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U.S. Army Corps Engineers
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Technical Letter
No. 1110-2-581

31 July 2014

EXPIRES 31 JULY 2019

Engineering and Design

METHODS TO IDENTIFY OPTIMUM DRILLING DIRECTION FOR GEOTECHNICAL EXPLORATION AND ROCK ENGINEERING

1. Purpose. This engineer technical letter provides technical guidance and analytical methods to identify the optimum drilling direction of a borehole. The objective of optimization is to determine an explicit borehole orientation, i.e., azimuth and inclination, which will intersect the maximum number of discontinuities that exist within a rock mass. These methods have critical applications in geotechnical exploration, in-situ testing, foundation and rock slope drainage, reduction of foundation uplift, permeation grouting, as well as other practical applications in geotechnical engineering and rock engineering.

2. Applicability. This engineer technical letter applies to U.S. Army Corps of Engineers commands having design and/or construction responsibilities for civil works projects. The user of this ETL, as a member of a project PDT, is responsible for seeking opportunities to incorporate the Environmental Operating Principles (EOPs) wherever possible. A listing of the EOPs is available at:
http://www.usace.army.mil/Missions/Environmental/EnvironmentalOperatingPrinciples.aspx

3. Distribution Statement. Approved for public release, distribution is unlimited.

4. References. See Appendix A.

FOR THE COMMANDER:

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CHAPTER 1

Introduction

1-1. Purpose. The purpose of this engineer technical letter is to provide technical guidance for analytical methods to identify the optimum drilling direction of a borehole. Three methods are described: Linear Sampling Bias Index (LSBI); Linear Sampling Angular Deviation (LSAD); and Discontinuity Frequency Extrema Method (DFEM). The three methods produce essentially equivalent results. These methods may be used individually or in combinations to both obtain and verify results. The optimum drilling direction is the orientation, i.e., azimuth and inclination, along which a borehole can intersect the maximum number of discontinuities that exist within a given rock mass. Intersecting the maximum number of discontinuities in a borehole for a given drilling length will assist in accurately characterizing bedrock discontinuities and can have critical applications in both geotechnical exploration and rock engineering.

1-2. Background.

a. A rock mass is distinctively different from other structural materials used in civil engineering. It is typically heterogeneous and anisotropic and is composed of a system of rock blocks and fragments separated by discontinuities forming a material in which all elements behave in mutual dependence as a unit (Matula and Holzer, 1978). Rock mass properties are characterized in part by the shape and dimensions of the rock blocks and fragments, and their mutual arrangement within the rock mass, which is as defined by the spatial orientation, frequency, persistence, and condition of the existing discontinuities. Discontinuities affect both physical and hydrological properties of the rock mass, including stability, failure modes, deformation, permeability, reinforcement and support requirements, excavation effort, as well as the response of the rock mass to loading and blasting.

b. Discontinuities typically display preferred orientations. Discontinuity data can be collected using one or more of several available survey methods. Properly conducted surface surveys can furnish data with a high probability of accurately representing the orientation and physical conditions of the discontinuities within the rock mass at depth may differ from those near the ground surface. Weathering, aperture, stress relief, groundwater impacts, infilling properties and other physical differences discontinuities may exhibit between surface and deeper expressions may be better evaluated with a more detailed design approach to drilling. These data can be evaluated and then analyzed to determine an *optimum drilling direction* of a borehole. Calculation of the optimal orientation requires some measure of angular dispersion of the joint sets around the borehole for a rock mass with multiple joint sets.

c. Drilling and logging of boreholes is a commonly used exploration method to obtain samples at depths for geotechnical site investigations or to provide access for installing geotechnical instrumentation, foundation drains, permeation grouting or for performing in-situ testing. Terzaghi (1965) pointed out that linear sampling of fractures has an orientation sampling-bias such that discontinuities separated from boreholes by angles of 30° or less fall into a 'blind zone.' Boreholes drilled without consideration of this sampling-bias may statistically under-represent or completely miss critical joint sets. To improve the efficiency of a drilling program often requires that the borehole intersect as many discontinuities as possible per unit length of borehole. The ability to explicitly orient a borehole in advance of drilling with the intent of intersecting as many discontinuities as possible per unit length of borehole can be of considerable benefit in geotechnical engineering, since the mechanical and hydrological behavior of a rock mass is normally controlled by the presence of existing discontinuities.

1-3. Assumptions. The methods used to identify the *optimum drilling direction* are based upon the following general assumptions:

a. The frequency or spacing between individual discontinuities within a discontinuity set is uniform throughout the analyzed region; subsequently, the mean discontinuity frequency or spacing of each discontinuity set is used.

b. The persistence of the existing discontinuities is larger than the dimension of the region investigated.

c. The diameter, length, and orientation of any borehole are known.

d. The analysis of sampling bias is based on a two dimensional projection.

e. 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.

1-4. Objective. The preferred drilling direction varies with the drilling objective. If the objective of geotechnical drilling is to maximize core recovery, then the optimal drilling direction would be the direction that could avoid as many discontinuities as possible. Conversely, if the objective of geotechnical drilling is to encounter as many discontinuities as possible or to collect subsurface discontinuity data, then the optimal drilling direction would be the direction along which the maximum number of discontinuities would be intersected. For the purpose of this engineer technical letter, the *optimal drilling direction* is defined as the drilling direction along which the maximum number of discontinuities is intersected.

CHAPTER 2

Origin of Discontinuities

2-1. Introduction. A discontinuity, for the purpose of this engineer technical letter, is considered as a relatively continuous break in rock mass integrity and does not include conditions such as quartz seams, so-called "healed" fractures where mineral filling has restored rock mass integrity, or gradational changes in lithology. Discontinuities are significant in design and construction as they directly affect the strength, bearing capacity and durability of the materials involved and they contribute to or dominate the manner in which groundwater travels in a rock mass. The origins, frequency, aperture, persistence, degree of relief and shape of the discontinuities interact with the properties of the rock mass and the properties of any discontinuity in-fill materials to establish the structural integrity, as well as the hydraulic conductivity of the rock mass.

2-2. Diagenetic Discontinuities.

a. Diagenetic discontinuities are those that occur as a result of the processes and environment present during the formation of the rock mass. The primary usage of the term implies sedimentary environments; however there may be conditions that occur during the crystallization or re-crystallization in igneous and metamorphic rock respectively that can result in either diagenetic discontinuities or rock fabric conducive to later formation of discontinuities.

b. Sedimentary Diagenetic Discontinuities. The majority of diagenetic discontinuities that are significant in the design and construction of projects are bedding planes. Bedding planes are surfaces between layers of sedimentary rock that occur as a consequence of some change in depositional environment, including whether it is a change in the mineral composition or distribution of constituent minerals of the sediment, the grain size distribution, the degree of angularity or roundness of sediment, hydrologic setting, i.e., depth of water, degree of turbulence, direction of flow/waves, etc., or an change in the rate at which the sediments are deposited. The origin of bedding planes may be one or more of these or other causes in combination. Bedding planes may be subtle or pronounced as a consequence of the degree of contrast among the factors that result in the character of the overall rock mass that results. Bedding planes may or may not be characterized by partings or separation – breaks in the continuity of the rock mass. They may or may not be characterized by changes in the physical properties of the rock mass that are most important is design – strength, durability and permeability.

c. Changes in the mineral composition may be visually obvious or very subtle. The change may be a result of the erosion upstream or at the source of the sediment reaching a change in the source material, or it may reflect the eruption of volcanoes, changes in sea level that impact the distance from the source, and thereby change the constituent proportions by virtue of hydrologic sorting or mineralogic persistence or durability.

d. Grain size distribution may change as a result of hydrologic environmental change, including depth, distance of transportation from source, or in the case of carbonates, type of marine life that is the source of sediment. Mineral durability also impacts grain size distribution.

e. The degree of sediment grain roundness is a function of mineral type, distance of transport and whether or not the sediment is re-worked.

f. If the rate of deposition becomes negative, i.e., more material is being removed than deposited, the discontinuity may be considered an *erosional unconformity*. Erosional unconformities may exhibit a variety of textures from smooth and subtle to rough irregular surfaces with fragments of eroded underlying material included within either the overlying bed or within the discontinuity as filling. If present, this filling may be either lithified or unconsolidated.

g. Diagenetic discontinuities may result from other causes, subsequent to deposition including but not limited to compaction or differential settlement, pressure-induced mineral dissolution and re-crystallization, hydrothermal effects, or mass movements that occur prior to lithification. The most common of these are stylolites, presented as step-like discontinuities or sutures in carbonate rock that are characterized by discontinuities perpendicular and parallel to the bedding plane directions.

h. Reef structures in carbonate rock present challenges with respect to discontinuities because the complexity of shapes and sizes of discontinuities resulting from reefs are not readily quantifiable, nor do they lend themselves to numerical modeling.

2-3. Cooling. Cooling of rock masses may result in discontinuities as breaks resulting from thermally-induced contraction, or in igneous or metamorphic rock from the solidification of one rock unit at different rates or sequentially before emplacement of another unit. Among the more common types of thermally-induced discontinuities are columnar jointing that occurs primarily in massive basalt units, and the horizontal discontinuities between extrusive igneous rock units. Tension cracking in igneous and metamorphic rocks also forms as a result of cooling and contraction of the rock mass. In low viscosity lavas cooling of this type can also for, lava tubes that may be challenging to address in design of structures at these sites.

2-4. Shrinkage. Shrinkage may result in sedimentary rock masses as they are compacted by overlying materials and as they lose moisture/water content. These cracks may be subtle to pronounced, and may exhibit patterns or be random in orientation.

2-5. Tectonic. Tectonic discontinuities are breaks or shearing planes that result from movement of a consolidated rock mass on a large scale. They may range in scale from small shear zones to major fault zones. Tensional joints may be formed in response to more subtle tectonic structures, such as anticlines, arches or other regional tectonic features. These joints typically appear in joint sets with sub-parallel or parallel orientations.

2-6. Geomorphological. Discontinuities may result from geomorphic activity – surface and near-surface materials altered by the actions of weathering, erosion and mass movement of surface materials. These may include near horizontal tensional relief joints that form in response to erosion of surface deposits by glaciers or moving water – streams and surface runoff. Tensional joints forming sub-parallel or parallel to river valleys may also be considered geomorphological discontinuities.

2-7. Induced Fractures. Discontinuities formed by construction activities, i.e., excavation and loading of rock masses, are anthropogenic or induced fractures. These may include cracks in rock excavations that result from unloading or removing confinement and may appear in quarry walls, cut rock slopes, underground excavations, tunnels and shafts. Some shear fractures may result from overloading rock in the course of construction, whether by exerting loads by adding permanent loads or in the course of moving equipment and materials.

2-8. Karst. Karst discontinuities are caused by the wide-scale dissolution and removal of carbonate or other soluble rock masses. Karst features typically occur in limestone and dolomite rock masses exposed to circulating, slightly acidic groundwater, which dissolves and removes the calcium carbonate or other soluble constituents leaving cavities and voids. Karst features can range from small individual features to extremely large interconnected systems that may extend over large geographic areas. Carbonate foundations typically exhibit high permeability fracture systems, even in the absence of discrete cavities. The permeable fractures may have preferential orientations with strong interconnections to other fractures. Lesser fractures feed groundwater to these larger fractures through interconnected fractures that result in a highly transmissive conduit flow system that often exhibits rapid flow. Although karst features may take advantage of joint patterns or other types of discontinuities, they can also be inherently random in regards to their spatial distribution, which often makes it problematic to locate karst features with conventional exploration methods alone.

2-9. Miscellaneous. Structural Features. In concept, any structural feature in or around rock has the potential to result in discontinuities through the effects of combinations of the causes described in the preceding discussions. These can occur as a result of changing stress fields and the rock mass responding to those changes by yielding, compressing, fracturing or becoming more permeable either by themselves or in combination with tectonic activity, weathering and anthropogenic impacts. These are discontinuities, as they express themselves as a change in the rock mass properties that are important in design for strength and permeability considerations.

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CHAPTER 3

Features of Discontinuities

3-1. General.

a. A discontinuity is defined as any significant interruption in the rock fabric, mechanical break or fracture of negligible tensile strength existing within a rock mass; it has a low shear strength and high fluid conductivity when compared to the rock itself (Priest, 1993). The term "discontinuity" is used in this engineering technical letter as a collective term for all structural breaks in geologic materials regardless their origin, age, type, condition or geometry. The term "joint" is also used as a generic term by rock engineers to include such structural breaks and may be used interchangeably with “discontinuity.” The term “fracture” is considered in this engineering technical letter as a non-systematic discontinuous feature of a rock mass. Fractures are not in sets or parallel and while they could occur in large numbers, their distribution is generally more random.

b. As there are not any distinct and universally accepted rules or nomenclature for a terminology of discontinuities for engineering purposes, Brekke and Howard (1972) suggest using scale, based on aperture, persistence and occurrence; and character, based on occurrence of filling material. Subsequently, joints and related features can be divided into three main groups, as shown in Table 3-1.

Table 3-1
Types of Joints and Related Features

Nomenclature	Typical Length
Micro-fissures	< 10 mm (0.4 inches)
Joints	0.1 - 100 m (0.3 - >300 ft)
Weakness zones	> 30 m (100 ft)

(1) Micro-fissure is usually considered as a defect or flaw in the rock material (Brekke and Howard, 1972) and is therefore considered as a rock material parameter, rather than genuine discontinuity. Micro-fissures will not be considered herein.

(2) A joint is a discontinuity plane of natural origin along which there has been no visible displacement (ISRM, 1975; NRMG, 1985).

(3) Weakness zones including faults, which is a discontinuity zone along which there has been recognizable displacement, from a few centimeters to a few kilometers in scale. The walls are often striated and polished (slickensided) resulting from the shear displacement. Frequently rock on both sides of a fault is shattered and altered or weathered, resulting in fillings such as breccia and gouge. Faults may vary from millimeters to hundreds of meters (ISRM, 1978).

c. All rock masses contain discontinuities. Discontinuities affect the engineering behavior of rock masses. Significant properties of discontinuities include: (i) orientation (strike and dip); (ii) scale, frequency, continuity, density and spacing; (iii) openness, roughness, type and degree of infilling, moisture conditions, hardness and degree of weathering; (iv) mechanical properties (shear strength and deformability); and (v) hydraulic properties (permeability or conductivity). All of the aforementioned discontinuity properties play some critical role in controlling the design or performance of an excavation or civil engineering structure constructed in rock. However, only the fundamental spatial geometric parameters of discontinuities, such as orientation, spacing and persistence will be considered in the analyses described in this engineer technical letter.

d. Discontinuities generally occur as sets, with each set consisting of regular joints sub-parallel to each other. In each set, the discontinuities have approximately the same orientation and generally the same physical characteristics (Priest, 1993). Several sets of discontinuities are often developed in a rock mass, three to four sets being most common and one or more of them may be statistically dominant.

e. Discontinuities often have an irregular or curvilinear geometry over an areal scale; however, there is usually a scale at which the geometry of the discontinuity is sufficiently planar to be represented by a single orientation or spacing value.

3-2. Orientation.

a. The geometry of a discontinuity depends on how it propagates and terminates. Joint geometry is controlled by the geometry of the rock mass, loading conditions, and interactions with other joints within the rock mass. Joints in layered rocks are commonly formed perpendicular to the depositional layers. Joints often initiate at flaws, such as a sedimentary irregularity and propagate away from that flaw if sufficient energy is provided by the loading conditions imposed on the rock mass. In layered rock masses, joint segments in adjacent layers commonly form a composite joint that still maintains a roughly rectangular geometry. The existence of thin shale lamina between other depositional layers may cause offsets in the composite joints. Thick shale layers usually impede jointing, resulting in strata-bound joints, which are joints contained only in certain stratigraphic layers. In volcanic rock, thermally driven joints form perpendicular to the cooling surfaces. Individual joints are also composites of joint segments formed by cycles of incremental growth. Their longest dimension is perpendicular to the cooling surface. For rock emplaced at or near the surface, the cooling surface is usually the upper and lower surfaces of the rock mass, so the longest dimension of the joint is usually vertical.

b. The orientation of discontinuities is defined by the three-dimensional orientation of the line of maximum dip of a particular plane and by the angle between true north and the projection of this line on the horizontal plane. Discontinuities are usually considered as planar features and their actual orientation can be defined by using one of two methods: (i) strike and dip angles, or (ii) dip direction and dip angles. These angles are discussed below and illustrated in Figure 3-1.

(1) *Strike, a_s (compass quadrant system divided into four 45 degree quadrants).* This the compass direction of a line formed by the intersection of a horizontal plane and an inclined geologic plane, such as a discontinuity, fault, fracture, etc. Because it is a compass direction, the strike is usually expressed relative to North or South. Hence, strike is expressed as "North (or South) and number of degrees East" or "North (or South) and number of degrees West", such as "N30°E" or "S45°W".

(2) *Dip angle,* y_d ($y_d \leq 90°$). This is the angle between a horizontal plane and the maximum inclination of surface of the plane, as shown in Figure 3-1. The true dip angle is always measured perpendicular to the line of strike. A plane with a dip angle (maximum inclination) of 65º from the horizontal would be reported as a dip equal to 65°.

(3) *Dip direction, a_d (azimuth system where $0° \leq a_d \leq 360°$).* This is the azimuth (compass) direction toward which the plane is inclined. Dip direction is measured clockwise from true north and varies between 0° and 360°, such as 235°. Azimuth (compass) method versus quadrant method for reporting direction is illustrated in Figure 3-2.

(a) Orientation of joints are most often defined by their dip and dip direction and reported in the form of *dip direction* (three digits) / *dip angle* (two digits). As an example, a plane with a dip angle (inclination) of 45º towards the east (90º) would be reported as 090/45.

(4) *Apparent Dip* – This is the inclination angle of a line on a sloping geologic plane as measured in a direction that is oblique to the strike direction. The apparent dip is always less than the true dip and varies between 0° and the true dip. An illustration of true dip and apparent dip is shown in Figure 3-3.

c. Lineations are linear structural features found within rocks. A lineation might be a specific, individual feature in a rock mass; a population of elongate minerals, fossils, etc.; or the intersection of two planes, which inherently forms a line. Intersection lineations are linear structures formed by the intersection of any two surfaces in a three dimensional space. The orientation of a linear feature or lineation is defined by trend, plunge and rake. Trend, plunge, and rake along a planar surface are illustrated in Figure 3-4.

(1) *Trend, a_t (azimuth system where $0° \leq a_t \leq 360°$).* This is the azimuth (compass) direction of horizontal projection of the linear feature measured as degrees clockwise from true north, such as 85° and reported as 085.

(2) *Plunge*, b_p ($-90° \leq b_p \leq 90°$). This is the acute angle between the tilted linear feature and a horizontal plane measured as degrees downward from a horizontal plane, such as 37° and reported as 37. A line directed below the horizontal line is described as a positive plunge and a line directed upward has a negative plunge.

(a) Orientation of trend and plunge is reported in the form of *trend* (three digits)/*plunge* (two digits). As an example, a lineament with a plunge (inclination) of 60º at a trend of 235º would be reported as 235/60. Conversely, 235/25 refers to a line plunging downward at an angle of 25° towards an azimuth of 235° and 155/-40 refers to a line plunging upward at an angle of 40° towards an azimuth of 155°.

(3) *Rake (pitch),* y_r ($y_r \leq 90°$). This is a single angle, measured in a plane of specific orientation, between the lineament and a horizontal line. Rake (pitch) gives the orientation of linear features that occur in a plane. Measurement of rake is usually done using a protractor along the plane and measuring the angle between the strike line and the linear feature. Trend and plunge are used to describe the orientation of linear feature, but only rake describes linear features that exist in a specific plane.

d. An alternative convention is the right-hand rule. In the right-hand rule convention, the dip is always oriented to the right hand (clockwise) side of the designated strike line when looking downwards. In practical terms, this means that you identify one end of the strike by determining which way you must face to have your right hand point in the direction of the dip; you record the direction in which you are facing as the strike direction. The advantage of this system is that no dip direction is necessary.

3-3. Spacing.

a. Joint spacing (S_j) is the perpendicular distance between adjacent discontinuities along a line of specific location and orientation. Discontinuity spacing is often used as a measure of the 'quality' of a rock mass. Measurements of joint spacing are different on different measuring faces and in different measuring directions. Often an apparent spacing is measured in the field and the true spacing must be obtained by correcting the bias produced by the line survey. Recommended ISRM (1978) descriptions for joint spacing to be used in numerical method of analysis are shown in Table 3-2. Other classifications of joint spacing are available, including Deere (1964), EM 1110-1-2908 Rock Foundations, and the USBR Engineering Geology Field Manual (2001). The ISRM (1978) joint spacing classifications are used herein since they are compatible with the rock mass rating (RMR) system (Bieniawski, 1988).

Table 3-2
ISRM Classification of Joint Spacing (S_j)

Description	Joint Spacing
Extremely close spacing	< 0.02 m (< 0.75 inches)
Very close spacing	0.02 – 0.06 m (0.75 - 2.4 inches)
Close spacing	0.06 – 0.2 m (2.4 – 7.5inches)
Moderate spacing	0.2 – 0.6 m (7.5 inches - 2 ft) -
Wide spacing	0.6 – 2 m (2.0 - 6.5 ft)
Very wide spacing	2 – 6 m (6.5 – 20 ft)
Extremely wide spacing	> 6 m (> 20 ft)

b. Joints spacing is often expressed as the mean spacing between adjacent discontinuities, measured normal to the joint plane. However, three separate types of discontinuity spacing may be used:

(1) The spacing between a pair of immediately adjacent discontinuities as measured along a linear traverse and referred to as *total spacing*.

(2) The spacing between a pair of immediately adjacent discontinuities from the same joint set (group) as measured along a linear traverse and referred to as *set spacing.* Discontinuity set spacing can be estimated by selecting only those discontinuities detected in a linear traverse survey (scanline) that have an orientation within some specific range.

(3) The set spacing as measured along a linear traverse survey (scanline) that is parallel to the mean normal to the joint set and referred to as *normal set spacing*.

c. The terms *joint spacing* and *average joint spacing* are often used in the description and assessments of rock masses. Where more than one joint set occurs, this measurement is often based upon surface observations given as the average of the spacing for all existing joint sets. There is often some uncertainty as to how this average value is calculated (Palmström, 2001). Average spacing for three joint sets (JS) is found using [$1/S_{avg} = 1/S_{JS1} + 1/S_{JS2} + 1/S_{JS3}$] and not using [$S_{avg} = (S_{JS1}+S_{JS2}+S_{JS3}) / 3$]. For example, the average spacing for three joint sets with following joint spacing: $S_{JS1} = 1.0$ ft, $S_{JS2} = 0.5$ ft, and $S_{JS3} = 0.2$ ft have an average spacing (S_{avg}) equal to 0.125 ft, and not (S_{avg}) 0.57 ft.

d. The term *joint spacing,* when used in the technical literature, often does not clearly indicate what the joint spacing includes. It is difficult to know whether a joint spacing referred to in the literature represents a total spacing, a set spacing, or a normal set spacing, or if the spacing is true or apparent. There is often much confusion related to the use of joint spacing and caution must be used when applying joint spacing data obtained from the technical literature.

e. Joint frequency (l) is the inverse of joint spacing and is the number of joint per linear measure, typically measured in feet or meters. Joint frequency is then defined as the number of joints per unit length and is the inverse of joint spacing (S_j). Joint frequency may be determined for total spacing (S_{jt}), set spacing (S_{js}), and normal set spacing (S_{jn}) joints and given by:

$$\lambda = 1 / S_j \tag{3-1}$$

where:
λ = Joint Frequency, and
S_j = Joint Spacing

f. When logging drill cores the average lengths of core pieces (joint intercept) are seldom true joint set spacing, as joints of different sets are included in the measurement. In addition, random joints, which do not necessarily belong to any existing joint set, are also often encountered in the drill core.

g. For a borehole, the *apparent fracture frequency (F = 1/Sa)* along the borehole is related to the joint set dip angle (a). The joint set spacing (S) is given by (Amadei, 2008):

$$F = 1 / S_a = \cos a / S = f \cos a \quad (3\text{-}2)$$

(1) Where $f = 1/S$ is the *true fracture frequency* measured in a direction perpendicular to the joint set. This equation can be generalized to the case of a borehole oriented at any angle with respect to a joint set of spacing S_j and a known orientation.

(2) Let *n1*, *n2*, and *n3* be the direction cosines of the normal to a joint set and *lh*, *mh*, and *nh* be the direction cosines of a unit vector parallel to the borehole axis. The fracture frequency in the borehole direction is then given by (Amadei, 2008):

$$F = (l_h n_1 + m_h n_2 + n_h n_3) / S_j \quad (3\text{-}3)$$

h. The use of the probability density distribution permits calculation of the probable block size and the likelihood that certain intersections will occur.

3.4 Persistence.

a. Persistence is the areal extent or length of a discontinuity and can be quantified by observing the trace lengths of discontinuities on exposed rock surfaces. Persistence is sometimes defined as the ratio of joint segment to total area measured in the plane of the joint. A joint that can be followed without interpretation for the full distance of the joint has a persistence of 1.0.

b. Joints commonly terminate at another joint. Joints that terminate in massive rock are often called discontinuous joints. Such joints can be foliation partings, en echelon joints in addition to many of the smaller joints, that is, those joints that are less than 3 feet long. One joint set will often be more persistent than the other sets and the joints of the other existing joint sets will therefore tend to terminate against the dominant joint set.

c. Most bedding joints are highly persistent; however, the horizontal dimension of other individual joint types may be very limited in their extent. Persistence of joints parallel to bedding may extend more than a few hundred feet while the persistence of non-bedding joints is rarely more than a few tens of feet. Although the lateral dimension of a single joint may occasionally extend a few hundreds of feet. Major structural features such as faults may extend for several hundreds of feet or even miles. ISRM suggested descriptions for joint persistence is shown in Table 3-3.

d. Individual joints may connect to form long linear arrays. Adjacent fractures may also overlap slightly and link over a broad range of scales. The geometry of joint overlap and the subsequent connectivity and relative persistence of joints is strongly influenced by the state of stress. If the differential regional stress is small, i.e., hydrostatic state of stress, the tendency of adjacent fractures to interact and connect is strong. For a large differential stress the tendency for linkage and connectivity is weak, so joint traces are straight and linear and overlap for long distances without being connected. The joints in such a system would be poorly connected and the subsequent connectivity between the joints would be low, even though the individual joints are relatively long and straight.

Table 3-3
ISRM Suggested Description for Joint Persistence

Suggested Description	Surface Trace Length
Very low persistence	< 1 m (3 ft)
Low persistence	1 – 3 m (3 - 10 ft)
Medium persistence	3 – 10 m (10 – 33 ft)
High persistence	10 – 20 m (33 ft – 66 ft)
Very high persistence	> 20 m (66 ft)

e. Joint persistence is an important rock mass parameter, but one of the most difficult to quantify. Joint persistence and joint connectivity have strong influences on the hydraulic and mechanical behavior of the rock mass. Persistence and connectivity are difficult to measure and often the only way to obtain these parameters is by direct observation of exposed joints on outcrops or excavation surfaces. Joint continuity or persistence can be distinguished by the terms *persistent*, *sub-persistent* and *non-persistent* (ISRM, 1978) or more simply as *continuous* and *discontinuous*. Illustrations of persistent versus non-persistent joints in a rock mass are shown in Figure 3-6.

3.5 Geometry of Joints.

a. A linear traverse, that is, a single straight-line survey, also known as a scanline, results in an orientation sampling bias (USBR 2001). Terzaghi (1965) pointed out that linear sampling of fractures has an orientation sampling-bias such that discontinuities separated from a linear traverse by angles of 30° or less fall into a 'blind zone.' Joint orientation measurements taken without consideration of this sampling-bias may statistically under-represent or completely miss critical joint sets. This is called *line bias.* The number of intersecting discontinuities is proportional to the sine of the angle of intersection. Terzaghi suggested that application of a geometrical correction factor based upon the observed angle between the traverse line and the normal to a particular discontinuity. Weighting factors may also be applied to the discontinuities that are sampled to compensate for a reduced sample size for those discontinuities with an unfavorable orientations relative to the linear traverse used for sampling. True discontinuity (set) spacing and trace lengths can be obtained by correcting the bias produced by straight line surveys.

b. The orientation, dimension, spacing, persistence and shape of individual joints are often difficult to obtain, because the entire extent of a discontinuity is difficult to observe and interpret in three dimensions. Detailed studies of three-dimensional outcrops are needed to determine the geometry of individual joints in both layered and massive rock masses. Collecting and interpreting the trace geometry of joints is recognizably problematic and a significant, rigorous, and meticulous effort is needed to be successful. Methods and techniques are available that can be used to systematically collect, analyze, and graphically present three dimensional joint orientation, spacing, and persistence data.

3.6 Joint Sets.

a. Joints sets comprise a number of approximately parallel discontinuities of the same type and age having approximately the same inclination and orientation. As a result of the processes involved in the formation of joints, most discontinuities occur in sets (groups) which have generally preferred orientations. Joint sets can be described by their areal and vertical extent, the spacing or density of individual fractures, and the statistically orientation distribution. The complex three-dimensional structure of discontinuities is often referred to as a discontinuity network or as a joint set. An illustration of one joint set versus three joint sets and a random joint in a rock mass is shown in Figure 3-7.

b. The number of joint sets can vary and may range up to five. Typically one joint set cuts the rock mass into plates, two perpendicular joint sets cuts the rock mass into columns and three joint sets cuts the rock mass into blocks, and four or more joint sets cuts the rock mass into mixed shapes of blocks and wedges. The ISRM suggested classifications for joint sets is shown in Table 3-4.

Table 3-4
ISRM Suggested Classifications for Joint Sets

Classification	Description
I	Massive, occasional random fractures
II	One joint set
III	One joint set plus random fractures
IV	Two joint sets
V	Two joint sets plus random fractures
VI	Three joint sets
VII	Three joint sets plus random fractures
VIII	Four or more joint sets
IX	Crushed rock, earth-like

c. In many cases one joint set is dominant, being both larger and/or more frequent than joints of the other sets in the same rock mass. This set is often referred to as the main joint set or as primary joint set.

3.7 Jointing in Igneous Rocks.

a. Plutonic rocks are often broken along numerous discontinuity surfaces. Although unjointed and unweathered plutonic rock certainty does exist. Discontinuities can range from microscopic fissures to joints and faults that can be traced across adjacent outcrops and open excavations. The most prominent discontinuity structures are sheet joints, also known as exfoliation joints and lift joints. These fractures generally follow the trend of the topography, are parallel to the average slopes on hillsides, are vertical behind cliffs and are horizontal beneath level ground. Sheets joints divide the rock mass into slabs or sheets, a few centimeters thick near the ground surface and becoming successively thicker with depth until sheet joints vanish completely at depths of approximately 60 meters (Goodman, 1993).

b. In plutonic igneous rock such as granite, gabbro, diorite, etc. usually three sets of joints are developed caused by tensional forces set up in a rock body as a result of cooling. these three sets of joints, two are often vertical and perpendicular to each other, while one will be more or less horizontal (sheet joints). They divide the rock into more or less prismatic blocks. Sheet joints, which are more or less parallel to the surface of the ground, enable the extraction of rock slabs (Terzaghi, 1946).

c. The joint spacing in igneous rocks may range between a few centimeters and several meters. Fresh joints are often medium sized rough and planar. In some areas, the orientation and the spacing of the joints in granite is very constant over large areas, whereas in other areas it varies in an erratic manner. Regular, large blocks developed in rocks used as building stone often facilitate extraction of regular blocks in plutonic rocks.

d. In basaltic rocks, where uniform cooling and contraction in a homogeneous magma has taken place, columnar jointing is common, which results in hexagonal columns orientated at right angles to the surface of cooling. The columns commonly measure from one to three decimeters across. Since the joints between the columns are open, water can circulate freely through them. Terzaghi (1946) mentions that in igneous rocks which cooled rapidly the joints are generally closely spaced, and that in contrast to basalt, rhyolite has a tendency to develop closely spaced and irregular joints.

3.8 Jointing in Sedimentary Rocks.

a. Sedimentary rocks also commonly contain three sets of joints, one of which is invariably parallel to the bedding planes. The other joints commonly intersect the planes at approximately right angles (Piteau, 1970; Terzaghi, 1946; Deere et al., 1969).

b. Even when strong sedimentary rocks like limestone and well cemented sandstones predominate, thin argillaceous intercalations (shale partings) can introduce pervasive weakness planes.

c. In limestone and sandstone, the joint spacing of each set is often approximately one meter (3 feet) in length. In shale, they are generally closer, and they may be so close that no intact specimen can be secured with a width of more than a centimeter (0.4 inches) (Terzaghi, 1946). During excavation, shale often disintegrates into small angular fragments along very small weakness planes. The surfaces of the fragments of some shales are shining and striated from slickensides. Nieto (1983) has observed that flat-lying sedimentary rocks display the most regular spacing.

3.9 Jointing in Metamorphic Rocks.

a. In metamorphic rocks, one joint set is often parallel or sub-parallel to the foliation or schistocity with two or more sets of joints oriented approximately at right angles to this direction (Deere et al., 1969; Piteau, 1970; Terzaghi, 1946). Varying amount of random joints are often present in addition to the regular joint sets. In many cases, the jointing is irregular as the number of random fractures exceeds the joints connected to regular joint sets.

b. Intercalated gneisses and schists, phyllites and slates usually display well developed foliation planes which contain concentration of weak, platy or elongated minerals of mica, chlorite, amphiboles, pyroxenes. These planes can easily split to form foliation joints (Nieto, 1983).

c. The most significant direction of weakness (cleavage) in metamorphic rocks can be independent of the primary layering after the rock has undergone regional metamorphism. Selmer-Olsen (1964) noted that where tensile and shear stresses had directions other than along cleavage, cleavage partings and joints often cut each other at oblique angles to form rhombohedral blocks. This type of pattern is often found in regions with metamorphism in connection with mountain range folding and in fault zones of crushed rocks developed by shear stresses.

