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Sampling Bias of Discontinuity Orientation Measurements for Rock Slope Design in Linear Sampling Technique : A Case Study of Rock Slopes in Western North Carolina

선형 측정 기법에 의해 발생하는 불연속면 방향성의 왜곡 : 서부 North Carolina의 암반 사면에서의 예

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요 지

불연속면의 방향성은 암반의 과도변형이나 안정성에 영향을 미치는 특성 때문에 암반사면의 안정성 평가에 있어서 매우 중요한 역할을 한다. 불연속면의 방향측정에는 시추공(borehole)을 이용한 측정법이나 노두에서의 scanline을 이용하는 측정법과 같은 선형 측정법이 보편적으로 이용되나 이러한 측정 기법을 이용하여 획득한 자료들은 측선의 방향에 따라 쉽게 왜곡된다. 이러한 왜곡을 수정하기 위한 가중치 (weighting factor)가 적용되어도 특정 방향의 측선을 따라 자료를 획득할 경우 그 왜곡은 쉽게 보정되어지지 않는다. 즉, 불연속면의 방향자료 수집을 위해 이용된 선형 측선이 불연속면의 방향과 평행할 경우 대부분의 측선과 평행한 불연속면들은 조사 결과에 포함되지 않으며 이러한 현상은 불연속면들의 방향성 파악에 심각한 오류를 발생시킬 수 있다.

본 연구에서는 수직 측선(borehole)에 의해 수집되어진 방향자료들과 수평 측선(scanline)에 의해 수집되어진 방향자료들을 비교하였다. 서로 다른 두 방법에 의해 수집되어진 방향자료들은 큰 차이를 보이며, 이로 인해 불연속면들의 대표적인 방향성 결정에 장애가 되어진다. 불연속면의 경사각 분포와 수평과 수직 측선에 의해 수집되어진 자료들의 비교를 위해 등면적 극 평사투영망(polar stereo net)을 이용하였다.

Abstract

Orientation data of discontinuities are of paramount importance for rock slope stability studies because they control the possibility of unstable conditions or excessive deformation. Most orientation data are collected by using linear sampling techniques, such as borehole fracture mapping and the detailed scanline method (outcrop mapping). However, these data, acquired by the above linear sampling techniques, are subjected to bias, owing to the orientation of the sampling line. Even though a weighting factor is applied to orientation data in order to reduce this bias, the bias will not be significantly reduced when certain sampling orientations are involved. That is, if the linear sampling orientation nearly parallels the discontinuity orientation, most discontinuities orientation data which are parallel to sampling line will be excluded from the survey result. This phenomenon can cause serious misinterpretation of discontinuity orientation data because critical information is omitted.

In the case study, orientation data collected by using the borehole fracture mapping method (vertical scanline) were compared to those based on orientation data from the detailed scanline method (horizontal scanline). Differences in results for the two procedures revealed a concern that a representative orientation of discontinuities was not accomplished. Equal-area, polar stereo nets were used to determine the distribution of dip angles and to compare the data distribution for the borehole method versus those for the scanline method.

Keywords : Discontinuity, Linear sampling methods, Sampling bias, Equal areal polar stereonet

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1. Introduction

Both the outcrop mapping method and the borehole sampling method are common procedures used to collect discontinuity characteristics such as orientation, size, frequency and joint surface geometry. In particular, borehole methods can provide valuable information when the area of outcrop is limited and a construction project requires the characteristics of discontinuities in the deep subsurface. In addition, there are a number of rock mechanics tests that can be conducted on drill cores and in boreholes. Therefore, many engineering projects include borehole drilling at the investigation stage and a great number of data and design parameters are provided and estimated based on results of borehole sampling even though the method involves major difficulties. One significant problem is that the core can rotate during drilling. Another difficulty is that the core may be too small to measure discontinuity size.

In contrast, outcrop mapping has the advantage of involving a relatively large volume of rock, which enables the direct measurement of discontinuity characteristics. Additionally, geological and spatial relations between discontinuities are easily observed by using this method. However, if rock faces are damaged or degraded, this method cannot produce good quality data. Outcrop mapping methods, most commonly used, are the scanline method and window sampling techniques.

However, when we utilize both discontinuity orientation data measured by scanline method and borehole method simultaneously, we should note that these two sampling methods collect orientation data based on two different orientations of sampling lines. That is, the fact that the sampling line in borehole method is vertical and the scanline on the rock face is a horizontal line causes serious differences in measured discontinuity orientation data.

In many textbooks and papers, the sampling bias caused by different directions of sampling lines has been discussed. However, the practical examples are quite limited because of lack of measured orientation data from borehole sampling method.

