Analysis of Tieback Slopes and Walls Using STABL5 and PCSTABL5

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The purpose of this study was to develop a convenient method for assessing the stability of tieback structures using the simplified methods of slices. The Load Distribution Method was developed to transmit the load from a row of tiebacks to the potential failure surface for use with the simplified methods of slices. The load from a row of tiebacks is assumed to form a uniform line load that is distributed to the potential failure surface. This distribution is based on Flamant's distribution of stresses through a semi-infinite elastic medium. STABL5 and PCSTABL5 are limiting equilibrium slope stability programs that contain the Load Distribution Method routines. These programs may be used to analyze the stability of tiedback slopes for landslide stabilization, as well as to determine the overall stability of tiedback walls. The programs consider multiple rows of tiebacks, multiple tiedback structures as well as tieback loads, inclination, and length. The method developed was found to give good results and is applicable to those problems in which the application of a semi-infinite elastic half space may be used to model the slope conditions, and which may be modeled using a two-dimensional analysis. This paper is a brief review of some of the previously available methods for analyzing the overall stability of tiedback structures. In addition, a discussion of the capabilities of STABL5 and PCSTABL5 is presented, and the development of the Load Distribution Method is summarized. The assumptions used in the development of the Load Distribution Method are discussed, along with the implications and limitations of using Flamant's distribution. The effect of tieback load on the factor of safety is also presented, along with recommendations concerning factors of safety for overall stability of tiedback slopes and walls.

The use of tiebacks in geotechnical engineering, transportation, construction for support of transportation routes, construction excavations, and landslide control has increased substantially within the last 10 to 15 years. As a result, the need for a reliable and practical method of analyzing the internal and overall (external) stability of slopes and retaining walls subjected to tieback anchor loads has become evident.

Tiebacks are routinely used for both temporary and permanent support of excavated slopes. Tiedback or anchored retaining structures for temporary and permanent support of excavations may consist of soldier piles with wood lagging, sheet piling, drilled concrete pile walls, or concrete diaphragm walls constructed using the slurry trench method. Tiedback retaining structures for stabilization of embankments and slopes may be continuous along the length of a slope, as in soldier piles and wood lagging, or may be discontinuous, as in tiedback drilled piers with concrete bearing pads or buttress elements placed on the face of the slope.

The analysis of the stability of tiedback structures is a complex problem. The stability of these structures is influenced by, but not limited to (a) the lateral earth pressure behind the wall; (b) the deformation of the soil-structure system; (c) tieback characteristics (individual tieback loads, inclination, horizontal spacing, overall length, size of anchor, method of construction); and (d) soil characteristics. The analysis of tiedback structures is further complicated by the fact that a two-dimensional model is used to model a three-dimensional problem. Analysis of the overall stability of tiedback structures is only one of the many considerations in the design of tiedback structures for excavation support or slope stabilization. Because many factors influence the stability of tiedback structures, and because relatively little is known about these factors at the time of design, a conservative approach is often used by geotechnical engineers and design-and-build tieback contractors in the design of tiedback structures.

Previously available methods for determining the internal and overall stability of multiple tiedback structures (*1–3*) often involved errors in the statement of the problem, or required that arbitrary assumptions be made to perform the calculations, usually by hand (*4*). In addition, it was extremely difficult and tedious to take into consideration nonhomogeneous soil conditions and multiple tiebacks with the previously existing methods of stability analysis. Therefore, there existed a need for a convenient and logical method for determining the internal and external stability of multiple tiedback retaining structures considering nonhomogeneous soil conditions.

The purpose of this study was to develop a rational and convenient method of assessing the internal and overall stability of tiedback and anchored retaining structures. As a result, the Load Distribution Method (LDM) was developed for analyzing the stability of tiedback slopes and walls in conjunction with the simplified methods of slices contained in the STABL programs. The LDM was originally programmed in the slope stability programs STABL4 and PCSTABL4 (*5, 6*) and is also contained in STABL5 and PCSTABL5. The STABL5 and PCSTABL5 versions retain all the capabilities and options of STABL4 and PCSTABL4. However, STABL5 and PCSTABL5 are the only versions of STABL with the enhanced capabilities of analyzing potential failure surfaces, including tiedback slopes and walls, using Spencer's method of slices. The focus of this paper will be on the LDM developed by the author because it is this method that is used most frequently.

CAPABILITIES OF STABL5 AND PCSTABL5

The STABL5 and PCSTABL5 programs calculate the factor of safety against slope failure by a two-dimensional limiting

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equilibrium method. These programs are written in FORTRAN and contain routines for analyzing slopes and walls subjected to tieback loads. PCSTABL5 is the microcomputer version of the mainframe STABL5 program and contains all the options and capabilities of STABL5. The calculation of the factor of safety against slope instability may be performed using (a) the Simplified Bishop method of slices, which is applicable to circular shaped failure surfaces; (b) the Simplified Janbu method of slices, which is applicable to failure surfaces of a general shape, or; (c) Spencer's method of slices, which is applicable to surfaces having a circular or general shape.

The STABL5 and PCSTABL5 slope stability programs feature unique techniques for random generation of potential failure surfaces for subsequent determination of the more critical failure surfaces and their corresponding factors of safety. Circular, irregular, and sliding block surfaces may be generated and analyzed using either a random search technique or specific input of the coordinates of a given potential failure surface.

The programs are capable of handling heterogeneous soil systems, isotropic and anisotropic soil strength parameters, excess pore water pressure caused by shear, static groundwater and surface water, pseudo-static earthquake loading surcharge, and tieback loading. The tieback loading feature provides for the input of horizontal or near-horizontal tieback or line loads for analyzing the internal and overall stability of tiedback or braced slopes and retaining walls.

Plotted output is provided as a visual aid to confirm the correctness of problem input data. Error messages are generated within the program to pinpoint locations where input data are inconsistent with STABL5/PCSTABL5's input requirements. Free-format data input eases the task of input file preparation, which results in a reduction of input mistakes.

Plotting routines are provided for Calcomp-type plotters (STABL5 version) and for Hewlett-Packard plotters for use with the microcomputer version PCSTABL5. The PLOTSTBL program is a BASIC program for plotting the graphical output from PCSTABL5 using either a Hewlett-Packard HP-7470A two-pen plotter or an HP-7475A six-pen plotter. PLOTSTBL reads the plotted output file created by PCSTABL5, which contains commands and coordinates for plotting.

ANALYSIS OF TIEDBACK WALLS AND SLOPES

Tiebacks tie a structure to a stable soil mass through an anchor secured in the earth. The components of a typical tiedback retaining structure are shown in Figure 1. The anchor is attached to a steel tendon, which is also connected to the retaining structure. After installation of the tendon and grouting of the anchor, the tendon is stressed (pulled) to the desired load using hydraulic jacks. This load is then locked off and permanently applied to the structure. The load in the steel tendon applies a stabilizing force to the structure that is developed by the anchor in the stable soil mass. Tiebacks are different from deadman anchors in that the tieback anchor is made through a hole drilled or driven into the soil for installation of the tendon.

