Detection of covered rock separation strata based on borehole camera technology

Chuanying Wang
Institute of Rock and Soil Mechanics, The Chinese Academy of Sciences, Wuhan, Hubei, China and Carleton University, Ottawa, Ontario, Canada
K. Tim Law
Carleton University, Ottawa, Ontario, Canada
Weichun Sun
Institute of Rock and Soil Mechanics, The Chinese Academy of Sciences, Wuhan, Hubei, China

ABSTRACT
The technology of covered rock separation strata (CRSS) to reduce subsidence by grouting (RSG) has played an increasingly important role in controlling surface subsidence. The key for successful application of this technology lies in the correct determination of separated strata space suitable for grouting and timely application of grouting to achieve effective control of surface subsidence. However, the knowledge on the characteristics of CRSS and the separation strata rules is limited to theoretical analysis and numerical simulation. There is a lack of actual detection result and analysis. This paper briefly describes CRSS RSG technology and the status of its application, proposes an advanced detection method using the digital borehole camera (DBC) technology to detect the separation strata development. The method is applied to some boreholes at a mining site in Tangshan, China, which yields the correct area and scale of the separation strata development. The information is then used for the successful grouting process of the separation strata. Therefore, it is concluded that: 1) DBC is an advanced exploration technology, capable of determining strata separation development area and scale; 2) borehole images acquired by DBC technology is of high precision and provides useful design parameters; and 3) DBC technology is applicable to CRSS detection.

RÉSUMÉ
La technologie de couches séparées de roche couverte (CRSS – Covered Rock Separation Strata) dans le but de réduire la subsidence par scellement (RSG – Reduce Subsidence by Grouting) a joué un rôle progressivement plus important dans le contrôle de subsidence superficielle. Le succès de cette technologie dépend de la détermination précise des couches séparées convenables au scellement et une application dans les meilleurs délais pour atteindre un contrôle efficace de la subsidence superficielle. Néanmoins, la connaissance des caractéristiques de la CRSS et les règlements de couches séparées est quand même limitée à l'analyse théorique et la simulation numérique. Il y a un manque au niveau du résultat et de l'analyse de vraie détection. Cet article décrit brièvement la technologie CRSS RSG et l'état de son application. De plus, on propose une méthode de détection avancée grâce à la caméra numérique de trou de sonde (DBC – Digital Borehole Camera) afin de détecter le développement des couches séparées. On applique cette méthode à certains trous de sonde à un site minier à Tangshan en Chine qui donne la superficie et le développement des couches séparées adéquats. Donc, on conclut que 1) la DBC, une techonologie d'exploration avancée, est capable de déterminer la superficie ainsi que l'échelle du développement de couches séparées; 2) Les images de trou de sonde saisies par la technologie DBC sont de haute précision et fournissent des paramètres de design utiles; 3) la technologie DBC est applicable à la détection de CRSS.

1 INTRODUCTION

Strata separation is a phenomenon that a separation is generated along the strata during the process of mining covered rock subsidence movement (Guo et al., 1999). As is well known, the top stratum in the excavated area will form “three zones”, i.e., caving zone, cracked zone and curving zone after the underground coal bed is mined, featuring damage of caving and breaking, curving and subsidence. The strata separation generated in caving and cracked zones are usually short in time to develop. In the curving zone, a strata separation space is formed from the inharmonious curving and subsidence between strata due to the difference of stratum structure and rock quality, featuring large extent and takes long time to develop; and sometimes the space persists permanently. This covered rock separation strata (CRSS) space may result in surface subsidence. One effective way to mitigate this problem is to reduce the subsidence by grouting (RSG). However, the knowledge on the characteristics of CRSS and the separation strata rules is limited to theoretical analysis and numerical simulation at present. There are no actual result and analysis. Therefore, it is of important practical significance to detect the strata separation, and correctly determine its specific location, development area and extent to provide design parameters for the grouting process. The method utilizing the advanced detection technology, the digital borehole camera technology, has been found to be successful for this purpose. Furthermore, this method also has important theoretical value because it provides detailed first-hand materials for studying CRSS and its characteristics.