3.10 Statistical Distribution of Joints.

a. The most commonly measured geometric properties of jointing are spacing (or density), trace length, and orientation. Based on results from numerous publications, the statistical distribution of joint density can often, as shown in Table 3-5, be modeled by an exponential function.

b. Reported distributions of joint trace length are less consistent than those for spacing, perhaps caused in part by strong biases implicit in many common sampling plans and in part by the way data are grouped into histograms prior to analysis. Log-normal distributions are perhaps the most frequently reported, but given size biases in the way samples are collected; many different in situ distributions would produce approximately log-normal samples (Baecher and Lanney, 1978). Many workers have used exponential distributions in analysis, primarily for computational convenience, but there is little empirical verification of this assumption, see Table 3-5.

c. From studies made for a probabilistic slope stability analysis, Herget (1982) found log-normal distribution for dip, dip direction, hardness, and strength of fillings, and negative exponential distribution for spacing, trace length, and waviness. As noted by Hudson and Priest (1979), since the exponential density of joints is fully defined by one parameter, a simple relationship exists between rock quality designation (RQD) and average joint spacing (*l*) for hard, unweathered rocks as follows (Priest, 1993):

$$RQD = 100 \text{ x } e^{-0.1\, l} \, (0.1\, l + 1) \quad (3\text{-}4)$$

Table 3-5
Statistical Distribution of Joints
Based on Merritt and Baecher (1981)

Source	Spacing	Trace Length	Shape
Snow (1968)	exponential	-	-
Robertson (1970)	-	exponential	equidimensional
Louis and Perrot (1972)	exponential	-	-
McMahon (1974)	-	log-normal	-
Steffen et al. (1975)	-	exponential	-
Bridges (1976)	-	log-normal	oblong
Call, Savely, Nicholas (1976)	exponential	exponential	-
Priest and Hudson (1975)	exponential	-	-
Baecher, Lanney, Einstein (1977)	exponential	log-normal	equidimensional
Barton (1977)	-	log-normal	equidimensional
Cruden (1977)	-	censored exp.	-
Baecher and Lanney (1978)	exponential	log-normal or exp.	-
Herget (1982)	exponential	exponential	-

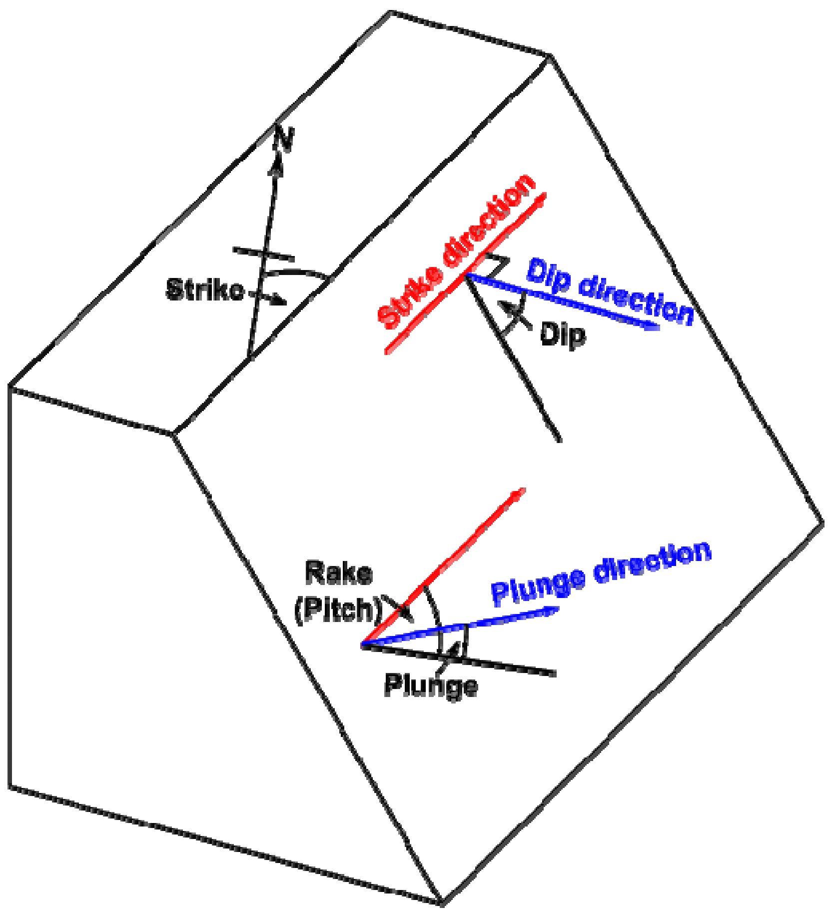


Figure 3-1. Illustration of Strike and Dip and Rake and Plunge (Davis, 1984)

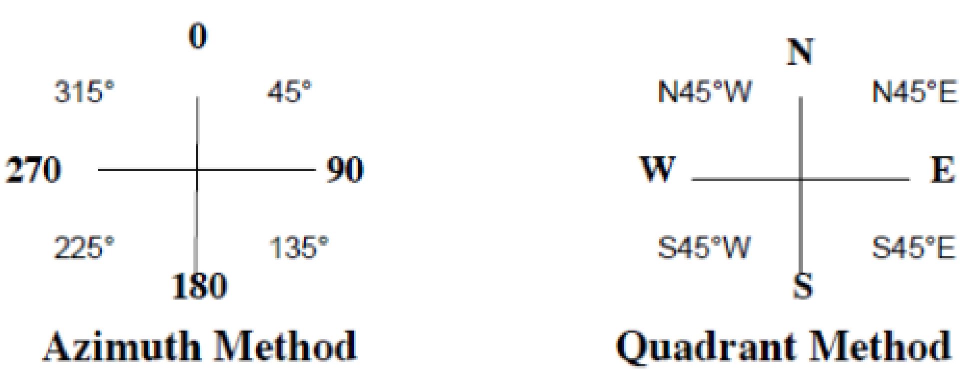


Figure 3-2. Azimuth (compass) method versus quadrant method for reporting strike

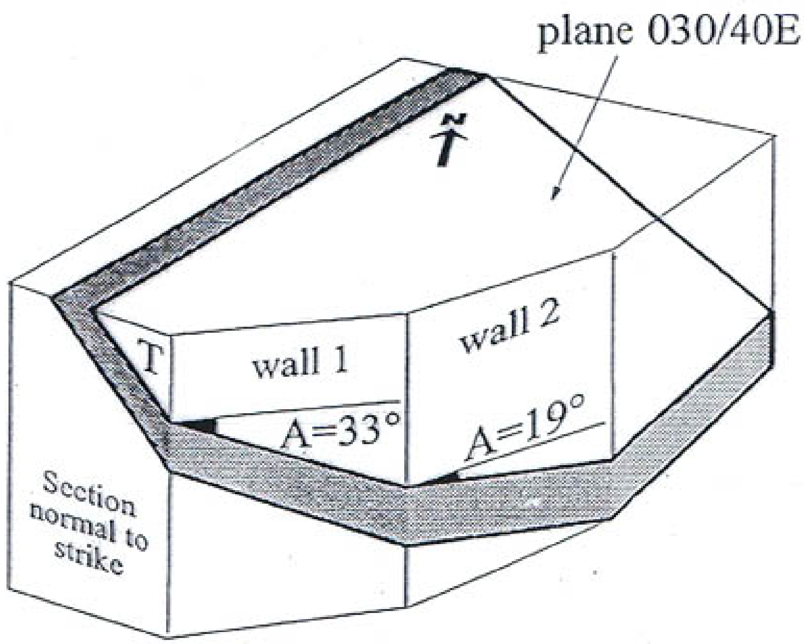


Figure 3-3. Illustration of strike and true dip in a section normal to strike and apparent dip in wall 1 and wall 2 (Burger and Harms, 2001)

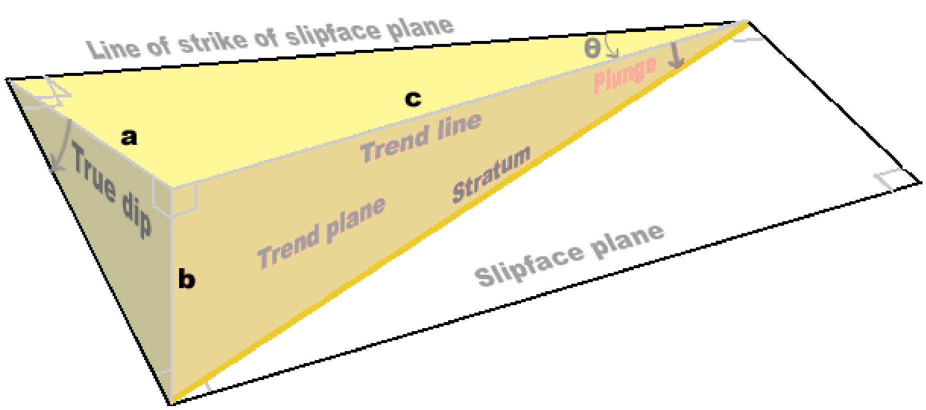
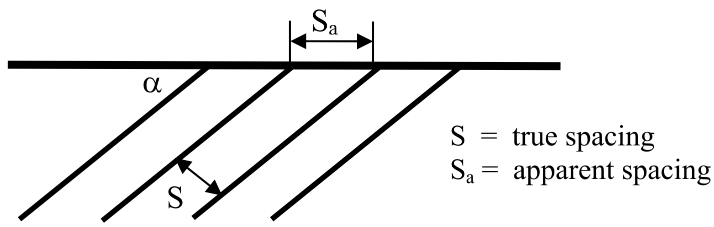
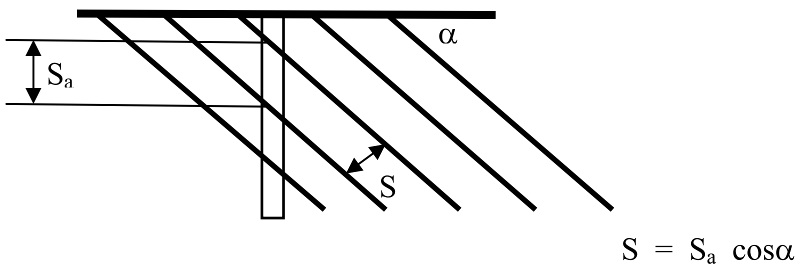


Figure 3-4. Illustration of trend, plunge and rake (θ) along a planar surface (Martel, 2004)



(a)



(b)

Figure 3-5. Difference between apparent and true fracture spacing for a rock mass cut by a single joint set where: (a) apparent spacing measured from the horizontal ground surface and (b) apparent spacing measured in a vertical borehole (after Amadei, 2008)

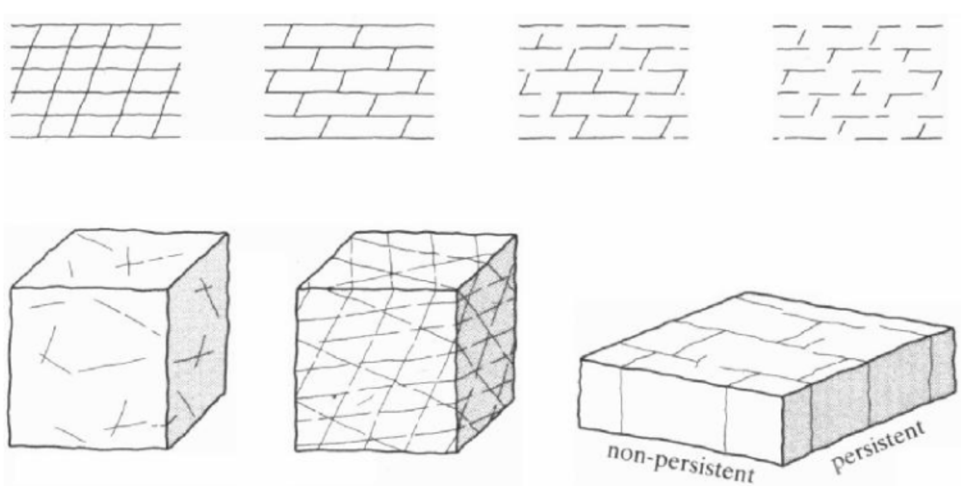


Figure 3-6. Illustrations of persistent versus non-persistent joints in a rock mass (ISRM, 1978)

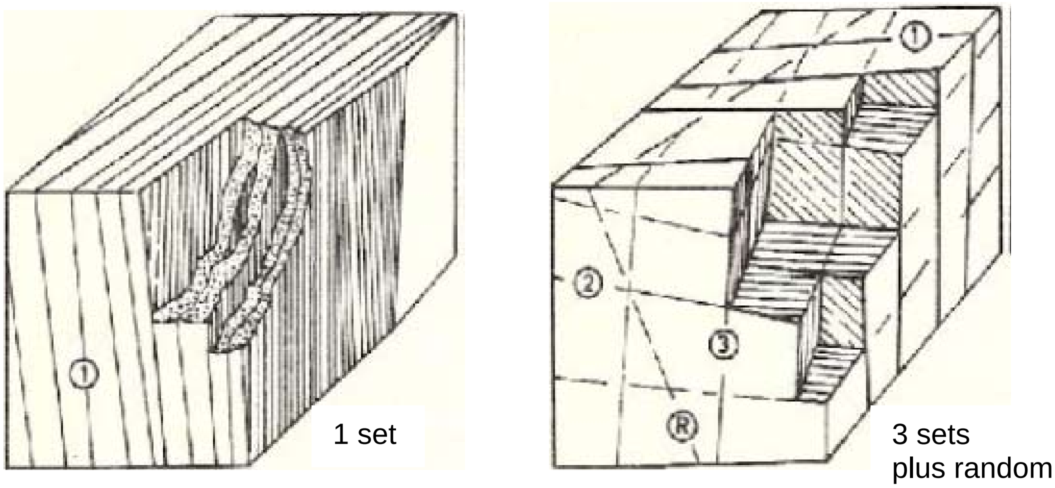


Figure 3-7. Illustration of one joint set versus three joint sets plus a random joint in a rock mass (ISRM, 1978)

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CHAPTER 4

Measurement of Discontinuities

4-1. Borehole Logging.

a. Borehole logging entails the accurate and precise graphic and verbal description and classification of the materials produced during drilling boreholes; characterizations of the subsurface based upon the visual assessment of the materials, the loss or gain of drilling fluid; and documenting the action and response of the drill rig to the subsurface during advancement of the tools. Core size should be selected based upon the general rock quality, and larger core may be necessary to provide adequate detail for analysis, particularly in marginal rock conditions. Larger rock core tooling will minimize borehole deviation which reduces potential introduction of error in measurements referenced to borehole direction. In the context of measurement of discontinuities, borehole logs are of some importance, but are of greater importance when other methods are employed in connection with logging. The procedures to be used in borehole logging are specified in more detail in EM 1110-1801 dated January, 2001. Additionally, many districts have internal guidance with respect to boring logs, based upon the project type and local conditions. In preparing boring logs it is important to consider not only the specific purpose for which borings are drilled, but that there may be subsequent use of the information obtained which is not anticipated at the time. Drilling is costly and time consuming, and if valuable subsurface information is available from previous borings, it can be used to expedite design.

b. Of importance to investigations of discontinuities are the observations of joint or fracture tightness, orientation with respect to the plunge of the borehole, degree of weathering, and presence or absence of fine-grained or granular infilling materials. The actual orientation may be difficult to discern with conventional core, but if the rock is bedded and the bedding strike and dip are known, it may be possible to geometrically resolve the orientation of joint patterns or other discontinuities. This requires that the boring log include the plunge/orientation data of the borehole – and that this information be in a format that is useful to the analysis. Conventional borehole logs may also provide data on spacing of discontinuities and the properties of non-aligned discontinuities like vugs or solution features.

c. Characterization of discontinuities with respect to the joint roughness may be performed on rock core, and should be entered on the log using standardized nomenclature – again described in greater detail in the Engineer Manual on Geotechnical Investigations (EM 1110-1-1804). The extent of weathering or alteration may be observed in core and described on the log, as well. Similarly where the degree of tightness assumed based upon measurement of core lengths versus length of cut, and also implied by the degree of fit between rock on the two surfaces at the discontinuity can be useful to the designer in assessing the rock mass properties. It is also possible, although less likely, that discontinuities exist that do not present themselves as breaks in the rock – that the rock may be held together by mineral precipitates, fine-grained infilling, or some kind of interlocking of the rock along the discontinuity, as occurs in stylolites. These features should all be documented in the log of a core hole.

4-2. Oriented Core. Oriented core borings utilize a system of modified coring tools that scribe an alignment line on the core as it feed into the core barrel. This line is then utilizes to align the pieces of the core in the core box for logging, and the line is correlated to the compass direction as a reference to determine the orientation of discontinuities. The system requires more care than conventional and wireline coring, but the results are far more useful in assessing the orientations of discontinuities of interest. In contrast to a mechanically scribed line, newer systems of oriented coring tools utilize digital electronic accelerometers and magnetometers coupled with a recorder in a non-magnetic slug that is attached to the top of the core barrel. The device adds approximately 1.5 feet to the length needed inside the outer core barrel, so a smaller inner barrel may be needed, or an extension of the standard or wireline barrel maybe added to accommodate the device. Once attached, the device records the orientation of the core barrel throughout the run, and that information can be then used to determine the orientation of any feature of interest in the core. Regardless of the method used, periodic calibration checks should be included in the Quality Assurance/Quality Control procedures in place.

4-3. Borehole Cameras.

a. Borehole cameras (also referred to as downhole cameras) are used often in conjunction with oriented core and/or geophysical tooling. The advances in electronics have resulted in a growth of this type of investigative tool in recent years. After completion of the boring, the hole is flushed with clean water to remove excess suspended material and remove as much of the drill cuttings or mud residue from the borehole walls as possible. The tooling is then lowered at a constant rate on a cable that is spooled over a calibrated pulley, providing an indication of depth, which is electronically recorded on the digital camera log. Conventional borehole cameras operate in one of two modes: side-looking and downhole. The side-looking view is the view looking through a side window of the camera, and obviously only provides a view of the portion of the borehole wall facing that window. The cable typically is flexible enough that orientation is difficult to assess, as the camera and cable may swing and twist in a borehole. The downhole mode is a fisheye view looking down the hole as the camera advances. This mode distorts angles, making it less useful in determining the exact orientation of discontinuities.

b. Newer technologies being used to obtain greater detail from boreholes include infrared and ultraviolet cameras and systems that perform full scans of the sidewalls. Infrared cameras may be useful in detecting groundwater flow and direction of flow in boreholes, as the groundwater will contrast with the water used as drilling fluid. Ultraviolet cameras utilize a UV light source and provide an opportunity to monitor the appearance and movement of indicator dyes such as fluorescein, that are visible under UV light. Full perimeter camera tooling, such as the BIPS system provide a complete 360-degree scan of the boring wall, with color enhanced imagery. Discontinuities and any filling of discontinuities are clearly depicted by these systems in an oriented graphical log that is plotted as an unfurled cylinder. This permits greater detail and inspection of the rock and provides assessment of the rock mass as a whole, including the characteristics of the joints – their orientation, any filling material present, and the aperture and roughness of the discontinuities, as opposed to assessment based upon core alone, which may be damaged during drilling. The imaging provided also may detect intersections of discontinuities that might be damaged in core or may appear simply as zones of core loss. By combining the log generated by a BIPS, Optical Acoustic Televiewer system or similar system, and the core itself, a detailed table of the discontinuities and their characteristics is readily prepared for each borehole

4-4. Linear Scanline Sampling.

a. A linear traverse, also known as a *scanline*, is a single straight-line (1D) survey conducted in the course of a geologic and engineering investigation at an exposed rock surface. Exposed rock surfaces may be either above ground or below ground. Taking measurements at exposed rock surfaces has the advantage of utilizing a relatively large surface sampling area, which allows for the direct observation and subsequent measurement of critical geologic features from a statistically significant number of discontinuities. Critical features may include discontinuity type; orientation; persistence and termination; spacing; aperture widths, infilling type, roughness, and water condition; waviness length and amplitude; etc. Geological relationships between the various discontinuity groups may also be observed and recorded. Pertinent information may also be collected on the exposed rock units, such as rock type, bedding thickness and attitude, fracturing, weathering, permeability, cut slope stability, etc. Because the mapping criteria are performance based engineering characteristics, rock units need not conform to formally recognized stratigraphic rock formations.

b. One disadvantage of conducting a scanline at an exposed rock surface is that it may not be located immediately adjacent to the particular area of interest. In this event, the spatial variability of the properties measured must be considered. Since discontinuity characteristics, like other rock mass properties, vary with distance to some degree. Spatial variability of the measured discontinuity properties are not considered explicitly in the analyses contained in this engineer technical letter. However, geostatistical methods, such as the semi-variogram or kriging techniques, may be applied to analyze the spatial variability of discontinuity characteristics. Another disadvantage of conducting a scanline at an exposed rock surface is that the rock surface may suffer from blasting damage, may be degraded by physical or chemical weathering, or may be covered by vegetation, talus, soil, or other debris.

c. The exposed rock surface should be mapped according to measurable or otherwise describable physical properties or features at a scale useful for the specific project. A rock unit is generally consistent in its mineralogical composition, geologic structure, and hydraulic properties and its boundaries are delineated by measurable or otherwise describable physical properties or features. It is traced in the field by surface and subsurface mapping techniques. A rock unit is prevailingly, but not necessarily, tabular in form and uniformity in thickness is often not a determining factor for consistency of discontinuity characteristics. Once a rock unit has been established and subsequently mapped, it can be defined by classification elements and analyzed for performance in relation to selected performance objectives.

d. A measure of the relative predictability or homogeneity of the structural domain and the lithology of the rock unit from one expose rock surface to another or from the location of the mapped exposure to the actual project location is called “outcrop confidence.” Three levels of outcrop confidence are described (Part 631, Geology Chapter 12, 2002), namely:

(1) Level I: High. Rock units are massive and homogeneous, and are vertically and laterally extensive. Site geology has a history of low tectonic activity.

(2) Level II: Intermediate. Rock characteristics are generally predictable, but have expected lateral and vertical variability. Structural features produced by tectonic activity tend to be systematic in orientation and spacing.

(3) Level III: Low. Rock conditions are extremely variable because of complex depositional or structural history, mass movement, or buried topography. Significant and frequent lateral and vertical changes can be expected.

e. A scanline survey is an inventory of all structural discontinuities that intersect a linear traverse of specified length and orientation and is used to systematically inventory a variety of attributes of joints and fractures including joint set spacing and orientation, joint roughness, joint face alteration, aperture width, and type of infilling. There is no recognized method to conduct a scanline survey that is universally accepted. In fact, it is desirable to adapt the method to suit the local rock conditions. The scanline survey should be conducted as appropriate to provide pertinent data that is commensurate with the objectives and scope of the project. General guidelines have been discussed in the technical literature (Priest, 1993) that provides suitable guidance to conducting successful scanline surveys, including:

(1) The exposed rock surface in the area of interest must be a clean, approximately planar, well exposed rock surface that is also relatively large in regards to the size and spacing of the discontinuities exposed and accessible for measurement and study. Cleaning can be accomplished by whatever means is necessary and available, including power equipment, hand tools, or pressurized air or water.

(2) The exposed rock surface should be representative of the geologic features encountered across the project site.

(3) The exposed rock surface should be stable; free of loose, detached, or semi-detached rock, other debris, or dangerous overhangs; and should thoroughly inspected by highly qualified personnel and judged to be inherently safe.

(4) An ideal sample zone should contain between 150 and 350 discontinuities, of which about 50% should have at least one end visible.

(5) The exposed rock surface should be representative of the geologic features encountered across the project site.

(6) Scanlines themselves are simply a measuring tape, typically between 5 to 100 ft long, pinned with masonry nails and wire and often aligned along the strike and the line of maximum dip. A recommended working length is typically 30 to 50 feet, although shorter or longer lengths may be used, if practical. Widely spaced joints may require a longer survey line to obtain a meaningful average. In some instances, outcrop limitations require shorter lines. For each persistent joint set, determine average spacing by dividing the length of the survey line by the number of joints in the set that intersects the survey line. A typical scanline intersecting one discontinuity set is shown in Figure 4-1.

(7) The measuring tape should be pinned back to conform to the face geometry for irregular rock exposures. Deviations in the scanline of less than about 20° from a straight line have a negligible influence on the sampling regime and can be ignored. Larger deviations can be accommodated simply by splitting the scanline into sub-scanlines, measuring the joint attributes along shorter linear traverses.

(8) To improve the quality of the survey data in any given dimension, multiple scanline surveys should always be conducted. Establish scanlines along different rock faces and at different orientations. The actual number of scanline sets needed is a function of the size and geologic complexity of the site. However, it is generally recommended that 10 to 20 scanlines are needed and 1,000 to 2,000 discontinuities be sampled to provide an adequate characterization of a site (Priest 1993). The aim is to impose rigorous sampling regime that will allow statistical analyses of the data, although it is often difficult to practically achieve that level of sampling. To accurately infer a population from sampled statistics, samples have to thoroughly represent the population.

(9) When several sets of discontinuities are present, one of the scanlines may be oriented perpendicular to one of the dominant sets, and other scanlines may preferably be oriented perpendicular to the second set. A more practical procedure is to set up three scanline directions on horizontal or tilting faces with at least one scanline oriented perpendicular to a dominant fracture set. One of the other two scanline sets should be perpendicular to the first scanline, and the third scanline set should be about 45^o to the other scanlines as shown in Figure 4-2. Multiple sets should be taken at various locations across the exposed rock face to collect sufficiently representative data. The trend and plunge of the scanlines must be recorded along with the discontinuity data.

(10) When the exposed rock surface is cut by several erosional and structural faces (e.g., cliff faces, joint planes), fourth and fifth scanline sets should be established both perpendicular and parallel to the layers to ensure a more complete sampling of the three dimensional (volumetric) distribution of the discontinuities.

(11) Additional scanlines should be conducted on a second rock exposure, approximately at right angles to the other scanlines. This will establish two mutually perpendicular axes for scanlines and will help minimize orientation sampling bias.

(12) If required, a vertical scanline may be also conducted. In situations where the vertical component is unexposed or inaccessible, drilling logs or drill core samples of nearby test holes, if available, may be to estimate the vertical joint spacing. A drill hole is a scanline. To determine the average spacing of bedding plane partings or sheeting joints on steep outcrops, a telescoping range pole or a weighted tape against the face may be used to facilitate measurement. When scanlines are conducted on three mutually perpendicular axes, the mean block size for the rock mass may be calculated by taking the cube root of the product of the average joint set spacings for the three surveyed directions.

(13) In structural domains where joint set patterns are systematic, a scanline survey conducted nearly parallel with the trend of a dominant discontinuity set may result in undersampling and sample bias, that is, joints that are perpendicular to the scanline have a higher probability of being sampled than joints that are parallel to the line, hence the introduction of orientation or sampling bias. To compensate and correct for this reduction in sample size, the size of the measured fracture with low angles relative to the scanline need to be weighted (Priest, 1993). Corrections for linear sampling bias are shown in Figure 4-3.

(14) Plot the location of each scanline survey on a geologic evaluation map and record its location, orientation, elevation, ground coordinates or stationing, the trend and plunge of the scanline, and the condition of the exposed rock face. Scanline data is recorded on a specially-designed scanline logging form. Several examples of typical scanline logging forms are provided in Appendix B.

(15) It is desirable, but not necessary, to start position the start of each scanline at a discontinuity. Starting from the origin of the scanline, observe and record on the scanline logging form all of the pertinent characteristics of every natural discontinuity and lineation crossing the scanline traverse. If needed, expose fracture planes using a chisel and hammer to ensure that the measurement of the true plane of the discontinuity or natural fracture, that is, its strike and dip.

(16) Measure the attributes of all structural discontinuities that intersect the scanlines according to guidance presented in Appendix B, recording the information on an appropriate specially-designed scanline logging form included in Appendix B. There is no one best scanline logging form, select the best form for the specific application or develop a suitable hybrid form that will best meet the intended need.

(17) Natural fractures can be distinguished from the blast related fractures by their larger size and smoother surfaces, systematic orientations (in sets), and possible veins, plumose and slickenside structures, coating, and stains which are missing in smaller, more irregular, rough, and randomly-oriented artificial fractures that commonly radiate from a point of explosion.

(18) Joint and fracture patterns may be difficult to differentiate in complex structural domains. However, if the scanline surveys collect a sufficiently representative sample of joints

for assessment of critical joint attributes, subtle joint patterns can often be differentiated using statistical analysis afforded by joint orientation diagrams.

(19) It is also important to take digital color photographs of the rock face and the scanline, including a scale and appropriate labels, before completing the scanline measurements. Attach visible markers at 3-ft intervals across the rock surface for reference. Retake photographs if the scanline moved during the measurements.

(20) Also take photographs of the rock exposure from several angles to record irregular rock surfaces. If possible, position the camera at mid-height of the rock exposure with the lens axis positioned normal to the rock surface. If the rock exposure is particularly high that the camera must be tilted upward at an angle nearing 30°, significant distortions of the rock face will occur in the photograph. In this case, use a camera with a long focal length lens mounted on a tripod located some distance away from the rock face, and preferably on higher ground.

(21) Finally, the accuracy of linear scanline is generally limited by the environment in which mapping is carried out, such as, the visible parts of joints are often limited; joints at a distance cannot be directly measured; the difference between discontinuities and other types of fractures is somewhat subjective; and the accuracy of direct and indirect measurements is unknown.

f. Equipment needed to conduct a scanline survey includes a suitable measuring tape at least 6-ft in length to measure joint spacing, calibrated in tenths of feet; and a compass and clinometer with an inclinable sighting device incorporating a reflected image of a horizontal bubble, such as a Silva, Brunton, Clar, Freiberger, Suunto, or comparable professional pocket transits. The clinometer should also have a suitable linear measuring scale that can be used to accurately measure joint aperture openings.

g. The aperture, or opening, of a discontinuity can be accurately estimated using feeler gauges.

h. Surface asperities (irregularities) with a wavelength of less than about 100 mm (4 inches) are referred to as roughness (Priest, 1993). Roughness can be expressed in terms of Barton’s Joint Roughness Coefficient (*JRC*). Typical discontinuity roughness profiles and associated *JRC* values are shown in Figure 4-4. Joint roughness often exhibits a component *i*, called the effective roughness angle due to visible roughness and other surface irregularities (Barton and Choubey, 1977).

i. Scanline surveys can be conducted either *subjectively*, that is, only those discontinuities which appear to be important may be measured; or *objectively*, that is, all of the discontinuities intersecting the traverse line are measured. Objective surveys are time consuming and may results in a considerable amount of field data that must be analyzed. Subjective surveys should only be conducted where the local structural domains are clearly recognized. Objective surveys should be conducted where the local structural domains have not been delineated.

j. General guidance on conducting scanline surveys is provided in Appendix B. Specific procedures for conducting detailed scanline surveys and techniques for analyzing data are provided in the *Engineering Geology Field Manual* (USBR, 1998); *Rock Characterization Testing and Monitoring, Suggested Methods for the Quantitative Description of Discontinuities in Rock Masses* (ISRM, 1981); and in *Discontinuity Analysis for Rock Engineering* (Priest, 1993).

k. To complete a scanline survey, measure the attributes of all structural discontinuities that intersect the scanline according to guidance presented in Appendix B. Record the measurements on an appropriate specially-designed scanline logging form, such as those included in Appendix B.

l. Boreholes may also be used as scanlines. The easiest way to record discontinuity characteristics is to fix a thin, straight measuring tape to form a scanline along the axis of the core. It is recommended that the measuring tape be extended so that its distant markings correspond directly with borehole depths. The precise depth of the intersection between the borehole scanline and each discontinuity is then recorded on the logging form. The orientation of each discontinuity may also be recorded on a graphic log. The angle in degrees between the discontinuity normal and the axis of the borehole can be measured using a protractor and recorded on the scanline logging form. It must be recognized that borehole scanlines do not provide an effective method for determining discontinuity orientation, since core can rotate during extraction. So special sampling and analysis techniques are needed to determine the true orientation of the sampled discontinuities within the rock mass (Priest, 1985). Discontinuity surface geometry and infill properties of the discontinuities intersected by the borehole may be described and recorded. In many rock masses, it may be difficult to differentiate between natural discontinues and drilling induced fractures. However, the size, orientation, surface geometry and other clues may indicate whether the discontinuity is a fault, shear, joint, bedding plane, parting, cleavage, foliation, drilling induced crack, or other geologic feature. Zones of broken rock should be described and recorded in terms of their extent along the borehole. The nature of infill may be observed and recorded as clean or in-filled with clay or mineral deposits, etc. Discontinuity surface roughness may be observed and recorded. Indications of aperture, such as infill or surface staining, degree of weathering, etc., may indicate if the discontinuity was open, partially open or tight. Discontinuities that show signs of water flow may be described and recorded. While other geologic features, such as discontinuity persistence and termination, are not obtainable using borehole scanlines, many of the other scanline input parameters are easily observable in a borehole scanline.

m. A fractured rock mass is comprised of three components: a discontinuity network, a matrix block, and infilling along the discontinuities. The geometry of a single discontinuity is characterized by its location, orientation, spacing and persistence. Several discontinuities of the same type create a discontinuity set, which produces discontinuity spacing (frequency). Several interconnecting discontinuity sets creates fracture network that facilitates fluid flow and affect rock mass stability. Therefore, it is important to fully characterize, measure, and then evaluate the discontinuities contained in a rock mass. A range of parameters can be measured in discontinuities (ISRM 1978; Hudson 1989). The important discontinuity characterization parameters are summarized in Table 4-1. These parameters may be obtained from a comprehensive scanline survey. Methods of analysis for determining the important parameters discussed in Table 4-1 are discussed in Appendix C. A completed scanline survey is provided in Appendix D.

Table 4-1
Discontinuity Characterization Parameters and Measurements that may be obtained from Scanline Survey Data

Parameter	Description
Number of Sets	Number of discontinuities sets present in the structural domain
Orientation	Azimuth and inclination of discontinuities sets present in the structural domain
Spacing	Perpendicular distance between adjacent discontinuities of the same set
Persistence	Trace lengths of the discontinuities observed in the exposure
Density	
▪ Linear	Number of fractures per unit length
▪ Areal	Cumulate length of fractures per unit area of exposure
▪ Volumetric	Cumulate fractured surface area per unit bulk rock volume
Fracture area and shape	Area of fracture surface and its shape
Volumetric Fracture Count	Number of fractures per cubic volume of rock
Matrix Block Unit	Block size and shape resulting from the fracture network
Connectivity	Intersection and termination characteristics of discontinuities
Aperture	Perpendicular distance between adjacent rock walls of a discontinuity, the space can be either air-filled, coating-filled or water-filled
Asperities (roughness)	Projections of the wall-rock along the discontinuities surface
Wall Coatings and Infill	Solid materials occurring as wall coatings and in-fill along the discontinuity surface
Water Flow (seepage)	Condition of the water existing along the discontinuity surface

4-5. Window Sampling.

a. Window sampling, also known as a Scanplane or cell mapping, is an alternate (2D) discontinuity measurement technique (Pahl, 1981). The measurement techniques are essentially similar to those used in a linear scanline, except that all discontinuities that have a portion of their trace length within a defined area of the exposed rock face are measured, as opposes to only those discontinuities that intersect a linear scanline. This approach reduces the sampling biases for orientation and size that occurs with linear scanlines; however, discontinuity curtailment problems remain where the rock face is of limited extent.

b. The sampling window is defined by establishing a rectangular sampling grid on the exposed rock face. The window should be as large as possible to minimize sampling bias effects, with each side of a length such that it intersects between 30 and 100 discontinuities. It is recommended that two separate windows of similar dimensions should be used on an adjacent rock face. This adjacent rock face should be orthogonal to the first sampling window, if possible.

c. Pahl (1981) identified three classes of discontinuities that are measured in window sampling:

(1) Discontinuities that intersect the window and have both ends visible in the window are classified as *contained* within the window.

(2) Discontinuities that intersect the window and have only one end visible in the window are said to *dissect* the window. The other end is obscured by the extending beyond the limits of the window.

(3) Discontinuities that intersect the window and have only one end visible in the window are said to *transect* the window. Both ends are obscured by the extending beyond the limits of the window.

d. Window sampling is usually accomplished using a large print color photograph where the discontinuity traces for the *contained*, *dissect,* and *transect* categories are counted, as shown in Figure 4-5.

e. Windows sampling is primarily used to estimate discontinuity trace lengths. An example is provided in Figure 4-6. Discontinuity trace lengths can be obtained by counting the number of discontinuities in each of the three classes and applying the following equation:

$$m_L = [\, w\, h\, (1 - \phi_c + \phi_t)\,] \;/\; [\, (w \cos \phi + h \sin \phi\,)\,(\,1 + \phi_c - \phi_t\,)\,] \qquad (4\text{-}1)$$

where:

m_L = mean trace length
w = width of sampling window
h = height of sampling window
ϕ_c = n_c / n
ϕ_t = n_t / n
ϕ = angle between discontinuity trace and the vertical

and:

n_c = number of traces that *contained* within the sampling window
n_t = number of traces that *transect* the sampling window
n = total number of traces observed to intersect the face

f. The primary shortcoming of window sampling is that is does not provide any information on the discontinuity orientation, frequency, or other characteristics that are obtained from a scanline survey. Trace lengths are often obtained from a large color print of a photograph of the rock face. Scanline sampling may be performed within the window, also known as an areal survey; however, windows often contain a large number of small discontinuities which makes it difficult to keep track of which discontinuities have been measured, making the process more tedious and laborious that a linear scanline survey. Only the trace length segments of the fractures that lie within the rectangular window are measured in an areal survey, i.e., they are censored. If the trace extend beyond the window, the direct observation of whether one, both, or neither end of the discontinuity trace is visible is not observed or recorded, which may be valuable information.

g. Excavation maps and/or foundation geologic maps are often made to provide a permanent record of conditions during excavation. These maps are used in making the most equitable contract adjustments; provide otherwise unattainable information for use in diagnosing postconstruction problems and in planning remedial action; and allow for a better interpretation of postconstruction foundation instrumentation data (EM 1110-1-1804). Excavation maps and/or foundation geologic maps can usually provide adequate descriptions of geologic features (e.g., trace and dip of exposed joint planes, rock types, bedding, fracturing, joints, shear zones, etc.) for conducting desktop Window sampling surveys. If all critical geologic features exposed by the excavation are meticulously mapped, adequately described, and suitably detailed, these maps may also be appropriate for use in a scanline survey.

h. Both linear scanline and window mapping techniques have the disadvantage of only mapping exposed surfaces, thus they cannot be used in determining joint properties behind the exposed surface. When the two methods were compared in the Mount Isa Mines project (Landmark and Villaescusa, 1992), scanline mapping was found to be slow, but accurate, while cell mapping was found to be less accurate, but more measurements were taken.

(1) The general advantages of scanline mapping over window mapping include:

(a) Accuracy (Landmark and Villaescusa, 1992).

(b) Systematic and easy to control (Piteau, 1970; 1973; Brady and Brown, 1993).

(c) Data from line sampling is easy to further process and analyze (Priest and Hudson, 1981 and Piteau, 1970).

(2) Advantages of window mapping over scanline mapping include:

(a) Fast surveying, that is, more measurements are taken (Mathis, 1987 and Landmark and Villaescusa, 1992) especially considering the limiting factors in underground mapping, which are time, access, lighting and exposure.

(b) Sparsely scattered joint sets are not readily detected with scanline mapping, but are generally detected by window mapping, hence local variations in properties are easily detected resulting in better knowledge of variability (Mathis, 1987).

4-6. Terrestrial Digital Photogrammetry (TDP). The use of terrestrial digital photogrammetry is a developing technology at present. It involves non-aerial photographs taken in a manner so as to facilitate statistical data collection from rock faces. It is important to take high resolution digital photographs for this purpose, preferably with sunlight directly on the face if at all possible. The digital images should be taken at an angle slightly offset from normal to the rock surface being scanned to optimize the contrast and pick up shadows that will indicate the presence of discontinuities. It is also helpful to take the photographs in a manner that will allow them to be stitched together to show a complete profile if possible. A means of determining scale - regularly spaced marks or a tape may serve to aid in this respect. The collection of discontinuity data from the photographs may be done manually or using scanning software, some of which has been developed in recent years. The development of software for this specific application is likely to progress as the sophistication of computer codes increases. Whether the analysis is done manually, by resolving the orientation of discontinuities by direct measurement off of photographs, or if it is performed by software, establishing ground truth and field verification is necessary. Under no circumstances should a software program be utilized without some degree of field checking to establish that the discontinuities are real and not the shadows of trees, watermarks on a cliff face, or some other anomaly.

4-7. Structural Data Presentation.

a. Regardless of the methods utilized for the collection of discontinuity data, the method of presenting data visually and numerically should be such that a minimum of data management or recompilation is necessary. Orientation data for each feature should be entered either manually or systematically generated by the scanning software in spreadsheet form that can be directly loaded into a graphical program and readily presented graphically, as well as in a clear table format. Statistical analysis of joint sets or other features of concern should be performed – if clearly evident sets of discontinuities are observed. Data for each set should be evaluated for each set independently, and the range of variability determined. This will make it possible to perform sensitivity analysis on the data for each set, and include it in the overall evaluation. Graphical formats for presenting data include bar charts stereo nets and rose diagrams for each set and/or for all discontinuity data, if the data are not so cumbersome to make such illustrations too busy. Bar charts showing the distribution of variability in each set may be presented individually, along with a presentation of all data, to justify grouping clearly distinct sets of joints or other discontinuities.

b. Correlation graphs may be used to illustrate relationships between variables, e.g., joint aperture may be distinctly different in different joint sets; or the presence or absence of clay infilling may be unique to one joint set. These considerations are valuable in developing drilling plans to optimize grouting or drainage control. Spacing frequency is often a distinctive characteristic of individual join sets, including bedding planes. Data may also be utilized to determine the sequence of jointing in some cases where one set of joints is offset by another, as may be the case where one joint set tends to be very long and another set appears to have lengths that equate to the spacing of an intersecting set.

