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RESEARCH OF DRILLING AND BLASTING METHOD BASED ON A SUPER-LARGE CROSS-SECTION CAVERN IN HONG KONG

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Abstract: With the increasing demand for urban underground space, the construction of oversized caverns has become an important issue in the field of underground engineering. The traditional drilling and blasting methods face challenges such as difficult design, large charge and large blasting volume when applied to the construction of oversized caverns. In this paper, a large cavern project in Hong Kong is used as an example to systematically study the drilling and blasting method applicable to super-large cross-section caverns. The method adopts large-diameter holes (51mm), micro-differential blasting technology, combined with high-precision rock drilling cart for fully automatic drilling, which significantly improves the blasting efficiency, reduces the rate of duds, and effectively controls the problem of over-under-excavation. By optimizing the arrangement of the holes and the selection of explosives, the average amount of explosives per cubic meter of rock was reduced to 1.2kg, which significantly saves the construction cost. In addition, the method is excellent in safety, environmental protection and flexibility, and the vibration monitoring points are provided at the construction site. So, the vibration generated by blasting has minimal impact on the surrounding environment. The research results of this paper provide an important reference for the construction of similar super-large cross-section caverns by drilling and blasting method, which has a high popularization value.

Keywords: super-large cross-section cavern; drilling and blasting method; differential blasting; rock drilling cart; blasting efficiency

1. INTRODUCTION

With the growing demand for underground space in urban development, the construction scale of tunnels and caverns projects is constantly expanding. Such projects usually face challenges such as complex surrounding environment, variable geological conditions, high construction costs, and technical difficulties, among which the excavation construction is particularly critical (Wang et al., 2010, Yan, 2019). In recent years, the development of mega-section tunnels and caverns construction technology is closely related to the rapid growth of transportation demand. Many early construction tunnels have been unable to meet the current transportation needs, prompting the development of larger span engineering construction. From the beginning of the 21st century, single tunnel 2 lanes gradually developed to single tunnel 3 lanes, 4 lanes, construction technology has made great progress. However, there are still few super-large cross-section caverns in the world, and the related technology system has yet to be perfected (Tan et al., 2019, Zhang et al., 2010, Chen et al., 2018, Zhang et al., 2020, Bi et al., 2011 & 2021).

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As the traditional construction method of tunnels and caverns, the drilling and blasting method plays an important role in infrastructure construction. With the continuous expansion of tunnel construction scale, drilling and blasting construction technology has experienced a leapfrog development from manual operation to mechanization and intelligence. According to the International Tunneling Association statistics, the global tunnel construction to the use of drilling and blasting method of construction is dominated by the proportion of China is as high as more than 70% (Guo et al., 2007). However, for the application of drilling and blasting method for large section tunnels and caverns there are still major difficulties. From the perspective of engineering mechanics, the distribution of surrounding rock loads and mechanical properties of support in mega-span tunnels have significant special characteristics. As the section size increases, the problem of surrounding rock stability becomes increasingly prominent, and engineering problems such as surrounding rock instability and lining structure cracking are prone to occur (Zhao et al., 2018, Huang et al., 2017, Zhang et al., 2001).

In recent years, China has made a series of breakthroughs in the field of super-large cross-section underground engineering (Zhu et al., 2002). The Liantang Tunnel of the Shenzhen Eastern Transit Highway, which was opened in 2018, created a record for the world's largest section highway tunnel at the time, with an excavated section of 428.5m2. The project included a variety of complex section forms. The New Badaling Tunnel of Beijing-Zhangzhou Highway is a typical representative of large-section tunnels constructed by drilling and blasting method, and its underground station project contains 78 large and small chambers, with the largest single-arch span of 32.7 m, and the construction process adopts the advanced technologies of mechanized construction and information management, which provides valuable experience for similar projects.

Currently, the section area of the world's largest span underground cavern has reached 1000 square meters, and China has made significant progress in this field, such as Chongqing Railway Hongqihegou Station, which has achieved 760 square meters of large section excavation. However, for this kind of large cross-section project, there are still many technical challenges in the selection of construction methods, parameter optimization, equipment development. The solution of these problems will be directly related to economy and safety of oversized section underground projects (Wang et al., 2010).

With the continuous growth of the demand for underground space development, the following development trends will be faced in the mega-section underground engineering: 1)construction technology will develop in the direction of intelligence and refinement, and new technologies such as digital twin and artificial intelligence will be more widely used; 2)the concept of green construction will be deeply rooted in the engineering, and environmentally friendly blasting technology and low-carbon support materials will be gradually promoted; 3) the research and development of standardized and modular construction equipment will enhance the engineering efficiency; 4) the cross-integration of disciplines will promote the innovative development of design theory. These technological advances will provide new ideas and methods for solving the technical difficulties currently faced (Tan et al., 2023, Yang et al., 2023, Tan et al., 2018, Wang et al., 2018, Hong et al. 2018). This paper describes the research and application of drilling and blasting construction method for oversized caverns in Hong Kong as an example, aiming to provide some engineering reference and theoretical guidance for similar oversized cavern projects in the future.

