A New Method for Characterization of Discontinuity Based on Digital Borehole Camera Technology

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Abstract

Digital Borehole Camera Technology is an advanced method for engineering geologic investigation, which can identify a large number of subsurface rock discontinuities and calculate the geometric parameters. With the characteristics of big number, accurate and deep buried, these parameters reveal the spatial distribution and combination form. A new mathematics description method is proposed based on discontinuities characteristic points which include information of occurrence and depth. Then, this method is used for research in connectivity of discontinuities and gets some innovative research results. This research provides new ideas for stability evaluation of rock mass based on discontinuities geometrical characteristics.

Keywords: structural plane, Digital Borehole Camera Technology, discontinuity characteristic points

1. Introduction

Rock mass is a geologic body composed of rock blocks and structural plane which split rock (Also known as discontinuity). The distribution and combining form of structural planes in space formed the structure of rock masses, which is the critical factor of engineering geological characteristics and mechanical property of rock masses. Only a few structural planes developed in rock masses can be seen from outcrop rock area or artificial excavation face, however, more of the structural planes are in the interior of rock masses and very difficult to be observed directly. [2-4] Digital Borehole Camera Technology provides a new method to explore structural planes in the interior of rock masses. It can go deep into rock masses through borehole, identify the structural plane and calculate the geometric parameters. By this technology, greater number and more accurate data will be given for the research on statistical regularities of structural plane. [5-6]

There are many differences between structural plane data obtained from outcrop rock and borehole. For example, the former data contains information of trace length but does not contain information of depth; however, the latter contains information of depth but does not contain information of trace length. So the traditional analytical methods used in outcrop rock data are not applicable to the data from borehole. In view of the above considerations, this paper put forward a new method suitable for the structural plane data obtained from borehole. This method transforms the structural plane geometric parameters into coordinate point, and every coordinate point is the comprehensive performance of geometric parameters. It makes structural plane data more numerical and easier to carry out statistical analysis. [7-8]

2. Characterization of Discontinuity in Borehole

2.1 Basic assumption

Geometric feature of structural plane is the foundation to research mechanical properties of rock masses. The most basic geometric parameters include occurrence, width, space, trace length etc. In order to transform and analyze these geometric parameters, we firstly make the following assumptions:

(1) The structural plane is a space plane of unlimited extension;

(2) Using the right hand rule of 3D Descartes coordinate system.

2.2 Discontinuity characteristic point under local coordinate system

To establish local coordinate system, we choose the center of borehole orifice to be the base point of coordinate system. The positive X axis points to the East, the positive Y axis points to the North and the positive Z axis points to Vertical.

Describing the structural plane in three-dimensional space with a point, we call this point structural plane characteristic point and denote it by Pc defined as the crossover point between structural plane and normal vector (i.e. plane normal) of structural plane from base point of coordinate system. There are one to one corresponding features of structural plane and structural plane characteristic point, reflecting the space form and space position of structural plane.

Setting Pc coordinate as (Xc, Yc, Zc), the equation described by this point is:

$$X_c \bullet (x - X_c) + Y_c \bullet (y - Y_c) + Z_c \bullet (z - Z_c) = 0 \quad (2.1)$$

Also can be expressed as:

$$X_c \bullet x + Y_c \bullet y + Z_c \bullet z - (X_c^{\,2} + Y_c^{\,2} + Z_c^{\,2}) = 0 \quad (2.2)$$

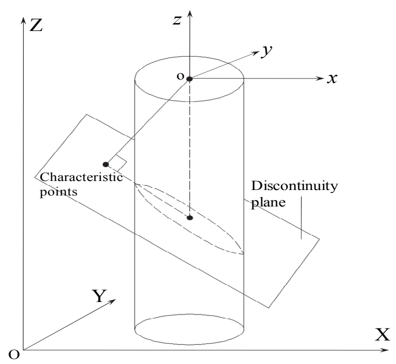


Fig.1 Schematic description of structural plane characteristic point

Setting the dip direction of structural plane described by characteristic point as α, the dip as β and the crossover point between Z axis and structural plane as R_z, the equations of these parameters are:

$$\alpha = \arctan\frac{Y_c}{X_c}$$
$$\beta = \arctan\left(\frac{\sqrt{X_c^{\,2} + Y_c^{\,2}}}{Z_c}\right) \quad (2.3)$$
$$R_z = \frac{X_c^{\,2} + Y_c^{\,2} + Z_c^{\,2}}{Z_c}$$

Or as below:

$$X_c = R_z \bullet \cos\beta \bullet \sin\beta \bullet \cos\alpha$$
$$Y_c = R_z \bullet \cos\beta \bullet \sin\beta \bullet \sin\alpha \quad (2.4)$$
$$Z_c = R_z \bullet \cos\beta \bullet \cos\beta$$

Through the above conversion formula, the geometric parameters (dip, dip direction and depth) will be converted into characteristic point coordinates under the local space coordinate system.