Assumptions are made in the design of a tiedback retaining structure concerning the lateral earth pressure distribution behind the proposed wall. On the basis of the assumed lateral earth pressure distribution, the location and magnitude of load applied to each tieback is determined for the internal (local) stability of the wall. The structure-anchor system must be designed to resist the lateral earth pressures with a suitable factor of safety (FOS). The tieback must then be designed to carry the computed load. The length of the tendon and anchor of the tieback must be made long enough so that the tieback is beyond the area that would be disturbed by wall movements and it will not pull out of the soil mass in which it is secured.

Tiebacks tie a structure to a soil mass that must also be

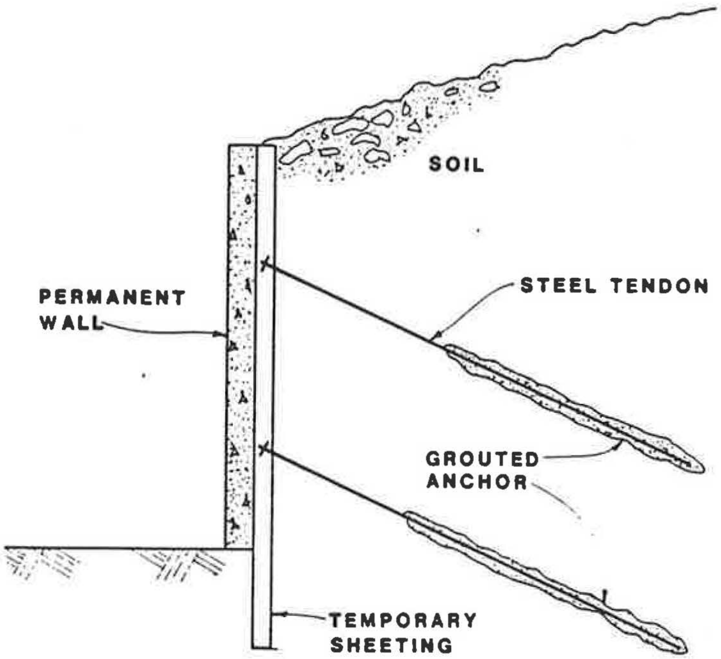


FIGURE 1 Components of a tiedback retaining structure.

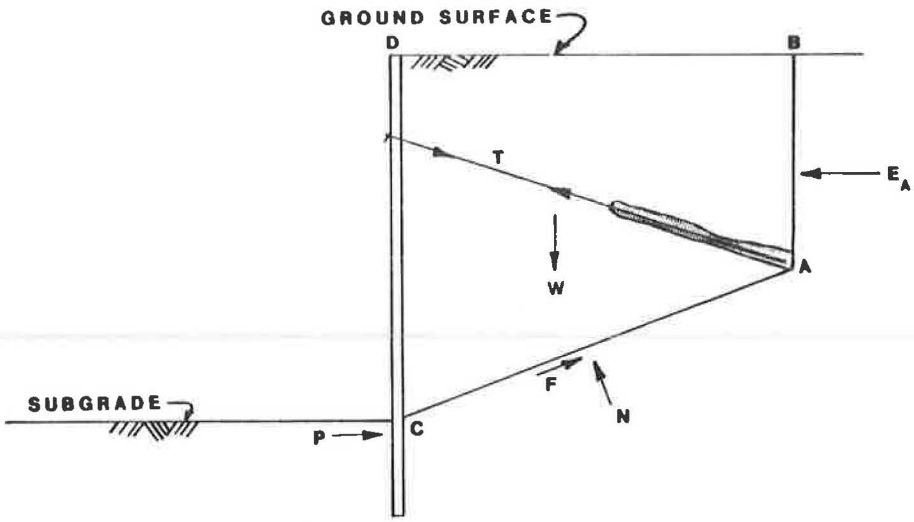


FIGURE 2 Soil mass analyzed for overall stability analysis (*7*).

both internally and externally stable. The shape of the soil mass analyzed for overall stability is often taken to be wedge shaped, as shown in Figure 2. If a tiedback wall is properly designed and the tiebacks have the desired capacity, the pressure on the wall and the tieback will create stabilizing internal forces within this soil mass. The soil-structure-anchor system is then considered to be internally stable.

In addition to ensuring the internal stability of the soil-structure-anchor system, the overall stability of the system must also be checked and a suitable FOS determined. The determination of the FOS for any potential surface that passes behind the ends of the tiebacks is considered a FOS with respect to overall (external) stability (Figure 3*A*), whereas the FOS for any potential failure surface that passes between the ends of the tiebacks and the wall is considered a FOS with respect to internal stability (Figure 3*B*).

If the external stability is insufficient, it may be increased by modifying the tieback geometry. This is usually accomplished by lengthening the tiebacks. Because the loads in the tiebacks are internal forces within the soil mass wedge, they do not increase the overall stability of the system. Increasing the load on the tiebacks or increasing the number of tiebacks will only serve to increase the internal stability of the wedge. Because the cost per tieback increases as the length increases, it is desirable to determine the shortest length of tiebacks, while providing a suitable FOS with respect to external stability.

For the overall stability of the soil-structure-anchor system, the soil mass of Figure 2 is often analyzed. The wedge shape of Figure 2 may be used to expedite hand calculations and is a simplification of the actual conditions. This soil-structure model forms the basis of the Krantz method. The forces tending to displace the soil mass are weight of the soil mass, W, and the earth pressure, E_a, on plane, AB. The earth pressure, E_a, on plane, AB, is usually taken as the active earth pressure, although the at-rest earth pressure condition is sometimes used, (*Z*). The external forces resisting displacement of the soil mass are the tangential and normal forces, F and N, on the failure plane, AC. The failure surface, AC, may not be straight as shown, but may be curved depending on the soil parameters. In addition, if the retaining structure penetrates some distance below the subgrade, passive resistance, P, will be mobilized at the base of the wall. The FOS with respect to overall stability is defined as the ratio of the sum of the resisting forces to the sum of the driving forces. A typical suitable FOS for this type of analysis is 1.5 or greater (*8*).

It is important to stress that the tieback force is an internal force within the wedge and does not affect the external stability of the soil mass. The tieback applies a load to the wall that pushes on the soil. The forces between the wall and the anchor are equal and opposite, which tends to compress the soil.

The Krantz method is based on the soil mass of Figure 2 (*1*). The Krantz method is based on laboratory tests and analyses in which an external pull (force) is applied to the soil wedge. This method requires the calculation of an external force that would be required to displace the soil wedge in which the tiebacks are anchored. The external force is taken as the possible tieback load. This method involves serious errors in the statement of the problem that make it inappropriate for determining the overall stability of anchored structures (*4*). The errors result from the fact that the method assumes that the tiebacks pull on the soil without pushing on the wall. The analysis proposed by Krantz assumes that the tieback force is an external force acting on the soil wedge, whereas the tieback force is actually an internal force in this wedge. The tieback is in tension between the wall and its anchor and is not related to the force required to move the wedge. It is therefore inaccurate to treat the tieback force as an external force acting on the wedge that results in mixing internal and external forces (*4*).

