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Research Article

A Rock Mass Classification Method for Tuff Tunnel Based on the High-Pressure Gas Expansion Method

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A precise rock mass grade result is crucial for directing the tunnel excavation engineering design. A novel rock mass classification method for tuff tunnel based on the high-pressure gas expansion method (HPGEM) was proposed, which was primarily built on field test data previously acquired by the research team. The main achievements are as follows: combined with field data and the HPGEM rock-breaking theory, analyzing the rock uniaxial compressive strength, rock mass integrity index, and the relationship between the gas generator unit consumption and fitted the relevant equations. After that, the rock optimal uniaxial compressive strength (about 150 MPa) and the rock integrity factor (about 0.85) were obtained. With reference to the BQ rock mass classification method, a new rock mass classification method that applied to HPGEM was proposed. This study fills the gap of the appropriate rock mass classification method requested on HPGEM.

1. Introduction

The intricate urban pipeline network and complex surface/underground building led to the adverse construction environment of a tunnel. Traditional dynamite blasting is carried out with extreme vibrations, so it is difficult to meet the demands of construction under the higher vibration limit condition. As a result, the innovative rock-breaking techniques have been developed such as gas blasting [1], mechanical excavation [2], and tunnel boring machine (TBM) [3]. However, these techniques have some drawbacks on certain aspects. For instance, gas blasting has expensive equipment and complex operation requirements [4], the mechanical excavation is ineffective and has a narrow field of application [5], and the TBM equipment is expensive and necessitates large construction site [6]. These drawbacks constrain the efficient construction of hard rock tunnel excavation near important buildings in urban construction. The "high-pressure gas expansion method" (HPGEM) [7] was proposed to address these drawbacks. This is an emerging rock-breaking method, and its working principle is as follows: in the sealed condition, with the gas generating agent in the expansion pipe as the active ingredient, chemical and physical reaction occurs, and in a very short time, a large amount of high-temperature and high-pressure gas is released, which expands the surrounding rock and does the work, and then achieves the effect of rock breaking. The HPGEM method is characterized with strong rock-breaking capacity and low vibration hazard. However, the working principle of HPGEM is significantly different from that of dynamite blasting. The traditional rock mass classification method of tunnel (such as rock quality designation (RQD) [8], tunneling quality index (Q) [9], rock mass rating (RMR) [10, 11], geological strength index (GSI) [12], and China national standard basic quality (BQ) [13]) is mainly based on the stability (solidity) of the rock mass; thus, the weak the quality of the rock mass, the better the blasting effect. For HPGEM, when the strength and integrity of the rock mass is higher (within certain limits), the rock-breaking effect is better. Also, when the strength of the rock mass is lower and the integrity is poorer, HPGEM cannot complete the rock-breaking work because the gas escapes through the cracks. This characteristic is completely opposite to dynamite blasting. Therefore, the existing method of tunnel rock classification is not applicable to HPGEM at all.

The classification of engineered rock mass dates back to the 18th century, and the Russians categorized rock mass into five grades based on their hardness. In the early 1960s, the Europeans further subdivided it into six categories of the rock mass [14]. The rock mass classification method for design purposes started to emerge at the turn of the 20th century; the most well-known ones are Vickers hardness classification [15], Terzaghi classification [16], etc.; in the middle of the century, the rock mass classification method for describing the stability of the surrounding rock started to emerge, including Vutukuri classification of the surrounding rocks [17] and Deere classification of the RQD index [18]. In addition, the standard for engineering classification of rock mass (China, GB/T 50218-2014) [13] divides rock mass into five grades primarily based on rock hardness and rock mass integrity, which is a method that combines qualitative and quantitative aspects. As science and technology have advanced in recent years, the rock mass classification method has benefited. For instance, Liu et al. [19] trained classification samples of the rock mass surrounding the tunnel using the improved BQ method while the tunnel was being built. They then used the trained classification samples to create an intelligent SVC rock mass classification model. A "site-specific" classification method of rock mass based on entropy weight-TOPSIS-grey correlation analysis was developed by Dai et al. [20]. By collecting rock feature information and training neural networks, the literature [21] is able to recognize different types of rock mass and grades them. This method overcomes the shortcomings of previous classification methods and provides a more accurate and reliable rock mass classification method for underground mining. Gong et al. [22] investigated the rock-breaking process of TBM construction and proposed a number of construction prediction models [23–25], which offered theoretical guidance for the categorization of tunnel-surrounding rock. Qi and Wu [26] discussed in detail the influence of three aspects of geological conditions, construction equipment, and on-site management on the digging speed of TBM construction and carried out a hierarchical prediction study on the rock quality of TBM construction based on the classification of the surrounding rock of traditional dynamite blasting construction and fuzzy mathematical methods. Alemdag et al. [27] indirectly estimated the deformation modulus by means of neural networks, neuro-fuzzy, and genetic programming, which provided assistance in determining the results of rock body classification.

