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Identifying the Optimum Drilling Direction for Characterization of Discontinuous Rock

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ABSTRACT

Discontinuities (joints, fractures, bedding planes, faults) are ubiquitous within rock masses. Understanding and characterizing the nature of the discontinuities is the fundamental requirement of rock engineering. With a few exceptions, the engineering properties of most rock masses are influenced by the nature of the structure as opposed to the intact rock. Discontinuities govern the mechanical and hydrological behavior of the rock mass.

During site investigations, drilling and logging of boreholes is one of the most commonly used methods of investigation, because of its relatively low cost, because of the large volume of data it provides, and because boreholes can be drilled to the exact location where the rock mass needs to be characterized. Nevertheless, drilling still incurs significant costs, and in order to maximize efficiency, it is highly desirable to maximize the information content and the reliability of the borehole data. For the purposes of this article, the optimal drilling direction is defined as the direction along which the maximum number of discontinuities is intersected. Because the probability of intersecting a given discontinuity is greatest with a borehole perpendicular to that discontinuity, it follows that for every orientation of discontinuity there exists an optimum drilling direction.

This article proposes a method that can find the optimum drilling direction based on the analysis of linear sampling bias, assuming that there is some a priori knowledge of the structure. This is quantified by a linear sampling bias index (LSBI), which is a function of the relative angle between the orientation of the borehole and the mean orientation of the normals of each of the discontinuity sets. The optimum drilling direction is the direction along which the LSBI is minimized.

INTRODUCTION

The characterization of the discontinuities (joints, fractures, bedding planes, faults, and other breaks in the continuity of the intact rock) in rock masses is an important consideration in rock engineering projects. Often it is the nature of the discontinuities, not of the intact rock, that governs the mechanical and hydrological behaviors of the fractured rock. In rock engineering analysis it is necessary to understand the mechanical and hydrological behavior of rock masses in order to predict such aspects of design and construction as:

1. The stability of a rock mass
2. The possible failure modes
3. The expected amount of deformation as a result of applied structural loads and time
4. The degree and effect of water infiltration
5. The remediation and support design
6. The amount of effort needed to excavate the rock
7. The response to blasting

The nature of the mechanical and hydrological properties of intact rock are well understood, but our understanding of discontinuous rock masses is significantly less developed. Boreholes and exposed rock outcrops—and to a lesser extent pilot tunnels and trial excavations—are commonly used to explore and characterize the ground conditions. Drilling is by far the most useful, in part because it is considerably less costly than pilot tunnels and trial excavations, but more important, unlike surface rock exposures, it is in general the only method that can be used to characterize the rock mass exactly where such characterization is required.

Although not always used in practice, the current state of the art in drilling can utilize logging the visible discontinuity orientations in oriented core or from borehole video. The only other alternative for discontinuity characterization is trial excavations and mapping of the discontinuities on the walls and faces of the excavation. In analyzing the discontinuities, the attributes of the individual discontinuities must be identified, measured or

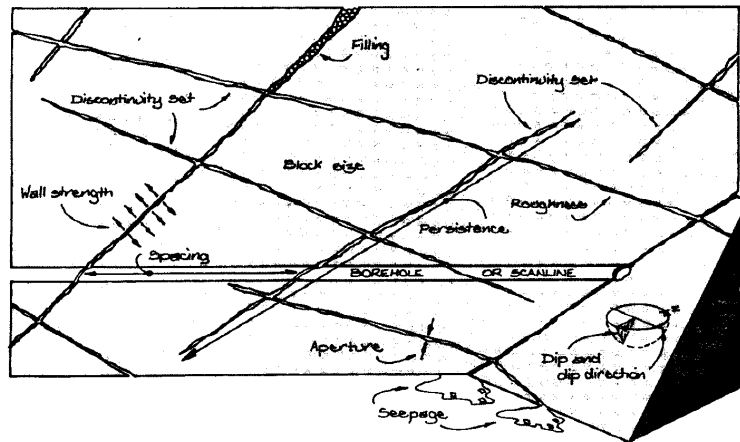


Figure 1. Schematic of a borehole intersecting a rock mass (Hudson, 1989).

characterized, and input into a predictive model. Methodologies for this have been proposed or are being used by Kulatilake and Wu (1984a, 1986), Kulatilake and others (1990), Baecher (1983), Dershowitz and Einstein (1988), Hudson and Priest (1979, 1983), Priest (1994), and others. Models in the past have tended to be physical or electrical analogs; models are now predominantly numerical but also utilize empirical rock mass classification and prediction systems. The attributes for discontinuity classification are described in ISRM

Commission on Standardization of Laboratory and Field Tests (1978) and are shown figuratively by Hudson (1989) (Figure 1). These include orientation, spacing, persistence, roughness, alteration, and infilling.

The advantage of mapping a two-dimensional exposure is of course that more and better data can be obtained, which can ultimately result in a better characterization. The advantage of oriented borehole core logging or borehole video logging is that it is much more cost effective and is capable of exploring much deeper and much larger volumes of ground, an important consideration when the ground conditions are not homogeneous or when the area to be investigated is far below the ground surface.

To improve the efficiency of drilling as a means of discontinuity data acquisition requires that each borehole intersect as many discontinuities as possible per unit length of borehole. In general terms, this means intersecting the discontinuities as close to orthogonally as possible. This requires the determination of optimum drilling angle and direction, which in turn requires at least partial a priori knowledge of the orientation of the rock structure. A first approximation can be obtained from surface mapping or previously collected data.

In this article a method of finding the optimum drilling direction is proposed. This is an iterative approach in which drilling results from one hole can be analyzed and used to determine the optimum orientation of the next.

BIAS DUE TO LINEAR SAMPLING

Borehole discontinuity data are more readily available than two-dimensional discontinuity mapping data.

