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The Application Of Automatic Recognition For Structural Plane From Borehole Imaging Logs At Wudongde Hydropower Station

Chuanying Wang 1
State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China, chywang@whrsm.ac.cn

Xianjian Zou 2
State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China, xjzou@whrsm.ac.cn

Zengqiang Han 3
State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China, zqhan@whrsm.ac.cn

SUMMARY: As a breakthrough progress in the development of borehole imaging technology, digital panoramic borehole camera technology has been widely employed in actual projects, such as geotechnical engineering, hydropower and mining engineering, and a large number of actual high-accuracy borehole images have been obtained. The borehole images accurately record the geological features, especially for the structural features of discontinuities. However, the identification of these features is usually done by hand with large workload, which is usually affected by many human factors. To solve this problem, this paper takes a practical borehole in drilling engineering as example to show the application of an automatic recognition method for the identification of structural planes in the borehole image logs, which are obtained by our Digital Panoramic Borehole Camera System (DBCS) at Wudongde hydropower station, Yunnan, China. The automatic recognition method uses image gray, gradient values and projection method to distinguish the occurrence region of structural planes. Then, standard sine function matching method is employed to search the structure plane in the region. Lastly, the optimal sine curve is screened out and adopted as the feature curve of structure plane. And the related parameters of feature curve are analyzed and converted into the parameters of structure plane. This method realizes the automatic recognition and parameters extraction of structure planes in borehole image. Results show the structural planes of borehole image logs can be automatically recognized quickly within 2 hours for 100 m depth borehole image, and about 90 % discontinuities can identified continuously without human intervention. The related structural parameters of discontinuities, such as plane central position, orientation, dip angle and fracture width, can be also obtained from the process of automatic recognition. These obtained parameters are reliable and match actual engineering situation within an acceptable error range. It solves the problem of manual operation and human intervention. Compared with traditional methods, the automatic recognition of structural planes had greatly improved the progress of project and saved a lot of time with high working efficiency and easy, convenient way. For example, For 12 boreholes each about 50 meters in depth, the method has a 98 % detection rate for major structural planes for each borehole, with an accuracy rate of 87 % and a deviation less than 4 %, in a total period of about 3 hours. The application of the automatic recognition method provides a successful example for actual engineering project. It promotes the development and application of borehole image signal processing in drilling engineering.

KEYWORDS: Drilling engineering , borehole image, automatic recognition, structural plane

1 INTRODUCTION

Knowledge of a rock body's structural stability is often necessary in geotechnical, geological, oil extraction, and also geological disaster control projects. The reliability of a project can heavily depend on the structural planes found in rock bodies, such as joints, faults, weak planes, and bedding planes (Genter and Castaing et al., 1997; Williams and Johnson, 2004; Bae and Kim et al., 2011). A digital panoramic borehole camera system can obtain high-definition images from structural planes within boreholes that offer an accurate representation of their characteristics. The accurate identification of structural planes and rapid extraction of their parameters are highly valuable in the practice of prospection, engineering design and construction (Wang and Ge et al., 2002; Cunningham and Carlson et al., 2004; Han and Wang et al., 2013).

The present identification of structural planes in borehole images relies heavily on human reading. Generally, the structures identification and parameter extraction process may involves computer-aided pre-processing or characteristic curve fitting, using human-assigned control points on a structural plane's sine curve or other necessary parameters, to obtain fitted values (Schepers and Rafat et al., 2001; Assous and Elkington et al., 2013; Malone and Hubbard et al., 2013). This is a laborious and slow process that requires human intervention, and its results often vary depending on individual readers, introducing inaccuracy to the conclusion(Wang and Hu et al., 2010; Zohreh and Junin et al., 2014). In engineering practice, particularly when the boreholes are deep or numerous, the manual identification process can become a drain on time and human effort. Thus automatic recognition of borehole images becomes valuable.

In this study, we build on the earlier works and numerous high-definition images captured by the digital panoramic borehole camera system developed by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, and propose a method of automatic borehole image recognition based on clustering and characteristic functions. The method has been successfully applied to the geological survey for Wudongde Hydropower Plant to good results, effectively solving its engineering problems and reducing its time load.

