The Computerized Design Program for Tunnel Blasting

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Abstract

In this study, a computer program to design tunnel blasting pattern has been developed. The program consists of two parts; one is for tunnel blasting pattern design and the other is for blasting modeling to estimate the peak particle velocity, the distribution of fragmentation and the excavation damage zone.

We modified the design method of tunnel blasting pattern suggested by Langefors because it provided undesirable pattern in blasting practices such as considerably large center cut and too large burden for V-cut as drilling length increased. As a result, the burden and spacing were reduced to practically appropriate amounts. In addition, the correlation between rock mass rate, RMR, and rock constant in blasting, *c*, was analyzed based on the data collected from twenty three tests of tunnel blasting. It was concluded that the correlation between them was fairly good enough to be applied in cut design. In order to check the validity of the modified methods and their practical applicability, test blasting was carried out at two different tunnel construction sites in Korea. The results were satisfactory in that the average rate of advance was 90% and the overbreak did not cause additional support.

Futhermore, the developed program is capable of estimating peak particle velocity by using (a) the existing vibration equations, (b) the vibration equation obtained by test blasting to check out the practical applicability of the designed blasting pattern. Feedback is implemented into the program to adjust the designed blasting pattern and control the vibration.

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 a computerized design program for tunnel blasting has been carried out. In Korea, an automated design program for tunnel blasting was developed by Choi (1998), based on the method suggested by Langefors (Langefors and Kihlström, 1978). The program was modified by Kim (1999), 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 (abbreviated as Langefors' formulae, hereafter) was modified based on the correlation and the results of the test tunnel blasts. The computerized design program for tunnel blasting was developed with the modified formulae.

Conventional Designing Method of Tunnel Blasting

Among the various practical design methods of the tunnel blasting pattern, the Swedish method suggested by Langefors 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

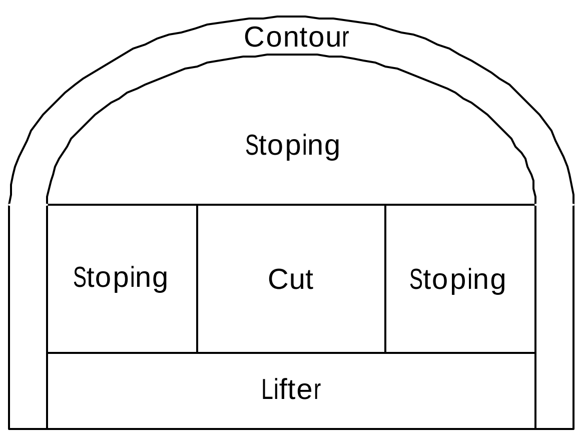


Figure 1: Classification of tunnel cross section by blasting conditions

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

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.

Modified Designing Method of Tunnel Blasting

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 kg/m^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 1.3*B*, 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 kg/m^3. Blasting in rock with a strata perpendicular to the blast direction occasionally gave a *c*-value ranging from 0.5 to 1.0 kg/m^3. In practice, all other normal fissured rock materials, from sandstone to granite, can be described by a *c*-value of approximately 0.4 kg/m^3 (Persson et al., 1994).

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

$$c = 5.73 \times 10^{-3} RMR + 0.057 \qquad (1)$$

Modification of Design Formulae for Cut Section

The Langefors' formulae were modified to consider both the geological and explosives conditions. Kim (2002) 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 Figure 1. However, the modified formulae for the cut (i.e., Burn-cut and V-cut) section design are only mentioned in this paper.