According to the development history of rock mass classification methods, it is necessary to establish a "site-specific" rock mass classification method for specific construction methods and geological conditions. Presently, there is no research on the rock mass classification method of HPGEM, which may cause misjudgment in construction progress. Therefore, this paper took a tuff tunnel as the engineering background, attempted to discuss the influence of uniaxial compressive strength and rock mass integrity on gas generator unit consumption (GGUC), and on this basis, draws on the BQ method and finally tried to propose a rock classification method applicable to HPGEM rock breakage in tuff tunnels. This study may fill the gap of the rock mass classification method applicable to HPGEM and lays the foundation for the wide application of this emerging method in engineering.

2. Principles of HPGEM for Rock Breaking

The HPGEM combines the high efficiency of explosive blasting with the gas expansion characteristics of liquid carbon dioxide phase-change fracturing. The apparatus (expansion pipe) for the HPGEM consists of the following three main parts [7]: the gas generator storage pipe (gas generator containers), the iron pipe (air-conducting function), and the wire (used to connect electrical triggers), as shown in Figure 1.

The rock-breaking mechanism of the HPGEM can be divided into three stages (Figure 2).

2.1. High-Pressure Gas Initially Impacts the Surrounding Rock at High Velocity. The gas generator in the expansion pipe can produce a significant volume of gas instantaneously when cracking the rock using a HPGEM. As the expansion pipe is completely sealed by the pressed slurry material and the rock mass exerts a confining pressure on the pressed slurry material, the pressure inside the expansion pipe also rises rapidly (caused by the rapid generation of gas) and the pressure inside the expansion pipe is much greater than the confining pressure. The compaction pressed slurry material, by virtue of its strength and the confining pressure, can resist damage in a very short period of time, which further leads to an increase in the pressure in the expansion pipe. Subsequently, the pressed slurry material is crushed by the confining pressure generated by the high-pressure gas, and this pressure is then rapidly applied to the surrounding rock.

Compared to dynamite blast [28], this stage is due to insufficient shock wave, which prevents the expansion pipe near the compression pressed slurry material and the rock mass from being crushed, but it can still directly break the rock in a small way, causing the rock to cause some small secondary fissures. Compared to other gas blasting, HPGEM in this stage is of the wider range of broken rock and more comprehensive due to the high pressure, so its break diameter increases.

2.2. High-Pressure Gas "Wedged" into Rock Fissures. At this stage, high-pressure gas is "wedged" into the surrounding rock mass at high speed along primary and secondary fissures, thus expanding and extending these fissures. At the same time, the development of fissures makes the rock mass strength weakened. This point is similar to the explosive explosion generated by the explosive gas rock-breaking mechanism, but different from the liquid carbon dioxide phase change fracturing method, where carbon dioxide for the first time becomes a part of the action of the rock mass facing the energy-discharging piece of the rock body, and the

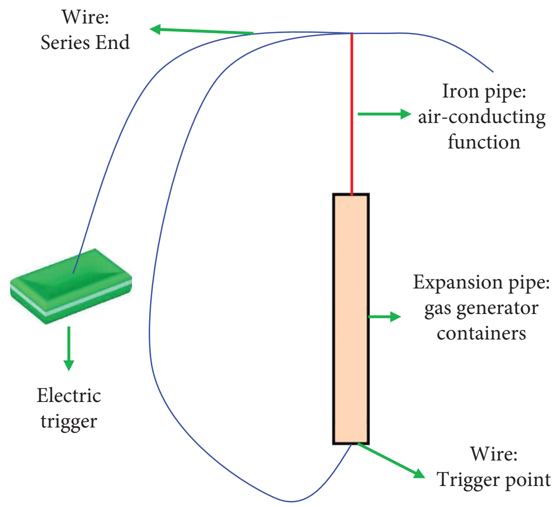

Figure 1: Expansion pile schematic.

