ROCK QUARRYING
Blast Design

NTNU
Department of Building and Construction Engineering
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREFACE</td>
<td>2</td>
</tr>
<tr>
<td>0 INTRODUCTION</td>
<td>4</td>
</tr>
<tr>
<td>1 GEOLOGY</td>
<td>7</td>
</tr>
<tr>
<td>2 DRILLING</td>
<td>22</td>
</tr>
<tr>
<td>3 CHARGING</td>
<td>38</td>
</tr>
<tr>
<td>4 FIRING PATTERNS - INITIATION</td>
<td>52</td>
</tr>
<tr>
<td>5 BLASTING RESULT</td>
<td>68</td>
</tr>
<tr>
<td>6 EXAMPLES</td>
<td>81</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>93</td>
</tr>
</tbody>
</table>
This project report is part of a project programme on rock blasting techniques and rock quarry production consisting of the following reports:

14A-95 ROCK BLASTING TECHNIQUE Blasting with Restrictions
14B-97 ROCK BLASTING TECHNIQUE Bench Blasting*
12A-98 ROCK QUARRYING Locating and Modelling**
**12B-98 ROCK QUARRYING Blast Design
12C-98 ROCK QUARRYING Prognosis and Costs***
12D-98 ROCK QUARRYING Loading and Transport****

A considerable amount of information has been systematised and brought up to date through these reports - to be used for:

- Locating and modelling of rock quarrying
- Blast design
- Calculation of capacity and costs
- Cost analysis, tender, budgeting and cost control
- Choice of method and equipment.

The basis for the report is work studies and statistics from quarrying in Norway. The reports are partly based in the Ph.D. thesis "Rock Blasting Technique" by Arne Lislerud.

* The report will be replaced by PR 12B-98 ROCK QUARRYING Blast Design
** The report is expected to be published in 1999.
*** The report will replace PR 11-90 BENCH BLASTING Capacity and Costs.
    Expected published in 1999.
**** The report will replace PR 12C-92 ROCK QUARRYING Loading.
    Expected published in 1999.

Front page photo: Stig O. Olofsson
The report provides basis for making blast designs, and gives further insight in matters concerning necessary drilling, blastability, charging, delay times etc.. Necessary drilling and charging gives the basis for calculation and choice of equipment when planning rock quarrying.

The project group alone is responsible for all evaluations and conclusions in the report.

The report has been completed by the civil engineers John Ivar Fagermo.

Financial support has been granted by:

Statkraft Anlegg AS	Atlas Copco Rock Drills AB
Scandinavian Rock Group	Dyno Nobel
Vegdirektoratet	Statsbygg
Veidekke ASA	Tamrock OY
NCC Eeg-Henriksen AS

For reference, we ask for the following to be used:


Trondheim, May 1998

Odd Johannessen
Professor
INTRODUCTION

Data from the report give the basis for the construction of blasting plans and optimisation of rock quarrying. In every single quarry it will be necessary to accomplish test blasts, experiments and adjustments for optimising quarry operations related to rock production.

Subjects related to geology, blast ability and working ability of explosives in different rock types, will basically be related to each other for most types of rock blasting in construction engineering, both over and under the surface.

KEY FACTORS

High accuracy through all parts of the process from surveying and planning, via start of drilling till the round is fired, is fundamental for achieving a respectable blast result.

Among other things, this affects:

- Planning
- Surveying and setting out holes
- Adjustment of drill pattern
- Adjustment of specific charge
- Delay times and ignition pattern
- Accurate drilled length (rotating laser)
- Properly selected stemming material
- Control and supervision of the work (accomplished accuracy).

When optimising quarry operations, it is often difficult to accomplish several elements of improvement simultaneously. It is very important to try out one thing at a time and be sure of the conclusions from each single specific adjustment. Elements of improvement must be effectuated according to a mutual superior strategy.

It is important to keep up the process of improvement, and always be interested in getting better and more accurate in craftsmanship skills. This to gain competence and effectuate the potential in a long time perspective.

