EVALUATING ROCK MASS INTEGRITY BASED ON WHOLE-HOLE IMAGING

C.Y. Wang, Institute of Rock and Soil Mechanics, The Chinese Academy of Sciences, Wuhan, Hubei, China
Carleton University, Ottawa, Ontario, Canada
K.T. Law, Carleton University, Ottawa, Ontario, Canada
Z.C. Pang, Institute of Rock and Soil Mechanics, The Chinese Academy of Sciences, Wuhan, Hubei, China
X.W. Ji, Jiangsu Hydrogeology and Engineering Geology Survey Institute, Huaian, Jiangsu, China

ABSTRACT
The core-drilling method is the most direct and effective method for evaluating rock quality by means of Rock Quality Designation (RQD). However, this method sometimes introduces adverse effects on the integrity of the rock core that might lead to misleading results when the rock mass is relatively fractured and the core recovery is low or when the mechanical perturbation breaks up the core during the drilling. By comparing actual cores and borehole images made from whole-hole imaging, this paper briefly describes the basic principle of the borehole camera technology with particular reference to whole-hole imaging. Based on the geometrical characteristics of parameters of rock mass structure obtained from whole-hole imaging, one can describe the characteristics of integrity (I) and fracturing (F) of the rock mass in a borehole. A new definition for describing rock mass quality is proposed by means of the index of rock mass integrity (IRMI) where IRMI = I / (I + F). Through applications to actual boreholes, comparison between RQD and IRMI are presented. Conclusions are drawn from the comparison, which include: (1) borehole camera can be used to overcome the shortcoming of core drilling; (2) whole-hole imaging produces a new and better evaluating method on rock mass integrity; (3) a new definition on rock mass integrity (IRMI) is proposed; and (4) mechanical perturbation during drilling is the main reason that the IRMI is usually higher than the RQD.

RÉSUMÉ
La méthode d'échantillon de terrain est la méthode la plus directe et efficace pour évaluer la qualité rocheuse par Designation de Qualité Rocheuse (RQD). Par contre, cette méthode entraîne parfois des effets défavorables sur l'intégrité qui pourraient fausser les résultats lorsque la masse rocheuse est relativement fracturée et le rendement du noyau est faible ou lorsque la perturbation mécanique casse le noyau durant le forage. En comparant les vrais noyaux avec des images de l'imagerie entière de forage, cet article décrit brièvement le principe de base de la technologie de photographie de forage avec référence particulière à l'imagerie entière de forage. Avec les caractéristiques géométriques des paramètres de la structure rocheuse obtenus par l'imagerie, on est capable de décrire les caractéristiques de l'intégrité (I) et de la fracturation (F) d'une masse rocheuse d'un trou de forage. Une nouvelle définition pour décrire la qualité de la masse rocheuse est présentée selon l'indice d'intégrité de la masse rocheuse (IRMI), IRMI = I / (I+F). Avec l'application sur de vrais trous de forage, on présente des comparaisons entre RQD et IRMI. Les conclusions, par conséquence, incluent les suivants: (1) Photographie de trou de forage peut être utile pour surmonter les défauts du forage du noyau. (2) L'imagerie entière de forage produit une nouvelle méthode améliorée d'évaluation de l'intégrité de la masse rocheuse. (3) Une nouvelle définition de l'intégrité de la masse rocheuse (IRMI) est présentée. (4) La perturbation mécanique durant le forage est la cause principale d'un IRMI habituellement plus élevé que le RQD.

1. INTRODUCTION
Core drilling has long been an important and indispensable method widely used in various geotechnical projects for deep exploration of structural integrity of rock mass. It has been playing a tremendous role for engineering foundation reconnaissance, and providing first-hand geological data for engineering design and construction. In this method, an index Rock Quality Designation (RQD) (Deere, 1964) is conventionally defined as the cumulative length of core pieces longer than 10cm in a run divided by the total length of the core run. The RQD is an important parameter for quantitatively evaluating rock quality, as well as the basic input parameter for two main Rock Mass Classifications (RMR and Q) (Bieniawski, 1976 and Barton et al., 1974). Thus, its accurate measurement has a vital significance.

The progress of modern science and technology, such as optics, computer, digital video etc., has greatly propelled the rapid development of rock mass reconnaissance
technology. The most representative technology is the optical borehole imaging system (Kamewada et al., 1989 and Wang et al., 2002) appeared in the late 1980s. The system uses optical technology to explore undisturbed borehole wall on which geological information is maintained. Especially, the structural characteristics of rock mass could be visually, completely and accurately described in the system, namely visualization borehole. Further, the geometrical characteristics of discontinuity could also be collected by digital technique in the system, namely digitized borehole. All these created conditions for establishing files of digitized borehole and for evaluating structural integrity of rock mass.

