Integrated Application of Borehole GPR and Borehole Imaging for Geological Survey

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ABSTRACT
Site investigation with drilling of boreholes to reveal the geological features at a site usually encounters a number of difficulties. The drill core is one dimensional from which the spatial characteristics of the geological features cannot be clearly defined. After the drill core is taken out of the ground, it may not reveal accurately the true in-situ state of the rock mass. While increasing the number of boreholes may improve the reliability of the results, it is still difficult to accurately ascertain the characteristics of the undrilled area between the boreholes, and the cost and time required will increase. This paper describes a new integrated exploration method based on combining borehole radar and borehole imaging technology. With this method, the physical and geometrical characteristics of the rock mass at and around a borehole can be revealed. Therefore the geological structures and unfavourable features if any in the vicinity of the borehole can be rapidly and accurately determined. A case study was carried out for a rapid transit system located in limestone formation in Tengzhou County, Shandong Province, China. Application the method leads to the following conclusions. 1) Radar technology and borehole imaging are complementary with each other in yielding information on the joint patterns, underground caverns, existence of metallic objects and disturbance from the ground surface. 2) The radar cross section and borehole image together provide important data for the accurate interpretation of the geological features in and around a borehole. 3) The borehole radar and the borehole imaging conducted together give useful results for evaluating rock mass quality.

RÉSUMÉ
Site investigation avec le forage de trous de sonde pour révéler le géologiques sur un site de rencontres en général un certain nombre de difficultés. La carotte de forage est une dimension à partir de laquelle les caractéristiques spatiales des caractéristiques géologiques ne peuvent être clairement définis. Après la carotte de forage est sorti du terrain, elle mai ne pas révéler avec précision la véritable in-situ l'état de la masse rocheuse. Alors que l'augmentation du nombre de forages mai améliorer la fiabilité des résultats, il est encore difficile de déterminer avec précision les caractéristiques de la zone undrilled entre les trous de forage, et le coût et le temps requis va augmenter. Ce document décrit une nouvelle méthode d'exploration intégrée fondée sur la combinaison de forage de puits et de l'imagerie radar de la technologie. Avec cette méthode, la physique et les caractéristiques géométriques de la masse rocheuse à et autour d'un trou de forage peut être révélée. Par conséquent, les structures géologiques et des caractéristiques défavorables éventuels dans le voisinage du trou de forage peut être déterminé rapidement et avec précision. Une étude de cas a été réalisée pour un système de transport rapide située dans la formation de calcaire dans Tengzhou County, Shandong Province, China. Application de la méthode conduit aux conclusions suivantes. 1) la technologie de radar et de l'imagerie de forage sont complémentaires les uns avec les autres en donnant des informations sur les modèles communs, des cavernes souterraines, l'existence d'objets métalliques et des perturbations de la surface du sol. 2) Le radar cross section image et le trou de forage ainsi que de fournir des données importantes pour l'interprétation correcte des caractéristiques géologiques dans et autour d'un puits. 3) Le forage du trou de forage et de radar d'imagerie menée donnent des résultats utiles pour l'évaluation de la qualité de la roche massive.

1 INTRODUCTION

Having long been a major means for evaluating rock mass quality, site investigation finds wide application in various engineering surveys to fulfill significant engineering purposes. With the complexity of geological conditions, however, the current level of drilling technology still encounters many difficulties in accurately evaluating rock mass quality, which include: 1) unsophisticated survey tools produce results of low quality; 2) Rock core damage caused by mechanical disturbance during drilling is often neglected; 3) the rock core is one dimensional, which may not reveal accurately the true in-situ state of the rock mass; and 4) large amount of drilling work and the drilling area cannot be changed in accordance with the in situ state. In view of these difficulties, it is necessary to integrate various state-of-the-art geological exploration technologies to improve the reliability of rock mass evaluation.

The digital panoramic borehole camera system (Wang et al., 2002) has now become an important tool for engineering geological exploration. It performs similar functions as the human eye with the ability to directly view the borehole wall to form high-precision images, give a panoramic view of borehole information and accurately provide structural parameters (Wang et al., 2007 and Williams et al., 2004) such as fracture, fracture width and the like. Therefore it gives an accurate and reliable account of the engineering geological conditions of the subsurface in the immediate vicinity of the borehole. This system has been playing an increasingly important role (Wang et al., 2005) in a great number of practical engineering applications, especially in evaluating rock mass integrity.