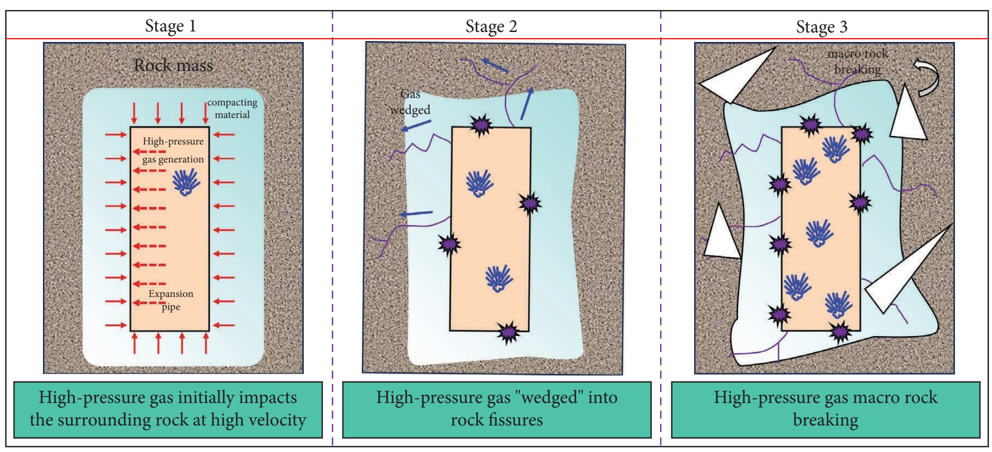

Figure 2: Rock breaking by the HPGEM mechanism.

rock body has nothing to do with the situation of the fissures. On the other hand, the high-pressure gas expansion method is to release the high-pressure gas comprehensively and uniformly into the surrounding rock mass. Therefore, even if the release time and the acting pressure are the same, the rock-breaking effect of the high-pressure gas expansion method may be more uniform, whereas the liquid carbon dioxide phase change fracturing method may have greater uncertainty.

2.3. High-Pressure Gas Macro Rock Breaking. After the initial high-pressure gas wedged into the rock mass, the subsequent high-pressure gas influx along the previous fissure channels and form an interconnected pressure body, which is then transformed into the quasistatic pressure acting on the rock mass; on the other hand, the initial high temperature and high pressure of the gas acting on the rock mass will derive tensile and shear stresses in the rock mass. Under the dual action of quasistatic pressure and tensile and shear stresses, the rock mass will be macroscopically damaged.

3. Tuff Tunnel Rock Mass Classification Method Based on HPGEM

As the engineering environment becomes more and more complex, the factors considered in the rock mass classification methods become more and more comprehensive, detailed, and specialized [29, 30]. The mainstream rock mass classification standard [13] currently used in China is mainly based on the stability of surrounding rocks and is divided on the basis of geologic factors, which mainly includes the strength of rocks and rock mass integrity. Regarding the method of tunnel rock mass grading under TBM construction conditions, a majority number of scholars [31, 32] take the construction efficiency of TBM as its key comprehensive index. Also, the construction efficiency is mainly obtained by analyzing its influencing factors. Although there are many factors affecting the construction efficiency, geological factors have always been the most critical, especially the uniaxial compressive strength of rock and the integrity of rock mass, and these two factors have a significant influence on the results of rock mass classification.

In view of this, this paper refers to the selection of indices for rock mass classification in TBM construction, and considering, at the same time, the influence of single consumption of gas generator on the efficiency of rock breaking, the uniaxial compressive strength of the rock, and the integrity of the rock mass are selected as the evaluation indices for the classification of HPGEM rock mass. Combined with the BQ rock mass classification method, we try to propose the HPGEM rock mass classification method for tuff tunnels.

