Comparison of tunnel blast design models

Shokrollah Zare *, Amund Bruland

Department of Civil and Transport Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Received 11 May 2005; received in revised form 2 September 2005; accepted 12 September 2005

Available online 2 November 2005

Abstract

Blast design has direct influence on the time consumption and construction cost of drill and blast tunnels. Two tunnel blast design models based on parallel hole cut, NTNU blast design model and Swedish blast design model, are discussed and evaluated in this article.

Both models suggest smooth blasting and in both models cut design depends on drill hole length and empty hole diameter. For lifter and stoping holes the Swedish model gives higher burden values, indicating a lower number of holes. Generally, The NTNU model gives longer uncharged length which indicates lower explosives consumption.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Tunnel blast design; Parallel hole cut; Drill and blast tunnelling; Drilling pattern; Charging

1. Introduction

Tunnel blasting is a much more complicated operation than bench blasting because the only free surface that initial breakage can take place toward is the tunnel face. Because of the high degree of constriction or fixation, larger charges will be required, leading to a considerably higher specific charge than in bench blasting (Persson et al., 2001).

The basic principles for the method of charge calculation are those developed by Langefors and Kihlstrom (1978), first time published in 1963.

The most important operation in the tunnel blasting procedure is to create an opening in the face in order to develop another free surface in the rock. This is the function of the cut holes.

Cuts can be classified in two groups:

- Parallel hole cuts.
- Angle hole cuts.

The first group is most used in operations with mechanised drilling, whereas those of the second have fallen in disuse due to the difficulty in drilling (Jimeno et al., 1995).

As to drilling, this has become more mechanised in the last decades, based on the development of hydraulic jumbos, with one or more booms, the trend has been toward parallel hole cuts as they are easier to drill, do not require a change in the feed angle and the advance is not as influenced by the width of the tunnel, as happens with angle cuts.

In current drill and blast tunnelling, bulk explosives, i.e., ANFO and emulsion are widely used in the blasting operation and cartridged explosives are less used.

The two blast design models to be investigated are the NTNU and Swedish models. The NTNU blast design model developed by the Department of Civil and Transport Engineering at NTNU (1975, 1995) is an empirical blast design model based on the parallel hole cut. The first version of the model was published in 1975. From the first publication, the model has been updated four times (1979, 1983, 1988 and 1995).

The Swedish model is also based on the parallel hole cut. The Swedish model started with Langefors and Kihlstrom (1963) and has been further developed afterwards. Holmberg published the complete blast design model in 1982.
(Holmberg, 1982) and recently updated by Persson et al. (2001).

2. NTNU model

The tunnel blast design model is described in the Project Report 2A-95 (NTNU, 1995). The tunnel face divides into cut, stoping (easers), lifters (invert), row nearest contour and contour. Smooth blasting with double contour blasting is recommended, i.e., the charging density in the contour and row near the contour is reduced. The design for each part depends on the following rock and geometry parameters, which should be evaluated and determined in advance:

- Rock mass blastability.
- Drill hole diameter.
- Drill hole length.
- Skill level of the tunnel crew.

2.1. Cut design

In the parallel hole cut used in the NTNU model, the blasting starts against an opening that is established by drilling one or more empty (large) holes. Three standard parallel hole cuts are shown in Fig. 1.

The empty hole cut presupposes that the rock, which is blasted at each detonation interval, must have space for expansion (at least 80%) to secure full throw out. This requires precise drilling and correct firing sequence.

The necessary area of empty holes is given in Fig. 2. The recommended distance between an empty hole and the first charged hole is shown in Table 1.

When placing the other cut holes, the burden is set in relation to the basic width for the established opening (Fig. 3). The basic width is the width of the existing opening perpendicular to the direction of blasting, \( W_1 \) or \( W_2 \) in Fig. 3, basic width for hole number one or two. The recommended burden in Fig. 3 must be checked for enough expansion space, especially for hole number two in the cut, where Fig. 3 may give too high value for burden.

For each detonation interval, one has to control that the existing opening gives space for necessary expansion of the rock that will be blasted. This must be done by detailed calculations for the first two detonation intervals; visual evaluation is enough for the remaining holes.

The cut is designed for an average pull of 90% of drill-hole length for 45 mm drillhole diameter and 96% for 64 mm drillhole diameter.

2.2. Drilling pattern

The drilling pattern for a specific tunnel depends on the following parameters:

- Drill hole diameter.
- Drill hole length.
- Rock mass blastability.
- Tunnel cross-section.
- Look-out angle.
- Skill level of the tunnel crew.

After the cut has been designed, the design of the drilling pattern should follow the sequence:

- Contour.
- Row nearest the contour.
- Lifters.
- Stoping.

