Article

Development of an automated design program for tunnel blasting

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In this study, a computer program to design a tunnel-blasting pattern was developed. The program consists of two parts; one is for the tunnel blasting design and the other is for the blasting modeling to estimate the peak particle velocity, the excavation damage zone and the fragmentation distribution. The design method of tunnel blasting pattern suggested by Langefors[1] was modified to produce the model. In addition the correlation between the rock mass rating, i.e., the RMR, and the rock constant in blasting, *c*, was analyzed based on the data collected from 23 tunnel blasting tests. The correlation between them was good enough to be applied in cut design. Furthermore, the developed program is capable of estimating the particle velocity by using (1) the existing vibration equations and (2) the vibration equation obtained by test blasting to examine the practical applicability of the designed blasting pattern.

1. Introduction

The design of a blasting pattern is important for determining the blasting efficiency, tunnel wall damage, the vibration and the noise level caused by the blast. The allowable peak particle velocity with respect to any adjacent structures and the powder factor depend on the optimum pattern selection. However, in Korean tunnel construction sites, blasting operations have been performed on the basis of the experience of blasting engineers. Therefore, there may be some differences between the designed pattern and the real drilling pattern.

In order to eliminate this difference and standardize a tunnel blasting pattern, the development of an automated design program for tunnel blasting is. In Korea, an automated design program for tunnel blasting was developed by Choi[2], based on the method suggested by Langefors[1]. The program was modified by Kim[3], based on the results of several test blasts. However, the program had a disadvantage in that the geological conditions were inadequately considered due to a lack of the test blasts. As a complementary measure of this disadvantage, the correlation between the RMR and the rock constant (*c*) was investigated using the results of many tunnel blasts. Moreover, the formulae for the tunnel blast design suggested by Langefors[1] (abbreviated as Langefors' formulae, hereafter) was modified based on the correlation and the results of the test tunnel blasts. The automated design program for tunnel blasting was developed with the modified formulae.

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2. Designing method of tunnel blasting

2.1. Conventional designing method of tunnel blasting

Among the various practical design methods of the tunnel blasting pattern, the Swedish method suggested by Langefors[1] has been most widely accepted. It considers the influence of the rock on blasting represented by a 'rock constant', designated *c*, representing the base charge concentration required for a satisfactory blasting performance. The formulae are provided to describe how the powder factor and the other blast design parameters should be varied for a particular blasting geometry. The following are the controlling parameters used in the Swedish method.

- Rock constant
- Drill hole diameter, Look-out, Drilled depth
- Empty drill hole diameter, Number of empty drill holes (if case of Burn-cut)
- Weight strength of explosive

The tunnel cross section is divided into 4 main parts (Fig. 1): Cut, Stoping, Lifter and Contour. The Cut section is classified into the Burn-Cut and the V-Cut.

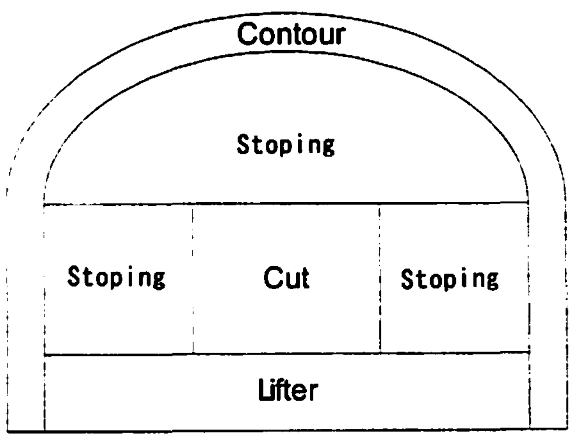


Fig. 1 Classification of tunnel cross section by blasting conditions.

The essential design parameters for tunnel blasting include the burden, spacing and the explosive charge. They differ in both different rock mass and blasting conditions. Therefore, a different section will have different design parameters on the basis of the calculation results obtained from the Swedish method. However this calculating method was obtained from the tests conducted on the stiff rocks in Scandinavia. Therefore, specific field trials are recommended in order to optimize a blasting design for rock that differs either in the strength or structural characteristics from the Scandinavian granites in reference.