Unfortunately, the Krantz method and others based on this method (*2, 3*) are still used today. In light of the inaccuracies of the methods based on the Krantz method, it is the opinion of the author and of Schnabel (*4*) that this type of analysis should be discontinued in practice because of the errors in the model.

Other Uses and Methods Proposed

Other methods have been proposed *9–11*) that use a wedge-shaped soil mass, but properly consider the tieback force to

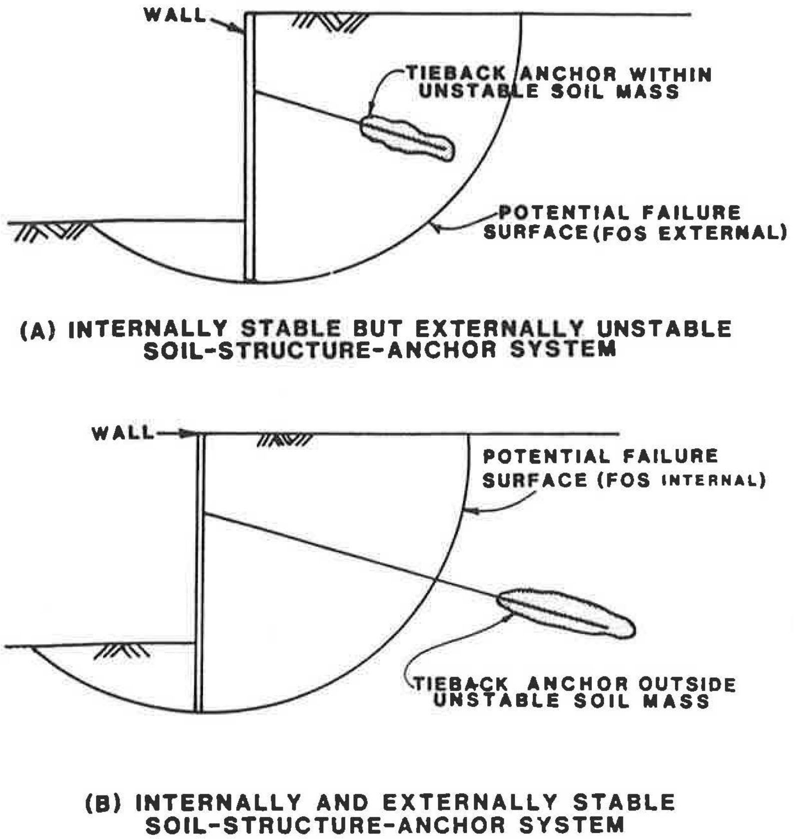


FIGURE 3 Modes of tiedback wall stability and instability.

be an internal force within the soil mass. These methods are rather straightforward for homogeneous soil conditions and a single row of tiebacks. However, the hand calculation required for these analyses becomes cumbersome and tedious for multiple rows of tiebacks, layered, or nonhomogeneous soil conditions. In some cases the method is not able to account for these conditions or the definition of the FOS breaks down for purely cohesive soils.

Tiedback retaining structures are frequently used for the control of landslides. These structures, in addition to supporting the soil mass directly behind the structure, must also apply a sufficient resisting force to the sliding mass that it is intended to stabilize. Not only must the tiedback retaining wall, shown in Figure 4, be able to resist the lateral earth-pressure forces produced by the soil mass directly behind the wall (shaded portion), but it must also apply a resisting force sufficient to stabilize the sliding soil mass above the landslide failure surface.

A sliding mass can be stabilized by increasing the resisting forces that act on it, or by decreasing the driving forces.

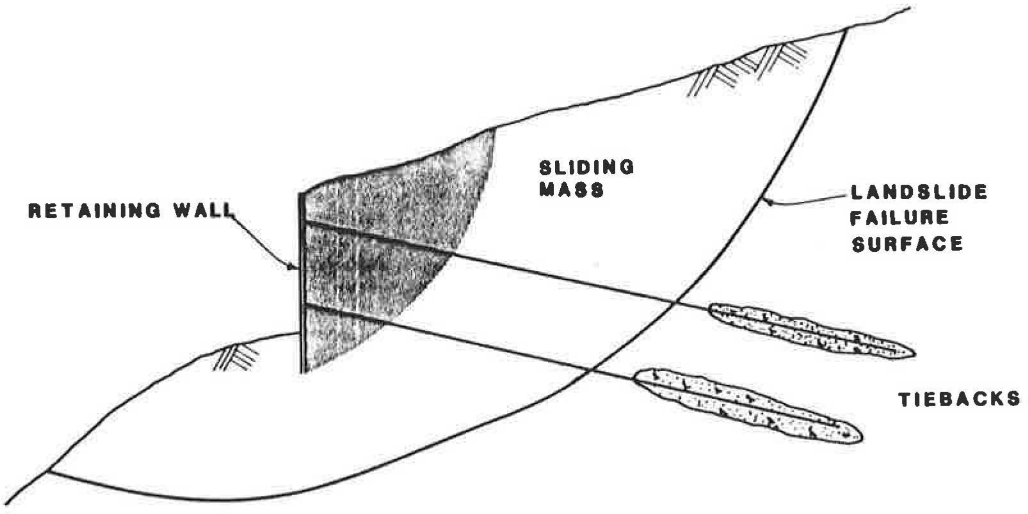


FIGURE 4 Landslide stabilization using tiebacks.

Tiebacks stabilize a sliding soil mass by increasing the resisting forces. Tiebacks can penetrate the sliding surface and apply increased normal and tangential forces to the sliding body. Tiebacks are an excellent tool for stabilizing landslides because they provide a force that acts in nearly an ideal direction for resisting the driving forces, without seriously aggravating the stability of the slope.

It can be seen from Figure 4 that the largest component of the tieback force acts in a horizontal direction. The tiebacks also provide a component of force to the soil mass that increases the normal force on the sliding surface. For soils with frictional characteristics, it can be seen from Equation 1 that by increasing the effective normal force, and hence effective normal stress, N', on the sliding surface, the resistance to sliding at the sliding surface will be increased.

$$S = c' + N' \tan \Phi' \tag{1}$$

where

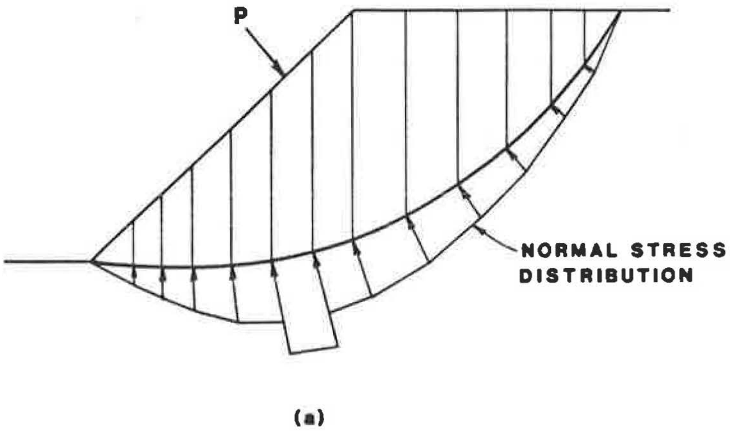
S = soil shear strength,
c' = effective soil cohesion,
N' = effective normal stress, and
Φ' = effective angle of shearing resistance.