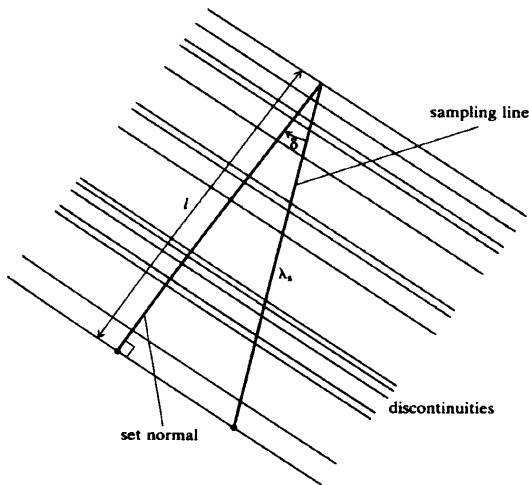


Figure 2. A single discontinuity set intersected by a sampling line (Priest, 1985).

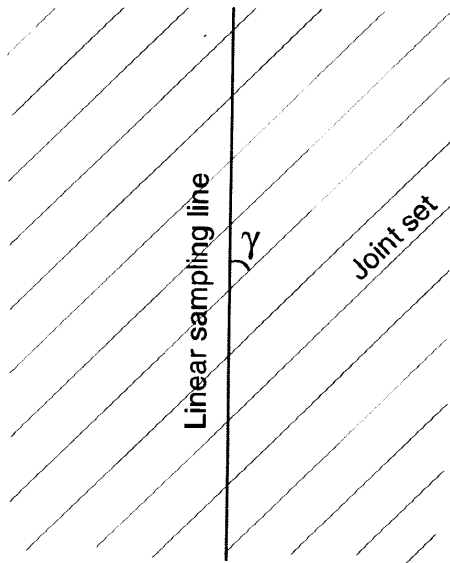


Figure 3. Schematic drawing to illustrate the concept of the linear sampling bias index of one discontinuity set relative to the linear sampling line.

However, because of the size limitation of the core diameter (usually less than 100 mm), not all discontinuity parameters can be measured. An example of this is persistence. Practically, a single borehole gives only a one-dimensional view of the ground investigated. For data sampling from borehole, the following issues have to be taken into account:

1. There may be bias as a result of linear sampling.
2. Some discontinuity parameters, such as persistence, cannot be obtained from borehole core and borehole images.
3. Some discontinuity parameters measured from borehole, such as orientation, spacing, and frequency, provide only apparent values, which need to be converted into true values.

As early as 1965, Terzaghi (1965) described the possible sources of error in joint survey and developed a correction for orientation data for planar discontinuities of infinite size. Her article summarized the important biases of a linear survey:

1. The sampling line will tend to intersect preferentially the larger, or more persistent, discontinuities.
2. The sampling line will tend to intersect preferentially those discontinuities whose normals make a small angle to the sampling line.

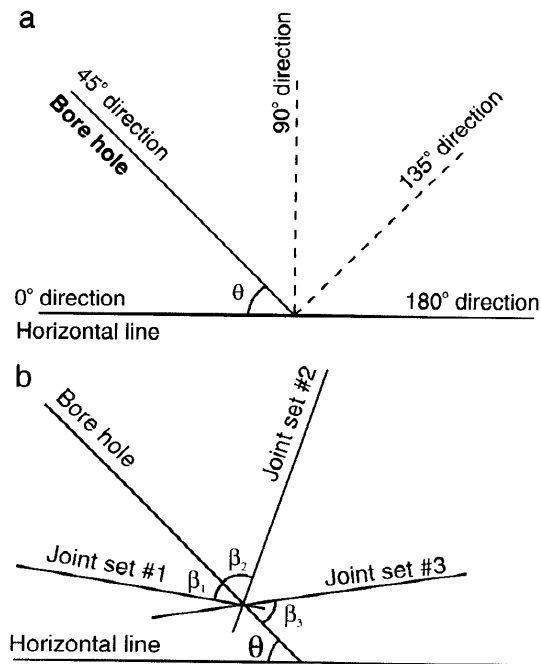


Figure 4. (a) Schematic drawing showing the definition of the inclination (θ) of the borehole in a vertical projection. (b) Schematic drawing showing the definition of the angle (β_i) between the borehole inclination (θ) and the discontinuity dips in a vertical projection.

The second bias is determined mostly by the relationship between the borehole direction and the orientation of the intersected discontinuity sets. Kulatilake and Wu (1984b) developed a correction of observed orientation data based on the probability of discontinuities intersecting a vertical plane. Priest and Hudson (1981) explained the nature of the sampling bias. They also suggested ways to quantify this kind of bias (Hudson and Priest, 1983; Priest, 1985). For a single set of discontinuities, the true frequency (λ) of the discontinuity set is defined as the number of the discontinuities per unit length along a sampling line that is normal to the orientation. If the sampling line is not perpendicular to the discontinuity orientation, the frequency along the sampling line is called an apparent frequency (λ_s) (Figure 2). The following equation expresses the relationship between the true frequency and the apparent frequency (Priest, 1985). Apparent frequency is always less than or equal to the true frequency.

$$\lambda_s = \lambda \cos \delta \quad \text{Eq. 1}$$

where λ is the true frequency of a discontinuity set, λ_s is the apparent frequency of a discontinuity set, and

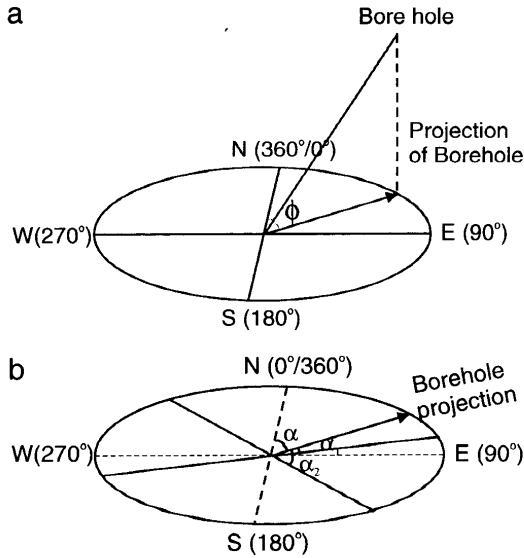


Figure 5. (a) Schematic drawing showing the definition of azimuth (ϕ) of borehole (upper hemisphere projection). (b) Schematic drawing showing the definition of the angle between the borehole azimuth and the strikes of the discontinuity sets in a horizontal projection.