For the contour, the row nearest the contour and the lifter holes there are guiding values for burden and spacing and there are also guiding stoping area values for stoping holes. Guiding values for burden, spacing and stoping area for 5 m drilled length are shown in Table 2.

For the contour the values are given as intervals. The lowest values are for 20 m² tunnels, the highest for 120 m² tunnels. For other cross-sections, the values may be interpolated.

The burden and spacing are given at the bottom of the round. At the face, eccentricity at the bottom of the holes (e.g., look-out angle) must be subtracted.

![Fig. 1. Large hole cut for 45 mm drill holes, numbers indicates millisecond detonators interval (NTNU, 1995).](image-url)
For drilled length different from the basis (5 m), the values must be corrected by a correction factor for drilled length ($K_{bl}$ in Figs. 4 and 5). For correction, the inverse of $K_{bl}$ should be multiplied with the area ($S \times B$).

2.3. Charging

Necessary consumption of explosives for cartridged and bulk explosives are given in guidance graphs for planned tunnel cross-section. See Figs. 4, and 5 for ANFO.

Tunnel rounds are usually charged with ANFO or emulsion, cartridged explosives may also be used; when water is a problem, ANFO can not be used efficiently. The contour is normally charged with special contour charges, e.g., tube charges or detonating cord. ANFO or emulsion may also be used in the contour and the row nearest contour when mechanised charging systems are used. The charging density in the contour with double contour blasting is 20–25% and in the row nearest the contour it is 40–60% of normal charging density. The double contour refers to the contour and the row nearest the contour.

Necessary charging depends on the following parameters:
- Drill hole diameter.
- Drill hole length.
- Rock mass blastability.
- Type of explosives (cartridge or ANFO/emulsion).
- Tunnel cross-section.
- Skill level of the tunnel crew.

![Fig. 2. Necessary empty hole area for parallel hole cut (NTNU, 1995).](image-url)
In the NTNU experience ANFO and emulsion explosives have approximately the same charging density.

Uncharged length (UL) is defined as a function of the drill hole length \( L \), uncharged length for the cut and lifter holes is \( UL = 0.1L \) and for other holes \( UL = 0.3L \).

### 2.4. Firing pattern

Firing pattern must be planned so that each hole or group of holes, gets as favourable confinement and throw conditions as possible. That is ensured by trying to establish a smaller version of the final cross-section shape around the cut, and then enlarging this shape. It is also essential to check that the rock blasted at every interval number has space for expansion.

The general sequence is cut, stoping, row nearest the contour, contour, lifter and finally corner holes of the lifter.

### 3. Swedish model

This chapter is generally based on (Persson et al., 2001) and (Holmberg, 1982) where further details may be found. The tunnel face is divided into five separate sections as shown in Fig. 6. Cut, two stoping sections, contour and lifters. Each will be treated separately during calculations. Four-section cut type is used as a parallel hole cut. Design calculation depends on the following parameters:

- Length of drillhole.
- Diameter of drillhole.
- Linear charge concentration.
- Maximum burden.
- Type of explosive.
- Fixation factor (Langefors and Kihlstrom, 1978).
3.1. Cut holes

The four-section cut is used as a dominant type of parallel hole cut (Fig. 7). Drillhole length depends on the empty hole diameter and there is a direct relation between the drillhole length and the empty hole diameter as shown in Fig. 8. The resulting advance per round (pull) is assumed to be 95%. In the case with two empty holes in the cut instead of one, the equivalent diameter must be used in the calculations.

The distance between the empty hole and the blastholes in the first quadrangle should not be more than 1.7 times the diameter of the empty hole to obtain breakage and a satisfactory movement of the rock. Breakage conditions differ very much depending upon the explosive type, structure of the rock and distance between the charge hole and the empty hole (Persson et al., 2001).

As shown in Fig. 9, for burden larger than $2\phi$, where $\phi$ is empty hole diameter, the break angle is too small and a plastic deformation of the rock between the two holes is produced. Even if the burden is less than $\phi$, but the charge concentration is high, a sintering of the fragmented rock and cut failure will occur. For this reason, the recommended burden is $B_1 = 1.5\phi$.

For the first quadrangle the recommended burden should be checked by the empirical equation (Persson et al., 2001, p. 221) and may be modified based on actual charge concentration or other parameters. In the equation, the burden depends on linear charge concentration, drillhole diameter, empty hole diameter, rock constant and type of explosive.

The four holes in the first quadrangle are placed with the same distance from the empty hole (Fig. 7). To calculate the rest of the quadrangles ($B_2$ to $B_4$), it is considered that a rectangular opening already exists (Fig. 10) and linear charge concentrations are known. The burden will be calculated by the equation (Persson et al., 2001, p. 222) where burden depends on rectangular opening, linear charge concentration, drillhole diameter, rock constant and explosive type.