The sum of improvements will most often be visualised in the form of higher efficiency and lower repair- and maintenance costs.
Figure 0.1 Overview for relations which influence the blasting process.
0. INTRODUCTION

PRODUCTS

The different products related to rock blasting operations, such as explosives and detonators, will continuously be developed. New products will often be available on the market. Different suppliers worldwide will also offer products that are almost identical under different product names.

Dyno Nobel has for several years been the dominating supplier for the Norwegian market when it comes to explosives, blasting agents, detonators etc. For this reason, some of the product names and labels used in the report originate from Dyno Nobel.
### 1. GEOL OGY

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 BLASTABILITY</td>
<td>8</td>
</tr>
<tr>
<td>1.10 Introduction</td>
<td>8</td>
</tr>
<tr>
<td>1.11 Anisotropy of Rock</td>
<td>9</td>
</tr>
<tr>
<td>1.12 Explosive</td>
<td>9</td>
</tr>
<tr>
<td>1.13 Classification of Rock</td>
<td>9</td>
</tr>
<tr>
<td>1.14 Blastability Index</td>
<td>10</td>
</tr>
<tr>
<td>1.15 Example</td>
<td>11</td>
</tr>
<tr>
<td>1.16 Experience Values</td>
<td>12</td>
</tr>
<tr>
<td>1.2 FRACTURING</td>
<td>13</td>
</tr>
<tr>
<td>1.20 Introduction</td>
<td>13</td>
</tr>
<tr>
<td>1.21 Blast Direction</td>
<td>14</td>
</tr>
<tr>
<td>1.3 FRAGMENTATION</td>
<td>19</td>
</tr>
<tr>
<td>1.31 Summary</td>
<td>19</td>
</tr>
<tr>
<td>1.32 Variation of Mean Rock Size d50</td>
<td>21</td>
</tr>
</tbody>
</table>
1.1 BLASTABILITY

1.10 Introduction

When deciding the management of the rock quarry, it is important to consider the following:

- geological conditions, as joints and quality differences
- topography and quarry limits
- wished blast results

Blastability represents the influence of rock mechanical parameters on the blasting result. Blastability is a relative measure. Determination of necessary drilling (specific drilling) and necessary charging (specific charging) must be related to a valuation/calculation of the rock mass blastability.

The Blastability Index (SPR) describes the blastability of the rock.

Rock mass blastability is given by

- rock type blastability
- rock mass fracturing

Rock type blastability is influenced by

- anisotropy
- density
- sonic velocity for the actual rock type
- charging density of the explosive (energy content)
- mineralogy and grain binding.
1. GEOLOGY

1.1 Blastability

1.11 Anisotropy of Rock

The anisotropy is particularly large in schistose and mica-rich rock types. Anisotropy has a negative influence on blastability. The directional dependent rock strength gives directional dependent blasting-effects.

Anisotropy $I_a$ for dry velocity of sound is given by $I_a = \frac{c_a}{c_\perp}$

Tensions is almost not influenced by blastability in bench blasting.

1.12 Explosive

For uniform SPR-values there are provided specific data for charge density and detonation velocity. Table 1.1 shows the parameters for different explosives.

<table>
<thead>
<tr>
<th>EXPLOSIVE</th>
<th>CHARGE DENSITY</th>
<th>DETONATION VELOCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamite</td>
<td>1,06</td>
<td>3000</td>
</tr>
<tr>
<td>Anolit</td>
<td>0,95</td>
<td>2200</td>
</tr>
<tr>
<td>Emulsion slurry</td>
<td>1,20</td>
<td>4250</td>
</tr>
</tbody>
</table>

Table 1.1 Uniform explosive values.

1.13 Classification of Rock

A classification of blastability for different rock types is shown in Table 1.2.