The borehole ground penetrating radar (GPR) (Serzu et al., 2004) uses radar pulses to obtain an image of the subsurface. This technique has the advantage of yielding high-resolution radargram of the subsurface rock mass around the borehole. It is, therefore, an effective method (Kim et al., 2004) for acquiring the two-dimensional information of rock mass at and around a borehole. Hence GPR technology and digital imaging (Cunningham et al., 2001 and Cunningham, 2004) are complementary to each other in producing useful and reliable data for evaluating the rock mass characteristics.

This paper proposes a new integrated exploration method based on combining borehole radar and digital imaging. The research aspects and the application to a case study are presented.

2 BOREHOLE GPR

Borehole radar is a broad spectrum electromagnetic technology for ascertaining the subsurface media distribution. It radiates pulses of 50□250MHz radio waves into the rock media around the borehole by means of a transmitting antenna, and receives the reflected return signals using a receiving antenna. Figure 1 shows the borehole radar system – SIR20. The principles involved are similar to geological radar applied at the ground surface. As the radar wave propagation is influenced by the electromagnetic properties and geometrical characteristics of rock and soil, the strength and waveform of the received waves may change. Hence, the structures and features of the detected rock mass can be inferred based on the travel time, amplitude and waveform of the received waves. In addition, if the electrical conductivity of the subsurface rock mass exceeds a certain value, the single-hole radar will become ineffective due to the fact that electromagnetic waves are unable to travel in the form of waves in high-conductivity media. In this case, two other methods can be used: namely, the crosshole radar or the vertical radar profiling (VPR). Both collect important geological information on the basis of the head wave amplitude and arrival time.

Figure1. Borehole radar system – SIR20

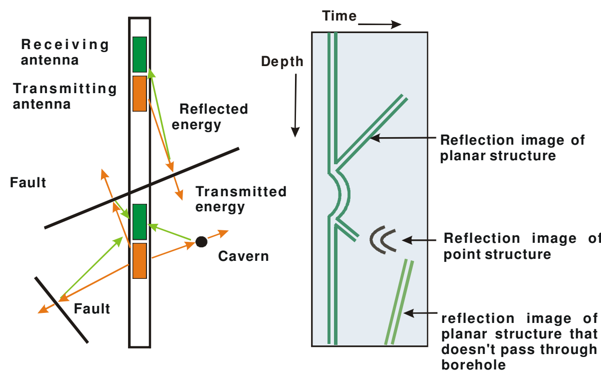


Figure 2. Antennas of single-hole radar detection and the faults measured, as well as radar image of a cavern

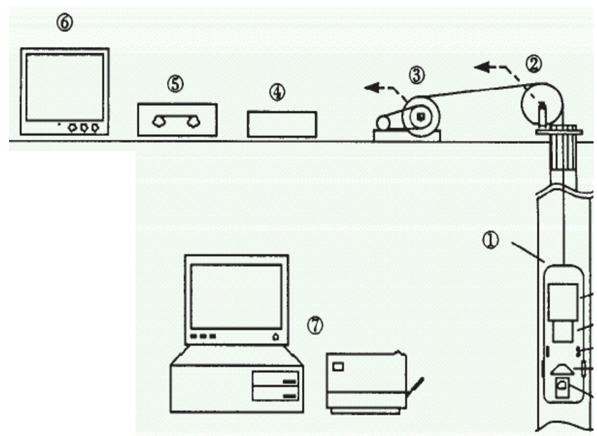
For radar detection, the transmitting antenna and the receiving antenna are placed in the same borehole at a fixed spacing. An optical cable is used to trigger the transmission signal and collect data to eliminate additional interference to the antennas, which could be introduced with the use of an ordinary cable. The antennas in common use for borehole radar are the dipole antennas that can radiate and receive signals from 360° space. As in geological radar, the interpretation of the reflected waves yields the geological features in the ground. This is done through event tracking and examining the waveform and strength of the return signals. When unfavourable geological conditions (e.g. fracture, bedding, crack, fracture zone, karsts or groundwater) exist in the rock mass, the electric conductivities of them are different from that of the intact rock mass. Therefore, strong reflected waves are formed. Meanwhile, diffracted waves are possibly generated when encountering different rock properties, generating a hyperbola on the time domain. The difference of the interpretation of borehole radar mainly lies in the interpretation of space domain. For geological radar, all reflections come from a half space, but for the borehole radar, reflections are from 360° radial range. Generally speaking, it is difficult to locate the reflectors by using the single-hole radar data, by which only the distance of the reflector can be obtained. When the reflector is a plane, the included angle between the plane and the borehole can also be determined. For point objects, the reflected signals are characterized by a hyperbola. For fractures that do not intersect the borehole, the reflected signals appear as an oblique line. The included angle between the oblique line and the borehole is dependent on the included angle between the fracture and the borehole. When the fracture intersects the borehole, the reflection mapping looks like a pair of open scissors. Accordingly, the form of the fracture can be inferred. Figure 2 shows a single-hole radar detection with the antennas, and the radar images for a relatively simple geological environment. The reflection and transmission of the radar wave signals reveal three typical unfavourable geological conditions, namely, a cavern, two faults, one that intersects the borehole and the other not. However, in real situations in which the geological features in the rock mass are more complex and discontinuous, the single-hole radar detection method requires some degree of subjectivity in the interpretation process and the results are subjected to uncertainties and limitations. In this case, it becomes especially important to integrate multiple exploration methods, making full use of the advantages of each method to complement one another for the best results.