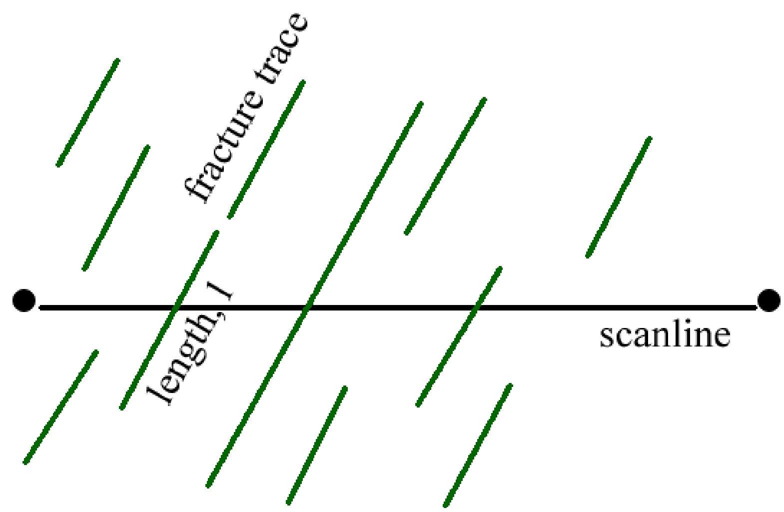

Figure 4-1. Scanline intersecting one discontinuity set (after Priest 1985)

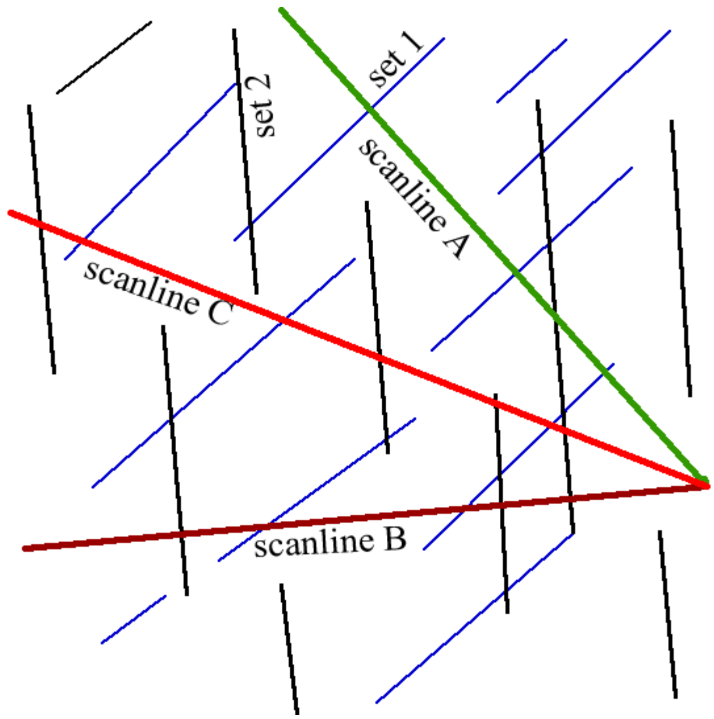

Figure 4-2. Preferred orientation of three scanlines for three discontinuity sets (after Priest 1985)

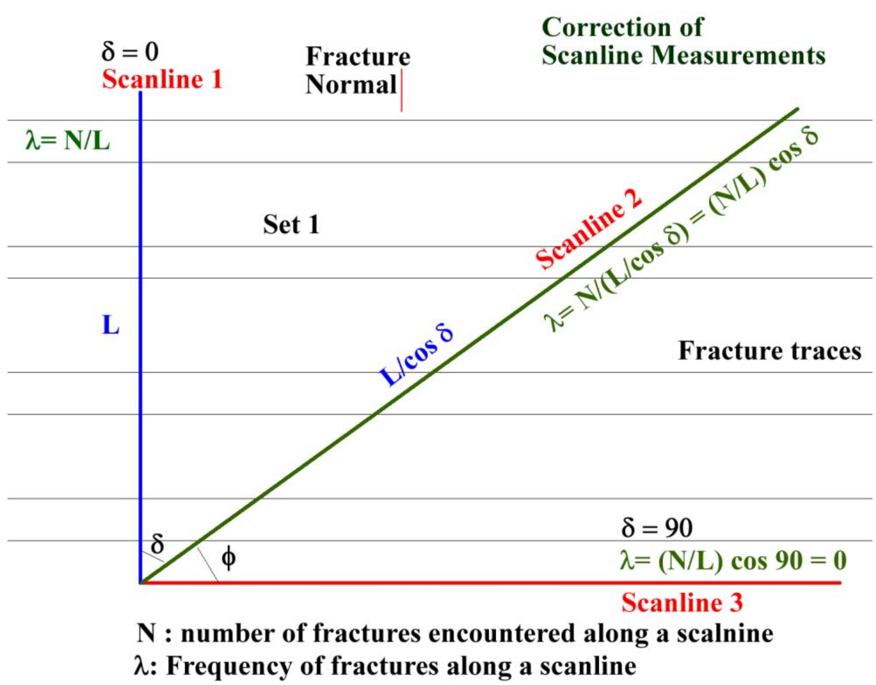

Figure 4-3. Corrections for linear sampling bias (after Priest 1985)

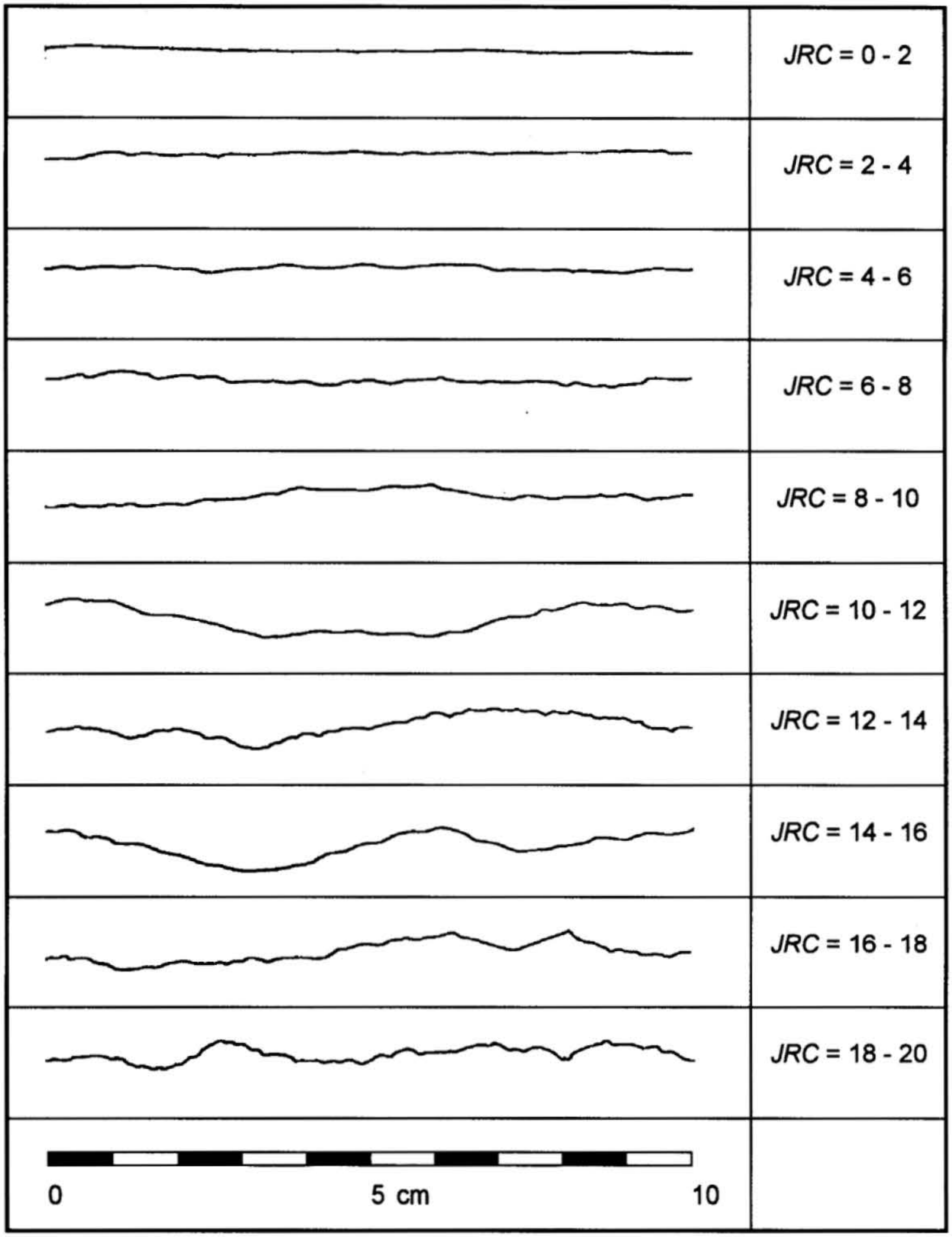

Figure 4-4. Typical discontinuity roughness profiles (after Barton and Choubey, 1977)

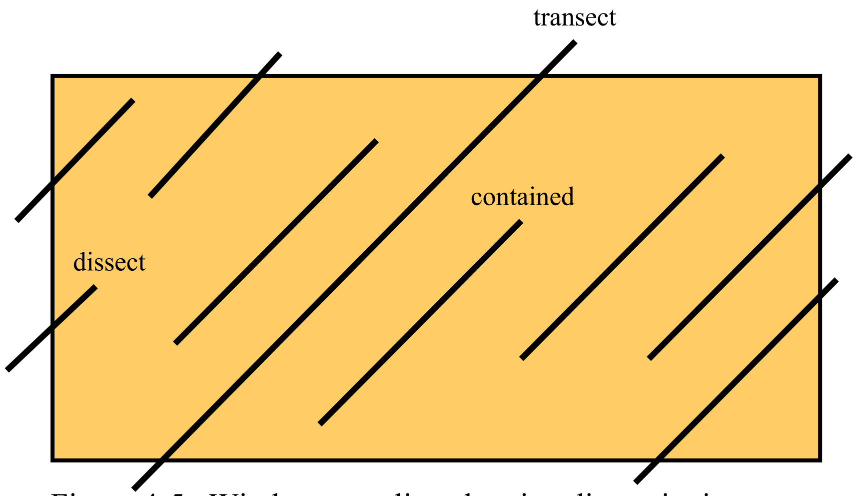

Figure 4-5. Window sampling showing discontinuity traces

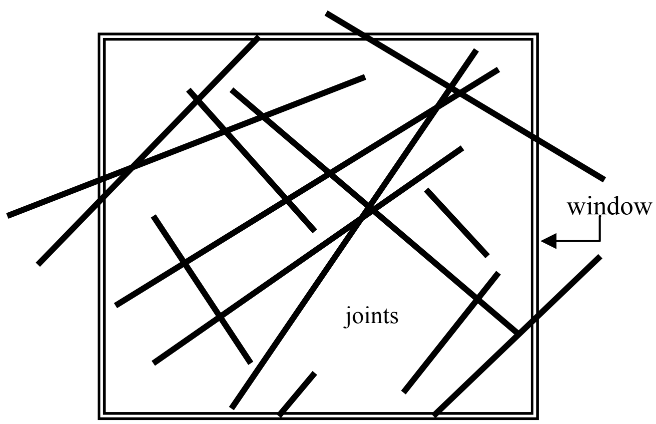

Figure 4-6. Window sampling showing joints

CHAPTER 5

Rock Quality Designation

5-1. Background.

a. Rock Quality Designation (RQD) was developed by Deere (1964) to provide a quantitative estimate of rock mass quality. RQD is based on a modified core recovery procedure which, in turn, is based indirectly on the number of fractures in the rock mass as observed in the rock cores from a drill hole. Instead of counting the fractures, an indirect measure is obtained by summing up the total length of core recovered but counting only those pieces of core which are 4-inches in length or longer, and which are hard and sound. RQD is intended to represent the rock mass quality in-situ. Excellent quality rock has an RQD of more than 90%, good quality rock has an RQD of more than 75%, poor quality rock has an RQD of less than 50%, and very poor quality rock has an RQD of less than 25%. RQD is a directionally dependent parameter and its value may change significantly, depending upon the borehole orientation.

b. Discontinuity frequency is the inverse of discontinuity spacing. Frequency can be defined in terms of occurrence per unit volume, unit area or unit length. Linear discontinuity frequency is the simplest and most commonly used method, and is defined as the number of discontinuities intersecting a unit length of a sampling line such as a scanline or drill core.

c. Hudson and Priest (1983) stated that discontinuities are never similarly distributed in all directions and as a result, spacing values depend on the direction of the drill core. They established the relationships that allow the estimation of discontinuity frequency along any orientation for a given discontinuity set of known orientation and spacing. This relationship allows detailed analysis of frequency variation and can be used to estimate the directions and magnitudes of the maximum and minimum frequency values for a given rock mass

5-2. Rock Quality Designation (RQD).

a. Rock Quality Designation (RQD) was developed by Deere (1964) to provide a quantitative estimate of rock mass quality from a drill core log. RQD is the percentage of intact core pieces longer than 4-inches in the total length of the run and is fundamental to different rock mass classification schemes. The value of 4-inches has been referred to as the threshold value. RQD is defined as:

$$\text{RQD} = 100 \sum_{i=1}^{n} \frac{\bar{X}_{ti}}{L} \qquad (5\text{-}1)$$

Where X_{ti} is the length of the i^{th} total spacing that exceeds the threshold value *t,* out of a sample of *n* spacing values. The parameter *L* is the length of the sampling line along which RQD is required.

b. RQD is relatively easy to calculate and has been a widely accepted measure of rock mass quality. For RQD calculation, a borehole is regarded as a sampling line, intersecting discontinuities whose total spacing represents intact pieces of rock and where both ends of each core run is assumed to occur at discontinuities.

5-3. Theoretical RQD (TRQD).

a. The relation between theoretical RQD (TRQD) and linear discontinuity frequency, λ, has been derived for different discontinuity spacing distribution forms by various authors, including, (Priest and Hudson, 1976), (Sen and Kazi, 1984), and (Sen, 1993). The theoretical RQD for a general threshold value *t*, which is denoted as TRQD, can be found by summing these total lengths for all values of *x* between the threshold value *t* and the maximum possible value, which is taken to be *L*, and then expressed as a percentage of *L* using:

$$\text{TRQD t} = 100\,\lambda \int_t^L x e^{-\lambda x}\, dx \qquad (5\text{-}2)$$

b. Priest and Hudson (1976) derived the following relationship between the TRQD and linear discontinuity frequency per linear foot (λ), where discontinuity spacing follows an exponential distribution:

$$\text{TRQD} = 100\, e^{-0.1\lambda}\,(0.1\lambda + 1) \qquad (5\text{-}3)$$

c. According to Wallis and King (1980), the advantage of TRQD is that different threshold values can be applied. In other words, the percentage of the drill core comprising intact lengths which are equal to or longer than any minimum threshold value, not necessarily the standard 4-inches, can be assessed. Equation 5-3 can then be written as:

$$\text{TRQD} = 100\, e^{-t\lambda}\,(t\lambda + 1) \qquad (5\text{-}4)$$

where:
t is the threshold
λ is the discontinuity frequency along a scanline

d. The discontinuity frequency λ, which is the inverse of the mean of the discontinuities, was calculated using the relation:

$$\lambda = {}^{N}/_{L} \qquad (5\text{-}5)$$

where:
N is the number of the discontinuities that intersect the scanline
L is the length of the sampling line

e. From Equation 5-4, the percentage of scanline containing intact lengths above any required threshold can be found. Priest and Hudson (1976) have discussed the theoretical basis for these relations and the statistical precision of the resulting estimates and have shown that the negative exponential distribution does in fact apply to discontinuities in the sedimentary rocks.

f. RQD, which is an important input parameter to rock mass classification systems, is determined from the spacing between consecutive discontinuities (Priest, 1993). According to Priest (1993), adopting the conventional threshold level of 4-inches gives an RQD that is sensitive to mean spacing up to approximately 11.8-inches and that RQD increases by only 5 percent in response to an increase in mean spacing beyond this value, as shown in Figure 5-1. An improved sensitivity of RQD to higher values of mean spacing can be achieved by increasing the threshold level. This approach is appropriate when designing larger excavations in rock.

g. Along with the conventional threshold value of 4-inches, threshold values of 6-inches, 8-inches, 10-inches, 12-inches, 14 inches, and 16-inches were used to determine RQD using Equation 5-2. The relationship between RQD of different threshold values and mean discontinuity spacing ($1/\lambda$) in feet have been plotted individually as shown in Figure 5-1.

h. From Priest and Hudson (1976), a graph showing $TRQD_t$ for the threshold value of 4-inches plotted against discontinuity spacing λ is shown in Figure 5-2. A linear relationship is given by the tangent to the curve. The equation for the this tangent is given by:

$$TRQD_t \ \text{y} \ 110.4 - 3.68\,\lambda \tag{5-6}$$

i. The above equation provides a reasonable approximation for $TRQD_t$ over the range of $6 < \lambda$ 16 m^{-1} (Priest, 1996).

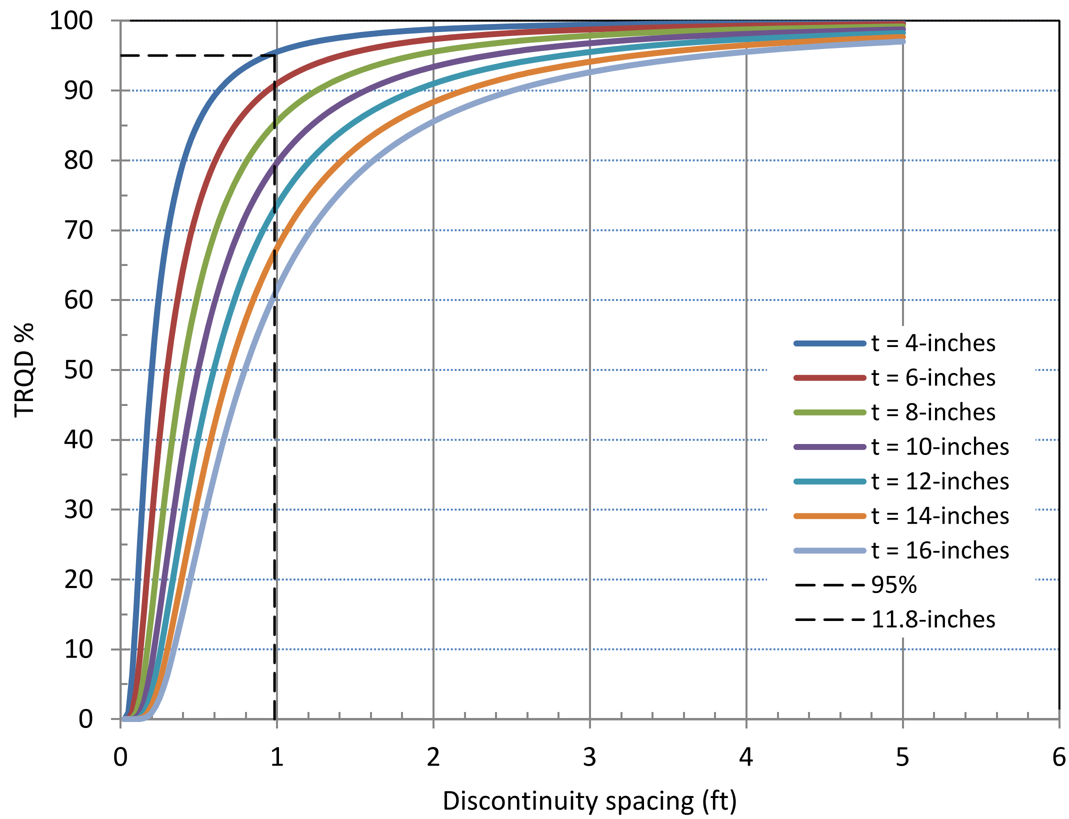

Figure 5-1. Variation of $TRQD_t$ with mean frequency spacing for the range of $TRQD_t$ threshold values shown on the graph (after Priest and Hudson, 1976)

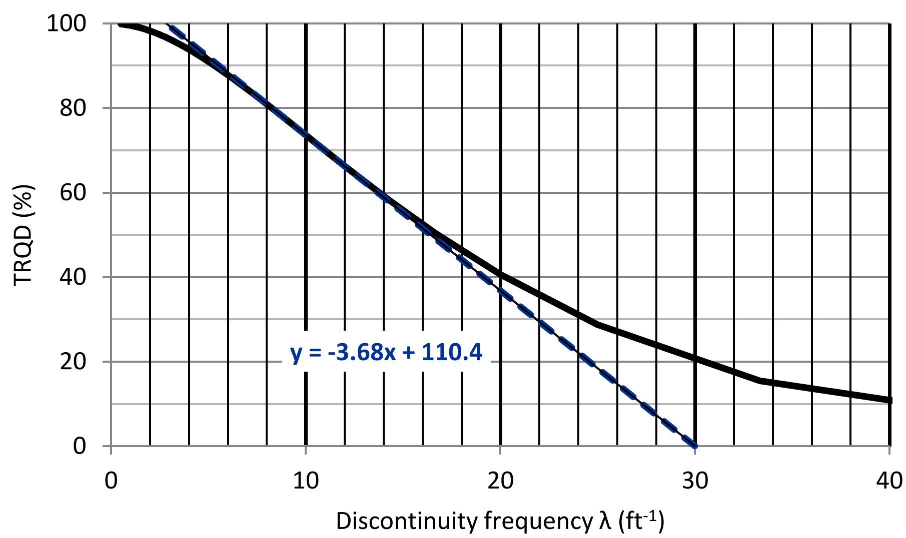

Figure 5-2. Relationship between TRQD and mean discontinuity spacing (after Priest and Hudson, 1976)

CHAPTER 6

Linear Sampling Bias Index (LSBI) Method

6-1. Background.

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

(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.

b. The second bias is determined mostly by the relationship between a 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. Various researchers including Priest and Hudson (1981), Hudson and Priest (1983), and Priest (1985) suggested ways to quantify this kind of bias. For a single set of discontinuities, the true frequency (l) 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). 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.

$$\lambda_s = l \cos d \qquad (6\text{-}1)$$

Where l is the true frequency of a discontinuity set, λ_s is the apparent frequency of a discontinuity set, and d is the angle between the normal of the discontinuity orientation and the sampling line.

c. In the above equation, the term cos d gives a quantitative value of the bias. If cos d 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. The sampling line is along the optimum drilling direction if cos d equals 1. Conversely, if cos d equals 0, then the sampling line is perpendicular to the normal of the discontinuity orientation and the sampling bias is defined as infinite.

d. Several sets of discontinuities are often developed within a rock mass, three to four sets being the most common. Low-grade metamorphic rocks routinely contain four or more regularly spaced and extensive joint sets (Goodman, 1993). Sedimentary rocks that are gently to moderately folded typically exhibit regularly spaced joints sets that are orientated to the direction of folding. In addition to bedding joints, sedimentary rocks generally contain two systematic joint sets at right angles to one another and each extending downward and perpendicular to the bedding. One set typically extends in the direction of bedding dip and the other in the direction of bedding strike (trend of the line of intersection of the bedding and the horizontal). The distance between joints varies from about a few inches to a few hundred feet. Limestone is a brittle rock that is typically crossed by numerous joint sets. In igneous rocks, jointing is usually quite irregular. Although in granite, two vertical sets often form at right angles to one another while another set of cross joints orientated in a nearly horizontal direction frequently occur. Intrusions of molten rock, when cooled, form sills and dikes, which exhibit columnar jointing where three sets of joints perpendicular to the cooling surfaces intersect each other at angles of about 120°. These form polygonal columns of rock that range from about 3-inches to about 20-feet in diameter; the size depends on the rate of cooling of the intrusive rock - the faster the cooling, the smaller the columns. Systematic sheeting joint sets, as well as cross joint sets can also occur in various rock types and rock masses.

e. Discontinuity sets in nature are not oriented in perfectly parallel directions. Subsequently, it becomes more and more complex to determine the optimum sampling direction as the number of discontinuity sets increases and their spatial (3D) geometric orientations become more and more diverse.

f. A method for performing "bias corrections" (weighting) for Terzaghi's 'blind zones' for frequency-type borehole data are available in Berg (2012).

g. A method has been proposed by Maerz and Wu (2002) 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 discontinuity 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.

6-2. Concepts.

a. 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.

b. 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 a borehole can intersect as many discontinuities as possible for a given drilling length.

c. The orientation of a borehole is defined by two parameters, azimuth (direction) and inclination (dip). 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. The optimum azimuth can be determined by examining only the projections of the strikes onto a horizontal plane and the optimum inclination can be determined by examining only the projections of the dips onto a vertical plane. A horizontal plane is then used to identify the optimum drilling azimuth, because all strikes can be projected onto this 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 arbitrarily selected an east-west vertical projection was selected.

6-3. Theory.

a. To determine the optimum angle of drilling, an objective function is required to minimize the linear sampling bias of the borehole with respect to each discontinuity orientation is required. This function is known as the Linear Sampling Bias Index (LSBI).

b. If there is a single discontinuity orientation and α is the angle between the borehole azimuth and the strike of the discontinuity set (*i*), then LSBI is defined as follows:

$$LSBI_{\phi} = {}^{1}\!/_{\sin\alpha} \quad (6\text{-}1)$$

c. For a situation with *n* discontinuity orientations, the overall LSBI would then be the summation of the LSBI calculated for each individual discontinuity set.

$$LSBI_{\phi} = \sum_{i=1}^{n}\left(\frac{1}{\sin\alpha_i}\right) \quad (6\text{-}2)$$

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 6-2 is minimized by considering all possible values of ϕ. If one of the *n* discontinuity sets is perfectly horizontal, then (n-1) discontinuity sets must only be considered, because the strike of a horizontal discontinuity set is not defined.

d. The concept of LSBI can also be applied to borehole inclination and the projection of dip of a discontinuity set to a vertical east-west plane. An inclination less than 90° indicates the borehole dips toward the east, whereas greater than 90° indicate dip toward the west (the north-south direction is a special case). Angle (β_i) between the borehole inclination and the discontinuity inclination is always taken as the lesser angle between the two.

e. 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

$$\text{LSBI}_\theta = \sum_{i=1}^{n}\left(\frac{1}{\sin\beta_i}\right) \tag{6-3}$$

Where LSBI_θ 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 conventions are used, based on an upper-hemisphere projection. North is 0° or 360°, with a clockwise positive convention. Borehole inclination is related to the azimuth as follows:

(1) If the azimuth is between 0° and 180°, then borehole inclination is between 90° and 180°.

(2) If the azimuth is between 180° and 360°, then the borehole inclination is between 0° and 90°.

6-4. Discussion.

a. By applying the LSBI method, a single borehole could orientated by azimuth and inclination to drill through as many discontinuities as possible. 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, from scanline surveying, from published data, or estimated from regional structural trends. Data from the preliminary borehole can also be used to orient the second and all subsequent boreholes.

b. The LSBI method is based on the assumption that the frequency (spacing) of the discontinuity sets is relatively uniform. The average frequency within a discontinuity set is typically used in the analysis, although non-uniform frequency (spacing) is often encountered in many rock masses. Since the LSBI is a summation of the sampling bias components of all the discontinuity sets, not every discontinuity set has equal frequency and the contribution of each set to the overall sampling bias varies from set to set. If needed, the LSBI can be weighted to compensate for discontinuity frequencies that are significantly non-uniform. This can be weighted by the following factor:

$$w_i = \frac{\lambda_i}{\sum_{i=1}^{n}\lambda_i} \tag{6-4}$$

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.

c. Considering the non-uniform discontinuity frequency (spacing), a modified LSBI can be given as follows:

$$LSBI = \sum_{i=1}^{n}\left(\frac{\lambda_i}{\sum_{i=1}^{n}\lambda_i} \text{ X } \frac{1}{sin\gamma_i}\right) \qquad (6\text{-}5)$$

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

6-5. Examples.

a. Examples of identifying the optimum borehole orientation using the Linear Sampling Bias Index (LSBI) method are presented in Appendix F Example Linear Sampling Bias Index (LSBI) Method. Examples include the one discontinuity set, two discontinuity sets, three discontinuity sets, and four discontinuity sets cases.

b. Detailed and comprehensive discussions on the Linear Sampling Bias Index (LSBI) method are provided by Maerz and Zhou (2002).

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CHAPTER 7

Linear Sampling Angular Deviation (LSAD) Method

7-1. Background.

a. The Linear Sampling Angular Deviation (LSAD) method (Haneberg, 2009) builds upon the Linear Sampling Bias Index (LSBI) approach taken by (Zhou and Maerz, 2002). While the LSBI method produces correct results, it suffers from several shortcomings that hinder its efficacy, specifically:

(1) The LSBI method treats the two components of discontinuity orientation, namely, strike and dip, separately by using projections onto horizontal and vertical planes. Two graphs are therefore, required to represent the degree of bias associated with different borehole orientations.

(2) The LSBI method is based upon the reciprocal of the sine of the separation angle between a hypothetical borehole and a discontinuity. The advantage of a reciprocal approach is that it strongly penalizes the most unfavorable borehole orientations when optimizing the drilling direction. The disadvantage is that as the denominator approaches zero, as it does when the borehole and discontinuities are nearly parallel, the LSBI grows asymptotically large and, in the limit, becomes non-numeric. This makes it difficult to numerically evaluate and graph the results without truncating the LSBI function.

(3) The strike and dip based formulation of in the LSBI method does not work for horizontal planes, because the strike angle is undefined, and they suggest that horizontal discontinuities be disregarded when optimizing the drilling direction.

(4) Fourth, the LSBI is unit-less so its geometric significance is not easy to comprehend.

7-2. Concepts.

a. The LSAD method builds upon the approach taken by Zhou and Maerz (2002) by incorporating changes that make it more functional and geometrically significant.

b. The LSAD method treats both strike and dip simultaneously using a measure of the standard deviation of the angles between a potential borehole orientation and the lower hemisphere poles. Thus, the results can be shown in a single graph using Cartesian coordinates or in a lower hemisphere projection. The graphs exhibit meaningful units of ±degrees and does not become asymptotically large or non-numeric. The method penalizes the most unfavorable orientations by summing the squares of angular deviations.

c. Like the LSBI method, some a priori knowledge of discontinuity orientations must exist to use the LSAD method to optimize drilling directions. Prior knowledge of the discontinuity structure can be obtained from conducting a comprehensive scanline survey, as well as from published reports or existing geologic maps.

d. It must also be emphasized that if more than one set of discontinuities exists, optimization relative to all of the sets is always a form of compromise. In some situations it may be prudent to avoid compromises and plan the drilling program with a variety of orientations optimized to the orientation of a single discontinuity set.

7-3. Theory.

a. The direction cosines or unit vector components of a borehole described by plunge δ_b and azimuth θ_b is defined as follows (Priest, 1993; Pollard and Fletcher, 2005):

$$b = \begin{Bmatrix} b_x \\ b_y \\ b_z \end{Bmatrix} = \begin{Bmatrix} \cos\delta_b & sin\theta_b \\ cos\ \delta_b & sin\theta_b \\ -sin\ \delta_b & \cdots \end{Bmatrix} \qquad (7\text{-}1)$$

b. In this note, the z-axis is taken to be positive upwards; hence, a downward-directed borehole has a negative z component. The direction cosines for the lower hemisphere pole to a discontinuity with dip δ_d and dip direction θ_d are, in comparison:

$$d = \begin{Bmatrix} d_x \\ d_y \\ d_z \end{Bmatrix} = -\begin{Bmatrix} \sin\delta_b & sin\theta_b \\ sin\ \delta_b & cos\theta_b \\ cos\ \delta_b & \cdots \end{Bmatrix} \qquad (7\text{-}2)$$

c. The angle a between unit vectors **b** and **d** is, from basic vector analysis, given by the dot product of the two vectors, given by:

$$\cos\alpha = \mathbf{b}\cdot\mathbf{d} = b_x d_x + b_y d_y + b_z d_z \qquad (7\text{-}3)$$

d. Borehole sampling bias is minimized when the borehole is normal to a discontinuity (Terzaghi, 1965; Zhou and Maerz, 2002), in which case the borehole and pole coincide and α=0.

e. Vertical planes require special consideration because the concepts of downward and upward directed poles become meaningless. For vertical discontinuities, Equation 7-3 should be evaluated using both **d** and **-d** and the smaller of the two α values retained.

f. Estimation of the optimal drilling direction in a situation in which several discontinuity sets exists requires that some measure of angular dispersion of discontinuity sets around the borehole be minimized. One such angular measure is the normalized sum of the squared angular differences between the borehole and the poles to *i* = 1…*n* discontinuity sets, given by:

$$\sigma_\alpha^2 = \frac{1}{n}\sum_{i=1}^{n} arccos^2\left(\mathbf{b}\cdot\mathbf{d_i}\right) \qquad (7\text{-}4)$$

Where $\mathbf{d}_i$ contains the direction cosines for the i^{th} of n discontinuity sets.

g. Results can be plotted in Cartesian coordinates. Establish a Cartesian grid ranging over $-1 \leq x \leq +1$ and $-1 \leq y \leq +1$, then calculate the plunge and azimuth of each point on the grid for which $x^2 + y^2 \leq 1$ using:

$$r = \sqrt{x^2 + y^2} \tag{7-5}$$

$$d_b = \frac{1}{2}\left[180^{o} - 4\arcsin\left(\frac{r}{\sqrt{2}}\right)\right] \tag{7-6}$$

$$\theta_b = 90° - \arctan(y/x) \tag{7-7}$$

h. For each calculated plunge and azimuth pair, calculate a σ_α value using Equation 7-4 and contour the results.

7-4. Discussion.

a. Equation 7-4 is similar in form to the angular variance of vectors with respect to their mean (Borradaile, 2003) and has units of degrees or radians squared, depending on the input units. Taking the square root of Equation 7-4 yields a quantity analogous to an angular standard deviation, which has units of ±degrees or ±radians. The standard deviation is the Linear Sampling Angular Deviation (LSAD).

b. The optimum drilling direction is found by either plotting σ_α over the ranges $0° \leq \delta \leq 90°$ and $0° \leq \theta \leq 360°$ and visually identifying minima. Minima are sought because they represent drilling directions that should produce the smallest aggregate difference, given by Equation 7-4, between the borehole and the poles to the discontinuities or, in other words, directions that are most likely to minimize bias. Maxima, on the other hand, represent drilling directions that should be avoided because they decrease the likelihood of intersecting discontinuities and will maximize bias.

7-5. Examples.

a. Examples of identifying the optimum borehole orientation using the LSAD method are presented in Appendix G Example Linear Sampling Angular Deviation (LSAD) Method. Examples include the one discontinuity set, two discontinuity sets, and three discontinuity sets cases.

b. Detailed and comprehensive discussions on the Linear Sampling Angular Deviation (LSAD) method are provided by Haneberg (2009).

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CHAPTER 8

Discontinuity Frequency Extrema Method (DFEM)

8-1. Background.

a. Two parameters influence discontinuity patterns: the orientation of the discontinuity and their frequencies. Orientation of fractures is often based on the state of stress within the rock mass in often resulting from stress difference and orientation of the principal stresses. In contrast, the frequency or spacing of fractures is based on the properties of the rocks in which the fractures have formed. Discontinuity frequency is a fundamental measure of the degree of fracturing that exists within a rock mass.

b. The simplest and most commonly used measure of discontinuity frequency is linear frequency. Linear discontinuity frequency is expressed in terms of the number of discontinuities that occur along a unit length of rock mass and is a fundamental measure of the degrees of jointing in the rock mass.

8-2. Concepts.

a. Linear discontinuity frequencies are commonly obtained from scanline surveys or boreholes. Linear discontinuity frequencies can be applied to all of the existing discontinuities in a rock mass or to only one discontinuity set in the rock mass. The linear frequency along a line normal to the set of parallel planar discontinuities is λ. The apparent linear frequency λ_s along a sampling line that makes an acute angle δ to the set normal is given by:

$$\boldsymbol{\lambda}_s = \boldsymbol{\lambda} \cos \delta \qquad (8\text{-}1)$$

The angle δ is acute, since λ_s must always be positive. If there are N parallel planar discontinuity sets, the total frequency λ_s along a sampling line is given by the sum of the frequency components as follows:

$$\boldsymbol{\lambda}_s = \sum_{i-1}^{N} \lambda_i \cos \delta_i \qquad (8\text{-}2)$$

Where δ_i is the acute angle between the sampling line and the normal to the *i*th set, λ_i is the normal to the *i*th discontinuity set, and ($-90° \le \delta_i \le +90°$).

b. If the sampling line has a trend α_s and plunge β_s, then the mean normal to the *i*th discontinuity set has a trend α_{ni} and plunge β_{ni}, and:

$$\cos \delta_i = \cos(\alpha_s - \alpha_{ni}) \cos \beta_s \cos \beta_{ni} + \sin \beta_s \sin \beta_{ni} \qquad (8\text{-}3)$$

8-3. Theory.

a. Linear discontinuity frequency in a fractured rock mass varies with the orientation of the line along which the frequency is measured. Subsequently, unique line orientations can exist where maximum and minimum discontinuity frequencies occur (Priest, 1993).

b. An alternate expression for total discontinuity frequency λ_s can be obtained by replacing cos δ_i in Equation 8-2 with cos δ_i from Equation 8-3, then:

$$\boldsymbol{\lambda}_s = m_x \cos\alpha_s \cos\beta_s + m_y \sin\alpha_s \cos\beta_s + m_z \sin\beta_s \qquad (8\text{-}4)$$

Where:

$$m_x = \sum_{i=1}^{N} \lambda_i \cos\alpha_{ni} \cos\beta_{ni} \qquad (8\text{-}5)$$

$$m_y = \sum_{i=1}^{N} \lambda_i \sin\alpha_{ni} \cos\beta_{ni} \qquad (8\text{-}6)$$

$$m_z = \sum_{i=1}^{N} \lambda_i \sin\beta_{ni} \qquad (8\text{-}7)$$

Subject to the critical requirement that all angles δ_i between the discontinuity set normals and the sampling line are acute.

8-4. Discussion.

a. If the sampling line was rotated about an origin and through a sequence of orientations in a three-dimensional rock mass, it would be possible to calculate the total discontinuity frequency for each orientation. The frequency for a given sampling line could then be represented by the length of a line, or vector, radiating from the origin and extending parallel to the sampling line. The ends of the lines would generate a three-dimensional surface representing the variation of discontinuity frequency for the given discontinuity structure.

b. A cross-section taken through one such three-dimensional surface, generated by taking a horizontal section through the locus generated by the discontinuity sets, would show the frequency loci for each discontinuity set expose in a planar rock face.

c. Abrupt changes in the frequency loci, called cusps, occur where the sampling line lies parallel to one of the existing discontinuity sets. These cusps are V-shaped valleys in the discontinuity frequency locus, tracing the orientations of the existing discontinuity sets. These cusps occur because the transition of the sampling line from one side to the other of a discontinuity plane required a reversal of the associated normal to maintain the angle of δ_I as acute. The orientations of these cusps always represent a minimum value for discontinuity frequency ($\boldsymbol{\lambda}_s$).

d. The global minimum frequency can be found be summing the discontinuity frequencies for all existing joint sets. Cusps are associated with local minima because any sampling line that is parallel to one of the existing discontinuity sets in a group of sets ignores the frequency components from that set and generates a local minimum. These local minimum are the cusps on the frequency loci that are closest to the origin and represent smaller joint frequencies, or a larger joint spacing. The cusp that is the very closest to the origin is referred to as the minima extrema. The cusps on the frequency loci that are farthest from the origin represent larger joint frequencies, or a smaller joint spacing. Conversely, the cusp that is the very farthest from to the origin is referred to as the maxima extrema.

8-5. Examples.

a. Examples of the discontinuity frequency and frequency extrema method are presented in Appendix H Example Discontinuity Frequency and Frequency Extrema Method.

b. Detailed and comprehensive discussions on the Frequency Extrema Method are provided in Priest (1993).

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CHAPTER 9

Applications

9-1. General. Application of the analytical methods described in this engineer technical letter can be used to define an *optimum drilling direction*, that is, the direction along which a borehole can intersect as many discontinuities as possible for a given drilling length. This analytical tool has numerous geotechnical exploration and rock engineering applications. Several specific applications of the methods are discussed below.