<table>
<thead>
<tr>
<th>Good blastability (SPR = 0.38)</th>
<th>Coarse-grained homogeneous granites, syenites and quartz diorites. E.g. &quot;Swedish granite&quot;.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium blastability (SPR = 0.47)</td>
<td>Rock types with blastability between good and poor. For example gneiss.</td>
</tr>
<tr>
<td>Poor blastability (SPR = 0.56)</td>
<td>Metamorphic rock types with slated structure, often with high content of mica, and a low compressive strength. Characteristic for these rock types are a high level of anisotropy. For instance mica schist in the Rana region in Norway.</td>
</tr>
</tbody>
</table>

Table 1.2 Rock type classification according to blastability (SPR).
Table 1.2 shows a rough classification of blastability for some regular rock types. The classification is based on experience from rock sites in Norway. The SPR-values shows the scale for calculated blastability.

1.14 Blastability Index

The formula for calculating the blastability index (SPR) is shown in [1.1]. The index is meant as an aid in the evaluation of blastability, and assumes access to laboratory data from representative samples of the particular rock. Calculated SPR declares a level for blastability. **The index does not take into consideration the rock mass fracturing and orientation of fractures.**

\[
SPR = \frac{0.736 \cdot I_a^{0.61} \cdot LT^{0.72}}{c_{1000} \cdot \left( \frac{w}{c} \right)^{0.25} \cdot \rho^{0.19}}
\]

\[ [1.1] \]

- \( I_a \) = anisotropy = \( c_l / c_\perp \)
- \( c_l \) = sonic velocity (dry) parallel to foliation (m/s)
- \( c_\perp \) = sonic velocity (dry) normal to foliation (m/s)
- \( c \) = \( (c_l + c_\perp) / 2 \) = sonic velocity - dry (m/s)
- \( \rho \) = density of rock (g/cm\(^3\))
- \( LT \) = charging density of explosives (kg of explosives per volume unit of drillhole)
- \( w \) = detonation velocity of explosive (m/s)
1.15 Example

Below is an example of calculation of blastability for a specific quarry where the explosive was emulsion slurry (Slurrit 510) with a charging density (LT) = 1.20 kg/dm³.

**Input Data**

\[
\begin{align*}
    c_\parallel &= 2794 \text{ m/s} \\
    c_\perp &= 2469 \text{ m/s} \\
    I_a &= \frac{2794}{2469} = 1.13 \\
    LT &= 1.20 \text{ kg/dm³} \\
    c &= \frac{c_\parallel + c_\perp}{2} = 2632 \text{ m/s} \\
    w &= 4500 \text{ m/s} \\
    \rho &= 2.73 \text{ g/cm³}
\end{align*}
\]

\[
SPR = \frac{0.736 \cdot 1.13^{0.61} \cdot 1.2^{0.72}}{\left(\frac{2632^{0.4}}{1000}\right) \cdot \left(\frac{4500}{2632}\right)^{0.25} \cdot 2.73^{0.19}} = 0.44
\]

Calculated SPR indicates a blastability between medium and good. The rock type in the example was a relatively homogeneous limestone. Limestones has often considerable surface crumbling, with open joints. This will influence the blastability in a negative direction.
1. GEOLOGY

1.1 Blastability

1.16 Experience Values

Figure 1.1 SPR-values for samples tested in the Rock Engineering Laboratory at NTNU. The experience values are based on a limited data foundation.
1. GEOLOGY

1.2 FRACTURING

1.20 Introduction

The discontinuity (weakness surface) to the rock mass influence the blastability.

The weakness surface are recognised by little or no shear strength along the surfaces.

One distinguishes between

- Systematically fractured rock mass
  - parallel orientated joints and fissures
  - foliation planes or bedding planes
- Marked single joints
- Filled joints
- Crushed zones and zones with mineral- or clay fill.

Fracturing is characterised by rate of fracturing (-type and frequency) as well as orientation (angle between blast-direction/backwall and weakness planes.

Joints (Sp) Includes continuous joints. These joints can be open (e.g. bedding joints in granite) or filled with clay or weak minerals, e.g. calcite, chlorite or similar minerals.

