A new excavation technology of blasting combined with TBM

Ke Man, Xiaoli Liu and Zhifei Song

School of Civil Engineering, North China University of Technology, Beijing, China; State Key Laboratory of Hydroscience and Hydraulic Engineering, Tsinghua University, Beijing, China

ABSTRACT

The technical feasibility of drilling and blasting or TBM excavation method is the key to determine the underground engineering. In view of the high strength, high abrasiveness and good integrity of hard rock in site, and considering the damage of surrounding rock must be controlled within a reasonable range, the blasting combined with TBM method has been proposed here. While the combined method has been further carried out in Water Supply Project in Jilin to assess and evaluate it, which including single-hole blasting, five-hole blasting, eleven-hole blasting and blasting combined with TBM tests. It is found that some certain blasting tests is useful and essential to the combined method, as it can provide the blasting parameters designed for the combined method. The blasting of multi-hole simultaneous initiation with interval charge structure should be adopted strictly. Meantime, one roll of explosive in each blasting hole can produce obvious blasting phenomenon. Simultaneously, by means of vibration monitoring, borehole TV observation and sound wave measurement, it can be judged that the damaged degree is rather small. After pre-blasting, the average speed of TBM driving is 17.41 mm/min, increased by 42.3% than that of the previous cycle. It shows that the new method not only achieves a relative efficient excavation, but also rock damage has been controlled. Moreover, the shortcomings of low speed and high tool wear of TBM excavation in hard rock could be avoided and the excavation efficiency could be improved using the combined method. Therefore, it seems to be a practical technology, which can play full advantages of each existed method, while can avoid the defects of themselves. However, this new excavation technology needs further confirmation through more engineering verification. The results obtained in this paper have guiding significance and promising application in the underground excavation and other civil engineering.

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1. Introduction

The technical feasibility of drilling and blasting or TBM excavation method is one of the key factors for underground engineering (Bruland 1998a, 1998b; Barton, 2000;
Bieniawski et al. 2008; OECD/NEA 2013; Rostami 2016). In view of the high strength, high abrasiveness and good integrity of hard rock, the damage of surrounding rock must be controlled within a reasonable range. Simultaneously, there are more difficulties for the relevant tests on blasting and TBM construction for hard rock (Bäckblom et al. 2004; Read 2004; Liu et al. 2016). The suitability concerned excavation method using blasting or TBM method could be assessed further in this paper.

Drilling and blasting method is the traditional excavation method in underground engineering, which is considered to be suitable because of its simple mechanical structure, lighter loading weight and flexible system, simplicity of operation and maintenance, low energy consumption and high efficiency. Therefore, drilling and blasting method has been widely used in rock tunnel excavation (Rostami 1997; Dai and Yang 2000; Lin 2002; Gu et al. 2005). To speed up the excavation efficiency, it is mainly subject to three important factors, i.e., blasting effect, loading and transportation efficiency, in which the “blasting” means to improve the blasting effect. Therefore, blasting technology is one of the key technologies affecting the excavation speed and restricting the excavation quality (Wang et al. 2008; Yang et al. 2014; Zhongwen et al. 2015; Chen et al. 2016; Yang et al. 2017). Meanwhile, TBM method is a widely used mechanical excavation method, which uses different distribution of knives and cutters to break rock mass (Bruland 1998; Gong 2006; Gong et al. 2012; Macias 2016). However, the TBM driving speed under extremely hard rock condition is rather slow, which is restricted by the cutting head rotation speed, penetration depth and other indicators, as well as rock excavatability, wear resistance and other factors (Barton, 2000; Bieniawski et al. 2007; Bieniawski and Grandori 2007; Yagiz 2008; Gong and Zhao 2009; Hassanpour et al. 2011). Furthermore, in the process of blasting construction, the surrounding rock is damaged to a greater extent. Especially compared with TBM method, the EDZ (Excavation Damaged Zone) of surrounding rock often reaches at a level of centimeter, which is higher than millimeter level of EDZ caused by TBM (Liu and Liang 2000; Cho et al. 2013; Delisio and Zhao 2014; Gong et al. 2016; Liu et al. 2016). Therefore, how to combine these two different excavation methods, how to play full advantages of their methods respectively, and how to avoid the defects of their own methods, is a very worthwhile topic.