9-2. Foundation Drains. The hydraulic conductivity of a jointed rock mass is commonly controlled by its secondary permeability and in most civil engineering applications; the secondary permeability would dominate the drain design procedures. Drains are used to dispel dangerous uplift pressures beneath hydraulic structures and to be effective, must be correctly placed in three-dimensional space to intersect hydraulically significant discontinuities that are capable of fracture flow. This requires the drain hole be drilled at the *optimum orientation and inclination* to maximize the efficacy of the uplift reduction drains, which would inhibit pore pressure within the foundation.

9-3. Geotechnical Investigations. Within a rock mass, discontinuities occur at a variety of scales, from microscopic to continental. Discontinuities are critical features in rock mechanics and rock engineering because they have a principal impact of the stability of engineered structures and excavations. Discontinuities also provide pathways for fluid flow and as hence, are important in hydrogeology, including both groundwater flow and contaminant transport problems in rock. In regards to discontinuities, key properties include location, identification, and characterization. Drilling and logging of boreholes is the most commonly used method of geotechnical site investigation. Improving the efficiency of drilling in acquiring critical data on key properties of discontinuities often means that each borehole must intersect as many discontinuities as possible per unit length of borehole. This requires the borehole be drilled at the *optimum orientation and inclination* to maximize the efficacy of the drilling and sampling program.

9-4. Permeation Grouting. Permeation grouting is the most used grouting technique (Warner, 2004). Permeation rock grouting is sometimes referred to as penetration grouting since it involves the filling of defects in the rock mass, such as individual discontinuities and discontinuity sets, with cementitious grout. Grouting may be done to reduce the fluid flow through a rock mass or to strengthen the rock mass, or a combination of both. A thorough understanding of the discontinuity structure of the rock foundation is fundamental to a successful rock grouting program. For grouting to be effective in a jointed rock mass, all rock mass defects, such as systematic joints and fractures, must be accessible from at least one grout hole (Warner, 2004). This requires that the grout holes be drilled at the *optimum orientation and inclination* so that the grout hole can intersect as many discontinuities as possible for a given drilling length, thereby achieving the Warner's accessibility requirement.

9-5. Verification Holes. Exploratory holes are often drilled into a permeation grout curtain as a means to evaluate and verify grout intrusion into the joints, fractures and fissures in the rock mass. Holes drilled and tested after closure is deemed to have occurred to test the closure decision are normally termed verification holes. For verification holes to be effective, an exploratory hole must be drilled at the *optimum orientation and inclination* so that the exploratory holes can intersect as many discontinuities as possible for a given drilling length to maximize the number of joints encountered and thereby, the efficacy of the verification hole process.

9-6. Pressure (Packer) Testing. Pressure (packer) tests are routinely performed in rock to determine rock mass permeability. Packers are designed to isolate a section of a borehole to perform pressure tests. The permeability calculation assumes laminar flow in an isotropic, homogeneous medium. Although in reality, the test water take is effectively controlled by properties of the fractures existing within the rock mass. Obtaining representative and appropriate hydrologic values is critical in any geotechnical site investigation. Exploratory drill hole orientations introduce a significant bias into pressure (packer) test results. The orientation of the drill hole relative to the fractures has a direct effect on the number of fractures intercepted by the hole. Drill holes should be oriented to cross as many fractures as possible not only for more meaningful permeability tests, but also to get more meaningful rock mass design parameters (USBR, 2010). This requires the drill hole used for pressure (packer) testing be drilled at the *optimum orientation and inclination* to intersect as many fractures as possible to achieve credible rock mass permeability results.

9-7. Geotechnical Instrumentation. Geotechnical instrumentation is used to verify design parameters, verify the suitability of a new construction method, diagnose causes of an adverse event, and for verification of satisfactory performance (USBR, 1987). Seepage occurs is virtually every dam through joints, cracks, and bedding planes in the dam foundation and abutment rock. Hydrostatic pressure measuring devices are used to measure the pressure differential between the reservoir head and the downstream pool (tailwater). In a dam foundation, the location of a pore pressure device must intersect discontinuities that communicate hydraulically with the general discontinuity pattern in the foundation (Wyllie, 1999). This requires the bore hole for the pressure measuring devices be drilled at the *optimum orientation and inclination* to intersect as many fractures as possible so that device may be installed in measurement zones that cross hydraulically significant discontinuities.

9-8. Groundwater Wells. Prior to the installation of groundwater monitoring, groundwater sampling, and/or groundwater recovery wells, exploratory borings and related subsurface investigations are needed to define the geology beneath the site and to assess groundwater flow paths and velocity (Aller, Bennett, Hackett, et al., 1991). The main flow paths in fractured rock are along discontinuities. Because the occurrence and movement of groundwater in the subsurface are closely related to structural geology, the discontinuities at the site influence the location, design and methods used to install groundwater monitoring wells. Discontinuities also facilitate the storage and movement of fluids through most rock masses, as well as affect the direction of groundwater flow and/or contaminant transport beneath the site (Singhal and Gupta, 2010). This requires that monitoring wells be drilled at the *optimum orientation and inclination* to maximize the efficacy of the well in intersecting those discontinuities along which groundwater flow and/or contaminant transport occurs. Methods for optimizing the orientation of water-supply boreholes in fractured aquifers may also be found in Banks (1992).

9-9. Rock Slopes. The stability of rock slopes is often controlled by the structural geology of the rock mass in which the slope is excavated. The properties of discontinuities that are most critical to the stability of the rock slope include orientation, persistence, roughness, and infilling (Wyllie and Mah, 2004). Where discontinuities have a preferred orientation, they can impart a substantial anisotropy to the rock mass (Priest, 1993). Where discontinuity persistence is much shorter than the slope dimensions or where discontinuity orientation is not unfavorable, discontinuities may only indirectly influence stability of a rock slope. Use of scanlines to collect geologic data, as described in this engineer technical letter, can provide the mean and frequency distributions of pertinent geologic data that are necessary for an efficient and effective design of a new rock slope or for adequate reinforcement of an existing rock slope. For any given rock mass, unique orientations that provide minimum and maximum discontinuity frequencies exist, both for individual joint sets and globally. The interaction between the minimum and maximum discontinuity frequencies and the orientation and geometry of a rock slope can have a significant impact on its stability.

9-10. Optimization of Drilling Direction. If more than one set of discontinuities exists, as they usually do, optimization of drilling direction relative to all of the discontinuity sets is always a compromise (Haneberg, 2009). The optimization techniques may be applied based upon the intention to intercept as many discontinuities as possible or to focus on intercepting those discontinuities of greatest significance, or those that pose the greatest risks – be they of structural or seepage control. In some situations, the orientation of one joint set may be most critical to the stability of a rock mass or a structure founded in or on rock - such as discontinuities that are unfavorably orientated immediately downstream of a major hydraulic structure or in a critical rock slope. One set of joints may be more permeable and therefore present greater risks for piping material than another, even if it is less prevalent. In that case, it may be prudent to avoid compromises and plan the subsurface investigation program with a variety of drilling orientations, each optimized to the orientation of a single discontinuity set. In such cases, a less-than-dominant set posing greater risk, these may be targeted using the optimization techniques by screening them once the data are collected for analysis.

9-11. Drilling Constraints. Regardless of the resulting optimized drilling orientation developed by the methods the actual orientation used may be limited by factors outside the numerical analysis. The physical characteristics of the site and the limitations of equipment and access must be taken into account prior to designating an orientation to boreholes in a drilling work plan, scope of work or contract. It might be ideal to orient boreholes at an inclination of 50-degrees below horizontal based upon the analysis, but the mechanics of executing such an orientation may prevent it from being practical or feasible to do so. The access and logistics of a site may preclude using equipment that might otherwise be able to achieve the optimized orientation as well. Under these conditions it becomes necessary to run through alternative scenarios to determine the best practical solution during the analysis, rather than after equipment and personnel have been mobilized. Drilling tolerance and the potential for deviation should also be considered when putting the results of these methods into application. Smaller diameter tooling is more prone to deviation during drilling, and the greater the depth and the more complex and variable the geology, the greater the potential for boreholes to wander off target. The greater the inclination from vertical the more likely the borehole is to deviate from the desired orientation, all other factors being equal. Although this discussion focuses on rock, borehole stability in badly fractured or weathered rock, or in mixed rock and soil geology will also have to be considered because the same stability impacts to the project that are being investigated may play into borehole stability as well. A tolerance in the range of 3-percent as a starting point should be considered in planning borehole arrays regardless of the method used to develop the alignments. Greater control may be achieved, but may also require larger tooling and equipment and more specialized contractors or more expert personnel.

9-12. Theoretical Rock Quality Designation (TRQD). The theoretical RQD (TRQD) can be used as a tool to help align excavations for cut rock slopes, trenches, tunnels, quarries, etc. Specifically, an excavation may be orientated along the maximum TRQD, that is, when high RQD (high quality) rock is beneficial to the stability of a rock slope or tunnel. Alternately, the theoretical RQD (TRQD) can also be used as a tool to help align an excavation in rock with the orientation along the minimum TRQD, that is, when low RQD (low quality) rock is beneficial to the excavation of rock, such as trenches, conduits, troughs, ditches, channels, pits, etc.

9-13. Project Example - CUP McCook Reservoir.

a. The Chicago Underflow Plan (CUP) McCook Reservoir is a large 10-billion-gallon reservoir located in the southwestern suburbs of Chicago to hold combined sewer outfalls from the Metropolitan Water Reclamation District of Greater Chicago's Mainstream Tunnel System. It is being excavated to a depth of approximately 275-feet into dolomite, with overburden thicknesses in the range from 20 to 50-feet thick. The original design for the reservoir was to utilize an existing quarry in the Silurian dolomite deposits located near the MWRDCG's Stickney Wastewater Treatment Plant; however, local concerns and negotiations with residents and landowners resulted in relocating the project to the MWRDCG's Lawndale Avenue Solids Management Area (LASMA) facility. A location view is shown in Figure 9-1.

b. The LASMA location for the McCook Reservoir site presents several geotechnical challenges by virtue of the orientation of the dominant rock joint sets with respect to the real estate boundaries and geometry and location of water bodies. The tract of land owned by MWRDGC is an elongate parcel set between the Chicago Sanitary and Ship Canal and the Des Plaines River and Interstate 55. Additionally, the size, shape and alignment of the reservoir are designed to allow for maximum reservoir volume over any stability considerations. To maximize the capacity of the reservoir, it is being excavated in a shape fitted within the property lines of the LASMA site leaving enough offset to provide for a perimeter road, the LASMA railroad spur along the southern border, utilities.

c. The existing quarry provided an extensive area over which geologic features of the Silurian bedrock could be evaluated, and with an appropriate understanding of the inherent variability in the region, the discontinuity measurements could be extrapolated from the McCook (Vulcan Materials) Quarry to the new McCook Reservoir site. Several rounds of subsequent borings were drilled at the LASMA McCook Reservoir site to establish the geotechnical criteria for the design from 1997-2002. These borings were used to conduct physical testing of core, geophysical logs, enhanced borehole videologging, detailed rock core logging, water pressure testing and Optical Acoustic Televiewing, and these studies were combined with the earlier studies of the Vulcan McCook Quarry.

d. The general geology of the area consists of variable thicknesses of overburden underlain by approximately 300 to 350-feet of Silurian dolomite sequence within the Niagaran Series. The dolomite bedrock ranges from thinly laminated shaley dolomite to massive dolomite with occasional chert nodules and vugs. Some inter-reef shallow carbonate slightly inclined structures are evident in the area; however, in general the strata are nearly horizontal to slightly dipping to the southeast. Underlying the Niagaran Series is the Ordovician Maquoketa Series: a series of shales, dolomitic shales and shaley dolomites that will act as an aquiclude into which the groundwater containment measures will be tied to control inflow and outflow seepage. The overburden at the LASMA site consists of glacially-transported materials ranging from colloidal-sized rock flour to very large boulders. The density also varies from soils having N-values below 20 to material that exceeds Torvane shear values of 8 TSF.

e. The results of mapping at the Vulcan McCook Quarry indicate that there are two major joint sets within the site area. The most common set has a strike ranging from N20°W to N57°W with an average strike of N46°W. The spacing of the common set ranges from less than 1 foot to as much as 300 feet. The other major joint set trends in a northeast direction with a strike ranging from N34°E to N60°E and an average strike of N48°E. Joint spacing ranges from less than 1 foot to a maximum of 225 feet. All major joints within the quarry are steeply dipping. Dip measurements range from 80° to 90°. Upon general inspection, the northeast trending joints tended to be more open/free of infilling; whereas the northwest trending joints tended to be more often clay-filled.

f. In addition to the jointing, there are occasional "buckle zones" where compression causes the bedrock to heave and some pressure relief spalling has been observed in faces parallel or sub-parallel to major joint sets.

g. A series of borings was drilled and tested for hydraulic conductivity at the site to evaluate the potential impacts of the reservoir on surrounding groundwater and the impacts of groundwater infiltration on construction and operations of the reservoir. The man-made Chicago Sanitary and Ship Canal is located along the southeast side, excavated into bedrock by explosives in the early 20th Century to a depth of approximately 30-feet, and the relocated course of the Des Plaines River is along the northwest side of the facility. Both of these waterways are protected by the provisions of the Clean Water Act, and so the reservoir design includes an overburden cutoff wall and a double row grout curtain around the entire reservoir site in order to mitigate concerns for CSO constituent seepage from the reservoir to the water bodies. The in-situ permeability of the bedrock at the site, as summarized in Table 9-1, was such that very little grouting would be required if this project were simply for water, but the nature of the reservoir constituents led the regulatory agencies involved in oversight to require grouting to mitigate outflow.

Table 9-1
Summary of Packer Test Results CUP McCook

Formation [1/]	Hydraulic Conductivity (cm/sec)			Number of Tests [2/]
	Geometric Mean	Maximum	Minimum	
Racine	$6.55x10^{-5}$	$2.70x10^{-3}$	$2.30x10^{-6}$	31
Racine / Sugar Run	$2.96x10^{-5}$	$6.10x10^{-4}$	$4.60x10^{-6}$	6
Sugar Run	$2.87x10^{-4}$	$2.87x10^{-4}$	$2.87x10^{-4}$	2
Sugar Run / Joliet	$3.46x10^{-6}$	$9.01x10^{-4}$	$2.10x10^{-8}$	8
Joliet	$1.99x10^{-5}$	$3.44x10^{-4}$	$6.60x10^{-8}$	34
Joliet / Kankakee	$6.51x10^{-6}$	$2.87x10^{-4}$	$1.30x10^{-7}$	16
Kankakee	$5.13x10^{-6}$	$5.70x10^{-2}$	$4.00x10^{-8}$	42
Kankakee / Elwood	$1.15x10^{-4}$	$8.28x10^{-3}$	$6.10x10^{-6}$	24
Elwood	$5.29x10^{-5}$	$3.00x10^{-3}$	$2.30x10^{-8}$	43
Elwood / Wilhelmi	$3.87x10^{-5}$	$5.90x10^{-3}$	$7.06x10^{-7}$	16
Wilhelmi	$2.29x10^{-6}$	$8.50x10^{-4}$	$1.50x10^{-8}$	45
Wilhelmi / Ft. Atkinson	$4.82x10^{-7}$	$9.10x10^{-6}$	$1.00x10^{-7}$	8
Ft. Atkinson	$1.86x10^{-7}$	$3.82x10^{-6}$	$9.30x10^{-9}$	10
Ft. Atkinson / Scales	$3.11x10^{-7}$	$8.40x10^{-6}$	$8.00x10^{-9}$	15
Scales	$7.30x10^{-7}$	$1.50x10^{-5}$	$4.80x10^{-8}$	12

[1/] Test intervals spanning a contact zone between formations are indicated separately.
[2/] Includes multiple tests results of a tested zone.

h. The geometry of this footprint is unfortunately not orthogonal to the principle joint sets in the Silurian dolomite sequence into which the reservoir is being mined. In fact, the orientation is nearly parallel to the two major non-horizontal joint sets, as shown in Figure 9-3, a configuration that is the antithesis of ideal when locating high-walled excavations in rock. The geometry of the reservoir with respect to the joint sets has a great potential for the formation of elongate unstable rock wedges as depicted by Figure 9-4.

i. The grout curtain consists of rows of grout holes drilled inclined in opposing directions at 15-degrees from the vertical, parallel to the reservoir perimeter. The inclination of 15-degrees was arrived at during the test program as a compromise between the low probability of intercepting high angled joints with vertical holes and the high probability of intolerable borehole deviation resulting from low-angle borings. The alignment parallel to the reservoir was necessary because of the constraints of the real estate involved. – drilling deep inclined borings in a manner that they would optimally intercept both major high-angle joint sets would result in borings extending beyond the property lines of the LASMA facility. The depth required to tie the grout curtain into the top of the aquiclude also made it necessary to configure the array of holes in the corners of the grout curtain in fan-shaped fashion, as shown in Figure 9-5.

j. The CUP McCook Reservoir highwalls and approximately 7,000-linear foot of double-row grout curtain were constructed along alignments contrary to optimum - in rock that would ordinarily require minimal feature-driven grouting and minimal rock support, had the project configuration been developed based upon geotechnical considerations alone. While we can develop numerical and analytical methods to optimize excavation wall configurations and borehole alignments, we are seldom given the opportunity to construct project features based solely on the geotechnical optima. However, by using a wide spectrum of analytical methods, we will be able to balance the geotechnical considerations with the other factors involved in decision making. The location, geology and the alignment of the features of the McCook Reservoir site are demonstrative of the need to understand the orientation and spacing of discontinuities and also the ways in which non-technical or non-engineering considerations can result in sites and/or designs being chosen contrary to how they might have been optimally. The techniques of identifying and characterizing discontinuities at a site are just as important in such cases, as we still have to deal with them as well as circumstances allow.

9-14. Summary. Other applications in rock engineering and geotechnical investigations where the *optimum drilling direction* of a borehole may prove valuable certainly exist. Application of the analytical methods described in this engineer technical letter can be an important analytical tool in the investigation, design, and construction of engineered structures located on or in rock.

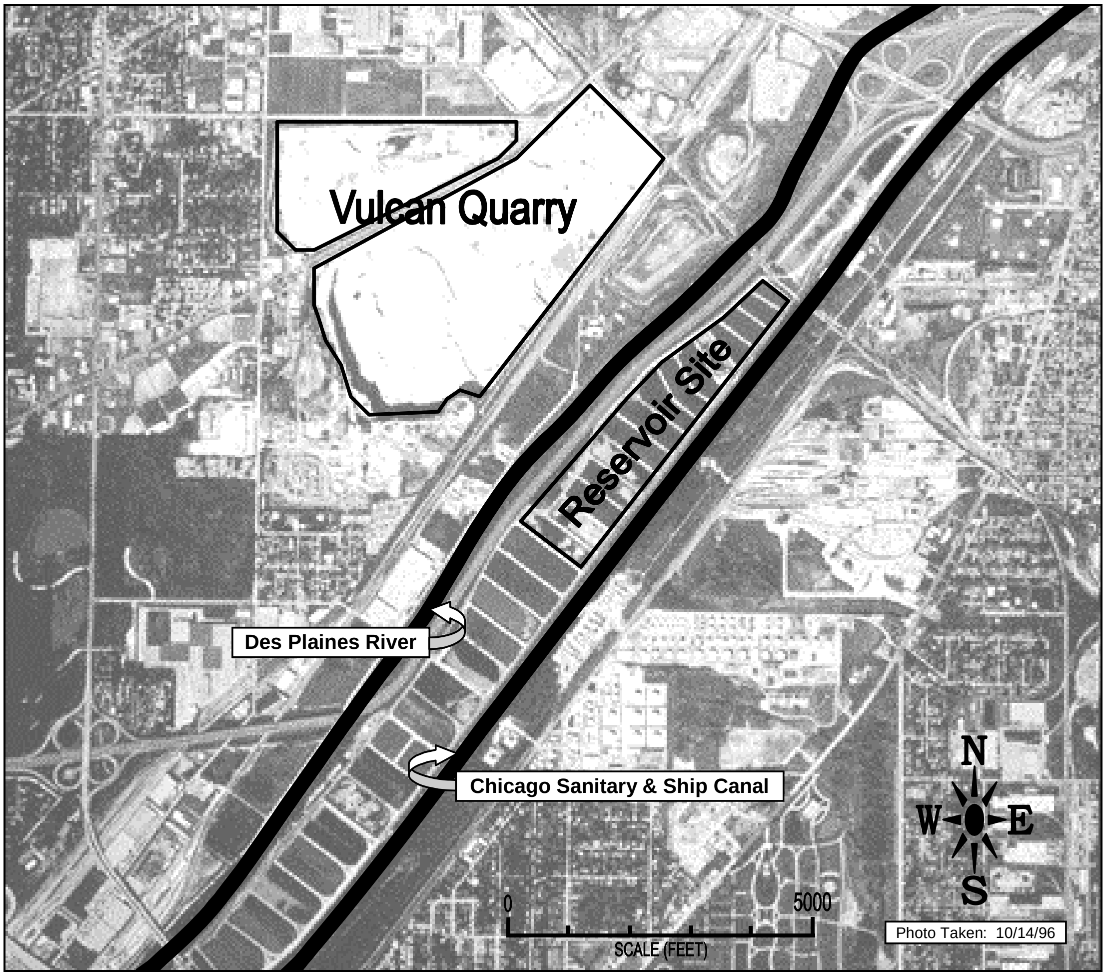

Figure 9-1. Locations of Vulcan McCook Quarry and LASMA/McCook Reservoir

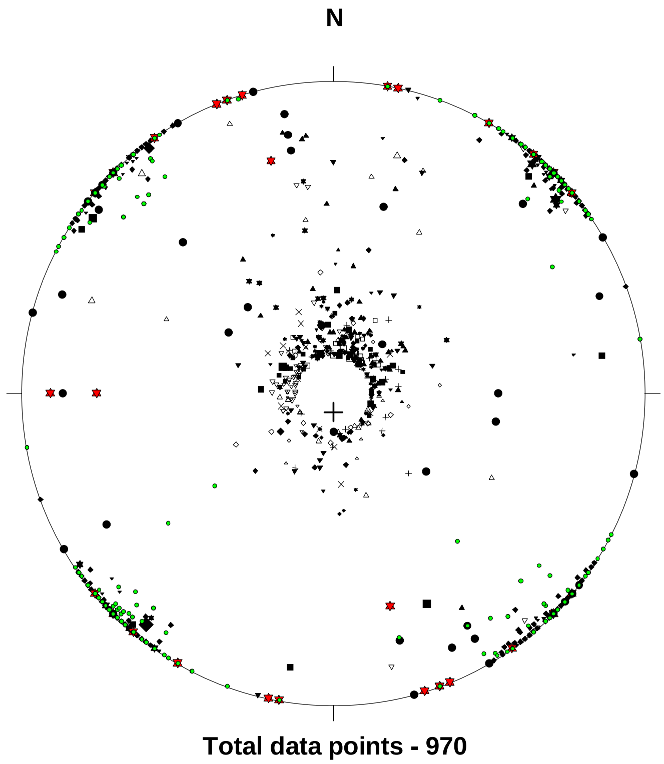

Figure 9-2a. Pole plot illustrating discontinuity data from Vulcan McCook Quarry

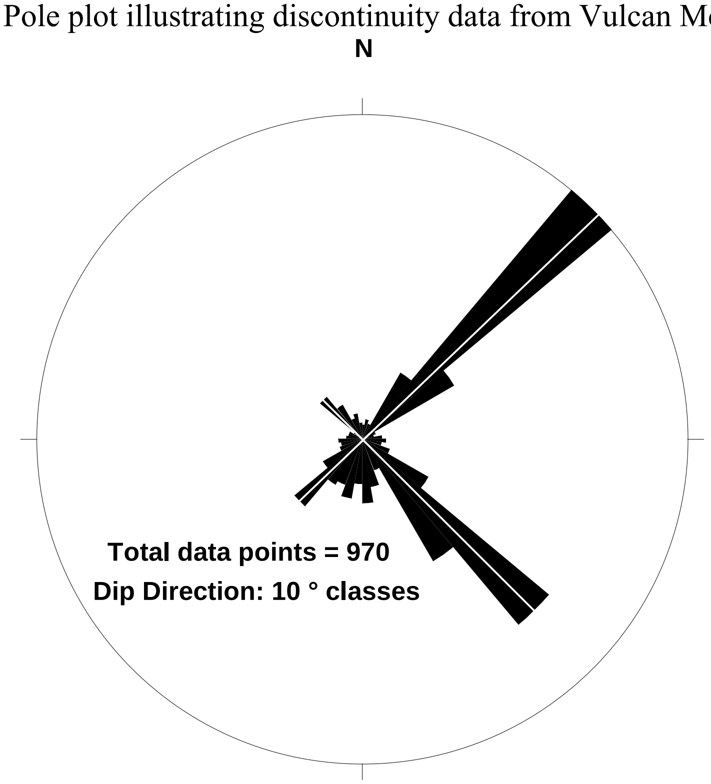

Figure 9-2b. Rose Diagram of rock joint dip directions at Vulcan McCook Quarry

Figure 9-3. Wedge formation by sub-parallel joint along north wall

Figure 9-4. Northern excavation (Stage 1)

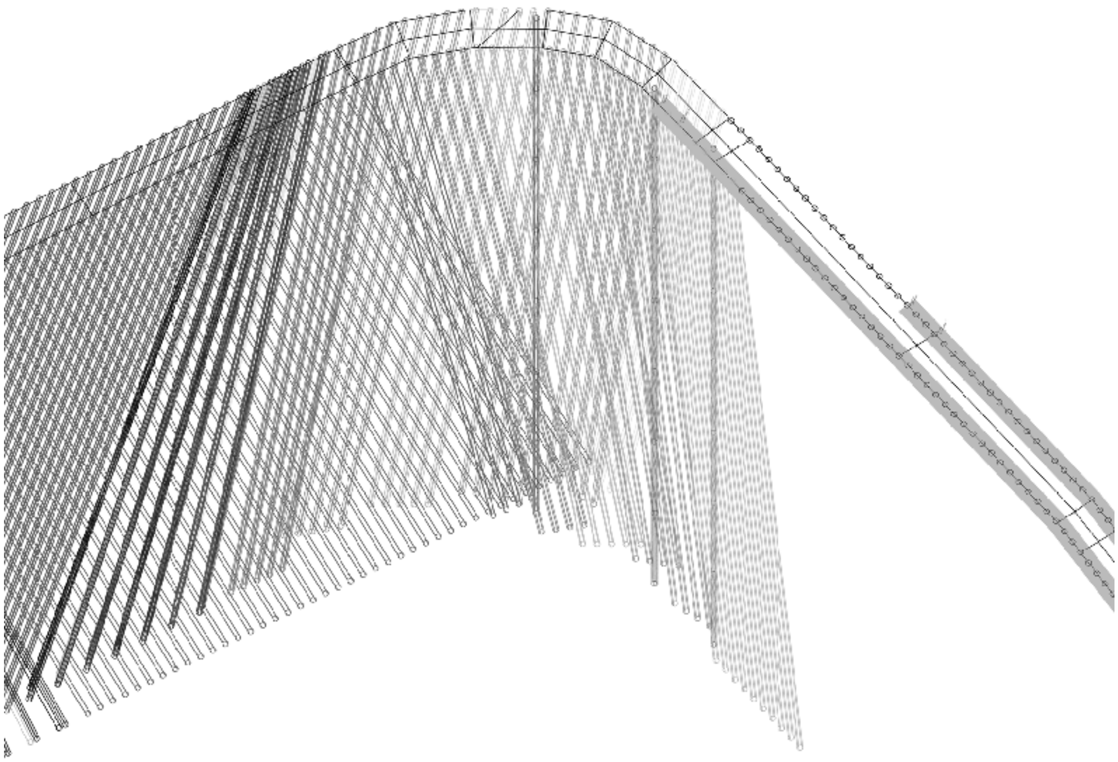

Figure 9-5. Schematic 3-D view of corner grout hole array

CHAPTER 10

Case History

10-1. Background.

a. Equilibrium seepage patterns develop within the bedrock beneath a hydraulic concrete structure, with the resultant vertical load recognized as external uplift. Uplift is one of the primary loads that affect the stability of a hydraulic concrete structure founded on bedrock (Novak, 2001). Uplift loads decrease the resistance of the structure to sliding. Interstitial pore pressures develop within the bedrock as a result of preferential seepage occurring along the existing discontinuities with the rock mass (secondary permeability), and to a lesser degree, by seepage within the pore structure of the rock (primary permeability). The flow region within the bedrock is a function of the site-specific geology (Murphy, 2002). Uplift pressures are controlled by the flow regime within the rock foundation. The pore pressure distribution is largely governed by the orientation, condition (aperture, asperities, filling, etc.), frequency, persistence and connectivity of the joint sets existing within the rock foundation.

b. Natural fractures have inhomogeneous distributions of properties, including apertures, even along an individual joint. The hydraulic properties of fractured rock can abruptly change with both depth and areal extent. Hydraulic conductivity of fractures can vary over many orders of magnitudes and fractures with the same fluid flow properties along their entire length probably do not exist, despite the fact that the effective lengths (horizontal dimension) of individual joints rarely exceed a few tens of feet. Hence, actual uplift pressures are frequently indeterminate. It is therefore, customary to assume uplift as a linear pressure distribution envelope acting vertically upward beneath a hydraulic concrete structure. Pore pressures are assumed to diminish linearly from the headwater (pool elevation) at the upstream face of the structure to the tailwater pressure, or zero, as appropriate, at the downstream toe of the structure. If pressure relief drains are provided, a bilinear pressure distribution envelope is assumed.

c. Drain holes drilled in the rock foundation downstream from the grout curtain are routinely provided beneath hydraulic concrete structure. These drains are routinely drilled from a drainage gallery where the open drains are then discharged. The drainage gallery typically extends the full length of the dam and serves as a collection main for seepage from foundation drainage holes and from the interior drainage holes, if any. A gutter and system of weirs located along the downstream wall of the gallery are often provided that allow for the observation and determination of flow rates for the foundation drains.

d. When drains are provided, the internal pore pressure distribution in the foundation rock is dependent upon the drain size, depth, location, and spacing. For a major of hydraulic concrete structure, drains are usually drilled in one or more lines of holes downstream of the grout curtain. The size, spacing, and depths of the drains are often assumed on the basis of past experience or technical judgment. Rules-of-thumb have been historically used to specify the spacing, depth and orientation of the drains. Drains are usually spaced on ten-foot centers and with depths dependent upon the grout curtain and reservoir depths (USBR, 1976). For example, drain depths vary between 20 to 40 percent of the full reservoir depth and 35 to 75 percent of the grout curtain depth.

e. The effectiveness of the drains in intercepting seepage, and hence reducing pore pressures within the foundation rock, is a direct function of how successful the drains are in intersecting the preferential seepage occurring along the existing discontinuities within the rock mass. The use of rules-of-thumb guidance for drain installations do not categorically evaluate the spacing and depths of the drains in regards to the geometric properties of the existing discontinuities in the rock foundation. Drains that do not systematically intersect the existing discontinuities may not effectively diminish the internal pore pressure distribution in the foundation rock.

f. Methods presented in this engineer technical letter can be used to optimize the orientation of the drains to intersect the *maximum number* of *discontinuities* that exist within the rock foundation of a hydraulic structure. These methods can be used to effectively evaluate the spacing and depths of the drains with regards to the geometric properties of the existing discontinuities in the rock foundation, assuming that a priori knowledge of the pertinent discontinuity properties is available. A case history from an unspecified hydraulic structure is presented below. Geologic and structural data used in the analysis were provided courtesy of Gannett Fleming, Inc., 207 Senate Avenue, Camp Hill, PA 17011.

10-2. Site Geology.

a. Stratigraphy. The dam is underlain by Middle Devonian sandstones and shales that were deposited in marginal-marine to nonmarine environments. A 1950 geologic map of the area around the dam site described the rock is as “grey, medium to fine-grained sandstone; thin-bedded siltstone; dark grey shale.” More recent geologic mapping describes the general rock group as a wedge-shaped mass of siliciclastic rocks, which consists of non-marine red and green shale and cross-bedded sandstone with plant and fish remains beneath the dam site. The formation has an estimated thickness of 500 feet beneath the dam.

b. Structure. The structure is described as “undeformed to very gently folded, dips < 5°, Lower and Middle Paleozoic rocks.” Based on dips determined using an optical level, an average dip of 1.5° to the south was reported for the strata at the dam site.

c. Outcrop Mapping. The area of mapping extended from downstream end of the spillway apron and for a length of approximately 100 feet in a downstream direction. The rock was identified as primarily greenish-gray to gray sandstone, which weathers to brown, gray and black. Layers of calcareous mudstone, shale, and siltstone, ranging in thickness from 1.6 to 4.5 feet, were also encountered.

10-3. Scanline Survey.

a. A scanline survey was performed on a rock exposure on the right side of the outlet channel and immediately below the dam. The scanline survey was performed on five traverses, which were not entirely continuous because of covered areas and height limitations. The traverses were designated, in upstream order, as A, B, C, D, and E. Each traverse was worked in an upstream direction.

b. A photograph of the rock exposure on east side of gorge below the dam spillway is shown in Figures 10-1 and 10-2. Traverse A is shown in Figure 10-3.

c. A tabulation of measurements and observations, such as length, continuity, roughness, infilling, thickness, waviness, and moisture, for the 45 total joints measured from the scanline surveys performed at the dam site is shown in Table 10-1. The rock units were labeled according to rock type with each rock type numbered in ascending order from the lowest unit visible to the highest unit.

10-4. Joint Orientation.

a. A rose diagram of the strikes of the 44 vertical to sub-vertical joints measured in the scanline survey is presented as Figure 10-4. Within this figure, solid radial lines represent bearing in 10-degree increments, circular grid lines represent a percentage of measurements in 2-degree increments and the lengths of shaded areas correspond to percentage of joint strike measurements falling within each 10-degree increment of bearing. The rose diagram reveals three joint clusters: Joint Set 1 trending N43°E (043); Joint Set 2 trending N75°W (285); and Joint Set 3 trending N5°W (355).

b. The majority of measured joint surfaces were vertical or nearly vertical and all but one had a dip of 75° or greater. A Stereograph of great circles corresponding to the 44 vertical to sub-vertical joint surfaces measured at the dam site is presented as Figure 10-5. The dashed grey lines represent great circles.

c. Joint Set 1 contains 26 joints. Joint surface orientations measured within Joint Set 1 range from N17°E to N69°E in strike and from 75°NW to 86°SE in dip. As shown in Table 10-2, the average strike and dip of Joint Set 1 = N43°E/89°NW.

d. Joint Set 2 contains 14 joints. Joint surface orientations measured within Joint Set 2 range from N63°W to N85°W in strike and from 84°SW to 82°NE in dip. These joints tend to be shorter and less continuous than the joints of Joint Set 1. The combination of Joint Set 1and Joint Set 2 would produce a blocky appearance in the bedrock. As shown in Table 10-3, the average strike and dip of Joint Set 2 = N75°W/88°NE.

e. Joint Set 3 contains four joints. Joint surface orientations measured within Joint Set 3 range from N00°W to N10°W in strike and from 87°W to 90° in dip. These joints tend to be shorter and less continuous than the joints of Joint Set 1 and Joint Set 2 and were only present in sandstone. As shown in Table 10-4, the average strike and dip of Joint Set 3 = N5°W/89°SW.

f. The orientation and coordinates for Joint Sets 1, 2, and 3 are shown in Table 10-5.

10-5. Joint Spacing.

a. Measurements taken during the detail line survey provide an apparent spacing of joints along each traverse. The orthogonal spacing between joints can be calculated by the equation:

$$n_n = d_n(\sin\phi_n \cos\theta_n \sin\phi\cos\theta + \sin\phi_n \sin\theta_n \sin\phi\sin\theta + \cos\phi_n \cos\phi) \qquad (10\text{-}1)$$

Where:

n_n = the orthogonal joint spacing of joint set n
d_n = the apparent joint spacing of joint set n
ϕ_n = the plunge of the pole to joint set n
θ_n = the trend of the pole to joint set n
ϕ = the plunge of the traverse
θ = the trend of the traverse

b. An average apparent joint spacing was calculated for each joint set for each traverse having at least two measurements for the joint set. The traverse trend was determined from field measurement using a GEO Pocket Transit. In cases where the traverse trend was not constant, a weighted average trend was calculated based on the lengths of each traverse segment. The true average joint spacing was calculated, and then a weighted average was calculated for each joint set based on the respective length of the traverses. As shown in Table 10-6, the weighted calculated average true joint spacing for Joint Set 1 = 3.7-ft; Joint Set 2 = 5.5-ft; and Joint Set 3 = 6.8-ft. The greater spacing of Joint Set 3 may reflect a bias resulting from the set striking roughly parallel to the trends of the traverses, since only four of the 44 measured steeply dipping joints belong to Joint Set 3.

10-6. Joint Persistence.

a. Joints persistence was determined in the scanline survey. A histogram of measured joint persistence versus frequency is shown in Figure 10-6.

10-7. Drain Orientation.

a. Linear Sampling Bias Index (LSBI) Method. The orientation of the drain was analyzed using LSBI methodology, as discussed in Chapter 6. The three joist sets used in the LSBI analysis are shown in Table 10-5.

(1) Inclination. LSBI results for drain inclination for the three joint sets are shown in Figure 10-6. LSBI is minimized at 0° borehole inclination direction relative to a horizontal plane, which indicates a horizontal drain. Since the dip of the three joint set are all vertical or nearly vertical, a horizontal foundation drain would be both rational and effective, but is not a practical inclination for drilling foundation drains for a hydraulic structure. Based upon an examination of Figure 10-7, a 45° inclination is not significantly less favorable than horizontal and is a practical inclination for drilling and was subsequently selected.

(2) Azimuth. LSBI results for drain azimuth are shown in Figure 10-8. LSBI is minimized at about 139° and 320°. These azimuths represent the optimum drilling direction for the three joint sets.

b. Discontinuity Frequency Extrema Method (DFEM). The orientation of the drain was also analyzed using DFEM methodology, as discussed in Chapter 8. The three joist sets used in the LSBI analysis are shown in Table 10-5. Results of the DFEM analyses are presented in Table 10-7 and shown as a polar plot in Figure 10-9 and as an X-Y scatter plot in Figure 10-10. As discussed above, a 45° inclination was assumed. The optimal azimuth for the drains occurs where the cumulative frequency of all three joint sets is maximized, as shown in Table 10-9 and illustrated as curve 'Freq JS1 JS2 JS3' in Figure 10-9 and Figure 10-10. Results of the DFEM analysis for the three joint sets indicate that the optimal azimuths for the drain occur at about 139° and 320°.

c. Discussion. A drain installed with an azimuth of 139° is considered as a practical orientation, since it is the orientation that is closest to perpendicular to the 71.2° orientation for the axis of the hydraulic structure. The analysis indicates that a drain installed with an azimuth of 139° and at an inclination of 45° will intercept a joint belonging to Joint Set 1 every 5.4-ft, a joint belonging to Joint Set 2 every 14.8-ft, and joint belonging to Joint Set 3 every 16.9-ft, as shown in Table 10-7. A foundation drain orientation with a 139° azimuth and a 45° inclination is the optimum direction along which a drain can intersect the maximum number of discontinuities for a given drain length. This orientation would be the most effective orientation to intersecting the most seepage, thereby effectively reducing uplift pore pressures in the rock foundation.

