of safety obtained by the simplified Janbu method were always lower than those obtained using Spencer's method. Janbu's method gave results between 86 to 98 percent of the factor of safety obtained with Spencer's method. Less variation between the results from the two methods was observed for lower interface friction angles and taller heap heights.

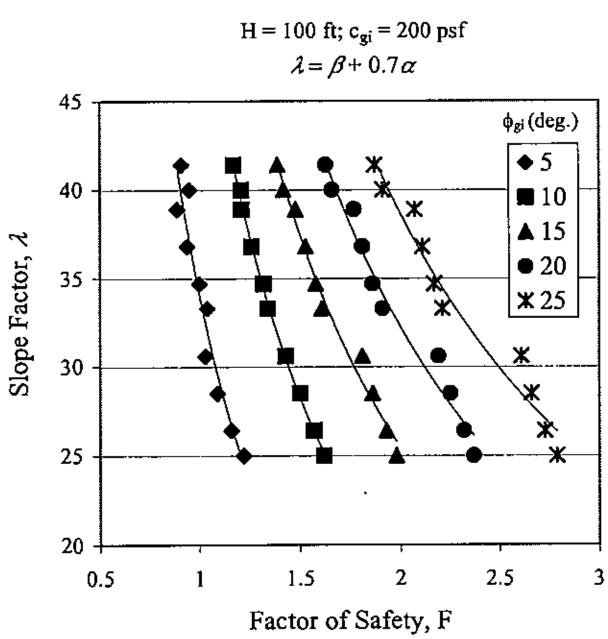

Figure 2. Example results of stability analyses showing power type curve fit to data points.

Ore Heaps in Seismic Zones

The stability of an ore heap in a seismic zone is typically evaluated using a pseudo-static procedure, in which the slope is subjected to a horizontal force equal to a seismic coefficient times the acceleration of gravity. The factor of safety is decreased due to the additional driving forces.

If the factor of safety for the pseudo-static case is less than one, displacement of the heap may occur during a seismic event. In order to facilitate the preliminary determination of the heap configuration, a minimum required factor of safety under static conditions could be set so that the heap remains stable under seismic forces, dependent on the magnitude of the seismic coefficient.

Such a relationship was determined for a seismic coefficient of 0.1, with the range of heap configurations and material properties analyzed in this paper. The required static factor of safety was mainly dependent on the slope of the ore heap. The resulting minimum static factors of safety that resulted in a pseudo-static factor of safety equal to one for a seismic coefficient of 0.1 are summarized in Figure 5.

Conclusions

The stability of ore heaps with geomembrane liners was evaluated assuming that the critical failure surface passed along the lining system for some distance and then up through the ore. The charts developed as part of this study provide accurate results, but should be considered preliminary for the reason that other modes of failure must also be evaluated. Although the form of failure with ore sliding on the a weak interface within the lining system is typically the most critical, a stability analysis of the cover system and a stability analysis that includes the subgrade beneath the leach pad should be performed.

The shear strength of various soils to geomembrane material was summarized. For smooth geomembranes, a friction angle of 11, 18, and 26 were the average values for clay, sand, and gravel materials respectively. The use of textured geomembrane can significantly improve the interface friction by 60 to 90 percent. While an indication of shear strength parameters for various materials has been presented, the data are so sensitive to specific materials that literature values should never be used for final design purposes.

Janbu's simplified method yield factors of safety lower than Spencer's method. The simplified Janbu method yields conservative results, although

