Preconditioning High-Strength Boulders for TBM Tunnelling by Ground Drilling and Blasting

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Abstract: A spherical weathering body, also called a boulder, is an element of complex geological strata and presents a significant challenge to tunnelling by a tunnel-boring machine (TBM). In this study, ground-based drilling and blasting were used to precondition boulders. To determine the specific charge needed for preconditioning blasting, model blasts were conducted, and the relationships among the specific charge, fragment size, and overburden depth in the model blasts were investigated. The determined specific charge from the model blasts was then modified by considering the overburden depth and used to precondition the boulders for practical TBM tunnelling. The results indicate the following: (1) model blasts were effective in determining the correct specific charge and predicting boulder fragment sizes resulting from blasting; (2) the boulders met in practical TBM tunnelling were successfully preconditioned by using the determined specific charge; (3) the determined specific charge was 3.26 kg/m³, corresponding to an average fragment size 4.5 cm with an overburden of zero and increased with increasing overburden; (4) fragment sizes were dependent on both the specific charge and overburden depth. Our conclusions can be used to accurately determine the specific charge instead of empirical formulas.

Keywords: preconditioning; high-strength boulder; TBM tunnelling; specific charge; blasting

1. Introduction

The increasing number of underground subway projects undertaken around the world has revealed more complex strata in tunnelling with TBM machines. For example, spherical weathering bodies, as shown in Figure 1, form part of a stratum and usually cause serious problems for TBM excavation. In this stratum, the maximum uniaxial compressive strength (UCS) of boulders can be up to 200 MPa. In this case, TBM cutters must be changed frequently because they will wear quickly due to the high-strength boulders [1]. As a result, the advance rate of the TBM decreases, and the project costs increase [2,3].

Figure 1. Boulders as spherical weathering bodies.
To address this problem, pretreating the boulders before the TBM approaches them is necessary. Possible methods to pretreat such boulders include: (1) fragmenting the boulders by drilling and blasting from the ground [4,5], (2) reinforcing the weathering strata surrounding the boulders before tunnelling, (3) breaking the boulders with explosive or static fragmentation agents from the tunnel, a common practice in mining engineering [6], and (4) artificially treating the boulders during TBM excavation [7]. Among the above methods, the first is the most commonly used in TBM tunnelling, and is similar to that used in breaking down a hanging roof in mining [8]. Because boulders are often confined, with an insufficient free surface exposed, two challenges then appear when this method is applied: how to determine the proper specific charge or powder factor, and how to predict the fragment sizes after boulders are blasted, since the sizes must be suitable for operation with a TBM muck haulage system. If the specific charge used in boulder blasting is too large, the blasting costs will be high, and adverse effects such as high vibration on the nearby structures and facilities will be induced. Conversely, if a specific charge is too low, the boulder will either be fractured into fragments that remain too large, or not broken at all. In either case, it will be difficult for the TBM to perform a successful excavation.

Some researchers have conducted relevant research. A new type of specific charge structure by means of a shaped-charge structure was proposed for boulder blasting and the main parameters were studied [4]. Boulder blasting models with a single hole and double hole were established separately, and the relation between the strength of boulder, size of boulder, specific charge, and minimum safety distance were studied [5]. Two or more high explosive strips were arranged uniformly to initiate the main charge in the borehole in order to form the detonation wave collision. The shield tunneling rate was increased by 42.74%, and the blasting cost was reduced by 26.74% [9]. Sun [10] analyzed the effects of the charge, borehole spacing, interval charging, and continuous charging on the fragmentation in boulder blasting, and obtained the maximum fragmentation corresponding to different row spacing and charging structures. In order to improve the blasting effect, the empty hole was applied in boulder blasting [11]. Although many results have been obtained and some new technologies have been applied in boulder blasting, in order to study the ground movement patterns in case an undetected large boulder is accidentally encountered by tunnelling, a hybrid extension method encompassing both convexity control and overlap detection was developed, and several influence factors including the boulder size, orientation, position, and morphology were included [12]. Another factor, the failure mechanism of ground subsidence due to removing large isolated boulders in the sand matrix by tunnelling, was studied and the ground subsidence hazards were analyzed [13]. Unfortunately, few studies have researched the determination of the proper specific charges or the prediction of fragment sizes when blasting boulders.