Both components of the tieback force on the failure surface tend to increase the resisting forces on the sliding mass. Any type of stability analysis performed on slopes subjected to tieback loads should consider both components of resistance offered by a tiedback structure for landslide stabilization.

Slope Stability Program Method

Slope stability computer programs based on a limiting equilibrium method of slices are routinely used for determining the stability of slopes and embankments. It is therefore logical to attempt to use such an analysis tool for the determination of the stability of tiedback structures used for landslide control. However, existing limiting equilibrium slope stability computer programs, with the exception of the recent versions of STABL, do not properly account for the presence of tieback loads in the determination of the FOS. This is especially true for the simplified methods of slices, such as the Simplified Bishop method and the Simplified Janbu method, which do not satisfy both force and moment (total) equilibrium (*12, 13*).

When vertical uniform distributed loads are present on the crest of the slope, there are no major drawbacks to using the Simplified Bishop or Janbu methods. However, when using



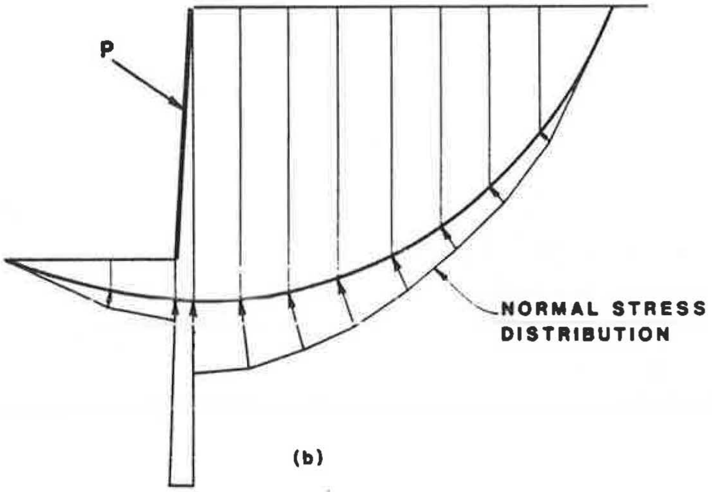


FIGURE 5 Normal stress distribution on failure surface considering a concentrated load.

these methods for near-horizontal and inclined concentrated tieback loads, these methods are inappropriate for the following reasons:

1. The vertical component of an inclined tieback load is taken into account in the numerator of the FOS only on the slice on which it acts. This does not conform to the idea that stresses applied to the ground surface are diffused throughout the soil mass (*14–17*). Shown in Figure 5*A* is the distribution of normal stress on the failure surface caused by the presence of a concentrated load, such as an inclined tieback load, *P*, applied to the face of a slope. It is clear from this figure that the tieback load is only taken into account on the slice on which it acts. The normal stress on this slice is greatly increased, whereas nearby slices remain unaffected. As a result, the soil resistance calculated for the slice on which the tieback load acts (Equation 1) will be extremely high, whereas the soil resistance of nearby slices will remain unchanged by the presence of the tieback load. The result is that the real FOS for the slice on which the tieback load acts will be very high, whereas the FOS of the remaining slices will be unchanged. This problem is especially critical when the width of the slice is small, as is typically true for near-vertical tiedback retaining structures, shown in Figure 5*B*.
2. The horizontal component of a concentrated tieback load is taken into account only in the denominator of the FOS. It will be seen later that the horizontal component of the tieback load produces normal and tangential forces on the base of the slices that contribute to the stability of the slope.
3. A concentrated horizontal load whose line of action passes through the center of rotation will not be taken into account in the FOS determination with the Simplified Bishop method of slices because the moment arm of the load will be zero; hence the resisting moment from such a load will also be zero.

It is apparent from this discussion that the previously available slope stability programs using the simplified methods of slices are not capable of properly accounting for the presence of concentrated loads such as tieback loads. In reality, large compressive stresses, resulting from the presence of a tieback load, are distributed throughout the soil mass to the base of nearly all the slices of the sliding mass. These stresses cause the normal and tangential stresses to be increased on the base of every slice of any failure surface that passes between the tieback anchor and the retaining structure. Any analysis for determining the stability of slopes subjected to tieback loads should consider these increases in stresses at the base of each slice of the sliding mass.

LOAD DISTRIBUTION METHOD: STABL5 AND PCSTABL5

In an attempt to account for the diffusion of compressive stresses throughout a soil mass caused by the presence of tieback loads, the author has developed the LDM, for use with the simplified methods of slices. The LDM was originally programmed in the slope stability computer programs STABL4 and PCSTABL4, and is also contained in the STABL5 and PCSTABL5 programs. The LDM eliminates the drawbacks inherent to computerized slope stability analyses as already discussed. Unlike other slope stability programs, STABL5/PCSTABL5 distributes the force from a concentrated load throughout the soil mass to the whole failure surface and hence to nearly all slices of the sliding mass. STABL5 and PCSTABL5 are the only known limit equilibrium slope stability programs that attempt to account for the distribution of force to the failure surface caused by concentrated boundary loads, such as tieback loads.

The LDM routines in STABL5/PCSTABL5 are applicable to circular and noncircular failure surfaces and are specifically formulated to handle tieback loads, but are also capable of handling other types of loads applied to the ground surface such as strut loads from a braced excavation. A detailed discussion of the derivation of LDM is beyond the scope of this paper. However, the reader may consult Carpenter (*18*) for the complete derivation of the LDM.

Theory

A post-tensioned tieback applies a force to the structure that it supports. This force is developed by the tieback anchor within the soil mass. Because the forces between the wall and the tieback anchor are equal and opposite, they place the soil between the structure and the anchor in compression.

The LDM diffuses the stresses caused by the tieback load to the potential failure surface. This is accomplished by replacing the load applied to the ground surface with a statically equivalent distribution of forces applied to the midpoint of the base of the slices along the potential failure surface. By doing so, the load is distributed to the base of all, or nearly all, of the slices, depending on the slope geometry. The diffusion of stresses within the slope and the increase in forces along the potential failure surface are therefore considered in the determination of the FOS.

