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**DETECTION OF MULTILAYER CAVITIES BY EMPLOYING RC-DTH AIR HAMMER SYSTEM
AND CAVITY AUTO SCANNING LASER SYSTEM**

**WYKRYWANIE PUSTEK OBEJMUJĄCYCH KILKA WARSTW PODŁOŻA PRZY WYKORZYSTANIU
UKŁADU ZŁOŻONEGO Z MŁOTA PNEUMATYCZNEGO WGLĘBNEGO Z ODWROTNYM OBIEGIEM
PŁUCZKI RC-DTH I AUTOMATYCZNEGO UKŁADU LASEROWEGO DO SKANOWANIA**

The subterranean cavities are seriously threatened to construction and mining safety, and it's important to obtain the exact localization and dimensions of subterranean cavities for the planning of geotechnical and mining activities. Geophysical investigation is an alternative method for cavity detection, but it usually failed for the uncertainly solution of information and data obtained by Geophysical methods. Drilling is considered as the most accurate method for cavity detection. However, the conventional drilling methods can only be used for single cavity detection, and there is no effective solution for multilayer cavities detection have been reported. In this paper, a reverse circulation (RC) down-the-hole (DTH) air hammer system with a special structured drill bit is built and a cavity auto scanning laser system based on laser range finding technique was employed to confirm the localization and dimensions of the cavities. This RC-DTH air hammer system allows drilling through the upper cavities and putting the cavity auto scanning laser system into the cavity area through the central passage of the drill tools to protect the detection system from collapsing of borehole wall. The RC-DTH air hammer system was built, and field tests were conducted in Lanxian County Iron Ore District, which is located in Lv Liang city of Shan Xi province, the northwest of china. Field tests show that employing the RC-DTH air hammer system assisted by the cavity auto scanning laser system is an efficiency method to detect multilayer cavities.

Keywords: multilayer cavities detection; RC-DTH air hammer; drill bit; cavity auto scanning laser system

Podziemne wgłębienia i pustki stanowią poważne zagrożenie dla budowy oraz dla działalności górniczej; dlatego też podstawowym zagadnieniem jest ich dokładna lokalizacja i określenie wymiarów. Jest to niezbędne dla planowania prac geotechnicznych i wydobywczych. Badania geofizyczne są alternatywną metodą wykrywania podziemnych zagłębień, zazwyczaj jednak okazują się nieskuteczne ze

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względu na niepewność rozwiązań oraz danych uzyskiwanych za pomocą metod geofizycznych. Wykonanie odwiertu jest najdokładniejszą metodą wykrywania zagłębień i pustek, jednakże konwencjonalne metody prowadzenia wierceń pozwalają na wykrycie jednego tylko zagłębienia, nie ma też skutecznego rozwiązania kwestii istnienia zagłębień i pustek przechodzących przez liczne warstwy górotworu. W pracy omówiono zastosowanie układu młota pneumatycznego wglębnego z odwrotnym obiegiem płuczki, wyposażonego w odpowiednie urządzenie wiertnicze, oraz układu skanera laserowego wykorzystującego technikę dalmierza do potwierdzania lokalizacji pustek i ich wymiarów. Prezentowany młot umożliwia dokonanie odwiertu w zagłębieniach i pustkach znajdujących się w warstwach wierzchnich, następnie w zagłębieniu tym umieszczane jest laserowe urządzenie skanujące powierzchnię komory wprowadzane poprzez główny kanał w urządzeniu wiertniczym, tak by zabezpieczyć skaner na wypadek osunięcia się ścian otworu. Układ składający się z młota pneumatycznego zbudowano i przetestowano w warunkach polowych w zagłębieniu miedziowym w okręgu Lanxian, w pobliżu miasta LV Liang w prowincji Shan Xi, w północno-zachodnich Chinach. Badania przeprowadzone w terenie wykazały, że zastosowanie układu złożonego z młota pneumatycznego wglębnego RC-DTH wraz z laserowym skanerem jest skuteczną metodą wykrywania pustek przechodzących przez liczne warstwy.