In underwater blasting, the specific charge $q_w$ is often determined using the Swedish empirical formula [14], as follows:

$$q_w = q_1^1 + 0.01h_1 + 0.02h_2 + 0.03h_3$$

where $q_w$ is in units of kg/m$^3$, $q_1$ is the basic specific charge in bench blasting, (kg/m$^3$), $h_1$ is the water depth (m), $h_2$ is the overburden depth (m), and $h_3$ is the bench height (m).

This formula has been revised and used in pretreating boulders in various underground construction projects such as the Hitachi sewers in Japan [15], the Guangzhou and Shenzhen underground subways [16], and the Taishan Nuclear Power Plant in China. However, the results from these projects were not satisfactory. Because boulder blasting and underwater blasting differ (such as in confinement conditions), there is also a marked deviation between the actual required specific charge and the value calculated by the empirical formula in Equation (1) for underwater blasting [17]. Another technique similar to boulder blasting is the blasting preconditioning method used in mining engineering [18,19]. Similar to boulder blasting, preconditioning also needs a suitable specific charge.

The aforementioned studies indicate that the specific charge is a crucial parameter in boulder blasting. Although specific charges in ordinary blasting have been studied
in numerous publications [6,14,20–28], results from ordinary blasting cannot be directly applied to determine a proper specific charge in boulder blasting. Accordingly, the specific charge and size distribution of fragments in boulder blasting by using model blasts were studied in this paper. First, a preliminary design for boulder blasting when excavating water-intake tunnels for the Taishan Nuclear Power Plant is introduced. Then, the blasting design is revised by using similarity criteria and by considering the effect of overburden on the specific charge and fragment sizes. Finally, this revised design was applied to boulder blasting during a practical TBM excavation. Through the research results, a new calculation method to determine the specific charge can be obtained instead of the empirical formula, which means that the technology of boulder blasting can be improved.

2. Engineering Background

2.1. Water-Intake Tunnels

The water-intake tunnels of the Taishan Nuclear Power Plant are located between the Yaoguzui and Dajin Islands in China, and are 4330 m long and 9 m in diameter. The overburden of the tunnels is between 11 and 29 m, and the pillars between the two tunnels are an average of 29.2 m in width. The tunnels were excavated by a slurry-balanced TBM manufactured by Herrenknecht AG (Schwanau, Germany). The strata of the water-intake tunnels are complex, composed mainly of boulders and granite bedrock with an average UCS of ~100 MPa. The geological profile of the water-intake tunnels is shown in Figure 2.

![Geological profile of the water-intake tunnels](image)

**Figure 2.** Geological profile of the water-intake tunnels (the colors represent the UCS values of the rock masses).

2.2. Preliminary Design for Boulder Blasting

The purpose of the preliminary boulder blasting design was to determine a preliminary specific charge so that the blasted fragments could be administered by the TBM muck haulage system. Because the diameter of the slurry pipeline of the muck haulage system is 40 cm, the average blasted fragment size should be less than 30 cm, so that they can be successfully transported through the pipeline.

In this study, after the preliminary specific charge was determined, a series of model blasts was performed to modify the preliminary specific charge. Then, ground-based boulder blasting was performed for practical TBM tunnelling. Holes with a diameter of 90 mm were vertically drilled using a geological drill rig. No. 2 package explosives with a diameter of 60 mm were of a type widely used in China. Non-electric detonators were used in the holes, whereas electric detonators were employed outside the holes for initiation.

The preliminary specific charge was determined by the Swedish empirical formula in Equation (1), with \( q_1 \) revised to \( q^*_1 \), which was two times higher than the bench-blast specific charge \( q_1 \), and \( q^*_1 \) was increased by 10% to account for the vertical blasthole.
Taking $q_1 = 0.5 \text{ kg/m}^3$ [29], we have

$$q_1^{*} = (1 + 10\%) \times 2 \times 0.5 \text{ kg/m}^3 = 1.1 \text{ kg/m}^3 \quad (2)$$

Considering most of the tunnel overburden is 18 m and the average preconditioning height is 4 m (i.e., $h_1 = 20$ m, $h_2 = 18$ m, and $h_3 = 4$ m), the specific charge $q_b$ for boulder blasting can be calculated as

$$q_b = q_1^{*} + 0.01 \times h_1 + 0.02h_2 + 0.03 \times h_3 = 1.78 \text{ kg/m}^3 \quad (3)$$

Equation (3) can be used to determine the charge weight required to fragment a boulder if its volume is known. Figure 3 shows the design of an explosive charge for boulder blasting.