2.2. Modified designing method of tunnel blasting

2.2.1. Determination of rock constant(c)

The rock constant, c, is an empirical measure of the quantity of explosive required to loosen 1 m^3 of rock. When blasting in different Swedish rocks, it has been found that the value for c lies in the vicinity of 0.4 kgm^{-3}. The c-value can be determined by trial blasting in a vertical drill hole with a hole diameter of approximately 32 mm. The vertical bench will be approximately 0.5 to 1 m high. The drill hole will have a depth of 1.3B, and the burden will be equal to the bench height. The c-value is obtained by multiplying the amount of explosive used per cubic meter of rock by a factor of 1.2, which was obtained by trial and error and from practical experience. Blasting in brittle crystalline granite gave a c-value equal to 0.2 kgm^{-3}. Blasting in rock with a strata perpendicular to the blast direction occasionally gave a c-value ranging from 0.5 to 1.0 kgm^{-3}. In practice, all other normal fissured rock materials, from sandstone to granite, can be described by a c-value of approximately 0.4 kgm^{-3} [1].

However it was difficult to obtain c-values by trial blasting in the field under tunnel construction. Therefore, in order to obtain the c-values easily, this study analyzed the correlation between the c-values and the RMR that is generally used as a criterion of rock classification for tunnel design in Korea. The c-values were estimated by substituting the blasting results into the Langefors' formulae. The estimation had an assumption that an advance rate of > 85 % is accompanied by an ideal charge condition in the tunnel blasting.

The data used for the linear regression analysis between the RMR and the rock constant(c), were collected at highway construction sites in Korea. Equation (1) shows the analysis result using 23

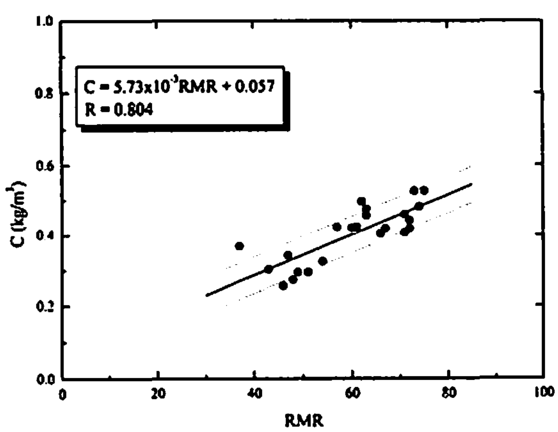


Fig. 2 Correlation between the rock constant(c) and the RMR values.

data sets and the correlation coefficient was 0.804 (Fig. 2).

$$c = 5.73\times10^{-3}RMR + 0.057 \qquad (1)$$

2.2.2. Modification of design formulae for cut section

The Langefors' formulae were modified to consider both the geological and explosives conditions. Kim[5] presented modified formulae to determine the blasthole location (spacing and burden) and the charge weights per blasthole for the cut, the stoping, the lifter and the contour sections that is shown in Fig. 1. However, the modified formulae for the cut (i.e., Burn-cut and V-cut) section design, are only mentioned in this study.

(1) Burn-cut

The cut section designed by the Langefors' formulae had problems that a size of the cut section was designed largely in the given rock constant, shown as Fig. 3(a), and the rock mass conditions was not adequately reflected. To correct the problems, the formulae for the cut design were modified, based upon the results of tunnel blastings. The modified formulae are as follows:

1st quadrangle : $B_1 = 1.5\phi\dfrac{0.35}{c}$ (2)

Linear charge concentration: $l = 240\dfrac{d\cdot\phi\cdot c}{S_{ANFO}}$ (3)

2nd and 3rd quadrangle : $B_n = 1.02\sqrt{A'_{n-1}\cdot\phi}$ (4)