According to the technical requirement of underground excavation, not only the efficient excavation effect should be achieved, but also a litter bit rock damaged zone should be satisfied. TBM excavation in hard rock has the shortcomings of relative slow excavation speed and high tool wear ratio, so it is necessary to study the method in depth to improve the excavation speed. However, the blasting technology has the advantages of controllable excavation speed in hard rock. Therefore, it may be a practical technical research to combine these two excavation methods. At the same time, considering the directional fracture blasting technology in the drilling and blasting construction process, which a slight loosening and pre-splitting effect could be achieved. Then how to control the pre-splitting effect, and how to apply the method to TBM tunneling is a new and prospective research technology.

In order to understand the influence of blasting vibration on surrounding rock damage, the damage is monitored by blasting vibration monitoring, acoustic wave detection, micro seismic monitoring, borehole television observation and acoustic
emission monitoring and so on (Lu et al. 2009; Fu et al. 2010; Li et al. 2016; Yan et al. 2016). Through the analysis of the blasting monitoring results, the blasting parameters would be optimized and the appropriate blasting scheme will be determined. Then, the blasting design would be guided and the fine blasting would be realized, so as to the damage of surrounding rock could be reduced and the safe operation of the engineering structure could be ensured.

Through the in-site test of blasting combined TBM in the Water Supply Project in Jilin, which aims at transferring water from Songhua River to the middle cities of Jilin Province, the construction performance under different construction methods and parameters is carried out and analyzed. Some important parameters such as blasting boles charge and detonator segments and TBM efficiency in extremely hard rock mass are obtained. The feasibility of the new method is studied and a series of monitoring are carried out. The construction efficiency and rock damage degree of the method are comprehensively evaluated. The following is a detailed description of the content of this combined method.

2. Background of water supply project in Jilin

The test site is in the II bid of Water Supply Project in Jilin using TBM. The engineering geological conditions are as follows: the general trend of the excavation route is from NE to SW, and the landform is medium-low mountains, hills and inter-valleys. Along the route, the mountain topography is continuously undulating, and vegetation is developed. The elevation range is from 250 m to 774 m, and the maximum buried depth of the cave is 536.8 m. The total length of the valley is about 3700 m. The stratigraphic lithology includes tuff and andesite of Nanloushan Formation of Lower Jurassic, sandstone and conglomerate of Yangjiagou Formation of Lower Permian, sandstone of Fanjiatun Formation of Upper Permian and Yanshanian granite.

The excavation length of TBM in the first stage is 6865 m and the pile number is $22 + 413 \sim 15 + 548$ in the Water Supply Project in Jilin. According to the rock exposure condition, it is basically consistent with the pre-design. The II type rock is 1237.2 m, the III type rock is 453.9 m and the IV type rock is 446.8 m. During the construction of $21 + 061 \sim 18 + 924$ section, it was found that the rock strength was rather high, and a third-party testing was organized to sample and measure the rock core strength respectively. The rock strength corresponding to the pile number of this section were shown in Table 1.

| No. | Pile No. | Testing data | Report data | Uniaxial compress strength (MPa) |
|-----|----------|--------------|-------------|---------------------------------|
| 1   | K20 + 855| 2015.6.29~2015.7.2| 2015.7.2 | 264.8 |
| 2   | K20 + 110| 2015.7.7~2015.7.10| 2015.7.10| 281.7 |
| 3   | K19 + 800| 2015.7.30~2015.8.2| 2015.8.2 | 244.1 |
| 4   | K19 + 600| 2015.8.7~2015.8.10| 2015.8.10| 212.7 |
| 5   | K19 + 050| 2015.8.29~2015.9.2| 2015.9.2 | 202.5 |