Słowa kluczowe: wykrywanie pustek przechodzących przez liczne warstwy górotworu, młota pneumatyczny wglębny z odwrotnym obiegiem płuczki, urządzenie wiertnicze, laserowy skaner pustek

1. Introduction

The presence of natural subterranean cavities in karst topographies and man-made subterranean cavities, such as the sinkholes and the abandoned underground mines, are seriously threatened to infrastructures and mining safety (Grandjean & Leparoux, 2004; Nagib & Lorenz, 1988; Mochales et al., 2008; Liu et al., 2008; Chalikakis et al., 2011; Militzer et al., 1977). The sudden collapse of sinkholes or cavities produced by mining activities had caused lots of accidents in china, and the costs of economic and lives related to the damage caused by catastrophic collapses are shocking (Luo, 2005; Wu, 2010; Liu, 2012). Therefore, it's important to obtain the exact localization and dimensions of subterranean cavities for the planning of geotechnical and mining activities.

Accurately positioning subterranean cavities is a difficult task for engineers, and several detection techniques have been used to detect subterranean cavities. Geophysical investigation is considered as the most economical method for subterranean cavities detection (Grandjean & Leparoux, 2004; Chalikakis et al., 2011). Ground-penetrating radar have been employed to map subterranean cavities successfully (Chamberlain et al., 2000; Beres et al., 2001; Leucci & Giorgi, 2005; Mochales et al., 2008). In addition, microgravimetry is also widely used for detecting subterranean cavities (Beres et al., 2001; Giorgi & Leucci, 2014). Other geophysical methods such as electrical resistivity tomography (Schoor, 2002; Leucci & Giorgi, 2005; Cardarelli et al., 2010) and seismic methods (Cardarelli et al., 2010; Kosecki et al., 2010) are also used for subterranean cavities detection. However, geophysical investigation for the subterranean cavities detection is not always effective for its uncertain solution of data, and the highly variable and unpredictable target characteristics (Mochales et al., 2008; Cardarelli et al., 2010). It is difficult to detect subterranean cavities accurately by using the geophysical investigation methods. In many cases in the assessment and monitoring phases, conventional drilling method is considered as an accurate method to detect subterranean cavities, and drilling assisted by other known information is an effective method for subterranean cavities detection (Leucci & De Giorgi, 2005; Zhang et al., 2010). Unfortunately, most geophysical investigation methods and conventional drilling methods can only be used for single cavity detection. And the multilayer cavity often exist in

nature or be left by disordered exploitation. There is no effective solution for multilayer cavity detection-which has been reported.

In order to realize the multilayer cavities detection, a reverse circulation (RC) down-the-hole (DTH) air hammer system with a special structured drill bit is developed, and a cavity auto scanning laser system based on laser range finding technique is employed to measure the dimensions of the cavities. The RC-DTH air hammer system has been designed and the field test of this drilling method assisted by the cavity auto scanning laser system has been conducted, which will be detailedly described in this paper.

2. Introduction of cavity auto scanning laser system

The Cavity auto scanning laser system is based on the laser range finding technique, and its basic principle is to record the round tripping propagation time of the laser, then calculate the measured distance (L) using the follow equation (Li et al., 2004):

$$L = ct/2$$

where c is the propagation speed of laser in air, t is the round tripping propagation time of laser.

As the most 3D laser detection systems, the cavity auto scanning laser system also uses internal reference frame to determine the coordinates of the scanning point as shown in figure 1. Both axis x and axis y are in the cross direction scanning plane and perpendicular to each other. The z axis is perpendicular to the cross direction scanning plan. Point O and P are the laser detection system and the scanning point, respectively. The length of OP is obtained and recorded by the laser detection system, the cross direction scanning angel α and longitudinal scanning angle θ of each laser impulse are synchronously measured by an accurate clock controlling coder. Thus the $x/y/z$ coordinates can be obtained through the triangular relationship. The auto scanning laser system manufactured by MDL is one of the commercial cavity auto-scanning system, which could well fit to the cavity detection by drilling method. The detector is 50 mm in diameter. Its maximum range to a passive target is up to 150 m and the minimum range is 0.5 m, with the resolution of 1 cm.