The application of CRSS RSG technology was initiated in Poland at the beginning of the 1980s. Industrial wastes were used to fill the CRSS space through boreholes to effectively reduced surface subsidence. Fan (Fan et al., 1985) introduced this technology in China. He and his team made an industrial test in the coal mine of Laohutai of Fushun Mine Area and estimated that the surface subsidence was reduced by over 60% (Zhang, 1998). In 1998, Kailuan Group Company cooperated with Shandong University of Science and Technology. They conducted theoretical studies on the technology of multi-level RSG in CRSS zones and proposed the concept of injection-production ratio, which laid a foundation for the theory of surface subsidence prediction. Furthermore, they made a practical application at 3696 and 3694 fully mechanized cave in faces of Kailuan (Group) Tangshan Mine, in which the maximum subsidence was only 178mm and 429mm, respectively (Zhong et al., 2001).

CRSS RSG technology uses fly ash–wastes discharged from thermal power plant as the filling material. The fly ash is mixed with water to form a liquid at a certain bulk density. The fly ash-waste liquid is injected into the strata separation space of the covered rock after being pressurized at the surface grouting station. The liquid is settled and compacted and forms a fly ash compacted wet grey body that supports the upper covered strata and subsequently reduces surface subsidence. Its principles are shown in Figure 1 (Sun et al., 2008). Table 1 summarizes the practical experience gained in China in the past decades on CRSS RSG technology.

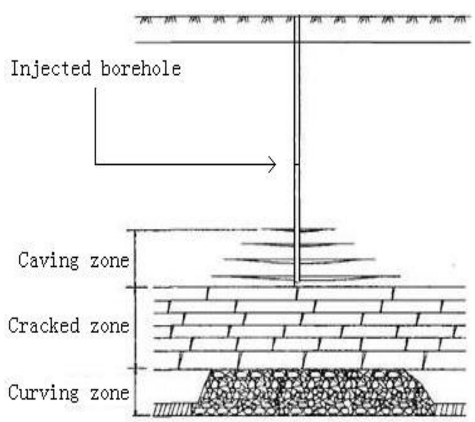

Figure 1. Schematic diagram of strata separation grouting

2 BOREHOLE IMAGING TECHNOLOGY

Borehole imaging technology (Wang et al., 2005) is a geological investigation method, which can be used to view directly a borehole wall as a human eye and carry out the description, collection and analysis of the geological information. With the application of optical transformation, it becomes possible to observe the 360° borehole wall. The breakthrough of this panoramic technology propels the borehole camera technology rapidly into a digital age.

The digital panoramic borehole camera system (Wang et al., 2002) is the typical representative of this age, because: 1) by adopting the innovative optical transformation (the frustum mirror) and visualization of azimuth and depth information, a two-dimensional image containing spatial information of the 360° borehole wall, i.e., panoramic image, is obtained; 2) by using digitization video and programming, a digital image of the real borehole wall can be rebuilt and it can visually describe the whole borehole; and 3) by establishing and managing correlative geological information database, it makes possible the rapid searching, picking up and analysing of the data.

In this system there are two methods of forming digital borehole images, namely, seamless stitching algorithm and scan line algorithm. The former 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 data on the circle with millimetre spacing. The collected scan lines are heaped up along depth direction to form the borehole image with millimetre accuracy, called a whole-hole image. The image can be used to describe continuous or whole borehole wall, but it ignores the tiny structural characteristics (less than 1.0 mm size). Thus, it becomes possible to evaluate the rock mass integrity based on the whole-hole image.

A borehole Image directly and visually reflects the geological characteristics in a borehole and creates conditions for engineers/geologists to make an accurate geological evaluation. How to collect quantitative information, however, is a problem that borehole camera technology must solve. Early borehole camera used simulation technology to obtain quantitative information by estimate. Nowadays borehole camera, such as the digital panoramic borehole camera system, can make accurate measurements by using digital technology. Theoretically a planar crack is represented by a sine curve on an unrolled image of borehole. The amplitude and phase angle of the sine curve can be calculated using computer software. Furthermore, the dip direction and dip angle of the planar crack can also be determined by selecting three points on the sine curve. The operating process can be realized on the computer in the form of human-machine interaction. Figure 2 is a borehole image with results of the orientation and aperture of observed cracks.