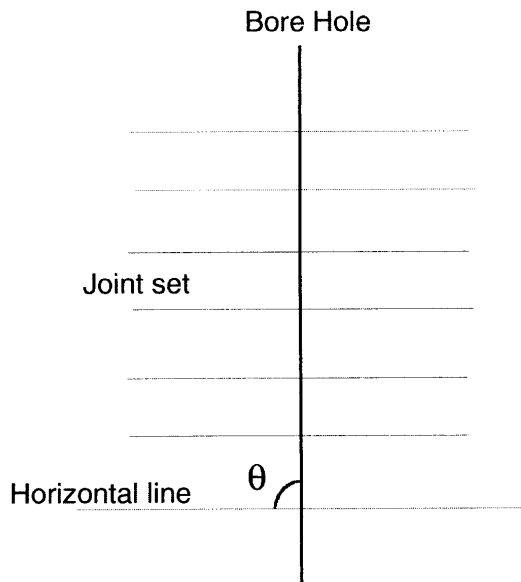


Figure 6. The simplest example assumes there is only one set of horizontal planar discontinuities with uniform spacing and infinite persistence (shown in a vertical projection). In this example, the optimum drilling direction is vertical direction, and $\beta = 0$.

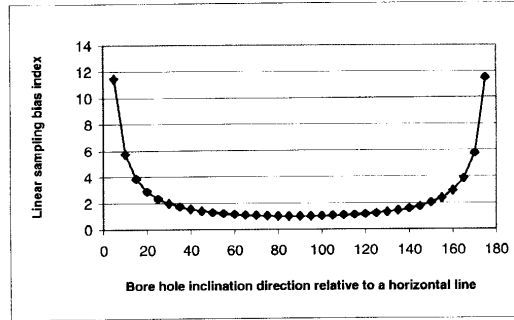


Figure 7. Linear sampling bias index for the case of a single set of horizontal discontinuities, reaching its minimum value when the borehole is vertical (90° from the horizontal plane).

δ is the angle between the normal of the discontinuity orientation and the sampling line.

In the above equation, the term $\cos\delta$ gives a quantitative value of the bias. If $\cos\delta$ equals 1, the sampling line is parallel to the normal of the discontinuity orientation, and the sampling bias is the minimum for this idealized situation. In other words, the sampling line is along the optimum direction if $\cos\delta$ equals 1. If $\cos\delta$ equals 0, then the sampling line is perpendicular to the normal of the discontinuity orientation, and the sampling bias is defined as infinite.

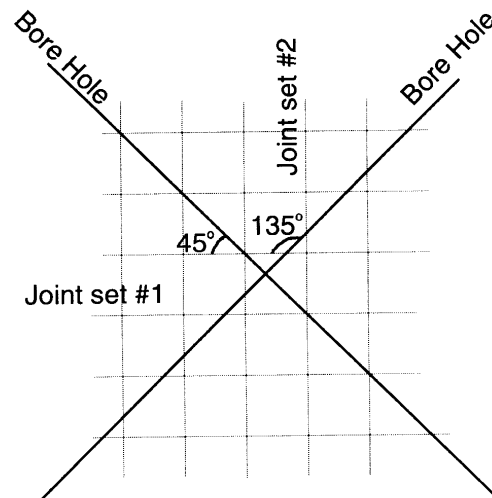


Figure 8. Example of two sets of orthogonal discontinuities, one horizontal, the other vertical (shown in a vertical projection). There are two optimum drilling directions in this particular case; either 45° or 135° from the horizontal plane will be the best drilling direction.