![Design for boulder blasting](image)

**Figure 3.** Design for boulder blasting. (a) Blast design for boulders shorter than 2 m; (b) blast design for boulders taller than 2 m. S denotes the inter-boulder spacing and varies from 0.8 to 1.2 m.

Large boulders were blasted by multi-row blasting in this study. Because no free surface or swelling space was available for the first row of blastholes, they were simultaneously initiated so that a swelling space was created for the subsequent row [6]. After creating this space, the blastholes in the following rows were fired sequentially.

3. Model Blasts

As mentioned previously, the aim of the model blasts was to modify the preliminary specific charge to determine its final value for practical boulder blasting in TBM tunnelling. In what follows, the parameters relevant to the model blasts are described and the results of the model blasts are presented.

3.1. Similarity Criteria

The similarity criteria for boulder blasting were established by the $\pi$ theorem and dimensional analysis, considering the material similarity, geometric, and dynamic similarities. Two parameters affecting the specific charge are the overburden depth and fragment size, and both are considered in the model blasts. The values and dimensions of the main variables influencing the specific charge in the model blasts are listed in Table 1 and Equation (4).

$$Q = f(V_e, \rho_e, r, l_e, \rho_b, V_p, \sigma_b, l_b, D, H, \rho_{(0)}, v_0) \quad (4)$$
where $Q$ is a dependent parameter and all others are independent. Here, $V_e$, $\rho_e$, and $r$ are the fundamental parameters. According to the $\pi$ theorem and dimensional analysis, the similarity criterion can be obtained by assigning a value of 1 to $\pi_1$ to $\pi_8$ in Equation (5).

\[
\begin{align*}
\pi_1 &= r/l_e \\
\pi_2 &= r/l_h \\
\pi_3 &= r/D \\
\pi_4 &= l_h/H \\
\pi_5 &= \sigma_b/\rho_e V_e^2 \\
\pi_6 &= \rho_b V_e/\rho_b V_p \\
\pi_7 &= \rho_b V_p/\rho_0 v_0 \\
\pi_8 &= Q/\rho_e r^3 \\
\end{align*}
\]

Table 1. Values and dimensions of the selected physical variables.

<table>
<thead>
<tr>
<th>Number</th>
<th>Parameter</th>
<th>Name</th>
<th>Unit</th>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q</td>
<td>Weight of explosive</td>
<td>kg</td>
<td>M</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>$V_e$</td>
<td>Detonation velocity of explosive</td>
<td>m/s</td>
<td>L T$^{-1}$</td>
<td>4000</td>
</tr>
<tr>
<td>3</td>
<td>$\rho_e$</td>
<td>Density of explosive</td>
<td>kg/m$^3$</td>
<td>ML$^{-3}$</td>
<td>1200</td>
</tr>
<tr>
<td>4</td>
<td>$r$</td>
<td>Charge radius</td>
<td>m</td>
<td>L</td>
<td>0.045</td>
</tr>
<tr>
<td>5</td>
<td>$l_e$</td>
<td>Charge length</td>
<td>m</td>
<td>L</td>
<td>0.90</td>
</tr>
<tr>
<td>6</td>
<td>$\rho_b$</td>
<td>Density of boulder</td>
<td>kg/m$^3$</td>
<td>ML$^{-3}$</td>
<td>2800</td>
</tr>
<tr>
<td>7</td>
<td>$V_p$</td>
<td>P-wave velocity of boulder</td>
<td>m/s</td>
<td>L T$^{-1}$</td>
<td>4000</td>
</tr>
<tr>
<td>8</td>
<td>$\sigma_b$</td>
<td>Strength of boulder</td>
<td>N/m$^2$</td>
<td>M/(LT$^2$)</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>9</td>
<td>$l_b$</td>
<td>Length of boulder</td>
<td>m</td>
<td>L</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>$D$</td>
<td>Average size of fragments after blast</td>
<td>m</td>
<td>L</td>
<td>0.30</td>
</tr>
<tr>
<td>11</td>
<td>$H$</td>
<td>Overburden of boulder</td>
<td>m</td>
<td>L</td>
<td>11–29</td>
</tr>
<tr>
<td>12</td>
<td>$\rho_0$</td>
<td>Density of overburden</td>
<td>kg/m$^3$</td>
<td>ML$^{-3}$</td>
<td>2600</td>
</tr>
<tr>
<td>13</td>
<td>$v_0$</td>
<td>P-wave velocity of overburden</td>
<td>m/s</td>
<td>L T$^{-1}$</td>
<td>2400</td>
</tr>
</tbody>
</table>

