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ORIGINAL PAPER

Validity of the NTNU Prediction Model for D&B Tunnelling

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Abstract

The Norwegian University of Science and Technology (NTNU) has since the early 1970s published prediction models for estimated production rates, time consumption, and costs for rock works. Since the early development of the NTNU models the tunnelling industry has continuously improved and the models have been updated on several occasions. The NTNU models are presently being updated to better fit the modern tunnelling trends in Norway. The current prediction model for D&B blast design is in this research paper compared with new data from thirteen recent Norwegian tunnel projects. The paper demonstrates that the empirical methodology behind the prediction model is still highly relevant, but some further improvements and additional empirical relations are suggested to enable the model to better cope with the recent 16 years of development in technology, equipment, contractual-issues and blast design. The new datasets show that modern D&B tunnelling employ more drill holes and specific charging per blast round than before. The current NTNU model thus under-predicts the actual tunnelling performance in the blast design. Some suggestions are made for further improving the model, where the updated drill length, the contour requirements, and the tendency to including the longitudinal ditches into the main blast are suggested as the main reasons for the disparity in drill hole numbers. Yet, the current trend in specific charging seem to have doubled since the early 2000s and cannot be explained by the increase in drill holes alone. Further development ought to be included in the blastability index (SPR) so that geological conditions that are on the extreme side of poor blastability can be properly accounted for in the blast design.

Highlights

- Validation of prognosis model for drill and blast tunnelling
- Collection and treatment of tunnelling production data
- Evaluation of blastability for tunnelling applications
- The use of explosives in tunnelling has dramatically increased
- The use of drill holes in conventional tunnelling has increased

Keywords Drill and blast tunnelling · Blastability · Performance · Construction time · Disputes

1 Introduction

The Norwegian University of Science and Technology (NTNU) has since the early 1970s published prediction models for estimated production rates and time consumption and costs for rock works. The NTNU models are openly available for the tunnelling industry and are based on empirical relations between geological data and measured performance data. The empirical data originates mainly from actual tunnel projects and are collected through contributions from contractors and tunnel owners. The data are also correlated to field and laboratory studies executed by PhD

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and MSc students at NTNU. The initial NTNU prediction models with versions in English language date back to 1975 and 1983. The current range of updated NTNU prediction models now include versions for hard rock TBM tunnelling (Macias 2016; Bruland 1998), rock quarrying and cut blasting (Olsen 2009) and models for drill and blast tunnelling (Zare 2007a, b; Rønn 1997). The primary goal of these models has been to serve as guidelines for planning of works, project scheduling and cost estimates. The prediction models are neutral and unbiased and thus they constitute a basis that can be used for many aspects. In recent years one important aspect has been to provide an independent base for disputes on tunnelling, i.e. construction time or advance rates, and the NTNU models are still frequently used and referred to by the tunnelling industry.

Since the early development of the NTNU models the tunnelling industry has continuously improved and the models have been updated several times. The main background data from which the current NTNU models originate is primarily derived from the 1990s and early 2000s, which mainly contained input data from single tube tunnels constructed in rural areas. Since then, however, tunnelling activity in Norway has gradually moved, from rural hydropower tunnels and traffic tunnels connecting remote communities, to urban infrastructure tunnels in the major cities in Norway.

Urban dual tube road and rail tunnels today are often excavated with alternating tunnel faces, which means that one machine package and tunnelling crew, consisting of one drilling jumbo, loading, hauling, and rock support equipment alternates from one tunnel tube to the other during construction. The time expenditure related to moving equipment and work force, from one tunnel face to the other, have a great influence on the performance and production capacity. If the planned performance at one tunnel face is interrupted, e.g. due to increased need for pre-grouting or extensive rock support, this will influence the availability of the equipment on the alternating tunnel face. Furthermore, modern infrastructure tunnels in Norway today have seen a steady increase in the quantity of rock support and pre-excavation grouting used in the tunnel design, facilitating more time expenditure on each round of tunnel blast. The impact of such incidents is not a part of the current NTNU prediction models.

