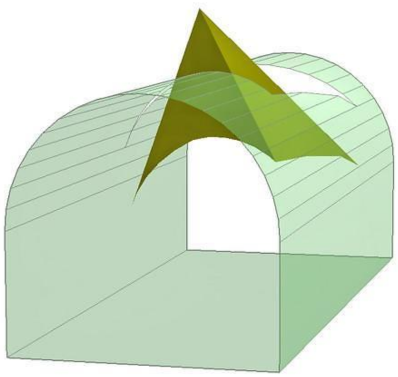
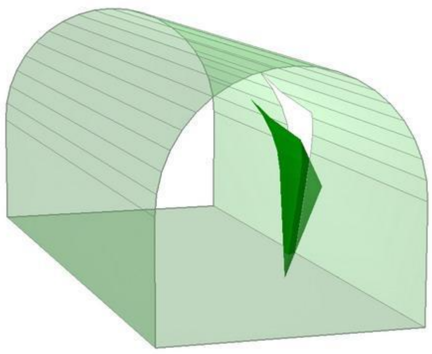
Structurally controlled instability in tunnels

Introduction

In tunnels excavated in jointed rock masses at relatively shallow depth, the most common types of failure are those involving wedges falling from the roof or sliding out of the sidewalls of the openings. These wedges are formed by intersecting structural features, such as bedding planes and joints, which separate the rock mass into discrete but interlocked pieces. When a free face is created by the excavation of the opening, the restraint from the surrounding rock is removed. One or more of these wedges can fall or slide from the surface if the bounding planes are continuous or rock bridges along the discontinuities are broken.



Roof fall



Sidewall wedge

Unless steps are taken to support these loose wedges, the stability of the back and walls of the opening may deteriorate rapidly. Each wedge, which is allowed to fall or slide, will cause a reduction in the restraint and the interlocking of the rock mass and this, in turn, will allow other wedges to fall. This failure process will continue until natural arching in the rock mass prevents further unravelling or until the opening is full of fallen material.

The steps which are required to deal with this problem are:

1. Determination of average dip and dip direction of significant discontinuity sets.
2. Identification of potential wedges which can slide or fall from the back or walls.
3. Calculation of the factor of safety of these wedges, depending upon the mode of failure.
4. Calculation of the amount of reinforcement required to bring the factor of safety of individual wedges up to an acceptable level.

Identification of potential wedges

The size and shape of potential wedges in the rock mass surrounding an opening depends upon the size, shape and orientation of the opening and also upon the orientation of the significant discontinuity sets. The three-dimensional geometry of the problem necessitates a set of relatively tedious calculations. While these can be performed by hand, it is far more efficient to utilise one of the computer programs which are available. One such program, called UNWEDGE[1], was developed specifically for use in underground hard rock mining and is utilised in the following discussion.

Consider a rock mass in which three strongly developed joint sets occur. The average dips and dip directions of these sets, shown as great circles in Figure 1, are as follows:

Joint set	*dip°*	*dip direction°*
J1	70 ± 5	036 ± 12
J2	85 ±8	144 ± 10
J3	55 ± 6	262 ± 15

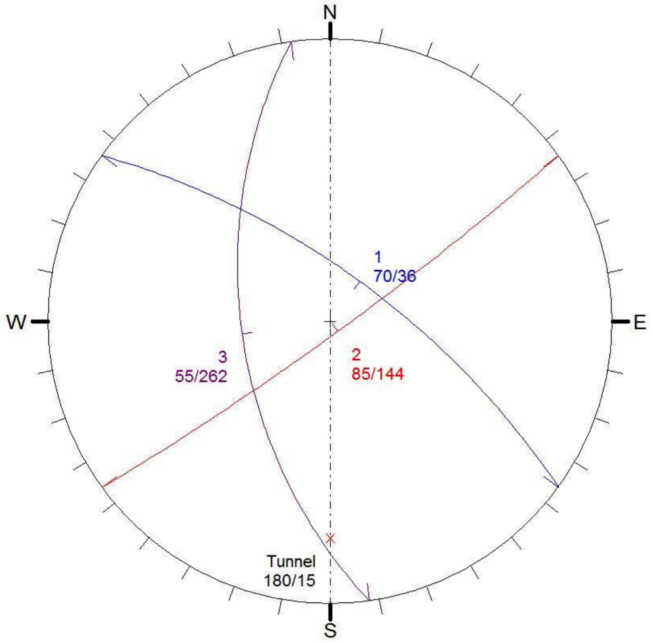


Figure 1: An equal area lower hemisphere plot of great circles representing the average dip and dip directions of three discontinuity sets in a rock mass. Also shown, as a chain dotted line, is the trend of the axis of a tunnel excavated in this rock mass. The tunnel plunge is marked with a red cross.