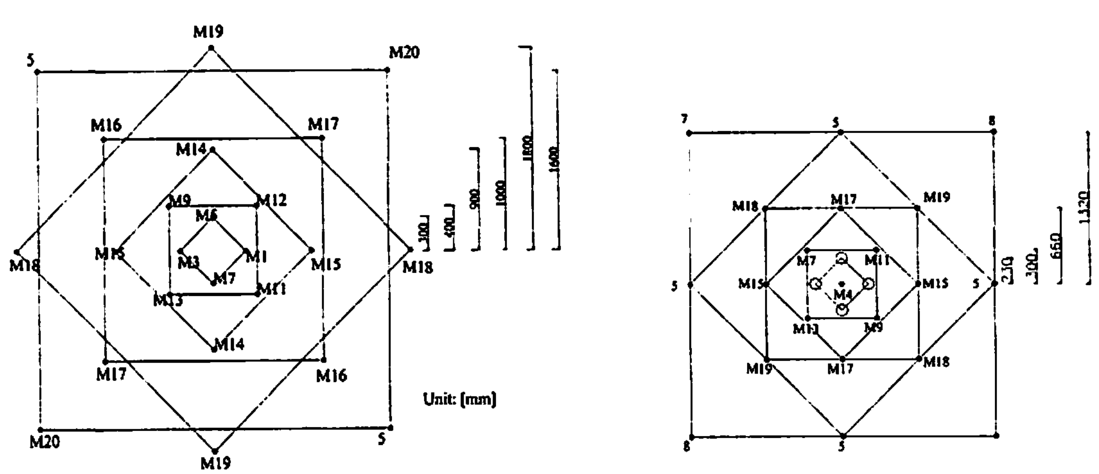
4th quadrangle and over : $A_n = 2\cdot a_{n-1}$ (5)

where ϕ is the diameter of the empty drill hole (in meters), a is the distance between a blasthole and a center of the cut section (in meters), d is the diameter of blastholes (in meters), l is the linear charge concentration (in kgm^{-1}), S_{ANFO} is the weight strength relative to ANFO, and B_n and A_n are the burden and the side length of n^{th} quadrangle (in meters), respectively.

In the original Langefors' formulae, a burden of the 1st quadrangle is only determined by the diameter of the empty drill hole. However, in a practical tunnel blasting operation, the burden is determined according to the rock mass conditions. Therefore the original formula was modified according to equation (2), i.e., the modified formula reflected the rock mass conditions. Furthermore, in the case of using the original formulae, the 5th and 6th quadrangles occupy a domain of the inner quadrangle, as shown in Fig. 3(a). Therefore the explosive energy is not used effectively. Consequently, the modified formula (equation (5)) determines the burden of the quadrangle more than 5th geometrically (Fig. 3(b)) to consume the explosive energy efficiently.

(2) V-cut

The tunnel design that uses the Langefors'



(a) (b)

Fig. 3 Comparison of cut design (H=4.5m, c=0.46kgm^{-3}).
(a) Cut designed by Langefors' formulae. (b) Cut designed by modified formulae.

formulae increases both the burden and the charge weight per blasthole. As a result, the formulae are inappropriate for a tunnel construction site. Modification of the V-cut design formulae focuses on a correcting this.

In the original Langefors' formulae, the burden is a linear function of a drill hole diameter. The cut design method does not reflect the rock mass conditions and whenever the hole diameters are equal, the burden of the cut always has an equal value regardless of the rock mass conditions. To correct this, the optimum burden of the cut is calculated by equation (6).

$$B = 21.5d \times \frac{0.35}{c} \tag{6}$$

The modified formula reflects the rock mass conditions by setting the rock constant on the basis of 0.35 kgm^{-3} similar to the Burn-cut. In addition, the constant, 21.5, was determined from the collected data at the highway construction sites.

The original formula for determining the linear charge concentration q (in kgm^{-1}) does not reflect the rock mass conditions sufficiently, in the same way as the original formulae for the burden of cut. Therefore the original formula was modified (equation (7)).

$$q = 1000\frac{c \cdot d^2}{S_{ANFO}} \tag{7}$$

The linear charge concentration in the column should be equal to the charge concentration for the bottom charge.

Therefore the linear charge concentration (q) increases, as the rock mass conditions improve and the hole diameter increases, and decreases with increasing the relative strength of the explosive.