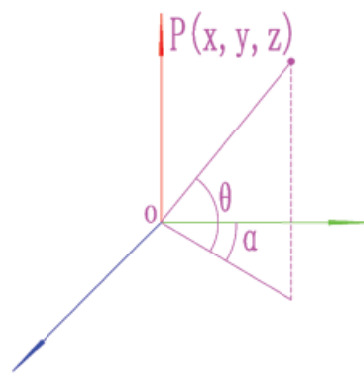


Fig. 1. A schematic of 3D laser scanning

3. Structure design of the DTH air hammer

Because of the impact loads at the bit inserts in percussion drilling are much higher than the load levels typically achieved in rotary drilling, and the total contact time of inserts with the rock is substantially less than during rotary drilling (Melaned et al., 2000), the DTH air hammer can provide high penetration rate and have been widely used in mining (Franca, 2011). In conventional DTH air hammer drilling methods, the compressed gas is pumped down into the drill

pipe and out through the drill bit directly, then carrying drill cuttings into the annulus between drill pipe and borehole to return to the surface. It always fails to carry the drill cuttings out of the borehole while drilling in leakage strata or broken formations. Using such a method to detect cavities can penetrate the first cavity rapidly. However, after penetrating the roof of the first cavity and getting into the cavity, then drilling in the floor of the cavity, the conventional DTH air hammer system can't form a borehole wall in the empty area which cause the drill cuttings carried out through the borehole bottom unsuccessfully. What's more, the air hammer and drill bit of the conventional DTH air hammer system are not allowed the detection system through it into the cavity, and the borehole formed by this drilling method is easy to collapse when there is unconsolidated formation upper the roof of the cavity, for the formation nearby the borehole is seriously disturbed by the rising airflow. It usually failed to put the detection system into the cavity, or the detection system is stuck in the borehole and unable to recycle. Different from the conventional DTH hammer, the RC-DTH air hammer has a hollow-through shaft, as shown in Fig. 2. The compressed air is pumped into the double-passage swivel by the flexible air input tube. Then it flows through the annular space between the inner and outer walls of the double-passage drill pipe, the hollow-through DTH air hammer. After driven the DTH air hammer, the discharged gas flows out through the drill bit to carry the drill cuttings upward through the central passage of the drill tools instead of the annular space between drill pipe and borehole, then the drill cuttings are carried out through the flexible discharging tube and collected by a cyclone separator.

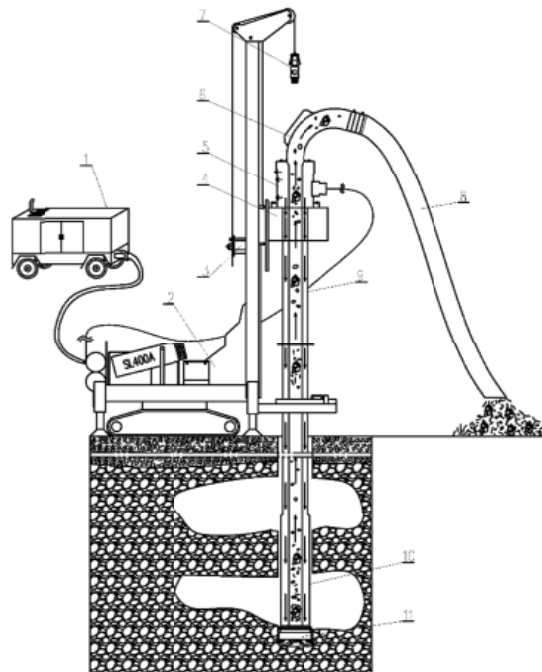


Fig. 2. Schematic of the hollow-through DTH air hammer drilling system
 1 – air compressor; 2 – drilling rig; 3 – winch; 4 – power unit; 5 – dual – wall tap; 6 – goose neck tube;
 7 – elevator; 8 – flexible discharging tube; 9 – dual – wall drill pipe; 10 – RC – DTH hammer;
 11 – the drill bit

The use of reverse circulation drilling method instead of conventional circulation drilling method has advantages to detect cavities since the cuttings can carry out from the borehole bottom smoothly whether there are leakage strata or broken formations, or cavities. What's more, the hollow-through shaft of the RC-DTH air hammer permits the detection system getting into the cavity area through the center passage of the drilling tools directly without being taken out the drilling tools, which can protect the detection system from jam of collapsed borehole wall, as shown in figure 3. It also has advantage to dust control during drilling process since the flexible discharging tube can be long enough so that its end can be placed at an ideal place, and its outlet can be connected to a cuttings and dust collector placed far from the drilling site. There is no sealing mechanism used at the mouth of borehole and the reverse circulation is formed by the guiding of the drill bit for its specially designed structure. The schematic of the detection processes are shown in figure 2 and figure 3. In the drilling process, the drilling system works normally until the drill bit penetrates the roof of the cavity. Once the cavity roof is penetrated, the air hammer and the drill bit skidded down a segment due to gravity and limited by the semi-circle clips, and the RC-DTH air hammer will stop work immediately because of its valve mechanism is failed. In the detection process, locking the lower drill pipes on the drill deck to prevent the drilling tools from falling into the cavity and removing the drill pipe upper the ground firstly; then, putting the detection system into the cavity through the center passage of the drilling tools to obtain the dimension information of the cavity; finally, taking out the detection system after finishing the detection, and adding joints to continue drilling process to detect the cavity below the upper one.