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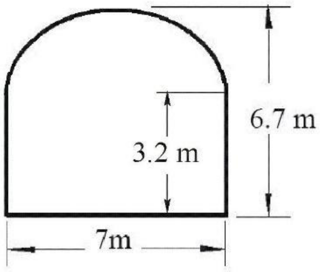
[1] Available from www.rocscience.com.

It is assumed that all of these discontinuities are planar and continuous and that the shear strength of the surfaces can be represented by a friction angle $\phi = 30°$ and a cohesive strength of zero. These shear strength properties are very conservative estimates, but they provide a reasonable starting point for most analyses of this type.



Tunnel section

A tunnel is to be excavated in this rock mass and the cross-section of the ramp is given in the sketch. The axis of the tunnel is inclined at 15° to the horizontal or, to use the terminology associated with structural geology analysis, the tunnel axis plunges at 15°. In the portion of the tunnel under consideration in this example, the axis runs due north-south or the trend of the axis is 180°.

The tunnel axis is shown as a chain dotted line in the stereonet in Figure 1. The trend of the axis is shown as 0°, measured clockwise from north. The plunge of the axis is 15° and this is shown as a cross on the chain dotted line representing the axis. The angle is measured inwards from the perimeter of the stereonet since this perimeter represents a horizontal reference plane.

The three structural discontinuity sets, represented by the great circles plotted in Figure 1, are entered into the program UNWEDGE, together with the cross-section of the tunnel and the plunge and trend of the tunnel axis. The program then determines the location and dimensions of the largest wedges which can be formed in the roof, floor and sidewalls of the excavation as shown in Figure 2.

The maximum number of simple tetrahedral wedges which can be formed by three discontinuities in the rock mass surrounding a circular tunnel is 6. In the case of a square or rectangular tunnel this number is reduced to 4. For the tunnel under consideration in this example, four wedges are formed.

Note that these wedges are the largest wedges which can be formed for the given geometrical conditions. The calculation used to determine these wedges assumes that the discontinuities are ubiquitous, in other words, they can occur anywhere in the rock mass. The joints, bedding planes and other structural features included in the analysis are also assumed to be planar and continuous. These conditions mean that the analysis will always find the largest possible wedges which can form. This result can generally be considered conservative since the size of wedges, formed in actual rock masses, will be limited by the persistence and the spacing of the structural features. The program UNWEDGE allows wedges to be scaled down to more realistic sizes if it is considered that maximum wedges are unlikely to form.

Details of the four wedges illustrated in Figure 2 are given in the following table:

Wedge	Weight - tonnes	Failure mode	Factor of Safety
Roof wedge	44.2	Falls	0
Right side wedge	5.2	Slides on J1/J2	0.36
Left side wedge	3.6	Slides on J3	0.40
Floor wedge	182	Stable	∞