The distribution of stresses to the potential failure surface used in the LDM is computed according to Flamant's distribution of stresses through a semi-infinite elastic half-space (*15*), as proposed by Tenier and Morlier (*19*). Flamant's distribution of stresses was adapted to the problem of tiedback slopes and walls because of its simplicity while evaluating and attempting to correct the potential errors associated with applying this method to analysis of tiedback slopes and walls. It is recognized that soils are not necessarily elastic and that tiedback slopes or walls do not necessarily conform to a semi-infinite elastic half space. Although soils do not generally behave as elastic materials, many solutions to the distribution of stresses throughout soils have shown that this approach is practical and reasonable for engineering purposes (*14, 16, 17*). Although Flamant's formula is based on planar stress, it will be seen later that the distribution of stresses obtained using Flamant's distribution of stresses, modified to ensure that the stress distribution obtained is in static equilibrium with the applied tieback load, seems reasonable when compared to finite element studies performed by Tenier and Morlier (*19*).

The primary assumptions used in the formulation of the LDM may be summarized as follows:

1. It is assumed that a linearly elastic half space model may be used to generally describe the slope conditions being analyzed,
2. A uniform line load is assumed to exist horizontally between adjacent tiebacks so that the three-dimensional tieback problem may be analyzed using a two-dimensional analysis, and,

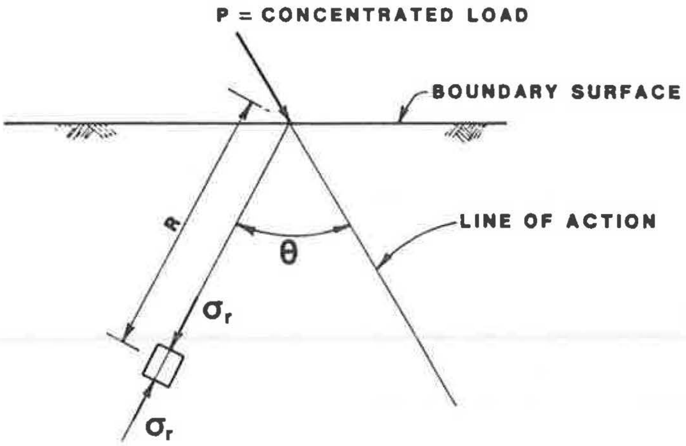


FIGURE 6 **Flamant's distribution of stress.**

3. The stresses around the grouted anchor are not considered in the analysis.

The significance of these assumptions will be discussed later with respect to the limitations of the analysis.

The distribution of stresses obtained using Flamant's equation is resolved into a distribution of discrete forces acting at the midpoint of the base of the slices. The resulting force distribution is modified so that the distribution of forces along the failure surface is in static equilibrium with the load applied to the ground surface.

According to Flamant (*15*), for a semi-infinite mass subjected to a concentrated load, *P*, the distribution of stresses is radial and is given (see Figure 6) by:

$$\sigma_r = 2(\mathrm{P}) \cos \Phi/(\pi)(R) \times (\text{compression}) \qquad (2)$$

where

σ_r = radial stress at a point,
P = concentrated load applied to an elastic half space,
R = distance to the point in question, and
Φ = angle formed by the line of action of the oncentrated load, and the line connecting the point of application of the load on the boundary surface and the point in question.

If the trial failure surface intersects the tendon portion of a row of tiebacks, an equivalent line load is calculated for them. If the trial failure surface passes behind or through the grouted anchor, the tieback load is not considered in the determination of the FOS because the tiebacks are internal to the sliding mass. The individual tieback load, *P*, for a given row of tiebacks, is divided by the corresponding horizontal spacing, *H*, between tiebacks. The resulting equivalent line load is designated as TLOAD (Figure 7), and is inclined from the horizontal by an angle, INCLIN.

The author assumes that the replacement of discrete tieback loads by an equivalent line load is valid for tiedback structures because tiebacks are normally closely spaced (horizontally)

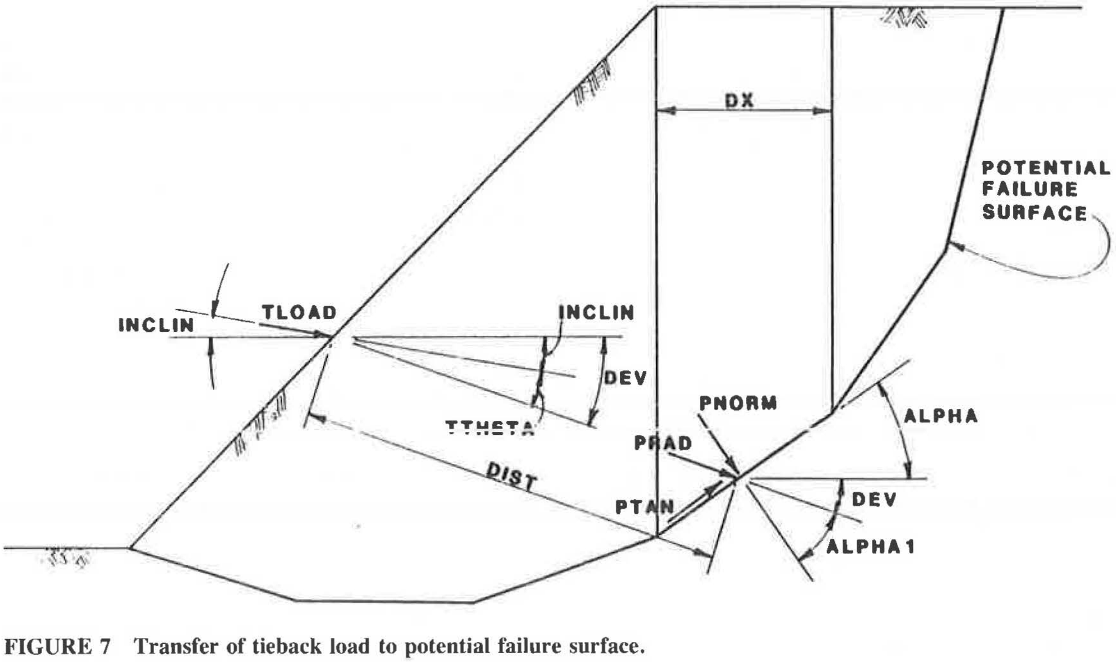


FIGURE 7 **Transfer of tieback load to potential failure surface.**

and are anchored to horizontal load-bearing elements, such as steel wales that transfer the tieback load to the retaining structure. Based on the assumption of a uniform line load being formed between tiebacks, the LDM neglects any three-dimensional effects that may exist. If horizontal load-bearing members are not present on a tiedback structure, or if the horizontal spacing between tiebacks is large, then this assumption is no longer valid.

The radial stress on the midpoint of the base of a given slice is calculated using Flamant's formula:

$$\sigma_r = 2\ (\mathrm{TLOAD})\ \cos\ (\mathrm{TTHETA})/(\pi)\ (\mathrm{DIST}) \qquad (3)$$

where

σ_r = radial stress at the midpoint of the base of the slice,
TLOAD = equivalent tieback line load for a row of tiebacks,
TTHETA = angle formed by the line of action of TLOAD, and the line connecting the point of application of the tieback on the ground surface and the midpoint of the base of the slice,
π = pi, and
DIST = distance between the point of application of TLOAD on the ground surface, and the midpoint of the base of the slice.