2 PRACTICAL APPLICATION OF BOREHOLE CAMERA

2.1 Digital panoramic borehole camera system

The digital panoramic borehole camera system is a smart geological survey system that keeps and analyzes a direct, disturbance-less panoramic camera record of borehole walls. By analyzing the walls directly, it avoids potential disturbance caused by coring process, allowing for an accurate and detailed representation of structural planes and rock strata in the borehole. The system provides a real-time full-360 degrees view of the borehole at all times, which can be examined on the spot or saved for later analysis.

Figure 1. Panoramic camera probes.

The probes, depicted in figure 1, are crucial to the digital panoramic borehole camera system. Containing a conic mirror that enables obtain of panoramic images, light sources, a magnetic compass and a CCD-based camera, the entire probe is sealed under high pressure, and can be used under water. The depth encoder is another positioning device of the system, consisting of a measurement wheel, an optoelectronic angle encoder, a depth signal collection IC board and an interface board. The system's software includes components for data acquisition and analysis, and can digitize the recorded video for analysis, perform recognition and interpretation of structural planes, and ensure the storage and maintenance of the data as borehole records and structural parameters for the rock body.

2.2 Borehole image characteristics analysis of Wudongde Hydropower Plant project

The Wudongde Hydropower Plant is the highest of four steps in the planned cascade-series hydropower facilities. Its dam site neighbors Luquan County, Kunming Municipality, Yunnan Province on the right bank of the river, and Huidong County, Sichuan Province on the left bank. The plant has a designed water level of 975 m, a total reservoir capacity of 5,863 million m^3. The dam is a double curvature arch dam with a maximum height of 265 m, and the power generators are underground, with six 735 MW generator groups on each bank, a total capacity of 8700 MW, and a mean annual generating capacity of 39,460 million KWh. Its key subprojects include the dam, the energy dissipation facility and the water diversion and power generation systems. The borehole system was used for the litho logical classification, survey of geological structures, determination of weak planes and unloading zones in rock bodies and other general hydrological and geological investigation in important locations of the dam site. Additionally, the project necessitated the investigation of the Jinpingzi landslide's bed rock morphology, landslide strips and cover layers, which would be used to confirm the landslide's stability and development trend.

Borehole images taken from 8 important locations in the dam site and the Jinpingzi Landslide Zone show that the panoramic camera system can acquire rock body structure images in real time that accurately reflect their features for engineering use. The borehole images are an indirect representation of rock body structures, originating as reflections on the camera probe's conic mirror. Their color depths depend on structures in the borehole walls, where gaps, fractures, cavities and broken regions' lower reflectivity results in darker colors (see figure 2).

The unfolded image of a structural plane in borehole record is a sine curve. A standard plane under ideal conditions should become a horizontal, standard sine curve, and under less ideal conditions the plane should also unfold into an approximate sine curve, as depicted in figure 2. The characteristics of structural plane include its location, dip direction, dip and gap width, which are reflected as the sine curve's location, amplitude, phase and line width. Other properties of the curve include its shape, color, intersections and the litho logy of surrounding rocks, such as metamorphic fractionation, structural joints, microscopic structural planes, and intrusive rock joints. These characteristics lead to infinite variations in the images, and are an obstacle to the development of automatic recognition.

Figure 2. An example of borehole camera images.

3 AUTOMATIC RECOGNITION OF STRUCTURE PLANES IN BOREHOLE IMAGES

The fast development of computer-aided image processing has led to the application of automatic recognition and panoramic camera technology. For this study, we propose a method based on clustering and characteristic functions. It uses the clustering of projections to partition structural plane areas in a full-borehole image, dividing the image based on the characteristic points of structural planes. For each partition, the iteration of characteristic sinusoidal functions is used to fit for the optimal sine curve, resulting in automatic detection and parameter extraction. The method has two components, partitioning of structural plane regions and matching of characteristics.

3.1 Structural plane region partitioning based on projection-clustering

Clustering is an approach to classification where the exact category of each specimen and any other prior knowledge is absent, the only criteria are the features of the specimens (e.g. all structural planes appear as approximate sine curves in borehole images), and certain measures of similarity are used (e.g. the shortest distance algorithm in hierarchical clustering) to classify specimens with similar or comparable features into categories (e.g. when projected vertically along the depth, all characteristic points of the same structural plane would concentrate within a short range, thus all characteristic points inside the range can be put into the same category). This approach enables the identification of individual structural planes in a borehole image.