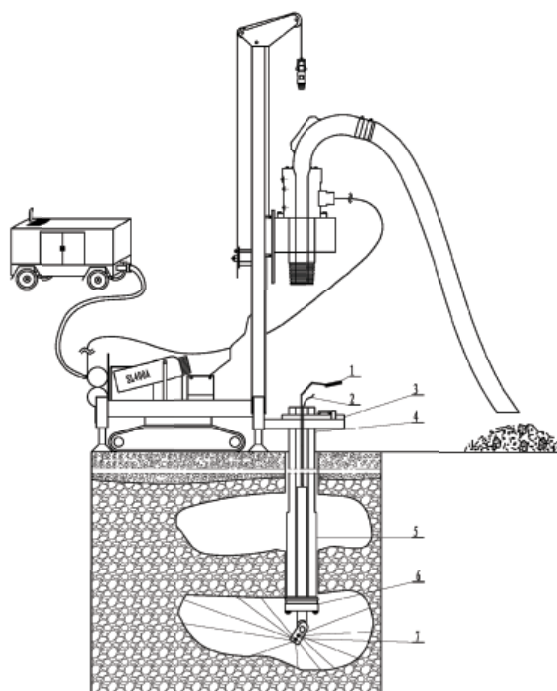


Fig. 3. Schematic of scanning process

1 – guid rod; 2 – cable; 3 – fork; 4 – drill deck; 5 – RC – DTH air hammer; 6 – drill bit; 7 – scanning unit

The structure of the RC-DTH air hammer specially designed for cavity detection is shown in figure 4. The RC-DTH air hammer designed for cavity detection in this work is 142 mm in outer diameter with a center passage diameter of 68 mm. The nominal pressure of the compressed air is 2.0 MPa with a piston travel of 140 mm.

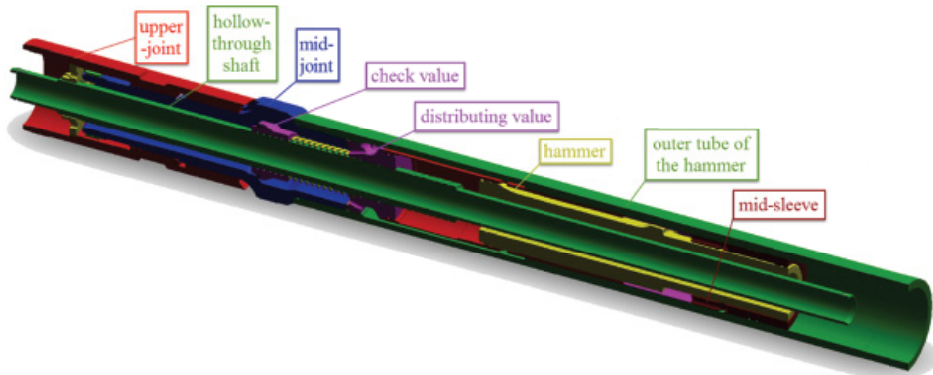


Fig. 4. Schematic of the hollow-through DTH air hammer

4. Design of the drill bit

In the RC-DTH air hammer system, the drill bit is the most key part in this system for the structure of the drill bit would directly influent on the forming of reverse circulation. Different from the conventional drill bit, the RC-DTH air hammer drill bit is based on the principle of the gas ejector, as shown in figure 5. As gas ejectors are gas-driven venture jet devices that use compressed gas to create a vacuum that can entrain or mix another gas stream, the RC-DTH air hammer drill bit can also utilize the energy of compressed air to create a pressure difference in the center passage of the drill bit to achieve the effect of suction. Figure 6 shows the structure of the RC-DTH drill bit.