Characterization of Discontinuous Rock

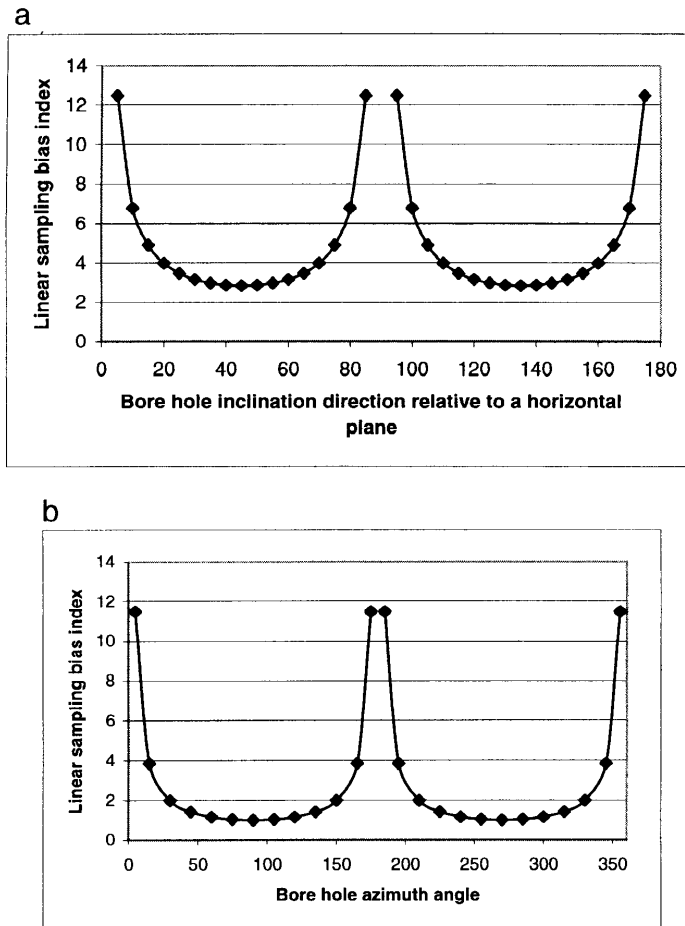


Figure 9. (a) Graphic shows that the linear sampling bias index reaches its minimum values when borehole has an inclination of either 45° or 135°. (b) Graphic shows the optimum azimuth of borehole is 90° or 270°.

In practice, it is rare to find a discontinuity set in which all discontinuities are oriented in a perfectly parallel direction. It becomes more and more complex to determine the optimum sampling direction as the variability of discontinuity orientation increases, or as the number of discontinuity orientations increases. As summarized by Martel (1999), the probability of encountering discontinuities of a specified orientation by a borehole depends on factors such as the following:

1. The abundance (frequency) of discontinuities in the region sampled
2. The orientation of the discontinuities with respect to the borehole
3. The size (persistence) of the discontinuities
4. The position of the discontinuities relative to the position of the borehole
5. The length of the borehole
6. The diameter of the borehole

NEW METHOD TO IDENTIFY THE OPTIMUM DRILLING DIRECTION

Basic Assumptions and Concepts

The preferred drilling direction varies with the drilling aims. For example, if the priority was to get maximum core recovery, then the preferred drilling direction would be the direction that could avoid as many

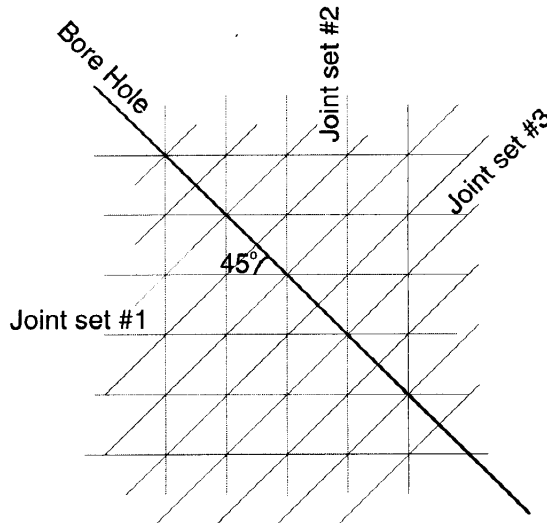


Figure 10. Example of three sets of discontinuities: Set 1 is horizontal, Set 2 is vertical, and Set 3 has a dip of 45° toward west (shown in a vertical projection). The optimum drilling direction is 45° from the horizontal plane. Compare this with the example of two discontinuity sets, noticing that the addition of Discontinuity Set 3 eliminates the borehole direction of 135° , because this direction is parallel to Discontinuity Set 3.

discontinuities as possible. On the other hand, if the priority were to collect discontinuity data, then the preferred drilling direction would be the direction along which as many discontinuities as possible would be intersected, provided that the chosen drilling direction did not result in drilling difficulties, poor core recovery, or unsatisfactory orientation of the core. For the purposes of this article, the optimal drilling direction is defined as the drilling direction along which the maximum number of discontinuities is intersected.

The method to identify the optimum drilling direction is based on the following assumptions:

1. The frequency or spacing between individual discontinuities within a discontinuity set is uniform throughout the analyzed region; consequently, the mean frequency or spacing of a discontinuity set is used.
2. The persistence of the discontinuities is larger than the dimension of the region investigated.
3. The diameter and length of the borehole is known.
4. The analysis of sampling bias is based on a two-dimensional projection.
5. Any direction that is parallel to the mean orientation of any discontinuity set has an infinite sampling bias and hence is excluded as an optimum borehole drilling direction.

This method is based on quantification of the linear sampling bias analysis. The optimization is done by using a linear sampling bias index (LSBI), which is a function of the relative direction of the borehole to the direction normal of the discontinuity orientations. The optimum drilling direction is then defined as the direction along which the minimum LSBI occurs.

The basic concept involves finding a drilling direction that has a minimum sampling bias for all discontinuities. The optimum drilling direction, as defined earlier, is the direction along which the borehole can go through as many discontinuities as possible for a given drilling length.

The orientation of a borehole is defined by two parameters, the azimuth (direction) and the inclination (dip). Finding an optimum drilling direction is a three-dimensional problem. To solve this problem, one might use vector algebra or stereographic projection (Priest, 1985). However, the optimum azimuth of the borehole is relevant only to the strikes of the discontinuity sets, whereas the optimum inclination of the borehole is relevant only to the dips of the discontinuity sets. More specifically, the optimum azimuth can be determined by examining only the projections of the strikes on a horizontal plane, and the optimum inclination can be determined by examining only the projections of the dips on a vertical plane.

Consider the simplest situation of a single discontinuity. If the discontinuity has, for example, a strike of 45° , the optimum azimuth of the borehole is always perpendicular to the strike no matter what the dip of the discontinuity set is. On the other hand, if the discontinuity has a dip of 60° , the optimum inclination is always 30° no matter what the strike of the discontinuity is. This also holds true for situations with multiple discontinuity orientations.

A horizontal plane is ideal to identify the optimum drilling azimuth, because all strikes can be projected onto this plane. In fact a strike is, by definition, a line projected on the horizontal plane. Horizontal discontinuities are a unique case, because the strike is undefined and must be handled as a special case.