In this paper, the differences and bias caused by different sampling orientation will be discussed by using the discontinuity orientation data obtained from scanline and borehole sampling in roadcuts of Interstate Highway 26 in North Carolina, USA. In addition, the weighting factor for correction of sampling bias and its limitation will be discussed.

2. Sampling Bias in Orientation Data from a Linear Survey

There have been many endeavors to obtain objective and representative orientations, based on measured data from linear sampling methods. As one of the efforts, statistical analysis has been applied and this requires measuring a large number of discontinuities to provide representative orientation data for a rock mass. In outcrop mapping, especially the scanline method, all discontinuities that intersect a sampling line on the rock face are measured for statistical analysis. The sampling line is usually positioned on the rock face either vertically or horizontally. For borehole sampling, all the discontinuities that intersect the borehole are measured and collected.

However, it should be noted that both the borehole and scanline methods are linear sampling procedures and although the linear survey involves an objective sampling approach, a single, linear sampling regime will bias the orientation data. That is, the sampling line tends to intersect preferentially those discontinuities whose normals make small angles to the sampling line (Priest, 1985). Terzaghi (1965) discussed this type of bias, proposing a geometrical correction factor based on the observed angle between the sampling line and the normal to a particular discontinuity. This bias was also discussed by Baecher (1983), Kulatilake and Wu (1984), and Priest (1985).

To illustrate the concept, consider a single set of parallel discontinuities of dip direction/dip amount α_d / β_d. Also assume that the frequency of discontinuities for this set, which is intersected by a sampling line normal to the set, is λ per unit length. A sampling line of general trend/plunge, α_s / β_s, will have a frequency λ_s that is less than or equal to λ and the acute angle between the sampling line and the set normal is δ (Fig. 1). A line of length l, parallel to the set normal, can be expected to intersect a total number N discontinuities given by

$$N = \lambda l \qquad (1)$$

A general sampling line, at angle δ to the set normal would have to be of length l/cos δ and the observed frequency along the sampling line is

$$\lambda_s = \frac{N\cos\delta}{l} \qquad (2)$$

However,

$$\lambda = N/l \qquad (3)$$

so

$$\lambda_s = \lambda \cos\delta \qquad (4)$$

This demonstrates that the number of discontinuities from a given set, intersected by a sampling line that makes an acute angle δ to the set normal, reduces to zero when δ approaches 90°. Therefore, the orientation data from linear sampling lines can be severely biased against fractures that are nearly to the direction of sampling.

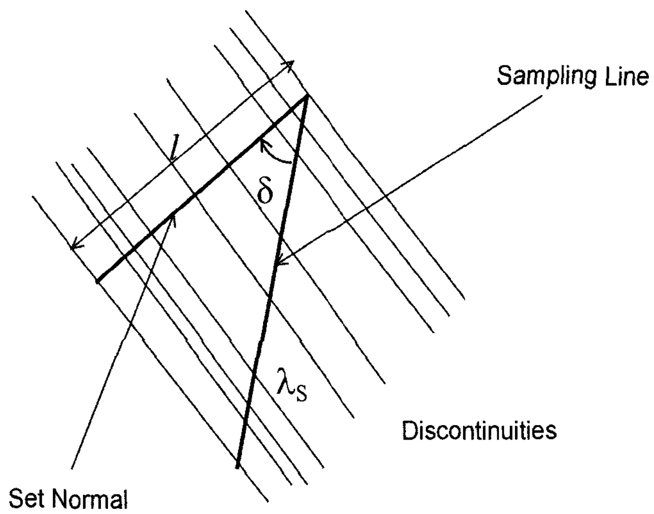


Fig. 1. Discontinuity set intersected by a sampling line of general orientation(after Priest, 1985)

3. Sampling Bias of Orientation Data Observed in Case Study

3.1 Site Introduction

The orientation data utilized in this paper were measured from roadcuts and outcrops of Interstate Highway 26 in North Carolina. This site is under construction to improve from state road 23 to Interstate Highway 26 (Fig. 2). Interstate 26 will traverse through mountainous terrain with rock cuts exceeding 120 m in depth. To design the safest and most economic slopes, a large amount of geological and geotechnical data was obtained.