For satisfactory breakage the calculated burden should fulfill two conditions:

- $B \leq 2A$ to prevent plastic deformation.
- $B > 0.5A$ to reduce aperture angle to less than $90^\circ$.

The uncharged length of the cut holes is equal to 10 times of the drillhole diameter.

3.2. Lifters and stoping holes

The burden for the lifters and stoping holes is in principle calculated with the same formula as for bench blasting.
The bench height is just exchanged for the advance, and a higher fixation factor is used due to the gravitational effect and to a greater time interval between the holes (Persson et al., 2001, p. 224).

The burden depends on the linear charge concentration, fixation factor, rock constant and explosive type. A condition that must be fulfilled is $B < 0.6H$ where $H$ is drillhole length.

The same fixation factor ($f = 1.45$) is used for lifters and stoping holes in section $B$ (breakage direction horizontally and upwards, Fig. 6). The fixation factor for stoping holes in section $C$ (breakage direction downwards, Fig. 6) is reduced to $f = 1.20$.

The spacing value of the lifter holes are equal to burden value ($S/B = 1$) and for both types of stoping holes the spacing is 1.25 times the burden values ($S/B = 1.25$).

Like the cut holes, the uncharged length of the lifter and stoping holes is 10 times the drillhole diameter. The linear
charge concentration in the column and the bottom charge (1.25B) may differ; the column charge can be reduced to 70% (of the bottom charge) for the lifter holes and 50% for the stoping holes. This is, however, not always common since it is time-consuming charging work. Usually the same concentration is used both in the bottom and in the column (Persson et al., 2001).

3.3. Contour holes

If smooth blasting were not to be used, the burden and spacing would be calculated according to stoping holes breaking downward. For smooth blasting, a spacing to burden ratio (S/B) of 0.8 should be used and the spacing between the contour holes is calculated from $S = kd$ where the constant $k$ is in the range of 15–16 and $d$ is the drillhole diameter.

The charge concentration is also a function of the drill-hole diameter $d$. For hole diameter up to 150 mm, the following equation is used:

\[
\text{Charge concentration} = 90d^2,
\]

where $d$ is expressed in metres and the charge concentration in kg/m. In smooth blasting the total hole length must be charged to avoid the collar being left unbroken.

4. Comparison of the models

4.1. Cut design

In both models parallel hole cut with empty hole(s) is used. The necessary empty hole area in the NTNU model depends on drill hole length, drill hole diameter and rock blastability (Fig. 2). In the Swedish model, the diameter of the empty hole only depends on drill hole length (Fig. 8). In both models drillhole length has direct relation to the diameter of empty or large hole(s) in the cut. For 5 m drilled length the NTNU model gives 165–270 cm² necessary area (depending on diameter and blastability) while the Swedish model gives 250 cm².

In the NTNU model the distance between an empty hole and the nearest charged hole (Table 1), depends on drill hole diameter and diameter of the empty hole. In the Swedish model this distance depends on the diameter of the empty hole (Fig. 9). NTNU model gives 1.5–2.5 times empty hole diameter depending on the diameter of the charged hole while the Swedish model gives 1.5 times the empty hole diameter.

Comparison of necessary empty hole area and distance between empty hole and the nearest charged hole shows that the NTNU model more precisely determines these values. The two models give values in the same range.

The design of the other cut holes in both models depends on dimension of existing opening, basic width in the NTNU model (Fig. 3) and opening width in the Swedish model (Fig. 10). Range of calculated burden in the Swedish model must be $0.5A < B < 2A$ while according Fig. 3, NTNU model suggests $0.5A < B < 1.5A$. So both models give more or less the same results.

The NTNU model uses at least 80% allowable expansion to secure full throw out in each firing sequence. This
gives more possibilities for design of any type of parallel hole cut with one or more empty hole(s).

4.2. Drilling pattern

In both models smooth blasting is recommended in the contour. The spacing to burden ratio for both models is presented in Table 3. With the same burden values, both models suggest equal or close to equal spacing values.

The burden value in the NTNU model depends on blastability, drillhole diameter and length, and for the contour holes also tunnel cross-section. The burden values for 45 mm drill hole with 5 m length are given in Table 4. In the Swedish model lifters and stoping holes are treated like bench blasting with higher fixation factor. The same formula is used to calculate the burden of the lifters and stoping holes with different S/B ratio and fixation factor. In smooth blasting the burden for the contour holes is calculated based on the spacing value. So the basis for contour calculation is different from the other holes.