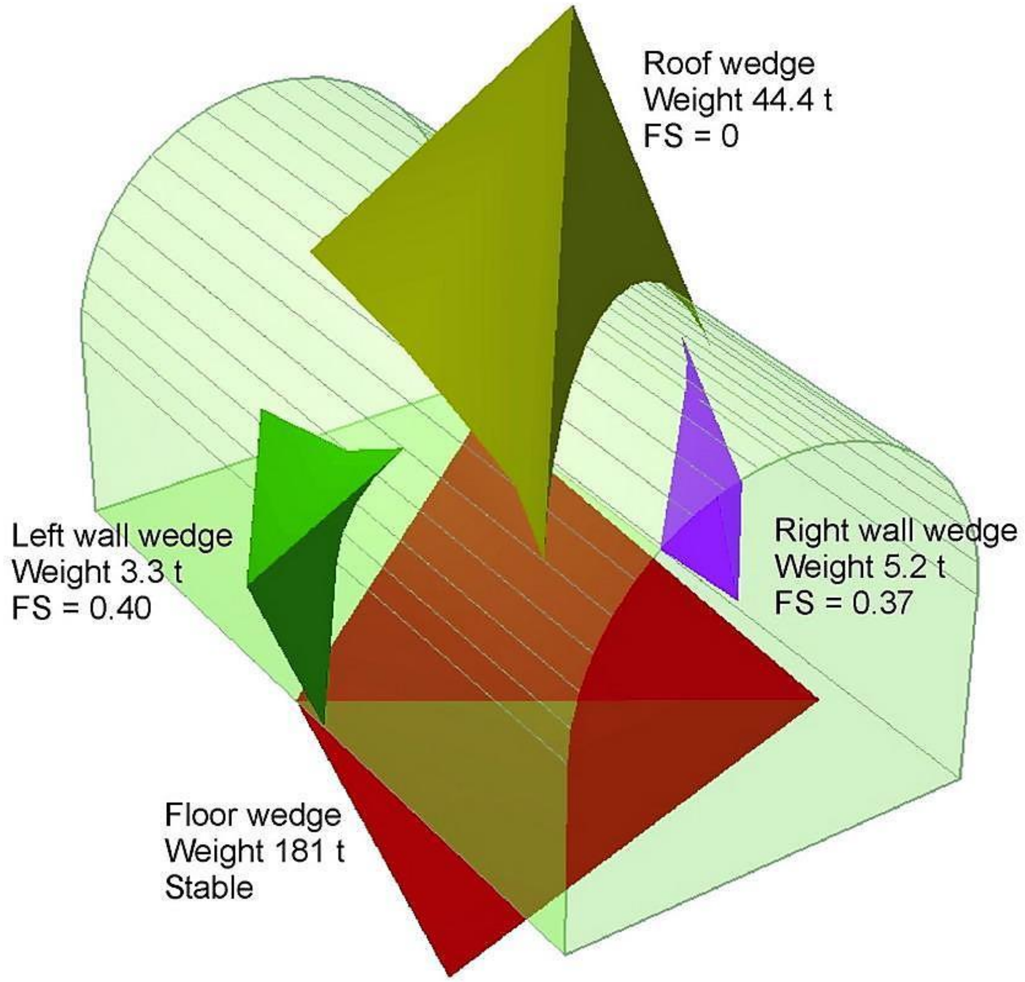


Figure 2: Wedges formed in the roof, floor and sidewalls of a ramp excavated in a jointed rock mass, in which the average dip and dip direction of three dominant structural features are defined by the great circles plotted in Figure 1.

The roof wedge will fall as a result of gravity loading and, because of its shape, there is no restraint from the three bounding discontinuities. This means that the factor of safety of the wedge, once it is released by excavation of the ramp opening, is zero. In some cases, sliding on one plane or along the line of intersection of two planes may occur in a roof wedge and this will result in a finite value for the factor of safety.

The two sidewall wedges are 'cousin' images of one another in that they are approximately the same shape but disposed differently in space. The factors of safety are different since, as shown in the table, sliding occurs on different surfaces in the two cases.

The floor wedge is completely stable and requires no further consideration.

Influence of in situ stress

The program UNWEDGE can take into account in situ stresses in the rock mass surrounding the opening. For the example under consideration, the influence of in situ stresses can be illustrated by the following example:

Stress	Magnitude	Plunge	Trend
Vertical stress σ_1	30 t/m^2	90º	030º
Intermediate stress σ_2	21 t/m^2	0º	030º
Minor stress σ_3	15 t/m^2	0º	120º

Wedge	Factor of Safety with no in situ stress	Factor of Safety with applied in situ stress
Roof wedge	0	1.23
Right side wedge	0.36	0.70
Side wedge 2	0.40	0.68
Floor wedge	∞	∞

The difference in the calculated factors of safety with and without in situ stresses show that the clamping forces acting on the wedges can have a significant influence on their stability. In particular the roof wedge is stable with the in situ stresses applied but completely unstable when released. This large difference suggests a tendency for sudden failure when the in situ stresses are diminished for any reason and is a warning sign that care has to be taken in terms of the excavation and support installation sequence.

Since it is very difficult to predict the in situ stresses precisely and to determine how these stresses can change with excavation of the tunnel or of adjacent tunnels or openings, many tunnel designers consider that it is prudent to design the tunnel support on the basis that there are no in situ stresses. This ensures that, for almost all cases, the support design will be conservative.

In rare cases the in situ stresses can actually result in a reduction of the factor of safety of sidewall wedges which may be forced out of their sockets. These cases are rare enough that they can generally be ignored for support design purposes.