The productivity in the Norwegian tunnelling industry has thus changed since the current model development and the over-all productivity has seen a descending trend due to a variety of reasons and factors (i.e. those mentioned above) that have an accumulated impact on how efficient the industry is able to produce one meter of tunnel. For the on-shore construction industry in Norway, the productivity rate has decreased by 10% in the period between year 2000 and 2018 (The Statistic Norway). The tunnelling industry, which is a part of the on-shore construction industry, is also included in this index. The reason for this decline on a national level is complex, but it is clear that for tunnelling the rock mass properties of Norwegian bedrock has not changed since the early 2000`s and cannot be the reason for the decline in productivity. In fact, the modern machine fleet, such as drilling jumbos, loading and hauling machinery, and explosives have seen incrementally improvements and are today capable of much higher production capacity, in meters per time unit, than in 2000. It is, therefore, relevant to ask the question on how well the NTNU prediction models currently fit to the current production trends.

The NTNU models are presently being updated to better fit the modern tunnelling trends in Norway. The presented study is part of this ongoing work and will highlight how modern drill & blast (D&B) tunnelling design is reflected by the NTNU prediction model for tunnel blast estimation. In this paper, a review of the prediction models published by Zare (2007a, b) and Rønn (1997) is compared with new data from 13 recent tunnel projects in Norway. The aim of the paper is to demonstrate that the empirical methodology behind the prediction model is still highly relevant, but some further improvements and additional empirical relations are suggested to enable the model to better cope with the recent 16 years of development in technology, equipment, and blast design.

2 The Blastability Index and Associated NTNU Prediction Models

The NTNU prediction model for underground blasting consists of three main elements, (a) *blast design*, (b) *advance rate*, and (c) *costs*. The model has been developed to provide a tool and methodology for economic dimensioning, choice of alternative solutions, time planning, cost analysis, tender, budget and cost control, choice of excavation method and equipment selection. The models are published in open access project reports, with corresponding spreadsheet software for calculations. The current version of the NTNU prediction model for D&B tunnelling is the version modified by Zare (2007a, b) and builds on the original work derived from earlier and less sophisticated models developed since the mid-1970s. The D&B tunnelling model estimates the theoretical minimum necessary number of charge holes and explosives consumption needed per blast round during excavation. The actual number of holes and explosives consumption is decided by the tunnel crew, which tend to include extra charge holes and explosives in an effort to achieve better blasting results or production rates. Some reasons for including extra charge holes are elaborated in the discussion section of this paper.

The main features of the NTNU D&B model is empirically based and rely on a description of the rock quality, the explosives and equipment specifications, and the size and geometry of the tunnel face, as is common for many prediction models in general (Holmberg 1982; Persson et al. 2001; Yang et al. 2005; among others). Already in 1975, a preliminary NTNU prediction model was prepared based on two charge hole diameters and two charge hole lengths that were typically in use by the industry at that time, namely the 34 mm size holes with 2.1 m drill hole length and the 45 mm size holes with 2.7 m drill hole length. An empirical relation of necessary drilling and specific charging was prepared for tunnels from 12 to 80 m^2 tunnel cross-sections (collaring area).

A key input parameter for the NTNU prediction model is the blastability index (SPR). The SPR was introduced into the NTNU prediction model in 1988 to enhance the model performance and to demonstrate the fundamental understanding that different rock types require different specific charging. The SPR was originally developed for surface bench blasting and shows a relation between the quantity of explosives (kg/m^3) required to break a given volume of rock into a certain degree of fragmentation. Originally this fragmentation criteria were aimed at achieving a size distribution where 50% of the blasted rock size is smaller than the 250 mm diameter sieving size. The SPR is estimated based on Eq. (1).