3 AN INTEGRATED EXPLORATION METHOD BASED ON COMBINING BOREHOLE RADAR AND BOREHOLE IMAGING

While each site investigating method has its strength and limitations, a combination of methods used together will strengthen the methods and remove a lot of the limitations. With the immense ongoing construction programs to develop the western regions in China, combination of site investigation methods becomes essential for the construction of major infrastructures including rapid transits, large and medium scale water conservancy and hydraulic power projects, and long, deep tunnels. One such combination is to integrate borehole radar and borehole imaging for evaluating rock mass integrity. This integration will have high potential of making significant contributions to the immense projects.

3.1 DESCRIPTION AND ADVANTAGES OF THE INTEGRATED EXPLORATION METHOD

The integrated exploration method based on combining borehole radar and borehole imaging (Figure 3) is the result of a multi-disciplinary approach. It integrates technologies in borehole imaging, exploration, and computer engineering. It covers engineering geological survey by reaching deep rock mass. Through computer technology, it provides comprehensive and accurate information on geological structures and features and the like. Consequently, it provides information that helps solve difficulties encountered in engineering practice. It reduces construction costs and yet ensures engineering quality and construction safety. Take for instance the design and construction of rapid transit projects. It is common for this type of project that designs proceed with the best existing geological information that may still be at variance with the actual situation. Unfavourable geological conditions not initially detected may surface at any time and pose difficulties in construction, or may even cause serious geologic hazards, such as collapse, roof fall, water burst or gushing mud, etc. The integrated method of combining borehole radar and borehole imaging, therefore, not only forms an important component in geological exploration, but also significantly furthers exploration technology. It is essential for hazard prevention, avoidance or reduction of loss caused by potential hazards, and enhancement of construction safety.



□ Panoramic camera head
□ Depth meter wheel
□ Winch
□ Depth impulsator
□ Video tape recorder
□ Video monitor
□ Computer and printer

Figure 3. Schematic diagram for the borehole imaging system

3.2 RESEARCH ASPECTS FOR THE INTEGRATED EXPLORATION METHOD

Figure 4 shows the schematic diagram for the integrated method of borehole GPR and borehole imaging.

There are several aspects that need to be investigated to fully utilize this new integrated exploration technology. They include:

1) Research on software and hardware maintenance, as well as image processing methods for digital imaging;
2) Data processing and analysis of borehole radar;
3) The operation flow and comprehensive analysis methods of the integrated exploration method; and
4) Research on engineering applications of the integrated exploration method.

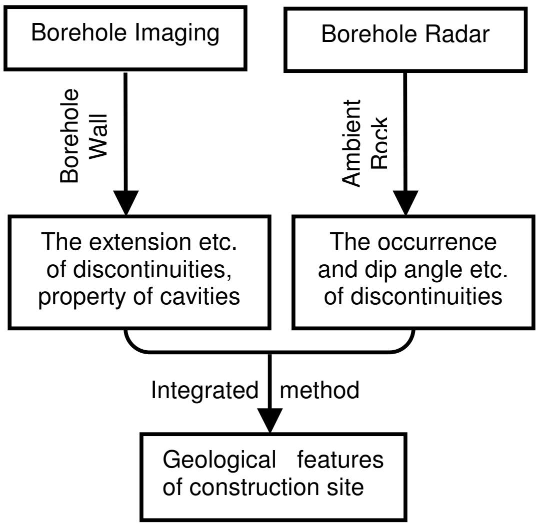


Figure 4. Schematic diagram for the integrated method of borehole GPR and borehole imaging