The similarity law shown in Equation (6) is composed of the parameters in Equation (5).

\[
f = (\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)
\]

3.2. Materials and Block Size

The sizes of the actual boulders in water-intake tunnels vary, and boulders with volumes of ~1 m$^3$ are common, so accordingly, dimensions of 1 $\times$ 1 $\times$ 1 m$^3$ were used for the modeled boulders. Thus, the blocks of the model blasts were 15 $\times$ 15 $\times$ 15 cm$^3$ according to the dimensional analysis described above. In other words, the ratio of block size to actual boulder size (the geometric similarity) was 1:7. The UCS, P-wave velocity, and density of the boulders were 100 MPa, 4000 m/s, and 2800 kg/m$^3$, respectively. The P-wave velocity of the overburden was 2600 m/s, and its density was 2400 kg/m$^3$. The velocity of detonation (VOD) and density of the No. 2 emulsion explosive were 4000 m/s and 1200 kg/m$^3$, respectively. The explosive charge radius was 45 mm and the charge length was 90 cm. The values of the parameters in Equation (5) can be determined by using the above data, and are as follows:

\[
\begin{align*}
\pi_1 &= 0.05 \\
\pi_2 &= 0.045 \\
\pi_3 &= 0.15 \\
\pi_4 &= 0.034 - 0.091 \\
\pi_5 &= 0.052 \\
\pi_6 &= 0.43 \\
\pi_7 &= 1.8 \\
\pi_8 &= 62.8
\end{align*}
\]
With these data, the parameters in the model blasts can also be calculated as:

\[
\begin{align*}
  r &= 0.68 \text{ cm} \\
  l_e &= 13.5 \text{ cm} \\
  \rho_c &= 1000 \text{ kg/m}^3 \\
  V_c &= 3200 \text{ m/s} \\
  \sigma_p &= 53.2 \text{ MPa} \\
  \rho_p &= 2200 \text{ kg/m}^3 \\
  V_p &= 3382 \text{ m/s} \\
  \rho_{30}v_0 &= 4.1 \times 10^6 \text{ kg/m}^2\text{s} \\
  D &= 4.5 \text{ cm}
\end{align*}
\]

(8)

The electric detonators had diameters of 6 mm, explosive weights of 0.7 g, and were 7 cm long.

The parameters of materials in the model can be determined according to the calculated results in Equation (8). The explosive was a No. 2 emulsion with a VOD of 3100–3300 m/s, and a density of 1000–1100 kg/m³. The overburden material was sand with a density of 1550–1650 kg/m³ and a P-wave velocity of 2500–2600 m/s. The blocks were made of C50 concrete with a density of 2200–2300 kg/m³, P-wave velocity 3300–3500 m/s, and UCS 52–55 MPa. The proportion of the C50 concrete block is listed in Table 2, and the field test pictures are shown in Figure 4.

Table 2. Composition of the block per cubic meter (kg).

<table>
<thead>
<tr>
<th>Cement</th>
<th>Sand</th>
<th>Gravel (5–10 mm)</th>
<th>Gravel (10–20 mm)</th>
<th>Fly Ash</th>
<th>Polycarboxylate Superplasticizer</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>376</td>
<td>659</td>
<td>468</td>
<td>703</td>
<td>94</td>
<td>4.7</td>
<td>145</td>
</tr>
</tbody>
</table>

Figure 4. Photographs of the C50 concrete blocks. (a) Determining the weight of blocks; (b) measuring the P-wave velocity of blocks; (c) measuring the UCS of blocks.