3.1. Rock Uniaxial Compressive Strength and GGUC. HPGEM is a rapid reaction in a confined space, generating a large amount of high-temperature and high-pressure gas, which in turn does work on the surrounding rock mass to achieve rock breaking. If the compressive strength of the rock mass is too low, it will lead to premature rupture of the rock mass in the vicinity of the expansion pipe, which may form a pressure vessel with a larger space, increase the uplift space of the individual expansion pipe, and thus lead to a lower peak pressure of rock breaking. This may even cause the primary fissure in the rock mass to penetrate, and the high-pressure gas will enter the external environment, resulting in failure of the rock breaking. Based on the literature [7] published by the research team, in the actual rock-breaking process, the lower the uniaxial compressive strength of the rock, the worse the effect of rock breaking, and when the uniaxial compressive strength of the rock is higher, it may achieve a better rock-breaking effect. At this time, in order to ensure the effect of rock breaking, it is necessary to reduce the hole distance and other parameters, which will lead to an increase in GGUC.

Field test data show that the cost of HPGEM is generally more than twice times that of dynamite blast without considering the cost of time. Therefore, HPGEM is recommended to be used in hard rock areas where dynamite blast is not suitable, especially when the uniaxial compressive strength of the rock is above 60 MPa, and its rock-breaking effect is significant. When the uniaxial compressive strength of the rock is lower than 30 MPa, the rock-breaking effect is poor, the GGUC is large, the cost is high, and sometimes, it cannot break the rock successfully. If HPGEM is used for rock breaking in hard rock tunnels, it can be observed that there is an obvious correlation between the uniaxial compressive strength of rock and GGUC. In order to figure out the relationship between the two so as to provide a basis for the later rock mass classification, the field test data were analyzed and the results are shown in Figure 3.

Based on the fitting results (polynomial curve fitting), it is found that there is an obvious binomial relationship between the uniaxial compressive strength of rock and GGUC. As the uniaxial compressive strength of the rock increases, the GGUC decreases gradually, but it has leveled off at close to 150 MPa. Therefore, it is hypothesized that HPGEM may be more suitable for application in harder areas, which not only saves material costs but also reduces time costs due to changes in the layout parameters. In addition, the derivation of the fitted equation was performed to find the uniaxial compressive strength of the rock at the lowest GGUC, i.e., the minimum GGUC $K_{\min} = 0.48\,\mathrm{kg{\cdot}m^{-3}}$ and the optimum rock uniaxial compressive strength $R_c = 159.35\,\mathrm{MPa}$.

3.2. Rock Mass Integrity and GGUC. Rock mass integrity is also one of the most important factors affecting rock-breaking effectiveness. Similar to the uniaxial compressive strength of rock, the discontinuous structure of rock mass, such as primary joints and fissures, will also have a significant influence on the rock-breaking effect of HPGEM and the high-temperature and high-pressure gases generated by HPGEM will be "prematurely relieved" due to the existence of primary structure of the rock mass, even leading to rock-breaking failure. In order to maintain the rock-breaking effect, it is necessary to take the same measures mentioned above, such as reducing the hole spacing and other parameters and increasing the unit consumption in exchange for the rock-breaking quality.

At present, the integrity of rock mass is divided into five grades as follows: complete, relatively complete, relatively broken, broken, and extremely broken, mainly based on qualitative indicators such as the development degree, combination degree, type, and corresponding structure type of the rock mass structural plane [33]. To study the relationship between the integrity of rock mass and the GGUC of HPGEM, a quantitative index of the integrity degree of rock mass should be introduced. In reference [13], the coefficient of integrity of rock mass is used as the quantitative index of the integrity degree of rock mass. If the coefficient of integrity of rock mass is not convenient to obtain, the volume joint number of rock mass can also be used instead. Table 1 shows the relationship between the integrity coefficient of the rock mass and the number of joints in the rock mass volume. Consistent with the analysis of rock uniaxial compressive strength, the relationship formula between rock mass integrity and GGUC was fitted by using the field test data. The original data and fitting results are shown in Figure 4.