A vertical plane is needed to identify the optimum drilling inclination, because all dips can be projected on such a plane. Because there is no unique vertical plane, an arbitrary one must be chosen. Although it does not matter which vertical plane is used, an east-west or north-south plane is most intuitive and conventional. For the purposes of the article we have arbitrarily selected an east-west vertical projection. This concept is exploited to expand the two-dimensional principle to three dimensions.

To determine the optimum angle of drilling, an objective function to minimize the linear sampling bias of the borehole with respect to each discontinuity orientation is required. For this we propose to define the term linear sampling bias index (LSBI).

Characterization of Discontinuous Rock

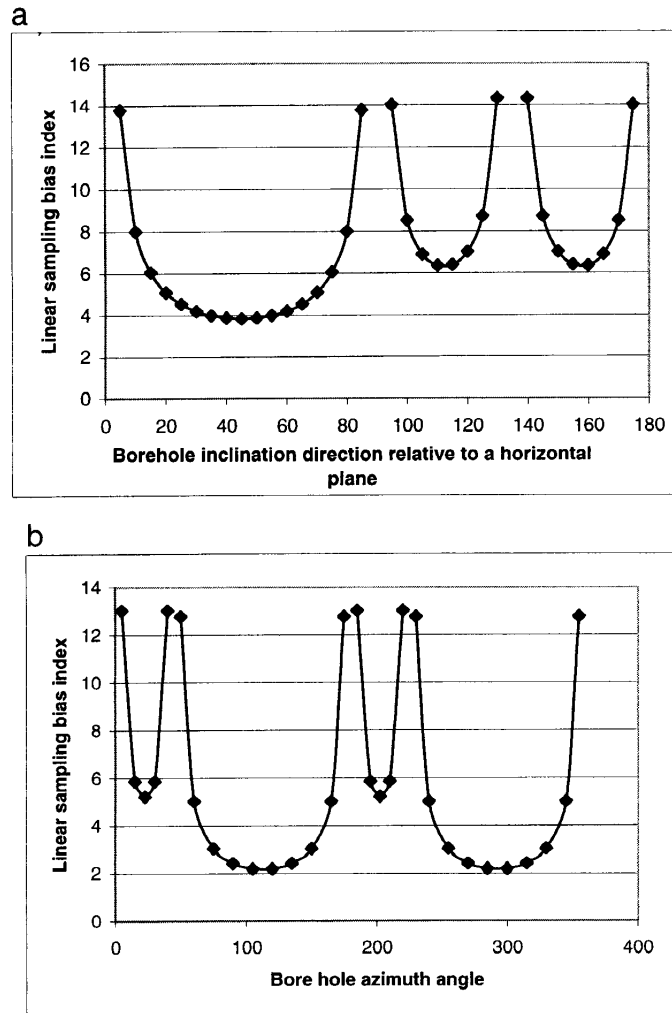


Figure 11. (a) Graphic shows that the linear sampling bias index reaches its minimum values when borehole inclination is 45° from the horizontal plane. (b) Graphic shows the optimum azimuth of the borehole is about 112° or 292°. Because of the angle convention, the minimum at 292° corresponds to the inclination of 45°.

We will describe this term from the simplest scenario and then expand it to general situations. If there is a single discontinuity orientation (Figure 3) and γ is the angle between the linear sampling line (borehole) and the discontinuity orientation, then we define LSBI as follows:

$$LSBI = \frac{1}{\sin \gamma} \quad \text{Eq. 2}$$

This concept can be readily expanded to describe the linear sampling bias of n discontinuity orientations. The

overall LSBI is the summation of the LSBI of each discontinuity set (orientations):

$$LSBI = \sum_{i=1}^n \left(\frac{1}{\sin \gamma_i} \right) \quad \text{Eq. 3}$$

where LSBI is the overall LSBI of n discontinuity sets, n is the number of discontinuity sets, and γ_i is the angle between the linear sampling line and the direction of the i th discontinuity set.

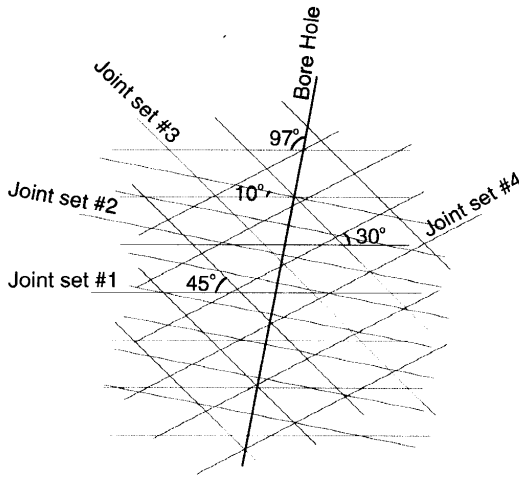


Figure 12. Example of four sets of discontinuities: Set 1 is horizontal, Set 2 has a dip of 10° toward west, Set 3 has a 45° dip toward west, and Set 4 has a 30° dip toward east (in a vertical projection). The optimum drilling direction is 97° (Maerz and Zhou, 2000).

The term *direction of the discontinuity sets* is purposely left vague here. The direction could be the dip of the discontinuity projected on a vertical plane, or it could be the strike of the discontinuity (which is a projection on a horizontal plane). This will become clear as the LSBI concept is used to identify the optimum azimuth and inclination of the borehole.

For a situation with n discontinuity orientations, let α_i denote the angle between the borehole azimuth and the strike of the i th discontinuity set. By applying the concept of LSBI to borehole azimuth and the projection of strikes of discontinuity sets on a horizontal plane we get the following:

$$LSBI_{\phi} = \sum_{i=1}^n \left(\frac{1}{\sin \alpha_i} \right) \quad \text{Eq. 4}$$

where $LSBI_{\phi}$ is the LSBI in terms of borehole azimuth, n is the number of discontinuity sets, and α_i is the angle between the borehole azimuth ϕ and the strike of the i th discontinuity set.