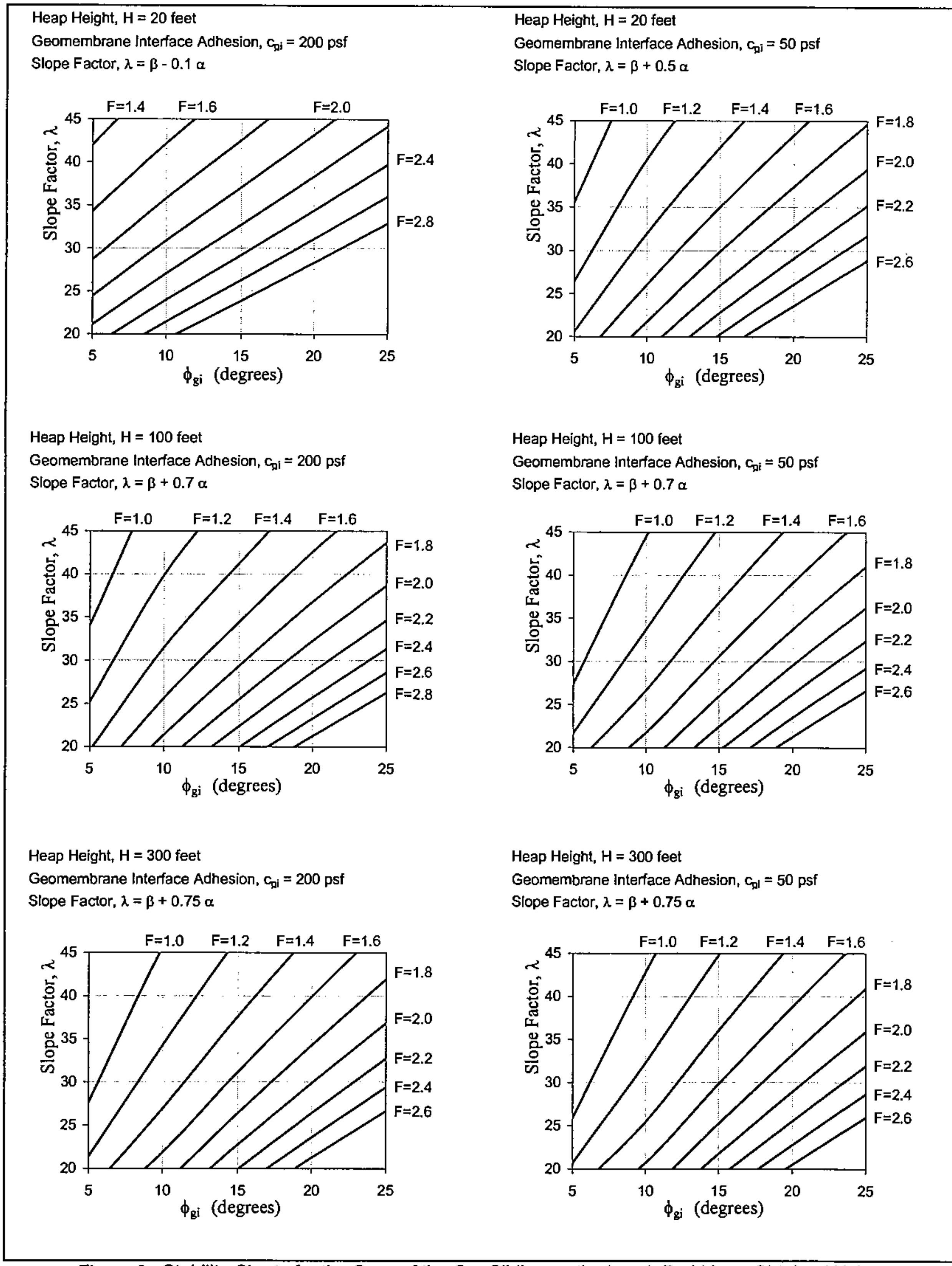

Figure 3. Stability Charts for the Case of the Ore Sliding on the Leach Pad Liner, Obtained Using Spencer's Method of Slices.