2. COMPARISON OF CORE AND BOREHOLE IMAGE

Figure 1 is a photo of actual cores from core drilling taken at the bridge foundation of Makou River Bridge, in the construction of Yiwan railway. The photo shows very few intact cores of more than 10cm, yielding a RQD value almost equal to zero. Thus the rock mass is considered to be fractured as interpreted using the conventional method. This, however, is not convincing in view of the complex geological conditions and the drilling process used. Thus it was important to ascertain the actual situation. Borehole imaging technique, therefore, was applied in the foundation. Figure 2 is a couple of borehole images formed by the technique. The left one is an unrolled image of the borehole wall and the right is a 3D image, called virtual coregraph. From Figure 2, a tangible result is presented visually, namely the region is lamella shale rather than broken rock mass. This result provides a reliable basis for the bridge foundation design. Through the comparison of Figure1 and Figure2, it is evident that the main reason for the fragmentized cores is mechanical disturbance during the drilling process and the special structural characteristics of the lamina shale. Mechanical disturbance is inevitable and many uncertain factors are also present. Consequently, if only core drilling is used for evaluating rock mass integrity, the reliability of results cannot be easily verified. However, the advent of the borehole imaging technique can remedy the shortcomings of core drilling. Furthermore, this technique can produce accurate measurements of crack orientation and aperture in a borehole and elaborate descriptions of lithology change, grain size, color, veins, etc. The technique therefore provides comprehensive geological information for accurate assessment of the rock mass integrity.

3. BASIC PRINCIPLE OF WHOLE-HOLE IMAGING TECHNIQUE

The key of the borehole imaging technique (Wang et al., 2002) is the breakthrough of panoramic technique using a frustum mirror and digital technique (Digital Video and Digital Image). The panoramic technique gives a plane image of the full-circumferential (or 360°) image of the borehole wall. The plane image is called panoramic
image after adding the location information. The digital technique carries out digitization of video images. The digital video images can be reverted to the actual images of the real borehole wall by the back transformation of the panoramic image. Figure 3 is a sketch of the principle of the borehole imaging technique.

There are two methods (Wang et al., 2005) of forming digital borehole images, namely seamless stitching algorithm and scan line algorithm. The former one uses the panoramic images with certain overlapped region to form the borehole images by stitching, called partial images. The partial images are seamless and their axial accuracy is higher, reaching 0.2mm. Thus, they are particularly useful for close examination of fine details of certain parts of the borehole wall. This technique, however, involves such a huge volume of data that it is difficult for a usual microcomputer to handle if the partial image is long. The latter uses a designated circle as a scan line on the panoramic image to collect the data on the circle at one-mm spacing. The collected scan lines are heaped up along depth direction to form the borehole image with one mm accuracy, called a whole-hole image. The image can be used to describe continuous or complete borehole wall, but it ignores the tiny structural characteristics (less than mm-level). Thus, it becomes possible to evaluate the rock mass integrity based on the whole-hole image.

The basic principle of the seamless stitching algorithm is shown in Figure 4. Two adjacent images with certain overlapped region are captured when the probe is located at different positions (Pos1 and Pos2). Through processing the two images, their overlapped region can be determined and stitched to form the seamless image.

The basic principle of the scan line algorithm is shown in Figure 5. At first, a circle on the panoramic image is designated as a scan line. When the probe is at Pos1 (shown in Figure 5-A), point A oriented west is just on the scan line. After being captured and processed, the scan line is placed into the borehole image at Pos1 (shown in Figure 5-D). When the probe continues to descend to Pos2 (shown in Figure 5-B), point B oriented south is just on the scan line and the depth difference of Pos1 and Pos2 just reaches the scan line spacing. At this time the scan line is captured and placed into the borehole image at Pos2. As the same above, the scan line at Pos3 (shown in Figure 5-C) is captured and placed into the borehole image at Pos3. When the probe continues to descend to the bottom, the scanning of the entire borehole is completed and a whole-hole image is formed.