In a borehole image, the gaps of structural planes are shown as dark strips similar to sine curves that are continuous and differ significantly from their surroundings in colors (see figure 2). The pixels that compose the dark sinusoidal strips are treated as characteristic points, which are highly concentrated in the projection of the image along depth. A more independent structural plane has better concentrated characteristic points, as shown in figure 3. This approach uses the minimum grayscale value and maximum gradient of each row of pixels to represent the row's grayscale information; the two values are combined into a characteristic signal for the automatic recognition process.

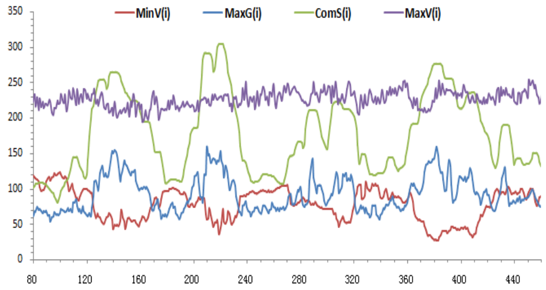

Figure 3. Characteristic signals for the recognition of structural planes.

In the figure, *MinV*(*i*) is the minimum grayscale value of all pixels in the *i*-th row, *MaxG*(*i*)is the maximum gradient of all pixels in the *i*-th row, and *ComS*(*i*) is the characteristic value for all pixels in the *i*-th row. *ComS*(*i*) is calculated as Equation (1) below, where 255 is the maximum grayscale value of a pixel in the image.

$$ComS(i) = 255 - MinV(i) + MaxG(i) \qquad (1)$$

Figure 3 shows that the ComS(i) signal can effectively convey the characteristics of a structural plane, and clearly represent the vertical distribution of structural plane areas in a borehole image. This step partitions all structural planes in the image into separate regions, ready for further analysis.

3.2 Sine function characteristic matching of structural planes

Since unfolded structural plane gaps are similar to sine curves in shape, we use sinusoidal function as their characteristic function. Iteration by changing the functions' locations, phases and amplitudes is used to match them to the images. Specifically, each row is used as the initial location of a function, for iteration of the function's amplitude and phase, and the total sum of characteristic pixels passed through by the function is tallied, to select the sine curve with the lowest total grayscale value as the characteristic curve in the location. The function follows Equation (2):

$$y(x) = y_0 - \frac{D}{2}\tan\beta \cdot \sin(x \cdot \frac{2\pi}{W} + \alpha) \qquad (2)$$

Where: y_0 is the initial location of the sinusoidal function, D is the diameter of the borehole, α is the dip direction of the plane, β is the dip of the plane, and W is the width of the unfolded image. The diameter D and width W are generally known constants. Here $D/2\ \tan\beta$ is the function's amplitude, and the dip β varies from 0° to 90°. The dip direction α is the function's phase angle, varying from 0° to 360°.

Therefore, the matching is performed by the following steps: first, using the partitioning from Section 2.1, iteration is performed starting from the first row of each structural plane region, by gradually increasing the dip direction and dip corresponding to the curve's phase and amplitude (0°~360° and 0°~90°), and the sum of characteristic values passed through by the curve is tallied; second, the curve with the greatest characteristic sum is used as the row's potential curve, and the iteration is performed on the next row; lastly, one or several sine curves are selected from all rows as characteristic curve(s) of the region's structural plane, and the process continues until all regions are iterated. Using these steps, the partitioning and function-matching for figure 2 have the following results:

Table 1. Sine curve matching results for structural planes in a borehole image.

No.	Depth (m)	Match points	Orientation (°)	Dip angle (°)
1	-3.218	1064	161.3	47.8
2	-3.423	471	157.5	49.3
3	-3.678	673	150.2	51.7
4	-3.979	2194	152.6	56.4
5	-4.184	352	148.3	43.2
6	-4.476	1347	164.7	36.8

It can be seen that a sine curve with the most matches is found for each row of the regions, and the optimal curves for the structural plane gaps are found among them. Obviously, the area with the largest number of matches is likely the center of a gap, and the areas around the center with the most rapid changes in number of matches are likely to be the gap's edges. This allows us to select the optimal sine curves to represent the gap.