2.3 Discontinuity characteristic point under global coordinate system

To establish global coordinate system, we choose orifice of the borehole at center of area or representative borehole to be the base point of coordinate system. The positive X axis points to the East, the positive Y axis points to the North and the positive Z axis points to Vertical.

Information of discontinuity characteristic point obtained in the previous section is calculated under the respective local coordinate system. In order to establish the relationship between different characteristic points, these information need normalization processing under global coordinate system. Supposing the origin point of local coordinate system is $P_{LO}(X_{LO}, Y_{LO}, Z_{LO})$ under global coordinate system, the discontinuity characteristic point $P_{CL}(X_{CL}, Y_{CL}, Z_{CL})$ under local coordinate system will be transformed into $P_{CL}'(X_{CL}', Y_{CL}', Z_{CL}')$ under global coordinate system. The conversion equations are as below:

$$X_{CL}' = X_{LO} + X_{CL}$$
$$Y_{CL}' = Y_{LO} + Y_{CL}$$
$$Z_{CL}' = Z_{LO} + Z_{CL} \quad (2.5)$$

The equation of structural plane under global coordinate system OXYZ is as below:

$$(P_{LO} - P_{CL}')(P - P_{CL}') = 0 \quad (2.6)$$

Hereinto, the point P is any point in global coordinate system OXYZ.

In addition, unit normal vector of structural plane is the same, as below:

$$\vec{n} = (X_{CL} / root, Y_{CL} / root, Z_{CL} / root) \quad (2.7)$$

Hereinto, $root = \sqrt{X_{CL}^{\,2} + Y_{CL}^{\,2} + Z_{CL}^{\,2}}$

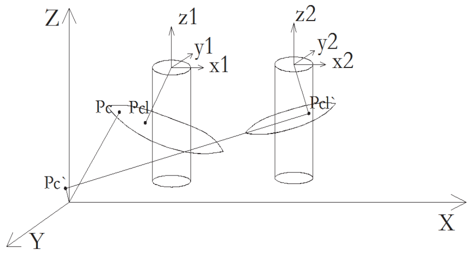


Fig.2 Discontinuity characteristic point under global coordinate system

Therefore, coordinate value of any point P(X, Y, Z) at the normal of structural plane from origin point of global coordinate system OXYZ is as below:

$$\begin{aligned} X &= t \bullet X_{CL} / root \\ Y &= t \bullet Y_{CL} / root \\ Z &= t \bullet Z_{CL} / root \end{aligned} \quad (2.8)$$

Hereinto, t is arbitrary value.

Take this formula 2.8 into formula 2.1, the value of t can be calculated as below:

$$t = root \bullet (1 + (X_{CL} \bullet X_{LO} + Y_{CL} \bullet Y_{LO} + Z_{CL} \bullet Z_{LO})) \quad (2.9)$$

The insertion point between normal of structural plane (discontinuity) from origin point and structural plane under global coordinate system OXYZ can be obtained. The coordinate of this point $P_c(X_c, Y_c, Z_c)$ will be calculated by characteristic point $P_{CL}(X_{CL}, Y_{CL}, Z_{CL})$ and origin point $P_{LO}(X_{LO}, Y_{LO}, Z_{LO})$ under local coordinate system.

$$\begin{aligned} X_c &= X_{CL} \bullet (1 + \frac{X_{CL} \bullet X_{LO} + Y_{CL} \bullet Y_{LO} + Z_{CL} \bullet Z_{LO}}{X_{CL}{}^2 + Y_{CL}{}^2 + Z_{CL}{}^2}) \\ Y_c &= Y_{CL} \bullet (1 + \frac{X_{CL} \bullet X_{LO} + Y_{CL} \bullet Y_{LO} + Z_{CL} \bullet Z_{LO}}{X_{CL}{}^2 + Y_{CL}{}^2 + Z_{CL}{}^2}) \\ Z_c &= Z_{CL} \bullet (1 + \frac{X_{CL} \bullet X_{LO} + Y_{CL} \bullet Y_{LO} + Z_{CL} \bullet Z_{LO}}{X_{CL}{}^2 + Y_{CL}{}^2 + Z_{CL}{}^2}) \end{aligned} \quad (2.10)$$

3. Discontinuity Connectivity Analysis Based on Characteristic Point

3.1 Introduction

In the engineering geological survey, in order to identify the geological conditions of a region, several boreholes need to be drilled. Structural plane is a geological interface with a certain size, which may be penetrated by more than one borehole. Therefore, when using borehole camera technology to detection discontinuities, different cutting trace of the same discontinuity may be seen in adjacent boreholes. The above is the principle of discontinuity connectivity analysis. [1]