4. INDEX OF ROCK MASS INTEGRITY

Rock mass is cut into various blocks by discontinuities. The size of the block reflects the rock mass integrity. A borehole penetrating the blocks is only of limited dimension, but the crack density and fractured features observed on the borehole wall will reveal the rock mass integrity. The RQD is the most typical application of the one-dimensional method for evaluating rock mass integrity. Its basic idea is to use ‘good cores’ (core piece longer than 10cm) to indirectly describe the fractured features. It is well known that there are many uncertain factors in the indirect method that might lead to wrong results. The case described in Section 2 gives a good example. The main problem of this conventional method lies in its inability to directly describe the fractured zone, which is of utmost interest for engineering design. The broken cores are not completely representative of the fractured zones, nor can the intact cores clarify the absence of open cracks. Therefore, the evaluation of the rock mass integrity should give emphasis on both the intact part and the weakened part, such as fractured rock mass, open cracks, etc. All these are difficult for core drilling to achieve.

Figure 3. Schematic of the imaging principle of digital panoramic borehole camera system
The borehole imaging technique remedies the shortcomings of core drilling. It gives descriptions of the intact part of the rock mass and quantitative measurements of various weakened geological features, such as fractured range, crack spacing, orientation, aperture, etc. The whole-hole imaging makes possible the visual showing with an image of the geometric distribution of these results. Consequently the borehole imaging technique could provide accurate geological information for evaluating rock mass integrity.

Based on the whole-hole imaging, a new index is proposed to describe the integrity of the rock mass: index of rock mass integrity (IRMI). Description of rock mass in the whole-hole image is divided into two components: I and F. The index I is defined as the cumulative length of intact segments of rock mass longer than 10cm, and F is the cumulative length of fractured zones, discontinuities and segments of the rock mass less than 10cm. The index of rock mass integrity (IRMI) is defined in percent of the ratio of the intact mass length (I) to the total rock mass length (I + F). Hence:

\[ \text{IRMI} = \frac{I}{I + F} \times 100\% \text{  } (1) \]

To calculate the IRMI, a relevant region is selected in the whole-hole image at first. And then it is necessary to identify and measure the integrity (I) and the fracture (F) in the region. The detailed steps are shown in the following example. Finally, the IRMI can be calculated by using Eq. (1).

As shown in Figure 6, the length of the region is 1.31m. The region is divided into 3 segments of intact rock mass longer than 10cm (I1, I2 and I3) and 3 segments of the fracture (F1, F2 and F3). F1, F2 and F3 correspond to a fractured zone, a crack with a certain aperture, and a length of intact rock mass less than 10cm long, respectively. By using the data shown in the figure, I and F can be expressed as

\[ I = I1 + I2 + I3 = 0.17 + 0.31 + 0.2 = 0.68 \]
\[ F = F1 + F2 + F3 = 0.31 + 0.04 + 0.28 = 0.63 \]

Hence, the IRMI can be calculated by using Eq. (1):

\[ \text{IRMI} = \frac{I}{I + F} \times 100\% = 51.9\% \]

5. ENGINEERING APPLICATION

Tsingtao Bay Bridge is the starting point of Tsingtao-Lanzhou Expressway of the national expressway network, and it is also the trunk line of “Five-Longitudinal, Seven-Transverse, and One-Ring Road Network of Shantung Province”. It is also the bridge of the “One-Road, One-Bridge and One-Tunnel Road Traffic Network of Tsingtao City” over Kiaochow Bay. Located at the north central part of Kiaochow Bay, the project starts at Highway 308 in the core urban area of Tsingtao, crosses over Kiaochow Bay, and ends at Yellow Island Economic-technological...
Development Area, which leads to Red Island in the north. The total investment of the project is estimated at about RMB 10 billion Yuans. When completed, the road length will be of 35.4 km, which includes the cross-sea bridge span of 26.75 km, the approach span of 5.85 km on the Tsingtao side, the approach span of 0.9 km on the Red Rock Cliff side and the Red Island tie line of 1.9 km.

This project utilized the digital panoramic borehole camera system for site investigation. Eighteen boreholes had been investigated. The boreholes were placed along the channel bridges (Cangkou Channel Bridge, Red Island Channel Bridge, Dagu River Channel Bridge), Red Island Interchange Bridge, the tie line and at locations where previous site investigation revealed some notable geological structures such as fault and weathered zone.

In order to compare with the conventional boring results, the micro and lightly weathered sections of three typical boreholes are described and analyzed in detail in this paper. The three boreholes are respectively XZK44, XZK57 and XZK212, which are close (Figure 7) to the notable geological structures as revealed in some previous site investigation.

5.1 Borehole XZK44

Conventional logging for the section from depths 50.40-60.42m gives the following information. The rock is micro weathered rhyolite, maroon in colour, porphyritic in texture and fluxion in structure. It is composed of phenocrystalline and matrix material, and its mineral constituent is mainly rhyacolite and quartz. The fractures and fissures are well-developed, and the hammering sound is clangourous. The rock sample splits along fissures when struck heavily. The length of the cylindrical core is 10-30cm. The core recovery is 70% and RQD=41. The core is fragmentized beneath the depth of 57.9m.