$$SPR = \frac{0.736 \cdot I_a^{0.6} \cdot LT^{0.7}}{\left(\frac{C}{1000}\right)^{0.4} \cdot \left(\frac{w}{C}\right)^{0.25} \cdot \rho^{0.2}}, \tag{1}$$

where I_a [−] is the dry sonic velocity anisotropy ratio (C_p/C_n) of the rock. C [m/s] is the average dry sonic velocity $\left(C_p + C_n\right)/2$, where C_p [m/s] is the dry sonic velocity perpendicular to rock foliation and C_n [m/s] is the dry sonic velocity parallel to rock foliation. Here, ρ [kg/m^3] is the density of the rock and w [m/s] is the detonation velocity of the main explosive type used in the blast. The LT [g/cm^3] is the charge weight per unit volume of drill hole. There are also several other blastability indexes in the literature that express the blastability of rock, applying numerous different properties and rock characteristics in their correlation. A review of Lislerud (1990) presents and compares several blastability evaluators for surface and tunnel blasting. These includes Johanessen (1973), Bergh-Christensen (1968), Lilly (1986), Kuznetsov (1973), Cunningham (1982), Rustan et al. (1983), Singh and Sastry, (1987), among others. These models are not further elaborated herein, as the aim of this paper is not to compare them, but to evaluate a potential new trend in Norwegian tunnelling with respect to the NTNU model.

The incorporation of the SPR into the NTNU prediction model is based on a qualiative description of the SPR. Johanessen (1973) was the first to describe a simple qualitative description of blastability for Norwegian rock types. The description is still in use for Norwegian D&B tunnels today. The basis by Johannessen (1973) was extended by Log and Moger (1997) who collected SPR laboratory results from a total of 135 rock samples, mainly from Norway (Fig. 1). In the NTNU prediction model, the classification of SPR by Johanessen (1973) is simplified into three blastability categories where simple, yet appropriate, key words on typical geological conditions are used to differentiate between classes, shown in Table 1.

When compared to other blastability indexes, there are two main negative arguments against the SPR index that are often mentioned in the literature. Firstly, the SPR demand special equipment for measuring P-waves to acquire the input data. Secondly, the SPR does not incorporate rock mass properties directly in terms of e.g. joint spacing and orientation, which has been shown to affect the blastability. Early on, Selmer Olsen (1964) stated that mica rich rock types (> 30% mica) and with a schistose structure along the mica layers are especially difficult in terms of blastability. Palmstrøm (1997) found that measurable parameters that influence the rock blastability are the Brittleness Value (Dahl et al. 2012), the excavation orientation compared to the orientation of the geological structure, and the content of mica minerals. To some extent, these are elements that can be explained by anisotropy of rocks, which is also reflected well in the SPR-formula. However, the SPR do in-fact have an indirect relation to these properties, also to some extent the joint spacing and the orientation, through the P-wave values which are affected by such properties. P-wave measurements can also be obtained quite easily by simple and portable laboratory methods, that can be installed on-site if required in tunnelling projects. The practiced aspect of acquiring the model parameters does thus not hinder its use.

The first extended version of the NTNU model was published by Rønn (1997) who updated the model with new data from the new developments within the tunnelling machine fleet at that time. New loading and hauling equipment and capacities were introduced and Rønn (1997) expanded charge hole diameter to include 45 mm and 64 mm diameter holes. Bulk slurry emulsion explosives were introduced in addition to ANFO and cartridge explosives. Blast design details encompassing tunnel cross-section shape, cut design, ignitor sequence and contour rows were also introduced. In addition to the design of the blast cut, the detailed design of the drilling pattern included the charge holes in the contour, holes in the row nearest the contour, the lifter holes as well as the stopers. The NTNU prediction model proposes charge hole spacing for all these holes based on the three rock blastability categories, poor–medium–good (Table 1). The output of the prediction model would then result in the total number of holes required to be drilled and charged to produce one blast round.

