Research Article

Application of Energy-Concentrated Hydraulic Blasting Technology in Tunnel Construction in China

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1. Introduction

In recent years, the construction of tunnel projects in China has developed rapidly, and the number of tunnels in China accounts for about 50% of the number of tunnels in the world [1]. According to the current data, as of the end of 2020, there are 16,798 railway tunnels in operation in our country, with a total length of about 19,630 km. Total operating mileage of urban subways is about 7,655 km. Also, there are more than 19,069 highway tunnels with a total mileage of more than 18,966.6 km [2–4]. Judging from the current trend, tunnel construction will continue to develop rapidly and steadily. The search for efficient tunnelling technology is a powerful way to promote tunnel development.

At present, tunnel construction is restricted by geological conditions [5–7]. Although mechanized construction technology is gradually applied in tunnel construction, rock tunnel is still dominated by drilling and blasting method, which has the advantages of strong geological adaptability, low excavation costs, and convenient construction [8]. However, conventional blasting has problems such as over and underexcavation, damage to surrounding rock, impact on surrounding buildings, and dust in the tunnel, as shown in Figure 1 [9]. The actual contour line of the tunnel is inconsistent with the design contour line due to factors such as surrounding rock geology, joint fissures, and blasthole setting, which is the problem of over and underexcavation. It will lead to secondary construction operations and affect subsequent support, waterproof board laying, and other processes. Moreover, serious over and underexcavation will even lead to poor arching effect of the surrounding rock, resulting in tunnel instability and damage [10, 11]. Since the load action of conventional blasting is usually severe, its large disturbance to the surrounding rock will cause damage to the surrounding rock, the expansion and penetration of internal cracks, and the deterioration of mechanical properties. As the surrounding rock damage continues to develop and evolve, it will cause the surrounding rock to fall off and lose stability. Urban subway construction is faced with a complex engineering environment, and the current...
development of transportation networks often faces intersecting situations. The strong vibration of conventional blasting is likely to affect existing buildings and surrounding residents. In addition, conventional blasting will also generate a large amount of dust in the tunnel, causing harm to operators; at the same time, it has higher requirements for ventilation. Therefore, solving the problem of over and underexcavation, reducing the damage of surrounding rock, avoiding the impact on the surrounding environment, and reducing the dust concentration have become the development direction of tunnel construction.

Initially, to reduce over-underexcavation and surrounding rock damage during tunnel excavation, traditional smooth blasting technology was gradually applied to tunnel construction. Smooth blasting adopts an uncoupled explosive structure to reduce the pressure after explosion; therefore, it can effectively reduce the over and underexcavation in the tunnel construction and reduce the disturbance to the surrounding rock, and reducing the dust concentration have become the development direction of tunnel construction.

This paper summarizes the principle of the ECHBT and its current applications in highway tunnels, railway tunnels, urban subway tunnels, and coal mine tunnels. The blasting effect of conventional blasting technology, HBT, and ECHBT has been analyzed. In addition, on the basis of literature review, this paper discusses the influencing factors and places that need to be optimized [15–19].

2. Principles of ECHBT

2.1. Principle of ECBT. Munrfe first discovered the phenomenon of energy gathering in 1856, but it was not systematically studied until the 20th century during the World War [20]. In 1948, Birkhoff et al. [21] first proposed the steady theory of energy-concentrated jets. Evans and Pugh et al. [22, 23] subsequently proposed different shaped charge structure models. In 1952, for the first time, the quasi-steady theory of energy-concentrated jets was proposed by Pugh and Eichelberger [23, 24]. The ECBT is to use the energy-concentrated effect to gather the explosive products to increase the energy flow density of the explosive and use the regularity of the movement direction of the explosive product to be perpendicular or roughly perpendicular to the surface of the charge [25], so that the rock mass forms cracks along the jet direction under the joint action of stress wave and detonation gas pressure [26].

As shown in Figure 2(a), the blasting effect of steel plates is different under different charge structures [27]. The experiment compared the blasting depth of the steel plate under the conditions of ordinary cylindrical charge, cutting tapered grooves, adding a metal cover to the tapered hole, increasing the distance between the metal cover and the steel plate, etc. It can be found that the hole depth continues to increase after the explosion, and the tapered groove and the metal cover structure can significantly increase the penetration depth of the steel target [28]. This effect of increasing local damage is called energy-concentrated effect.