Support to control wedge failure

A characteristic feature of wedge failures in blocky rock is that very little movement occurs in the rock mass before failure of the wedge. In the case of a roof wedge that falls, failure can occur as soon as the base of the wedge is fully exposed by excavation of the opening. For sidewall wedges, sliding of a few millimetres along one plane or the line of intersection of two planes is generally sufficient to overcome the peak strength of these surfaces. This dictates that movement along the surfaces must be minimised. Consequently, the support system has to provide a 'stiff' response to movement. This means that mechanically anchored rockbolts need to be tensioned while fully grouted rockbolts or other continuously coupled devices can be left untensioned provided that they are installed before any movement has taken place i.e. before the wedge perimeter has been fully exposed.

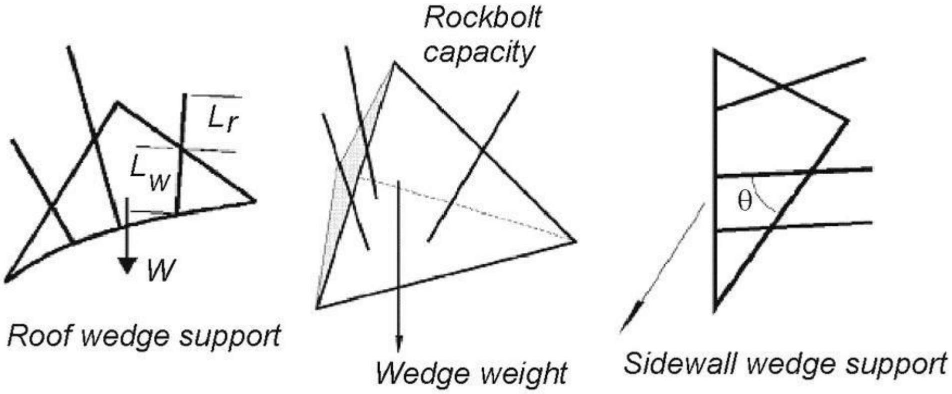


Figure 3: Rockbolt support mechanisms for wedges in the roof and sidewalls of tunnels

Rock bolting wedges

For roof wedges the total force, which should be applied by the reinforcement, should be sufficient to support the full dead weight of the wedge, plus an allowance for errors and poor quality installation. Hence, for the roof wedge illustrated in Figure 3; the total tension applied to the rock bolts or cables should be 1.3 to 1.5 × W, giving factors of safety of 1.3 to 1.5. The lower factor of safety would be acceptable in a temporary mine access opening, such as a drilling drive, while the higher factor of safety would be used in a more permanent access opening such as a highway tunnel.

When the wedge is clearly identifiable, some attempt should be made to distribute the support elements uniformly about the wedge centroid. This will prevent any rotations which can reduce the factor of safety.

In selecting the rock bolts or cable bolts to be used, attention must be paid to the length and location of these bolts. For grouted cable bolts, the length Lw through the wedge and the length Lr in the rock behind the wedge should both be sufficient to ensure that adequate anchorage is available, as shown in Figure 3. In the case of correctly grouted bolts or cables, these lengths should generally be a minimum of about one metre. Where there is uncertainty about the quality of the grout, longer anchorage lengths should be used. When mechanically anchored bolts with face plates are used, the lengths should be sufficient to ensure that enough rock is available to distribute the loads from these attachments. These conditions are automatically checked in the program UNWEDGE.

In the case of sidewall wedges, the bolts or cables can be placed in such a way that the shear strength of the sliding surfaces is increased. As illustrated in Figure 3; this means that more bolts or cables are placed to cross the sliding planes than across the separation planes. Where possible, these bolts or cables should be inclined so that the angle θ is between 15° and 30° since this inclination will induce the highest shear resistance along the sliding surfaces.

The program UNWEDGE includes a number of options for designing support for underground excavations. These include: pattern bolting, from a selected drilling position or placed normal to the excavation surface; and spot bolting, in which the location and length of the bolts are decided by the user for each installation. Mechanically anchored bolts with face plates or fully grouted bolts or cables can be selected to provide support. In addition, a layer of shotcrete can be applied to the excavation surface.

In most practical cases it is not practical to identify individual wedges in a tunnel perimeter and the general approach is to design a rockbolt pattern that will take care of all potential wedges. In the example under consideration the maximum wedge sizes have been identified, as shown in Figure 2, and it has been decided that in situ stresses will not be included in the stability analysis. Consequently, the wedges and their associated factors of safety shown in Figure 2 can be regarded as the most conservative estimate.