3.3. Implementation of Model Blasts

A total of six overburden depths (0, 0.3, 0.5, 0.7, 1.0, and 1.5 m) were used with a total of 35 blocks, with respective overburdens of three, seven, six, seven, six, and six blocks. The model blasts were carried out with the following steps. First, the explosive was loaded into an individual block that was buried by a specific overburden of a depth above-mentioned. Then, the explosive was fired, and the fragments were subsequently collected. Figure 5 shows the different stages in the process of a model blast.
3.4. Model Blast Results

3.4.1. Blast Craters at Different Overburden Depths

The results of the model blasts were dependent on the overburden depth, as shown in Figure 6. A blast crater appeared only with zero (Figure 6a) or 0.3 m (Figure 6b) overburden. In the former, the crater diameter was ~1.1 m, and fragments were thrown from the crater; in the latter, the crater diameter was ~0.3 m. With an overburden of 0.5 m (Figure 6c), no crater appeared, but a circular crack of diameter ~0.45 m was created on the surface. In addition to the crack, below the surface, a cavity surrounding the block was found when the overburden was removed. In other words, neither fragments nor a crater were found on the surface when the overburden was 0.5 m (see Figure 6d). When the overburden was over 0.5 m, only a cavity surrounding the block remained.

Figure 5. Photographs from the model blasts. (a) Explosive charged into a block; (b) block to be covered by a specific overburden; (c) blasting completed with 0.3 m overburden; (d) fragments collected after blasting.

Figure 6. Photographs from the model blasts. (a) Blast crater with zero overburden; (b) blast crater with 0.3 m overburden; (c) cracks on the surface with 0.5 m overburden; (d) cavity with 0.5 m overburden. (The red lines in (c) represent cracks after blasting.)
3.4.2. Fragmentation of Model Blasts

The results from the model blasts indicate that the average fragment size of a block decreases with an increasing specific charge at each overburden depth, as shown in Figure 7. In the figure, the specific charge was calculated by the charge weight and the volume of the block, and the average fragment size of a block was determined by sieving the fragments.

![Figure 7](image_url)

**Figure 7.** Relation between the specific charge and average fragment size from each block.

Of the 35 blocks, only 32 were reported because of a significant difference between the initial weights and the weights of all collected fragments in three blocks when the overburden depth was 1.5 m. The size distribution from the collected fragments is shown in Figure 8, indicating that a higher specific charge produces a smaller fragment size (better fragmentation) than a lower value at all overburdens tested.

![Figure 8](image_url)

**Figure 8.** Relation between the mass passing and fragment sizes at different overburdens and specific charges.
3.4.3. Relation between the Specific Charge and Overburden Depth

As previously mentioned, the maximum average size of fragments after boulder blasting should be less or equal to 30 cm in the TBM tunnelling, and the corresponding average fragment size in the model blasts should be 4.5 cm, as determined by Equation (8). Thus, in this study, fragments at or close to 4.5 cm at each overburden depth were defined as the optimum average fragment size, and the corresponding specific charge was defined as the optimum specific charge. The optimum specific charge corresponding to each overburden depth is shown in Figure 9, and the fitting equation is expressed as Equation (9).

\[ q = 1.7368h + 3.3855 \]  

(9)

where \( q \) is the optimum specific charge in kg/m\(^3\) and \( h \) is the overburden depth in m.

![Figure 9. Relation between the optimum specific charge and overburden depth.](image)

Equation (9) indicates that as the overburden decreased to zero, explosive energy was required to primarily break the boulder. As the overburden increased from zero, a portion of the explosion energy broke the boulder, and another portion overcame the overburden. This is because the high ground stress caused by the overburden can affect the propagation of blasting-induced cracks \[30\] and must be considered in the blast design \[31\]. Therefore, the higher the overburden, the greater the specific charge required.

3.4.4. Relation between the Specific Charge and Size of Fragments

The optimum specific charge is 3.26 kg/m\(^3\) with an overburden of zero in the model blasts, according to Figure 10, which is six times greater than that used in open pit mines \[29\]. The model blasts show that the relation between the optimum specific charge and average fragment size is not linear with respect to the overburden depth (Figure 10).

![Figure 10. Relation between the average fragment size and optimum specific charge.](image)
Figure 10 also indicates that when the overburden depth increases from zero to 0.3 m, the average fragment size increases, even when the specific charge increases. This is because the confining pressure induced by the increasing overburden strengthens the block, and more explosive energy is needed to blast the block than that required to blast one with zero overburden.

The average fragment size decreased linearly with an increase in specific charge when the overburden depth increased from 0.3 m to 1.0 m, which means that a little more explosive can be used to overcome the increasing overburden as it is not large.

However, when the overburden depth is over 1.0 m, the average fragment size increases, even when the specific charge increases. Thus, the normal addition of explosive cannot lead to a satisfactory result, and much more explosive must be supplied in order to sufficiently fracture a block.