2. PROJECT OVERVIEW

In May 2011, Development Bureau (DEVB) in Hong Kong briefed the Legislative Council Panel on Development on its plan to identify feasible reclamation sites, identify suitable existing government facilities that could be relocated to rock caverns, and conduct relevant technical assessments. In December 2017, DEVB issued a policy guideline on rock cavern development to increase land supply, which included the promulgation of the Rock Cavern Master Plans and related planning and technical guidelines. This mega cavern project is the first of its kind in the DEVB's plan to relocate government facilities into rock caverns, freeing up 28 hectares of land for other uses beneficial to people's livelihoods. The project mainly comprises site development, main cavern construction, cavern ventilation system and ancillary buildings, etc. Construction methods such as drilling and blasting, permanent anchor support, OHVD, etc., as well as carbon-reduction measures such as rubble disposal and rock recycling, etc., have been adopted.

This project is a complex urban environment of oversized section drilling and blasting method construction cavern group, most of the palisade in more than 200m2, the largest cavern palisade width of up to 32m, the height of up to 32m, need to be split into the upper, middle, and lower levels of blasting operations, the average size of palisade up to 300m2, a rare Hong Kong and even the world's oversized section. This paper combines the actual construction situation, introduces the drilling and blasting method applied to this type of section construction method, in the hope of providing reference for similar projects.

3. PRINCIPLE OF DRILLING AND BLASTING METHOD

Drilling and blasting method is the traditional rock excavation method. For general highway or municipal road tunnels, the palm face size is generally below 100m^2, and will not change the design with the increase in depth. It is only necessary to understand the geological conditions in order to carry out a relatively simple blasting design. However, for cavern projects, since the excavated space will be used for construction facilities, the size of the face is mostly over 100m^2. The drilling and blasting method has the characteristics of high design difficulty, large amount of explosives, and large amount of blasting engineering. At the same time, cavern groups with different vertical and horizontal combinations also have faces of different sizes. How to design the blasting form at the junction is also a difficulty in the drilling and blasting construction of cavern projects compared to tunnel projects.