The fitting results show that the pattern of GGUC with changing rock mass integrity is similar to that of rock uniaxial compressive strength. However, the decrease in GGUC is slightly greater than that caused by the uniaxial compressive strength of the rock. The GGUC decreases with increasing rock mass integrity, leveling off as it approaches 0.7. Therefore, it is hypothesized that HPGEM may also be more suitable for application in areas of higher rock mass integrity. Here, the minimum GGUC $K_{\min} = 0.6\,\mathrm{kg{\cdot}m^{-3}}$ and the optimum rock mass integrity index $K_v = 0.86$.

3.3. Construction of the Rock Mass Classification Method for HPGEM. Combined with the abovementioned analysis, an attempt is made to construct the tuff tunnel rock mass classification method.

With reference to the standard for engineering classification of rock mass (GB/T 50218-2014) [13], it is constructed using a combination of qualitative and quantitative methods, mainly quantitative methods. Among them, the

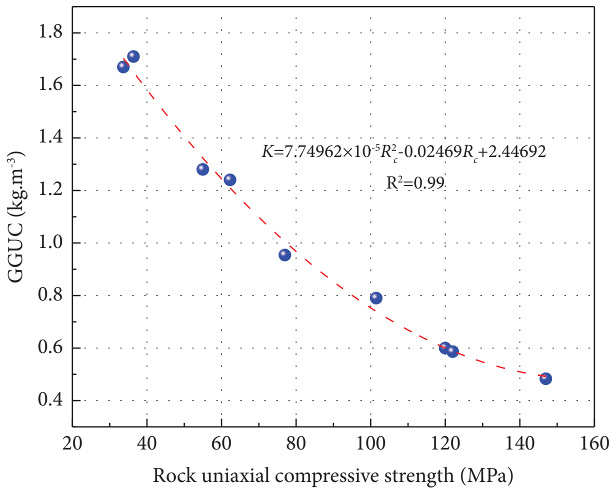

FIGURE 3: Relationship between rock uniaxial compressive strength and GGUC.

TABLE 1: Rock mass integrity index K_v and rock volume nodule number J_v.

J_v (strip/m^3)	K_v
<3	>0.75
3~10	0.75~0.55
10~20	0.55~0.35
20~35	0.35~0.15
≥35	≤0.15

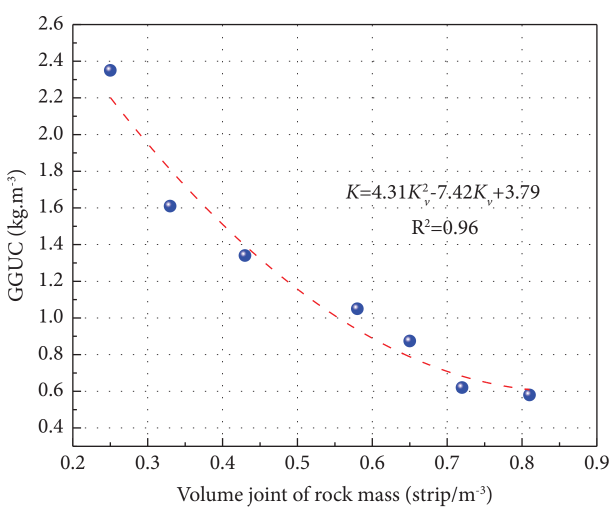

FIGURE 4: Relationship between rock mass integrity and GGUC.

qualitative basis is mainly the characteristics such as the degree of rock hardness and rock mass integrity, while the quantitative basis is the scoring value of the basic quality indicators of the rock mass. The rock uniaxial compressive strength R_c and the rock mass integrity coefficient K_v were used to complete the quantitative evaluation, and the interrelationships between the qualitative and quantitative indicators are shown in Tables 2 and 3, respectively.

The HPGEM as an emerging rock-breaking method has no rock mass classification method applicable to this rock-breaking technique. Two main parameters, uniaxial compressive strength of rock and the degree of rock mass integrity (qualitative indices are the number of structural surface groups, average spacing, the degree of combination of the main structural surfaces, and the type of structure and the quantitative index is the integrity coefficient), are selected to carry out the study of HPGEM rock mass classification for tuff tunnels. Also, drawing on the "Engineering Rock Mass Classification Standard" (GB/T 50218-2014) [13] and based on the fitting formula of the field test results, it is also classified into I_P, II_P, III_P, IV_P, and V_P, a total of five grades, and a new rock mass grade classification method is constructed, and the specific details are shown in Tables 4 and 5. In order to facilitate the differentiation and improve the practicability, the grading interval is slightly adjusted, for example, the uniaxial compressive strength of the rock mass of 154.375 MPa is adjusted to 150 MPa for grade I and the integrity coefficient of the rock mass of 0.949 is adjusted to 0.95 for grade I and so on. At this point, the tuff tunnel rock mass classification method based on the HPGEM was established.