Fissures (St) includes non-continuous joints, (can only be followed over parts of the face), filled joints with low shear strength and bedding plane fissures (partings) e.g. as in mica schist and mica gneiss.

Homogeneous Rock Mass includes massive rock without joints or fissures (may appear in intrusive dikes, sills, batholites etc.).

Increasing fissure joint degree (St) gives the rock better blastability. Large fissure joint degree (St) is typical for regional metamorphic rock types.

Systematically joints (Sp) makes the rock harder to blast, because lager blocks becomes isolated when the rock pile is being thrown forward, without being crushed. Fractured mountains are typical rocks overground.
1.21 Blast Direction

The blast direction should be adjusted according to geology/fracturing. In special cases where the blast direction is determined from other demands, the firing pattern can be used to control (overrule) blast direction and result.

Before starting drilling, the blast direction should be determined according to orientation of systematic fracturing in the rock. Fragmentation, backbreak, toe-problems and problems related to poor loosening along the bench floor/toe all have coherence with blast direction in relation to the systematic fracturing of the rock.

Investigations have proven that an optimum angle between blast direction and strike direction of the dominant fractures/weakness planes is approx. 20-45°.

For an optimum total result it is important to take into consideration the valuation of back-wall, toe- and bench-floor problems. This can be handled by orientating the back-wall along a weakness surface and the blast direction close up to the optimum angle. See section 4 Firing Patterns - Initiation.

For quarry operations, main fracture systems should be mapped and plotted on operational maps. The blast result should be followed up according to blast direction/main fracture system. The results from these studies will found a basis for further blast planning and quarry-management.

On the next pages some of the most common combinations of rock type, fracturing and blast results are discussed. These are:

- Anisotrope rock with vertical fracturing.
- Anisotrope rock with flat-lying fracturing.
- Rock with vertical fracturing and little anisotropy.
- Rock with flat-lying fracturing and little anisotropy.

In the following figures the angle between weakness planes and blast direction is given by the angle $\alpha$. Blast direction is defined to be perpendicular to the back-wall. Back-wall direction is described by A, B, C or D.
1. GEOLOGY

1.2 Fracturing

Anisotrope Rock with Vertical Fracturing

![Diagram of anisotropic rock with vertical fracturing](image)

Figure 1.2 Anisotrope rock with vertical fracturing.

Typical rock types are mica-gneiss and mica schist.

<table>
<thead>
<tr>
<th>Backwall-direction</th>
<th>Fragmentation</th>
<th>Backbreak and toe-problems</th>
<th>Bench-floor problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>medium 2)</td>
<td>small</td>
<td>medium</td>
</tr>
<tr>
<td>B</td>
<td>poor 1)</td>
<td>large</td>
<td>large</td>
</tr>
<tr>
<td>C</td>
<td>medium - good 3)</td>
<td>small</td>
<td>medium</td>
</tr>
<tr>
<td>D</td>
<td>medium 2)</td>
<td>small</td>
<td>medium</td>
</tr>
</tbody>
</table>

1) Gas venting along schistosity in the walls. Fly-rock problems and block is a result from this (particularly in the 1. row). Spacing must be reduced in the 1. row to reduce bench-floor and block-problems.

2) Confined holes in the round give poor breakage with bench floor problems (toes) as a result.

3) Blast direction C is most favourable. The angle is dependent of the rock anisotropy. The best result will appear with blast direction perpendicular to C and back-wall along D, in principle as shown in Figure 1.2. For this type of rock problems related to the establishment of a new bench floor will be the design basis for drill pattern.
Anisotrope Rock with Flat-lying Fracturing

Figure 1.3 Flat-lying fracturing. Typical rock types are mica-gneiss and mica-schist.