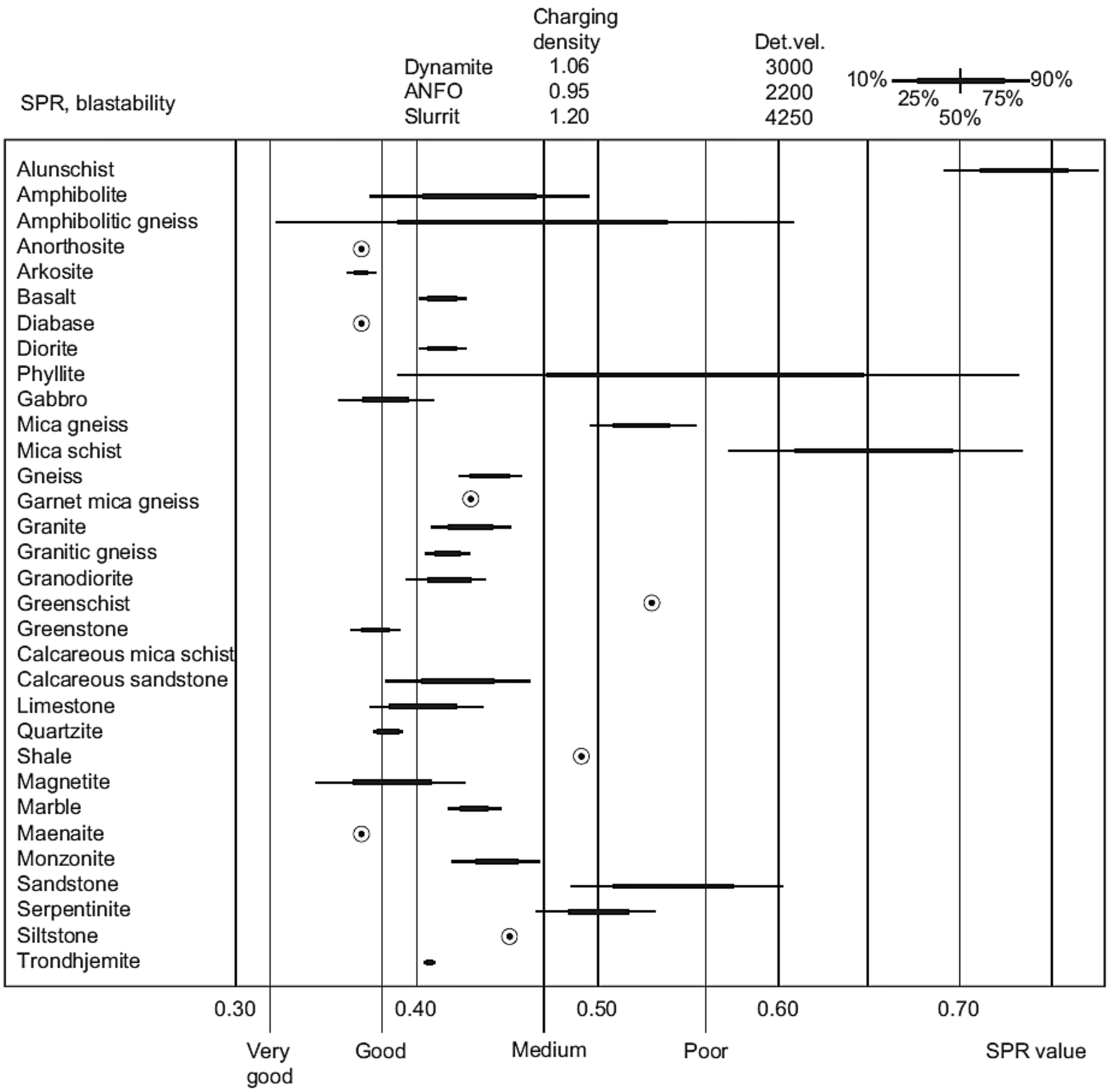


Fig. 1 Overview of SPR values for a selection of bedrock types, recorded by Log and Moger (1997). Slurrit refers to Dyno Nobel's slurry commonly used in Scandinavia in the 90's and onwards