10-8. Drain Length.

a. The drain length should be long enough to penetrate all three joint sets at least once. For a drain with azimuth of 139° and an inclination of 45°, Joint Set 3 has the greatest apparent spacing (16.9-ft). This suggests a minimum drain length of 17-ft in foundation rock.

b. Drain depth versus the number of joints encountered for each joint set and for the cumulative number of joints is shown in Table 10-8. A 25-ft drain depth would encounter 4 joints from Joint Set 1, 1 joint from Joint Set 2, and 1 joint from Joint Set 3. A 50-ft drain depth of would encounter 9 joints from Joint Set 1, 3 joints from Joint Set 2, and 2 joints from Joint Set 3. A 75-ft drain depth of would encounter 14 joints from Joint Set 1, 5 joints from Joint Set 2, and 4 joints from Joint Set 3. A 100-ft drain depth of would encounter 18 joints from Joint Set 1, 6 joints from Joint Set 2, and 5 joints from Joint Set 3. And a 200-ft drain depth of would encounter 37 joints from Joint Set 1, 13 joints from Joint Set 2, and 11 joints from Joint Set 3.

c. The true vertical depth (D_v) of a drain hole of length L with a 45° inclination is given by:

$$D_v = L \text{ G } \sin 45° \qquad (10\text{-}2)$$

d. A drain with an azimuth of 139° degrees is 68° degrees from the axis of the hydraulic structure, so the upstream distance (D_H), relative to the axis of the structure, of a drain of length L with a 45° inclination and an azimuth of 139° is given by:

$$D_H = \text{L G } \sin 45° \text{ G } \sin 68° \qquad (10\text{-}3)$$

e. Table 10-8 includes vertical depths and horizontal distances for drain holes of lengths trending 139 degrees and plunging 45 degrees. Drain depth versus number of joints encountered for each joint set and cumulative total number of joints is shown in Figure 10-11.

f. Finally, all drain lengths should be checked for both horizontal distance and vertical depth to ensure that the drain does not perforate the existing grout curtain, if installed.

10-9. Drain Spacing.

a. The drain hole spacing will be controlled by the apparent spacing of joint sets along the drain hole orientated to the gallery where the drain holes will be drilled. For drains with as azimuth of 139° and an inclination of 45°, Joint Set 3 will control the drain hole spacing since it has the greatest apparent spacing (16.9-ft) along the axis of the drain. The apparent spacing of drains along the gallery is given by:

$$\frac{n_n}{\sin \phi_n sin\theta_n} \qquad (10\text{-}4)$$

Where:

n_n = orthogonal spacing of joint set n

ϕ_n = dip of joint set n

θ_n = angle between the strike of joint set n and the axis of the hydraulic structure

b. The orthogonal spacing of Joint Set 3 is 6.85-ft. Joint Set 3 has a dip of 89° and a strike of N5°W, which is aligned at 76 from the axis of the hydraulic structure. The apparent spacing of Joint Set 3 along the axis of the gallery is given by:

$$\frac{6.85\ feet}{\sin 89°\sin 76°} = 7.06\ feet \tag{10-5}$$

c. To avoid gaps between drains, the drain spacing should not exceed 7-ft multiplied by the number of joints belonging to Joint Set 3 penetrated by the drain, which is determined by dividing the drain length by the apparent Joint Set 3 spacing along the drain (16.9-ft). Thus, the maximum drain spacing is given by:

$$7\ feet \times \frac{L}{16.9\ feet} \tag{10-6}$$

Where L = drain length (in feet).

d. According to Table 10-8, which provides the minimum number of joints belong to Joint Set 3 penetrated for various drain lengths, the maximum horizontal drain spacing should not exceed 14-ft for a drain length of 50-ft, 28-ft for a drain length of 75-ft, 35-ft for a drain length of 100-ft, and 77-ft for a drain length of 200-ft. To ensure good overlap between drains, the numerator in Equation 10-6 may be reduced. For example, replacing *L* with (*L - 16.9-ft*) would ensure that the drains overlap by the spacing of one joint. This would reduce the maximum spacing to 7-ft for a drain length of 50-ft, 21-ft for a drain length of 75-ft, 28-ft for a drain length of 100-ft, and 70-ft for a drain length of 200-ft. Additional drain spacing reductions may be required on major hydraulic structures, where *L* in Equation 10-6 can be replaced by (*L - 33.8-ft*) or more for longer drain lengths.

10-10. Summary.

a. A recommended drain design is as follows:

Feature	Value	Remarks
Drain Orientation	139°	Orientation is upstream and closest to perpendicular to the axis of the hydraulic structure
Drain Length	120-ft	Depth would encounter: 14 joints from Joint Set 1 5 joints from Joint Set 2 4 joints from Joint Set 3
Drain Spacing	15-ft	Maximum drain spacing (118-ft) was reduced by a (L-50.7-ft) to ensure overlap by three joints. This drain spacing was further reduced by a factor of two for redundancy and to account for geologic uncertainties associated with Joint Set 3

b. This drain design must be fully checked and verified to ensure that it is completely compatible other critical project features, notably the grout curtain.

10-11. Theoretical Rock Quality Designation (TRQD).

a. The Theoretical Rock Quality Designation (4-inch threshold value) along the selected orientation of the drain is 99.5%.

10-12. Conclusions.

a. Discontinuities typically exhibit preferred orientations. Scanline surveys are an effective method used to precisely collect both orientation and physical data on discontinuities which exist within a rock mass. These data can provide the *a priori* knowledge of the discontinuity structure of the rock foundation that is needed to effectively utilize the analytical methods described this engineer technical letter.

b. The hydraulic conductivity of a jointed rock mass is commonly controlled by its secondary permeability and in most civil engineering applications; the secondary permeability would dominate the drain design procedures. Drains are used to dispel dangerous uplift pressures beneath hydraulic structures and must be correctly placed in three-dimensional space to intersect hydraulically significant discontinuities that are capable of fracture flow.

c. Application of the analytical methods described in this engineer technical letter can be used to define an *optimum drilling direction*, that is, the correct orientation and inclination along which a borehole can be drilled to intersect as many discontinuities as possible for a given drilling length. This analytical tool has a direct application in the design of systematic drains installed in a jointed rock foundation.

d. The methods presented in this engineer technical letter can be explicitly used to accurately determine the orientation, depth and spacing of a foundation drainage system installed in a jointed rock foundation. As described herein, analytical methods are available that can supersede the long-standing rules-of-thumb methods that have historically been used to design the spacing, depth and orientation of foundation drains.

e. Primary and secondary permeability may overlap in some rock foundations. In these circumstances, rock foundations may exhibit primary permeability that is generally similar to secondary permeability. The methods presented in this engineer technical letter do not explicitly consider the affect of primary permeability on seepage and hence, cannot be used to properly design a foundation drainage system that is significantly affected by primary permeability. Flow nets, or other analytical or numerical methods, are required to design a foundation drainage system largely influenced by primary porosity.

10-13. Lessons Learned.

a. A linear traverse results in an orientation sampling bias. The more nearly the strike of a discontinuity parallels the path of a linear traverse, the less frequently discontinuities with that strike will be detected in the traverse. The strike of Joint Set 3 was sub-parallel to the overall average trend of the five completed traverses. Hence, the orientation of the traverse lines introduced significant sampling bias in Joint Set 3. This is the likely reason that only four joints (2.4% of the total number of joints encountered) were observed for Joint Set 3 in a total of 162 linear feet of traverse sampling.

b. When possible, scanline traverses should be performed in orthogonal directions to minimize sampling bias.

c. Forty-five discontinuities were measured in three joint sets in the five traverses performed. It is generally recommended that 10 to 20 traverses are needed and 1,000 to 2,000 discontinuities be sampled to provide an adequate characterization of a site (Priest, 1993).

d. Site access and limited areas of mapping surfaces often preclude the additional sampling that is needed to characterize a site with a high degree of confidence.

e. Conclusions based upon the limited sampling data available introduce significant epistemic uncertainty into the analytical process. This uncertainty should be recognized and considered in the design of a foundation drainage system for a major hydraulic structure.

f. Sound engineering judgment is required when applying the analytical methods used to determine the orientation, inclination, depth, and spacing for drains installed in the rock foundation of a major hydraulic structure.

Table 10-1
Joint Measurements and Observations

No.	Traverse			Rock Unit	Number of Joints	Joint Spacing (ft)	Strike		Dip		Length (ft)	Ends	Thickness (ft)	Infill	Water	Roughness	Waviness	
	ID	Trend	Dist. (ft)				Quad.	Deg.	Deg.	Quad.							Length (ft)	Amp (ft)
1	A	S45W	5	SS #1	1	-	N52E	52	90	-	9.0	1	-	-	2	3	1.0	0.03
2	A	S45 W	9	SS #1	1	-	N69E	69	90	-	5.0	2	-	-	2	3	0.6	0.06
3	A	S38 W	12	SS #1	1	-	N78W	102	10	SW	9.0	0	-	-	2	3	1.0	0.10
4	A	S25W	16	SS #1	1	-	N10W	350	90	-	1.6	1	-	-	3	3	0.6	0.01
5	A	S25W	19	SS #1	1	-	N42E	42	90	-	1.5	1	-	-	3	3	0.7	0.03
6	A	S10W	22	SS #1	5	5	N45E	45	90	-	2.0	1	-	-	3	3	0.5	0.03
7	A	S10W	25	SS #1	4	0.6	N8W	352	90	-	3.0	1	-	-	3	3	1.0	0.01
8	A	S10W	28	SS #1	4	0.9	N50E	50	90	-	1.5	1	-	-	3	3	0.7	0.04
9	A	S5 W	35	SS #1	5	1.0	N47E	47	90	-	2.0	2	-	-	3	3	1.0	0.01
10	B	S20W	0	SS #2	1	1.4	N63W	297	90	-	3.0	1	-	-	2	3	0.9	0.10
11	B	S20W	5	SS #2	1	-	N50E	50	86	SE	3.0	2	-	-	4	3	1.0	0.05
12	B	S10W	16	SS #2	1	-	N70W	290	85	NE	2.5	2	-	-	3	3	0.8	0.04
13	B	S10W	16	SH #1	1	-	N81W	279	87	NE	2.5	1	-	-	3	3	1.0	0.005
14	B	S10 W	17	SS #3	1	-	N77W	283	83	NE	5.0	1	-	-	3	3	1.0	0.05
15	B	S10 W	20	SS #3	3	1.0	N36E	36	88	NW	2.0	1	5	S,A	3	3	0.9	0.06
16	B	S10 W	20	SS #3	1	-	N45E	45	90	-	3.0	0	4	S	3	2	1.0	0.002
17	B	S10W	22	SS #3	1	-	N85W	275	84	SW	7.0	2	3	S,A	5	3	0.9	0.06
18	B	S10W	25	SS #3	1	-	N50E	50	90	-	5.0	2	4	S,A	5	2	-	-
19	B	S 10W	33	SS #3	1	-	N47E	47	87	SE	2.5	2	-	-	3	3	0.9	0.02
20	B	S10W	41	SS #3	1	-	N17E	17	90	-	3.5	1	-	-	4	2	0.2	0.001
21	B	S10W	51	SS #2	1	-	N42E	42	75	NW	10.0	1	3	S,A	4	3	0.5	0.02
22	B	S10W	47	SS #2	1	-	N69W	291	87	SW	2.0	0	-	-	3	3	0.8	0.05
23	C	S10W	0	SS #2	1	-	N77W	286	84	NE	12.0	1	3	A	3	3	0.7	0.03
24	C	S10W	3	SS #2	1	-	N32E	32	90	-	7.0	1	5	A,R	3	3	1.0	0.03
25	C	S13E	6	SS #2	1	-	N24E	24	90	-	10.0	2	3	A,R	3	2	0.8	0.02
26	C	S13E	8	SS #2	1	-	N74W	286	86	NE	15.0	2	3	A	3	3	0.8	0.02
27	C	S13E	10	SS #2	1	-	N32E	32	90	-	7.0	2	3	A	4	3	0.3	0.005
28	C	S13E	18	SS #2	1	-	N30E	30	90	-	3.5	2	3	A	4	3	0.8	0.07
29	D	S27E	2	MS #1	1	-	N77W	283	90	-	5.0	1	3	A	4	3	0.5	0.02
30	D	S27E	5	MS #1	1	-	N49E	49	90	-	45.0	2	6	A	5	3	2.5	0.30
31	D	S27E	11	MS #1	1	-	N75W	285	84	NE	5.0	1	-	-	4	3	0.3	0.005
32	D	S27E	12	MS #1	1	-	N47E	47	90	-	18.0	1	5	A	4	3	0.7	0.03
33	D	S27E	15	MS #1	1	-	N76W	284	82	NE	1.5	1	2	C	3	2	0.5	0.01
34	D	S27E	19	SS #2	1	-	N36E	36	90	-	10.0	1	3	A,R	4	3	1.0	0.03
35	D	S27E	23	SS #2	1	-	N43E	43	90	-	2.0	2	-	-	4	3	0.5	0.02

Table 10-1
Joint Measurements and Observations (Continued)

36	D	S27E	26	SS #2	2	1.0	N37E	37	86	NW	43.0	2	5	A,R	5	3	0.7	0.07
37	E	S17W	4	SS #3	1	-	N00W	360	87	W	4.0	1	-	-	3	2	0.8	0.005
38	E	S17W	8	SS #3	1	-	N46E	46	90	-	10.0	1	5	A	5	3	1.0	0.01
39	E	S17W	10	SS #3	1	-	N78W	282	85	SW	5.0	1	4	A	5	3	1.0	0.04
40	E	S17W	16	SS #3	1	-	N73W	287	88	NE	6.0	1	2	A	4	3	0.5	0.03
41	E	S17W	17	SS #3	1	-	N54E	54	88	NW	5.0	1	3	A	4	3	0.3	0.01
42	E	S17W	27	SS #3	1	-	N1W	359	90	-	4.0	0	3	A	4	2	0.5	0.01
43	E	S17W	31	SS #3	1	-	N45E	45	90	-	3.0	1	-	-	3	3	2.2	0.15
44	E	S17W	35	SS #3	1	-	N73W	287	90	-	7.0	1	6	A,R	4	3	1.0	0.07
45	E	S17W	36	SS #3	1	-	N55E	55	90	-	15.0	-	5	A,R	5	3	0.5	0.015

Rock Units	Ends	Thickness	Infilling	Water	Roughness
SS #4 = Sandstone #4	0 = Both ends of joint visible	1 = 0.00"	A = Air	1 = Joint is tight; flow does not appear possible	1 = Slickensided or polished
SH #2 = Shale #2	1 = One end of joint continues out of rock face	2 = 0.00" to 0.25"	C = Clay	2 = Joint is dry; no evidence of water flow	2 = Smooth
SS #3 = Sandstone #3	2 = Both ends of joint continue out of rock face	3 = 0.25" to 1.00"	R = Rock fragments	3 = Joint is dry; evidence of water flow	3 = Defined ridges
SH #1 = Shale #1		4 = 1.00" to 2.00"	S = Sand	4 = Joint is damp; no free water present	4 = Small steps
SS #2 = Sandstone #2		5 = 2.00" to 4.00"		5 = Joint shows seepage; occasional drops of water	5 = Very rough
MS #1 = Mudstone #1		6 = >4.00"		6 = Joint shows a continuous flow of water	
SS #1 = Sandstone #1					

Table 10-2
Summary of Joint Measurements and Observations for Joint Set 1

No.	Traverse			Rock Unit	Number of Joints	Joint Spacing (ft)	Strike		Dip		Length (ft)	Ends	Thickness (ft)	Infill	Water	Roughness	Waviness	
	ID	Trend	Dist. (ft)				Quad.	Deg.	Deg.	Quad.							Length (ft)	Amp (ft)
1	A	S45W	5	SS #1	1	-	N52E	52	90	-	9.0	1	-	-	2	3	1.0	0.03
2	A	S45 W	9	SS #1	1	-	N69E	69	90	-	5.0	2	-	-	2	3	0.6	0.06
5	A	S25W	19	SS #1	1	-	N42E	42	90	-	1.5	1	-	-	3	3	0.7	0.03
6	A	S10W	22	SS #1	5	5	N45E	45	90	-	2.0	1	-	-	3	3	0.5	0.03
8	A	S10W	28	SS #1	4	0.9	N50E	50	90	-	1.5	1	-	-	3	3	0.7	0.04
9	A	S5 W	35	SS #1	5	1.0	N47E	47	90	-	2.0	2	-	-	3	3	1.0	0.01
11	B	S20W	5	SS #2	1	-	N50E	50	86	SE	3.0	2	-	-	4	3	1.0	0.05
15	B	S10 W	20	SS #3	3	1.0	N36E	36	88	NW	2.0	1	5	S,A	3	3	0.9	0.06
16	B	S10 W	20	SS #3	1	-	N45E	45	90	-	3.0	0	4	S	3	2	1.0	0.002
18	B	S10W	25	SS #3	1	-	N50E	50	90	-	5.0	2	4	S,A	5	2	-	-
19	B	S 10W	33	SS #3	1	-	N47E	47	87	SE	2.5	2	-	-	3	3	0.9	0.02
20	B	S10W	41	SS #3	1	-	N17E	17	90	-	3.5	1	-	-	4	2	0.2	0.001
21	B	S10W	51	SS #2	1	-	N42E	42	75	NW	10.0	1	3	S,A	4	3	0.5	0.02
24	C	S10W	3	SS #2	1	-	N32E	32	90	-	7.0	1	5	A,R	3	3	1.0	0.03
25	C	S13E	6	SS #2	1	-	N24E	24	90	-	10.0	2	3	A,R	3	2	0.8	0.02
27	C	S13E	10	SS #2	1	-	N32E	32	90	-	7.0	2	3	A	4	3	0.3	0.005
28	C	S13E	18	SS #2	1	-	N30E	30	90	-	3.5	2	3	A	4	3	0.8	0.07
30	D	S27E	5	MS #1	1	-	N49E	49	90	-	45.0	2	6	A	5	3	2.5	0.30
32	D	S27E	12	MS #1	1	-	N47E	47	90	-	18.0	1	5	A	4	3	0.7	0.03
34	D	S27E	19	SS #2	1	-	N36E	36	90	-	10.0	1	3	A,R	4	3	1.0	0.03
35	D	S27E	23	SS #2	1	-	N43E	43	90	-	2.0	2	-	-	4	3	0.5	0.02
36	D	S27E	26	SS #2	2	1.0	N37E	37	86	NW	43.0	2	5	A,R	5	3	0.7	0.07
38	E	S17W	8	SS #3	1	-	N46E	46	90	-	10.0	1	5	A	5	3	1.0	0.01
41	E	S17W	17	SS #3	1	-	N54E	54	88	NW	5.0	1	3	A	4	3	0.3	0.01
43	E	S17W	31	SS #3	1	-	N45E	45	90	-	3.0	1	-	-	3	3	2.2	0.15
45	E	S17W	36	SS #3	1	-	N55E	55	90	-	15.0	-	5	A,R	5	3	0.5	0.015
MINIMUM							N17E	17	75	-	1.5	0	3	-	2	2	0.2	0.001
MAXIMUM							N69E	69	90	-	45.0	2	6	-	5	3	2.5	0.300
MEAN							N43E	43	89	-	8.8	1.4	4.1	-	3.7	2.8	0.9	0.045
MEDIAN							N45E	45	90	-	5.0	1	4	-	4	3	0.8	0.030

Table 10-3
Summary of Joint Measurements and Observations for Joint Set 2

No.	Traverse			Rock Unit	Number of Joints	Joint Spacing (ft)	Strike		Dip		Length (ft)	Ends	Thickness (ft)	Infill	Water	Roughness	Waviness	
	ID	Trend	Dist. (ft)				Quad.	Deg.	Deg.	Quad.							Length (ft)	Amp (ft)
10	B	S20W	0	SS #2	1	1.4	N63W	297	90	-	3.0	1	-	-	2	3	0.9	0.10
12	B	S10W	16	SS #2	1	-	N70W	290	85	NE	2.5	2	-	-	3	3	0.8	0.04
13	B	S10W	16	SH #1	1	-	N81W	279	87	NE	2.5	1	-	-	3	3	1.0	0.005
14	B	S10 W	17	SS #3	1	-	N77W	283	83	NE	5.0	1	-	-	3	3	1.0	0.05
17	B	S10W	22	SS #3	1	-	N85W	275	84	SW	7.0	2	3	S,A	5	3	0.9	0.06
22	B	S10W	47	SS #2	1	-	N69W	291	87	SW	2.0	0	-	-	3	3	0.8	0.05
23	C	S10W	0	SS #2	1	-	N77W	286	84	NE	12.0	1	3	A	3	3	0.7	0.03
26	C	S13E	8	SS #2	1	-	N74W	286	86	NE	15.0	2	3	A	3	3	0.8	0.02
29	D	S27E	2	MS #1	1	-	N77W	283	90	-	5.0	1	3	A	4	3	0.5	0.02
31	D	S27E	11	MS #1	1	-	N75W	285	84	NE	5.0	1	-	-	4	3	0.3	0.005
33	D	S27E	15	MS #1	1	-	N76W	284	82	NE	1.5	1	2	C	3	2	0.5	0.01
39	E	S17W	10	SS #3	1	-	N78W	282	85	SW	5.0	1	4	A	5	3	1.0	0.04
40	E	S17W	16	SS #3	1	-	N73W	287	88	NE	6.0	1	2	A	4	3	0.5	0.03
44	E	S17W	35	SS #3	1	-	N73W	287	90	-	7.0	1	6	A,R	4	3	1.0	0.07
MINIMUM							N85W	275	82	-	1.5	0	2	-	2	2	0.3	0.005
MAXIMUM							N63W	297	90	-	15	2	6	-	5	3	1.0	0.100
MEAN							N75W	285	86	-	5.6	1.1	3.3	-	3.5	2.9	0.8	0.040
MEDIAN							N74W	286	86	-	5	1	3	-	3	3	0.8	0.040

Table 10-4
Summary of Joint Measurements and Observations for Joint Set 3

No.	Traverse			Rock Unit	Number of Joints	Joint Spacing (ft)	Strike		Dip		Length (ft)	Ends	Thickness (ft)	Infill	Water	Roughness	Waviness	
	ID	Trend	Dist. (ft)				Quad.	Deg.	Deg.	Quad.							Length (ft)	Amp (ft)
4	A	S25W	16	SS #1	1	-	N10W	350	90	-	1.6	1	-	-	3	3	0.6	0.01
7	A	S10W	25	SS #1	4	0.6	N08W	352	90	-	3.0	1	-	-	3	3	1.0	0.01
37	E	S17W	4	SS #3	1	-	N00W	360	87	W	4.0	1	-	-	3	2	0.8	0.005
42	E	S17W	27	SS #3	1	-	N01W	359	90	-	4.0	0	3	A	4	2	0.5	0.01
						MINIMUM	N10W	350	87	-	1.6	0	3	-	3	2	0.5	0.005
						MAXIMUM	N00W	360	90	-	4	1	3	-	4	3	1.0	0.010
						MEAN	N05W	355	89	-	3.2	0.8	3.0	-	3.3	2.5	0.7	0.010
						MEDIAN	N04W	356	90	-	4	1	3	-	3	3	0.7	0.010

Table 10-5
Orientation and Coordinates of the Joint Sets 1, 2, and 3

Joint Set	Plane Compass				Polar Compass		Polar Spherical Coordinates	
	Strike	Azimuth	Dip	Dip Dir	Trend	Plunge	Θ	Φ
1	N43E	43	89	NW	133	-1	317	89
2	N75W	285	88	NE	195	-2	255	88
3	N5W	355	89	SW	85	-1	5	89

Table 10-6
Calculated Average True Joint Spacing

Joint Set	Plane		Pole				Traverse						Average Measured Apparent Spacing (ft)	Calculated Average True Spacing (ft)	Weighted Calculated Average True Spacing (ft)
	Compass Coordinates		Compass Coordinates		Spherical Coordinates		ID	Length (ft)	Compass Coordinates		Spherical Coordinates				
	Strike	Dip	Trend	Plunge					Trend	Plunge					
1	N43E	89NW	133	-1	317	89	A	30	202.5	0	247.5	90	6.0	2.1	3.7
	N43E	89NW	133	-1	317	89	B	46	192.0	0	258.0	90	7.7	4.0	
	N43E	89NW	133	-1	317	89	C	15	170.1	0	279.9	90	5.0	4.0	
	N43E	89NW	133	-1	317	89	D	21	153.0	0	297.0	90	5.3	4.9	
	N43E	89NW	133	-1	317	89	E	28	197.0	0	253.0	90	9.3	4.1	
2	N75W	88NE	195	-2	255	88	B	47	193.0	0	257.0	90	9.4	9.4	5.5
	N75W	88NE	195	-2	255	88	C	8	181.4	0	268.6	90	8.0	7.8	
	N75W	88NE	195	-1	255	89	D	13	153.0	0	297.0	90	6.5	4.8	
	N75W	88NE	195	-2	255	88	E	19	197.0	0	253.0	90	12.5	12.5	
3	N5W	89SW	85	-1	5	89	A	9	190.0	0	260.0	90	9.0	2.3	6.8
	N5W	89SW	85	-1	5	89	E	23	197.0	0	253.0	90	23.0	8.6	

Table 10-7
Summary of Joint Set frequencies and Joint Set spacings using the Discontinuity Frequency Extrema Method

Azimuth (degrees)	Inclination (degrees)	JS1 Frequency (1/ft)	JS2 Frequency (1/ft)	JS3 Frequency (1/ft)	Cumulative Joint Frequency (1/ft)	JS1 Spacing (ft)	JS2 Spacing (ft)	JS3 Spacing (ft)	Cumulative Joint Spacing (ft)
00	45	0.1337	0.1286	0.0072	0.26949	7.48	7.78	137.99	3.71
10	45	0.1074	0.1325	0.0251	0.26498	9.31	7.55	39.85	3.77
20	45	0.0780	0.1325	0.0421	0.25261	12.82	7.55	23.74	3.96
30	45	0.0463	0.1286	0.0578	0.23273	21.59	7.78	17.29	4.30
40	45	0.0133	0.1209	0.0717	0.20597	74.99	8.27	13.95	4.85
50	45	0.0200	0.1097	0.0834	0.21304	50.12	9.11	12.00	4.69
60	45	0.0525	0.0953	0.0924	0.24029	19.04	10.49	10.82	4.16
70	45	0.0834	0.0782	0.0986	0.26021	11.99	12.79	10.14	3.84
80	45	0.1117	0.0588	0.1018	0.27221	8.96	17.01	9.83	3.67
90	45	0.1364	0.0377	0.1018	0.27591	7.33	26.50	9.83	3.62
100	45	0.1569	0.0157	0.0986	0.27122	6.37	63.75	10.14	3.69
110	45	0.1726	0.0067	0.0924	0.27168	5.80	149.00	10.82	3.68
120	45	0.1828	0.0288	0.0834	0.29497	5.47	34.76	12.00	3.39
130	45	0.1875	0.0498	0.0717	0.30900	5.33	20.07	13.95	3.24
139	**45**	**0.1867**	**0.0674**	**0.0593**	**0.31336**	**5.36**	**14.85**	**16.86**	**3.19**
140	45	0.1863	0.0692	0.0578	0.31335	5.37	14.45	17.29	3.19
150	45	0.1794	0.0864	0.0421	0.30789	5.57	11.58	23.74	3.25
160	45	0.1669	0.1008	0.0251	0.29278	5.99	9.92	39.85	3.42
170	45	0.1493	0.1120	0.0072	0.26848	6.70	8.93	137.99	3.72
180	45	0.1270	0.1196	0.0109	0.25748	7.88	8.36	91.94	3.88
190	45	0.1007	0.1235	0.0287	0.25297	9.93	8.10	34.81	3.95
200	45	0.0713	0.1235	0.0458	0.24059	14.02	8.10	21.86	4.16
210	45	0.0396	0.1196	0.0614	0.22072	25.22	8.36	16.27	4.53
220	45	0.0067	0.1120	0.0753	0.19396	150.04	8.93	13.27	5.16
230	45	0.0266	0.1008	0.0870	0.21437	37.56	9.92	11.50	4.66
240	45	0.0592	0.0864	0.0960	0.24161	16.89	11.58	10.41	4.14
250	45	0.0901	0.0692	0.1022	0.26154	11.10	14.45	9.78	3.82
260	45	0.1183	0.0498	0.1054	0.27353	8.45	20.07	9.49	3.66
270	45	0.1431	0.0288	0.1054	0.27724	6.99	34.76	9.49	3.61
280	45	0.1636	0.0067	0.1022	0.27254	6.11	149.00	9.78	3.67
290	45	0.1792	0.0157	0.0960	0.29096	5.58	63.75	10.41	3.44
300	45	0.1895	0.0377	0.0870	0.31424	5.28	26.50	11.50	3.18
310	45	0.1942	0.0588	0.0753	0.32827	5.15	17.01	13.27	3.05
320	**45**	**0.1930**	**0.0782**	**0.0614**	**0.33263**	**5.18**	**12.79**	**16.27**	**3.01**
330	45	0.1861	0.0953	0.0458	0.32716	5.37	10.49	21.86	3.06
340	45	0.1736	0.1097	0.0287	0.31205	5.76	9.11	34.81	3.20
350	45	0.1559	0.1209	0.0109	0.28775	6.41	8.27	91.94	3.48
360	45	0.1337	0.1286	0.0072	0.26949	7.48	7.78	137.99	3.71

Table 10-8
Drain Depth versus Number of Joints Encountered for each Joint Set and Cumulative Total Number of Joints

Drain Depth (ft)	Joint Frequency (joints/ft)				Vertical Depth (ft)	Horizontal Distance (ft)
	JS1 (0.1867)	JS2 (0.0674)	JS3 (0.0593)	Cum. Total (0.3134)		
5	0	0	0	1	3.5	3.3
10	1	0	0	3	7.1	6.6
15	2	1	0	4	10.6	9.8
20	3	1	1	6	14.1	13.1
25	4	1	1	7	17.7	16.4
30	5	2	1	9	21.2	19.7
35	6	2	2	10	24.7	22.9
40	7	2	2	12	28.3	26.2
45	8	3	2	14	31.8	29.5
50	9	3	2	15	35.4	32.8
55	10	3	3	17	38.9	36.1
60	11	4	3	18	42.4	39.3
65	12	4	3	20	46.0	42.6
70	13	4	4	21	49.5	45.9
75	14	5	4	23	53.0	49.2
80	14	5	4	25	56.6	52.4
85	15	5	5	26	60.1	55.7
90	16	6	5	28	63.6	59.0
95	17	6	5	29	67.2	62.3
100	18	6	5	31	70.7	65.6
110	20	7	6	34	77.8	72.1
120	22	8	7	37	84.9	78.7
130	24	8	7	40	91.9	85.2
140	26	9	8	43	99.0	91.8
150	28	10	8	47	106.1	98.3
160	29	10	9	50	113.1	104.9
170	31	11	10	53	120.2	111.5
180	33	12	10	56	127.3	118.0
190	35	12	11	59	134.4	124.6
200	37	13	11	62	141.4	131.1

Figure 10-1. Rock exposure on east side of gorge

Figure 10-2. Rock exposure on east side of gorge, larger view

Figure 10-3. Traverse A beginning point is at the left end of the measuring tape, which extends 38.5 feet

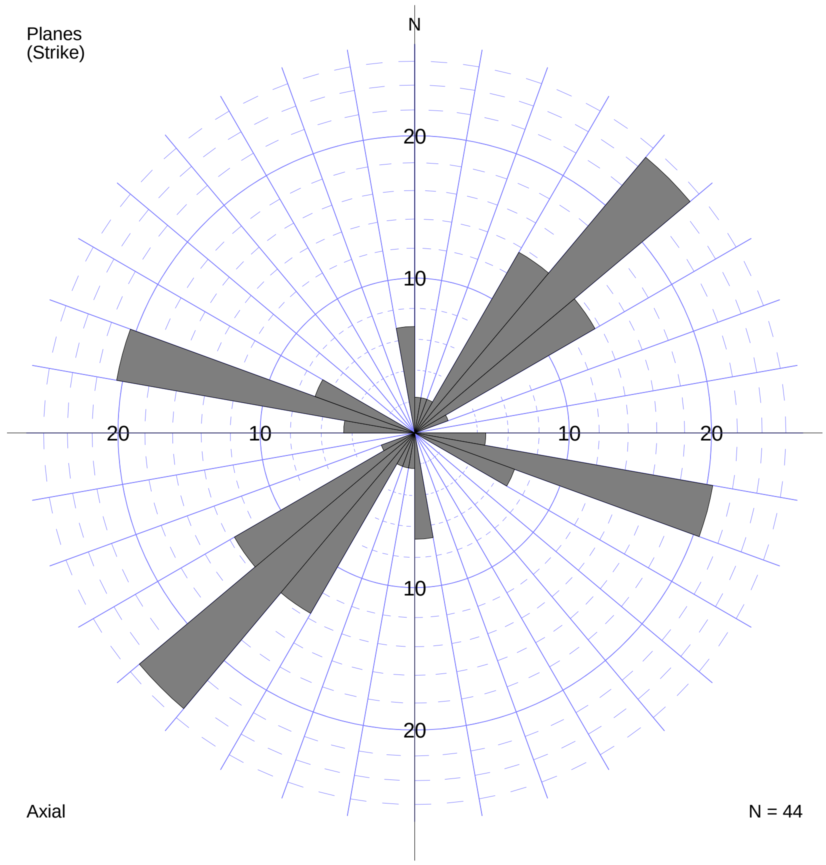

Figure 10-4. Rose diagram of strikes of 44 measured vertical to sub-vertical joints

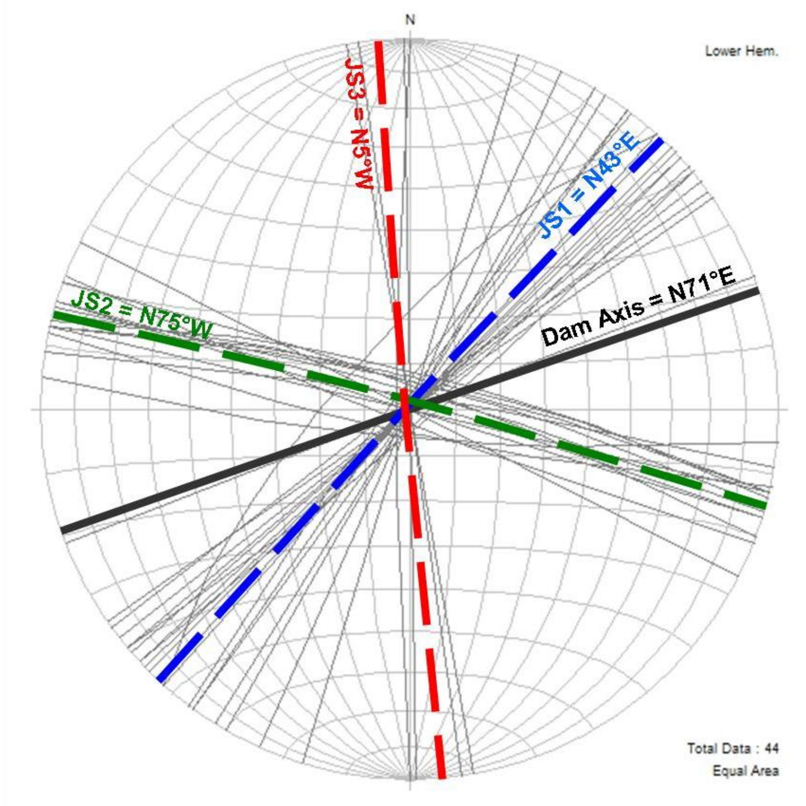

Figure 10-5. Stereograph of great circles corresponding to 44 vertical to sub-vertical joint surfaces