3.3 AN ENGINEERING APPLICATION

The integrated exploration method has already been applied at construction sites for energy, traffic, water conservancy and hydraulic power projects. Particularly, the method was used in some concrete dike projects. Through comprehensive interpretation of the digital borehole wall image and the borehole radar profile data, the geological features of the rock mass were revealed and specific information on fractures, joints and fracture zones in the rock mass and dikes were obtained. Data obtained from the preliminary trial and site investigation formed a good basis for performing the digital borehole camera system and borehole radar to provide better service to engineering practice.

Presented in the following is a case study on a rapid transit system located in a limestone formation in Tengzhou County, Shandong Province, China.

The rapid transit system places high requirements on the stability of construction site. In the routing scheme, therefore, sections with stable site conditions, proper groundwork and relatively favourable geological conditions were given priority. However, some areas with extremely complicated geological and terrain conditions could not be avoided. They include unfavourable geological structures like rupture, fracture zone, karsts, underground river, etc. Therefore accurate assessment of the site conditions along the route was essential for the success of the project. The state-of-the-art dynamic exploration technology based on combining borehole radar and borehole imaging was applied to this site for the first time. The information obtained with this method for a few boreholes gave an excellent description of the unfavourable geological conditions, resulting in expedition in engineering exploration, decrease in construction costs, reduction of hazards caused by these unfavourable geological conditions, and achievement of safety and stability of foundation.

According to conventional borehole information, digital panoramic imaging in 6 boreholes and borehole radar in 8 boreholes were performed. A lot of test results were acquired, of which, Figure 5 shows the comparison of the borehole radar image and the digital image obtained at 5.3m to the right of the borehole DK597+036.6. The digital borehole wall images and the radar images of these boreholes are compared and analysed as follows.

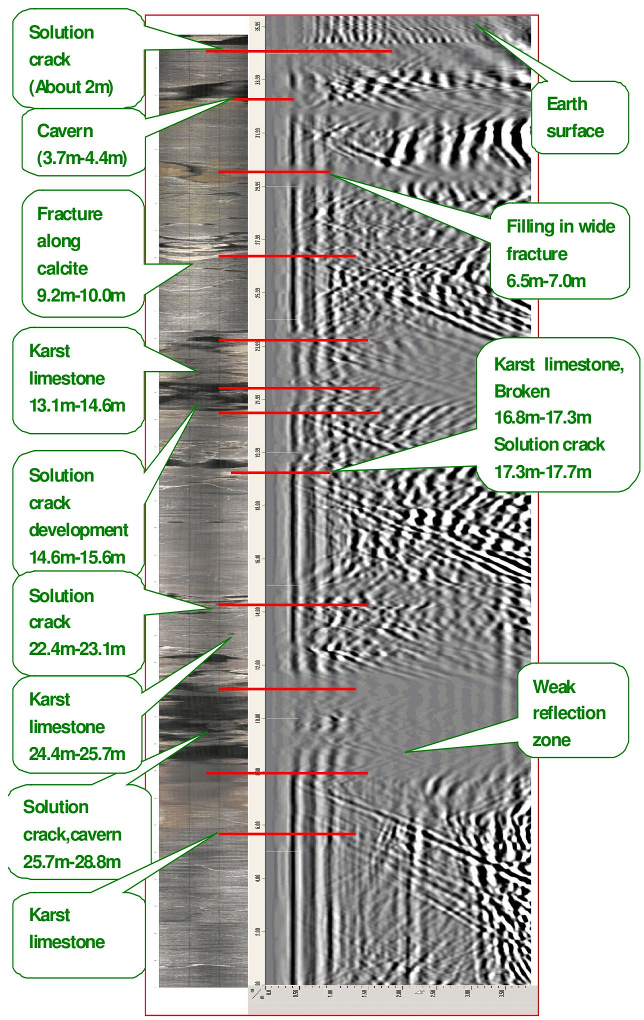
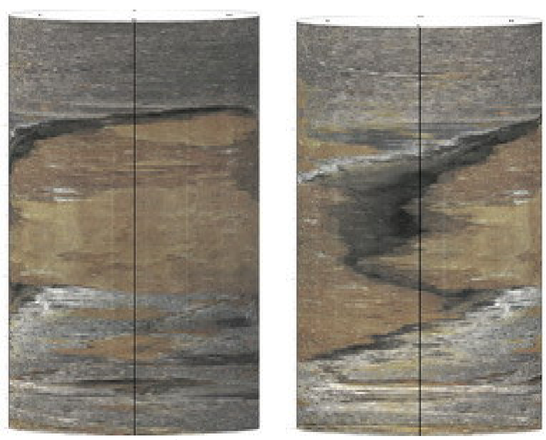