The blasting combined with TBM test is selected at the pile number of $20 + 060$. Comparing with the rock mechanics test results in laboratory, the uniaxial compressive strength in this area reaches 260 MPa~280MPa. The test is divided into two steps, while the first step is pure blasting test, aiming to explore and identify the
3. Blasting test

No. 2 rock emulsion explosive is selected here, which is widely used in civil engineering. And it has strong adaptability and water resistance. The main performances are as follows, the diameter of explosive is 32 mm, the density is 0.95 ~ 1.30 g/cm³, the detonation velocity is above 3500 m/s, the intensity is upon 12 mm, the detonation force is greater than 320 ml, the martyrdom distance is more than 8 mm, the explosion heat is 4015333 J/kg, the detonation temperature is 2654 °C, and the detonation pressure is 395000 N/cm². Using non-electric millisecond detonator, which has a high detonation rate, less blind and easy operation.

According to the field conditions, YT28 pneumatic legged rock drill is adopted here. The drilling diameter is 42 mm. The tunnel is provided with wind supply pipes for wind driving rock drills. The explosive quantity of each section is 200 g. Each millisecond detonator is installed at the bottom of the borehole, which is initiated by non-electric way. The depth of each bore hole is 1.8 m.

3.1. Single-hole blasting

There are five measuring points continuously setup at 10° below the horizontal level, and the interval was 1 meter. Before each testing, the thin shotcrete layer of the rock surface is removed, so that the vibrometer is tightly bonded with the rock wall. As shown in Figure 1.

According to the results of borehole TV, when centralized charge is used at the bottom of the borehole, the charge section is damaged seriously, and there are few new cracks in the non-charge section within 50 cm from the bottom of the borehole. However, there is no new cracks in the area 50 cm away from the bottom. It is indicated that the concentrated charge way is not conducive to the uniform distribution of bursting cracks in the hole.
When increase the explosive using the concentrated charge way, there has little effect on the initiation of cracks. From the blasting vibration results, with the blasting stress wave propagation, the vibration velocity in the normal direction of the free surface is the maximum.

### 3.2. Five-hole blasting

Based on the results of single-hole blasting test, the five-hole blasting were carried out. The location of holes is shown in Figure 2. In which, E hole is the charge hole and the remaining four holes are empty holes.

Setting holes around the blasting hole and utilizing the empty effect to benefit the formation of new cracks in the blasting hole and empty holes, and the cracks area initiated by the blasting is enlarged. Compared with the centralized charge way, the interval charge way is advantageous to the uniform distribution of explosive cracks along the axis of the borehole, and enhances the fracture degree of the rock. Moreover, the rock damage between blasting hole and empty hole is larger than that between two empty holes.

### 3.3. Eleven-hole blasting

On the basis of the above five-hole tests, eleven-hole blasting tests were carried out, respectively changing the explosive quantity and detonate sections. A typical eleven-hole test is illuminated as follows. The hole layout is shown in Figure 3, where the central hole and the six outer ring holes are the charge holes, and the remaining four holes are empty holes. Totally, there are sixteen monitoring holes drilled in advance around the blasting hole No.7 and No.8, for which each was round eight holes distributed in a same interval and space. Obviously, the damage of surrounding rock was carried out from the monitoring holes. The layout of these holes is shown in Figure 3 below.

The explosive charge and detonate section of each hole is shown in Table 2.

Every seven charge holes are loaded with one roll No.2 rock emulsion explosive, i.e., the explosive quantity is 200 g. Additional, using the interval charge structure at the bottom, and one roll explosive is divided into several segments, while each

![Hole distribution of the five-hole blasting.](image)

**Figure 2.** Hole distribution of the five-hole blasting.
interval is 300 mm. Sealing the hole with slime and mud. One non-electric millisecond detonator is loaded in each blasting hole, which is installed at the bottom, and the detonation is initiated by non-electric detonator in series.