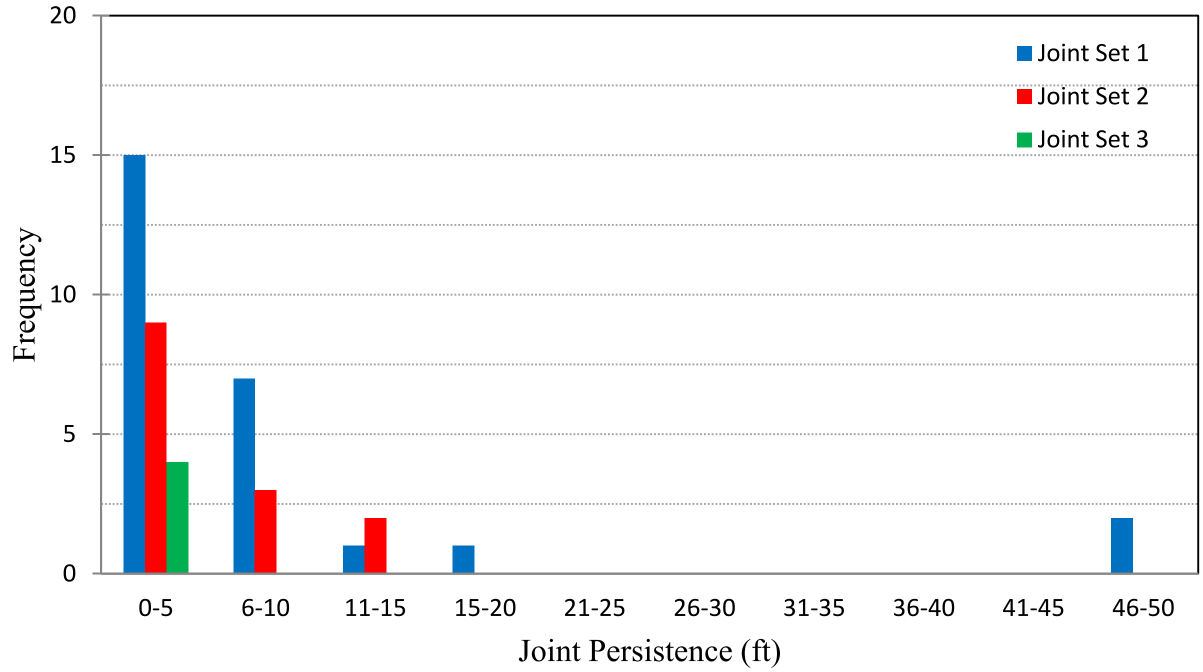

Figure 10-6. Histogram of joint persistence (ft) and frequency

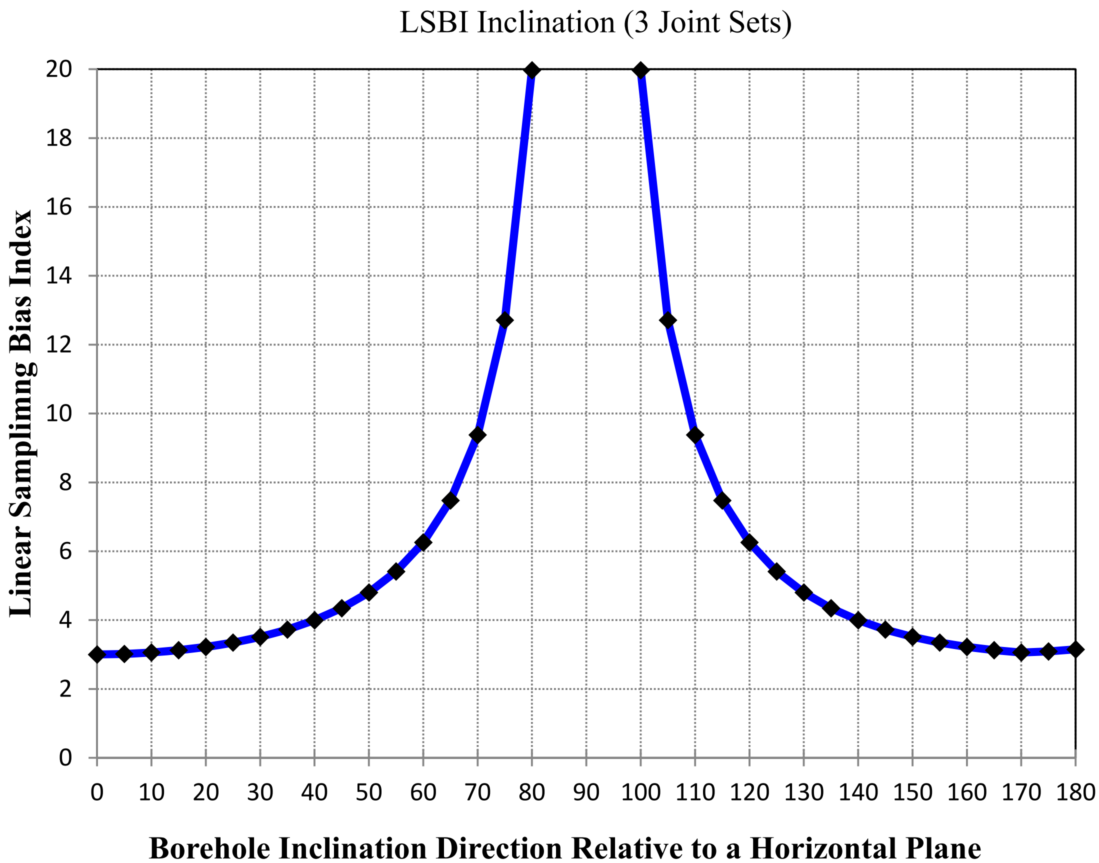

Figure 10-7. Linear Sampling Bias Index (LSBI) results for the three joint sets, indicating drain inclination

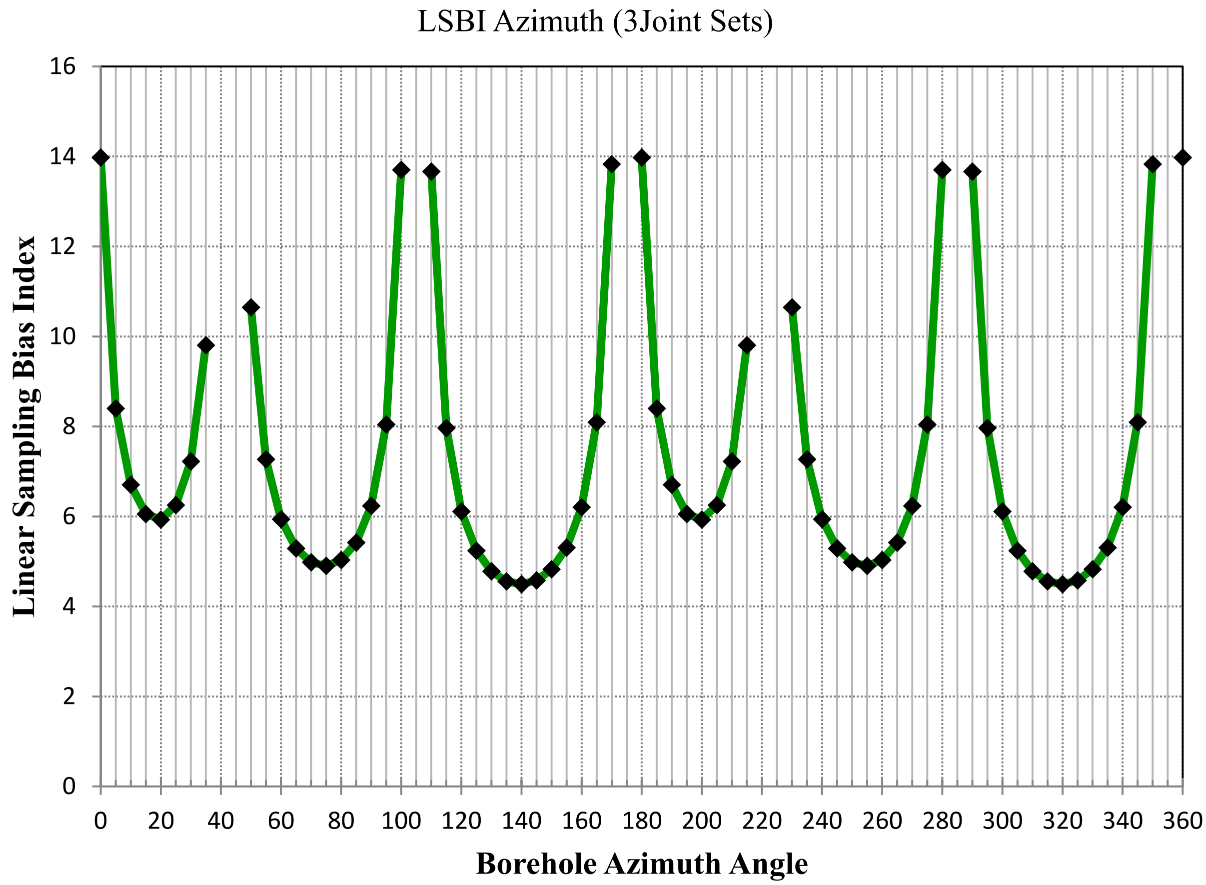

Figure 10-8. Linear Sampling Bias Index (LSBI) results for the three joint sets, indicating drain azimuth

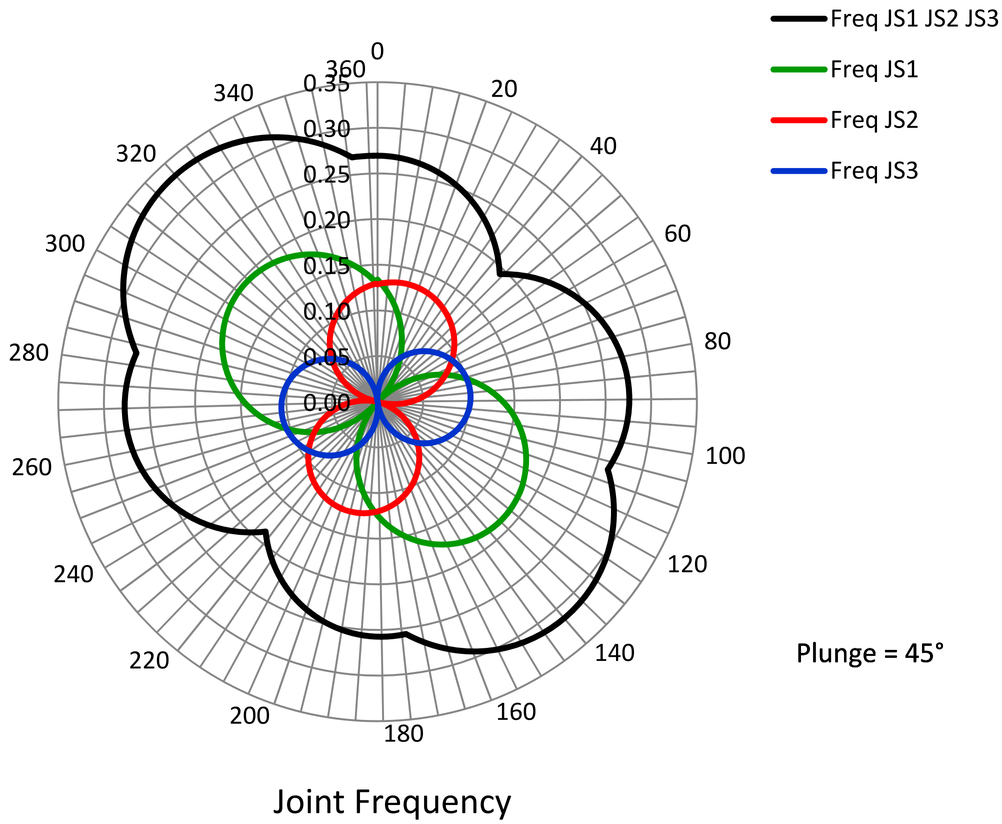

Figure 10-9. Polar plot of joint set frequencies using the Discontinuity Frequency Extrema Method, indicating drain azimuth

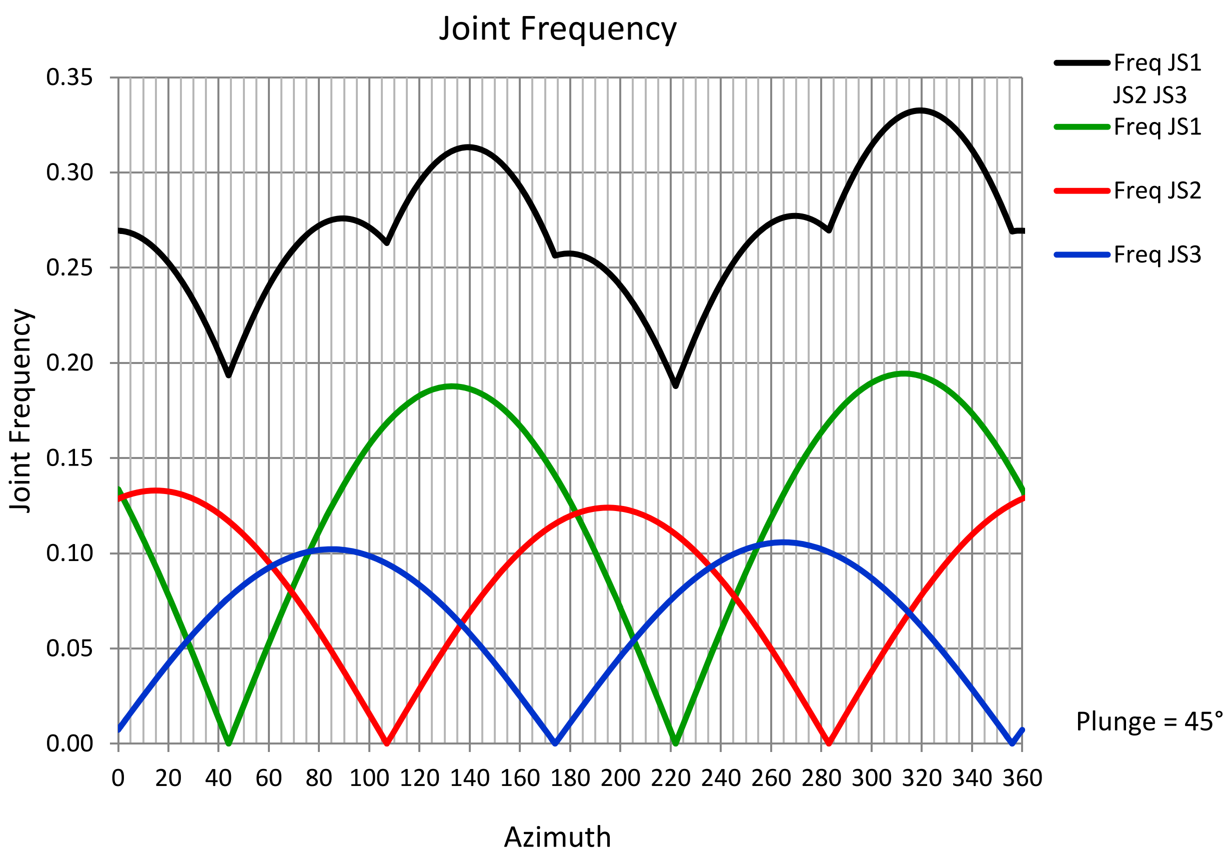

Figure 10-10. X-Y scatter plot of joint set frequencies using the Discontinuity Frequency Extrema Method, indicating drain azimuth

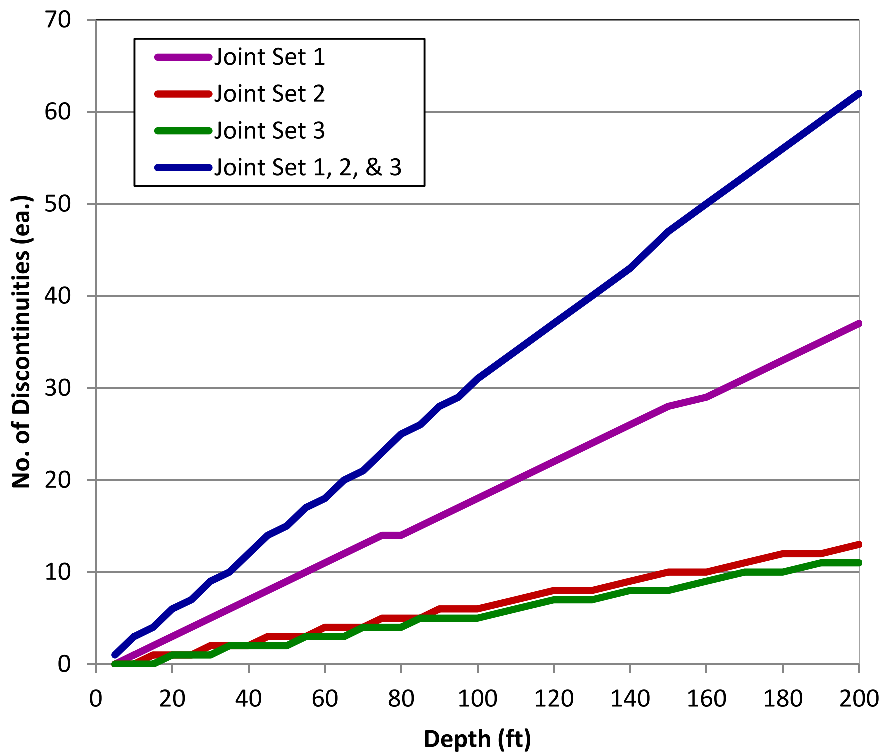

Figure 10-11. Drain depth versus number of joints encountered for each joint set and cumulative total number of joints

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CHAPTER 11

Summary and Conclusions

11-1. All rock masses contain discontinuities. Discontinuities generally occur as sets, with each set consisting of regular joints sub-parallel to each other. In each set, discontinuities usually have the same general orientation and exhibit relatively common physical characteristics. Several sets of discontinuities often developed in a rock mass, three to four sets being typical with one or more joint set being statistically dominant.

11-2. Discontinuities typically exhibit preferred orientations. Discontinuity orientation data can be systematically collected, analyzed, and evaluated. Numerous methods, such as scanline traverse surveys, can be used to methodically collect critical discontinuity data to characterize the discontinuity structure within a rock mass. Properly conducted scanline surveys can provide crucial data on both the orientation and the physical condition of the discontinuities existing within the rock mass with a reasonable probability of accurately. These data can provide *a priori* knowledge of the discontinuity structure within a rock foundation or rock slope.

11-3. Given *a priori* knowledge of the discontinuity structure of a rock foundation, the methods presented in this engineer technical letter may be used for numerous geotechnical, hydrogeological, environmental and rock engineering applications, including foundation drains; geotechnical site investigation and sampling; permeation grouting; permeation verification holes; pressure (packer) tests; rock slope design; and in the installation and placement of geotechnical instrumentation and groundwater monitoring or recovery wells.

11-4. Uplift is one of the primary loads that affect the stability of a hydraulic concrete structure founded on bedrock. The effectiveness of the foundations drains in intercepting seepage, and hence reducing pore pressures within a foundation rock, is a direct function of how successful the drains are in intersecting the preferential seepage occurring along the existing discontinuities within the rock mass. The analytical methods presented in this engineer technical letter can be used to rationally determine the optimal orientation, depth and spacing of rock foundation drains. Drains installed at the optimal orientation, depth and spacing would more effectively and efficiently diminish the internal pore pressure in a rock foundation beneath a major hydraulic structure.

11-5. Despite a rigorously executed site investigation program, considerable geologic uncertainties may still exist. Any site investigation program must be thoroughly evaluated for sampling bias and other deficiencies. Site investigation deficiencies and inadequacies must be considered by the design team when finalizing any geotechnical design.

11-6. Conclusions based upon limited sampling data may introduce significant epistemic uncertainty into the geotechnical design process. This uncertainty should be fully recognized and considered when applying the analytical methods described in herein. Sound engineering principles and judgment is required when applying the methods described in this engineer technical letter.

APPENDIX A

References

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Standard Guide to Site Characterization for Engineering, Design, and Construction Purposes

ASTM D653-09
Standard Terminology Relating to Soil, Rock, and Contained Fluids

ASTM D1452-80
Standard Practice for Soil Investigation and sampling by Auger Borings

ASTM D2113-08
Standard Practice for Rock Core Drilling and Sampling of Rock for Site Investigation

ASTM D4879-08
Standard Guide for Geotechnical Mapping of Large Underground Openings in Rock

ASTM D5875-96
Standard Guide for Use of Cable-Tool Drilling and Sampling Methods for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices

ASTM D5878-08
Standard Guides for Using Rock-Mass Classification Systems for Engineering Purposes

ASTM D6026-06
Standard Practice for Using Significant Digits in Geotechnical Data

ASTM D6032-08
Standard Test Method for Determining Rock Quality Designation (RQD) of Rock Core

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APPENDIX B

Conduction Scanline Surveys

B-1. Scanline Survey Procedures (Geotechnical Procedures Manual, 2007).

a. Review available information:

(1) Obtain and familiarize yourself with the plan sheets, cross sections and other available information before going into the field.

(2) Obtain and review geological reports and maps, air photos, previous geotechnical reports, etc., before going to the field.

(3) Identify potential problem areas such as high cuts, retaining wall sites, thick overburden, poor quality rock, fault zones, etc.

(4) Consider impact to nearby structures and topography inside and outside the right-of-way.

(5) At a minimum, take plan sheets and cross sections to the field.

(6) If possible, take topographic maps, proposed cut and fill slope limits, geologic maps, soil maps, etc.

b. Prepare Rock Mapping Plan. Below is an idealized plan for conducting scanline mapping. Some projects will undoubtedly require modification to this generalized plan and modifications must be tailored to the site and project.

(1) The first step is to identify the area of interest in a project. Conduct such office reconnaissance as is possible to identify the scope of work necessary to obtain geotechnical data needed for design. Obtain and examine air photos, geologic maps, hazard maps, project drawings, geologic survey reports, previous Department reports, etc.

(2) If necessary and feasible, conduct a brief field reconnaissance to establish the methods of mapping and fieldwork.

(3) Select a mapping technique suitable for the project and the field conditions. This decision may be made in the field.

(4) Begin field exploration. Examine the exposures starting with gross features and the “big picture” and work toward more detailed looks at smaller areas.

(5) Identify and mark, if necessary, the area or areas for mapping.

(6) Locate the area(s) in relation to geographic reference points, whether stationing, temporary reference stations or GPS coordinates.

(7) Establish a baseline for locating measurements within the mapping box. Describe the orientation of the baseline and its relationship with prominent features, with centerline and the trend of the cut or with the planned structure footprint, if available. Make sure the "north" used for field mapping is the same "north" used in developing project plans. Set compasses at "0" declination for field mapping and normalize the data to the proper declination as a step in the office analysis procedure (Note: This may complicate the preparation of field stereonets).

(8) At the appropriate level of effort, measure the orientation of discontinuities and their location with respect to the baseline.

(9) Describe the discontinuities and the rock mass using the ISRM guidelines to describe the various characteristics.

(10) Photograph the rock cut or exposure from a distance, if possible, and in as many close-ups or intermediate shots as necessary to record the necessary details. A digital camera with a preview screen is an invaluable tool for this purpose. Make detailed field sketches.

c. Conduct Mapping According to Plan.

(1) Record general views and details of the rock exposure for the existing exposure and the proposed cut. For photographs, use an appropriate scale in the photo, such as a stake or lathe painted contrasting colors at one-foot increments. The photos and sketch of the exposure will be a valuable aid for refreshing your memory during the analysis phase, after completion of the field work.

(2) Starting from the regional level and working toward more localized detail, summarize the geologic setting of the exposure in the context of regional and local geology and topography.

(3) Locate the exposure with respect to the project stationing or survey grid.

(4) Measure and record the shape of the existing cut or exposure. At a minimum, record length of exposure or cut, height at several locations, and existing slope angle.

(5) Observe and record details about existing rockfall, surface drainage, springs in rock exposures, effectiveness of existing ditch, apparent extent of weathering of exposed rock surfaces, existing slope angles, blast damage from original construction, evidence of previous blasting methods, presence of nearby facilities, structures, streams, or other features that might be affected by construction.

(6) Describe zones of similar conditions in the rock exposure by rock type and other obvious characteristics.

(7) Observe and record major discontinuity sets.

(8) Identify windows or scan lines for detailed mapping.

(9) Using the ISRM-based mapping forms, characterize the rock, identify, measure, and describe the discontinuities.

(10) Conduct detailed supplemental mapping in localized areas.

d. Field Book/Mapping Form Entries.

(1) For each data collection point enter the following information:

(a) Station or location.

(b) Distance right or left of proposed or existing centerline.

(c) Distance to top of cut.

(d) Distance to toe of cut.

(e) Distance to bottom of ditch (may be same as toe of cut).

(f) Distance to edge of ditch (top of foreslope).

(g) Distance to edge of existing or proposed pavement.

(h) Azimuth of tape or line.

(i) Azimuth of road moving along the tape or line (may need several).

(j) Discontinuity orientations.

(k) Discontinuity characteristics.

e. Forms. Example forms are shown as Figures B-1 through B-7. There form have been adapted from several sources and are generally based on the ISRM procedures (ISRM, 1978). These example forms provide a useful means of recording the mapping data outlined as follows. The Rock Mass Description Data Sheet describes the rock in terms of its color, grain size and strength. These forms provides for description of the rock mass in terms of its block shape and size, the state of weathering, and the number and spacing of discontinuity sets. The Rock Discontinuity Data Sheet is a form for describing the characteristics of discontinuities: type, orientation, persistence, aperture and width, fillings, surface roughness, and water conditions. References for each example form have been provided in each figure title.

f. Stereographic Projections. Stereographic projections, such as stereonets, pole plots and contour plots, pole density plots, and rose diagrams are invaluable methods for visualizing linear and planar geological features in 2-D and for performing manipulation and geometrical analysis of 3-D geologic features. Information on constructing and using stereographic projection techniques can be found in Lisle and Leyshon (2004) and Phillips (1983).

State of Alaska DOT & PF
Design & Engineering Services
Statewide Materials

ROCK MASS DESCRIPTION DATA SHEET

Project Name: ______________________

Project No: ______________________

Date: ______________

Field Party: ______________

Weather: ______________

GENERAL INFORMATION

Location [ ] Station/Hole No. [ ]

Locality Type [ ] Slope Length [ ] No. of Sheets of Discontinuity Data [ ]

1. Natural Exposure
2. Construction Excavation
3. Trial Pit
4. Trench
5. Adit
6. Tunnel
7. Drill Hole

Slope Height [ ] Sketch [ ]

Core Size [ ] Photograph [ ]

REMARKS (exposure type/age, stability condition, design issues etc.)

ROCK MATERIAL INFORMATION

Color [ ] [ ] [ ]

1. Light
2. Dark

1. Pinkish
2. Reddish
3. Yellowish
4. Brownish
5. Olive
6. Greenish
7. Bluish
8. Greyish

1. Pink
2. Red
3. Yellow
4. Brown
5. Olive
6. Green
7. Blue
8. White
9. Grey
10. Black

Grain Size [ ]

1. Very coarse - boulders (>12 in)
2. Coarse - cobbles (3-12 in)
3. Medium - gravel (0.2-3 in)
4. Fine - sand (0.003-0.2 in)
5. Very fine - silt/clay (<0.003 in)

Compressive Strength [ ]

	PSI	
S1 Very soft clay	<4	
S2 Soft clay	4-7	
S3 Firm clay	7-15	
S4 Stiff clay	15-35	
S5 Very stiff clay	35-70	
S6 Hard clay	>70	
R0 Extremely weak rock	35-150	
R1 Very weak rock	150-725	(Moldable by fingers, but retains fabric)
R2 Weak rock	725-3,500	(Hammer craters surface, sides pushed up)
R3 Medium strong rock	3,500-7,000	(Hammer creates smooth dent)
R4 Strong rock	7,000-15,000	(Hammer creates rough pit)
R5 Very strong rock	15,000-36,000	(Hammer rebounds)
R6 Extremely strong rock	>36,000	

Method to Determine Compressive Strength [ ]

1. Measured
2. Assessed

Rock Type [ ]

Qualifying terms to describe rock:

ROCK MASS INFORMATION

Fabric [ ]

1. Blocky
2. Tabular
3. Columnar
4. Shattered

Block Size [ ]

1. Very large (>216ft^3 or 6ft cube)
2. Large (8-216ft^3 or 2-6ft cube)
3. Medium (0.3-7ft^3 or 0.67-2ft cube)
4. Small (12in^3-0.3ft^3 or 2.3in to 0.67ft cube)
5. Very small (<12 in^3 or 2.3in cube)

State of Weathering [ ]

1. Fresh
2. Slight
3. Moderate
4. High
5. Complete
6. Residual Soil

Failure Mode e.g. Toppling, Wedges [ ]

No. of Major Discontinuity Sets [ ]

LINE SURVEYS TO DETERMINE DISCONTINUITY SPACING (OR DRILL HOLE ORIENTATION)

	Plunge of line / hole	Trend of line / hole	Length of line (m)	No. of Fractures	Spacing	Remarks / True Spacing
Line 1						
Line 2						
Line 3						

Discontinuity spacing

1. Extremely close (<1 in)
2. Very close (1-2.5 in)
3. Close (2.5 - 8 in)
4. Moderate (8 in - 2 ft)
5. Wide (2-6 ft)
6. Very wide (6-20 ft)
7. Extremely wide (>20 ft)

Appendix A. Forms
Effective October 1, 2003

A-2

Field Rock Classification
and Structural Mapping Guide

Figure B-1. Rock mass description data sheet (Geotechnical Procedures Manual, 2007)

State of Alaska DOT & PF
Design & Engineering Services
Statewide Materials

DISCONTINUITY SURVEY DATA SHEET

Project Name: ____________________ Date: ____________________
Project No: ____________________ Field Party: ____________________
Weather: ____________________

GENERAL INFORMATION

Location: [ ] Station/Hole No.: [ ] Disontinuity Data Sheet No.: [ ] of [ ]

NATURE AND ORIENTATION OF DISCONTINUITY

Station or Depth	Type	Dip	Dip Direction	Persistence	Termination	Aperture/ Width	Nature of Filling	Strength of Filling	Surface Roughness	Surface Shape	Waviness Wavelength	Waviness Amplitude	JRC	Water Flow	Remarks

TYPE
0. Fault Zone
1. Fault
2. Joint
3. Cleavage
4. Schistosity
5. Shear
6. Fissure
7. Tension Crack
8. Foliation
9. Bedding

PERSISTENCE
1. Very Low (<3 ft)
2. Low (3-10 ft)
3. Medium (10-30 ft)
4. High (30-60 ft)
5. Very High (>60 ft)

APERTURE/WIDTH
1. Very tight (<.004 in)
2. Tight (.004-.01 in)
3. Partly Open (.01-.02 in)
4. Open (.02-.1 in)
5. Moderately Wide (.1-.4 in)
6. Wide (>.4in)
7. Very wide (.4 - 4 in)
8. Extremely wide (4 in - 3 ft)
9. Cavernous (> 3 ft)

NATURE OF FILLING
1. Clean
2. Surface staining
3. Non-cohesive
4. Inactive clay or clay matrix
5. Swelling clay or clay matrix
6. Cemented
7. Chlorite, talc or gypsum
8. Other - specify

COMPRESSIVE STRENGTH OF INFILLING

	PSI
S1 Very soft clay	<4
S2 Soft clay	4-7
S3 Firm clay	7-15
S4 Stiff clay	15-35
S5 Very stiff clay	35-70
S6 Hard clay	>70
R0 Extremely weak rock	35-150
R1 Very weak rock	150-725
R2 Weak rock	725-3,500
R3 Medium strong rock	3,500-7,000
R4 Strong rock	7,000-15,000
R5 Very strong rock	15,000-36,000
R6 Extremely strong rock	>36,000

WATER FLOW (Open)
0. Discontinuity very tight and dry, water flow doesn't appear possible
1. Discontinuity dry, no evidence of water flow
2. Discontinuity dry, shows evidence of water flow e.g. rust staining
3. Discontinutiy is damp, but no free water present
4. Discontinuity shows seepage, occasional drops of water, no continuous flow.
5. Continuous flow of water (Estimate l/min and describe pressure i.e. low medium high)

WATER FLOW (Filled)
6. Filling materials heavily consolidated and dry; significant flow unlikely due to very low permeability
7. Filling materials damp, no free water present
8. Filling material wet, occasional drops of water
9. Filling materials show signs of outwash, continuous flow of water (Estimate l/min)
10. Filling materials locally washed out; considerable water flow along outwash channels (Estimate l/min and describe pressure)

TERMINATION
0. Neither end visible
1. One end visible
2. Both ends visible

SURFACE ROUGHNESS
1. Slickenslided
2. Smooth
3. Rough

SURFACE SHAPE
1. Planar
2. Undulating
3. Stepped

JRC (Joint Roughness)
0 Slickenslided, planar
5
10 Smooth, undulating
15
20 Rough, stepped

Field Rock Classification
And Structural Mapping Guide **A-3** **Appendix A. Forms**
Effective October 1, 2003

Figure B-2. Rock mass description data sheet (Geotechnical Procedures Manual, 2007)

g. Other forms and methods are available to conduct a scanline survey. Several example input data sheets are provided for information.

Area Survey of Discontinuity Attributes

Instructions for classifying discontinuity attributes by an area survey:

1. Assign each discontinuity an ID number and record on the summary data sheet; show its location on geologic evaluation map or sketch.
2. Select appropriate code numbers from tables 11 through 15 and record on data sheet.
3. Classify infilling using ASTM D 2488 (USCS); record soil classification symbols on data sheet.
4. Determine strength of infilling using tables 5 or 6; record on data sheet.

Table 11 Joint set spacing categories

Bedding plane partings	Joint sets	Spacing (meters)	Category
Massive/ unstratified	Extremely wide	> 6.000	1
Very thick-bedded	Very wide	2.000 - 6.000	2
Thick-bedded	Wide	0.600 - 2.000	3
Medium bedded	Mod. wide	0.200 - 0.600	4
Thin-bedded	Mod. close	0.060 - 0.200	5
Very thin-bedded	Close	0.020 - 0.060	6
Laminated	Very close	0.006 - 0.020	7
Thinly laminated	Shattered	0.002 - 0.006	8
Fissile	Fissured	< 0.002	9

Table 12 Discontinuity types

Discontinuity type	Code
Stratigraphic	
lithosome (sharp contact)	1
unconformity	2
Structural	
Plastic deformation	
Foliation	
— schistosity	3
— gneissosity	4
Banded rock	5
Folded rock	6
Fracture deformation	
Random fracture	7
Systematic joint set	8
Bedding plane parting	9
Sheeting joint	10
Slaty cleavage	11
Fault	12
Other	13

Table 13 Joint persistence categories

Joint persistence category	Trace length (meters)	Code
Very low	< 1	1
Low	1 - 3	2
Medium	3 - 10	3
High	10 - 20	4
Very high	> 20	5

Table 14 Aperture categories

Aperture category	Range (mm)	Code
Wide	> 200	1
Moderately wide	60 - 200	2
Moderately narrow	20 - 60	3
Narrow	6 - 20	4
Very Narrow	2 - 6	5
Extremely narrow (hairline)	< 2	6

Table 15 Weathering condition categories for joint face material (to support table 10)

Category	Weathering condition of joint face material	Code
Fresh	No sign of weathering.	1
Discolored	Iron-stained or discolored, but otherwise unweathered.	2
Disintegrated	Physically disintegrated to a soil condition with original fabric still intact. Material is friable and mineral grains are not decomposed.	3
Decomposed	Chemically altered to a soil condition with original fabric still intact. Some or all mineral grains are decomposed.	4

Figure B-3. Area survey of discontinuity attributes (Part 628 Dams, 1997)

Summary Data Sheet

Table #	12	Discontinuity measurements				13	14	15	D 2488	5, 6
Discon. ID #	Discon. type code	Trend (azim)	Dip (°)	Dip direction (azim)	Joint persis. (m)	Joint persis. code	Apert. categ. code	Joint weath. code	Infill. class (USCS)	Infill. strength (MPa)

Spillway Profile

1. In the space below sketch the spillway profile.
2. Label materials by ID (as given on page 1).
3. Show elevations of tops of materials, ground surface at major slope breaks, and flood plain.

Figure B-4. Summary data sheet (Part 628 Dams, 1997)

Project: ____________________ **DISCONTINUITY LOG** Sheet ___ of ___

Date: __________

Feature: ____________________ Location: ______________________ Recorded by: ___________

Traverse Id.	Northing (start)	Easting (start)	Elevation (start)	Trend	Plunge	Traverse Length	Tl. No. Obs.	Recording Method: Strike Azimuth and Dip Magnitude * / Dip Azimuth and Dip Magnitude / Feet / Meters

Number	Distance	Rock	Azimuth	Dip	C	E	R	M	H	W	O	T	HL	Notes and Comments

Continuity
- C1 <3 ft. (<1 m)
- C2 3-10 ft (1-3 m)
- C3 10-30 ft (3-10 m)
- C4 30-100 ft (10-30 m)
- C5 >100 ft (>30 m)

Ends
- E0 No ends visible
- E1 One end visible
- E2 Both ends visible

Roughness
- R1 Stepped
- R2 Rough
- R3 Moderately rough
- R4 Slightly rough
- R5 Smooth
- R6 Polished

Moisture
- M1 Dry, not possible
- M2 Dry, no evidence
- M3 Dry, some evidence
- M4 Damp, no free water
- M5 Wet, some drops
- M6 Cont. flow, low pres.
- M7 Cont. flow, high pres.

Wall Hardness
- H1 Extremely hard
- H2 Very hard
- H3 Hard
- H4 Moderately hard
- H5 Moderately soft
- H6 Soft
- H7 Very soft

Wall Weathering
- W1 Fresh
- W2 Slightly weathered to fresh
- W3 Slightly weathered
- W4 Moderately to slightly weathered
- W5 Moderately weathered
- W6 Intensely to moderately weathered
- W7 Intense. weathered
- W8 Very intensely weathered
- W9 Decomposed

Openness
- O0 Tight
- O1 <0.003 ft (<1 mm)
- O2 0.003-0.01 ft (1-3 mm)
- O3 0.01-0.03 ft (3-10 mm)
- O4 0.03-0.1 ft (10-30 mm)
- O5 >0.1 ft (>30 mm)

Thickness
- T0 None
- T1 <0.003 ft (<1 mm)
- T2 0.003-0.01 ft (1-3 mm)
- T3 0.01-0.03 ft (3-10 mm)
- T4 0.03-0.1 ft (10-30 mm)
- T5 >0.1 ft (>30 mm)

Healing
- HL0 completely, to strength of wall rock
- HL2 >50%, or weaker than wall rock
- HL3 <50%
- HL5 No induration

* Dip magnitude follows right-hand rule

Discontinuity Log 14HL
Version 1.0

Figure B-5. Discontinuity log (United States Bureau of Reclamation, 2001)

Field Mapping - Rock Structures*

1. Location, orientation, and number of planes are numeric. Data units are alphabetic and/or numeric. All other information is alphabetic.
2. Surface type, line type and rock type are three letter codes. Infilling water, form, roughness, and termination are one letter codes.
3. Record all codes and their full proper descriptions on a reference sheet.
4. Record position within the data unit or traverse under location. Each data unit should include data from within one sturctural unit only.
5. Thickness, spacing, and length are entered according to the size notation given below.

Traverse (Data Unit) Information

Data Unit ______ Northing ______ Easting ______ Elevation ______ Inclination ______

Bearing ______ Length ______ No. Points ______ Structural Unit ______ Formation ______ Declination ______ Observer ______

Remarks ______________________________

Size Notations (A through I mm, J through S m)

A	<0.26	E	12.5–25	J	0.3–0.6	O	9.0–18.0		
B	0.25	F	25–50	K	0.6–1.2	P	18.0–30.0		
C	0.25–6.5	G	50–100	L	1.2–2.4	Q	30.0–60.0		
D	6.5–12.5	H	100–200	M	2.4–4.5	R	60.0–120.0		
		I	200–300	N	4.5–9.0	S	>120.0		

Surface type
- C – Contact
- F – Fault
- S – Shear
- J – Joint
- B – Bedding
- L – Schistosity or Folitation
- V – Vein

Infilling
- A – Clay
- F – Iron metals
- W – Calcite
- K – Chlorite
- Q – Quartz
- P – Pyrite

Water
- W – Wet
- D – Dry
- M – Moist

Form
- P – Planar
- C – Curved
- U – Undulating
- S – Stepped
- I – Irregular

Roughness
- V – Very rough(JRC=25)
- R – Rough(JRC=15)
- S – Smooth(JRC=5)
- P – Polished(JRC=0)

Term
- 0 – neither end visible
- 1 – one end visible
- 2 – both ends visible

Data Unit ______ Job number ______

Location	Surface Type	Orientation Dip	Orientation Direction	Infillings 1	Infillings 2	Infillings 3	Thick	Water	Form	Rough	Spec	No. of Planes	Length	Term	Line Type	Orientation Dip	Orientation Direction	Rock Type

*Detailed instruction available in Rock Slopes Design, Excavation, Stabilization by Golder Associates.