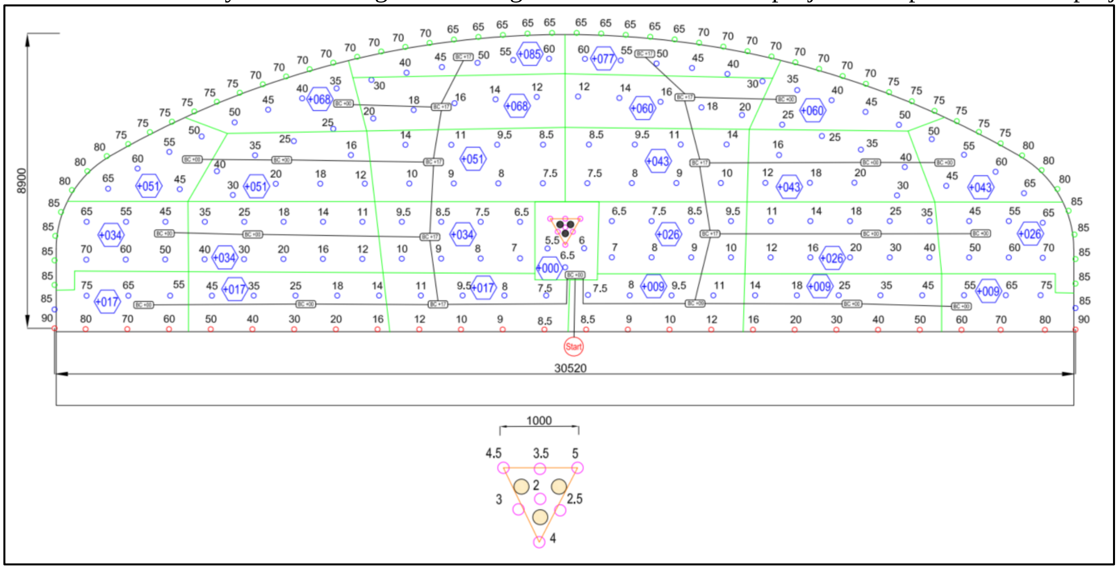

Figure 1. *Typical blasting design.*

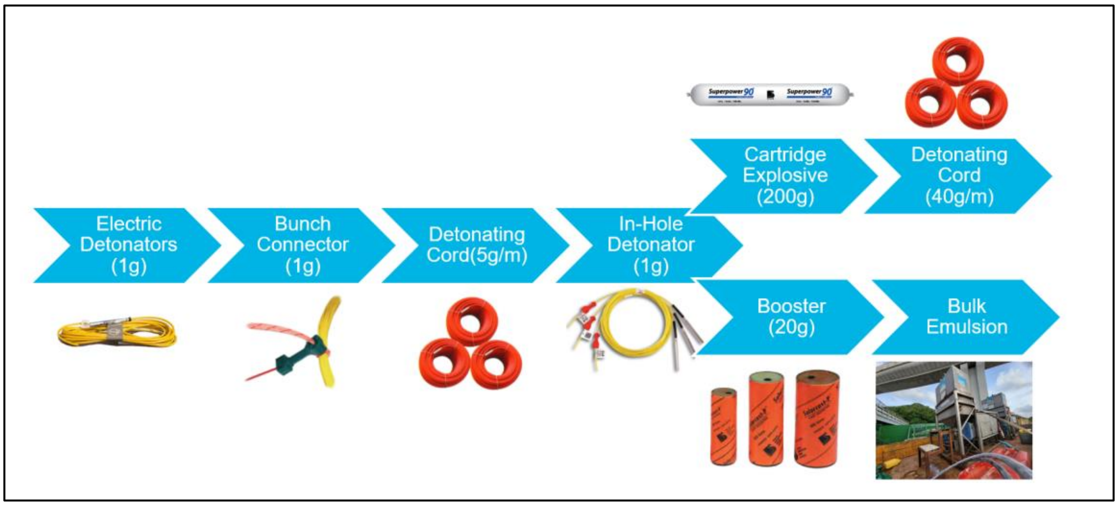

Figure 2. *Charging scheme.*

This method utilizes micro-difference blasting to construct tunnels with extremely large cross-sections, featuring rapid and simple construction, high flexibility, low cost, and high efficiency. After geological surveys are completed, the excavation face is first automatically drilled using a CNC drilling rig, into which emulsion explosives and electric detonators, as well as detonating cords, are placed according to the designed mix ratio; subsequent blasting operations follow, followed by quality inspection and evaluation of the blasting. The entire process centers on blasting design, combined with automatic drilling rig technology, significantly simplifying the tunnel support structure construction process, making it convenient and efficient. The following case study will focus on this rock cavern project.

It is suitable for tunnel projects with good geological conditions and super large sections. It is mainly used for rock caverns or tunnels with short distance and large blasting surface that are not suitable for shield machine construction, but it needs to ensure the excavation depth and efficiency of underground space projects. It has the following construction advantages:

(1) High blasting efficiency: Traditional blasting construction follows the approach of "short advance, dense holes, weak blasting," and due to limitations in operating machinery, the diameter of each blasting hole generally does not exceed 40mm, with no more than 1.5kg of explosives per meter, and the penetration depth does not exceed 4m. Using this method, under conditions of large-span full-face blasting, each blasting hole can reach 51mm, the explosive charge can reach 2kg/m, and the penetration depth is maintained at around 5m. Additionally, all blasting uses micro-difference blasting, allowing all explosives to be detonated within 10 seconds on a blasting face of about 300m², significantly improving the efficiency of cave group construction.

(2) High Flexibility: This method designs different blasting sequences and charge ratios for rock faces of varying sizes. After each blasting, geologists and supervisors evaluate the quality to determine the effectiveness of this blasting. Practical engineering has shown that this method offers high flexibility in blasting, with good blasting effects tailored to different blasting faces, free from template constraints, demonstrating significant versatility.

(3) High safety and environmental protection: This method has a high degree of mechanization, eliminating the need for manual operation by workers, ensuring construction safety. At the same time, over ten vibration monitoring points are installed around the project site. Based on data from each blasting and on-site experience, the vibrations generated by blasting can be negligible, with almost no impact on the surrounding environment, and people at the site do not feel the blasting process.

(4) High construction quality: This method uses high-precision rock drilling cart instead of air gun to ensure the quality of hole formation. Through the arrangement of precision micro-difference blasting, the blasting efficiency is significantly improved, the rate of silent blasting is reduced, and the over-excavation control of the blasting surface after blasting is good, and the amount of work that needs to be adjusted is less.

(5) High economic efficiency: This method has a high degree of mechanization, reducing labor costs and shortening construction periods, thus significantly lowering construction costs. At the same time, for the layout of blasting holes, under the premise of meeting the requirements for full-face blasting and depth in super-large sections, the spacing between bottom cut-off holes and auxiliary holes can be increased to over 1m, and the spacing between peripheral holes can be increased to over 0.6m. On average, each blasting hole can cover an area of 1.03m², with an average of only 1.2kg of explosives used per cubic meter of rock, greatly reducing the amount of explosives used and improving management efficiency.