Before blasting, there are eight monitoring holes set up on the right side of the two holes of No.7 and No.8 respectively, and the blasting influenced range can be observed precisely.

Simultaneously, hole TV technology is also applied to empty holes and monitoring holes. Primary cracks at 10 cm away from the bottom continue to grow, and new circumferential cracks appears near the primary cracks at 50 cm away from the bottom. There is no obvious crack in the monitoring holes.

Based on the sound wave method, the relationship between rock damaged degree $D$, rock integrity coefficient $K$ and sound wave velocity reduction rate $\eta$ is established.

\[
D = 1 - \frac{E}{E_0} = 1 - \left( \frac{C_{p2}}{C_{p1}} \right)^2 = 1 - k = 1 - (1 - \eta)^2
\] (1)

In which, $E_0$ is the rock elastic modulus before blasting, $E$ is the equivalent elastic modulus of rock after blasting.

It is stipulated in the Technical Specification for Excavation of Rock Foundation of Hydraulic Structures formulated in China that, when $\eta > 10\%$ the rock mass is judged to be damaged by blasting. In other words, when the $D$ reaches about 0.19, the rock could be considered to be damaged.

The damage of the rock between the charge hole No.5 and the empty hole No.2 before and after blasting is illuminated in Figure 4.

Moreover, the damage of the rock between empty hole No.2 and empty hole No.3 is described in Figure 5.

The rock damage between empty hole No.2 and blasting hole No.8 is described in Figure 6.
Furthermore, the rock damage between blasting hole No.8 and blasting hole No.9 is described in Figure 7.

It can be seen from the above Figures that the overall damaged range is relatively uniform, and the damaged degree is about 9% in average, the maximum damaged degree is not more than 16%, which is still under the threshold value 19%.

The sound wave velocity of the rock around blasting hole No.7 is measured. The result is shown in Table 3 and Figure 8.

Similarly, the sound wave velocity of the rock around blasting hole No.8 is measured. The result is shown in Table 4 and Figure 9.

It could be found that the sound wave velocity near hole No.7 and No.8 decreases fastest. The sound wave velocity decreases gradually with the distance increases from the monitoring target hole. For each monitoring hole, the sound wave velocity decreases gradually from the front of the hole to the end.

In advance, the damaged zone of the eleven-hole blasting under this situation is relatively small, just about 400 mm. It should be noted that the blasting effect is enhanced by the use of plugging measurement. The contribution of explosive gas to blasting can enlarge the damaged range.

From the above, it could be drawn that compared with single-hole blasting, the cracks formed by simultaneous initiation of multiple holes are obviously increased, which can also be significantly affected in the non-charge section of the blasting hole.

According to the distribution of blasting cracks, it is better to use interval charge way with simultaneous initiation than the centralized charge way. When the multi-hole detonates simultaneously, a roll of explosive charged in each blasting hole can produce an obvious effect. Plugging the charge hole can enhance the blasting effect and destroy the surrounding rock in a wider range.

### 4. Blasting combined TBM excavation test

Before the blasting combined TBM excavation test, TBM is required to retreat two cycles, totaling 3.6 meters, to provide the work space for drilling and blasting. At the same time, because the TBM excavation face is relatively large, which the diameter is 7.9 m, in order to facilitate drilling, three-layer scaffolding is overlapped and tailor-welded in advance, so that the highest level of scaffolding can reach the top of the drilling position. As shown in Figure 10.