Figure 5. Comparison of borehole radar image and digital image (5.3m to the right of DK597+036.6)

The images obtained by means of borehole radar and digital imaging are consistent with each other. The image representations of fractures, underground caverns, existence of metallic objects and disturbance from the ground surface can be found in both the optical image and the radar image. Through comparing the results, the differences and relation between the two images can be clarified. This also provides a basis for data fusion of the two sets of results. Figure 6 shows an example of a digital image clearly revealing the fracture and the condition of the fill material in the fracture at the borehole wall. The radar profile, however, shows a return wave curve in the form of open scissors, suggesting a zone of fractures extended to some distance from the borehole. This is due to the difference between the dielectric properties of the upper and the lower media at the fill-rock interface, giving rises to markedly different radar return waves reflecting from these two media. At other locations, absorption and attenuation of radar wave by aquifer, claypan and metallic objects weaken the return wave signals. For sections with metal pipes in the borehole, no noticeable return wave was received



(a) 6.1-7.5m (front) (b) 6.1-7.5m (back)

Figure 6. Fracture and fill material in the fracture at the borehole wall (5.3m to the right of DK597+036.6)

The number of joints can be determined from borehole radar and digital imaging, and based on this number, the integrity of rock mass can be preliminarily assessed.

Rock mass integrity refers to the degree of crack and fracture in the rock mass, which is largely dependent on two factors: structural plane and structural (rock) mass. A joint is a structural plane that adversely affects the rock mass integrity as it breaks up the rock mass. In general, the more developed the joint, the worse is the integrity of the rock mass.

Assessment of the rock mass integrity based solely on the RQD of rock cores and the number of fractures obtained from borehole imaging can be inaccurate. This is because the drilling process may damage the rock mass around the borehole and produce new fractures. These fractures will appear on the digital image and will be judged as intrinsic joint patterns, resulting in erroneous assessment of the rock mass quality.

On the other hand, the borehole radar can yield information on the characteristics of the mass within decametres around the borehole, where the influence of disturbance of the rock mass integrity due to drilling is reduced. Table 1 lists the number of fractures revealed in the digital images and in the radar images. The number of fractures shown in the radar images is consistently smaller than that in the digital images. This suggests that some fractures shown in the digital images were introduced during the drilling process and that the borehole radar survey can reveal the presence of joints in the rock mass at and some distance away from the borehole. Therefore, integrating borehole radar, borehole imaging and borehole coring will give a more accurate evaluation of the rock mass integrity.

Table 1. Statistics of fissures and fractures

Borehole Position	Borehole Depth(m)	Number of Fractures	
		Borehole Imaging	Borehole Radar
1.1m to the right of DK583+880.5	36.38	5	4
3.9m to the right of DK584+935.4	13.2	3	2
3.9m to the right of DK584+273.0	37.4	2	2
3.5m to the left of DK604+375.4	57.8	10	7
5.3m to the right of DK597+036.6	39.4	9	6

4 CONCLUSIONS

The integrated exploration method based on combining borehole radar and borehole imaging has profound implications not only for solving hardware research and development of a variety of exploration equipment, but also for improving the interpretation and fusion of exploration data. This paper discusses a new integrated exploration method based on combining borehole radar and borehole imaging technology and presents its application to a case study, and the following conclusions can be drawn.

1) Radar technology and borehole imaging are complementary with each other in yielding information on the joint patterns, underground caverns, existence of metallic objects and disturbance from the ground surface.
2) The radar cross section and borehole image together provide important data for the accurate interpretation of the geological features in and around a borehole.
3) The borehole radar and the borehole imaging conducted together give useful results for evaluating rock mass quality.

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