Computers & Geosciences 56 (2013) 56–61

Contents lists available at SciVerse ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Orientation uncertainty goes bananas: An algorithm to visualise the uncertainty sample space on stereonets for oriented objects measured in boreholes

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ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form
1 March 2013
Accepted 5 March 2013
Available online 14 March 2013

Keywords:
Drillcore
Borehole
Orientation uncertainty
Sample space
Stereographic projection
Algorithm

ABSTRACT

Measurements of structure orientations are afflicted with uncertainties which arise from many sources. Commonly, such uncertainties involve instrument imprecision, external disturbances and human factors. The aggregated uncertainty depends on the uncertainty of each of the sources. The orientation of an object measured in a borehole (e.g. a fracture) is calculated using four parameters: the bearing and inclination of the borehole and two relative angles of the measured object to the borehole. Each parameter may be a result of one or several measurements. The aim of this paper is to develop a method to both calculate and visualize the aggregated uncertainty resulting from the uncertainty in each of the four geometrical constituents. Numerical methods were used to develop a VBA-application in Microsoft Excel to calculate the aggregated uncertainty. The code calculates two different representations of the aggregated uncertainty: a 1-parameter uncertainty, the 'minimum dihedral angle', denoted by Ω; and, a non-parametric visual representation of the uncertainty, denoted by χ. The simple 1-parameter uncertainty algorithm calculates the minimum dihedral angle accurately, but overestimates the probability space that plots as an ellipsoid on a lower hemisphere stereonet. The non-parametric representation plots the uncertainty probability space accurately, usually as a sector of an annulus for steeply inclined boreholes, but is difficult to express numerically. The 1-parameter uncertainty can be used for evaluating statistics of large datasets whilst the non-parametric representation is useful when scrutinizing single or a few objects.

1. Introduction

Today, construction of underground facilities, such as tunnels for cars and trains, electricity cables or fresh/waste water are widespread. Examples of future, more challenging, constructions are the planned deeply seated, geological repositories for spent fuel from nuclear-power plants. For such constructions, not only the constructability is important, but also the possibility to predict the long-term behaviour from a safety aspect. A key to a successful construction and safety assessment is a well performed investigation of the rock, where the properties are accurately characterized. Together with size, intensity and spatial correlation, information about orientation of geological features such as fractures, foliations and rock contacts are important for stability, flow and transport modelling. The information is preferably acquired from the intended depth of the facility, but in advance of any excavated tunnel the only possibility to obtain direct information is through boreholes.

Gathering data to orient objects seen in a borehole does not only entail consideration of the measure of the orientation and the uncertainty of the object relative to the borehole, but also the measured orientation and uncertainty of the borehole itself.

The orientation uncertainty of a fracture is twofold. On the one hand it tends to blur an orientation model towards less concentrated or erroneously oriented set divisions. On the other hand, it might explain outliers that do not fit a conceptual model. In other words, the uncertainty is not necessarily a curse, but can be a solution in some situations. Consequently, it is very important to neither overestimate nor underestimate the sample space of the uncertainty. When analyzing the data, the estimated uncertainty can be used to rank the measured data and thus develop more accurate models of the rock.

Bleakly et al. (1985a, 1958b) and Nelson et al. (1987) attempted to estimate the magnitude of orientation uncertainty for fractures using a mechanical goniometer on oriented cores. The uncertainty was a rough estimation by simply adding scalar values to a one parameter uncertainty. However, to our knowledge no one has

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http://dx.doi.org/10.1016/j.cageo.2013.03.001

previously presented how to calculate or visualize the true sample space of the orientation uncertainty of objects measured in boreholes. The objective of this article is, thus, to develop a method to calculate and visualize the sample space using uncertainties in the parameters measured in boreholes.

2. Theoretical framework

The orientation of a linear object measured in a borehole, here expressed as trend and plunge of a fracture pole, can be calculated using four angles. These angles are the bearing and inclination, defining the direction of the borehole, together with two angles α and β relative to the borehole trajectory. The trend, plunge, bearing and inclination are, hence, defined in a global coordinate system whilst α and β are defined in a local coordinate system. Transformation of coordinates between the two systems is done using two rotation matrices called Y_{rot} and Z_{rot}.

2.1. Definitions

Global coordinate system, subscript $_G$, is defined as x_G coinciding with East, y_G with North and z_G is upwards, see Fig. 1a.

Local coordinate system, subscript $_{BH}$, is defined along the borehole. The origin, 0_{BH}, is defined as the intersection between the fracture plane and borehole trajectory. The axis z_{BH} coincides with the borehole trajectory. The axis x_{BH}, perpendicular to z_{BH}, points opposite to the reference line (in this paper defined as the roof of the borehole profile) i.e. x_{BH} is directed towards the floor of the borehole profile. The y_{BH}-axis is hence horizontal and perpendicular to the other two axes creating a right handed coordinate system, see Fig. 1.