The movement direction of detonation products after explosion is perpendicular to the charge surface. This law can be used to add energy-concentrated structures such as slits and grooves around the explosive. At present, there are two commonly used methods:
(1) An energy-concentrated structure is arranged in a specific direction around the explosive. The ABS blasting method, as shown in Figure 3(a), uses a concave reflector to produce an energy-concentrated effect, resulting in directional cracks in the hole wall [29]. The charge liner grooving method, as shown in Figure 3(b), sets a liner between the explosive and the hole wall, and there are wedge-shaped slits inside the bushing, which form a concentrated load to generate directional cracks [30]. The shaped energy-concentrated charge method, as shown in Figure 3(c), makes the charge-capsule structure with energy-concentrated grooves and makes the explosion products converge in the axial direction of the energy gathering tank to form an impact on the rock mass [31]. In the casing slit-shaped charge blasting method, a slit casing is arranged around the explosive, and energy-concentrated flow is generated in the direction of the slit, and the rock mass will preferentially produce cracks along the energy-concentrated flow direction, as shown in Figure 3(d).

(2) Set up cracks in the hole wall where the fracture surface is supposed to be formed. The common slotting methods are mechanical slotting method and high-pressure water cutter slotting method, as shown in Figure 4. Cut slits of a certain width and depth in advance at the position where cracks are to be formed in the hole wall, and the stress concentration occurs at the slits of the hole wall under the action of the explosive stress wave [32]. Use a high-pressure water jet to open the wall of the explosive hole groove, so that the explosive stress wave produces stress concentration in the slot [33].

After the explosion, the products will gather along the axis of the energy-concentrated structure, and the motion trajectory of the original detonation products will be changed to form a jet with high density, high speed, and high pressure, as shown in Figure 5. The movement direction of detonation products is affected by the initiation point of explosives and the shape of energy-concentrated structure. The velocity of the jet is the vector sum of detonation wave velocity, expansion velocity of mixed gas, and movement velocity of detonation products [34].

The jet hits the rock interface of the hole wall, and the hole wall obtains the same speed as the jet and continues to move forward. This speed is called the jet penetration velocity. Chen pointed out that the penetration of rock mass by energy-concentrated blasting can be divided into three stages [35].

(1) The pit-opening stage of the energy-concentrated jet: the free interface of the rock collapses and forms small cracks when the energy-concentrated jet impacts the rock mass [31]. In the casing slit-shaped charge blasting method, a slit casing is arranged around the explosive, and energy-concentrated flow is generated in the direction of the slit, and the rock mass will preferentially produce cracks along the energy-concentrated flow direction, as shown in Figure 3(d).

(2) The quasi-steady stage of jet penetration: the shaped-energy jet continuously destroys and perforates the rock, the energy distribution of the energy-concentrated jet tends to be stable, and the rock-breaking ability does not change with time.

(3) Action stage of pestle body and stress wave: the velocity of energy-concentrated jet decreases, the rock strength plays a leading role, and the rock breaking speed and ability decrease. However, the pestle still causes damage to the hole wall and the stress wave can promote further penetration of the formed cracks.

2.2. Principle of HBT. As early as during the World War II, Cookwood [36] and Beit [37] proposed the approximate theory of underwater explosion, and Taylor [38] proposed the bubble oscillation theory. In 1962, Horton et al. [39] used numerical methods to obtain theoretical solutions for the propagation and attenuation of shock waves from underwater blasting. In the late 1970s, Japan applied the
experience of hydraulic blasting to demolish urban buildings in tunnel blasting and invented the ABS method [40].