The text on the right side shows the orientation and aperture of cracks at the indicated location. Through collecting and storing geological information for a borehole, a whole database can be formed as the foundation for further analysis and statistics.

Table 1. Test summary on reducing subsidence by grouting into separated strata space

Test places	Working face	Mine thickness (m)	Coal bed dip angle (°)	API (m)	ILMDS (m)		Coefficient of mining $N=DH$		DMDS (mm)	EMDS (mm)	MSSR (%)	DIDS (%)	Coal cutting method	DST (m)	Remarks
					D_1	D_2	n_1	n_2							
Fushun Laohutai mine	512	25.7	26	602	120	427	0.20	0.71	712	2046	0.28	65	ID		
	518	36.6	30	619	82	345	0.13	0.56	1118	3240	0.28	65	SF		
	511	27.3	28	621	85	415	0.14	0.67	843	2254	0.30	63			
Datun Xuzhuang mine	7215	2.6	20-23	529	110	960	0.21	1.0	576	1170	0.24	3-66 (35)	SLW SC	155	FCS SDR 27% 663%
Xinwen Huafeng mine	1407	2.2	30	787	292	1100	0.37	1.00 84	1483	2310		36	DCMCM	0-8	
	1408			68	11	57	0.16						SC		
Yankuang Dongtan mine	14307 west	5.4	3	545	179	830	0.33	1.0	1159	1776	0.32	49-88 60	CMCM Cave in	110	FCS SDR 49% 88%
	14307 east	6.0	3	550	180	924	0.32	1.0							
	14308	9.3	3	547	195	1320	0.14 -0.33	0.56 -1.0							
Kailuan Tangshan mine	3694	9.8	5-15	789	90	380	0.11	0.48	187	1105	0.33	83			
	3694	10	5-15	764					429	1336	0.42	67.7	CMCM Cave in		
	3654	2.8	15	734	135	425	0.18	0.58							

Subscript explanation: API (Average production-injection); ILMDS (Inclined length of mining section size); DMDS (Measured maximum of surface subsidence); EMDS(Estimated maximum of surface subsidence); MSSR (Measured surface subsidence ratio); DIDS (Reduction ratio of surface subsidence); DST (Surface soil thickness); ID(Inclined delamination); SF (Sand filling); SLW (Strike longwall working); SC (Section cave in); FCS(Full cross section); SDR (Subsidence reduction rate); DCMCM(Delaminated comprehensive mechanized coal mining).

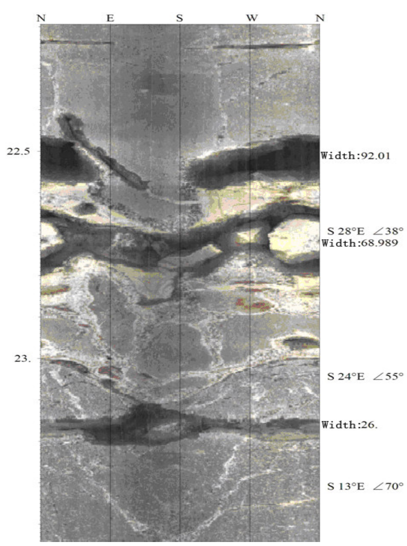

Figure 2. A borehole image with results of orientation and aperture of observed cracks

3 ENGINEERING APPLICATION

3.1 Engineering Introduction

The application of the method proposed here is illustrated with an example at Tangshan Mine that crosses five cities and counties in Hebei Province: Tangshan, Luanxian, luannan, Fengrun and Fengnan. It is located at latitude 117°25'-118°33'E and longitude 39°21'-39°52'N, adjacent to Yanshan Mountain to the north and facing Bohai to the south. The elevation of the north altitude is 296m and that of the south altitude is about 1-60m. The elevation of the coal bed is -560 – -1200m.

Jingshan Railway crosses the mining area and divides Tangshan Mine into two production areas, one in the east and one in the west. The length of the coal under the railway is nearly 10km. The geological reserves of the coal are about 200 million tons, occupying nearly half of the mine reserves. Both sides of the railway are populated with buildings, plus urban areas, enterprises and institutions.