4. CONSTRUCTION METHODOLOGY

4.1. Process flow

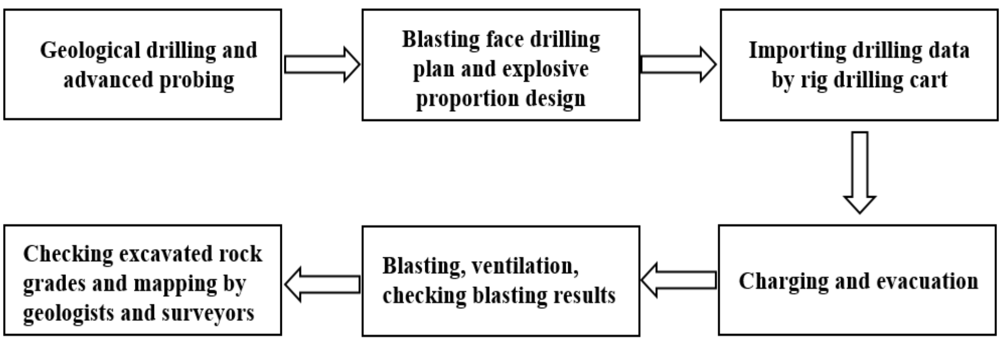

Figure 3. *Process flow diagram.*

4.2. Construction technology operation points

4.2.1. Pre-processing

For tunnel excavation using the drilling and blasting method, the preparatory procedures mainly include advanced drilling and pre-grouting of advance small pipes. The rock encountered in the project is generally classified as Grade I to Grade III grade, with sufficient strength and ideal weathering conditions, providing certain convenience for construction and support. After the tunnel geologist confirms which method should be used for the preparatory procedures, the blasting engineer designs the blasting based on actual conditions.

The selection and arrangement of explosive types, as well as the design of blasting holes, are related to the value of maximum charge quantity (MIC). The MIC value should be determined by selecting the minimum MIC value at all positions on the blasting face. Specifically, for a typical blasting face, only the MIC values at key locations need to be calculated, and the minimum among them is taken. The calculation formula is: PPV = 644(R/W1/2) -1.22, where PPV is generally taken as 25mm/s. In this project, R represents the distance between the blasting hole position and THEES (Tolo Harbour Effluent Export Scheme) Tunnel, and W is the MIC value.

4.2.2. Blasting design

4.2.2.1 Borehole design

This method employs a three-arm drilling cart, using unidirectional slotting for hole excavation, which includes both air holes and blasting holes (slotting holes, auxiliary holes, and surrounding holes). The diameter of the air holes ranges from 89 to 127 mm (commonly 102 mm), while the diameter of the blasting holes is uniformly designed between 42 and 51mm (commonly 51 mm), as shown in Figure 4. The selection of blasting hole diameters is also closely related to the MIC value. If the MIC exceeds 3 kg, the hole diameter is typically chosen to be Φ51 mm; if it is less than 3 kg, a diameter of 45 mm is generally selected. In this method, the MIC for all blasting faces reaches 10 kg, so most hole diameters are designed to be 51 mm.