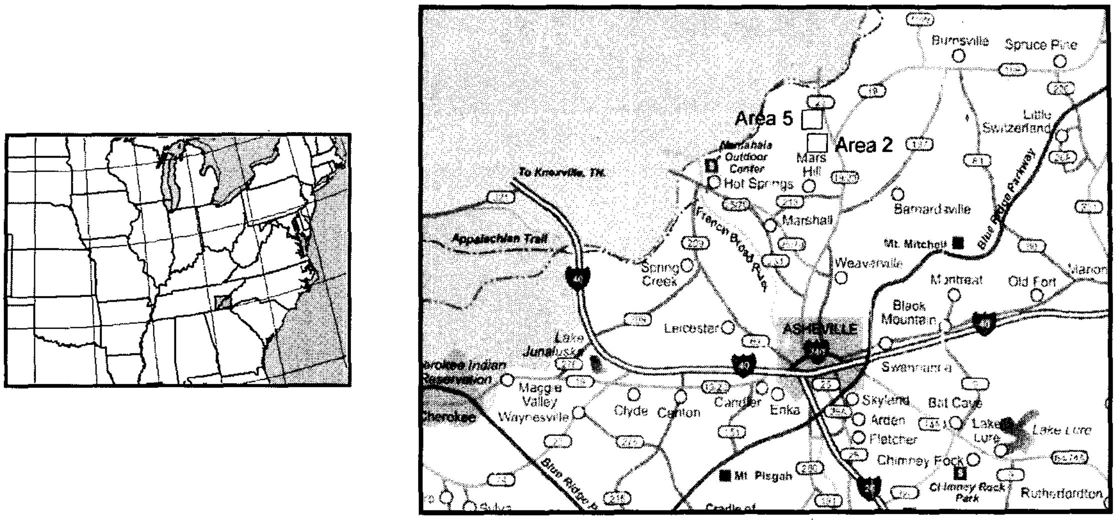


Fig. 2. Locations of study area

The predominant rock types of the site are granite, gneiss, and pegmatite. The foliations which are the predominant discontinuities in this area and also in gneissic rock, typically trend in a southeast direction with steep dip angle. This orientation creates many planes that daylight into the western slope face which could have the potential for failure. Folding has caused many variations in these directions, which is evident in the rock core as it changes depth and location. Uniaxial compressive strength tests on intact rock samples yielded strengths that ranged from 27 MPa to 206 MPa (Beard, 1997).

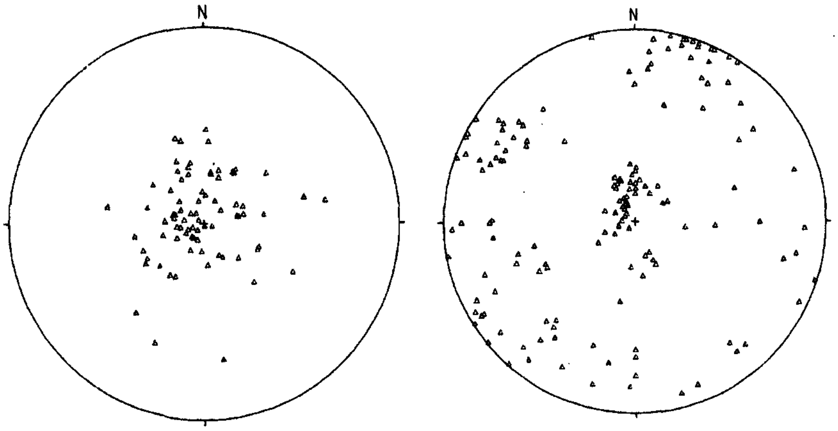
The two different study areas (Area 2 and 5 in the construction site) were selected for this case study since sufficient discontinuity orientation data which were measured from field mapping of outcrops and logging of rock core holes, were provided. In the borehole mapping method, rock core was placed in a goniometer and reoriented, so the dip and dip direction of discontinuities could be recorded (Beard, 1997). The other set of discontinuity data was measured directly from outcrops.

3.2 Sampling Bias of Discontinuity Orientation

As those data sets were acquired by two different linear sampling methods, the data might be biased by the orientations of the respective sampling lines. That is, the orientation of the sampling line in the borehole method is usually vertical and the scanline on the rock face is generally a horizontal directional line, so the data from borehole and outcrop could be affected by each direction of the sampling line: vertical and horizontal respectively. Therefore, prior to identifying sets and determining representative orientation data to be utilized in a rock mass stability analysis, the sampling bias caused by different directions of sampling lines should be scrutinized and corrected, if possible.