Because the thickness of the mineable coal bed is large in the mine area, multi-level repetitive mining may cause relatively large surface subsidence. Besides, the location is at the plain where the groundwater level in the Quaternary loose soils is shallow and the surface easily allows large pool of water to accumulate. If the traditional method were used to mine the coal bed under the railway, the course of the railway would have to be changed and buildings at both sides had to be moved. The potential consequence would be that plenty of non-arable lands are generated, land resources are wasted and many environmental and social problems are triggered. At the same time, the mining company would have to bear great economic burdens.

In order to carry out the coal mining without relocation of existing structures and facilitates, Kailuan Mining Bureau introduced the technology of treating mining-subsidence by high pressure ground grouting in June 1992. Some experience has been gained through testing the fifth coal bed (3652) and the ninth coal bed – sub-bed (3694) from 1992 to 1996. The grouting was successfully applied from April 1998 to February 2000 in the ninth coal bed 3696, 3694 (under the mined condition of the above fifth coal bed and the first sub-bed of the ninth coal bed) as the expected subsidence reduction was achieved and rich experience on grouting technique and project management has been gained.

To further understand the engineering geological conditions, we surveyed Boreholes $T_1$291 and $T_2$291 on Nov. 20, 2006 and Nov. 20, 2007, respectively by means of the digital panoramic borehole camera technique. From this, we determined the geological characteristics such as the stratum structural surface, joint fissure and structure evidence etc., in the tested area. The two boreholes $T_1$291 and $T_2$291 are near each other, with their plane coordinates being (383143, 70327) and (383145, 70329), respectively. Therefore, the survey results of the two boreholes enabled us to determine the conditions of the distribution characteristics and development scale of the strata separation.

3.2 Geological Condition of the Area

Tangshan Mine is located at a relatively gentle side at the south end of the northwest side diagonal to Kaiping forming a monoclinal structure. The thickness of the Quaternary loose soils in the area is about 98m, mainly consisting of interbeds of clay, sand, and silt soil. There is a 20m gravel layer at the lower part. The foundation of the coal measure strata is Ordovician Majiagou group strata, consisting of sediments of carbonate phase. The coal measure strata consist of permo carboniferous sea-land-inter-sandstone, mudstone and shale and coal bed. The entire coal measure strata belong to middle and slightly hard strata.

3.3 Borehole Condition

Borehole $T_1$291 reached a depth of 502m; with steel casing lining the top 169m. The digital panoramic camera detection depth is from 199.65m to 414.05m due to some hole blockage. Originally, it was planned to make a second camera detection in Borehole $T_1$291, but the hole collapse was severe and could not be restored. Therefore, near the original location of Borehole $T_1$291, Borehole $T_2$291 was drilled reaching a depth of 550m, with casing for the top 174m of the borehole, and digital panoramic detection was conducted from depths 174.30m to 539.70m. The locations of $T_1$291 and $T_2$291 are shown in Figure 3(A). Their images (310m-315m section) for comparison are shown in Figure 3($T_1$291 and $T_2$291).