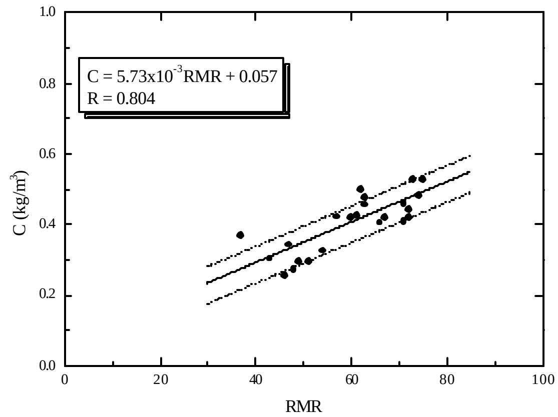
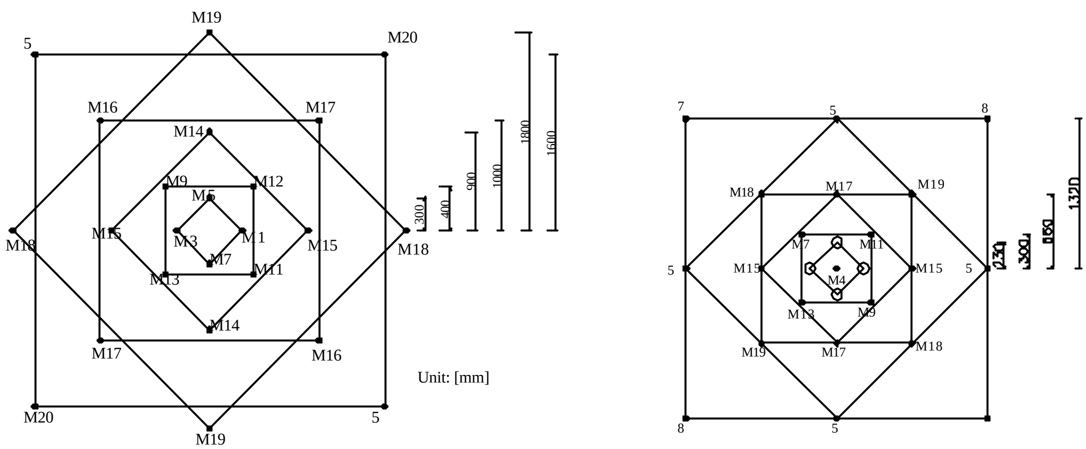


Figure 2: Correlation between the Rock Constant(c) and the RMR values



(a) Cut designed by Langefors' formulae (b) Cut designed by modified formulae

Figure 3: Comparison of cut design (H=4.5 m, c=0.46 kg/m^3)

Firstly, in case of the 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 Figure 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 : $B_1 = 1.5f\dfrac{0.35}{c}$ (2)

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

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

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

where f 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 kg/m), 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 1^{st} 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 5^{th} and 6^{th} 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 5^{th} geometrically (Figure 3(b)) to consume the explosive energy efficiently.

Secondly, the tunnel design that uses the Langefors' formulae for the V-cut 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 kg/m^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 kg/m) 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.

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 (kg/m^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 of the highway tunnel (V-cut)

	Number of blastholes	Used charge weight (kg)	Drilling length (m)	Advance (m)	Advance rate (%)	Specific charge (kg/m^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

Computerized Design Program for Tunnel Blasting

A computerized design program, TunDesing3 for tunnel blasting was developed and was introduced by Lee et al (2002). Especially, TunDesign was originally intended to produce blasting pattern designs automatically. But, through several upgrades, the program has been strengthened to enable the user to reflect his knowledge and experience in producing pattern designs. In this study, the updated version, TunDesign4 of the original program will be introduced. Like the TunDesign3, the updated program consists of two parts; one is the 'Pattern Design for Tunnel' part and the other is the 'Blasting Results Prediction' part to estimate the particle velocity, the excavation damage zone and the rock fragmentation by blasting.

Pattern Design for Tunnel

The developed program is adopted the modified formulae (equation (2)~(7)) for the cut section and the modified formulae that were studied by Kim (2002) for the stoping, the lifter and the contour sections. The program has many features including the features of the TunDesing3, which were introduced by Lee (2002). The additional features are as follows:

- Flexibility on Tunnel Shapes. TunDesign4 can design blasting patterns with various tunnel shapes created from not only existing templates but also AutoCAD drawings (Figure 4).