In the Swedish model the burden for the lifters and stoping holes depends on the linear charge concentration (drillhole diameter), fixation factor, rock constant, explosive type and S/B ratio. The burden values for 45 mm drillholes are given in Table 5. The other assumptions for lifters and stoping holes are as follows:

- Rock constant \( c = 0.4 \).
- ANFO density = 900 kg/m\(^3\).

<table>
<thead>
<tr>
<th>Hole type</th>
<th>Model</th>
<th>NTNU</th>
<th>Swedish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifters</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Stopping</td>
<td>1.2</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Row nearest contour</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contour</td>
<td>(~0.9)</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

The Swedish model recommends the contour burden in the range of medium blastability in the NTNU model. For the other holes the Swedish model gives considerably higher burden values especially when using ANFO as explosive. The following reasons illustrate the differences:

- The different rock parameters in the models. In the Swedish model, rock constant, the amount of explosive needed for loosening one cubic meter of rock, under Swedish conditions \( c = 0.4 \) is predominant in blasting operations.
- Indirect dependency of the burden value in the NTNU model to explosives type and charging density, is expressed only by rock mass blastability.
- The different uncharged length of the drillholes in each model.

The Swedish model does not take into consideration the drillhole length, while in the NTNU model when the drillhole length is different from the base (5 m) the burden must be corrected. This correction decreases the burden when the drillhole is longer than 5 m and increases the burden when the drillhole is less that 5 m. For example for 45 mm drillhole when the drillhole is 3 m correction increases the burden 3–4%. This correction has only minor effect on the general burden comparison.

4.3. Charging

As described in the Swedish model, in holes other than the contour, more emphasis is made on explosive type and charging density which are interdependent parameters with burden in the drilling pattern calculations. The NTNU model considers these parameters in the rock blastability evaluation (NTNU, 1995, pp. 13–15).

In the Swedish model, except for the contour, where the total drillhole length is charged with less charging density, the uncharged length is equal to 10 times the drillhole diameter. For a 45-mm drillhole the uncharged length is 0.45 m.

In the NTNU model the uncharged length depends on drillhole length. For cut and lifter holes 0.1L, for contour and stoping 0.3L. The uncharged length for 5 m drillhole is from 0.5 to 1.5 m. This indicates longer uncharged length...
and with the same charging density, the NTNU model gives lower explosives consumption in each hole.

4.4. Look-out angle

In both models the burden and spacing are at the bottom of the hole or round and must be corrected at the face according the look-out angle or drilling deviation.

4.5. User-friendliness

Since most data and values in the NTNU model are presented in graphs and tables, the model is easier for application for any tunnel cross-section, drillhole diameter and drillhole length. There are guidance graphs to check the final blast design outputs for any tunnel cross-section, i.e., number of holes, specific drilling and specific charging.

4.6. Comparison with an example

An example of blast design with the Swedish model is presented for a tunnel with 19.5 m² cross-section in (Holmberg, 1982), the main input are as follows:

- Drillhole diameter = 45 mm.
- Drillhole length = 3.2 m.
- Empty hole diameter = 102 mm.
- Explosive type = cartridged explosives.
- Explosive density = 1200 kg/m³.
- Rock constant = 0.4.

For the NTNU model the same input is used and medium blastability is assumed. Although in the blastability definition the Swedish granite is evaluated as good blastability, considering all Swedish rock types, the rock constant $c = 0.4$ is assumed be equivalent to medium blastability in this example for comparison.

A comparison of the four-section cut design and total blast design result are summarized in Tables 6 and 7.

4.7. Cost estimation

A cost comparison between two models is not within the scope of this paper. However, the fact that the Swedish model uses less drilling and more explosives then the NTNU model, indicates that the cost difference should not be significant between the two models.

5. Conclusions

Both models are developed by experience or empirical data. In both models parallel hole cut with empty hole(s) is used as cut type.

In both models cut design depends on drillhole length which determines the empty hole diameter. Both models give approximately the same value for the empty hole diameter, distance between empty hole and the nearest charged hole and burden for other cut hole based on established opening. The NTNU allowable expansion enables possibility for design of any type of parallel hole cut with one or more empty holes.

In both models, spacing to burden ratio for all holes are the same or close to each other.

Also both models suggest smooth blasting with more or less the same burden values. In the Swedish model, lifters and stoping holes are treated like bench blasting with higher fixation factor. For these parts, the Swedish model gives higher burden values, especially when using ANFO as explosive. The reason mainly comes back to the methodology of each model. The higher burden values indicate the lower number of holes in the Swedish model.

The recommended uncharged length of the drillhole in the two models is different, in the Swedish model it depends on the drillhole diameter and in the NTNU model it depends on drillhole length. Generally, the NTNU model gives longer uncharged length which indicates lower explosives consumption.

References