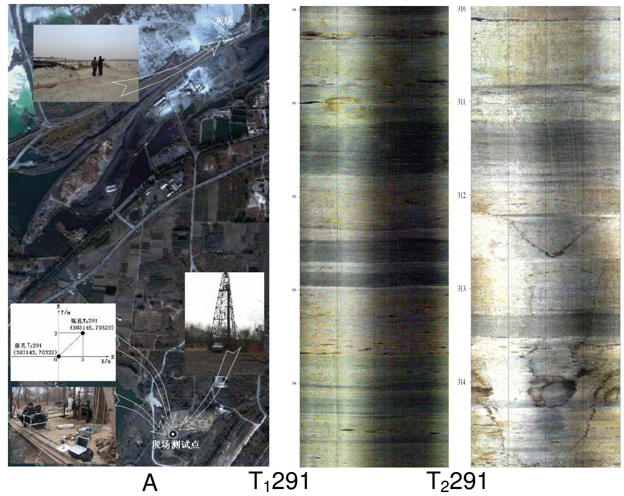

Figure 3. Borehole location and images of 310-315m section

3.4 Test Result and Analysis

For the convenience of comparative analysis and study of the development characteristics of the strata separation, this study counts only the gentle-inclination cracks (assuming it is same to the separation strata) at the same elevation of $T_1$291 and $T_2$291 (rock mass within the borehole depth range 200m-400m). And the result is as follows: 1) Borehole $T_1$291 has 82 cracks altogether with a total width of 1902mm; and 2) Borehole $T_2$291 has 184 cracks with a total width of 4609mm. Therefore, from the first to the second borehole, the total number of cracks has increased by 102 and the total crack width by 2707mm. When it is counted with 5m as one section, the result is listed in Table 2. Here: $\Delta T = T_2 - T_1$; T_1 and T_2 are the crack numbers within the 5m section in $T_1$291 and $T_2$291 boreholes. 2) $\Delta W = W_2 - W_1$; W_1 and W_2 are the sum of crack width within the 5m section in $T_1$291 and $T_2$291 boreholes. The change of the crack number difference and width difference along the depth reflects the distribution characteristics of the development crack along the depth as is shown in Figure 4 and 5. We know from the figures that the distribution of change of crack number along the depth is relatively even, but the crack development area can be approximately differentiated. The change of the crack width is relatively prominent, which is favorable to distinguish the development area of cracks. By comparing Figures 4 and 5, the development areas of cracks are basically consistent.

The changes of both crack number and crack width reflect the development characteristics of cracks. In order to comprehensively reflect its development characteristics and more clearly determine the development area of cracks, the ICD-Index of Crack Development is defined:

$$ICD = \Delta W \times (1 + \Delta T / (T_1 + T_2))$$

Table 2 Statistical results of 5m section

Depth(m)	$T_1$291		$T_2$291		ΔW (mm)	ΔT	ICD	Depth (m)	$T_1$291		$T_2$291		ΔW (mm)	ΔT	ICD
	W_1 (mm)	T_1	W_2 (mm)	T_2					W_1 (mm)	T_1	W_2 (mm)	T_2			
200	67	6	218	12	151	6	201	305	59	5	169	5	110	0	110
205	11	2	196	9	185	7	303	310	126	5	100	6	-26	1	-28
210	66	6	105	7	39	1	42	315	20	2	154	5	134	3	191
215	0	0	30	2	30	2	60	320	36	2	61	3	25	1	30
220	710	1	800	1	90	0	90	325	26	4	82	7	56	3	71
225	0	0	0	0	0	0	0	330	0	0	0	0	0	0	0
230	0	0	33	2	33	2	66	335	7	1	18	2	11	1	15
235	12	1	73	3	61	2	92	340	0	0	18	2	18	2	36
240	0	0	77	6	77	6	154	345	50	4	99	6	49	2	59
245	111	4	342	6	231	2	277	350	0	0	0	0	0	0	0
250	0	0	35	3	35	3	70	355	0	0	103	7	103	7	206
255	0	0	33	2	33	2	66	360	0	0	168	7	168	7	336
260	0	0	65	3	65	3	130	365	131	3	306	7	175	4	245
265	82	3	164	7	82	4	115	370	33	3	82	3	49	0	49
270	0	0	68	4	68	4	136	375	0	0	53	2	53	2	106
275	9	1	28	3	19	2	29	380	0	0	182	5	182	5	364
280	45	4	94	6	49	2	59	385	23	3	61	4	38	1	43
285	40	3	45	3	5	0	5	390	83	5	144	6	61	1	67
290	47	3	69	6	22	3	29	395	6	1	57	5	51	4	85
295	26	3	89	6	63	3	84	400	66	5	105	6	39	1	43
300	10	1	83	5	73	4	122								