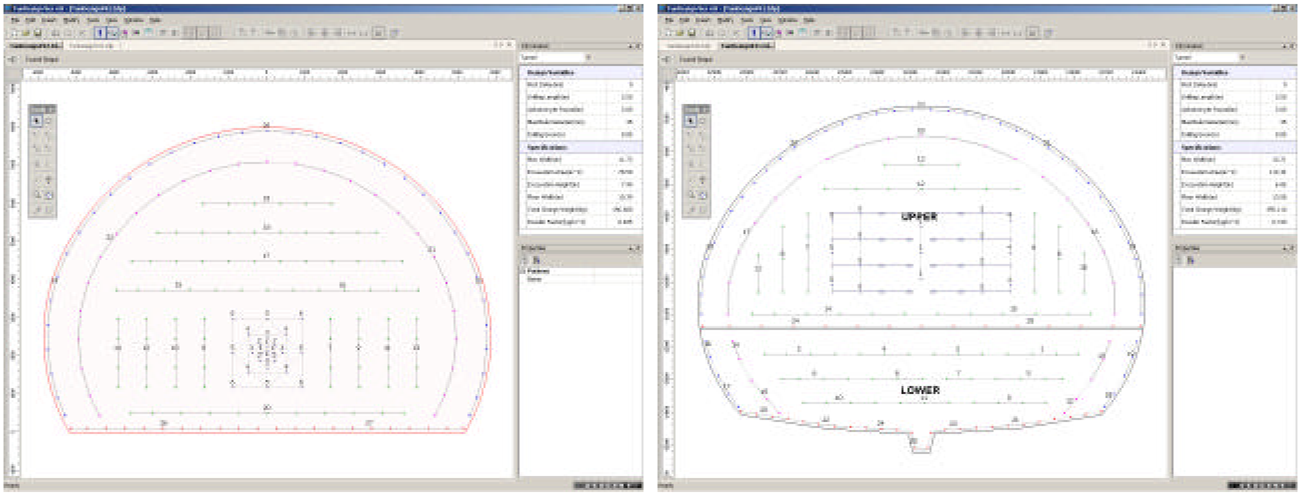


Figure 4: Designed pattern by the developed program for tunnel blasting

• Easily Build the Draft of Blasting Pattern. This program has a Pattern Generating Engine (PGE) and an Automated Alignment Engine (AAE). The TunDesign4 provides you a draft, which is almost completed, when you only input some parameters for the PGE. Moreover, the AAE of time sequence will lead you to easy and quick arrangement of detonators.

• Modifying Blasting Pattern. The TunDesign4 has a powerful editing function when you edit from the blasting patterns automatically created by the PGE or from the empty blasting patterns. You can edit the patterns easily and quickly by using an aligner, which can help you edit the blastholes. In addition, this program provides an intuitive interface so that you can arrange the detonator easily.

• Sequential Blasting. It is possible to carry out the sequential blasting when there are too many blastholes and insufficient detonators (Figure 5). If you divide sequential regions, this program will automatically rearrange the detonators. You can check over the arranged detonators with Sequence Simulation.

• Application of Various Cut. The program provides you various and automatically created cut, such as the cylinder-cut, the V-cut ad SUPEX-cut (Figure 6~8). Or you can make any shape of cut you want. Also you can import them from the other patterns.

• Application of Various Explosives. The TunDesign4 has a capacity of using the bulk explosives and the high-density charge of cartridge-type explosives.

• Verifying the Blasting Pattern. With the Sequence Simulation, you can check it visually whether the detonators are well arranged or not.

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 rock fragmentation and the excavation damage zone.