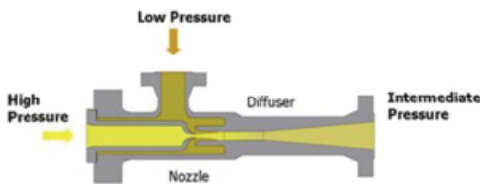


Fig. 5. Schematic of the gas ejector

Suction nozzles are located on the body of the drill bit, flushing nozzles are designed vertically to the bottom of borehole. The pressure restoring grooves are designed at the outlets of the flushing nozzles. The air jets out through the flushing nozzles to sweep the drill cuttings toward the center of the drill bit and cool working face of the drill bit. The air jets out through the suction nozzles to entrain air around them and produce a pressure difference in the central passage immediately above the borehole bottom. The drill cuttings are continuously drawn into the central passage of the drill bit and carried out of the borehole through the central passage of the drill tools due to the pressure difference between the central passage of the drill tools and annulus between drill pipe and borehole. Its suction capacity has directly influent on the forming of reverse circulation, and suction capacity is assessed by the mass flow rate of air entrained through annulus between the drill pipe and borehole. The

greater the pressure difference is, the more the air will be sucked from the annular space into the central passage, and the stronger suction capacity the drill bit will have

In order to permit the cavity auto scanning laser system to pass through the drill bit, a through-hole with a diameter of 60 mm is specially designed in the center of the drill bit. Two carbide ball tooth slant inlaid in the edge of the through-hole symmetrically with a distance of 55 mm to limit the dimension of drill cuttings, which can ensure the drill cuttings didn't block the center passage of the drill tools in the drilling process. Twelve Suction nozzles with diameter of 7 mm, elevation angle of 60 degrees and deflexion angle of 20 degrees, are divided into two layers. Two flushing nozzles with diameter of 8 mm are symmetrically distributed. The suction capacity of RC-DTH air hammer drill bits are usually evaluated by the Fluent software in the design process to investigate the internal flow field, and the internal flow field for this special designed drill bit is shown in figure 7. The input air mass flow rate is 0.1225 kg/s for this simulation model and the calculated entrained air mass flow rate of the annulus (Q_s) between borehole and drill pipe for this drill bit is 0.080 kg/s. The simulation results show that the parameter for this drill bit is benefit to the reverse circulation.

5. Field test

Established in 2009, Yuan Jiacun iron ore is affiliated to Taiyuan Iron & Steel (Group) CO., LTD., which is located in Lanxian county of Shanxi province, the northwest of China. The iron deposit is 4.2 km in length from south to north, 2.6 km in width from east to west. The total geological reserve of this iron ore is about eight hundred million tons. There are twenty-one ore bodies in this iron deposit. The ore body 10 is the biggest one and the geological reserve of this ore body accounts for 57.88% of the verified reserve, secondly for ore body 1 and 11, the geological reserves accounts for 17.62% and 10.94% of the verified reserve, respectively. The designed annual output of raw ore is twenty-two million tons, and the designed annual output of iron concentrate is 7.4 million tons a year. Now, the Yuan Jiacun iron ore is the biggest iron ore in Asia. Before the Taiyuan Iron & Steel (Group) CO., LTD. took over this iron ore in

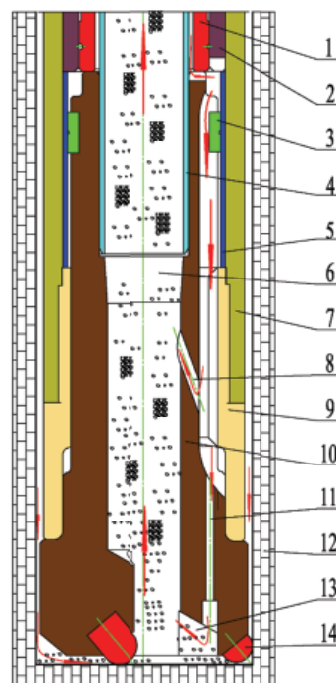


Fig. 6. Schematic of drill bit

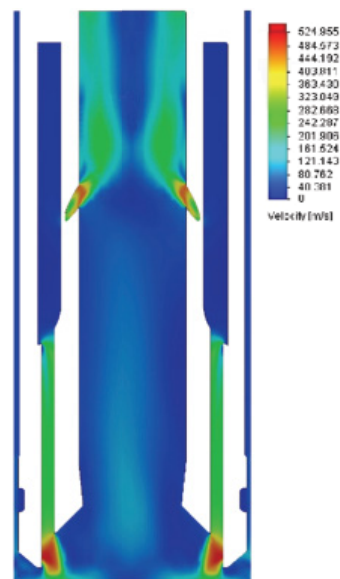


Fig. 7. Distribution of velocity magnitude at a representative longitudinal section