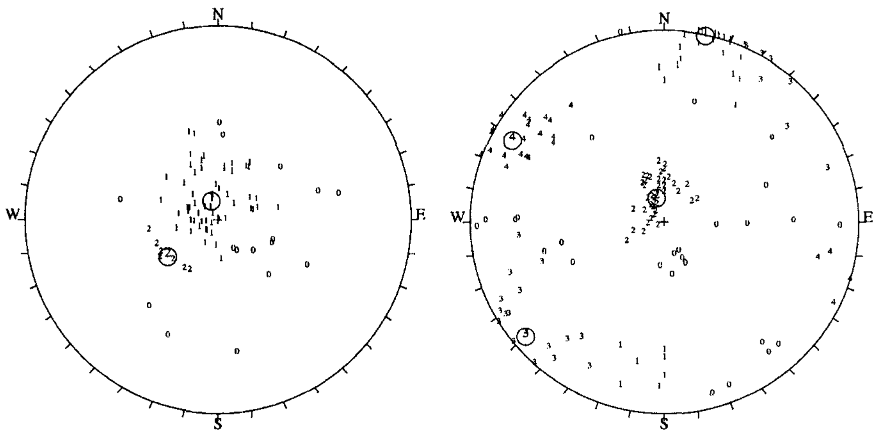
In order to compare the differences of orientation distribution, which were caused by different sampling lines, the measured orientations were plotted on two different equal-angle stereonets. Figures 3(a) and, (b) are lower hemisphere projections of discontinuity normals measured from borehole sampling and scanline sampling in Area 2 of Interstate 26 respectively. In Fig. 3(a), based on borehole sampling, note that there are a large number of poles of discontinuity normals near the center of the projection and very few poles are located near the circumference. In contrast, many poles in Fig. 3(b) are located near the circumference but the poles are distributed uniformly as compared to Fig. 3(a). This phenomenon is caused by the sampling bias explained previously, so the borehole method gives preference to discontinuities showing a horizontal orientation, whereas vertical discontinuities are given preference in the scanline method.

To compare the two sets of stereonets before correcting any bias, without any further processing and operation, the orientation data were analyzed by clustering. This is appropriate, as any significant preferred orientations should be apparent as clusters of normals in a stereonet. The orientation limits for each discontinuity set were identified by applying the clustering algorithm proposed by Shanley and Mahtab (1976), Mahtab and Yegulalp (1982), and Priest (1993). Figures 4(a) and (b) are stereo projections of clustered discontinuity normals collected from borehole and scanline survey in Interstate 26 Area 2. As observed in Figures 4(a) and (b), clustered sets in hemisphere projections are obviously different for the two stereonets. In Fig. 4(a), two discontinuity sets are shown with both having lower dip angles compared with the joint sets in Fig. 4(b). Joint set 1 (J1) has a mean dip direction and dip value of 160/22 and joint set 2 (J2) has 54/36. However, most joint sets in Fig. 4(b) have steep dip angles; J1 (192/89), J3 (50/86), and J4 (118/83). Only J2 has a low dip angle and this seems to be the same set as J1 in Fig. 4(a). These significant differences are apparently due to missing discontinuity poles which would be located near the circumference in Fig. 4(a). In other words, the discontinuities whose dip angles are relatively steeper are selectively omitted when the orientations are measured by borehole sampling.



(a) borehole method (b) scanline method in I-26 Area 2

Fig. 3. Lower hemisphere projections of discontinuity normals measured



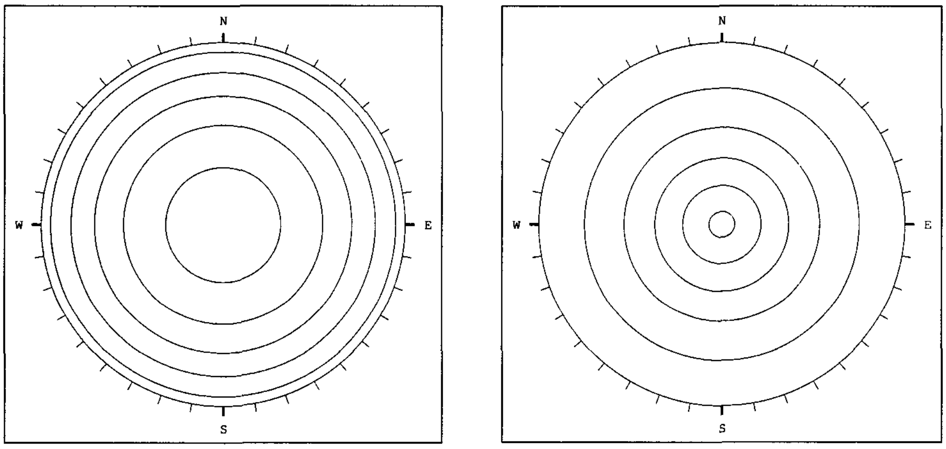
(a) borehole method (b) scanline method in I-26 Area 2

Fig. 4. Lower hemisphere projections of clustered discontinuity normals measured

3.3 Contoured Equal Area Polar Diagram

The relationship between measurement methods and distributions of poles can be clearly illustrated by polar diagrams (Terzaghi, 1965). Therefore, poles of the collected discontinuity normals are plotted on an equal-area polar diagram to analyze this relationship. Poles are uniformly distributed in an equal area polar diagram if the joint surveys are performed on outcrops and the outcrops are numerous with random orientation. In contrast, if the observations are made by the scanline method on a horizontal surface or the borehole method is used, joints with specific directions are not observed and unrecorded in the polar diagrams.