Figure 4 shows a typical pattern of 3 m long mechanically anchored 10 tonne capacity rockbolts on a 1.5 x 1.5 m grid. This pattern produces factors of safety of 1.40 for the roof wedge, 3.77 for the right sidewall wedge and 4.77 for the left sidewall wedge.

Shotcrete support for wedges

Shotcrete can be used for additional support of wedges in blocky ground, and can be very effective if applied correctly. This is because the base of a typical wedge has a large perimeter and hence, even for a relatively thin layer of shotcrete, a significant cross-sectional area of the material has to be punched through before the wedge can fail.

In the example under consideration, the application of a 10 cm thick shotcrete with a shear strength of 200 t/m^2 to the roof of the tunnel will increase the factor of safety from 1.40 (for the rockbolted case) to 8.5. Note that this only applies to fully cured (28 day) shotcrete and that the factor of safety increase given by the application of shotcrete cannot be relied on for short term stability. It is recommended that only the rockbolts be considered for immediate support after excavation and that the shotcrete only be taken into account for the long-term factor of safety.

It is important to ensure that the shotcrete is well bonded to the rock surface in order to prevent a reduction in support capacity by peeling-off of the shotcrete layer. Good adhesion to the rock is achieved by washing the rock surface, using water only as feed to the shotcrete machine, before the shotcrete is applied.

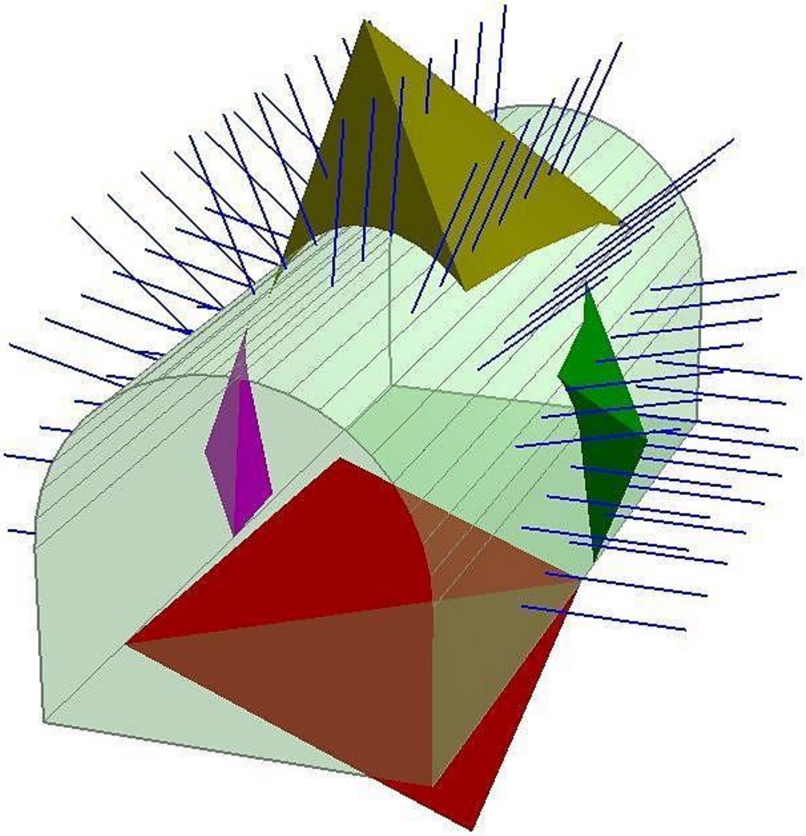


Figure 4: Rock bolting pattern to stabilize the roof and sidewall wedges in the tunnel example discussed earlier.

Figure 5: Ravelling of small wedges in a closely jointed rock mass. Shotcrete can provide effective support in such rock masses

The ideal application for shotcrete is in closely jointed rock masses such as that illustrated in Figure 5. In such cases wedge failure would occur as a progressive process, starting with smaller wedges exposed at the excavation surface and gradually working its way back into the rock mass. In these circumstances, shotcrete provides very effective support and deserves to be much more widely used than is currently the case.