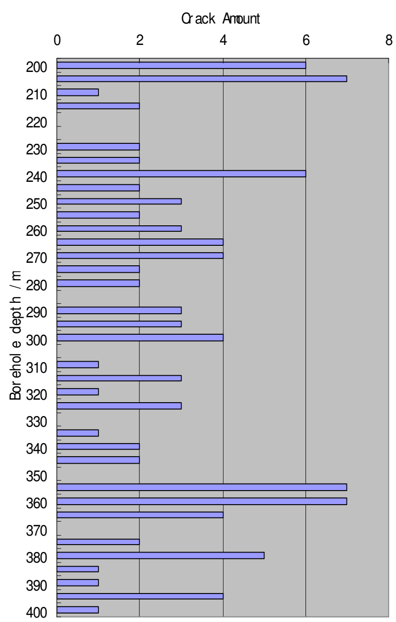

Figure 4. Distribution of crack amount

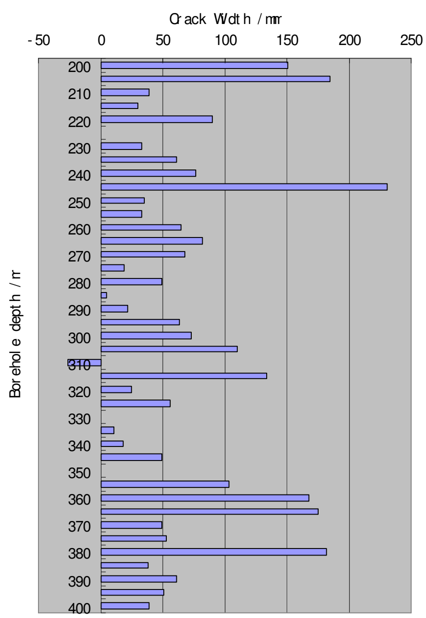

Figure 5. Distribution of crack width

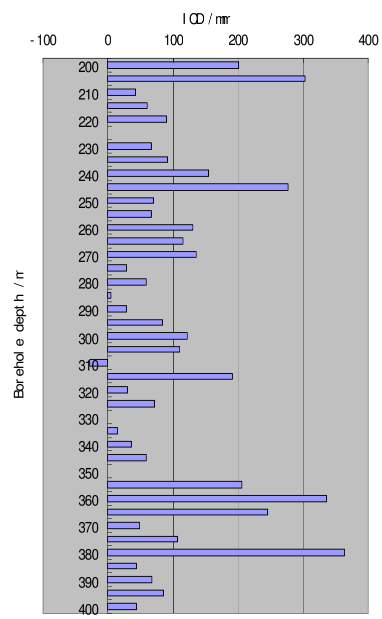

Figure 6. ICD distribution along depth

It can be shown from the above formula that ΔW must play a larger role when T_1 is large and if ICD is large; contrarily, when T_1 is small, a larger ΔT can amplify the role of ΔW if ICD is large.

According to the data in Table 2, the value of ICD can be calculated and listed in Table 2. Figure 6 shows the result of ICD distribution along the depth counted with 5m as one section. It is easy to find 4 developed crack areas from the figure: 1) 200m-210m; 2) 245m-250m; 3) 355m-370m; and 4) 380m-385m. The statistics show that the depth range of the four areas occupies 17% of the entire measured range, and the change of their crack width accounts for 44% of that of the entire statistical range.

3.5 Results

Through camera detection in Boreholes $T_1$291 and $T_2$291 and the statistical analysis of gentle-inclination cracks at the same position of the two boreholes (rock mass within the borehole depth range 200m-400m section), the follow results can be got:

1) The rock mass in this section has four crack development areas, located at, 200m-210m section, 245m-250m section, 355m-370m section and 380-385m section, respectively. They are the main areas for strata separation grouting.

2) The depth range of the four crack development areas occupies 17% of the entire statistical range, and the change of their crack width accounts for 44% of that of the entire statistical range.

4 CONCLUSIONS

In order to verify the strata separation space formed after underground coal bed mining, this paper proposes the use of the advanced detection technology, i.e. DBC technology, to detect the strata separation development area. Application to Boreholes $T_1$291 and $T_2$291 at Tangshan Mine was found to correctly determine the area and scale of the separation stratum development, which provides reliable parameters for the separation strata grouting process. The following conclusions can be drawn from the application:

1) DBC technology is capable of determining strata separation development area and scale.

2) The measurements on the borehole images acquired by means of DBC technology are of high precision and produce correct statistical results.

3) It is feasible that DBC technology is applicable CRSS detection.

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