When α is considered as the acute angle between the discontinuity and the sampling line, the number of intersections between the sampling line and joints in a given spacing is proportional to the sine of angle α of intersection. In a polar diagram, the successive contours, starting from the direction of sampling line, can be drawn as the loci of poles of joints which intersect the sampling line at angle α such as sin α is 0.1, 0.3, 0.5, 0.7, and 0.9 respectively. Such lines are called isogonic (equal angle) lines (Terzaghi, 1965). Figures 5(a) and (b) are idealized, contoured-diagrams of random joints observed in a vertical drill hole and on a horizontal outcrop, respectively. That is, in Fig. 5(b), the orientation of horizontal sampling line is plotted on the center of stereonet. Therefore, the discontinuities that have large α angle and have steep dip angles are plotted around the circumference of the stereonet. The discontinuities that have gentle dip and therefore have small α angle are plotted near the center of stereonet. In contrast, the orientation of vertical sampling line is plotted on the circumference of stereonet in Fig. 5(a). That is, the discontinuities which have gentle dip angles and therefore have large α angle, are plotted near the center of stereonet. Therefore, for example, if discontinuities measured by the scanline method are plotted on Fig. 5(b), many more poles will be on the isogonic line for sin α = 1.0 (the circumference of the circle) than on the line for sin α = 0.1. This is because the steeply dipping discontinuities are collected selectively in the scanline method. Similarly, a large number of poles measured from the borehole are located on the isogonic line for sin α = 1.0 and few poles are located on the sin α = 0.1; in Fig. 5(a), a large number of poles are plotted near the center of circle, which is due to sampling bias.

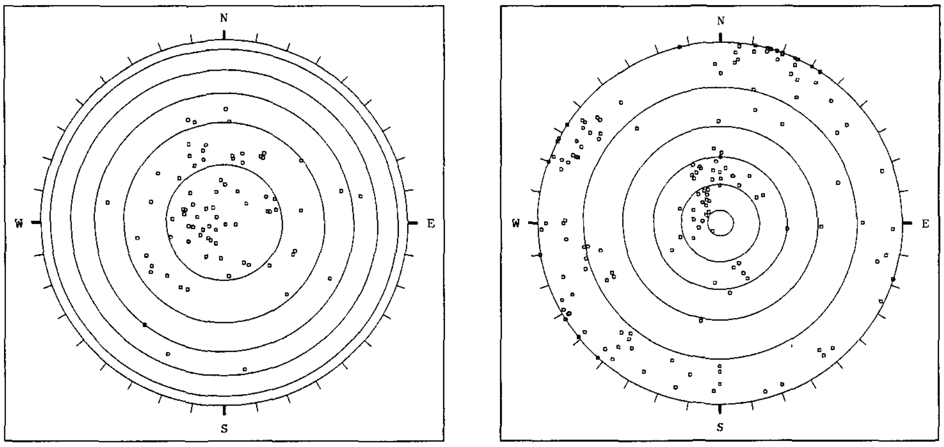


(a) in a vertical drill hole (b) on horizontal outcrop (after Terzaghi, 1965)

Fig. 5. Idealized contoured polar diagram of observation

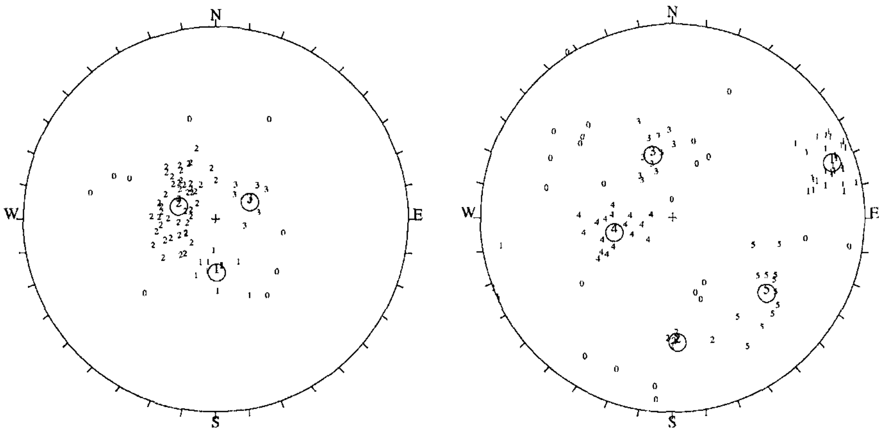
3.4 Analysis of Measured Orientation Data