2.3. Assessment of the modified design formulae

In order to validate the modified methods and their practical applicability, test blastings were carried out at two different tunnel construction sites in Korea. At a crude oil storage cavern construction site, the modified design method using a Burn-cut was checked. The RMR values were 45 (for STA.0+408.4), 66 (for STA0+20.5) and 71 (for STA.0+23.3). Table 1 shows the blasting results at the test site. In the other site, a highway construction site, the modified design method using a V-cut was examined. The RMR values were 58 (for STA.2+215.0), 59 (for STA.2+221.5), 54 (for STA.2+432.5) and 52 (for STA.2+436.0). Table 2 shows the results of the tunnel test blasting using a V-cut.

In Table 1 and 2, the results were satisfactory in that the average advance rate was 90 % and the overbreak did not cause additional support.

Table 1 Blasting results at the pipe tunnel and the water curtain tunnel (Burn-cut).

	Number of blastholes (Empty holes)	Used charge weight (kg)	Drilling length (m)	Advance (m)	Advance rate (%)	Specific charge (kgm^{-3})
STA.0+408.4	108 (2)	189.5	3.40	2.80	82.4	1.128
STA.0+ 20.5	79 (2)	138.0	3.40	3.15	92.6	1.604
STA.0+ 23.3	88 (2)	169.0	3.40	3.22	94.7	1.921

Table 2 Blasting results at the highway tunnel (V-cut).

	Number of blastholes	Used charge weight (kg)	Drilling length (m)	Advance (m)	Advance rate (%)	Specific charge (kgm^{-3})
STA.2+215.0	120	260.9	3.7	3.30	89.0	0.820
STA.2+221.5	117	257.7	3.5	3.04	86.9	0.879
STA.2+432.5	130	280.0	3.8	3.51	92.4	0.828
STA.2+436.0	115	245.0	3.3	3.08	93.3	0.825

3. Automated design program for tunnel blasting

In this study, a computer program to design a tunnel blasting pattern was developed. The developed program consisted of two parts; one was the 'Pattern Design for Tunnel' part and the other was the 'Blasting Results Prediction' part to estimate the particle velocity, the excavation damage zone and the rock fragmentation by blasting.

3.1. Pattern design for tunnel

The developed program was adopted the modified formulae (equation (2)~(7)) for the cut section and the modified formulae that were studied by Kim[5] for the stoping, the lifter and the contour sections. The program has many features, which are as follows:

- An ability to design a blasting pattern for various tunnel types (Fig. 4)
- An ability to design two types of cut, i.e., Burn-Cut and V-Cut
- An automatic determination of the ignition sequence and alignment of the detonator and explosive
- An ability to design a sequential blasting to use non-electronic detonators (Fig. 5)

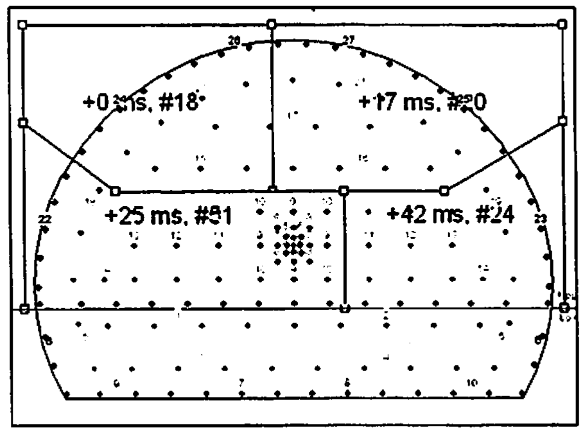


Fig. 5 Blast pattern for the sequential blasting.

- A function to modify the information of a blasthole (i.e., location, charge weight and delay timing)
- A function to modify the burden and spacing of overall blastholes