2004, there were thirty-six private enterprise mined in iron ore area. Underground mining method to mine rich ore is main mining method because of their scales are small. Both vertical shaft and footrill were used for these miners. Their total specified mining activity areas is 1.905 km², about 25% on the total area of the Yuan Jiacun iron ore. Because of the approval mining area for these miner is very small, the phenomenon of several miners mined in the same area with different depth at the same time is very common. The mining panel beyond the approved area cause goaf linked together. Although 57 tunnels and cavities had been measured by the government in 2006, the rest of the cavities are unknown for the collapse of the tunnels and cavities, which is serious threatened to the security of strip mining. There are four surface collapse had happened from 2011 to 2013, the first one came in April 2011, a collapse pit with a diameter of 10 m, depth of 8m formed located on the transport route. The most recent one came in September 2013, a collapse pit with a diameter of 23 m, depth of 5 m formed in the blasting operation area.



Fig. 8. Two types of drill bits

The works of detection of cavities are carrying out in the mining process since April 2011. Twenty-six cavities which are concentrate on ore body 1 and ore body 10 have been detected. About a quarter of the cavities is multilayer cavities and the deepest one is about 506 m. The geophysical methods such as the transient electromagnetic method, radon detective method, ground penetrating radar were used to detect the cavities at the beginning, five measure points were measured and validated by drilling method, and only one have cavity with a depth error of 5 m between the forecasted and actual. Five cavities were detected by conventional drilling method in 2011 and only one cavity had been forecasted by geophysical methods. The results of application of geophysical methods indicated that the accuracy of using geophysical methods to detect cavities is very low. Limited by the conventional drilling method, only upper cavity can be detected in the multilayer cavities area. Usually, the multilayer cavities take more risks for the separator of the upper and lower cavities is very thin and the multilayer cavity area is still dangerous after processing the upper cavity. The collapse pit occurred in

September 2013, the most recent one, is a case for multilayer cavities collapsing.

In order to verify the feasibility of using RC-DTH air hammer system to detect multilayer cavities by the assistant of cavity auto scanning laser system, a RC-DTH air hammer system with the parameters above mentioned is produced and field test was conducted in Yuan Jiacun iron ore. Two kinds of drill bit were designed. Structure of one of the drill bits is the same as described before, the only difference of another one is that there is sliding block at the bottom of the drill bit, as shown in figure 8. For sliding block drill bit, the sliding block well slide towards the center of the drill bit because the bit pressure to decrease the diameter of the through-hole, that well prevent large drill cuttings get into and block the center passage. When the drill tools is hanged in midair, the sliding block is slide towards edge of the drill bit for its weight to permit the cavity auto scanning laser system to get through into the cavity area. A top drive drill and an air compressor with a nominal air flow rate of 27.6 m³/min were employed in the drilling process.

The field test point is selected at a place where have two layers of cavities known previously, the upper one is named cavity 25-3 and the lower one is named cavity 42. There are about eight meters of unconsolidated formation upper the roof of upper cavity. The upper one is detected in the shot hole drilling process and the lower one is detected in an accident of inclination of borehole by using conventional drilling method. The borehole position is shown as figure 9. Point n13 and point n14 are the borehole position which had been finished previously. The point n17 is the borehole position for using RC-DTH air hammer system to drill. The data obtained by cavity auto scanning laser system indicated that the maximum length, height and width are 37.9 m, 11.5 m and 23.6 m for cavity 25-3, respectively. The maximum length and height are 66 m and 14.7 m for cavity 42 and the width is not clear for the line-of sight is blocked by the jamb. The estimated thickness of the roof of cavity 25-3 is 19m and the roof of cavity 42 is 10 m for borehole position n17 by using the scanning data. The average penetration rate is about 60 m/h for drilling in the unconsolidated formation and 25 m/h for drilling in the consolidated formation. Two drill bits were used in the drilling process and had a very good performance of reverse circulation, and blocking accident had never occurred in the experimental process for both of the two drill bits. After penetrating the roof of the cavity, the drill tools were fixed on the drill deck. Before putting the cavity auto scanning laser system into the cavity area, a hammer with a diameter of 50 mm and length of 0.6 m was used to discharge the drill cuttings stick on the wall of the center passage of the drill tools to ensure the center passage of the drill tools is open. Then the cavity auto scanning laser system was put into the cavity area to measure the dimension of the cavity. Both of the two cavities were measured and the results are