Water medium has the functions of energy storage, buffering, and water wedge in blasting. The difference between hydraulic blasting and conventional blasting is that it uses the incompressibility of water to store explosive energy and transfer it evenly to the surrounding rock wall of blasthole. At the same time, due to the buffering effect of water, the attenuation speed of stress wave generated after explosion in water is much less than that in air, which can reduce the energy loss in the propagation process and is conducive to the formation of cracks in rock mass. Moreover, the “water wedge” effect and “atomization” effect produced by water under the expansion of explosive gas are conducive to the expansion and penetration of cracks and reduce the dust concentration [41]. Under the condition of charging with different coupling coefficients, Xiao and Li [42] studied the explosion effects of explosives in water and air media, respectively. The research shows that when the decoupling coefficients are the same, the initial pressure of water medium (hydraulic blasting) on the hole wall is always greater than that of air medium (conventional blasting), and the blasting effect in water medium is better. With the increase of decoupling coefficient, the attenuation range of initial pressure produced by hydraulic blasting on the surrounding rock of hole wall is much smaller than that of conventional blasting, indicating that the water medium can better transmit blasting energy, the utilization rate of explosive energy is high, and the energy storage effect is obvious.

Shao et al. [43] used an analytical method to show the whole process of rock blasting by water pressure, that is, the formation and propagation of shock wave in water, the reflection and transmission of shock wave at the interface between water and rock, the transmission and attenuation of stress wave in rock mass, and the rock fracture caused by stress wave, as shown in Figure 6.

2.3. Technology of ECHBT. Professor He's team developed a new technology of “energy-concentrated hydraulic smooth blasting” based on the theory and engineering practice of ECBT and HBT [44]. The ECHBT combines the directional blasting effect of ECBT with the “water wedge” effect and “atomization” effect of HBT.

The conventional smooth blasting technology blasts the tunnel face in the order of cut-hole → auxiliary-hole → peripheral-hole. The cut-hole blasting forms a free surface, the auxiliary-hole blasting expands the excavation, and the peripheral-hole blasting forms an excavation
contour [45]. For the ECHBT, the charge structure and blasting method of cut-hole and auxiliary-hole are the same as those of conventional blasting, but the peripheral hole is obviously different. The hole spacing of conventional blasting is generally 40∼50 cm, while the hole spacing of ECHBT is 80∼100 cm. The energy-concentrated tube is used to replace the blasting roll and detonation transmission line. Water bags are installed at the bottom and upper parts of the hole, and the hole is blocked by clay, as shown in Figure 7.

At present, the energy-concentrated tube commonly used in engineering construction is antistatic and flame-retardant PVC material, and the length is usually 2 m to 3 m, which can be made according to the depth of the on-site blasthole. As shown in Figure 8, the energy-concentrated tube is composed of two half-walled tubes with a length of 28.35 mm, a width of 24.18 mm, and a wall thickness of 2 mm. The central part of the semi-wall tube is equipped with a “concentrating groove,” the top angle of the energy accumulation groove is 70°, the distance between the tops is 17.27 mm, and the adjustable concentrating direction of the two semi-wall tubes is 8°∼10° [46].

### 3. Application of ECHBT in Tunnels

#### 3.1. Improving Tunneling Efficiency

For long and large tunnels, increasing the cycle footage and improving construction efficiency are effective ways to shorten the construction period. The ECHBT produces energy-concentrated jets with high temperature, high pressure, and high speed, and the water wedge effect enhances the quasi-static effect of expansive gas, which can solve the problem of excessive spacing between blastholes in conventional blasting [8]. The distance between peripheral holes of conventional blasting is generally 40∼50 cm, while that of ECHBT is 80∼100 cm, which greatly reduces the number of peripheral holes and shortens the drilling time. The ECHBT increases the uncoupling coefficient of explosive charging, which is conducive to energy release and can significantly increase the cycle footage and shorten the tunneling period. Chen et al. [48] used the Jingling Tunnel of the Hangzhou-Shaoxing-Taizhou Expressway as the engineering support, and the tunnel was excavated by ECHBT and traditional smooth blasting, respectively. The comparison results showed that the average footage was increased by 18 cm per cycle by the ECHBT. The average footage per cycle of Zilinshan Tunnel is 2.8 m–3 m when using conventional blasting technology. After using the ECHBT, the tunneling per cycle is 3.5 m–3.8 m. Compared with the conventional blasting, the footage per cycle is increased by about 0.7 m [49]. Table 1 lists the difference in circulating footage between the ECHBT and conventional blasting technology. According to the data in the table, the ECHBT can increase the circulation footage of the tunnel by at least 10 cm and the maximum lifting ratio can reach more than 20%.