Figures 6(a) and (b) are contoured polar diagrams of discontinuities sampled by the borehole method and the scanline method in Interstate 26 Area 2. As observed in Fig. 6(a), few poles of discontinuities are located on the circumference of stereonet which means that steeper joints are omitted while others are recorded preferentially. There are no poles between the isogonic line for sin α = 0 and sin α = 0.3 in Fig. 6(a), that is, there are no poles whose dips range from 73° to 90° or all the poles whose dip angles range from 73° to 90° are omitted. However, in Fig. 6(b) the proportion of those poles whose dips lie between 73° to 90° is almost 52% of all discontinuities recorded from outcrops. Therefore, there is a major difference which indicates that the two different orientations of sampling lines yield significantly different results. According to the author's field survey and measurement in this research area (Park, 1999), the discontinuities that have steep



(a) borehole method (b) scanline method in I-26 Area 2

Fig. 6. Contoured polar diagrams of discontinuity observed

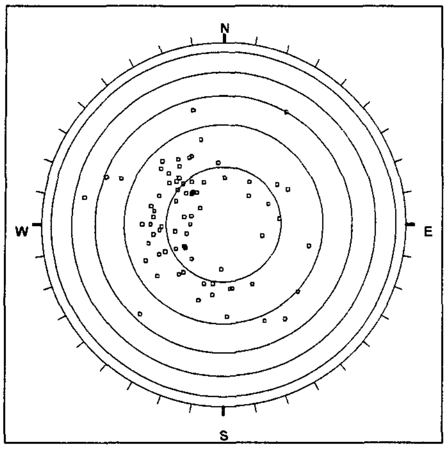


(a) borehole method (b) scanline method in I-26 Area 5

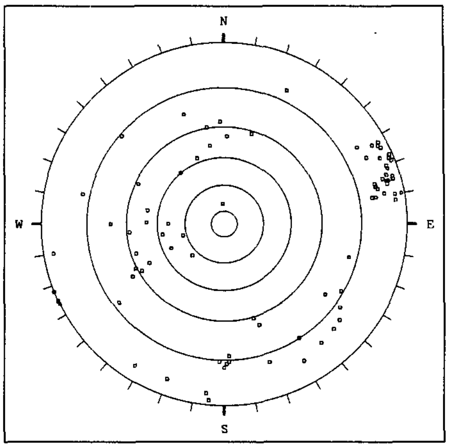
Fig. 7. Lower hemisphere projections of clustered discontinuity normals measured

dip angles, are common and predominant in field. Consequently, a large number of the steeply dipping discontinuities exist in the field but were not observed along the vertical sampling line. Therefore, this fact shows that after collecting discontinuity orientation data, the feasibility of orientation data should be evaluated and sampling bias should be corrected.

Figures 7(a) and (b) are stereo projections of clustered discontinuity normals for Interstate 26 Area 5. Fig. 7(a) is based on data obtained from the borehole sampling method and Fig. 7(b) is based on outcrop mapping. To examine the distribution of dip angles, data were plotted on contoured polar diagrams (Figures 8(a) and (b)). In these diagrams, orientation data which lie nearly parallel to the sampling line will not likely to be observed, as indicated by previous results. There are no poles with dip angles ranging from 70° to 90° in Fig. 8(a), however, the proportion of those poles is approximately 55% of all data in Fig. 8(b). Again the steeply dipping joints are not observed in borehole sampling. However, for the case of gently dipping discontinuities, the proportions of poles with dip angle less than 20° are 10 % versus 4 % in Fig. 8(a) and (b) respectively. This result is not as different as for the steeper poles, that is, based on the results of borehole sampling. Therefore, it could be said that the actual proportion of gently dipping joints in field is small so that the sampling result for gently dipping joints in the scanline method is more similar to the sampling result for gently dipping joints measured by borehole in this result. That is, the outcrop mapping method does not contribute as serious a bias as does the borehole method. Consequently, data from outcrop mapping in this case are less biased than those obtained by borehole mapping.



(a) borehole method



(b) scanline method in I-26 Area 5

Fig. 8. Contoured polar diagrams of discontinuity observed

3.5 Weighting Factor for Correction of Sampling Bias

The weighting factor, ω, is proposed by several researchers (Terzaghi, 1965; Goodman, 1976; Priest, 1985) to reduce the sampling bias. The concept of this factor is that the reduced sample size at the lower values of α can be compensated for, by assigning a higher weighting factor to those discontinuities (Priest, 1993). The weighting factor is given by

$$\omega = \frac{1}{\sin\alpha}, \qquad \alpha < 90° \qquad (5)$$

Priest (1993) suggested that this weighting would tend to balance the orientation sampling bias introduced by linear sampling for a large sampling size.