The optimum azimuth of the borehole is found when Equation 4 is minimized by considering all possible values of ϕ .

If one of the n discontinuity sets is perfectly horizontal, then $n - 1$ discontinuity sets need to be considered, because the strike of a horizontal discontinuity set is not defined.

Similarly, the concept of LSBI can be applied to borehole inclination and the projection of dip of discontinuity sets to a vertical east-west plane. The angle conven-

tion for borehole inclination (θ) is defined as shown in Figure 4a. Figure 4a is a vertical projection of the borehole inclination with a range from 0° to 180°. An inclination less than 90° indicates the borehole dips toward the east, whereas greater than 90° indicates dip toward the west (the north-south direction is a special case). Figure 4b shows the definition of the angle (β_i) between the borehole inclination and the discontinuity inclination. It is always taken as the lesser angle between the two.

By applying the concept of LSBI to borehole inclination and the projection of dips of discontinuity sets on a vertical east-west plane we get:

$$LSBI_{\theta} = \sum_{i=1}^n \left(\frac{1}{\sin \beta_i} \right) \quad \text{Eq. 5}$$

where $LSBI_{\theta}$ is the LSBI in terms of borehole inclination, n is the number of discontinuity sets, and β_i is the angle between the borehole inclination θ and the dip of the i th discontinuity set.

The following are the conventions used, based on an upper-hemisphere projection. The azimuth (ϕ) of the borehole is defined in Figure 5a. North is 0° or 360°, with a clockwise positive convention. Borehole inclination is related to the azimuth in the following fashion: If the azimuth is between 0° and 180°, then borehole inclination is between 90° and 180°. If the azimuth is between 180° and 360°, then the borehole inclination is between 0° and 90°. Figure 5b shows the lesser angle between the strike of the discontinuity set and projection of the borehole in a horizontal plane.

Examples of Identifying the Optimum Borehole Orientation

One Discontinuity Set

The simplest scenario is where there is only one discontinuity set. As an example, consider the case of a single set of horizontal parallel planar discontinuities with uniform spacing and infinite persistence (Figure 6). It is obvious that the optimum drilling direction for this case is the vertical direction, because it is guaranteed to intersect the maximum number of discontinuities with a certain drilling length. Using the notation β for the angle between the drilling inclination and the discontinuity dip, the $LSBI_{\theta}$ is defined as $1/\sin \beta$. Figure 7 proves that the $LSBI_{\theta}$ reaches its minimum (1.0 in this case) when the drilling direction is optimized (vertical). Because the optimum drilling inclination is 90°, the azimuth of the borehole is not defined, nor is it necessary to define. Any other drilling direction will give an $LSBI_{\theta}$ greater than 1.0. The worst drilling direction is when the borehole is horizontal, which is parallel to the discontinuity orientation; in such a case, the $LSBI_{\theta}$ is infinite.

Characterization of Discontinuous Rock

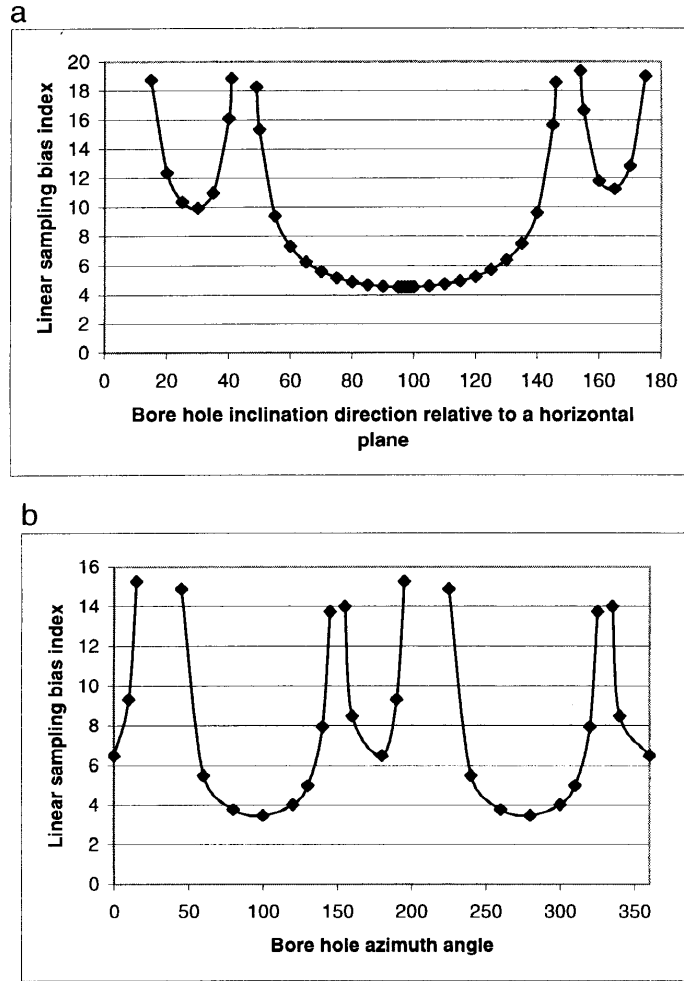


Figure 13. (a) In the example of four discontinuity sets, the linear sampling bias index reaches its minimum value when the borehole inclination is about 97° (Maerz and Zhou, 2000). (b) Graphic shows the best azimuth of this four-discontinuity-set situation is about 100° or 280°. Because of the angle convention, the minimum at 100° corresponds to the inclination of 97° (Maerz and Zhou, 2000).