| No. | Depth/m | Explosive quantity/kg | Detonate segments |
|-----|---------|-----------------------|------------------|
| 1   | 1.85    | Empty hole            |                  |
| 2   | 1.86    | Empty hole            |                  |
| 3   | 1.82    | Empty hole            |                  |
| 4   | 1.85    | Empty hole            |                  |
| 5   | 1.79    | 0.2                   | 3                |
| 6   | 1.85    | 0.2                   | 3                |
| 7   | 1.82    | 0.2                   | 3                |
| 8   | 1.8     | 0.2                   | 3                |
| 9   | 1.84    | 0.2                   | 3                |
| 10  | 1.84    | 0.2                   | 3                |
| 11  | 1.87    | 0.2                   | 3                |
4.1. Blasting scheme

The design map of the drilling holes is shown in Figure 11. A total of 15 boreholes were designed in the blasting scheme. The drilling depth was 2 m. Among them, there is a central hole in the center. There are six holes drilled in the inner circle with an angle interval of $60^\circ$ and eight in the outer circle with an angle interval of $45^\circ$. Moreover, two observation holes, i.e., the red color hole, are set at the lower left edge. The distance between the two observation holes is 0.5 m. Sound wave monitoring would be carried out to measure the disturbance to the rock.
caused by blasting. Additional, Borehole TV monitoring of the three black color holes is implemented.

According to the design drilling map, the local distribution of drilling hole is shown in Figure 12, mainly around the central hole.

Each hole is charge with one roll No.2 rock emulsion explosive with 200 g, which is divided into three segment and each interval is 300 mm. The interval charge structure is adopted. The charge structure is shown in Figure 13.

Blasting vibration measuring is also arranged here. One measuring point is arranged beside the observation hole on the free surface, three measuring points are

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**Figure 6.** Schematic of damaged degree between No.2 and No.8.

**Figure 7.** Schematic of damaged degree between No.8 and No.9.
arranged between the free surface and the cutter head with the interval one meter, and one measuring point is arranged on the cutter head, as shown in Figure 14.

4.2. Monitoring results

It is found that through borehole television monitoring, a few of radial blasting cracks were generated at 20 cm~80cm away from the bottom of the hole after pre-blasting. And there are no obvious new cracks appeared in the observation holes. At the same time, the damaged degree of the observation holes is shown in Figure 15.

It can be seen from that the damaged degree of surrounding rock is very small in this cross-section. And the distribution map of the blasting hole is suitable for the pre-blasting combined TBM, which means that the excavation damaged zone by the pre-blasting can be neglected. Additionally, the main frequency of the blasting signal is analyzed, which is expressed in Table 5.

Through the blasting vibration signal analysis, No.2 vibration meter is closest to the free face with a distance 1 m. And the maximum vibration velocity is 6.75 cm/s, which is within the controllable range according to the Blasting Safety Regulations. While, the vibration velocity and the main frequency of subsequent No.3 and No.4 points attenuate in turn.

4.3. TBM excavation efficiency analysis

After the pre-blasting, then it is the TBM excavation. The main purpose is to compare the TBM driving speed between the blasting cycle and the non-blasting cycle. A comparison chart of the three cycles of TBM driving is expressed in Figure 16, corresponding to the TBM excavation speeds before the pre-blasting cycle, in the blasting cycle, and after the cycle separately.

The results show that the average driving speed of TBM is 12.23 mm/min before the blasting. While, after the pre-blasting, the average speed of TBM in the charge section is 20.29 mm/min, which increases by 65.9%. However, for the non-charge section, the average speed of TBM is 15.89 mm/min, increasing by 29.9%. Totally, the