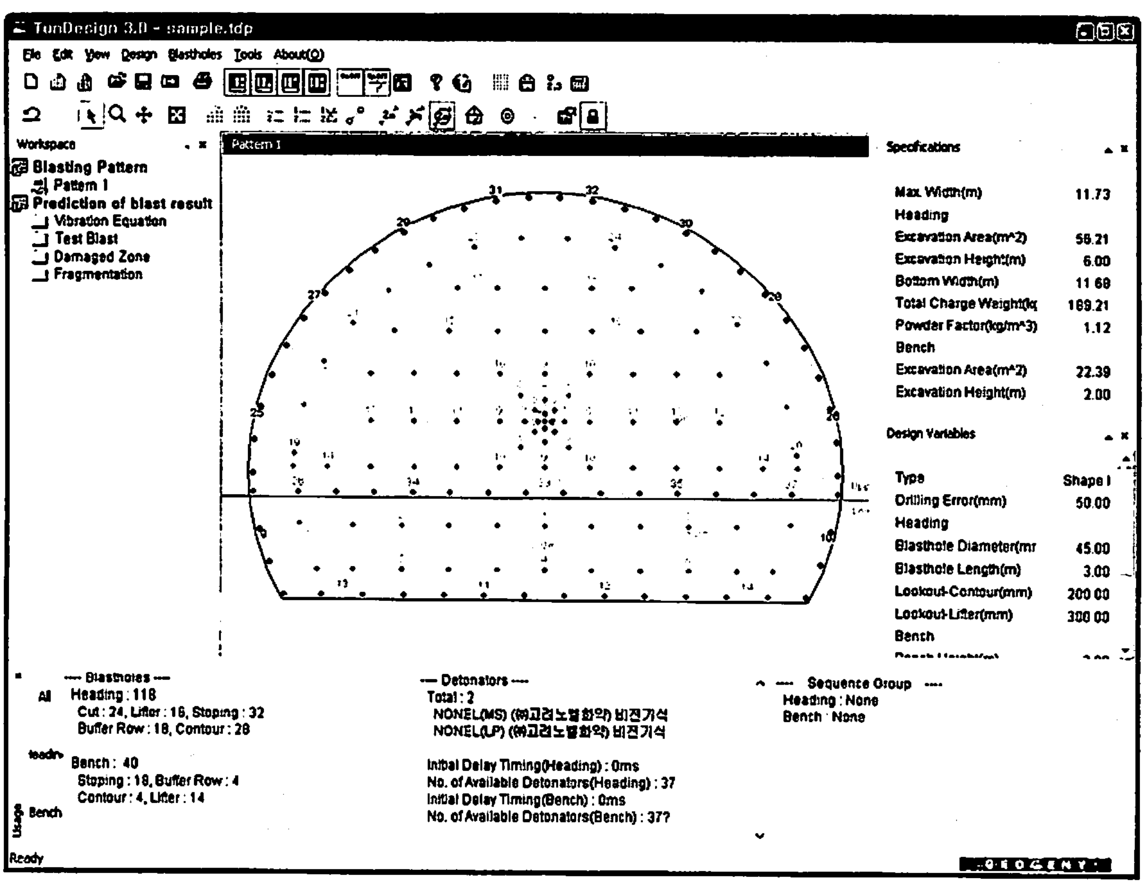


Fig. 4 Designed pattern by the developed program for tunnel blasting.

- A visual examination of the ignition sequence and delay timing
- A visualization to identify the quantity of detonators and explosives
- An ability to insert the dimensions easily and export the dimensions to a file.

3.2. Blasting results prediction

'Blasting Results Prediction' part of this program predicts the results of the tunnel blasting that was carried out according to the designed pattern. To confirm the designed pattern, this part was based on previous studies. This program can predict the particle velocity, the excavation damage zone and the rock fragmentation.

3.3.1. Predicting the particle velocity for designed blasting pattern

In this program, vibration equations were used to predict the vibration velocity of tunnel blasting based on the designed pattern. The vibration velocity can be predicted by two methods; one is to use the existing blasting vibration equations and the other is to use the results of test blasting at the tunnel construction site. The latter can more accurately predict the particle velocity than the former. Figure 6 shows the analysis results of the vibration velocity calculated from test blastings at a construction site.