<table>
<thead>
<tr>
<th>Back-wall</th>
<th>Fragmentation</th>
<th>Backbreak and toe-problems</th>
<th>Bench-floor problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>poor 1)</td>
<td>large 2)</td>
<td>large</td>
</tr>
<tr>
<td>B</td>
<td>good</td>
<td>some</td>
<td>medium</td>
</tr>
<tr>
<td>C</td>
<td>good</td>
<td>some</td>
<td>medium 3)</td>
</tr>
<tr>
<td>D</td>
<td>good 1)</td>
<td>some</td>
<td>medium - large</td>
</tr>
</tbody>
</table>

1) The problem with flat-lying schistosity in anisotrope rock is the fact that the most favourable blast direction goes along the flat-lying schistosity. The face-wall get too little stiffness when firing row by row, and the face-wall will have excessive buckling. This problem can be solved by using reduced bench height or small diameter drill holes.

2) Some backbreak and backslides on fissures along the schistosity (along the back-wall).

3) C is the most favourable orientation when it comes to blast direction and back-wall for fissure fractured rock.
1. GEOLOGY

1.2 Fracturing

Rock with Vertical Fracturing and little Anisotropy

Figure 1.4 Vertical fracturing, little anisotropy.

Typical rock types are quartzite and granite gneiss.

<table>
<thead>
<tr>
<th>Backwall</th>
<th>Fragmentation</th>
<th>Backbreak and toe-problems</th>
<th>Bench-floor problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>good</td>
<td>little</td>
<td>medium</td>
</tr>
<tr>
<td>B</td>
<td>slightly poor</td>
<td>some 2)</td>
<td>varying 4)</td>
</tr>
<tr>
<td>C</td>
<td>good -</td>
<td>much 3)</td>
<td>little 5)</td>
</tr>
<tr>
<td>D</td>
<td>good</td>
<td>little 1)</td>
<td>medium</td>
</tr>
</tbody>
</table>

1) Little backbreak, but it is possible to miss on the fracture direction, with large outfall along sliding-planes for $\alpha < 10^\circ$ as a result.

2) Rough and uneven back-wall. The back-wall gets more uneven with increasing extent of fracturing, increasing drillhole diameter and drillhole pressure. This results in more blocks in front of the rock pile.

3) Maximum backbreak for $\alpha = 45^\circ$, some larger blocks at the back of the rock pile due to fallout from the back-wall. Backbreak can be reduced by increasing the stemming in the back row.

4) Gas-pressure leak out in the wall, fly-rock, poor fragmentation (especially along the bench floor) and general bench floor problems as a result, especially in joint-fractured rock.

5) Bench floor problems may occur if a good 1. row is hard to achieve. A possible way to make this better is to drill along D and fire along C.
1. GEOLOGY

1.2 Fracturing

Rock with Flat-lying Fracturing and little Anisotropy

Figure 1.5 Rock with flat-lying fracturing and little anisotropy. Typical rock types are quartzite and granite gneiss.

<table>
<thead>
<tr>
<th>Backwall</th>
<th>Fragmentation</th>
<th>Backbreak and toe-problems</th>
<th>Bench floor problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>poor ¹)</td>
<td>very large ²)</td>
<td>large</td>
</tr>
<tr>
<td>B</td>
<td>good</td>
<td>some</td>
<td>medium</td>
</tr>
<tr>
<td>C</td>
<td>good +</td>
<td>little</td>
<td>medium ³)</td>
</tr>
<tr>
<td>D</td>
<td>good</td>
<td>little</td>
<td>medium - large⁴)</td>
</tr>
</tbody>
</table>

1) Much block from the uncharged part (stemming) when the rock has sheet printing. For terrain rounds the bench top should fall backwards, otherwise much block will mix into the parts of the rock pile that originate from the charged part. This is definitively the least favourable blast direction in joint fractured rock.

2) Extra sub-drilling is necessary to avoid bench floor problems.

3) C is the most favourable orientation according to fracturing if it is possible to achieve a proper backwall and 1. row.