| Table 3. Sound wave velocity of observation holes around No.7. |
|---------------|---------------|---------------|---------------|---------------|---------------|
|               | Depth (mm)  | Velocity after blasting (m/s) | Depth (mm)  | Velocity after blasting (m/s) | Depth (mm)  | Velocity after blasting (m/s) |
| No.            | i-m         | 50                  | j-n         | 50                  | k-o         | 50                  | l-p         | 50                  |
| 150            | 4516        |                     | 150         | 5379                | 150         | 5274                |
| 250            | 4712        |                     | 250         | 5659                | 250         | 5190                |
| 350            | 4990        |                     | 350         | 5060                | 350         | 5076                |
| 450            | 5190        |                     | 450         | 5764                | 450         | 5714                |
| 550            | 4870        |                     | 550         | 5914                | 550         | 5572                |
| 650            | 5381        |                     | 650         | 5714                | 650         | 5605                |
| 750            | 5186        |                     | 750         | 5944                | 750         | 5572                |
| 850            | 5047        |                     | 850         | 6197                | 850         | 5708                |
| 950            | 5364        |                     | 950         | 6227                | 950         | 5673                |
| 1050           | 5512        |                     | 1050        | 6304                | 1050        | 5814                |
| 1150           | 5893        |                     | 1150        | 6328                | 1150        | 5863                |
| 1250           | 6234        |                     | 1250        | 6407                | 1250        | 6019                |
| 1350           | 6374        |                     | 1350        | 6428                | 1350        | 6019                |
| 1450           | 6408        |                     | 1450        | 6340                | 1450        | 6058                |
| 1550           | 6425        |                     | 1550        |                     | 1550        |                     |
average speed of TBM driving is 17.41 mm/min, which is increased by 42.3%. Furthermore, in the next cycle after blasting, the average driving speed of TBM is reduced to 14.41 mm/min.

In the whole test process, the three excavation cycles are close adjacent construction intervals, which means the lithology could be considered consistent, so it is meaningful to compare the results. The uniaxial compressive strength can reach

Table 4. Sound wave velocity of observation holes around No.8.

| No.  | Depth (mm) | Velocity after blasting (m/s) |
|------|------------|-------------------------------|
| a-e  | 50         | 4312                          |
|      | 150        | 4512                          |
|      | 250        | 4430                          |
|      | 350        | 4745                          |
|      | 450        | 4950                          |
|      | 550        | 4538                          |
|      | 650        | 4936                          |
|      | 750        | 4636                          |
|      | 850        | 5202                          |
|      | 950        | 5108                          |
|      | 1050       | 5411                          |
|      | 1150       | 5613                          |
|      | 1250       | 5782                          |
|      | 1350       | 5960                          |
|      | 1450       | 6150                          |
|      | 1550       | 6216                          |
| b-f  | 50         | 4737                          |
|      | 150        | 4602                          |
|      | 250        | 4819                          |
|      | 350        | 4905                          |
|      | 450        | 5009                          |
|      | 550        | 4799                          |
|      | 650        | 5319                          |
|      | 750        | 5103                          |
|      | 850        | 5246                          |
|      | 950        | 5382                          |
|      | 1050       | 5511                          |
|      | 1150       | 5694                          |
|      | 1250       | 5839                          |
|      | 1350       | 5965                          |
|      | 1450       | 6018                          |
|      | 1550       | 6157                          |
| c-g  | 50         | 5085                          |
|      | 150        | 5202                          |
|      | 250        | 5263                          |
|      | 350        | 5243                          |
|      | 450        | 5202                          |
|      | 550        | 5325                          |
|      | 650        | 5347                          |
|      | 750        | 5499                          |
|      | 850        | 5521                          |
|      | 950        | 5733                          |
|      | 1050       | 5934                          |
|      | 1150       | 6013                          |
|      | 1250       | 6095                          |
|      | 1350       | 6236                          |
|      | 1450       | 6237                          |
|      | 1550       | 6224                          |
| d-h  | 50         | 5648                          |
|      | 150        | 5548                          |
|      | 250        | 5789                          |
|      | 350        | 5697                          |
|      | 450        | 5532                          |
|      | 550        | 5611                          |
|      | 650        | 5650                          |
|      | 750        | 5650                          |
|      | 850        | 5850                          |
|      | 950        | 5982                          |
|      | 1050       | 6092                          |
|      | 1150       | 6120                          |
|      | 1250       | 6206                          |
|      | 1350       | 6355                          |
|      | 1450       | 6311                          |
|      | 1550       | 6413                          |
260~280MPa through the sampling and mechanical test. Moreover, in the test process, the cracks on the face are not developed and relatively complete within the observed range. Therefore, it can be considered that the lithology has no change in the whole test process and the objective conditions are the same, so that the analysis could be convinced.