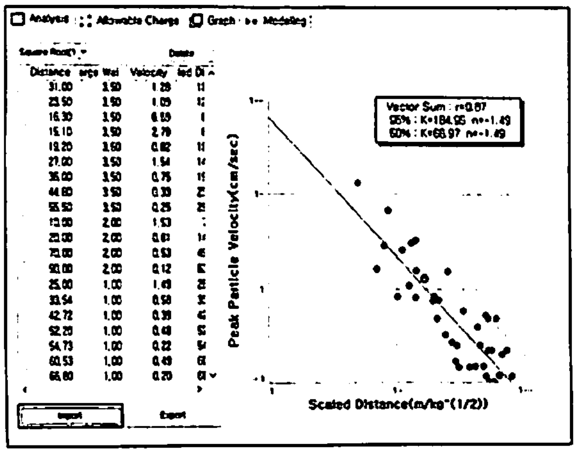


Fig. 6 Analysis result of vibration velocity by test blastings.

3.3.2. Predicting the excavation damage zone by tunnel blasting

This program adopted the strain damage model to predict the excavation damage zone. The most common outcome of the studies about the overbreak mechanisms is that the strain induced damage dominates. This may be true in very good quality rock masses but may not be as accurate as rock quality decreases. The model reported by Holmberg and Persson [6] was used to estimate the vibration velocity around a blasthole[7]. Figure 7 shows the output for predicting the excavation damage zone.

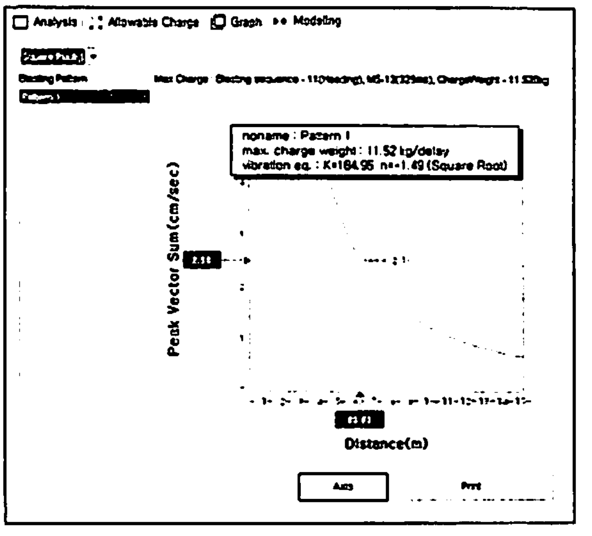


Fig. 7 Output of prediction results of the excavation damage zone.

3.3.3. Predicting the rock fragmentation by blasting

The Kuz-Ram model was adopted to predict the degree of fragmentation, which describes the size distribution of the blasted material. The model was

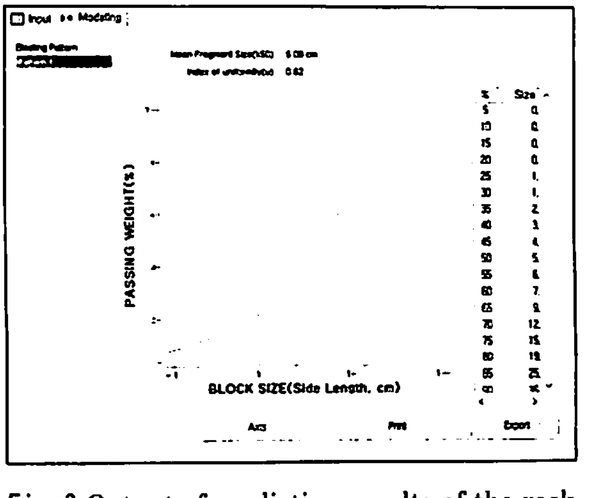


Fig. 8 Output of prediction results of the rock fragmentation by blasting.

developed by Cunningham[8], and was based upon the size distribution curve of Rosin-Rammler and the empirical equation of the average fragment size was obtained from the blast given by Kuznetsov[9]. Figure 8 shows the output for predicting the fragmentation distribution by blasting.

4. Conclusions

In this study, the design method suggested by Langefors was modified based on the blasting results at highway tunnels in Korea to represent the design parameters quantitatively. Several test blastings were carried out to test their practical applicability. In addition, the correlation between the rock constant and the RMR was analyzed in order to quantify the rock mass conditions. By adopting these methods, an automated design program for tunnel blasting was developed with capacity of predicting blasting results.

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