The authors applied this weighting factor to orientation data to reduce sampling bias observed in orientation data from borehole in Area 2 and 5. Therefore, all orientation data collected from boreholes were multiplied by this factor, then the corrected data were plotted on the stereonets and clustered by the same algorithm mentioned previously (Figures 9 and 10). However, the results of clustering the weighted data do not show any difference from those obtained by unweighted data. Consequently, the sampling bias in the borehole data was not significantly reduced by this weighting factor. In particular, for steeply dipping discontinuities, the measured orientation data seem to be too sparse to correct the bias in a joint survey. Therefore, another concept should be considered to correct sampling bias and evaluate this concern.

3.6 The Concept of Blind Zone

Terzaghi (1965) realized that the orientation data with small α angles to the sampling line were not observed and introduced the blind zone concept to explain these effects. She suggested that observations of joint orientation should be made at a moderately high angle, not less than about 30°, to prevent this effect. Goodman (1976) and McEwen (1980) subsequently estimated the size of the blind zone at 20°. Accordingly, any discontinuity within 20° or 30° from a borehole would be in the blind zone of the borehole. Therefore, the blind zone of borehole data on hemisphere projection can be applied to the stereonet by drawing a great circle 90° from the axial point of borehole. The zone is widened about ± 30° from the great circle on the stereonet. In contrast, the blind zone in outcrop horizontal mapping on the stereonet can be considered by applying a small circle of 30° from the center of stereonet. It should be noted that the blind zone does not depend on the data; it is instead a characteristic of the data source that affects the data (Yow, 1987).

When plots of discontinuities on hemisphere projections are examined in this research, the size of the blind zone in borehole data seems to be about 30° . However, there are no poles within 20° of borehole direction in Fig. 6(a) and Fig. 8(a). Nonetheless, it can be widened to 30° because in Fig. 6(a), only 3 orientation data points (about 4% of the total data) is within 30° from the borehole and in Fig. 8(a) only 1 data point (only 1% of the total data) is in the same zone. By contrast, when the outcrop mapping data are considered, it does not appear that the measured orientation data from outcrop mapping contain a blind zone. This is because 46 orientation data points and 11 data points, about 30% and 11% respectively of their total data, occur within 30° to sampling line in Figures 5(b) and 6(b) respectively. Even if a 20° blind zone is considered, 23 and 4 data points occur in blind zones, respectively.

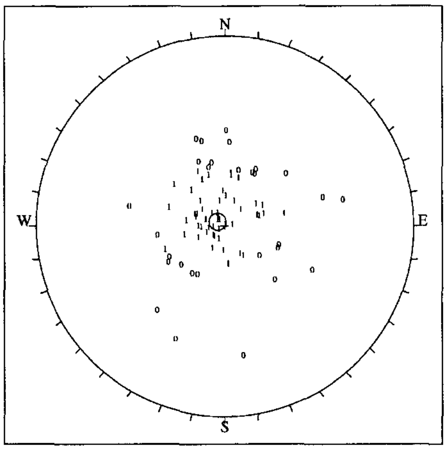


Fig. 9. Lower hemisphere projection of discontinuity normals, **weighted** and clustered in I-26 Area 2

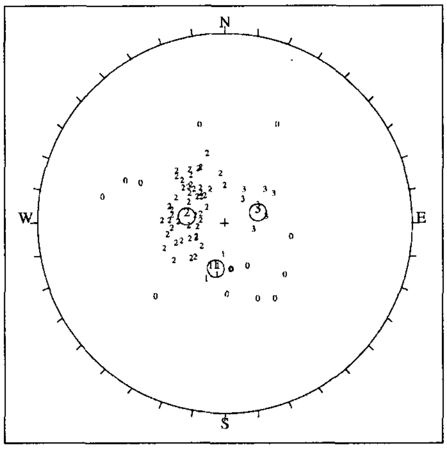


Fig. 10. Lower hemisphere projection of discontinuity normals, **weighted** and clustered in I-26 Area 5

On the whole, a large number of discontinuities with dip angles ranging from 60° to 90° (that is, α angles ranging from 0° to 30° in borehole data) in the field area were not observed and consequently not recorded due to the blind zone. As discussed previously, this effect limits the application of the weighting factor and correction of sampling bias.

According to the author's field mapping and reconnaissance in the exposed rock cut, the dominant discontinuity sets typically have a steep dip angle of about 84° (Park, 1999). Therefore, based on this experience and current analysis of orientation data, outcrop mapping is the more reliable source of orientation data for rock slope stability analysis because of two reasons: 1) results of the author's field experience and mapping are similar to the results of outcrop mapping. 2) As indicated in current research, for this location, orientation data from outcrop mapping are less biased than data from borehole sampling. For these reasons, more emphasis is placed on orientation data for discontinuity sets from outcrop mapping.