The radial force, PRAD, at the midpoint of the base of a slice because of a given tieback load, is calculated by multiplying the radial stress at that point in the soil mass by the length of the base of the slice (*DX*), see Figure 7. Because of slope geometry (i.e., slope is not a semi-infinite half space), location of the tiebacks with respect to the failure surface, and shape of the failure surface, the sum of the radial forces acting at the midpoint of the base of the slices in the direction of the line load is normally not in static equilibrium with the applied load, TLOAD. As a result, a single multiplication factor is applied to the radial forces acting on the base of all the slices so that the sum of these forces is in equilibrium with the applied load. The refined radial force acting on the base of each slice is broken into its components normal and tangential to the base of each slice, PNORM and PTAN, respectively.

The entire process outlined above is repeated for all additional rows of tiebacks. The normal and tangential components of the tieback loads due to all row's of tiebacks are summed on each slice, and it is these forces that are used in the FOS equations.

Distribution of Load to Failure Surface

The distribution of stress (and hence force) to the base of the slices of the sliding mass has been studied in detail to verify the reasonableness of the distributions generated. The following discussion examines the distribution of stresses to the potential failure surface produced by the LDM.

To clearly demonstrate the distribution of normal and tangential stresses (and hence forces) to a failure surface produced by the LDM, a simple 15-ft (4.57-m) high tiedback wall has been chosen as an example (Figure 8). Two different configurations of tiebacks are considered to demonstrate the change in distribution of stress produced along the circular potential failure surface shown with variation in tieback-failure surface geometry.

The wall is shown in Figure 8*A*, subjected to a horizontal tieback load of 25 kips. The 25-kip tieback load is replaced by an equivalent distribution of normal and tangential stresses on the failure surface as computed using the LDM. The distribution of normal stress along the failure surface is smooth and is largest at approximately the midpoint of the failure surface (point *B*).

The same wall is shown in Figure 8*B*, subjected to a tieback load of 25 kips inclined at 30 degrees from the horizontal. The normal stress distribution is similar to that of Figure 8*A*, except that the stress distribution is shifted lower on the failure surface.

Similar distributions are also obtained for tangential stresses. The stresses produced by more than one row of tiebacks are superimposed to produce a combined stress on each slice.

Tenier and Morlier (*19*) obtained similar distributions of normal and tangential stresses. They compared the results of finite element analyses with those obtained using Flamant's distribution of stresses corrected for static equilibrium. The results verified that the distributions of normal and tangential stresses obtained using Flamant's distribution of stresses, corrected for static equilibrium, were in good agreement with those obtained using a finite element model. Tenier and Morlier's analyses were performed on simple slopes subjected to tieback loads with homogeneous elastic soil parameters. The analyses did not consider nonhomogeneous soil conditions, ground water tables, pore pressures, or earthquake loading. STABL5 and PCSTABL5, on the other hand, are capable of handling all the conditions already mentioned.

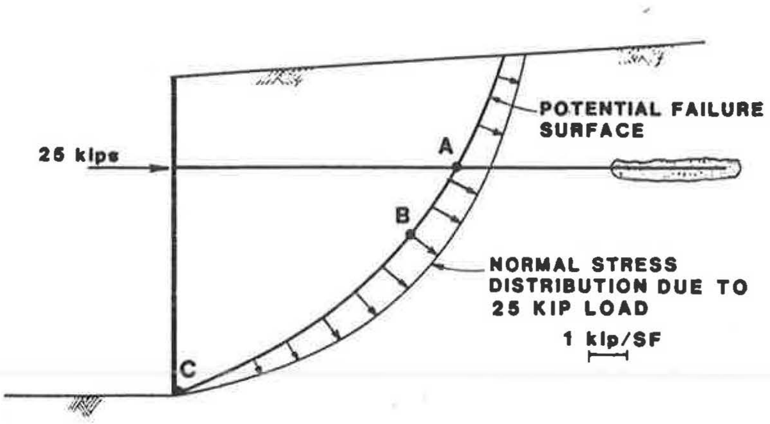
Load Versus Factor of Safety

One of the prime factors considered in the design of tiedback structures is the determination of the magnitude of the applied load required to ensure stability. The effect of the magnitude of the applied load was investigated for various soil conditions using the soil mass defined by the potential failure surface shown in the simple slope of Figure 9.

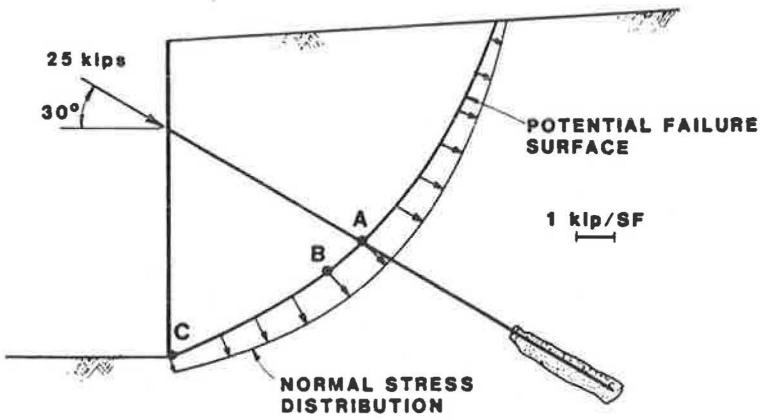
The effect of increasing the normal force on the failure surface, through the use of an applied load such as a tieback load, will not increase the mobilized soil resistance for slopes with purely cohesive soil characteristics (Equation 1) because $\Phi = 0$. Therefore, the distribution of the component of an applied load normal to the failure surface will have no effect on the overall stability of the slope. However, the tieback does offer resistance to sliding through the distribution of the component of the tieback load tangential to the potential failure surface.

Demonstrated in Figure 10 is the effect of increasing load on the FOS for three purely cohesive soil strengths for the slope shown in Figure 9. The FOS is observed to increase nearly linearly with an increase in applied load. Note that the increase in FOS is due only to the presence of the components of the load tangential to the potential failure surface.

For slopes with both cohesive and frictional soil strength characteristics, the resistance to sliding will be increased by the distribution of both the normal and tangential components of the applied load acting on the potential failure surface.



(a) TIEBACK HORIZONTAL



(b) TIEBACK INCLINED AT 30°

FIGURE 8 Slope model for load versus FOS studies.