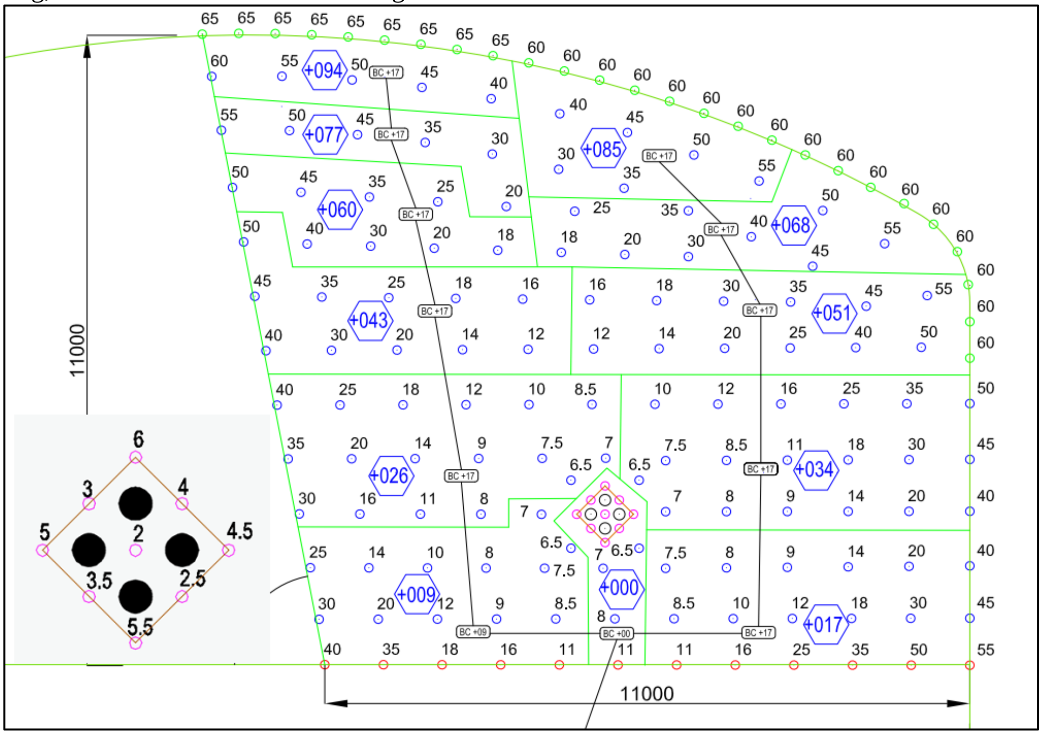

Figure 4. *Design of the borehole.*

The spacing between boreholes is larger due to the larger diameter of the drilled holes, which results in a greater amount of explosives being loaded into each hole. Therefore, the spacing between blasting holes is also greater than that of traditional drilling methods. The distance between auxiliary holes generally exceeds 1m, and the distance between peripheral holes generally exceeds 0.5m. On average, only one blasting hole is needed for every 1.03m² area of blasting face.

In terms of drilling depth, the filling length (Stemming) Ls should generally not be less than the hole spacing, the loading length (Emulsion Charge) Lc =MIC/1.59, and the drilling depth L=Ls + Lc. In this project, the hole depth is generally 5.0m to 6.0m.

The typical borehole drilling records are shown in Figure 5. In the case of using a three-arm automatic rock drilling car, the hole quality can be controlled very ideally.

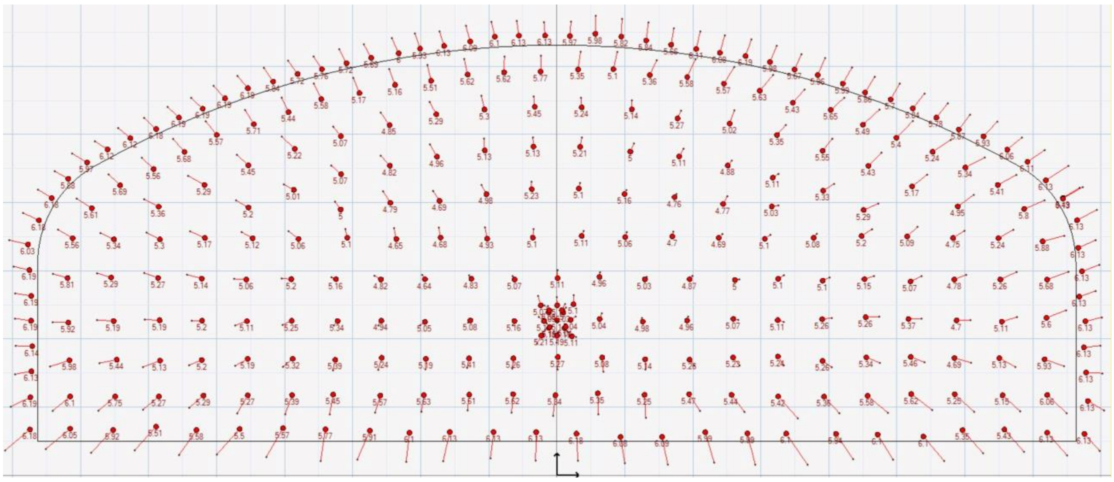

Figure 5. *Typical borehole records for the blasting face.*

4.2.2.2 MIC value

According to the requirements of relevant legal provisions and project characteristics, bagged emulsion explosive, bulk emulsion explosive, non-electric detonator, electric detonator (only used for initiation), detonating cord, igniter and other blasting materials are selected.

For the selection of explosives, generally, when MIC≤1.0kg, packaged emulsion explosive (cartridges) is selected; when MIC>1.0kg, bulk emulsion explosive (emulsion) is selected. This method involves achieving a MIC of 10kg at blasting face, so bulk emulsion explosive is mainly chosen for the main blasting holes except for the surrounding holes.

4.2.2.3 Arrangement of explosives

In order to enhance the blasting efficiency, save cost and control the rate of silent shots, this method only uses non-electric detonators and electric detonators in the selection of detonators. For a single blasting, electric detonators are only used at the initiation point, and all other holes are filled with non-electric detonators.