Table 1 Qualiative description of blastability based on Johanessen (1973)

SPR category	SPR value	Typical rock types
Poor	0.56	Metamorphic rocks with schistostic structure, often with high mica content and low compressive strength
Medium	0.47	Rocks in-between poor and good blastability
Good	0.38	Coarse grained homogenous granites, syenites and quartz-diorites
Very good	0.32	Limestone blasting (in surface blasting)

The modern version of the NTNU prediction model is that of Zare (2007a, b), which follow the same methodology and is still very similar to the version of Rønn (1997), but with updated empirical relations on skill level of the tunnelling crew, new equipment, and cost. The standard charge hole diameter was increased from 45 to 48 mm and new average values from tunnelling datasets were employed in the analysis. Figure 2 shows the difference in data points that constitute the base for the Rønn (1997) model and the model of Zare (2007a, b). The dataset of both models shows a relatively wide scatter and may not necessarily follow an ideal trend, but the trend line became quite distinct in the

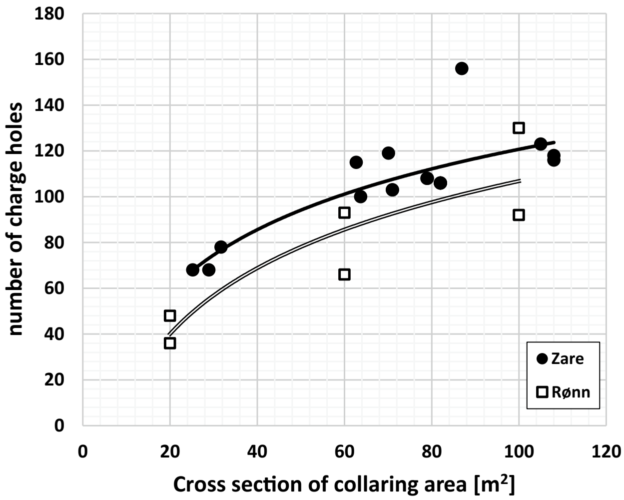


Fig. 2 Data used in by the Rønn (1997) and Zare (2007a, b) versions of the NTNU model, for 48–51 mm diameter drill holes

latter version of Zare (2007a, b). The model version of Zare (2007a, b) essentially shows that the tunnel blast designs in late 1990s towards early 2000s relied on more drill holes than in the model of Rønn (1997) and the NTNU D&B model was adjusted accordingly.

The parameters to be determined prior to estimation by the Zare (2007a, b) version of the NTNU prediction model are: rock mass blastability (SPR), drill hole specifications (length and diameter), skill level of the tunnelling crew, and actual tunnel cross-section (m^2). Figure 3 and Fig. 4 show the output from the NTNU model where the predicted number of necessary 48 mm drill holes for various tunnel cross-sections and SPR values (excluding large uncharged holes in the cut) are shown for a standard blast round. The NTNU model uses the 5.0 m drill length for a standard blast round, which can be compensated for the actual drill hole length and crew skill level in actual projects via a correction factor (K_{bf}). The designated blast round design can then be further used for estimation of construction capacity, e.g. measured by meters of tunnel produced per week on average, and subsequently the total construction time and cost estimate are estimated for the whole tunnel length.

Figure 4 shows that the current version of the NTNU prediction model estimates standard specific charge consumption in the range of 1.05–3.25 kg/sm^3, depending on SPR value and cross-section size of the tunnel ranging from 10 to 120 m^2 collaring area sizes. The pull in the model is 91% (ratio between drill hole length and achieved blasting depth), while the empirical data base that the model relies on obtained 95% pull. The reason for this is that the NTNU model is conservative and does not intend to over-estimate the performance. Since 2007, the prediction model has not seen any major official updates. However, a few studies have