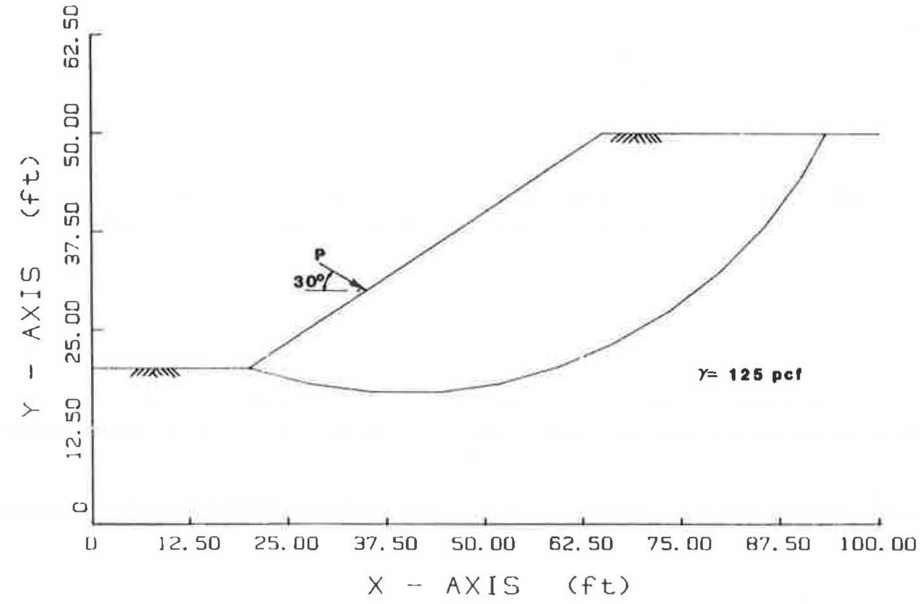


FIGURE 9 Slope model for load versus factor of safety studies.

The results obtained when the slope of Figure 9 was analyzed with three different $c \sim \Phi$ soil strength characteristics are shown in Figure 11.

As with purely cohesive soils, the FOS increases with increasing load. However, the rate of increase (slope of the lines) in FOS with increasing load is greater than that of Figure 10 for purely cohesive soil conditions.

For $c \sim \Phi$ soils, both components of the applied load distributed onto the failure surface act to increase stability. The FOS increases at a faster rate for the slope with $c \sim \Phi$ soil characteristics, because the distribution of the normal component of the load on the failure surface acts to increase the mobilized soil resistance. This resistance is in addition to the resistance offered by the distribution of the tangential component of the load along the failure surface.

Note that at large loads a rather significant increase in FOS is obtained even if the soil has a relatively small Φ value. In addition, inspection of Figures 10 and 11 indicates that the soil strength parameters chosen for stability analysis have a profound effect on the FOS. As in any stability analysis, the choice of soil strength parameters is one of the most critical factors affecting the FOS obtained (*20*).

Limitations

The use of STABL5 and PCSTABL5 for the analysis of the stability of tiedback slopes and walls is limited to those problems that lend themselves to the assumption that a uniform line load may be assumed to exist horizontally between tiebacks. Where this assumption is not valid, other methods of analysis may be more appropriate.

The analysis of the stability of tiedback structures using the LDM is appropriate in cases in which the overall slope may be generally modeled as a semi-infinite half space.

The LDM does not take into account the relative stiffness of individual soil layers because it is based on a solution of stress distribution through a homogeneous elastic half space. Hence, with the LDM, the stresses distributed to the potential failure surface are independent of the deformation characteristics of the soil profile. In other words, the load from a tieback will be distributed to a potential failure surface in the same way for both a homogeneous soil profile and a layered soil profile. This limitation is not significant for most layered soil profiles whose individual soil layers do not have grossly different stiffness characteristics. However, this limitation may be more significant for soil profiles that have grossly different soil layer stiffness characteristics. This topic is worthy of further investigation.

It is important to note that limiting equilibrium slope stability methods, as used in the STABL programs, do not consider displacements of the soil mass or the tiebacks. Displacements may result in increased loads on the tiebacks and reduced soil resistance.

Given the limitations already discussed, along with the assumptions used in the development of the LDM, the reasonableness of any solution provided by STABL or any other computer-generated solution must be judged by the engineer to ensure that the conditions analyzed are modeled properly, and that the solution obtained is reasonable.

The analysis of the stability of a tiedback structure is just one of many design considerations in the design of a tiedback retaining structure. STABL is only one tool for performing the stability calculations. Other considerations in the analysis

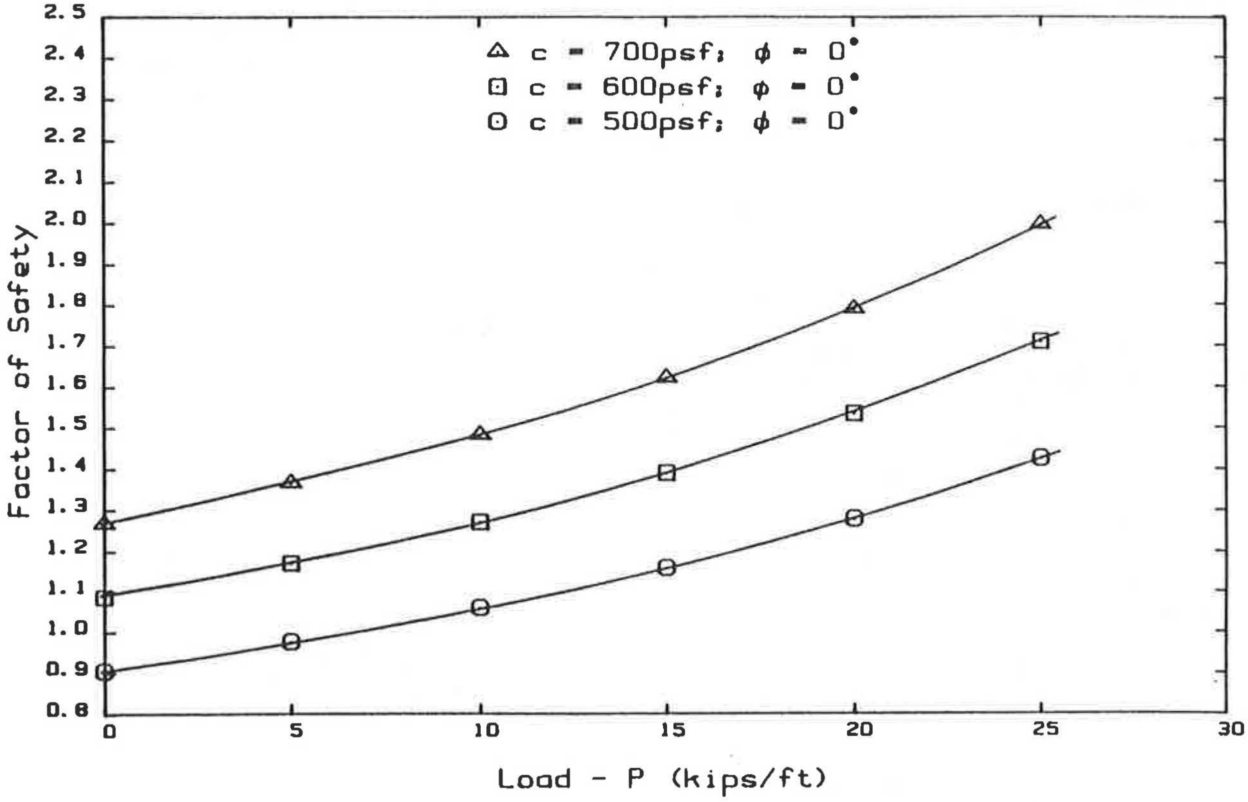


FIGURE 10 Load versus FOS for purely cohesive soil slopes.