If there is only one discontinuity set, the optimum drilling direction is the direction that is normal to the discontinuity set orientation. For situations involving multiple discontinuity sets, the analysis becomes more complicated. The optimum drilling direction is the direction along which the overall sampling bias is minimized.

Two Discontinuity Sets

Consider another example, with two sets of orthogonal discontinuities, one set horizontal and another set vertical with a strike of 180° (Figure 8). The optimum

inclination of the borehole is the direction at which the LSBI ($LSBI_0 = 1/\sin \beta_1 + 1/\sin \beta_2$) reaches its minimums. The results of this analysis are shown in Figure 9a and b. In this example, two minimum values of $LSBI_\phi$ are observed, an azimuth of 90° or an azimuth of 270°. By convention, the azimuth of 90° is associated with the inclination of 45° and the azimuth of 270° with the inclination of 135°.

Because the minimum values of $LSBI_\phi$ are identical, both orientations are equally optimal. This results because the discontinuities are distributed in a symmetrical pattern in this particular example. (There are of course

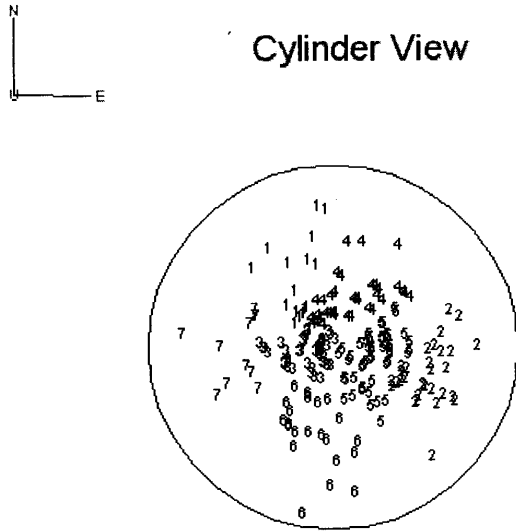


Figure 14. Graphic shows the result of discontinuity clustering analysis from 190-ft-long borehole. The position of each number represents the pole of each corresponding discontinuity. Seven discontinuity subsets are identified in this example.

four possible combinations of borehole azimuth and inclination, but only two are valid.)

Three Discontinuity Sets

Consider yet another example, with three sets of discontinuities. Set 1 is horizontal, Set 2 is vertical with a strike of 180°, and Set 3 has a 45° dip and 45° strike toward the west. Figure 10 is a two-dimensional projection of the inclination of discontinuities and borehole. The $LSBI_0$ ($LSBI_0 = 1/\sin \beta_1 + 1/\sin \beta_2 + 1/\sin \beta_3$) expressed as a function of rotation of the borehole inclination is shown in Figure 11a. According to Figure 11a, the optimal inclination is 45°. According to Figure 11b, the optimal azimuth is either 292° or 112°. By convention, the azimuth of 292° corresponds to the inclination of 45°, because an inclination of less than 90° indicates an azimuth of greater than 180°.

Four Discontinuity Sets

Consider one final example using four sets of discontinuities. Discontinuity Set 1 is horizontal, Set 2 has a 10° dip and a 20° strike toward east, Set 3 has a 45° dip and a 40° strike toward east, and Set 4 has a 30° dip and a 150° strike toward west. The optimum drilling inclination for this case is 97° (see Figure 12) from the horizontal plane. Figure 13a shows the $LSBI_0$ as a function of the angle between inclination of the

Table 1. Table shows the means of dip and dip of the seven discontinuity subsets (Maerz and Zhou, 2000).

Set	Dip Direction (°)	Dip Angle (°)
1	152	45
2	286	55
3	81	18
4	198	32
5	281	28
6	14	48
7	89	55

borehole and dip of the discontinuity sets. The $LSBI$ ($LSBI_0 = 1/\sin \beta_1 + 1/\sin \beta_2 + 1/\sin \beta_3 + 1/\sin \beta_4$) reaches its minimum value when the borehole inclination is 97° (toward west). According to Figure 13b and by the convention, the optimum azimuth of the borehole is about 100°.

DISCUSSIONS ABOUT THE METHOD

Modification for Discontinuity Sets with Non-Uniform Spacing

The analysis so far is based on the assumption that the frequency (spacing) of the discontinuity sets is uniform. This is usually not the case in practice. Discontinuity sets more often than not have non-uniform frequency, so that the average frequency within a discontinuity set is used. The $LSBI$ is a summation of the sampling bias components of all the discontinuity sets. Because not every discontinuity set has equal frequency, the contribution of each set to the overall sampling bias varies from set to set. This can be weighted by the following factor:

$$w_i = \frac{\lambda_i}{\sum_{i=1}^n \lambda_i} \quad \text{Eq. 6}$$

where w_i is weighting factor of the i th discontinuity set, n is the number of discontinuity sets, and λ_i is the average frequency of the i th discontinuity set.

Considering the non-uniform discontinuity frequency (spacing), the modified $LSBI$ can be re-expressed as follows:

$$LSBI = \sum_{i=1}^n \left(\frac{\lambda_i}{\sum_{i=1}^n \lambda_i} \times \frac{1}{\sin \gamma_i} \right) \quad \text{Eq. 7}$$

where λ_i is the angle between the borehole direction and the angle of the i th discontinuity set.