After calculation, the maximum charge amount per meter of 51mm diameter borehole designed for the project can reach 2kg/m under the premise of ensuring the environmental impact requirements (Section 4.2.5). If the depth of the borehole is calculated as 5m, then the MIC of each borehole can reach 10kg. Compared with the traditional method of drilling 3m deep with 38mm diameter borehole, the charge amount can be increased by about 3 times.

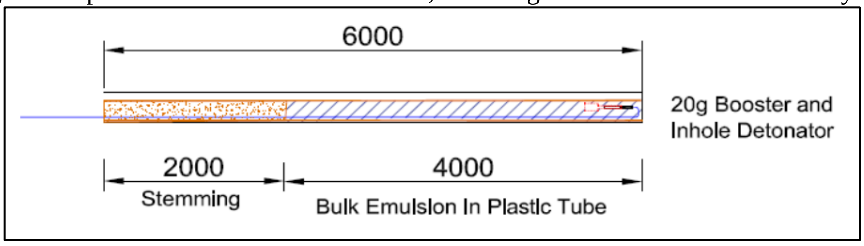

Figure 6. *Borehole charging diagrams.*

4.2.2.4 Design of differential blasting parameters

Due to production limitations, the delay time of the detonator will have an inherent error of about 2% during product design. At the same time, explosive manufacturers will not customize blasting materials with ideal delay times for projects. Therefore, when designing the delay time for micro-differential blasting, the time interval between holes should be larger as they move outward to ensure that the blasting progresses from the core to the periphery. In the design of the maximum blasting face, the maximum delay time for the outermost peripheral holes is 9000ms (i.e., 9s, as shown in Figure 1). All blasting faces can be completed within 10s. All of the blasting faces can be guaranteed to be completed within 10s.

4.2.2.5 Comparison with traditional methods

A detailed comparison with traditional method is shown in Table 1:

Table 1. *Comparison between traditional methods.*

Item	unit (of measure)	Traditional methods	Method in this paper
Bore size	mm	32~50	51
Auxiliary hole spacing	m	0.7~0.8	≥1
Number of holes required per square meter of surface	Nos.	1.8	0.97
Blasting depth	m	≤4	5
Maximum charge (per borehole)	kg	≤5	10
Unit consumption of explosives	kg/m^3	1.2~2.4	1.2
Operational staffing requirements	/	At least 1 person is required for each wind drill	3-arm automatic drilling
Construction environment and noise	/	Poor environment and high noise level	Good environment, moderate noise
Forms of grooving	/	Wedge, Straight	Straightness

4.2.3. Rock drilling cart

Three-arm rock drilling cart is used for hole construction. The blasting design diagram is input into the machine, and the automatic positioning and automatic drilling functions of the machine are used to realize automatic drilling construction, and the hole marking points made by the surveyor on the blasting surface are double confirmed, as shown in Figure 7.

Figure 7. *Automatic construction of rock drilling dolly.*

4.2.4. Charging and evacuation

The explosives are charged by the registered blasting workers.

(1) The loading inspection should be completed 30 minutes before the detonation, the blasting worker and the foreman worker start the clearance procedure, the blasting worker notifies the blasting engineer that the blasting will be carried out within 30 minutes, and the foreman worker notifies all the workers to start evacuating to the designated area;

(2) Fifteen minutes before the detonation, the foreman worker needs to make sure that he is the last person to evacuate, and the blasting worker will check again that everyone has evacuated;

(3) Two minutes before detonation, the gun king and the blasting engineer will confirm with the supervisor that all personnel have been evacuated and sign the confirmation form;

(4) One minute before detonation, the blasting engineer gives the order to the master gunner to detonate.

(5)After receiving the order, the total blasting worker carried out the detonation operation at the designated position.

4.2.5. Blasting monitoring and ventilation detection

During the blasting process, two indexes, namely peak vibration velocity of mass point (PPV) and overpressure of air shock wave (AOP), are mainly detected. The value of PPV and AOP is used to guide the design of the next blasting every time. The monitoring points and indexes of the two indexes are shown in Figure 8 and Figure 9 respectively.