It could be drawn that there is no obvious stripping phenomenon on the free surface after pre-blasting, which is beneficial to the TBM excavation. By means of
borehole TV and sound wave monitoring, it can be concluded that the damage to retained rock caused by the borehole arrangement is very small and controllable.
After pre-blasting, the average speed of TBM driving is 17.41 mm/min, which is increased by 42.3%.

5. Discussion and suggestion

5.1. Discussion

For single-hole blasting test, from the borehole television monitoring results, when using centralized charge, the crack initiation and expansion at the bottom of the borehole, corresponding to the charge section are obvious and it is damaged serious. It is indicated that concentrated charging could not conducive to the uniform distribution of bursting cracks in the hole. Especially, when concentrated loading, the increase of charge has little effect on the initiation of cracks in the non-charge section. Moreover, according to the results of blasting vibration monitoring, with the propagation of blasting stress wave, the vibration velocity in the Y direction, that is, the normal direction of the free surface is the highest. And with the increase of distance, the main frequency of X direction (i.e., toward the blasting source) and Y direction changes from low frequency to high frequency, while the main frequency of Z direction changes from high to low.

After pre-blasting, the average speed of TBM driving is 17.41 mm/min, which is increased by 42.3%.

Table 5. Blasting vibration velocity of monitoring points.

| Direction | No.4 vibration point | No.3 vibration point | No.2 vibration point |
|-----------|---------------------|---------------------|---------------------|
|           | $V_{\text{max}}$ (cm/s) | Main frequency (Hz) | $V_{\text{max}}$ (cm/s) | Main frequency (Hz) | $V_{\text{max}}$ (cm/s) | Main frequency (Hz) |
| X         | 1.44                | 285.72              | 5.08                | 499.99              | 6.75                | 2000.03              |
| Y         | 4.08                | 210.53              | 4.18                | 70.18               | 4.24                | 53.33                |
| Z         | 1.71                | 500                 | 5.62                | 799.98              | 4.61                | 1333.32              |
For the five-hole blasting test, four empty holes around the central hole are set up, and the empty effect is used to generate new cracks between the central hole and empty holes, which enlarges the crack area. Meanwhile, compared with the centralized charging, the interval charging is beneficial to the uniform distribution of explosive cracks along the borehole, also can enhance the fracture degree. Furthermore, the damage between blast hole and empty hole is larger than that between two empty holes.

For the eleven-hole blasting test, compared with single-hole blasting, the cracks formed by simultaneous initiation of multi-hole are obviously increased. More importantly, the cracks can also be significantly affected in the non-charge section. According to the cracks distribution after blasting, the blasting effect of multi-hole interval charge with simultaneous initiation is better than that of centralized charge with simultaneous initiation. It must be noticed that it is easy to cause rocks to be thrown using the multiply millisecond blasting method and the blasting pits would be occurred, which should be avoid or else the excavation speed of TBM after pre-blasting is limited and becomes much worse. Therefore, blasting of multi-hole simultaneous initiation with interval should be adopted strictly. Meantime, one roll of explosive in each blasting hole can produce obvious results, and the excessive loading may cause riprap.

According to the above blasting test, the blasting parameters and blasting characteristics of the rock could be studied deeply. Then the blasting scheme for the blasting combined TBM method could be designed and proposed, including blasting hole space distribution, charge way, explosive quantity, detonate segments and initiation series and so on. Meanwhile, the damage monitoring measurements are also arranged. After that, the exaction testing is carried out, and the testing result is very inspired and excited. It is found that the damage to rock is small and controllable. Meanwhile, the driving speed of TBM increased by 42.3% on average.