3.7 Comparison with Measured Orientation Data from Road Cut

The authors surveyed and measured discontinuity orientation data along a 100 m road cut in the Interstate 26 Area 2. The author's measurements are based on the scanline method for the road cut showing a straight extension in one direction. About 100 orientation data were collected. As observed in Fig. 11, the result of clustering based on these measurements, is similar to clustering result in Fig. 4(b), except joint set 3. That is, the discontinuity normals that were clustered in joint set 3 in Fig. 4(b) did not show up and were not clustered into a set in Fig. 11 A similar omission was observed in the plot of foliation orientation data measured from a straight extension of road cut. Fig. 12 shows the clustering results of foliation orientation data obtained from road cut in Area 2. Comparing Fig. 12 to Fig. 13, which is the clustering results of foliation data measured from outcrop in the same area, discontinuity normals did not plot around the dotted line in Fig. 12 The attitude of joint set

3 in Fig. 4(b), which does not appear in Fig. 11, seems to occur along the direction of the dotted line in Fig. 12 Therefore, omission of discontinuity normals in Fig. 11 and 12 could be due to the same cause, that is, the blind zone. As author's measurements are based on the scanline method for the road cut showing a straight extension in one direction, all data are measured along the same scanline direction. This may give rise to the blind zone effect. A fact that tends to support this idea is that the scanline orientation corresponds to the direction of the dotted line (Park, 1999). Terzaghi (1965) mentioned this possibility; "If there is a marked lack of balance in the distribution among outcrops, blind spot joints may be underestimated."

4. Conclusions

The orientation of discontinuities is one of the most important factors that control the rock slope stability. Most orientation data are collected by using linear sampling techniques, but these data are easily subjected to bias caused by the orientation of the sampling line. In order to reduce this bias, a weighting factor has been proposed but if the linear sampling orientation nearly parallels the discontinuity orientations, most discontinuity orientations which are parallel to sampling line are excluded from the survey result.

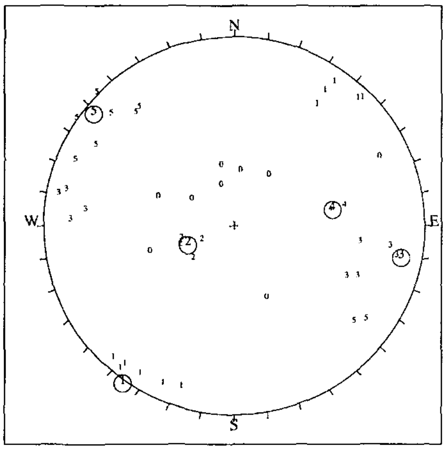


Fig. 11. Lower hemisphere projection of clustered discontinuity normals for joints in I-26 Area 2 measured from a straight road cut

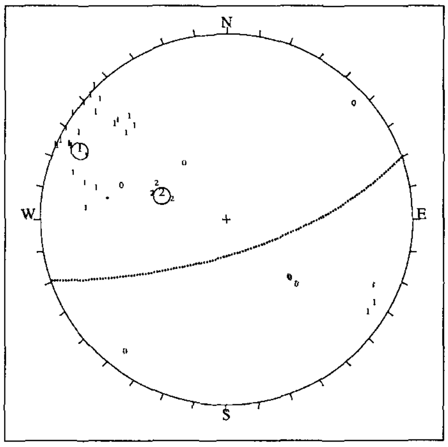


Fig. 12. Lower hemisphere projection of clustered discontinuity normals for foliations in I-26 Area 2 measured from a straight road cut

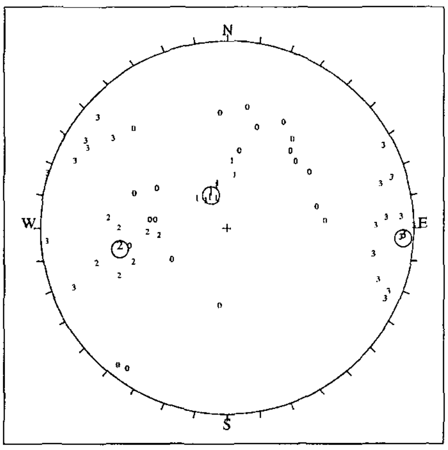


Fig. 13. Results of clustering process of foliation normals in I-26 Area 2 measured from outcrops

Based on a field survey of a completed road cut, steeply dipping joints are quite common in the study area. However, most of these steeply dipping joints were omitted from the polar diagram by using the borehole sampling technique, and differed significantly from the polar diagrams obtained from the horizontal scanline survey. This omission and bias yield a blind zone of absent data, due to the relative orientation of borehole and the discontinuities. This may yield significant loss of fracture data, overlooking important fracture orientations. Therefore, discontinuity orientation data must be evaluated with respect to data from field exposures before analyzing that data set for slope stability purposes. Sampling methods must be devised which will minimize this sampling bias.

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