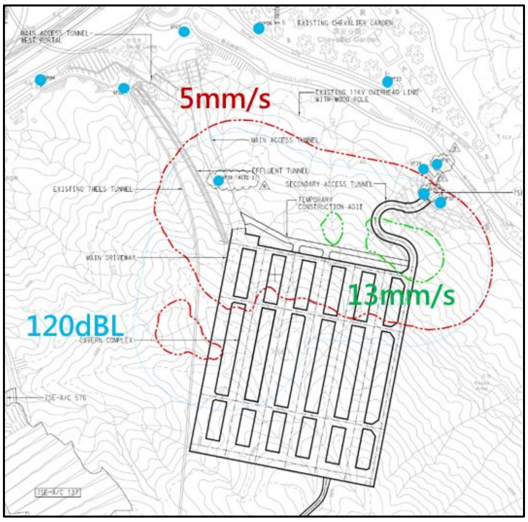

Figure 8. *Monitoring locations and vibration predictions.*

PPV		AOP	
Alert	90% of the PPV limit	Alert	118 dBL
Action	95% of the PPV limit	Action	119 dBL
Alarm	100% of the PPV limit	Alarm	120 dBL

Figure 9. *PPV and AOP related limit requirements.*

After the blasting is completed, continuous ventilation should be carried out to ensure the air quality in the cavern. The five gases in the air, including oxygen, methane, hydrogen sulfide, carbon monoxide and radon gas, should be monitored and controlled, and the wind speed in the cavern should meet at least 0.5m/s.

4.2.6. Blasting check

When the gas detection is basically qualified, the registered blasting worker will enter the tunnel to inspect the blasting face. After confirming safety, the blasting engineer and explosives supervisor will enter the tunnel to check the blasting face and ensure that all explosives have detonated. If any duds are found, they should be reported immediately and handled promptly; if immediate handling is not possible, clear signs should be set up nearby, and appropriate safety measures taken.

When handling a dud, no irrelevant personnel shall be present, and the boundary of the danger zone shall be guarded. Other operations shall be prohibited within the danger zone; when the blasting circuit of the borehole is confirmed to be intact after inspection, it can be reblastinged. When blasting a dud, the power supply shall be cut off immediately and the blasting network shall be short-circuited in time.

4.2.7. Geological inspection and blasting surface mapping

After the spoil is removed, a geologist conducts geological surveys on the tunnel excavation face to check if the exposed rock mass is stable and can specify reinforcement measures or require further clearance of hazardous rocks. The geologist calculates the NGI-Q value based on parameters such as the size of the exposed rock mass, interblock shear strength, and degree of joint development, to assess the stability of the rock mass. This determines the design support grade for the excavation face at that location. All geological survey records, Q-value calculations, and support structure designs should be documented and submitted for approval by the supervising engineer.

Before and after temporary and permanent shotcrete construction, the contour line of the excavation face must be surveyed, and the measurement data should be submitted for supervision and acceptance. For under-excavation, the excavation section should be surveyed at intervals of 1m, with the under-excavated areas marked and the over-excavated rock removed using a hydraulic hammer. After completion, re-surveying should be conducted; for over-excavated sections, if the over-excavation depth exceeds 200mm, permanent shotcrete backfilling should be used; if the over-excavation is at the bottom, Grade 200 graded fill material should be used for backfilling.

4.3. Explosives and equipment

The explosives and equipment involved in this method are shown in Table 2 and Table 3.

Table 2. *Materials required for construction of super-large cross-sections by drilling and blasting method.*

Serial number	**Name of material**	**unit (of measure)**	**Quantities**
1	Cartridge Explosives	Ton	10
2	Underground Bulk Emulsion Matrix	Ton	2900
3	Booster	Nos.	340000
4	Detonating Cord 5g	m	72000
5	Detonating Cord 40g	m	10000
6	In-hole delay Non-electric Detonators with around 9m signal tube	Nos.	336000
7	Surface/Bunch Detonators	Nos.	20000
8	Electric Detonators around 1.5m leg wire	m	4100
9	Electric Detonators w/ around 6m wire	m	3000
10	Electric Detonators Branch Wire / Bus Line 400m or 200m per coil	m	600
11	Lead in Line shock tube w/ detonator (STARLINE) 300m/roll	Nos.	100

Table 3. *Permanent spray anchor rapid support construction main mechanical equipment configuration.*

Serial number	**Equipment Name**	**Specification**	**Unit (of measure)**	**quantities**
1	Rock drilling cart	Epiroc X3E	Nos.	2
2	Lifting platform	AICHI SR182	Nos.	4

4.4. Quality control

When inputting the corresponding point data into rock drilling cart, the surveying department should conduct re-measurement at the face and mark the drill hole positions on the face to ensure that the automatic drilling is performed at the marked points without deviation. If any deviation is found, immediately stop the automatic drilling, confirm the issue, and continue drilling or switch to manual operation for mechanical drilling.

After the filling of explosives and wires is completed, a second inspection should be carried out to ensure that the type and quantity of filling materials are correct.