According to the statistical data in the table above, the grade of surrounding rock has little effect on the increase proportion of cyclic footage of ECHBT, and the different types of surrounding rock can cause large differences in cyclic footage. The increase ratio of the cyclic footage of the same grade of surrounding rock may be quite different. The increase ratio of the cyclic footage of tuff and dolomite of grade III differs by about 17%, and the cyclic footage of moderately weathered dolomite with surrounding rock grade III is 12.2% higher than that of dolomite with grades III and IV. Therefore, the grade of surrounding rock has little influence on the cyclic footage, but the type of surrounding rock is a key factor affecting the cyclic footage.

According to the on-site statistics of the process time, the footage per cycle of the ECHBT in Fenghuang Tunnel can be saved by about 1 h, and the construction period of the tunnel can be saved by about 14 days per 1 km [59].
The footage of each cycle of Liangdang Tunnel is 441 min by using ECHBT, and the time can be saved by 63 min compared with the HBT and 100 min compared with the traditional blasting technology. For example, the time saved in each process is shown in Figure 9 [45]. Considering the cycle time of drilling, charging, blasting, and spraying concrete, the Xiaguili Tunnel takes 12.3 hours per cycle for conventional blasting, while it takes 10.9 hours for ECHBT. In contrast, a total of 1.4 h can be saved per cycle [60].
3.2. Improving the Effect of Smooth Blasting. In the process of conventional drilling and blasting, there are overexcavation and underexcavation, and the face is formed poorly. By using the ECHBT, the phenomena of over and underexcavation, secondary blasting, or shotcrete can be effectively controlled [49]. Compared with conventional smooth blasting, the contour of the tunnel is smoother. The tunnel of Tianchi Pumped Storage Power Station adopts different technologies such as conventional blasting technology, HBT, and ECHBT for comparative analysis. The observation of on-site blasting effects, as shown in Figure 10, showed that the ECHBT has significant advantages in improving the flatness of the tunnel profile [61].

The effect of smooth blasting can also be judged based on the measurement of the trace retention rate of the blasthole on site. In contrast, the traces of the blasthole after the energy-concentrated hydraulic blasting are more intact [47]. Figure 11 shows the on-site measurement of over and underexcavation of the tunnel and the preservation rate of blasthole traces. According to the comparison, it can be seen that the ECHBT is beneficial to improve the smooth blasting effect.

In addition, Hu [12] used a three-dimensional laser tunnel profiler to scan the section produced by ECHBT on site, as shown in Figure 12. The results show that the overexcavation and underexcavation of the tunnel have been significantly improved. Compared with conventional blasting technology, the maximum overexcavation value of ECHBT can be reduced by 25%, and the average overexcavation area can be reduced by 46.8%, which can further reduce the amount of wet shotcrete.

To reduce the over and underexcavation of the tunnel face, the ECHBT is adopted for the fractured surrounding rock of grades IV and V of the Foeryan Tunnel of Chongqing Yanjiang Expressway. According to the field test, as shown in Figure 13, the waveform of the ECHBT is basically divided into three stages: 0~0.3 s, 0.3~0.9 s, and 0.9~1.5 s. In the first and second stages, the peak value of the vibration waveform is in the Z-axis direction and the absolute average value is the highest on the Y-axis. In the third stage, the peak value and absolute average value are both the highest on the Y-axis. The water wedge effect of ECHB can reduce the impact force in the X-axis direction and increase the impact force in the Y-axis and Z-axis directions at the same time, which can better control the tunnel blasting and reduce the occurrence of overexcavation [63].