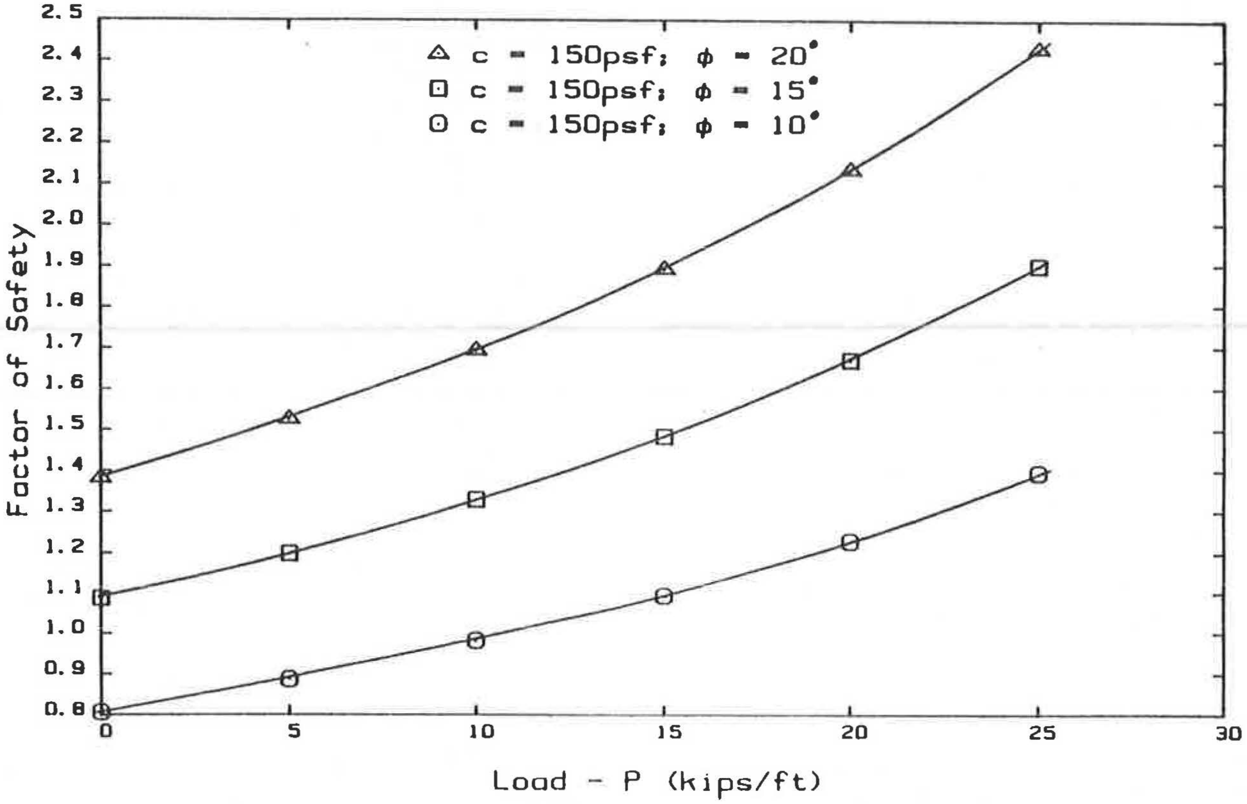


FIGURE 11 Load versus FOS for $c \sim \Phi$ soil slopes.

and design of tiedback structures must be designed and analyzed separately.

For a detailed discussion of the development and limitations of the LDM, the reader is encouraged to consult Carpenter (*18*).

SUMMARY

The purpose of this study was to develop a rational and convenient method of assessing the internal and overall stability of tiedback and anchored retaining structures. Such a method has been developed by the author in the LDM and is contained in the slope stability programs STABL5 and PCSTABL5. The LDM was developed for the analysis of tiedback slopes and walls for use with the simplified methods of slices. The programs contain routines that consider multiple rows of tiebacks, multiple tiedback structures as well as individual tieback loads, tieback inclination, horizontal spacing between tiebacks, and the length of individual tiebacks. The STABL programs are the only known slope stability programs that specifically consider the effect of tiebacks on the stability of tiedback slopes and walls.

Previously available methods for determining the overall stability of tiedback structures were reviewed and the usefulness and limitations of these methods were discussed. Parametric studies were performed during the development of the LDM to determine the reasonableness of applying the assumptions used in the method of solution to tiedback slopes and retaining walls. In addition, the effect of tieback load on the FOS was presented for several different soil conditions. These studies revealed that the method generally gives reasonable results. However, recognizing that a semi-infinite elastic half space model is assumed to generally apply to the problem of tiedback structures, and that a two-dimensional analysis is used to model a three-dimensional problem, a conservative approach should be used in selecting the minimum required FOS for tiedback slopes and walls using the LDM.

CONCLUSIONS

1. The LDM as programmed in STABL5 and PCSTABL5 programs is a useful tool for analyzing the overall stability of tiedback retaining structures for support of excavations or for slope stabilization. The method generally gives good results, but it is important to recognize what assumptions are used in the analysis and how these assumptions relate to the limitations of analyzing the stability of tiedback structures.

2. Analysis of the stability of tiedback structures is a complex problem and the stability of these structures is influenced by, but not limited to (a) the lateral earth pressure behind the wall; (b) the deformation of the soil-structure system; (c) tieback characteristics (individual tieback loads, inclination, horizontal spacing, overall length, size of anchor, method of construction); and (d) soil characteristics. The analysis of tiedback structures is further complicated by the fact that a two-dimensional model is used to model a three-dimensional problem. Recognizing that assumptions concerning these items are required and that assumptions concerning the distribution of loads are introduced into the calculation of the FOS using the LDM for tiedback slopes and walls, a conservative approach

should be used in selecting the minimum required FOS for tiedback slopes and walls.

3. The LDM is preferred over existing methods based on the Krantz method for analysis of the stability of tiedback structures because the LDM does not mix internal and external forces within the soil mass analyzed. It is the author's opinion that methods based on the Krantz method should be discontinued because such methods involve serious errors in the problem statement.

4. The reasonableness of any solution provided by STABL, or any other computer-generated solution, must be judged by the engineer to ensure that the conditions analyzed are modeled properly, and that the solution obtained is reasonable.

5. The soil parameters used in the analysis of the stability of slopes have a profound effect on the FOS. It was found that for a relatively small change in the soil parameters input, a relatively large change in the calculated FOS was obtained. Therefore, the results obtained from any stability analysis are only as reliable as the data input in the analysis.

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