Exhibit 6.10
Field Mapping - Rock Structures*
(Page 1 of 2)

Figure B-6. Field mapping form (Federal Highway Administration, 2007)

JOINT MEASUREMENTS AND OBSERVATIONS

No.	Traverse			Rock Unit	Number of Joints	Joint Spacing (ft)	Strike		Dip		Length (ft)	Ends	Thickness (ft)	Infilling	Water	Roughness	Waviness		Remarks
	ID	Trend	Distance (ft)				quad.	deg.	deg.	quad.							Length (ft)	Amp. (ft)	

ROCK UNITS

ENDS
0 = Both ends of joint visible
1 = One end of joint continues out of rock face
2 = Both ends of joint continue out of rock face

THICKNESS
1 = 0.00"
2 = 0.00" to 0.25"
3 = 0.25" to 1.00"
4 = 1.00" to 2.00"
5 = 2.00" to 4.00"
6 = >4.00"

INFILLING
A = Air
C = Clay
R = Rock fragments
S = Sand

WATER
1 = Joint is tight; flow does not appear possible
2 = Joint is dry; no evidence of water flow
3 = Joint is dry; evidence of water flow
4 = Joint is damp; no free water present
5 = Joint shows seepage; occasional drops of water
6 = Joint shows a continuous flow of water

ROUGHNESS
1 = Slickensided or polished
2 = Smooth
3 = Defined ridges
4 = Small steps
5 = Very rough

Figure B-7. Generic joint measurement and observations form

APPENDIX C

Discontinuity Characterization and Measurements

C-1. Discontinuity Characterization. A fractured rock mass can be considered to be composed of three basic features: (i) a rock matrix, (ii) a discontinuity network, and (iii) typically, infilling along the discontinuity surfaces. A single discontinuity can be characterized by its orientation, genesis, persistence, aperture, seepage, roughness, amplitude, infill, wall (shear) strength, etc. Multiple discontinuity planes exhibiting similar characteristics create a discontinuity set and exhibit systematic spacing (frequency). Different discontinuity sets, which may exhibit considerably different characteristics from the other sets, intersect and interconnect in the rock matrix to create a discontinuity network. The intersection of the existing discontinuity sets in the rock matrix not only facilitates fluid flow, but also defines the size and shape of the rock blocks existing within the rock mass.

C-2. Measurement Procedures.

a. General. The majority of rock masses in which civil engineering structures are built behave as discontinua, with the existing discontinuities within the rock mass determining its behavior and engineering properties. It is therefore critical that pertinent characteristics of existing discontinuities; such as orientation, spacing and persistence, be carefully characterized and accurately measured so that the optimum drilling direction can be correctly determined.

b. Orientation. The azimuth should measured in degrees counted counter clockwise from true north and expressed in a three digit number (015°, 160°, 235°, etc.) or by quadrant (N15°E, S20°E, S55°W, etc.). Data should be corrected to true north. The dip should be the maximum declination of the mean plane and expressed in degrees as a two digit number (05°, 30°, 75°, etc.). The dip direction and dip should be recorded in that order with three digit and two digit numbers separated by a line (015°/45°). The dip of the discontinuity should be measured using a down-dip base length exceeding the wave (amplitude) length of any surface undulations. In general, it is considered sufficient to read azimuth (strike or dip direction) to the nearest 5°, and dip to the nearest even number of degrees. Although if poles will be plotted, reading to the nearest degree may be needed to minimize the occurrence of coincident points. It is desirable to measure somewhere between 80 to 300 discontinuities in each set. A reasonable compromise is 150 discontinuities. Results should be presented both in tabulation and plotted on geologic maps, as block diagrams, as joint rosettes or as spherical projections.

c. Spacing. Whenever possible, the measuring tape sampling line should be held along the exposure such that the surface trace of the discontinuity set being measured is approximately perpendicular to the measuring tape. All distances between adjacent discontinuities are measured and recorded over a sampling length not less than 10 feet. Short sampling lines produce a small sample size and introduce problems of imprecision. If ten or more discontinuities are intersected in each scanline, the inaccuracies will be acceptable for most practical applications. Subsequently, the scanline sampling length should be greater than ten times the estimated true spacing. The distance should be measured with 5% of their absolute values. If the tape is not perpendicular to the discontinuity set, directional bias corrections are required to obtain the true spacing. Average apparent spacing (f_{sa}) can be measured by using a steel measuring tape placed at any convenient direction across the face of an exposed rock outcrop. This measurement must be corrected for sampling bias error (d) to determine the true discontinuity spacing, which is determined perpendicular to orientation of the discontinuity using:

$$f_s = f_{sa} \cos d \qquad \text{(C-1)}$$

Where θ is the acute angle between the discontinuity normal and the sampling line, f_s is the true spacing, and f_{sa} is the apparent spacing. The angle θ can be determined graphically using a spherical projection, using vector algebra methods, or from the following equation:

$$\cos d = C \cos(\alpha_n - \alpha_s) \cos \beta_n \cos \beta_s + \sin \beta_n \sin \beta_s \, C \qquad \text{(C-2)}$$

Where α_n and β_n are the trend and plunge of the normal to the discontinuity, respectively. And α_s and β_s are the trend and plunge of the scanl$_{in}$e, respectively. Results for each set should be presented both in tabulation and plotted on a histogram.

d. Persistence. Persistence is the areal extend or length of a discontinuity within a plane. It can be crudely quantified by observing the discontinuity trace lengths on the expose rock surface. The discontinuities of one particular set will often be more continuous that those of the other sets. The minor sets will tend to terminate against the primary features or they may terminate in solid rock. Individual rock exposures should be generally described according to the relative persistence of the different discontinuity sets that are present, such as persistent, sub-persisted, and non-persistent. Measure the persistence (discontinuity length) in both the direction of dip and in the direction of strike, if possible. Observe, record, and report whether the discontinuity extend beyond the exposed rock surface, terminates against another discontinuity, or terminates in intact rock material. Results should include the number of observations and the relevant lengths, presented in tabulated form.

C-3. <u>Joint Pattern Characterization</u>.

a. General. The data collected from a scanline survey can be used to further characterize the joint patterns in a rock mass. Since a rock mass is, in nature, a discontinuum, the discontinuity sets delineate blocks and control the in-situ block sizes within a rock mass. The block size dimensions and shapes are determined by the number of sets, by the spacing of the discontinuity sets, by the orientation of the discontinuity sets, and by the persistence of the discontinuities with the sets. Block size depends mainly on the differences between the spacing of the discontinuity sets. Block shape depends mainly on the orientation of the discontinuity sets. The volumetric joint count, which is a measure of the number of joints intersecting a volume of rock mass, is function of the mean spacing of all of the existing discontinuity sets. Block volumes depends mainly on the spacing of the discontinuity sets.

b. Volumetric Joint Count (J_v). The volumetric joint count (J_v) is a measure of the number of joints intersecting a volume of rock mass. It is defined as number of joints per ft³ or m^3. The volumetric joint count (J_v) has been described by Palmström (1982) and Sen and Eissa (1991, 1992). It can be measured from the joint set spacings within a volume of rock mass by:

$$Jv = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} \ldots + \frac{1}{S_r} \quad \text{(C-3)}$$

Where S_1, S_2, S_3 are the joint set spacings. Random joints can also be included by assuming a random spacing (S_r). Experience indicates that this can be set to S_r = 5 m; therefore, the volumetric joint count can be generally expressed in m^3 as:

$$J_v = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} \ldots + \frac{N_r}{5} \quad \text{(C-4)}$$

Where N_r = the number of random joints.

c. Block Volume (V_b). Where the individual rock blocks can be observed in an exposed surface, their volumes can be directly measured from relevant dimensions by selecting several representative blocks and measuring their average dimensions. However, rock block volumes can also be calculated from joint set spacing data. Where three joint sets occur the block volume is:

$$V_b = S_1 \cdot S_2 \cdot S_3 \cdot (\text{Sin}\alpha_1 \cdot \text{Sin}\alpha_2 \cdot \text{Sin}\alpha_3) \quad \text{(C-5)}$$

Where S_1, S_2, and S_3 are the spacings between the joint sets and α_1, α_2, and $\alpha_3$are the angles between the joint sets. Often the joint sets intersect at approximately right angles for which the block volume is:

$$V_b = S_1 \cdot S_2 \cdot S_3 \quad \text{(C-6)}$$

d. Correlation Between V_b and J_v. The block volume for three joint sets with intersecting angles $\gamma 1$, $\gamma 2$ and $\gamma 3$ is expressed as:

$$Vb = \beta \cdot Jv^{-3} \frac{1}{\sin \gamma_1 \cdot sin\gamma_2 \cdot sin\gamma_3} \quad \text{(C-7)}$$

Where β = the block shape factor given as

$$\beta = \frac{(\alpha_2 + \alpha_2 \cdot \alpha_3 + \alpha_3)^3}{(\alpha_3 \cdot \alpha_3)^2} \quad \text{(C-8)}$$

Where $\alpha_2 = S_2/S_1$ and $\alpha_3 = S_3/S_1$. Often the angles between the joints are approximately 90°; therefore, for practical purposes:

$$V_b = \beta \, J_v^{-3} \quad \text{(C-9)}$$

e. Volumetric Fracture Count (V_f). Volumetric fracture count is the total number of fractures per cubic ft (ft^3) or cubic meter (m^3) of rock volume and is determined by:

$$V_f = 1/f_{s1} + 1/f_{s2} + 1/f_{s3} \ldots + 1/f_{si} \quad \text{(C-10)}$$

Where f_{si} is the mean fracture spacing of the *i*th fracture set.

f. Matrix Block. A rock block is bounded by the fracture network is called a matrix block. Matrix block size are related to volumetric fracture count (V_f). The maximum number of matrix block (N_{bmax}) is determined by (Kazi and Sen, 1985):

$$N_{bmax} = \left(\frac{V_f}{3} + 1\right)^3 \quad \text{(C-11)}$$

APPENDIX D

Example Scanline Survey

No.	Traverse			Rock Unit	Number of Joints	Joint Spacing (ft)	Strike		Dip		Length (ft)	Ends	Thickness (ft)	Infill	Water	Roughness	Waviness	
	ID	Trend	Dist. (ft)				Quad.	Deg.	Deg.	Quad.							Length (ft)	Amp (ft)
1	A	S45W	5	SS #1	1	-	N52E	52	90	-	9.0	1	-	-	2	3	1.0	0.03
2	A	S45 W	9	SS #1	1	-	N69E	69	90	-	5.0	2	-	-	2	3	0.6	0.06
3	A	S38 W	12	SS #1	1	-	N78W	102	10	SW	9.0	0	-	-	2	3	1.0	0.10
4	A	S25W	16	SS #1	1	-	N10W	350	90	-	1.6	1	-	-	3	3	0.6	0.01
5	A	S25W	19	SS #1	1	-	N42E	42	90	-	1.5	1	-	-	3	3	0.7	0.03
6	A	S10W	22	SS #1	5	5	N45E	45	90	-	2.0	1	-	-	3	3	0.5	0.03
7	A	S10W	25	SS #1	4	0.6	N8W	352	90	-	3.0	1	-	-	3	3	1.0	0.01
8	A	S10W	28	SS #1	4	0.9	N50E	50	90	-	1.5	1	-	-	3	3	0.7	0.04
9	A	S5 W	35	SS #1	5	1.0	N47E	47	90	-	2.0	2	-	-	3	3	1.0	0.01
10	B	S20W	0	SS #2	1	1.4	N63W	297	90	-	3.0	1	-	-	2	3	0.9	0.10
11	B	S20W	5	SS #2	1	-	N50E	50	86	SE	3.0	2	-	-	4	3	1.0	0.05
12	B	S10W	16	SS #2	1	-	N70W	290	85	NE	2.5	2	-	-	3	3	0.8	0.04
13	B	S10W	16	SH #1	1	-	N81W	279	87	NE	2.5	1	-	-	3	3	1.0	0.005
14	B	S10 W	17	SS #3	1	-	N77W	283	83	NE	5.0	1	-	-	3	3	1.0	0.05
15	B	S10 W	20	SS #3	3	1.0	N36E	36	88	NW	2.0	1	5	S,A	3	3	0.9	0.06
16	B	S10 W	20	SS #3	1	-	N45E	45	90	-	3.0	0	4	S	3	2	1.0	0.002
17	B	S10W	22	SS #3	1	-	N85W	275	84	SW	7.0	2	3	S,A	5	3	0.9	0.06
18	B	S10W	25	SS #3	1	-	N50E	50	90	-	5.0	2	4	S,A	5	2	-	-
19	B	S 10W	33	SS #3	1	-	N47E	47	87	SE	2.5	2	-	-	3	3	0.9	0.02
20	B	S10W	41	SS #3	1	-	N17E	17	90	-	3.5	1	-	-	4	2	0.2	0.001
21	B	S10W	51	SS #2	1	-	N42E	42	75	NW	10.0	1	3	S,A	4	3	0.5	0.02
22	B	S10W	47	SS #2	1	-	N69W	291	87	SW	2.0	0	-	-	3	3	0.8	0.05
23	C	S10W	0	SS #2	1	-	N77W	286	84	NE	12.0	1	3	A	3	3	0.7	0.03
24	C	S10W	3	SS #2	1	-	N32E	32	90	-	7.0	1	5	A,R	3	3	1.0	0.03
25	C	S13E	6	SS #2	1	-	N24E	24	90	-	10.0	2	3	A,R	3	2	0.8	0.02
26	C	S13E	8	SS #2	1	-	N74W	286	86	NE	15.0	2	3	A	3	3	0.8	0.02
27	C	S13E	10	SS #2	1	-	N32E	32	90	-	7.0	2	3	A	4	3	0.3	0.005
28	C	S13E	18	SS #2	1	-	N30E	30	90	-	3.5	2	3	A	4	3	0.8	0.07
29	D	S27E	2	MS #1	1	-	N77W	283	90	-	5.0	1	3	A	4	3	0.5	0.02
30	D	S27E	5	MS #1	1	-	N49E	49	90	-	45.0	2	6	A	5	3	2.5	0.30
31	D	S27E	11	MS #1	1	-	N75W	285	84	NE	5.0	1	-	-	4	3	0.3	0.005
32	D	S27E	12	MS #1	1	-	N47E	47	90	-	18.0	1	5	A	4	3	0.7	0.03
33	D	S27E	15	MS #1	1	-	N76W	284	82	NE	1.5	1	2	C	3	2	0.5	0.01
34	D	S27E	19	SS #2	1	-	N36E	36	90	-	10.0	1	3	A,R	4	3	1.0	0.03
35	D	S27E	23	SS #2	1	-	N43E	43	90	-	2.0	2	-	-	4	3	0.5	0.02

No.	Traverse			Rock Unit	Number of Joints	Joint Spacing (ft)	Strike		Dip		Length (ft)	Ends	Thickness (ft)	Infill	Water	Roughness	Waviness	
	ID	Trend	Dist. (ft)				Quad.	Deg.	Deg.	Quad.							Length (ft)	Amp (ft)
36	D	S27E	26	SS #2	2	1.0	N37E	37	86	NW	43.0	2	5	A,R	5	3	0.7	0.07
37	E	S17W	4	SS #3	1	-	N00W	360	87	W	4.0	1	-	-	3	2	0.8	0.005
38	E	S17W	8	SS #3	1	-	N46E	46	90	-	10.0	1	5	A	5	3	1.0	0.01
39	E	S17W	10	SS #3	1	-	N78W	282	85	SW	5.0	1	4	A	5	3	1.0	0.04
40	E	S17W	16	SS #3	1	-	N73W	287	88	NE	6.0	1	2	A	4	3	0.5	0.03
41	E	S17W	17	SS #3	1	-	N54E	54	88	NW	5.0	1	3	A	4	3	0.3	0.01
42	E	S17W	27	SS #3	1	-	N1W	359	90	-	4.0	0	3	A	4	2	0.5	0.01
43	E	S17W	31	SS #3	1	-	N45E	45	90	-	3.0	1	-	-	3	3	2.2	0.15
44	E	S17W	35	SS #3	1	-	N73W	287	90	-	7.0	1	6	A,R	4	3	1.0	0.07
45	E	S17W	36	SS #3	1	-	N55E	55	90	-	15.0	-	5	A,R	5	3	0.5	0.015

Rock Units	Ends	Thickness	Infilling	Water	Roughness
SS #4 = Sandstone #4	0 = Both ends of joint visible	1 = 0.00"	A = Air	1 = Joint is tight; flow does not appear possible	1 = Slickensided or polished
SH #2 = Shale #2	1 = One end of joint continues out of rock face	2 = 0.00" to 0.25"	C = Clay	2 = Joint is dry; no evidence of water flow	2 = Smooth
SS #3 = Sandstone #3	2 = Both ends of joint continue out of rock face	3 = 0.25" to 1.00"	R = Rock fragments	3 = Joint is dry; evidence of water flow	3 = Defined ridges
SH #1 = Shale #1		4 = 1.00" to 2.00"	S = Sand	4 = Joint is damp; no free water present	4 = Small steps
SS #2 = Sandstone #2		5 = 2.00" to 4.00"		5 = Joint shows seepage; occasional drops of water	5 = Very rough
MS #1 = Mudstone #1		6 = >4.00"		6 = Joint shows a continuous flow of water	
SS #1 = Sandstone #1					

NOTE: The remarks column was omitted due to space limitations.

APPENDIX E

Orientation of Lines and Planes

E-1. Definitions of Points, Lines, and Planes (Martel, 2004).

a. A point is:

(1) Defined by one set of coordinates (an ordered triple in 3D coordinate systems).

(2) Defined by distance and direction from a reference point.

(3) The intersection of two lines.

(4) The intersection of three planes.

b. A line is:

(1) Defined by two sets of coordinates.

(2) Defined by two points.

(3) Defined by distance from a reference point and the direction of the line.

(4) The intersection of two planes

c. A plane is:

(1) Defined by three sets of coordinates.

(2) Defined by three points.

(3) Defined by distance and direction from a reference point.

(4) Defined by two intersecting or two parallel lines.

E-2. Geologic Conventions for Measuring Orientations.

a. Compass bearings.

(1) By quadrant, relative to north or south (<90°).

(2) By azimuth (0°< and <360°).

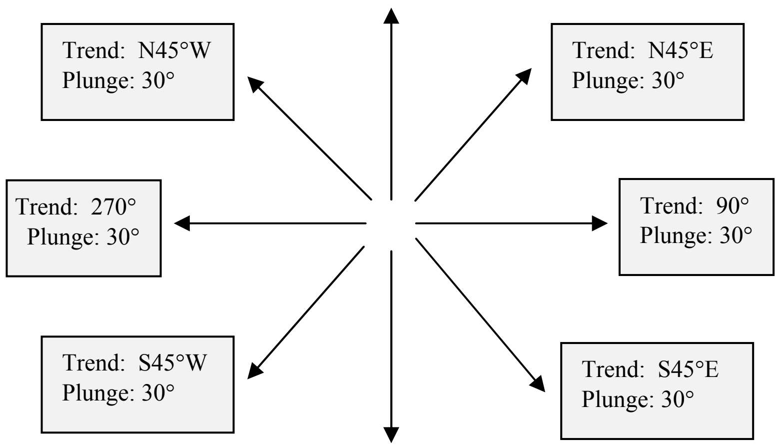
(3) Examples.

By Quadrant	N0°E	N45°E	N90°E	S45°E	S0°E	S45°W	S90°W	N45°W
By Azimuth	0°	45°	90°	135°	180°	225°	270°	315°

b. Trend. A compass bearing.

c. Plunge. An inclination below horizontal.

(1) Examples. The lines below all plunge at 30°.

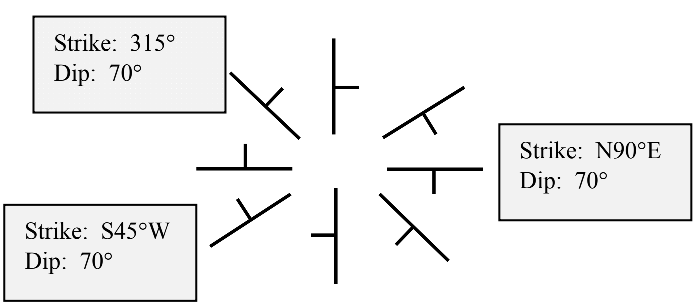


d. Planes.

(1) Strike. A compass bearing.

(2) Dip. An inclination below horizontal.

(3) Examples. The planes below all dip at 70°.



E-3. Geologic Methods for Describing Lines and Planes.

a. Orientations of geologic lines.

(1) Trend and plunge.

(a) Trend. The direction (azimuth) of a vertical plane containing the line of interest. Azimuth (compass bearing) is the direction of a horizontal line contained in a vertical plane. Measured by quadrant or degrees (°). Examples: by quadrants N90°E and N90°W or by azimuth 90° and270°. The trend "points" in the direction a line plunges.

(b) Plunge: The inclination of a line below the horizontal.

(2) Pitch (or rake). The angle, measured in a plane of specified orientation, between one line and a horizontal line.

(3) The orientations of geologic lines are shown in Figure E-1.

b. Orientations of geologic planes.

(1) Strike and dip are the orientations of two intersecting lines in a plane.

(a) Strike is the direction of the line of intersection between the inclined plane and a horizontal plane.

(b) Dip is the inclination of a plane below the horizontal ($0° \leq dip \leq 90°$).

(c) The azimuth directions of strike and dip are perpendicular.

(d) The direction of dip must be specified to eliminate ambiguity. The right-hand rule should be used. Examples: Strike N90°W Dip 45°N (right-hand rule). Dip and dip direction (azimuth of dip) may also be used to define strike and dip.

(e) Trend and plunge refer to lines.

(f) Strike and dip refer to planes.

(2) The trend and plunge of a pole is normal to plane. A pole is a line traditionally taken to point down. Pole trend = strike - 90°. Pole plunge = 90° - dip.

(3) The orientations of geologic planes are shown in Figure E-2.

E-4. Three Dimensional Coordinate Systems.

a. In the Cartesian coordinate system, points are described by their (x, y, and z) coordinates (see Figure E-3). The x, y, and z axes are right-handed and mutually perpendicular. The direction of a line is given by:

(1) The coordinates of pairs of points, such as (2, 5, 8) and (4, 10, 16).

(2) The difference in coordinates of pairs of points, such as:

$$\Delta x = x_2 - x_1$$
$$\Delta y = y_2 - y_1$$
$$\Delta z = z_2 - z_1$$

(3) The angles Ψ_x, Ψ_y, and Ψ_z. These are the angles between a line of unit length and the x, y, and z axes, respectively. The respective cosines of these angles (α, β, γ) are called the direction cosines.

Angle	Ψ_x	Ψ_y,	Ψ_z
Direction cosine	α	β	γ

(4) A line of unit length has a length of one. The length of a line is given by:

$$L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

$$L = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$$

b. Cylindrical coordinates are a 3D version of polar coordinates and are described by its (ρ, θ, and z) coordinates. The cylindrical coordinates of point *P* is defined by:

(1) The radial distance ρ is the Euclidean distance (viz., the "ordinary" distance between two points that one would measure with a ruler and is given by the Pythagorean formula) from the z axis to the point *P*.

(2) The azimuth θ is the angle between the reference direction on the chosen plane and the line from the origin to the projection of *P* on the plane.

(3) The height *z* is the signed distance from the chosen plane to the point *P*.

c. Spherical coordinates are described by their (r, θ, and ϕ) coordinates. The spherical coordinates of point *P* is defined by:

(1) The *radius (r)* or *radial distance* is the Euclidean distance from the origin *O* to point *P*. (Note: *r* here is different than the radial distance used for ρ for cylindrical coordinates.)

(2) The *inclination* (θ), or *polar angle,* is the angle between the zenith direction and the line segment *OP*.

(3) The *azimuth* (ϕ), or *azimuthal angle*, is the signed angle measured from the azimuth reference direction to the orthogonal projection of the line segment *OP* on the reference plane. (Note: In some spherical schemes, the angle between OP and the z-axis is used as the second angle.)

d. Conversions between coordinate systems are shown below.

Cartesian ← Spherical	**Spherical ← Cartesian**
$x = r\cos\phi\cos\theta$ α□ $= \cos\phi\cos\theta$ $y = r\cos\phi\sin\theta$ $\beta = \cos\phi\sin\theta$ $z = r\sin\phi$ $\gamma = \sin\phi$	$r = \sqrt{x^2+y^2+z^2}$ $1 = \sqrt{\alpha^2+\beta^2+\gamma^2}$ $\theta = \tan^{-1}(y/x)$ $\theta = \tan^{-1}(\beta/\alpha)$ $\phi = \sin^{-1}(z/r)$ $\phi = \sin^{-1}(\gamma)$
Cartesian ← Cylindrical	**Cylindrical ← Cartesian**
$x = r\cos\theta$ $y = r\sin\theta$ $z = z$	$r = \sqrt{x^2 + y^2}$ $\theta = \tan^{-1}(y/x)$ $z = z$

E-5. <u>Trend, Plunge and Pitch</u>.

a. Formulas of the orientations of trend, plunge, and pitch are provided below and shown on Figure E-4.

	Plunge (ϕ)	**Pitch (Ω)**	**Dip (d)**	**Ψ**
sin	$\frac{a}{e}$	$\frac{f}{e}$	$\frac{a}{f}$	$\frac{b}{c}$
cos	$\frac{c}{e}$	$\frac{d}{e}$	$\frac{b}{f}$	$\frac{d}{c}$
tan	$\frac{a}{c}$	$\frac{f}{d}$	$\frac{a}{b}$	$\frac{b}{d}$

b. Trend = θ = strike + Ψ = strike + $\cos^{-1}$ (d/c) = strike + $\cos^{-1}\{(\cos \Omega)/(\cos \varphi)\}$

c. Trend = θ = strike + Ψ = strike + $\tan^{-1}$ (b/d) = strike + $\tan^{-1}\{(\cos \delta)(\tan \Omega)\}$

d. Plunge = $\varphi = \sin^{-1}$ (a/e) = $\sin^{-1}\{(\sin \delta)(\sin \Omega)\}$

e. Pitch = $\Omega = \sin^{-1}$ (f/e) = $\sin^{-1}\{(\sin \varphi) / (\sin \delta)\}$

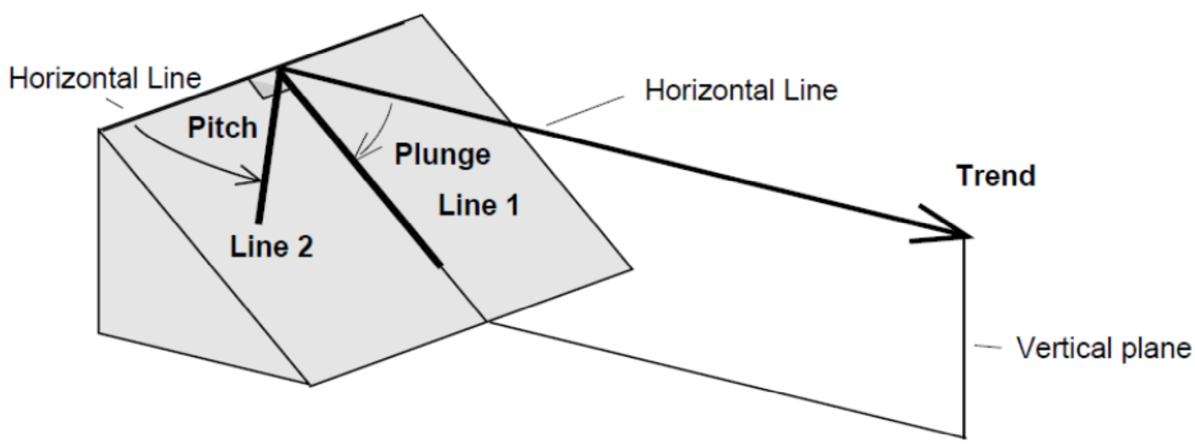


Figure E-1. Orientation of geologic lines (Martel, 2004)

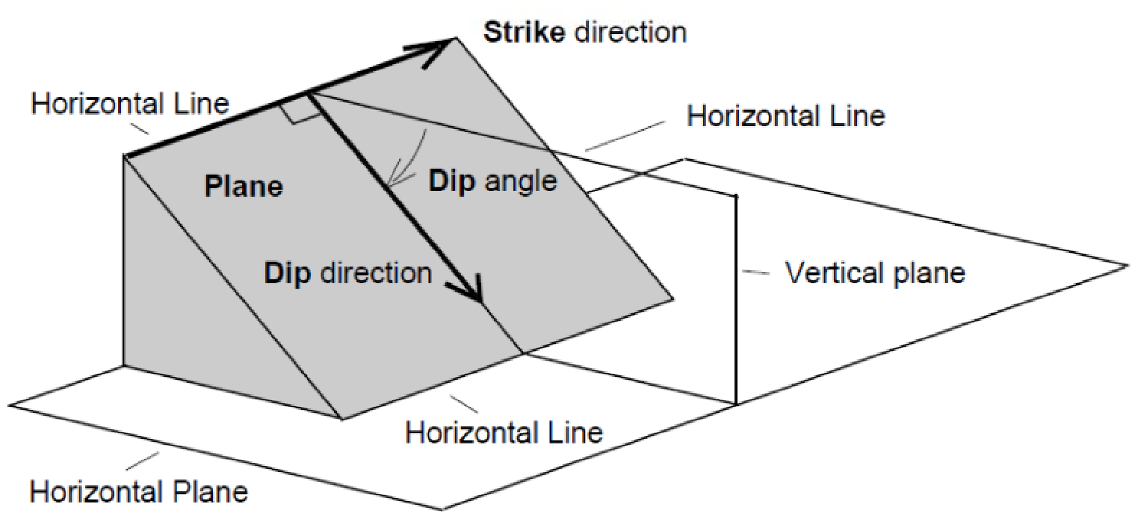


Figure E-2. Orientation of geologic planes (Martel, 2004)

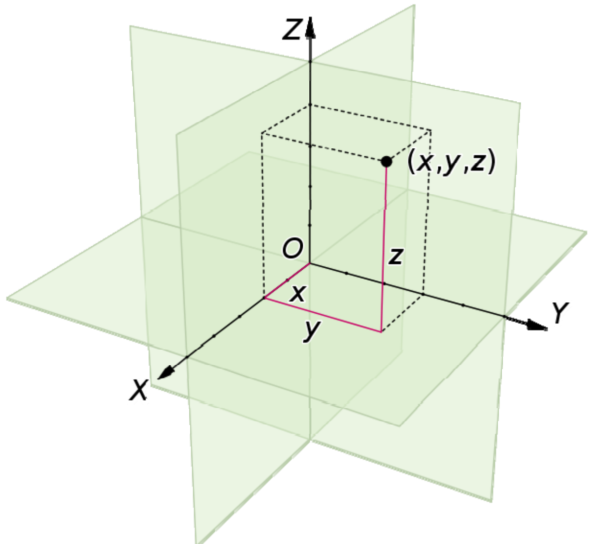


Figure E-3. Three dimensional coordinate system (Martel, 2004)

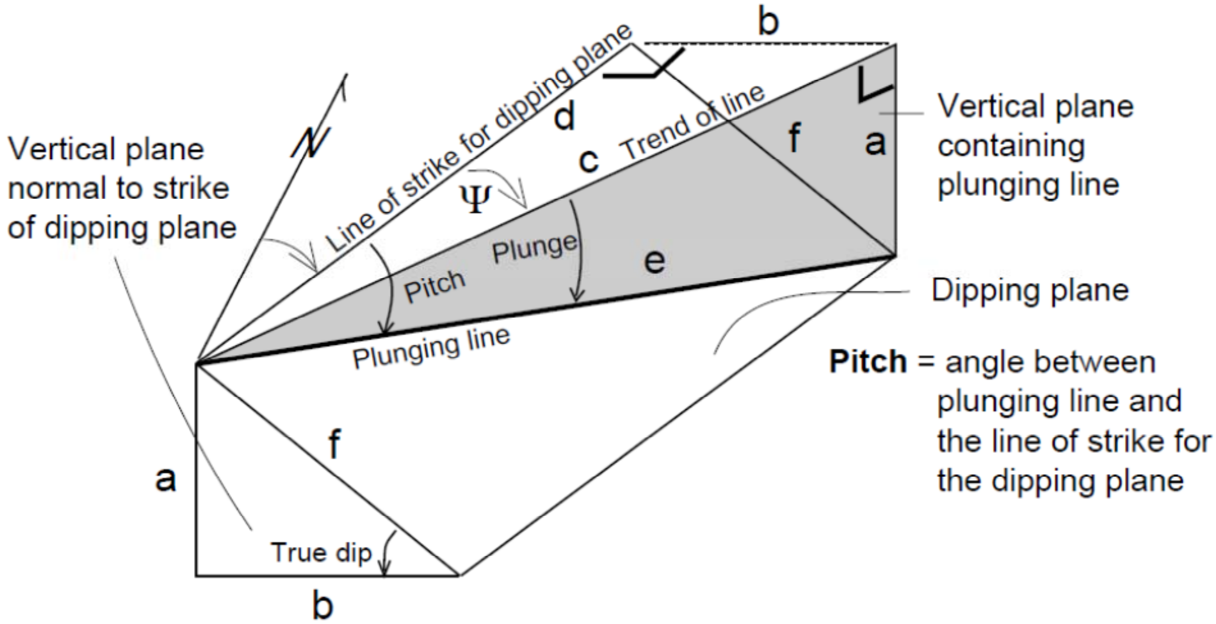


Figure E-4. Trend, plunge and pitch (Martel, 2004)

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APPENDIX F

Example Linear Sampling Bias Index (LSBI) Method

F-1. Background.

a. The Linear Sampling Bias Index (LSBI) method is a function of the relative angle between the orientations of the normals of each of the joint sets. Since the optimum drilling direction is the direction along which the maximum number of discontinuities is intersected, the optimum drilling direction is the orientation which the LSBI is minimized.

b. The LSBI method is illustrated using several simple examples involving one, two, three, and four joint sets. The following examples use the same discontinuity orientations as presented by Zhou and Maerz (2002). The objective of these examples is to duplicate the results presented by Zhou and Maerz, which would both illustrate and verify the methodology and equations used to obtain the results. Microsoft EXCEL 2000 was used to solve the appropriate equations and plot the corresponding graphs.

F-2. Examples.

a. One-Discontinuity Set.	Joint Set (JS) 1: Strike = 000° / Dip = 00°
b. Two-Discontinuity Sets.	Joint Set (JS) 1: Strike = 000° / Dip = 00° Joint Set (JS) 2: Strike = 180° / Dip = 90°
c. Three-Discontinuity Sets.	Joint Set (JS) 1: Strike = 000° / Dip = 00° Joint Set (JS) 2: Strike = 180° / Dip = 90° Joint Set (JS) 3: Strike = 045° / Dip = 45°W
d. Four-Discontinuity Sets.	Joint Set (JS) 1: Strike = 000° / Dip = 00° Joint Set (JS) 2: Strike = 020° / Dip = 10°E Joint Set (JS) 3: Strike = 045° / Dip = 45°E Joint Set (JS) 3: Strike = 150° / Dip = 30°W

F-3. Results.

a. One-Discontinuity Set. Results for borehole inclination for the one-joint set is shown in Figure F-1. Figure F-1 shows that the LSBI is minimized when the drilling inclination is 90° (vertical). Because the optimum drilling inclination is vertical, the azimuth of the borehole is not defined, nor is it necessary to define.

b. Two-Discontinuity Set. Results for borehole azimuth and borehole inclination for the two-joint sets are shown in Figure F-2a and Figure F-2b, respectively. Two minimal values of $LSBI_{azimuth}$ are shown at 90° and at 270°. There are four possible combinations of borehole azimuth and inclination, but only two are valid. 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 $LSBI_{azimuth}$ are identical, both orientations are equally optimal. This results because the discontinuities are distributed in a symmetrical pattern in this particular example.

c. Three-Discontinuity Sets. Results for borehole azimuth and borehole inclination for the three-joint sets are shown in Figure F-3a and Figure F-3b, respectively. Figure F-3a shows that the $LSBI_{azimuth}$ is minimized at either 112° or 292°. Figure F-3b shows that the $LSBI_{inclination}$ is minimized when the borehole inclination is 45° from the horizontal plane. 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°.

d. Four-Discontinuity Sets. Results for borehole azimuth and borehole inclination for the four-joint sets are shown in Figure F-4a and Figure F-4b, respectively. Figure F-4a, and by convention, shows that the $LSBI_{azimuth}$ is minimized at about 100°. The $LSBI_{inclination}$ is minimized when the borehole inclination is 97° towards the west.