3.3. Improving the Utilization Rate of Explosives. Water can produce “water wedge” effect under the expansion of explosive gas, and water medium can better transfer blasting energy, which makes the energy utilization rate of explosives in the ECHBT relatively high. According to statistics after the blasting of Jingling Tunnel, the explosive consumption per cubic meter of the concentrated energy hydraulic blasting is about 0.8 kg, and that of the conventional blasting is 0.9 kg, the explosive consumption per cubic meter can be saved by 11%, and the explosive consumption per cycle footage can be saved by 31.5 kg [48]. The blasthole depth of conventional smooth blasting in Zilinshan Tunnel is 3.5 m, the actual effective footage is 3.1 m~3.3 m, and the utilization rate of blasthole is 91.4%. When the depth of the blasthole remains the same, the actual effective footage of the ECHBT can reach 3.2 m~3.4 m, and the blasthole utilization rate is 94.2% [49]. It can be seen that the ECHBT can make the explosive energy fully act on the surrounding rock and use less explosives to increase the circulating footage while the blasthole depth remains unchanged, thereby increasing the utilization rate of the blasthole. Figure 14 shows the field statistics of explosive consumption and blasthole utilization rate of some tunnels under the ECHBT.
3.4. Reducing Dust Concentration. The water is atomized under the action of blasting, and the surface tension of the atomized water is used to absorb the dust generated by the blasting, which can play a significant role in dust reduction and shorten the time of ventilation and dust removal after blasting [66]. After 5 minutes of blasting, the P-512C portable microcomputer dust meter was used to detect 5 consecutive cycles of conventional blasting and 5 cycles of ECHBT at the exit of Luojiashan Tunnel. The dust content at 25 m away from the tunnel face is measured 5 minutes after blasting. The dust contents of conventional blasting technology and ECHBT are 16.1 mg/m³ and 8.0 mg/m³, respectively [54]. The dust content of the Liangdang Tunnel and the Xiaoshan (a) The effect of conventional blasting technology. (b) The effect of ECHBT [61].

Figure 10: (a) The effect of conventional blasting technology. (b) The effect of ECHBT [61].

Figure 10: (a) The effect of conventional blasting technology. (b) The effect of ECHBT [61].

![Graph showing overexcavation value for different tunnels](image)

Figure 11: Comparison of smooth effect. (a) Overexcavation value. (b) Preservation rate of blasthole traces [47–62].

Figure 11: Comparison of smooth effect. (a) Overexcavation value. (b) Preservation rate of blasthole traces [47–62].

![Graph showing preservation rate of blasthole traces](image)

Figure 12: Scanning results of (a) conventional blasting technology and (b) ECHBT [12].

Figure 12: Scanning results of (a) conventional blasting technology and (b) ECHBT [12].
Tunnel are reduced from 0.66 mg/m³ to 0.31 mg/m³ [45, 56]. The dust content of the Guanshan Tunnel is 15.5 mg/m³ and 5.1 mg/m³ under the two blasting techniques, respectively [50]. Through the on-site measurement of the dust content in the tunnel, the dust concentration of the ECHBT is 50% lower than that of the conventional blasting technology, and the effect of dust reduction is obvious.

In addition, dust concentration occupies an important index in the tunneling of coal mine. Excessive dust concentration will increase the harm to human body. Compared with conventional smooth blasting technology, the working environment of the tunnel is improved after the introduction of the ECHBT in Huhehusu Coal Mine [62]. Figure 15 compares the tunnel ventilation time under the ECHBT and conventional blasting technology, and it can be seen that the
3.5. Reducing Blasting Vibration. The field test of blasting vibration caused by conventional blasting is 0.568 cm/s, while the peak velocity of vibration caused by ECHB is 0.203 cm/s, and the reduction rate of vibration can reach 64.3% [67]. The Linjia’ao Tunnel is parallel to the Huangmaoshan Tunnel of the existing business line, and the large blasting vibration will have a serious impact on the adjacent existing Hangzhou-Shenzhen railway tunnel. The TC-4850 blasting vibrometer was used to measure the vibration velocities of conventional blasting and energy-concentrated hydraulic blasting. The results showed that the maximum vibration velocity in the Y direction under the conventional blasting method reached 1.8 cm/s, which could not meet the requirements of the specification. The ECHBT can reduce the vibration speed by more than 45%; even if the excavation footage increases, the vibration velocity can still be controlled below 1.8 cm/s. It can be seen that the use of ECHBT can effectively reduce blasting vibration [68]. The vibration produced by blasting in Tianchi Pumped Storage Power Station is monitored, two of the test results are shown in Figure 16, and it can be seen that the vibration frequency and vibration velocity produced by conventional blasting technology are significantly higher than those produced by ECHBT [61].