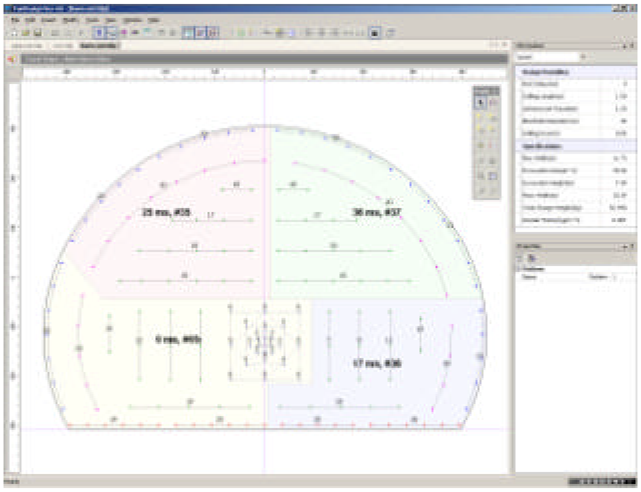


Figure 5: Blast pattern for the sequential blasting

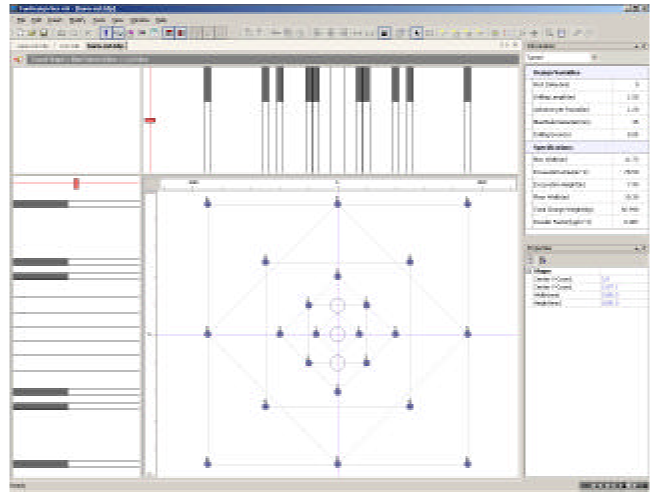


Figure 6: Blast pattern of the cut section using the cylinder-cut

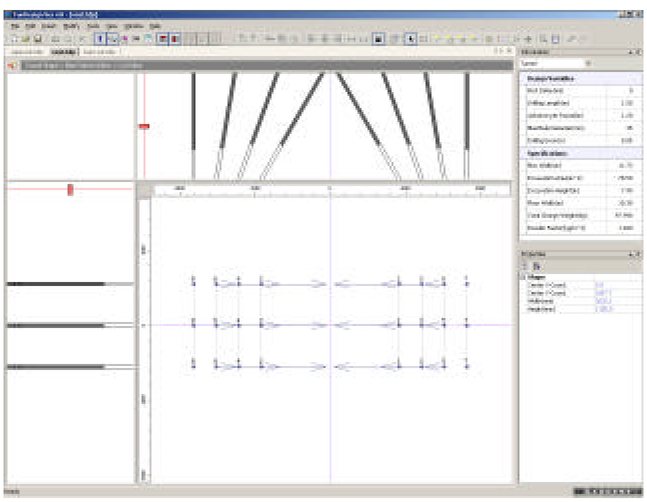


Figure 7: Blast pattern of the cut section using the V-cut

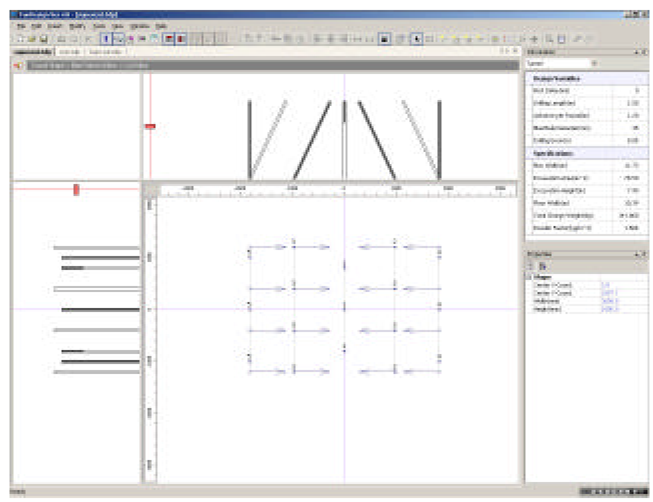


Figure 8: Blast pattern of the cut section using the SUPEX-cut

In this program, vibration equations are 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 9 shows the analysis results of the vibration velocity calculated from test blastings at a construction site.