4 APPLICATION AND ANALYSIS IN THE WUDONGDE HYDROPOWER PLANT PROJECT

Using the method, we analyzed the data from 8 boreholes in the Jinpingzi Landslide Zone. The image data from each borehole is automatically pre-processed by the digital camera system, with initial data acquired for partitioning of structural plane regions. The structural planes are detected, and the results, including parameters are stored in files. Figure 4 depicts the automatic recognition results for DJ1 borehole, depth 31~32 m.

Figure 4 shows the results of automatic recognition for images from figure 2. We have marked the detected edges of structural plane regions (blue lines), and an optimal sine curve has been found inside each region that best describe the structural plane (red lines). Figure 4 shows that the identified sine curves to be good fits for the respective structural planes.

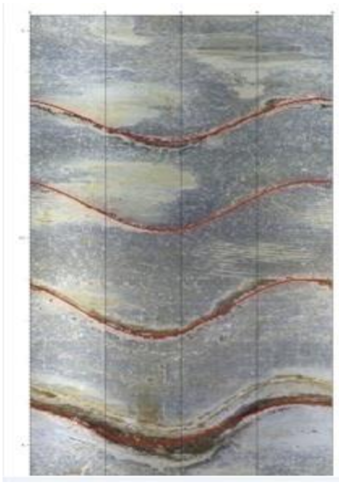

Figure 4. Partitioning and characteristic curve-matching results for borehole images.

With this method, the software can be used to automatically identify all structural planes in the image, and acquire their location, dip direction, dip and gap width parameters. We perform a statistical analysis on the results, for a whole comparison with that of human reading, to verify the reliability of the method. The results are shown in Table 2.

Here the results of human reading have been repeated verified, and can be considered to be accurate standard data. Therefore we use the human results to determine the accuracy of automatic recognition. If the deviation is lower than 15%, the method is considered accurate, and deviation larger than 15% is considered a failure of detection. The parameters include the location, dip direction, dip and gap width of the structural plane, and deviation larger than 15% in any of the four means the recognition has failed.

Table 2. Comparison: automatic recognition vs. human recognition of structural planes.

Type	Total	Accurate	Errors	Missed	Time
Human	100	100	0	0	3 days
Auto	98	87	21	8	5 hrs

Table 2 shows that using the human results as the standard, the automatic process has a detection rate of 98%, an accuracy rate of 87%, and the average deviation of parameters for planes that has been correctly detected is lower than 4%. Further review of these erroneous or missed areas shows that these structural planes are irregular planes with broken rock bodies, faint images or low image quality. They are often ambiguous, and require repeated comparisons to read even in human reading. In areas with high image quality and clear structural planes, the method can detect all structural planes and their parameters, with low deviation from results of repeated human readings. Therefore, the method is reliable for the recognition and extraction of structural planes. The method has greatly increased efficiency, saved time and effort, and accelerated the project's progress.

5 CONCLUSION

In this study, we acquired borehole image data from 8 boreholes in the Wudongde Hydropower Plant project's dam site and Jinpingzi Landslide Zone. The automatic recognition based on clustering and function-matching methods was performed on the data. The results indicate that the method can rapidly detect the majority of structural planes and their parameters including locations, dip directions, dips, and gap widths, and perform an initial classification and statistical analysis. The following conclusions can be made:

(1) In engineering practice, the automatic recognition based on clustering and characteristic function-matching can identify structural planes in full-borehole images, and extract parameters including locations, dip directions, dips and gap widths for marking and statistical analysis.

(2) In the Wudongde Hydropower Plant project, the method has a 98% rate of recognition for borehole images, with an accuracy rate of 87% and a deviation less than 4%, using a total period of 3 hours, displaying significantly higher efficiency than human reading.

(3) The application of automatic recognition can greatly increase efficiency and save time, providing reliable data and contribute to the development of borehole camera technology.

(4) Some errors or inaccuracies can still be encountered at structural planes with complex structures or low image quality, particularly in broken planes. We suggest using automatic recognition for a first pass, then compare the results with the original images manually, and make corrections if necessary, To ensure engineering quality and data accuracy.

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