3.4.5. Fragment Size

Figure 8 indicates that mass passing (the number of fragments that can pass through a series of sieves) decreases with an increasing overburden for a constant specific charge. For example, for a 23-mm sieve, 35.2%, 34.1%, 31.1%, and 26.8% of mass was passed for overburdens of 0.3, 0.5, 0.7, and 1.0 m, respectively, at a specific charge of 3.26 kg/m$^3$.

However, mass passing increases with increasing specific charge at a constant overburden. For example, with an overburden of 0.5 m and a 34-mm sieve, 86.4%, 93.9%, 93.3%, 94.8%, and 95.5% of mass was passed, corresponding to specific charges of 3.26, 3.85, 4.44, 5.04, and 5.63 kg/m$^3$, respectively. In brief, the fragment size is affected by the specific charge at a given overburden.

4. Determination of Specific Charge and Application to Boulder Blasting in Tunnelling

4.1. Effect of Confining Pressure on Boulder Blast Plan

With increasing confinement pressure, compressive rock strength [32,33] and fracture toughness [34–38] increase, as described in Equation (10) from Zhang [6].

$$\sigma_c = ap_c + b$$

(10)

where $pc$ is the confinement pressure and $a$ and $b$ are constants. Strain rates $\dot{\varepsilon} = 650–1090$ s$^{-1}$ correspond to dynamic loads of $a = 1.7$ and $b = 109$ [25]. A simple analysis of the influence of the confining pressure on model blasts revealed that when the overburden is increased from 0 to 1.0 m, the increment in compressive strength of the block is equal to 0.027 MPa, corresponding to a density of overburden of 1600 kg/m$^3$ and a confining pressure of 0.016 MPa. Increased rock strength makes it more difficult to fracture rock if more energy is not supplied.

4.2. Determination of Specific Charge

According to the ratio of geometric similarity 1:7 and Equation (9), the overburden depths in practical boulder blasting are 0, 2.1, 3.5, 4.9, 7.0, and 10.5 m, corresponding to 0, 0.3, 0.5, 0.7, 1.0, and 1.5 m for the model blasts, respectively. Their respective optimum specific charges are 3.26, 3.85, 4.44, 4.74, 5.04, and 5.93 kg/m$^3$ for practical boulder blasting.

As discussed in Section 3.4.4 and Figure 10, the relations between the optimum specific charge and overburden depth differ for different overburden depths. Therefore, the overburden depths in practical boulder blasting can be divided into three groups: 0–2.1 m, 2.1–7.0 m, and over 7.0 m. The corresponding relations between the optimum specific charge and overburden depth can be described by

$$\begin{cases} q = 0.28h + 3.26 & (0 \leq h \leq 2.1 \text{ m}) \\ q = 0.23h + 3.49 & (2.1 \text{ m} < h \leq 7.0 \text{ m}) \\ q = 0.25h + 3.26 & (h > 7.0 \text{ m}) \end{cases}$$

(11)
These formulae can be used to determine the specific charge in practical boulder blasting. The calculated specific charge values from Equation (11) are much higher than the ones from the Swedish formula given in Equation (I), as indicated in Table 3. By using Equation (11), the explosive charge weight corresponding to each practical boulder can also be determined.

**Table 3. Specific charge values from the Swedish formula and Equation (11).**

<table>
<thead>
<tr>
<th>Overburden Depth (m)</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific charge of Swedish formula (kg/m³)</td>
<td>1.10</td>
<td>1.37</td>
<td>1.52</td>
<td>1.67</td>
<td>1.82</td>
<td>1.97</td>
</tr>
<tr>
<td>Specific charge of Equation (11) (kg/m³)</td>
<td>3.26</td>
<td>4.64</td>
<td>5.87</td>
<td>7.01</td>
<td>8.26</td>
<td>9.51</td>
</tr>
<tr>
<td>Ratio of results of Equation (11) to that of Swedish formula</td>
<td>2.96</td>
<td>3.39</td>
<td>3.86</td>
<td>4.20</td>
<td>4.54</td>
<td>4.83</td>
</tr>
</tbody>
</table>

4.3. Application to Boulder Blasting in TBM Tunnelling

The rock-mass block index (RBI) before and after blasting, TBM advance rate, TBM advance time, and TBM thrust were selected to evaluate the determined specific charge and the boulder blasting method in this study.