In addition, it is often faced with a complex engineering environment in the construction of urban subway tunnels. There are various pipelines and existing buildings around, and the vibration velocity, noise, and excavation effect of conventional blasting are difficult to meet the requirements of urban construction. To avoid impacts on the surrounding residents and commercial streets, Shenzhen Urban Rail Transit Line 8 uses the ECHBT on site. Compared with conventional blasting technology, the electronic digital detonator combined with the ECHBT can effectively reduce the blasting vibration by 30%–60%, so as to meet the construction requirement that the blasting vibration velocity shall not be greater than 1 cm/s [69]. Gas and water supply pipelines, schools, pedestrian bridges, shopping malls, and other structures are distributed around the section from Xiayuan Station to Nangang Station of Guangzhou Metro Line 13. Through field tests, the vibration velocity of ECHBT is reduced by 9.3% from 16 cm/s to 1.27 cm/s compared with conventional blasting technology [65].

3.6. For Special Geology. Shen [70] pointed out that the implementation of smooth blasting in the surrounding rock with joints and fissures can effectively control the over-excitation phenomenon, reduce the disturbance to the surrounding rock, and ensure the stability of the surrounding rock. When the blasting disturbance of thin-layer horizontal surrounding rock is large, it will cause problems such as falling of surrounding rock vault and instability of surrounding rock. The “water wedge” effect of the ECHBT can reduce the influence on the radial direction of the tunnel, thus reducing the overbreak of the arch after blasting. Moreover, the stress wave of ECHBT can propagate effectively along the contour, and the attenuation effect is small. The traditional blasting methods used in Ziyili Tunnel, Fenghuang Tunnel, and Luojiashan Tunnel cannot meet the construction requirements. The ECHBT can effectively make up for the shortcomings of conventional blasting technology and improve construction efficiency. Moreover, the linear density of the charge in the energy-concentrated tube can be dynamically adjusted according to the surrounding rock conditions, and the high-pressure gas after the blasting of the ECHBT can be used to cut the rock surface along the direction of the energy collecting groove to reduce the damage to the surrounding rock and make the tunnel contour more round [53, 57, 59]; Figure 17 shows the application of ECHBT in broken stratum and horizontal thin stratum.

Facts have proved that under special geological conditions, the ECHBT has achieved good results. According to the existing data and literature, there is no application example of ECHBT in foreign countries, but its application in domestic tunnels is gradually increasing. The distribution in various regions of China is shown in Figure 18 [45–73], and it can be seen that the ECHBT is mainly applied in the mountainous areas of the Southwest China, Northwest China, and Central China, and the southwestern area is the most used. The Luojiashan Tunnel has developed karsts, and the use of ECHBT can effectively avoid further disturbance of karst fissures, thereby reducing engineering risks [59]. Karst landforms are widely distributed in Southwest China, especially in Guizhou. At present, the ECHBT is widely used in this region. By further optimizing the blasting parameters, it can be better applied to karst areas.

3.7. Reducing Construction Costs. The ECHBT has great advantages in economic benefits, which are mainly reflected in saving blasting materials, reducing support costs, and
improving production efficiency. As mentioned above, the spacing of peripheral blastholes is generally 40 cm–50 cm, while the spacing of peripheral blastholes of ECHBT is 80 cm–100 cm, which greatly reduces the number of peripheral blastholes, shortens the drilling time, and reduces the amount of explosives. The smooth blasting effect of the ECHBT is better, it reduces the serious problems of over and underexcavation, and the amount of sprayed concrete used in the tunnel is significantly reduced. Moreover, the reduction of each process time greatly improves the production efficiency. According to the comparison of on-site drilling and blasting costs, compared with conventional blasting technology, the cost per linear meter of the Jiaoding Tunnel can be reduced by 10.77% [49], the cost saving ratio of the Guanshan Tunnel is 32% [50], and the Xiaoshan Tunnel can reduce the cost by about 30% [54], while the Jinpingyan Tunnel’s reduction ratio can reach 36.99% [47]. Table 2 shows the statistics of the cost per meter of the Jinpingyan Tunnel. The ECHBT can not only reduce the drilling time but also save a large proportion of drilling costs. In addition, the support cost such as shotcrete can also be reduced due to the good control of excavation contour.