4. Discussion

The HPGEM, as an emerging low-vibration rock-breaking technology, can replace dynamite blast for some special sections. Researchers have already analyzed it. Cui et al. [34] reported a high-pressure foam fracturing method, which is a new mild rock-breaking method between high-stress loading rate blasting and low-stress loading rate hydraulic fracturing and has the advantages of no sparks, less dust, no harmful gases, and controllable rock-breaking shapes. Xiaoqiang et al. [35] developed a rock-breaking gas generator, and by carrying out on-site rock-breaking tests, monitoring its vibration, extracting the main component of the gas-blasting signal, and analyzing the time-frequency characteristics of the different components of the signal, it was found that this new type of rock-breaking gas generator blasting technology has a significant effect of vibration reduction and damage reduction and it is suitable for popularizing the application of earth blasting projects. The abovementioned two devices are shown in Figure 5.

Unfortunately, to the best of our knowledge, there are still no reports on the classification of rock mass based on this emerging rock-breaking method. If the traditional rock mass classification method is used to determine the excavation ability of the rock mass under the HPGEM, it will result in serious misjudgment. It has been shown that different methods of rock mass classification may yield very different rock mass grade results even in the same region [20]. Therefore, a rock mass classification method applicable to the HPGEM is essential to ensure the safety and efficiency of the project.

In this paper, a new method for classifying rock mass in tuff tunnels by HPGEM is constructed by drawing on the engineering classification of rock mass (GB/T 50218-2014)

Table 2: Relationship between R_C and the degree of hardness.

R_c (MPa)	Degree of hardness
>60	Hard rock
60~30	Harder rock
30~15	Softer rock
15~5	Soft rock
≤5	Extremely soft rock

Table 3: Relationship between K_v and the degree of rock integrity.

K_v	Degree of rock integrity
>0.75	Intact
0.75~0.55	Relatively intact
0.55~0.35	Relatively crushed
0.35~0.15	Crushed
≤0.15	Extremely crushed

Table 4: Tunnel rock mass classification for HPGEM.

Rock mass grades	R_C (MPa)	K_v	Quantitative indices (BQ value)
I_P	150~100	0.86~0.7	637.2~554
II_P	100~60	0.7~0.55	554~417.5
III_P	60~30	0.55~0.4	417.5~290
IV_P	≥150	≥0.86	≥637.2
V_P	≤30	≤0.4	≤290

[13] and the geological factors considered by TBM boring [33]. Combining the working principle of HPGEM with the field test results, it can be seen that there is a nonlinear relationship between the uniaxial compressive strength of the rock and the degree of rock mass integrity for the rock-breaking effect, which is diametrically opposite to the effect of traditional dynamite blast. Specifically, when the rock strength and rock mass integrity gradually increase, the GGUC required for rock breaking shows a gradually decreasing trend (stage 1: R_c: 0~120 MP and K_v: 0~0.7), which implies that the rock-breaking effect of the rock mass gradually increases. Subsequently, the GGUC required for rock breaking starts to stabilize gradually (stage 2: R_c: 120~180 MP and K_v: 0.7~0.9), at which time the stability of the rock mass reaches a high degree, which means that the rock-breaking effect will no longer increase with the increase of GGUC (Figures 3 and 4). Finally, the stability of rock mass is very good (stage 3: R_c: >180 MP and K_v: >0.9), and at this time, the unit consumption of aerosol required to break a certain unit of rock starts to increase and the rock-breaking effect starts to decrease; when the stability of the rock mass is so good, any rock-breaking method has a rock-breaking difficulty here.