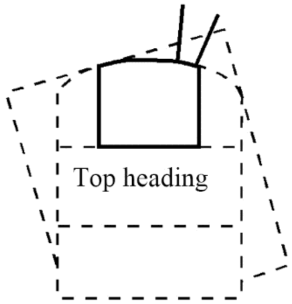
Consideration of excavation sequence

As has been emphasised several times in this chapter, wedges tend to fall or slide as soon as they are fully exposed in an excavated face. Consequently, they require immediate support in order to ensure stability. Placing this support is an important practical question to be addressed when working in blocky ground, which is prone to wedge failure.

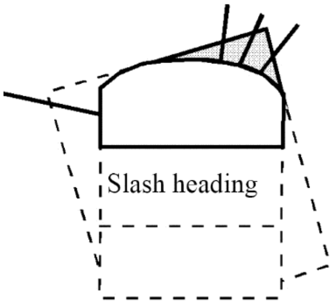
When the structural geology of the rock mass is reasonably well understood the program UNWEDGE can be used to investigate potential wedge sizes and locations. A support pattern, which will secure these wedges, can then be designed and rockbolts can be installed as excavation progresses.

When dealing with larger excavations such as caverns, underground crusher chambers or shaft stations, the problem of sequential support installation is a little simpler, since these excavations are usually excavated in stages. Typically, in an underground crusher chamber, the excavation is started with a top heading which is then slashed out before the remainder of the cavern is excavated by benching.

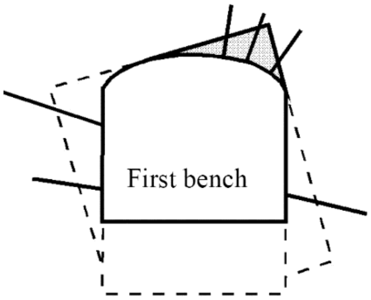
The margin sketch shows a large opening excavated in four stages with rock bolts or cables installed at each stage to support wedges, which are progressively exposed in the roof and sidewalls of the excavation. The length, orientation and spacing of the bolts or cables are chosen to ensure that each wedge is adequately supported before it is fully exposed in the excavation surface.



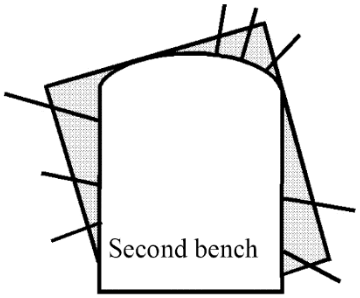
When dealing with large excavations of this type, the structural geology of the surrounding rock mass will have been defined from core drilling or access adits and a reasonable projection of potential wedges will be available. These projections can be confirmed by additional mapping as each stage of the excavation is completed. The program UNWEDGE provides an effective tool for exploring the size and shape of potential wedges and the support required to stabilise them.



The margin sketch shows a support design which is based upon the largest possible wedges which can occur in the roof and walls of the excavation. These wedges can sometimes form in rock masses with very persistent discontinuity surfaces such as bedding planes in layered sedimentary rocks. In many metamorphic or igneous rocks, the discontinuity surfaces are not continuous and the size of the wedges that can form is limited by the persistence of these surfaces



The program UNWEDGE provides several options for sizing wedges. One of the most commonly measured lengths in structural mapping is the length of a joint trace on an excavation surface and one of the sizing options is based upon this trace length. The surface area of the base of the wedge, the volume of the wedge and the apex height of the wedge are all calculated by the program and all of these values can be edited by the user to set a scale for the wedge. This scaling option is very important when using the program interactively for designing support for large openings, where the maximum wedge sizes become obvious as the excavation progresses.



Application of probability theory

The program UNWEDGE has been designed for the analysis of a single wedge defined by three intersecting discontinuities. The “Combination Analyzer” in the program UNWEDGE can be used to sort through all possible joint combinations in a large discontinuity population in order to select the three joints which define most critical wedges.

Early attempts have been made by a number of authors, including Tyler et al (1991) and Hatzor and Goodman (1992), to apply probability theory to these problems and some promising results have been obtained. The analyses developed thus far are not easy to use and cannot be considered as design tools. However, these studies have shown the way for future development of such tools and it is anticipated that powerful and user-friendly methods of probabilistic analysis will be available within a few years.

References

Hatzor, Y. and Goodman, R.E. 1992. Application of block theory and the critical key block concept in tunneling; two case histories. *In Proc. Int. Soc. Rock Mech. conf. on fractured and jointed rock masses*, Lake Tahoe, California, 632-639.

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