4. Influencing Factors and Optimization of the Effect of ECHBT

4.1. Influencing Factors of Blasting Effect. When explosives from adjacent blastholes explode at the same time, the generated stress waves propagate into the surrounding rock, and interference occurs in the rock mass between the

![Graph](image-url)
blastholes to generate tensile stress waves. When the stress exceeds the tensile strength of the surrounding rock, the rock breaks and cracks are formed, and then the detonation gas expands to further penetrate the cracks, as shown in Figure 19.

The energy-concentrated structure in the ECHBT can give priority to cracks in a specific direction, the water bag can cause the explosion to produce a “water wedge” effect, and the clay can prevent the detonation gas from exiting the blasthole. In the on-site construction, if the surrounding blastholes on the tunnel face are not on the same excavation contour line and the directions of the adjacent blasthole energy collecting grooves are inconsistent, the blasting effect will be affected, resulting in uneven tunnel contour or over and underexcavation. If the setting of water bag is unreasonable, the reduction of “water wedge” effect will affect the extension and penetration of rock cracks and lose the effect of dust removal. If the blasthole is not dense or the blocking length is insufficient, the air discharged from the blast hole will also affect the blasting effect. Studies have shown that drilling accuracy, direction of energy-concentrated groove, measurement and setting out, placement of water bag, and plugging of clay are the main factors affecting the on-site blasting effect, accounting for 89.63%, as shown in Figure 20 [76].

Observing and analyzing the whole process of on-site blasting, it can be found that the main problems are large deviation of drilling angle, wrong direction of
4.2. Research on Optimization. As mentioned above, the ECHBT has achieved good results in the application of practical engineering, but it is limited to test conditions and test technology, and there are still few theoretical studies on this technology. We can take appropriate measures to improve the quality of tunnel excavation on the site for the aforementioned factors affecting the effect of on-site blasting. However, the optimal value of key parameters such as charge structure, spacing of blasthole, and decoupling coefficient faced by ECHBT is still empirical and uncertain.

According to the current literature, the optimization of rock breaking parameters of ECHBT is mainly carried out by means of numerical simulation. ANSYS/LS-DYNA software can simulate various complex nonlinear problems and is widely used in the study of nonlinear dynamic impact and large deformation caused by explosion and high-speed collision [77]. Some scholars have studied the rock breaking mechanism and blasting parameters of ECHBT by using the numerical simulation software ANSYS/LS-DYNA. Based on the energy-concentrated blasting method of casing slit structure, Hu [12] simulated and studied the blasting effects of energy-concentrated tubes with different slit widths, different wall thicknesses, and different inner and outer diameters. The results show that the peak stress of the model without energy-concentrated tube is 0.808 GPa, while the peak stress of the model with energy-concentrated tube increases significantly, but it is affected by the parameters of energy-concentrated tube. The optimal slit width of the energy-concentrated tube is 4 mm, but the optimal wall thickness under the condition of whether the energy-concentrated tube is coupled with the explosive is different. When the inner and outer diameters of the energy-concentrated tube and the slit width are the same, the optimal wall thickness under the condition of whether the energy-concentrated tube is coupled with the explosive is 4 mm and 3 mm, respectively, in which the maximum stress peak under the coupled state is 1.74 GPa, which is 2.15 times that without the energy-concentrated tube, as shown in Figure 21.

Wang [68] established a double-hole blasting model to analyze the blasting effects of different blasthole spacings under the ECHBT and conventional blasting technology. The results show that the optimal hole spacing in conventional blasting is 50 cm, while the optimal hole spacing in ECHBT can be expanded to 70 cm. When the hole spacing is 50 cm, the two charging structures can form the penetration of the crushing area. When the hole spacing is increased to 70 cm, only the ECHBT can penetrate the surrounding rock, as shown in Figure 22. The double-hole spacing setting of this model is discontinuous, so the results may have deviation, and further densification spacing is needed for more in-depth research.