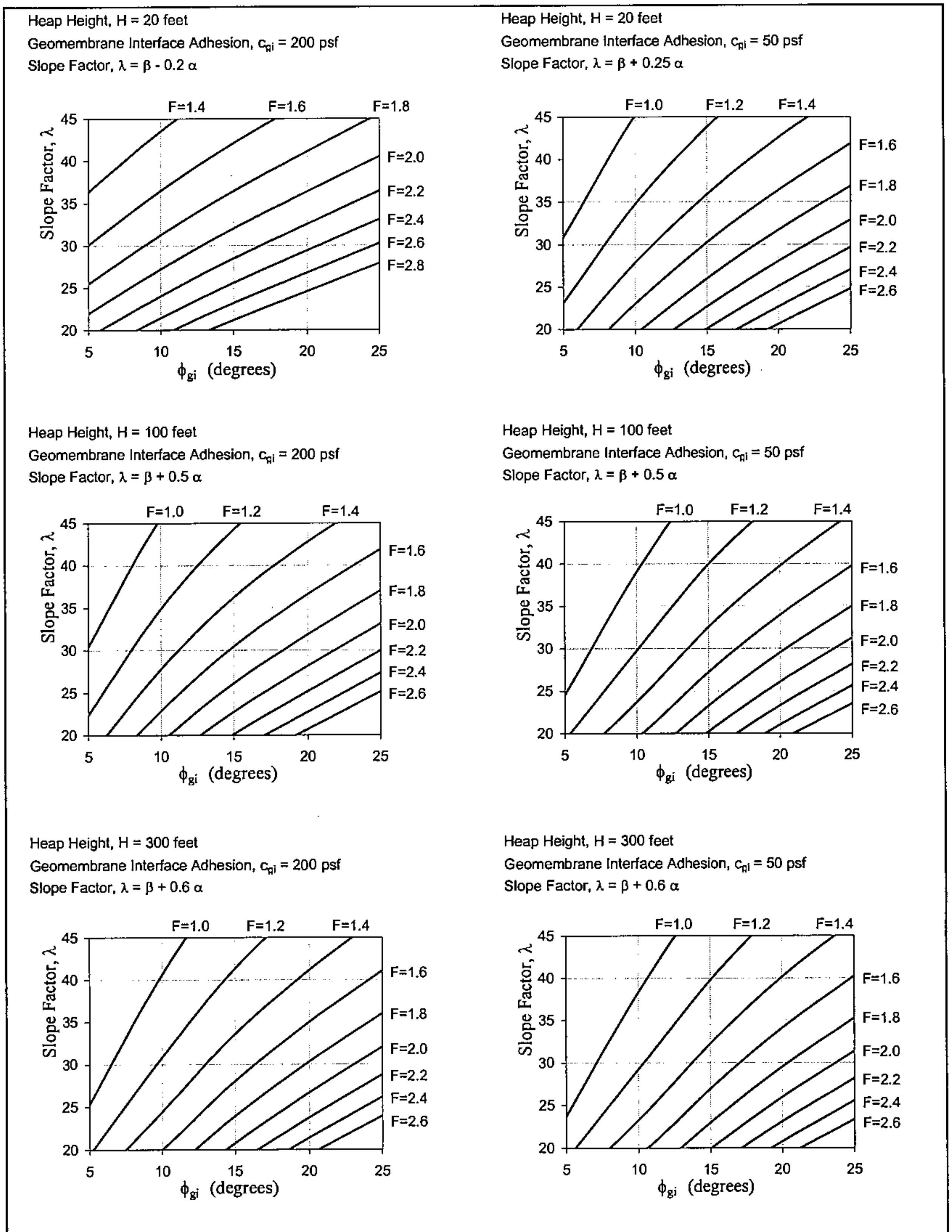

Figure 4. Stability Charts for the Case of the Ore Sliding on the Leach Pad Liner, Obtained Using the Simplified Janbu Method of Slices.

Spencer's method is arguably more accurate since it satisfies both moment and force equilibrium.

The stability charts included in this paper provide a quick reference to allow determination of a starting point from which to begin analyses for reclaiming an old ore heap.

It should be noted that other factors may govern the final heap slope grading such as erosion potential of steeper slopes. Re-vegetation requirements of the slopes may control the slope angle of the heap face.

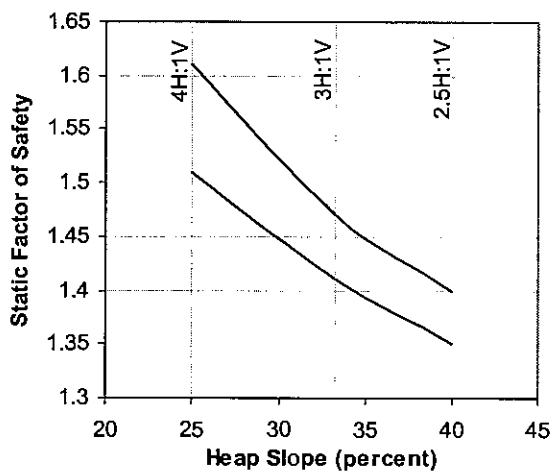

Figure 5. Upper and Lower Bounds for the static Factor of Safety for which the Pseudo-static Factor of Safety Equals One for a seismic coefficient of 0.1.

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