When the strength of the surrounding rock exceeds 150 MPa, the GGUC gradually increases and the corresponding cost also rises. Since the uniaxial compressive strength of rock is closely related to its fissure state and so on, in order to minimize the influence of integrity factors such as fissure and structural surface on the uniaxial compressive strength of rock, the test is specially chosen to be carried out on the palm face peripheral rock which has similar integrity of the rock mass, but the result of the test will inevitably be affected to a certain extent. In addition, due to the geological conditions of the test site, most of the tests in this series were selected in tuff tunnels, and the lowest uniaxial compressive strength of the surrounding rock in this series of tests was 31 MPa and the highest uniaxial compressive strength was 147 MPa, which did not cover tuff tunnels of various strengths. The fitting equations in Figure 3 are applicable only for tuff tunnels with rock uniaxial compressive strengths of 30 MPa–150 MPa, i.e., in the region of harder and partially harder tuffs. Also, when the peripheral rock integrity index exceeds 0.86, the GGUC will gradually increase and the corresponding cost will also rise, which is mainly due to the high integrity of the rock mass, leading to the high initial pressure in the expansion tube; at this time, because the area of the compression slurry materiel with lower strength becomes a weak zone, it in turn produces cracks and becomes a pressure relief zone for the high-pressure gases, which affects the final rock-breaking volume.

In addition, we did not find the area with better strength and integrity in the field, so the field test for rock uniaxial compressive strength greater than 150 MPa and integrity greater than 0.86 will be the research work to be done in the future. In addition to the two main geological factors of uniaxial compressive strength of rock mass and integrity coefficient of rock mass, GGUC is also affected by other factors, such as the main structural surface of the rock mass, groundwater conditions, tunnel direction, and the state of geostress. For example, the main structural surface of the rock mass is in the form of a rock mass and the integrity of the rock mass is in the form of a rock mass. Also, the main structural surface of the rock mass and the tunnel direction have a certain effect on the stability of the rock mass, the direction of the expansion pipe drilling, and the direction of high-pressure gas spillage; when the surrounding rock is in a state of high geostress, the GGUC will be increased, and if the surrounding rock is a brittle, intact, hard rock, there is the possibility of rock bursting; if the surrounding rock is softer, the larger deformation will affect the effect of rock breaking and the efficiency of the construction, which in turn affects the GGUC. Groundwater and the water content state of the rock mass will also affect the strength of the rock mass to a certain extent and reduce the stability of the surrounding rock. In addition, the nature of the compression slurry outside the expansion pipe is also an important factor affecting the rock-breaking effect, and these literatures [36, 37] provide references for subsequent improvements.

Similarly, due to the complexity and inhomogeneity of the rock mass, it is not possible to ensure that other geological factors except rock mass integrity are exactly the same in the test, and in particular, the relationship between the integrity of the similar rock mass and its hardness is very close; therefore, the relationship between the rock mass integrity index obtained from the test and the GGUC has a reference for other similar projects to break the rock but is for reference only. Also, due to the complexity and various anisotropies of rock masses [38], other geological factors may differ. However, to some extent, the correlation between

Table 5: Description and recommendations of tunnel rock mass classification for HPGEM.

Rock grades	Description	Excavation recommendations
I_P	At this point, the strength and integrity of the surrounding rock are moderate, neither because the strength is too high to increase the GGUC nor because the integrity is poor to cause rock-breaking failure	HPGEM rock breaking is highly recommended when dynamite blast is not applicable
II_P	At this point, the strength and integrity of the surrounding rock are slightly lower, the GGUC required for lower strength of the surrounding rock decreases, while the GGUC required for poorer integrity needs to increase	When dynamite blast is not applicable, it is recommended to use HPGEM rock breaking, which can effectively improve the rock-breaking efficiency and reduce the cost compared with other alternative methods
III_P	At this point, the strength and integrity of the surrounding rock is low although the strength is low, but the integrity is poor and will still lead to a poor rock-breaking effect	When dynamite blast is not applicable, HPGEM rock breaking can be considered and mechanical methods of rock breaking can be used as well
IV_P	At this point, the strength and integrity of the surrounding rock are too high, and the rock mass is difficult to be fractured by the high-pressure gas, and even if the rock breaking is successful, the GGUC required for this process is significantly higher	When dynamite blast is not applicable, HPGEM can only be used as a reference considering the cost and duration, but it is still recommended to use as the method for rock breaking
V_P	At this point, the strength and integrity of the surrounding rock are extremely poor and the large number of structural surfaces present in the rock mass can cause gas to escape, making it often difficult for HPGEM to be effective	When dynamite blasts are not applicable, mechanical methods may be a better method of rock breaking