After the blasting is completed, ventilation should be carried out for a certain period to ensure that the environment inside the cavern meets the operational requirements. Then the registered blasting worker shall enter the work face first to inspect the quality of the blasting. If any dud shots are found, immediate action should be taken to handle them with a second detonation; if the explosives are buried under debris and cannot be processed, relevant departments should be notified immediately for handling.

After ensuring safety, geologists and surveyors enter the site to control and check the quality of blasting. This includes whether the depth of blasting meets the requirements, whether the over-excavation is within the allowable range, whether there is a lack of excavation, and whether there are suspended stones.

4.5. Security measures

Tunnel workers must obtain the closed space work certificate and other approved certificates, and have undergone project safety training. Strict safety briefing is required before each process, and workers are not allowed to work alone.

Tunnel workers should wear the correct personal protective equipment, including safety helmet, reflective clothing, safety shoes, dust-proof masks, goggles and sound insulation earphones in designated areas.

There should be safety management personnel or traffic commanders in the tunnel working face to avoid workers from entering the operation range of large machinery or operating the machinery without authorization.

Welding or cutting work shall not be carried out in the tunnel. If relevant procedures are required, the regulations and safety management requirements shall be complied with, and the hot operation permit system shall be activated.

In case of emergency, the staff in the tunnel should evacuate to the outside of the tunnel in an orderly manner to the guard room, which is not only the passage for entering and exiting the tunnel, but also the temporary assembly point and work coordination center.

The area below the exposed rock surface and the area where shotcrete is sprayed is a restricted area, and it is forbidden to pass through within 1 hour after the completion of shotcrete spraying. All restricted areas should be enclosed by guardrails until the early strength of shotcrete is reached.

5. BENEFIT ANALYSIS OF ENGINEERING CASES

The drilling and blasting construction method described in this paper is a summary and improvement of traditional drilling and blasting techniques. Applying this construction method to the excavation of super-large cross-section caverns has several advantages, including simple construction procedures, high mechanization, high construction efficiency, and lower costs. It also demonstrates considerable flexibility in response to varying geological conditions at the excavation face. Taking the example of this super-large cross-section cavern project, preliminary economic benefits are estimated as follows: a cost savings of HKD 45 million, a time-saving of 6 months, with a total cost benefit of approximately HKD 65 million.

To optimize the utilization of urban land resources and address the aging facilities and odor issues at existing wastewater treatment plants, the Hong Kong government implemented the relocation plan for the Wastewater Treatment Plant in 2014. The project is divided into five main phases, which involve constructing the new cavern within the mountain near the original plant, relocating the existing plant into this new cavern, and updating the related facilities to free up approximately 28 hectares of land for other civilian uses. This project represents the second phase of the relocation plan, focusing on the construction of a 14-hectare main cavern cluster. The first phase, completed earlier, included the construction of a 340-meter-long main tunnel and its surrounding site leveling, retaining structures, road and drainage works, temporary traffic bridges, and community liaison centers. The main tunnel and the main cavern cluster were constructed using the drilling and blasting method, which is a large-section tunneling technique with a cross-sectional area exceeding 200m².

This project is a rare super-large cross-section cavern engineering in Hong Kong and even the world. It represents an optimized construction plan proposed after comprehensively considering factors such as laws and regulations, surrounding environment, geological conditions, cost, and schedule. The engineering team studied and compared various blasting hole layout schemes and explosive choices, overcoming challenges like dud explosions. They successfully applied and summarized the drilling and blasting method for super-large cross-section cavern, significantly improving construction efficiency, reducing costs and duration, with evident overall economic benefits.

6. CONCLUSION

This study proposes an innovative drilling and blasting construction method for the technical problems of super-large cross-section cavern construction in Hong Kong granite strata, and verifies its technical feasibility and economic benefits through engineering practice. The main conclusions are as follows:

(1) The three-arm rock drilling cart precision positioning system developed can realize high-precision drilling, and the design of large diameter Φ51mm blasting hole makes the single hole charge amount increase to 10kg, and the maximum single cycle advance reaches 5m, which greatly improves the blasting efficiency compared with traditional methods.

(2) The proposed graded micro-differential blasting system adopts a 9-second delay control structure, which successfully reduces the blasting vibration velocity of 300m² section and reduces the single consumption of explosives to 1.2kg/m³.

(3) The established mechanized construction system has realized the whole process of "drilling-loading-support" mechanized operation, reducing the demand for manpower by 33%, with small over-excavation rate and good overall contour surface flatness.

(4) Engineering applications have shown that this construction method can shorten the project duration by 6 months and reduce overall costs, forming a standardized construction system suitable for hard rock strata. The research findings provide important references for similar urban underground space development projects, with subsequent efforts focusing on the integrated application of intelligent propelling technology and digital twin systems.

7. ACKNOWLEDGMENTS

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