The Kuz-Ram model is adopted to predict the degree of rock fragmentation by blasting, which describes the size distribution of the blasted material. The model was developed by Cunningham (1983), 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 (Jimeno et al., 1995). Figure 10 shows the output for predicting the fragmentation distribution by blasting.

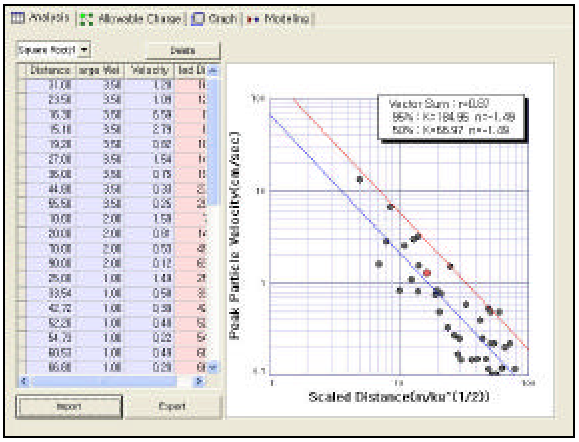


Figure 9: Analysis result of vibration velocity by test blastings

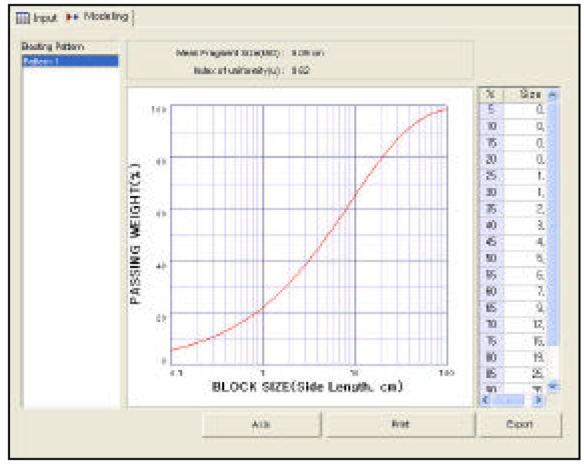


Figure 10: Output of prediction results of the rock fragmentation by blasting

This program adopts the strain damage model to predict the excavation damage zone by tunnel blasting. 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 (1979) was used to estimate the vibration velocity around a blasthole (Forsyth, 1993). Figure 11 shows the output for predicting the excavation damage zone.

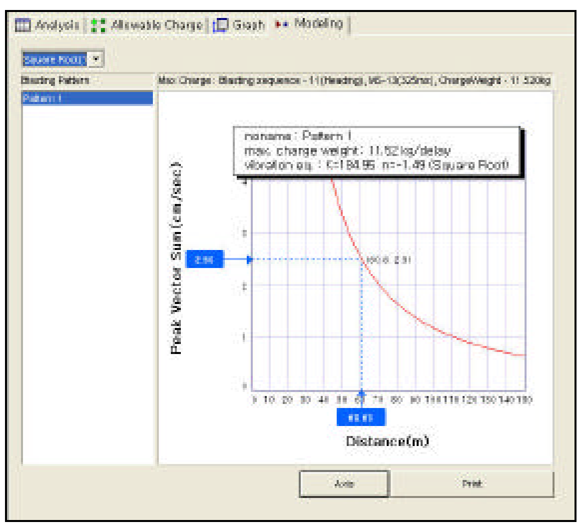


Figure 11: Output of prediction results of the excavation damage zone

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. 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, the computerized design program for tunnel blasting has been developed with capacity of predicting blasting results.

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