Feng [78] established models for grade IV and V surrounding rocks, respectively, to study the blasting effects of different peripheral hole spacing and explosive concentration, and the research process is shown in Figure 23. The research shows that when the surrounding rock grade is IV, the surrounding hole spacing is 60 cm and the explosive concentration is 0.55 kg/m, which can achieve better blasting effect; at class V, when the peripheral hole spacing is 80 cm and the explosive concentration is 0.48 kg/m, the excavation contour surface is smooth and the disturbance to the surrounding rock is small.

Computer software can simulate complex engineering projects to make up for the deficiency of field test conditions. As mentioned above, the numerical simulation method can be used to optimize the blasting parameters of ECHBT.
Figure 21: Relation curve between peak stress and (a) slit width and (b) wall thickness [12].

Figure 22: The damage range of surrounding rock when the blasthole spacing is 70 cm in (a) conventional blasting technology and (b) ECHBT [68].

Figure 23: The influence of blasthole spacing and explosive concentration on the blasting effect [78].
However, the current research is still not adequate. Although the slit width and wall thickness of energy-concentrated tube, blasthole spacing, and explosive concentration are studied, the optimal values of key parameters such as explosive decoupling coefficient and water are still uncertain. There are some problems in the study, such as the deviation of the value of the optimal parameters and the incomplete consideration of the influencing factors, and it is necessary to further reasonably set the research parameters. The results of numerical simulation need to be further compared with methods such as formula analysis and laboratory tests. Only when the theory is verified in practice can it be better applied to engineering practice.

5. Conclusion and Prospect

The ECHBT combines the advantages of ECBT and HBT. The energy-concentrated effect produces high-temperature, high-pressure, and high-speed energy-concentrated jet along a specific direction, resulting in stress concentration in the rock and cracks, so as to form an excavation contour on the tunnel face. HBT has the functions of energy absorption, buffering, and water wedge, which can better expand and extend the crack, promote the crack penetration, and reduce the vibration and dust concentration during blasting.

In recent years, ECHBT has achieved good application results in tunnel engineering. According to the existing literature, ECHBT has been applied to highway tunnel, railway tunnel, urban subway, and coal mine. From the blasting effect on site, compared with conventional blasting technology, ECHBT has the advantages of smoother excavation contour, effective control of over and underexcavation, increased cyclic footage, reduced dust concentration, and reduced disturbance to surrounding rock. At present, there are application examples of ECHBT in class II–V surrounding rock. It is worth noting that remarkable application effects are still achieved in special geology such as broken surrounding rock of grades IV and V and thin horizontal strata.

It has been only a short time since the emergence of ECHBT, and there is insufficient theoretical research and lack of corresponding technical standards. According to the field practice, the effect of ECHBT is affected by drilling accuracy, direction of energy-concentrated tank, measurement, placement of water bag, plugging of clay, and other factors. It is necessary to further standardize the operation to improve the blasting quality. At present, the numerical simulation software ANSYS/LS-DYNA is mainly used for the optimization of blasting parameters, which is due to lack of joint demonstration of the analytical method and test method. Moreover, the corresponding technical standards need to be formulated to face the complex and changeable engineering environment.

Compared with conventional blasting technology, the ECHBT has unique advantages and is an important development direction of tunneling technology. Although the theory of ECHBT has been put forward recently, it has achieved remarkable results in practical engineering. At present, it is mainly used in tunnel engineering in China, and no relevant literature is found in other countries and regions. However, from the existing engineering practice, the ECHBT is superior to the conventional blasting technology in all aspects and is more and more widely used in tunnel engineering. Moreover, there are also engineering cases of combining ECHBT with presplitting blasting technology. It not only has good blasting effect but also reduces the vibration of surrounding rock to a certain extent and provides a better foundation for the stability of surrounding rock. With the application of computer technology in tunnel engineering becoming more and more mature, the theory of ECHBT will continue to develop and improve. Therefore, we can expect that it can be maturely and widely used in tunnel engineering.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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