The results of the digital borehole camera imaging are shown in Figure 8. The fractures and fissures of the borehole wall beneath the depth of 52.6m are dense, and the attitude of stratum is horizontal or nearly horizontal. The fractures and fissures are more centralized and there are more rock fragments between the fissures as the borehole approaches the bottom. Fifteen segments of intact zones and fifteen segments of fracture zones have been identified, giving an Index of Rock Mass Integrity (IRMI) of 75%.

5.2 Borehole XZK57

Conventional logging for the section from depths 63.90 to 71.29m shows that the rock is lightly weathered rhyolitic lava breccia, brownish red in colour, lava brecciate in texture and blocklike in structure. The diameter of breccia is about 2-15mm, and the largest is 30-40mm. Its mineral constituent is mainly rhyolite with tufaceous debris, crystallinoclastic and volcanic dust in fractures and fissures. The fractures and fissures are well-developed, and the hammering sound is clangourous. The rock cores exist in both the cylindrical and cataclastic forms. The length of the cylindrical cores 10-20cm. The core recovery is 50% and RQD=20.
Figure 8. Image of fissures of the wall of Borehole XZK44

Figure 9. Image of fissures of the wall of Borehole XZK57

Figure 10. Image of fissures of the wall of Borehole XZK212
The results of the digital borehole camera imaging are shown in Figure 9. The borehole wall between depths of 64.2 and 65.5m is fragmentized, and the fracture is open without filling materials. The width of fracture can reach 1.12m in some parts, and the dropped fragments reach 187.2mm×150.5mm in size. The borehole wall between the depths of 65.7 and 69.3m is relatively intact. The fractures and fissures are more centralized and there are more rock fragments between the fissures as the borehole approaches the bottom of the borehole. The width of fracture reaches beyond 241mm at the depth of 69.7m near the bottom of borehole. Six segments of intact zones and seven segments of fracture zones have been identified, giving an Index of Rock Mass Integrity (IRMI) of 64%.

5.3 Borehole XZK212

Conventional logging for the section from depths 37.30-72.90m shows that the rock is micro weathered basalt, grey black in colour, porphyritic in texture and spiracular amygdaloidal in structure. The fractures and fissures are slightly developed, and the fracture is closed. The core is intact, slightly fragmentized in some parts, and in cylindrical or long-column form. The core recovery is 100% and RQD=90.

The results of the digital borehole camera imaging are shown in Figure 10. The mineral constituent of the borehole is mainly basalt. Except for some micro crack in some parts, the wall of borehole is relatively intact. Eight segments of intact zones and seven segments of fracture zones have been identified, giving an Index of Rock Mass Integrity (IRMI) of 95%.

5.4 Discussion

Based on the comparison of the conventional logging and the borehole imaging technique with the above three boreholes, it is found that:

1. Conventional borehole logging and digital borehole camera imaging each has its own characteristics in describing the boreholes. The former is more suitable for describing the color, shape, composition, constitution and physical characteristics, while the latter emphasizes the structural features, such as description and measurement of the joint, fissure, fault and fragment, etc.

2. The Index of Rock Mass integrity (IRMI) can accurately reflect the structural features of the rock mass because of the high resolution images of the entire borehole wall with the advanced borehole camera system.

3. Mechanical disturbance during the drilling process causes degradation in the rock core, resulting in the decrease of Rock Quality Designation (RQD). Therefore, the Index of Rock Mass Integrity (IRMI) is usually higher than Rock Quality Designation (RQD).

6. CONCLUSION

By examining the principle for the digital borehole imaging technique, introduction of the new index of rock mass integrity (IRMI), evaluation of actual engineering application, it is concluded that:

1. The digital borehole camera system overcomes the shortcomings of the conventional borehole logging method.

2. The digital borehole camera system provides a viable method to evaluate the Index of Rock Mass Integrity (IRMI).

3. The Index of Rock Mass integrity (IRMI) is usually higher and more reliable than Rock Quality Designation (RQD) because of degradation of the rock cores due to the drilling process.

7. ACKNOWLEDGEMENTS

The authors would like to thank Mr. Chen Xiaodong of the HPDI whose sponsorship has made this research possible. They also would like to thank Jiangsu Hydrogeology and Engineering Geology Survey Institute for providing rock mass evaluation data.

References