Figure 16. Comparison of the driving speed of the TBM under three cycles.
The flowchart could be provided to review the work process mentioned above in Figure 17.

To sum up, using pre-blasting method can significantly improve the tunneling efficiency of TBM, and the blasting combined TBM method is a very promising research direction for the engineering construction, especially in the extremely hard rock geological condition.

5.2. Suggestion

Generally speaking, the excavation progress is controllable in blasting construction. The key lies in how to coordinate two factors, that are the blasting speed and rock damage, which are contradictory and mutually restrictive each other. If the blasting speed is blindly pursued, the explosive quantity would be increased, the hole number would be decreased, the drilling time is decreased, and the blasting effect is poor, causing a relatively large damaged degree on the surrounding rock. If only the rock damaged degree is requested, the explosive quantity will be decreased, the number of surrounding holes asked to be increased. Then, the drilling time is increased and the blasting effect is favorable, but the excavation speed is slow. Therefore, how to find a reasonable balance point between these two factors, not only can achieve high-efficient blasting speed but also can make a small damaged degree, it is indeed a philosophical problem. Thus, it is necessary to carry out pre-blasting test before TBM excavation, to draw up a reasonable construction key factor curve, and to explore a suitable blasting combined TBM method.

Through blasting tests, reasonable blasting parameters are selected. According to the rock lithology, the blasting parameters such as the resistance line, uncoupled charge structure, detonation sequence, plugging length, etc. are selected to determine the blasting parameters of each blasting hole, especially the central hole. And the effect of smooth blasting and pre-splitting blasting could be determined.

Figure 17. Road-map of the blasting combined TBM excavation test.
The real-time monitoring technology of blasting vibration can be quantitatively measured, and the rock damage can be predicted, so the blasting parameters of the next blasting cycle can be optimized. At the same time, before and after the blasting, the pre-drilled observation holes were tested by sound wave and borehole television observation, and the rock damaged degree could be quantitatively evaluated and determined.

According to the blasting results obtained from the blasting test, the blasting parameters such as drilling layout, explosive quantity and detonator section needed for the blasting combined TBM method are designed. In addition, vibration monitoring, sound wave testing and borehole TV observation are carried out at the same time. Then, the excavation efficiency, tool wear and slag discharge of TBM are analyzed and compared. Furthermore, aiming to achieve an efficient excavation speed and controllable damaged degree, the follow-up parameters about blasting combined TBM excavation should be facilitated and optimized.

In addition, it should be mentioned that the hydraulic drilling rig can be used instead of the manual work in the process of drilling hole of this new proposed excavation method, to improve the drilling speed and efficiency.

6. Conclusions

Based on Water Supply Project in Jilin, the combined test of blasting and TBM has been carried out, including single-hole blasting, five-hole blasting, eleven-hole blasting and pre-blasting combined TBM test.

1. It is found that blasting tests is useful and essential to the combined method. As it can provide the blasting parameters designed for the combined method. The blasting of multi-hole simultaneous initiation with interval charge structure should be adopted strictly. Meantime, one roll of explosive in each blasting hole can produce obvious results.

2. By means of vibration monitoring, borehole TV observation and sound wave measurement, it can be judged that the damaged degree is very small. After pre-blasting, the average speed of TBM driving is 17.41mm/min, increased by 42.3% than that of the previous cycle.

It should be pointed out that for the new excavation method of blasting combined TBM, the micro loosening of rock to be excavated can significantly improve the TBM driving efficiency. However, due to the limitation of test amount, this conclusion needs further confirmation through engineering verification, and the feasibility and effectiveness of the loose blasting way should be evaluated comprehensively. The results obtained in this paper have guiding significance and promising application in the geological disposal of high-level radioactive waste and underground excavation.

Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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