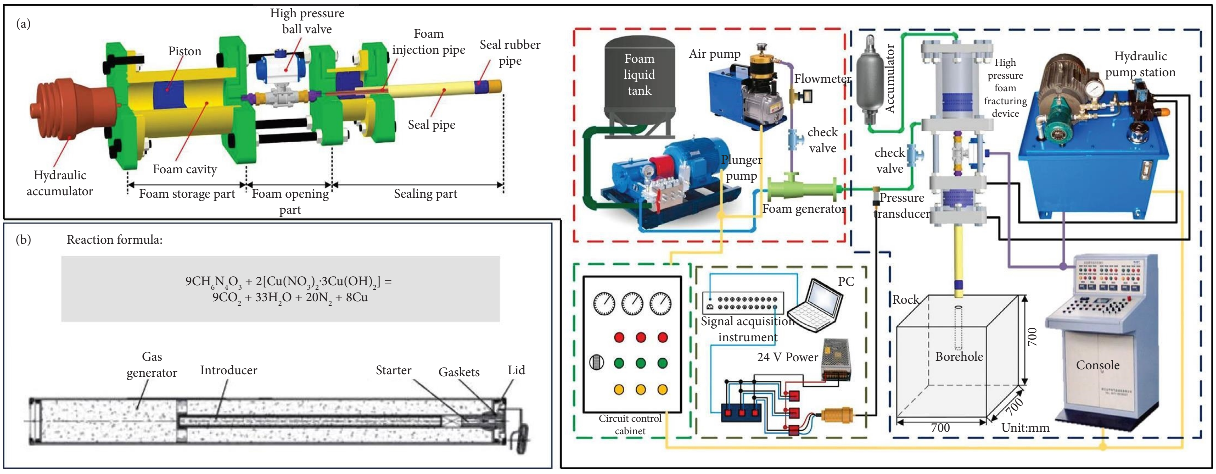

FIGURE 5: High-pressure expansion rock-breaking method: (a) high-pressure foam fracturing [34] and (b) rock-breaking gas generator [35].

integrity and hardness between similar rock masses (tuff) is stronger [12], so the relationship between the integrity factor of the rock mass and the GGUC obtained from the test is useful for other similar projects of rock breaking but for reference only.

5. Conclusions

Based on the field test data of the high-pressure gas expansion method in the early stage of the research team, this paper proposes a new rock mass classification method for the high-pressure gas expansion method in tuff tunnels, which fills the gap of the "appropriate" rock mass classification method in the process of its application, combining with the typical rock mass classification. The following conclusions are obtained:

(1) Combined with the field test data of the high-pressure gas expansion method, it is found that the unit consumption of gas generator tends to level off with the increase of uniaxial compressive strength and rock mass integrity, which means that the rock-breaking efficiency will no longer increase when the uniaxial compressive strength and rock mass integrity increase to a certain degree.

(2) The equations between rock uniaxial compressive strength, rock mass integrity, and gas generator unit consumption are fitted, and the optimal ranges of rock uniaxial compressive strength (about 150 MPa) and rock mass integrity (about 0.85) for the application of high-pressure gas expansion in tuff tunnels are given by combining the fitted equations with the principle of the high-pressure gas expansion method.

(3) With reference to the Chinese engineering classification of rock mass (GB/T 50218-2014), a new method of rock mass classification for tuff tunnels applicable to the high-pressure gas expansion method is proposed, which classifies the surrounding rock into five grades and gives suggestions for the engineering application of different surrounding rock grades.

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.

Authors' Contributions

D.L., B.D., Q.D., J.S., and H.P. conceptualized the study; D.L. and H.P. developed the methodology; D.L. contributed to software, investigation, data curation, and original draft preparation; H.P. validated the study and contributed to formal analysis, resources, and review and editing; B.D. contributed to visualization; Q.D. supervised the study; J.S. contributed to project administration. All the authors have read and agreed to the published version of the manuscript.

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