Situations with Multiple Local Minimums

In the following discussions, concepts are illustrated by using the inclination of borehole as an example. The

Characterization of Discontinuous Rock

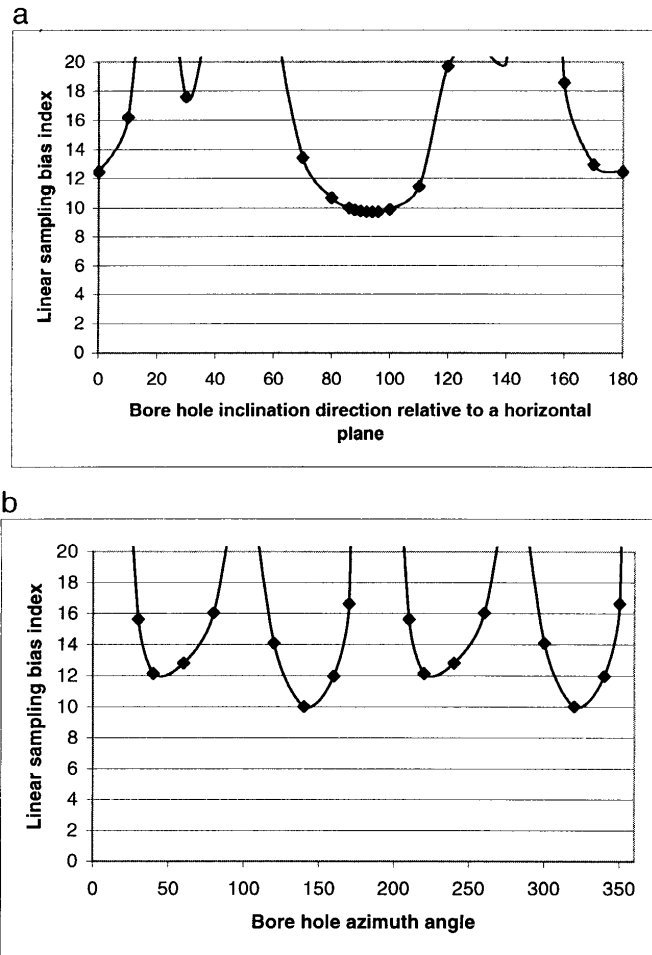


Figure 15. (a) In this example using real data, the linear sampling bias index reaches its minimum value when the borehole inclination is about 94° (Maerz and Zhou, 2000). (b) Graphic shows that the best azimuth of this seven-discontinuity-set situation is about 140° or 320° . Because of the angle convention, the minimum at 140° corresponds to the inclination of 94° (Maerz and Zhou, 2000).

same principles are applied to the azimuth of the borehole. To generalize this method to accommodate for n sets of discontinuities, denote the LSBI as $F(\alpha_i)$ and α_i as the angle between the dip of the i th discontinuity set and the inclination of borehole. As the borehole direction rotates clockwise from horizontal to vertical and to horizontal again, α_i changes correspondingly.

The basic idea of finding the optimum drilling direction is to find the direction along which the minimum LSBI is obtained, that is, to find the point correspond-

ing to the minimum value of function $F(\alpha_i)$ (Equation 2). Within a locally continuous domain, local minimums of the function may be obtained when the derivative of the function is 0.

Notice that there are possibilities to have more than one solution, because this function could have more than one local minimum. For example, in the situation of two orthogonal discontinuity sets (Figure 8), the optimum drilling direction could be either 45° or 135° . In the examples of three discontinuity sets (Figure 10) and

four discontinuity sets (Figure 12) shown earlier, there are three local minimum values of LSBI. The following are some general rules for situations with multiple local minimums.

For inclinations:

1. Where there is more than one local minimum, the one with the lesser value is more optimal.
2. The one with the greater value, although less optimal, may be used because of other restraints, such as equipment limitations on, for example, the inclination of drilling.
3. Where there is more than one local minimum, and these are equal, each of the orientations is equally optimal. Where there is more than one local minimum both for inclination and for azimuth, not all combinations of inclination and azimuth are valid within the context of the projection and the definition of angle parameters.

For azimuths:

1. The azimuth chart is periodic in that the section for 180° – 360° is a repeat of the section between 0° and 180° , and there will be two equal local minimums. Only one of these is valid, and it is determined by the relation between the projection of the inclination and azimuth of a borehole. If the inclination of borehole is toward west (inclination greater than 90°), then the azimuth of the borehole is the one that is less than 180° . If the inclination of the borehole is toward east (inclination less than 90°), then the azimuth of the borehole is the one that is greater than 180° .
2. So far, the analysis has been based on a west–east vertical projection. If the inclination of the borehole is exactly to the north or south, a north–south vertical projection is more suitable than a west–east vertical projection. In a north–south vertical projection, if the inclination of borehole is toward north (inclination greater than 90°), then the azimuth of the borehole is in the range of 90° to 270° . If the inclination of the borehole is toward south (inclination less than 90°), then the azimuth of the borehole is in the range from 270° to 360° or from 0° to 90° .

APPLICATIONS

Figure 14 shows the cluster analysis results of discontinuities along a 190-ft-long borehole in argillite formations. There are 232 discontinuities in total. Seven joint sets are identified. Table 1 shows the output results from the program CYLINDER (a software package used for multivariate analysis of discontinuities from orientated borehole; for detailed discussion of this approach, please refer to Maerz and Zhou, 1999).

The average dips and the dips of the seven discontinuity sets were input into the optimum drilling direction analysis. According to Figure 15a and b and the relation between the projection of inclination and azimuth of a borehole, the optimum drilling direction for this situation is at an azimuth of about 140° , with an inclination of about 94° (toward west).

CONCLUSIONS

This article proposes a method to identify the optimum drilling direction, along which a single borehole can intersect as many discontinuities as possible. The idea of this method is based on the linear sampling bias analysis, quantified as a linear sampling bias index (LSBI). The optimum drilling direction is defined as the direction along which the minimum linear sampling bias is obtained.

By means of this method, a single borehole could drill through as many discontinuities as possible, resulting in less drilling. The precondition of this method is that there is some a priori knowledge of the number and orientation of discontinuity sets. This precondition may be obtained from data from a preliminary borehole or from surface or other mapping data, or it may be estimated from regional structural trend. Data from the preliminary borehole can then be used to orient the second and subsequent boreholes.

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