Under global coordinate system, two fractures P_1, P_2 in adjacent boreholes are indicated by characteristic points coordinate $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$. The distance between two characteristic points can be expressed as below:

$$|P_1P_2| = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \quad (2.11)$$

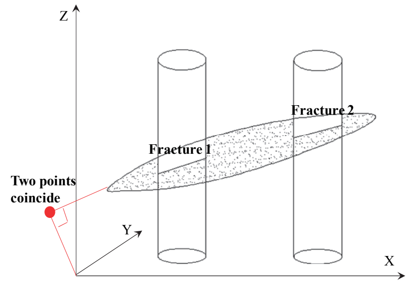


Fig.3 Sketch map of discontinuity connectivity analysis

Every fracture has the only corresponding characteristic point coordinate under global coordinate system. Under ideal condition, if the distance of two characteristic points is zero (namely the two points coincided), these two fractures may be belong to the same structural plane (namely they have connectivity), as shown in Fig.3. But in the actual situation, due to the measurement precision and error limit, the two points are impossible to completely coincide. Therefore, a minimum is setting as the criterion whether they have connectivity and the formula is as below:

$$\begin{cases} |P_1P_2| \le \varepsilon & P_1、P_2 \text{ have connectivity} \\ |P_1P_2| > \varepsilon & P_1、P_2 \text{ not have connectivity} \end{cases} \quad (2.12)$$

The value of ε will be setting based on required computational accuracy.

$|P_1P_2|$ is the distance between two fractures characteristic points. If the value of $|P_1P_2|$ is less than ε, the two fractures may be belong to the same structural plane. With the further analysis on rock feature up and down the structural plane, the result will be confirmed. If the value of $|P_1P_2|$ is greater than ε, the two fractures are not on the same plane.

3.2 Case analysis

Taking boreholes of a hydropower station dam foundation grouting test as an example, connectivity analysis between adjacent boreholes is carried out based on the above method. The location of boreholes in this engineering field is shown as Fig.4. The origin point of local coordinate system is setting at the center of every borehole orifice. According to the principle of middle construction, the origin point of global coordinate system is setting at the center of borehole DJ-1 orifice. The positive X axis points to the East, the positive Y axis points to the North and the positive Z axis points to Vertical.

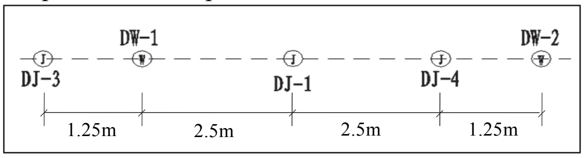


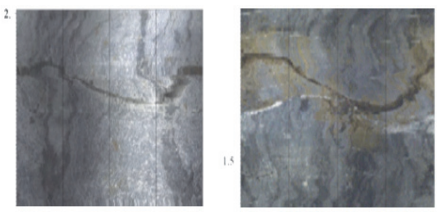
Fig.4 Location of boreholes

Fracture P_1 is located in borehole DW-1 with dip direction of SW238.5°, dip of 50° and depth of 2.164m. Fracture P2 is located in borehole DJ-3 with dip direction of SW228.4°, dip of 55.3° and depth of 1.316m. Transforming the parameter information into characteristic point under local coordinate system, we can get the coordinates are P_{1CL} (0.908, 0.557, -0.894), P_{2CL} (0.461, 0.409, -0.426). Then we can get the normalized coordinates P_1 (-1.874, -2.518, 1.845), P_2 (-1.832, -2.514. 1.842) through transforming under global coordinate system.

The distance of the two points P_1P_2 is as below:

$$|P_1P_2| = \sqrt{(-1.874+1.832)^2+(-2.518+2.514)^2+(1.845-1.842)^2} = 0.042$$

Assuming the judgment standard of connectivity is ε=0.1, the distance of the two points P_1P_2 is less than this standard. Therefore, we can initially determine that these two fractures may belong to a same discontinuity. Through observing the rock feature around the fractures, they are both gray rock, the lithology is very similar and the width are 7.13mm and 7.26mm. In the end, through the above analysis, we can basically determine that these two fractures have connectivity and belong to a same discontinuity. The images of these two fractures are as below:



Fracture 1 in DW-1 Fracture 2 in DJ-3

Fig.5 The two connected fractures in adjacent boreholes

4. Conclusions

According to the particularity of structural plane in borehole, a new mathematical description method is proposed based on characteristic point and the conversion formula for transforming geometric parameters into characteristic point coordinate is derived. This method is applied to fractures connectivity analysis and the connectivity condition is developed. Though the case analysis, this method is proved correct and feasible.

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