the same as previous measurement. The actual thickness of the roof calculated by the length of drill tools is 17 m and 12.5 m for cavity 25-3 and cavity 42, respectively. Figure 10 shows the space form of the two cavities.

The field tests have shown that the use of RC-DTH air hammer assistant with cavity auto scanning laser system can detect multilayer cavity successfully. As shown in figure 10, the collar 1 and collar 2 are the borehole trajectories of previous drilling. And the collar 3 is the borehole trajectory for RC-DTH air hammer. The scanning data shows that a straighter hole was obtained by using the RC-DTH air hammer method. Using the RC-DTH air hammer system can also greatly enhance working environments, as shown in figure 11.

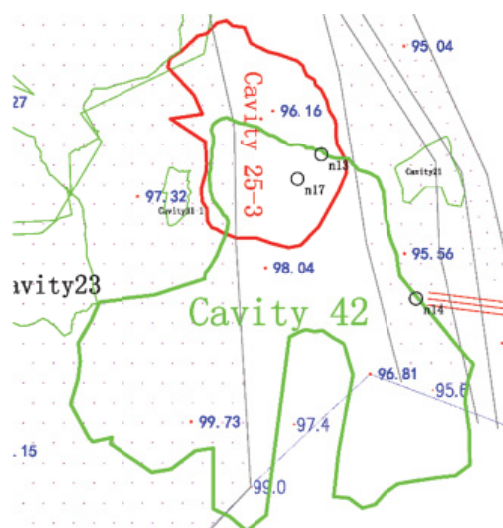


Fig. 9. Sketch of the position of borehole

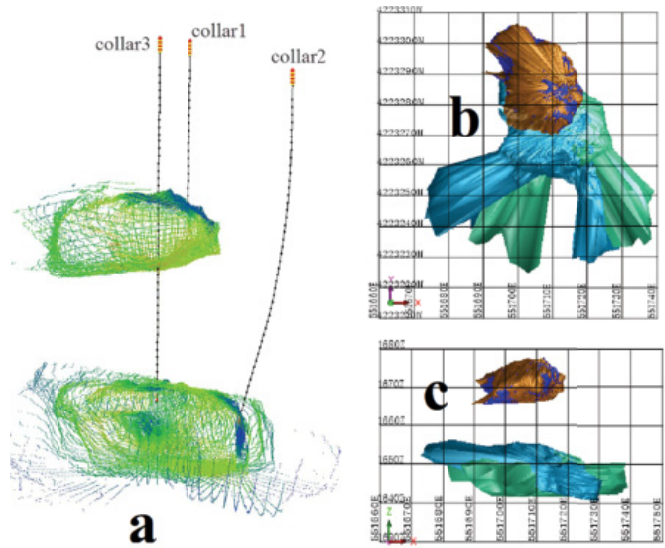


Fig. 10. 3D shape of two cavities
 a: The point cloud data obtained by the scanning system; b: top view of the two cavities;
 c: front view of the two cavities



Fig. 11. The field testing site
 a: the dusty drilling site by using conventional drilling method; b: the clean drilling site by using RC-DTH air hammer drilling method; c: cores obtained by RC-DTH air hammer drilling method; d: preparation of detection after drilling by using RC-DTH air hammer drilling method; e: the detection unit of the cavity auto scanning system; f: scanning process by using the cavity auto scanning system

6. Conclusions

ARC-DTH air hammer system including the RC-DTH air hammer and drill bit were designed and built. The method of employing RC-DTH air hammer system to detect the multilayer cavities by the assistant of cavity auto scanning laser system is proposed. The field tests of multilayer cavities detection have conducted successfully in Yuan Jiacun iron ore, and the results shows that this method is an efficiency way for multilayer cavities detection.

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