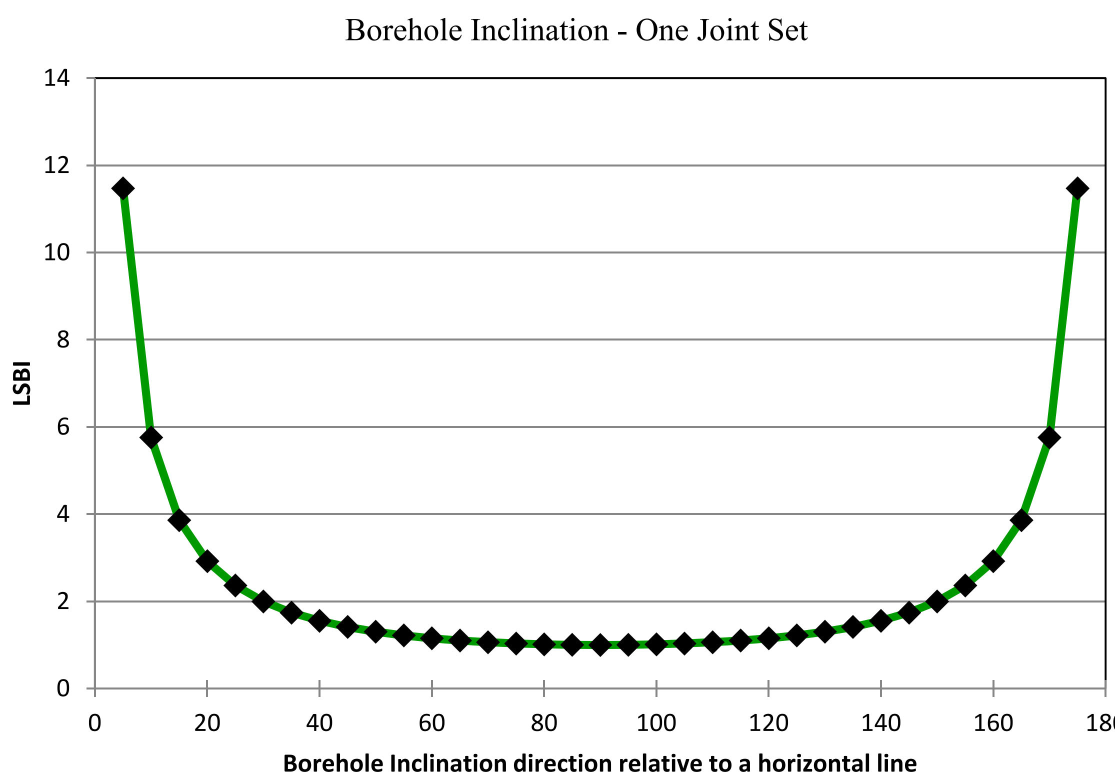
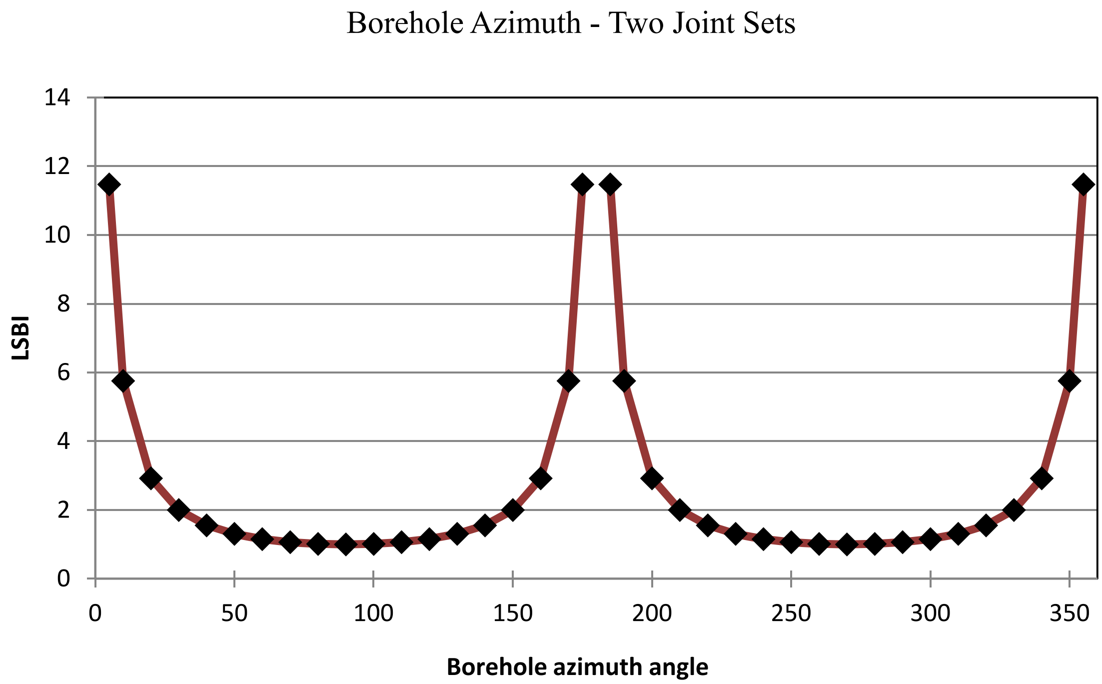
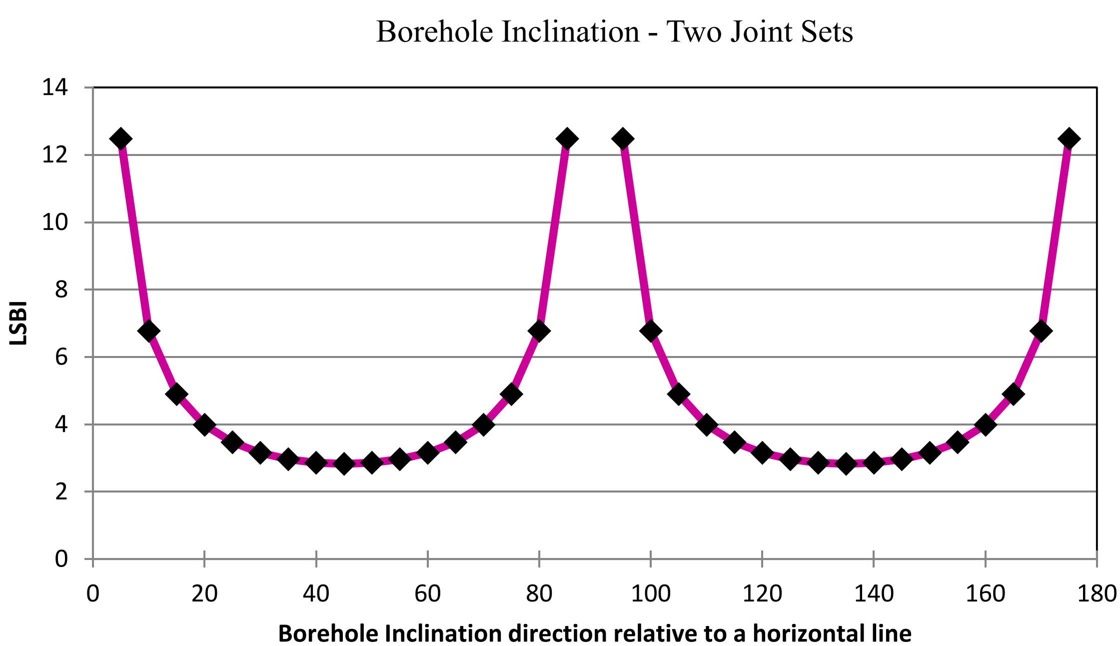


Figure F-1. Example for one discontinuity set

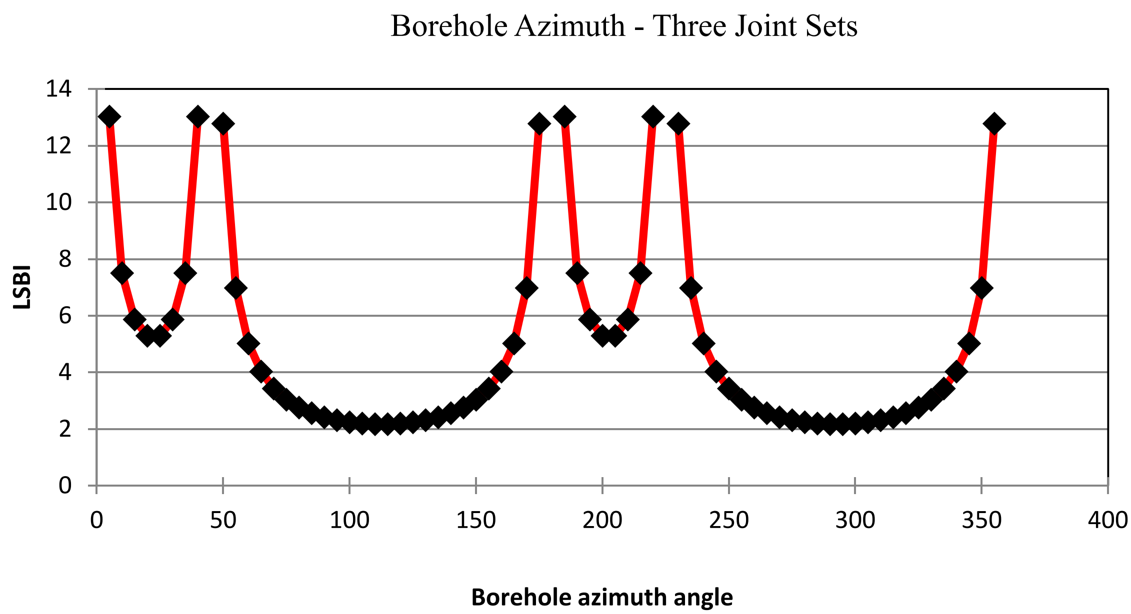


(a)

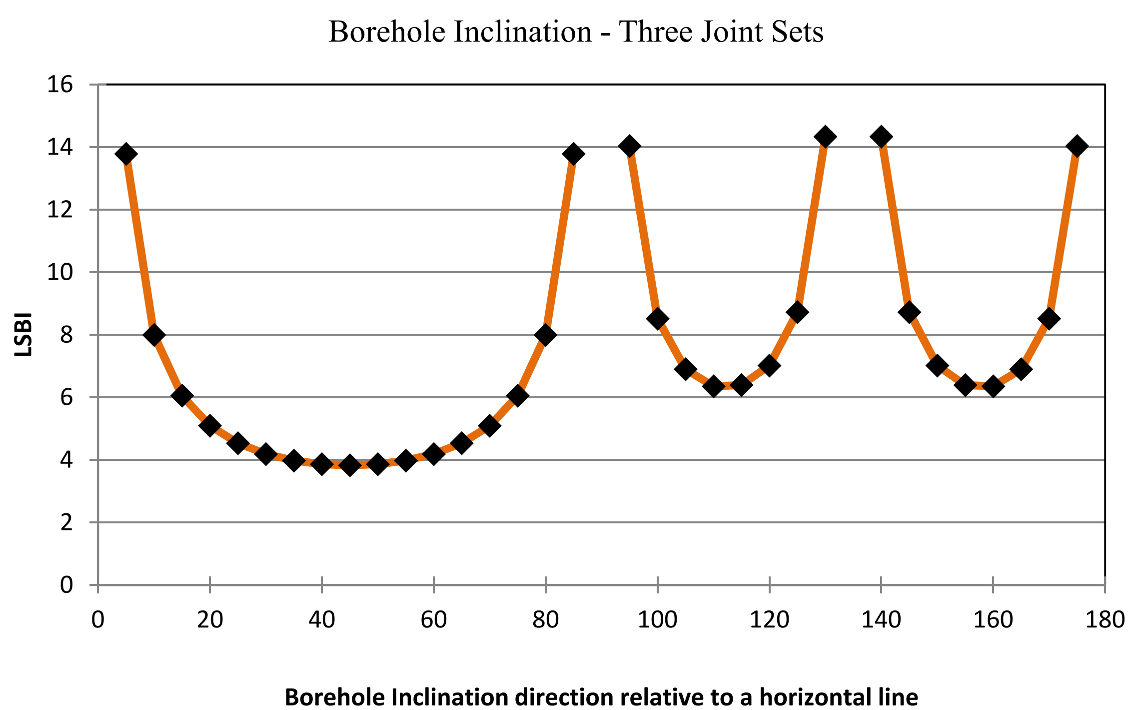


(b)

Figure F-2. Example for two discontinuity sets

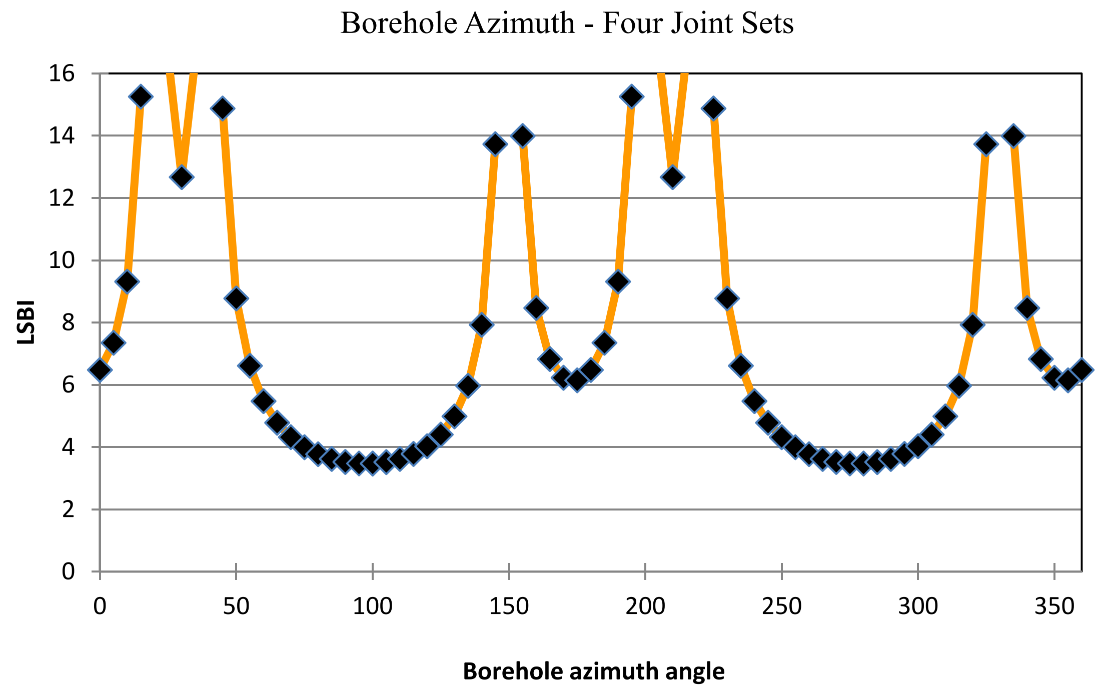


(a)

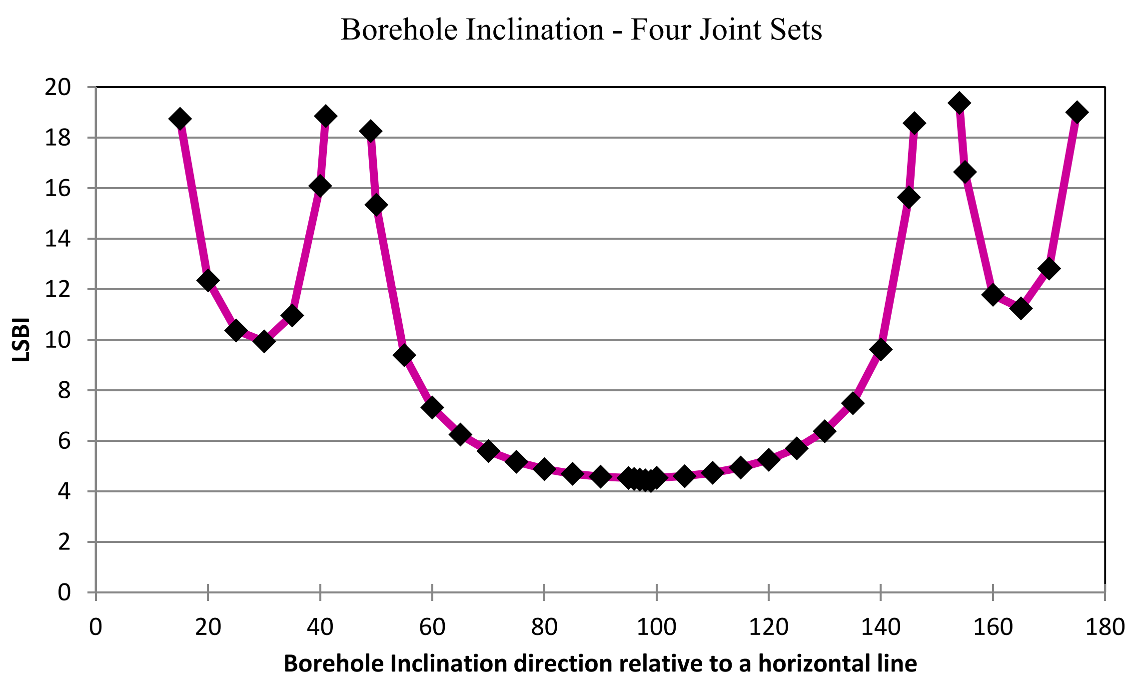


(b)

Figure F-3. Example for three discontinuity sets



(a)



(b)

Figure F-4. Example for four discontinuity sets

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APPENDIX G

Example Linear Sampling Angular Deviation (LSAD) Method

G-1. <u>Background</u>.

a. The Linear Sampling Angular Deviation (LSAD) method is the normalized sum of the squared angular differences between the borehole and the poles to $i = 1 \ldots n$ discontinuity sets. The optimum drilling direction is found by plotting the angular variance over the ranges 0° ≤ dip ≤ 90° and 0° < strike < 360° using Cartesian coordinates and visually identifying minima. Minima are sought because they represent drilling directions that should produce the smallest aggregate difference between the borehole and the poles to the discontinuities or, in other words, directions that are most likely to minimize bias. Maxima difference would then represent drilling directions that should be avoided, because it would decrease the likelihood of intersecting discontinuities and will maximize bias. Unless the intent of the drilling is minimize the intersections with discontinuities. For example, drilling to obtain intact rock samples for subsequent physical, chemical, or petrographic analysis and testing.

b. The LSAD method is illustrated using several simple examples involving one, two, and three discontinuity sets. The following examples use the same discontinuity orientations as presented by Haneberg (2009). The objective of these examples is to duplicate the results presented by Haneberg, which would both illustrate and verify the methodology and equations used to obtain the results. Microsoft EXCEL 2000 was used to solve the appropriate equations and plot the corresponding graphs.

G-2. <u>Examples</u>.

a	One-Discontinuity Set.	Joint Set 1: Dip = 45° / Dip Direction = 045°
b.	Two-Discontinuity Sets.	Joint Set 1: Dip = 00° / Dip Direction = 000°
		Joint Set 2: Dip = 90° / Dip Direction = 090°
c.	Three-Discontinuity Sets.	Joint Set 1: Dip = 00° / Dip Direction = 000°
		Joint Set 2: Dip = 90° / Dip Direction = 090°
		Joint Set 3: Dip = 90° / Dip Direction = 000°

G-3. <u>Results</u>.

a. One-Discontinuity Set. Results for borehole inclination for the one-joint set is shown in Figure G-1. The LSAD minimum of occurs for a borehole with an inclination/azimuth of 45°/225°.

b. Two-Discontinuity Set. Results for borehole azimuth and borehole inclination for the two-joint sets are shown in Figure G-2. Two minimal values of LSAD occur at 45°/090° and

45°/270°. Because the two LSAD minima are equal in value, drilling in either of those directions should produce statistically identical results. A vertical borehole, which is the default choice in many geotechnical exploration programs, would result in LSAD values in the range of 60° to 65°, compared to the LSAD minimum value of 45°.

c. Three-Discontinuity Sets. Results for borehole azimuth and borehole inclination for the three-joint sets are shown in Figure G-3 Two sets of vertical discontinuities result in four LSAD minima with borehole orientations of 35°/045°, 35°/135°, 35°/225°, and 35°/315°. Because the LSAD minima are equal in value, boreholes in each of the four directions should yield similar results and, in practice, only one of the directions would need to be chosen. If a vertical borehole was drilled, the existence of two sets of vertical discontinuities would impact the sampling bias that would be introduced by choosing vertical boreholes, which would completely ignore two of the three discontinuity sets. This would result in LSAD values in the range of 70° to 75°, compared to the LSAD minimum value 54.7°.

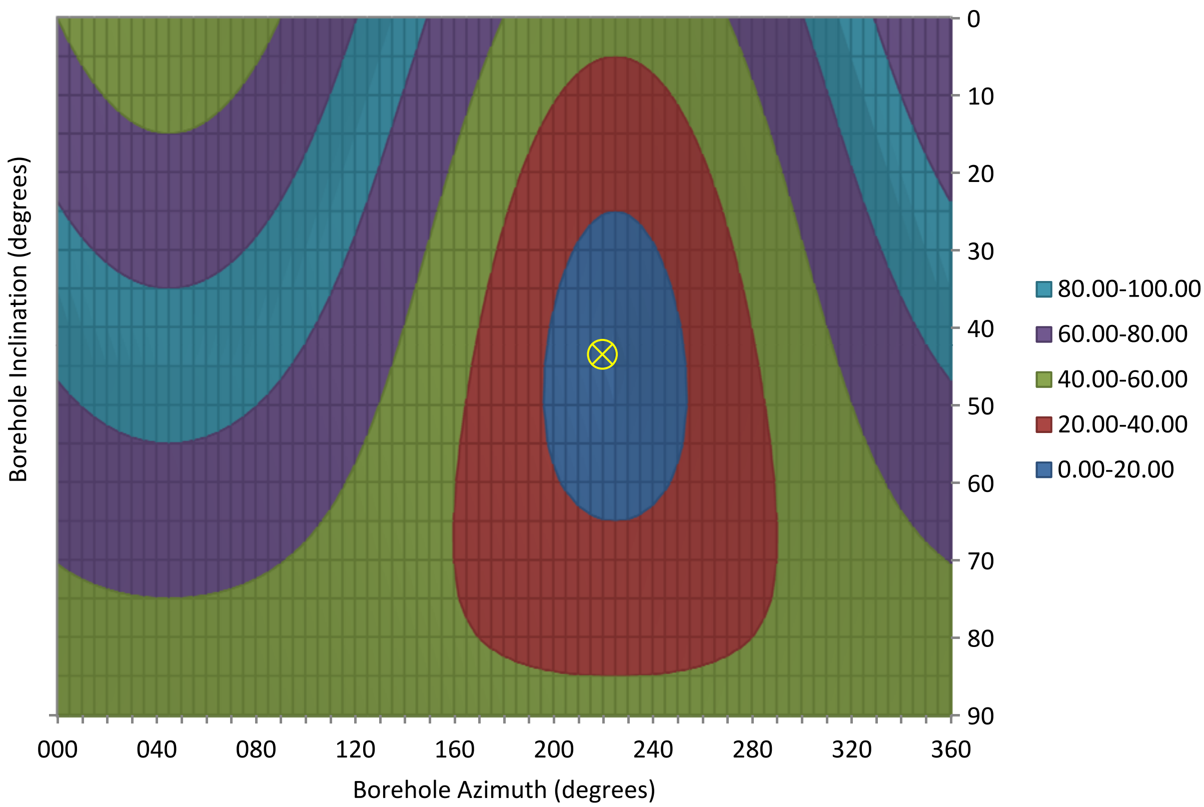

Figure G-1. Cartesian contour plot of Linear Sampling Angular Deviation (LSAD) for a single discontinuity set with an orientation of 45°/045°. This configuration produces a single minimum at 45°/225°

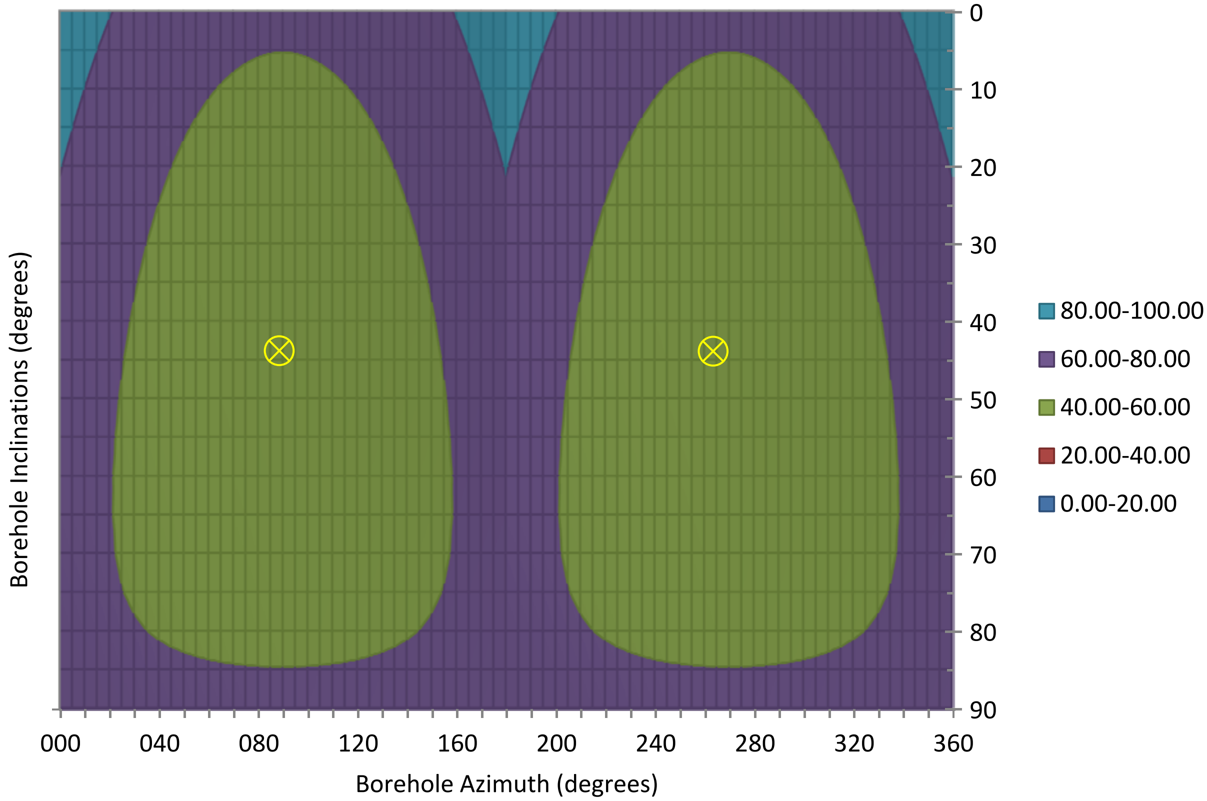

Figure G-2. Cartesian contour plot of linear sampling angular deviation (LSAD) for two discontinuity sets: one horizontal (00°/000°) and one vertical with a north-south strike (90°/90°). This configuration produces two minima at 45°/090° and 45°/270°

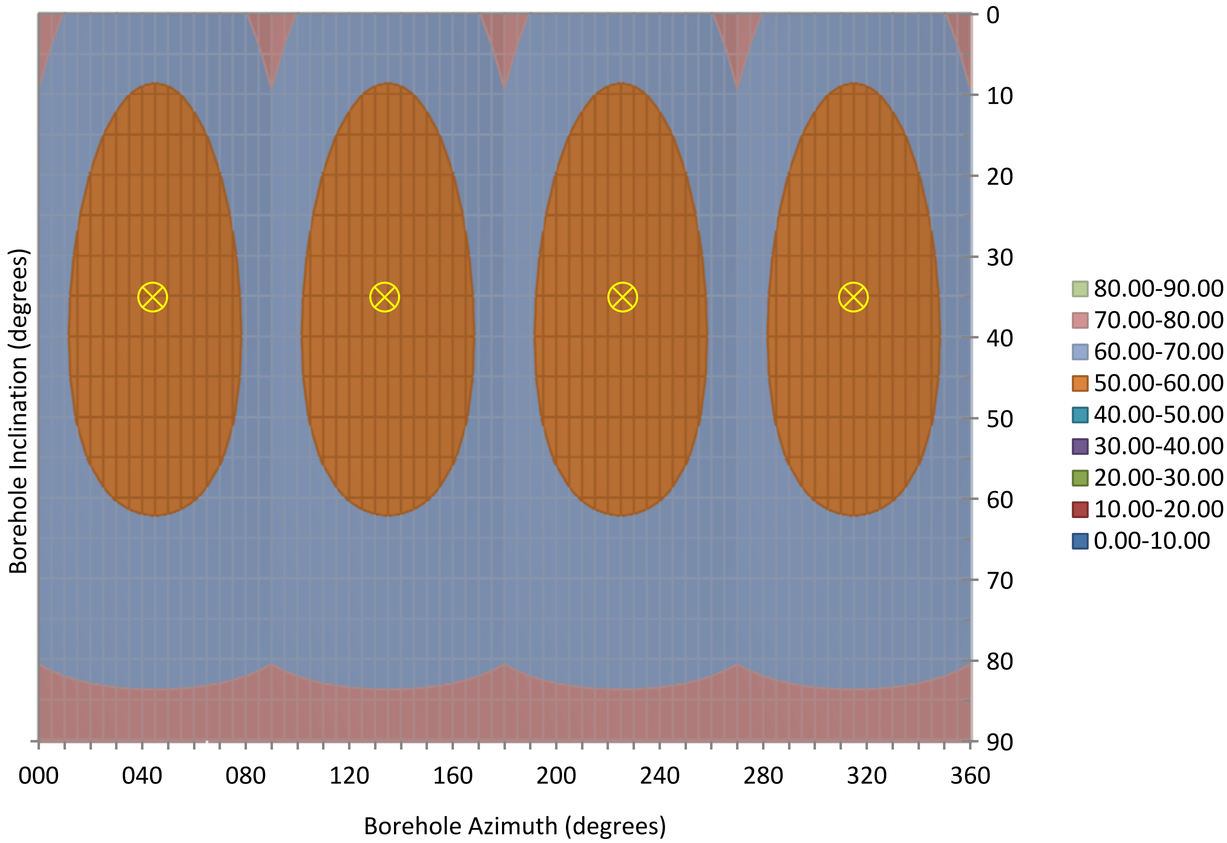

Figure G-3. Cartesian contour plot of Linear Sampling Angular Deviation (LSAD) for three discontinuity sets: one horizontal (00°/000°), one vertical with a north-south strike (90°/°, and one vertical with an east-west strike (00°/000°). This configuration produces four minima at 35°/045°, 35°/135°, 35°/225°, and 35°/315°

APPENDIX H

Example Discontinuity Frequency Extrema Method (DFEM)

H-1. Background.

a. If a sampling line was rotated about an origin through an arbitrary set of orientations in a particular three-dimensional rock structure, it would be possible to calculate both the individual and the total discontinuity frequencies for each orientation (Priest, 1993). The frequency for a given sampling line orientation could then be represented by the length of the line extending from the origin and paralleling the sampling line. This line is referred to as a frequency vector. The end points of a large number of frequency vectors would generate a three-dimensional surface representing the variation of discontinuity frequency for a particular three-dimensional rock structure. A horizontal cross-section through the three-dimensional surface would generate loci for the frequency vectors for the given discontinuity sets. Frequency vectors can then be determined along any known sampling line. A sampling line may be a foundation drain, a drill hole for site investigation, a tunnel section, a planar rock surface, etc.

b. Abrupt changes in the frequency vectors, called cusps, occur when the rock structure contains sets of parallel planar discontinuities. The cusps occur because the transition of the sampling line requires a reversal of the associated normal as the sampling line transitions from one side of the discontinuity plane to the other side. These cusps are V-shaped valley in the discontinuity frequency locus. The orientation of the cusps is defined by the intersection between adjacent pairs of discontinuities. Such orientations are associated with local minima because the sampling line that is parallel to the line of intersection will not intersect any discontinuities from that set. A sampling line that is parallel to the line of intersection between two sets ignores the frequency components from both sets, and subsequently generates a local minimum. The global minimum discontinuity frequency for the rock structure can be found by inspecting each line of intersection, that is, each of the cusps, for discontinuity frequency minima.

H-2. Example.

a. A rock mass has four discontinuity sets with their orientations as follows:

Set No.	Azimuth	Inclination	Normal Frequency (ft^{-1})
1	144°	14°	6.81
2	331°	57°	2.27
3	034°	61°	4.78
4	222°	39°	1.84

b. Determine the cumulative discontinuity frequency for: (a) a horizontal sampling line; and (b) a sampling line with a trend of 345° and a plunge of 20°; and (c) a sampling line with a trend of 240° and a plunge of 25°.

H-3. Results.

a. The cumulative frequency vectors for the four discontinuity sets for a horizontal cross-section are shown in Figure H-1.

b. The discontinuity frequency vector for a sampling line with a trend of 345° and a plunge of 20° is about 10.2 ft $^{-1}$ and is designated by a red-X in Figure H-2.

c. The discontinuity frequency vector for a sampling line with a trend of 240° and a plunge of 25° is about 2.7 ft $^{-1}$ and is designated by a red-X in Figure H-3.

d. The loci from Figures H-1, H-2, and H-3 shows that the frequency discontinuity variation is a mathematically discontinues function in three dimensions.

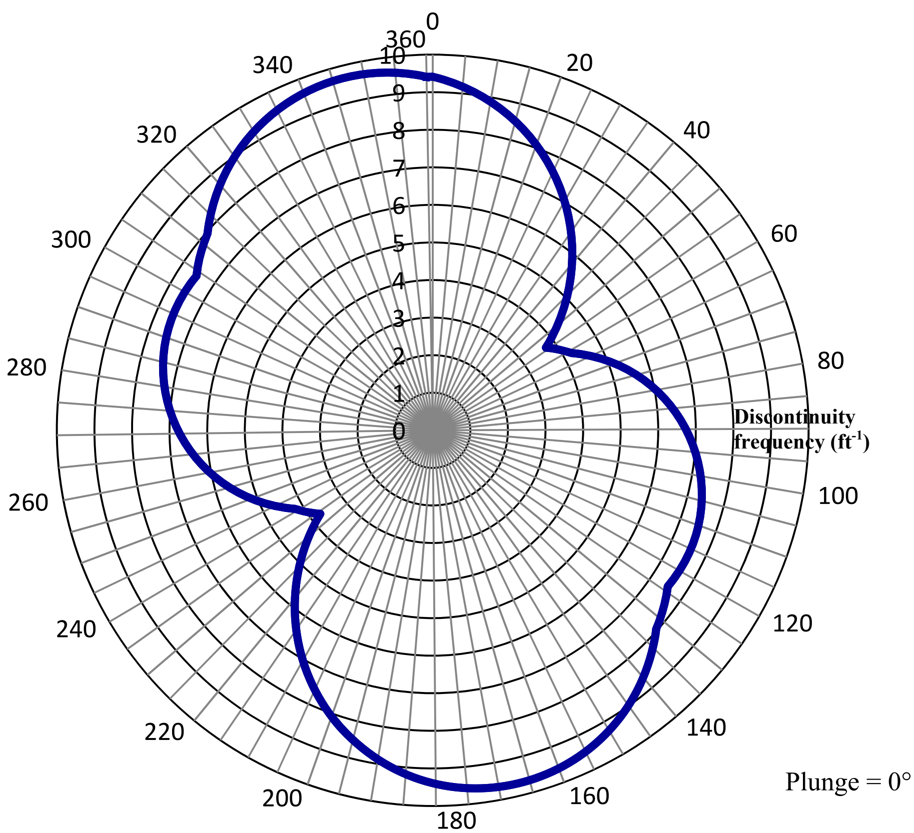

Figure H-1. Discontinuity frequency vectors for a horizontal plane

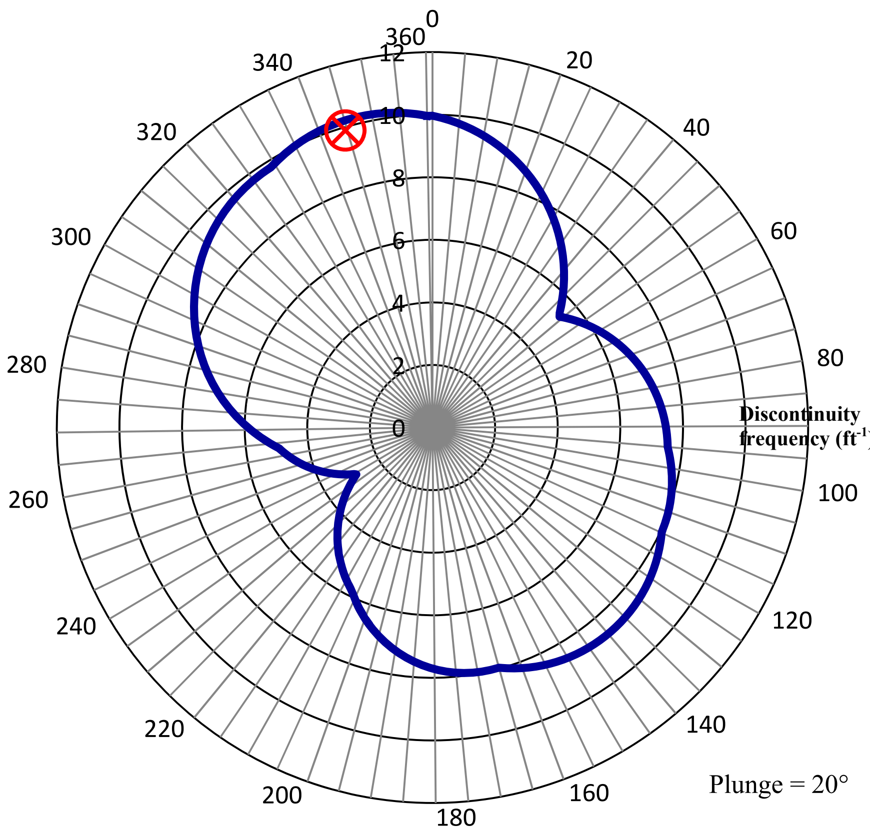

Figure H-2. The discontinuity frequency vector for a sampling line with a trend of 345° and a plunge of 20° is about 10.2 ft^{-1} and is designated by a red-X.

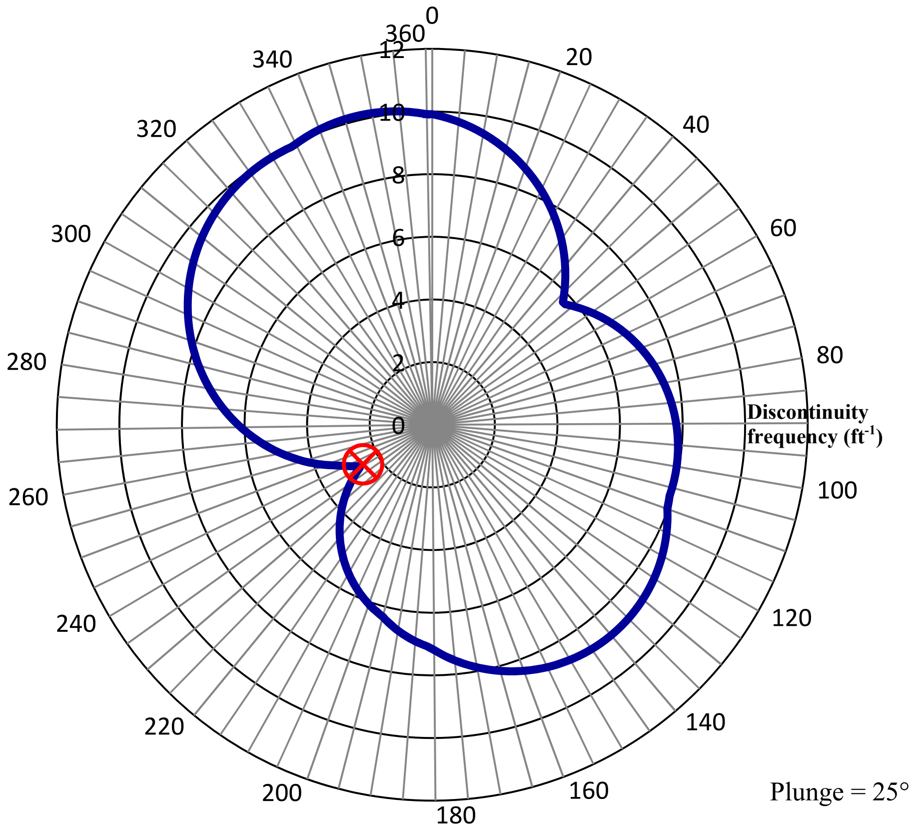

Figure H-3. The discontinuity frequency for a sampling line with a trend of 240° and a plunge of 25° is about 2.7 ft^{-1} and is designated by a red-X.