Bearing, B, is the angle between North (y_G-axis) and the borehole trajectory projected to the horizontal x_G–y_G-plane, see Fig. 1a. The angle is measured clockwise from north and has a value between 0° and 360°.

Inclination, I, is defined as the acute angle between the horizontal plane, i.e. x_G–y_G-plane, and the trajectory of the borehole, see Fig. 1a. The value of the inclination can be between −90° and 90°, where $I<0°$ corresponds to a borehole pointing downwards.

Alpha angle, α, is the acute dihedral angle between the fracture plane (the blue circle in Fig. 1a, and grey in Fig. 1b) and the trajectory of the borehole, see Fig. 1. The angle is restricted to be between 0° and 90°, where 90° corresponds to a fracture perpendicular to the borehole, i.e. the trajectory of the borehole is parallel to the normal vector of the plane.

Beta angle, β, is the angle from a reference line (in this paper defined as the line of the top of the roof of the borehole profile) to the lower inflexion point of the fracture trace on the borehole wall, i.e. where the perimeter of the borehole is the tangent of the fracture trace, see Fig. 1. The angle is measured clockwise looking in the direction of the borehole trajectory and can hence be between 0° and 360°.

Trend is the angle between North (y_G-axis) and the downward pointing fracture pole (normal vector) projected to the horizontal x_G–y_G-plane. The angle is measured clockwise from north and can be between 0° and 360°. (Trend equals strike −90°, and dip direction −180°.)

Plunge is the angle between the horizontal plane, i.e. x_G–y_G-plane, and the fracture pole, i.e. the downward pointing normal vector of the fracture. The value of the angle can be between 0° and 90°. (plunge equals 90°−dip)

$\mathbf{Y}_{\mathrm{rot}}$ is the mathematical rotation matrix working around the Y_G axis, positive rotation is counter clockwise, CCW.

$\mathbf{Z}_{\mathrm{rot}}$ is the mathematical rotation matrix working around the Z_G axis, positive rotation is counter clockwise, CCW.

2.2. Equations

Using the definition of the local system, the normal vector $\mathbf{n}_{\mathrm{BH}}$ of the fracture plane is calculated from α and β using:

$$\mathbf{n}_{\mathrm{BH}} = \begin{bmatrix} n_{x_{BH}} \\ n_{y_{BH}} \\ n_{z_{BH}} \end{bmatrix} = \begin{bmatrix} \cos(\beta)\times\cos(\alpha) \\ \sin(\beta)\times\cos(\alpha) \\ \sin(\alpha) \end{bmatrix} \tag{1}$$

The trend and plunge of the fracture pole are calculated using the normal vector of the fracture plane, $\mathbf{n}_{\mathrm{G}}$, (in the global

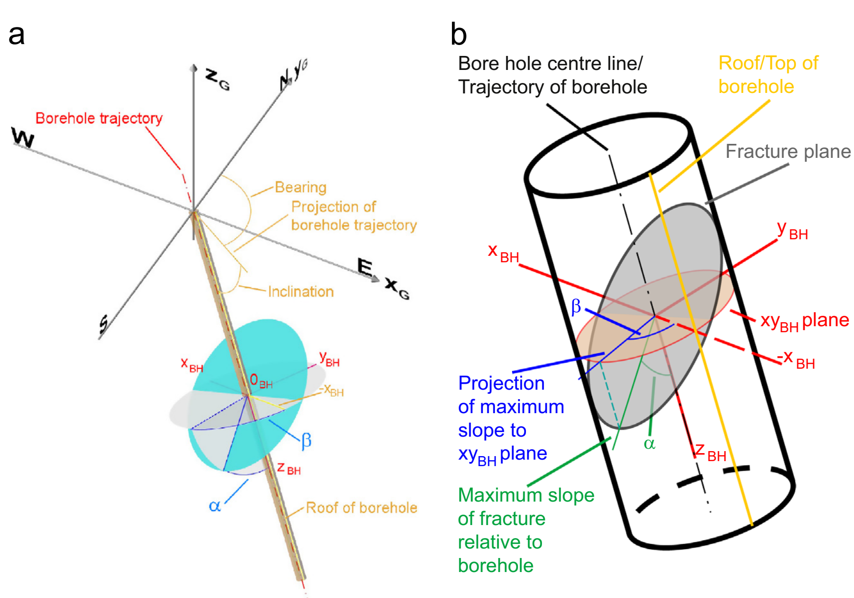

Fig. 1. (a) Definition of the four angles: bearing, B, inclination, I, which defines the orientation of the borehole, and the two angles α and β which are orientations of the measured structure relative to the orientation of the borehole. (b) Close-up showing the local α and β angles related to the local borehole co-ordinate system.