4) Bench-floor problems are reduced with increased sub drilling. Necessary sub drilling depends on dip direction of the fracturing. D is an easier way to operate rotary drilling compared to top-hammer drilling when the bench floor is the sub drilling section from the overlying level that has to be removed (excavated).
1.3 FRAGMENTATION

1.31 Summary

During detonation the shock waves will exceed the pressure- and the tension- capacity to the rock. The rock will be crushed closest to the drill hole, and crack radial out from the hole. The gas pressure will loosen and throw the blast forward. The fragmentation of the rock pile is not even in all parts of the pile, but varies according to where in the round the fragmented material originates from.

Primary Fragmentation

Controllable factors on the bench that influence primary fragmentation:

- drill hole diameter.
- charge weight per hole (the charge-concentration effect).
- peak-values for stress-waves out from the hole.
- charge distribution in the bench.

Secondary Fragmentation

The secondary fragmentation is an additional breakage that starts when fragmented material accelerates out from the bench in the blast direction. The additional breakage is attributed to:

- loosening of fragments in the bench - that triggers the high compressive stress levels (and conserved elastic energy).
- confined gas-pressure in the drill hole accelerates the rock and throws the rock mass outwards on the bench floor.
- collisions between fragments in the air and between fragments and the sole (bench floor).

Fragmentation is influenced by the original fracturing of the rock. This applies both during the detonation and in the following operations, such as loading, transportation, crushing and placing of the rock.
A study of the rock pile shows that:

- The most coarse fractions in the pile originate from the shoulder-/edge section of the pile, in addition to the area from the uncharged part (stemming). Rock from the uncharged part forms a "coat" of coarse fragmented rock that covers the top of the pile. Changing the stemming length (UL) rapidly gives change according to fragmentation of this part of the pile.

- Fragmentation of the shoulder section is heavily related to bench-top conditions, whether the bench top is terrain or a sub drilling section from an overlying bench.

- The part of the rock pile that originates from the area between the bench floor and top of the charging column (charged part of the round) is the most crushed part in the pile.
1.32 Variation of Mean Rock Size $d_{50}$

For a large number of bench rounds the following variation area has been found for mean particle size $d_{50}$.

<table>
<thead>
<tr>
<th>Bench blasting related to</th>
<th>Application of blasted rock</th>
<th>Mean particle size $d_{50}$ [mm]</th>
<th>Loading equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarrying</td>
<td>crushing</td>
<td>125 - 290 1)</td>
<td>wheel loader</td>
</tr>
<tr>
<td>Rockfill dams</td>
<td>supporting fill</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fine zone fine zone coarse zone coarse zone</td>
<td>160 - 2)</td>
<td>wheel loader wheel loader wheel loader wheel loader +hydraulic excavator.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 - 250</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>250 - 320</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 440 3)</td>
<td></td>
</tr>
<tr>
<td>Mining</td>
<td>crushing</td>
<td>160 - 250 4)</td>
<td>wire excavator + wheel loader</td>
</tr>
<tr>
<td>Road construction</td>
<td>foundation/ support layer</td>
<td>200 - 310</td>
<td>hydraulic excavator</td>
</tr>
</tbody>
</table>

Table 1.3 Variation area for mean particle size $d_{50}$.

1) Mean particle size depends on crusher capacity, gap opening in the coarse crusher and saleability of quarry dust (waste).

2) Rounds with large content of rock to transition zone ($d_{max} = 200$ mm).

3) Rounds with large content of rock for slope protection (rip-rap). Demands to rock in supporting fill is $d_{max} = 2/3$ of layer thickness.

4) Rounds with the largest mean particle size have been registered in ore with low rock mass strength.

The relationship between portions of coarse and fine material can vary for blasted rock, even with the same $d_{50}$ (grain size distribution curves have different progress, but crosses through the same $d_{50}$). This can relate to rock-mass qualities, drill-hole diameter, bench height, specific explosive consumption and operational conditions in the quarry (terrain bench or flat floor bench).