4.3.1. Results of Core Drilling

RBI is defined as the sum of the drill-core weight recovery ratios (recovered core length to drilled length) at different lengths. This index reflects the properties and structure of the rock mass, and can be determined by [39].

\[
RBI = 3C_{r3} + 10C_{r10} + 30C_{r30} + 50C_{r50} + 100C_{r100} \quad (12)
\]

where

- \(C_{r3}\) is the recovery ratio at core-drilling length 3–10 cm;
- \(C_{r10}\) is the recovery ratio at core-drill length 10–30 cm;
- \(C_{r30}\) is the recovery ratio at core-drill length 30–50 cm;
- \(C_{r50}\) is the recovery ratio at core-drill length 50–100 cm;
- \(C_{r100}\) is the recovery ratio at core-drill length over 100 cm.

The quantity and positions of the core-drilling holes before and after blasting were decided by the boulder size, as shown in Figure 11. There were at least two core-drilling holes before and two holes after blasting.

![Figure 11. Core drilling before and after blasting (a > 1/3 W; b > 1/3 lb).](image)

In the diagram, W is the boulder width, \(a\) is the width between the core-drilling holes before and after blasting, and \(b\) is the height between the core-drilling holes before and after blasting.

The rock cores obtained before and after blasting are shown in Figure 12. The RBI before blasting and after blasting are indicated in Figure 13.
Based on Figures 12a and 13, the rock cores remained intact and most RBIs exceeded ten before blasting, but the rock cores were broken with all RBIs < 5 after blasting. In addition, most fracture surfaces of the rock cores were fresh, indicating that the fracture surfaces were created by blasting (Figure 12b).

4.3.2. Analysis of TBM Tunnelling Parameters

Three TBM parameters, the advance rate, advance time, and thrust (see Figure 14), were compared in the section where boulders were not found and in the section where the boulders were preconditioned by ground-based blasting. The ordinary section was from K0 + 360 to K0 + 406, corresponding to 139–170 segment rings, and the section with boulders was from K0 + 310 to K0 + 360, corresponding to 106–138 segment rings.

Figure 12. Results of core drilling. (a) Rock cores before blasting; (b) rock cores after blasting; (c) fracture surface of rock cores after blasting.

![Figure 12. Results of core drilling.](image)

Figure 13. RBI before and after blasting.

![Figure 13. RBI before and after blasting.](image)
Figure 14. Comparison of TBM parameters from the ordinary section (blue color) and from the preconditioned section (red color). (a) Advance rate; (b) advance time; (c) thrust. Dashed and solid horizontal lines denote the average TBM parameter in the ordinary and preconditioned sections, respectively. The numerals are the corresponding values.

In Figure 14, the average advance rate in the ordinary section was 15.5 mm/min, while that in the preconditioned section was 13.8 mm/min. The main reason for the difference in the rate is that the advance rate was reduced artificially due to safety concerns. The average advance time in the ordinary section was 121 min/segment ring, and 108 min/segment ring in the preconditioned section. The average thrust was 18,739 kN in the ordinary section, and 18,035 kN in the preconditioned section. There was no marked difference in the values of the three parameters between the ordinary and preconditioned sections, meaning that preconditioning was successful, and the preconditioned section could be excavated as an ordinary section.
5. Conclusions

In order to accurately determine the specific charge in boulder blasting, blasting model tests were designed and implemented. Relationships between the specific charge, overburden depth, and fragment size were discussed, and some valuable results were obtained as follows:

1. Model blasting is effective for determining the optimum specific charge in ground-based boulder blasting.
2. The optimum specific charge determined in this study was 3.26 kg/m$^3$ with zero overburden, which was five times greater than the specific charge in bench blasting. As the overburden increased, the corresponding optimum specific charge increased.
3. The fragment size was influenced by both the specific charge and overburden depth.
4. The modified specific charge was three times greater than the specific charge given by the Swedish empirical formula. This corrected specific charge has been proven to be reliable in practical boulder blasting, and can be used by other similar projects.

Although the results in this paper are meaningful, they were obtained based on the strength of the boulder being 100 MPa, the average fragment size was 30 cm, and the overburden depth was between 0 to ~10.5 m. Therefore, the results can be referenced by other similar TBM projects. If the construction conditions are different, for example, the strength of the boulder is not 100 MPa, the average fragment size is not 30 cm, and the overburden depth is more than 10.5 m, the results in this paper cannot be referenced directly. However, the method in this paper can be referenced.

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