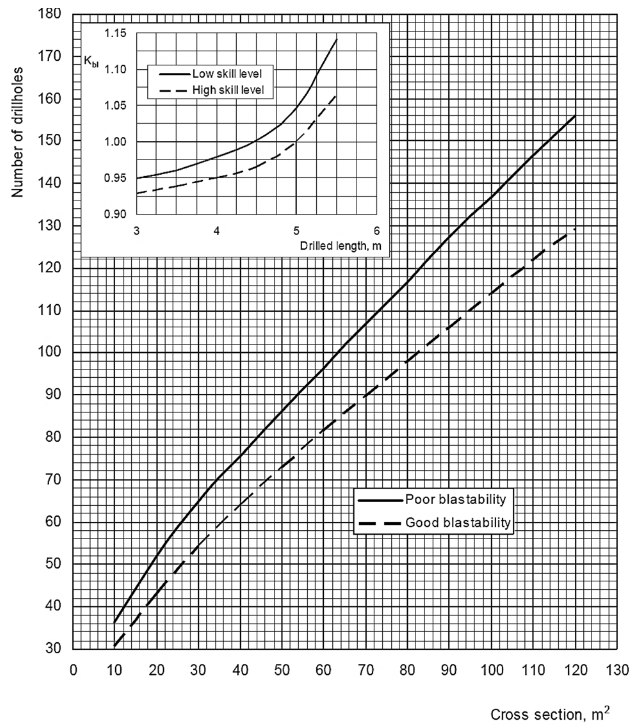


Fig. 3 Necessary number of 48 mm drill holes versus tunnel cross-section, excluding large holes in the cut (Zare 2007a, b)

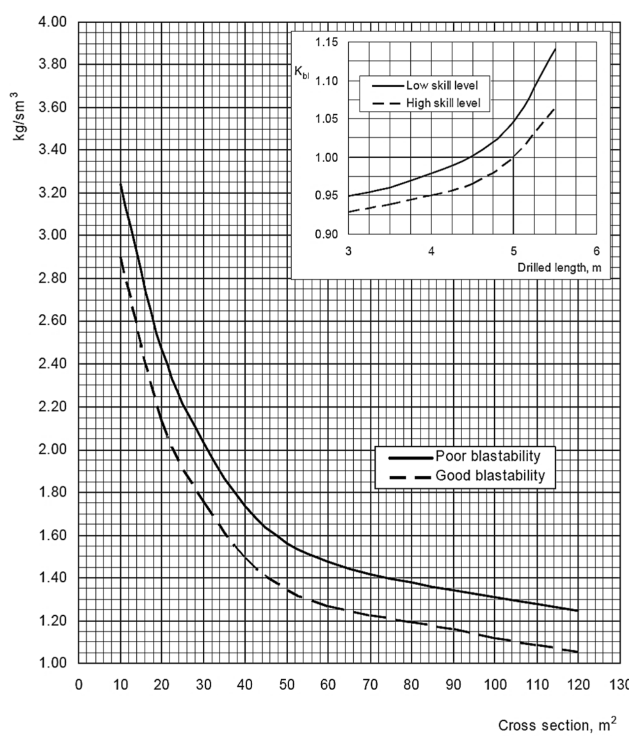


Fig. 4 Necessary charging of ANFO in 48 mm drill holes for various tunnel cross-section sizes (Zare 2007a, b)

been conducted to evaluate its validity and relevance (Zare & Bruland 2006; Tufte-Rødberg 2019).

3 Research methods

New specific charging (kg/sm^3) and drilling data (number of charged holes per blast) from thirteen recently completed D&B tunnelling projects in Norway from 2016 until 2022 is analysed. The project selection has aimed at making available a variety of D&B conditions with different geology, equipment, operational crew, tunnel cross-sections, and tunnel lengths. In the data sets, slurry bulk emulsions are used.

The new datasets are compared to the historical datasets reported in the literature, particularly the datasets from Zare (2007a, b). Zare (2007a, b) presents averaged datasets for both specific charging and drilling from 14 older Norwegian tunnels (Fig. 2), 11 of which have slurry emulsion as the main explosive type and three have ANFO as the main explosive type. The SPR values range from medium to good. Tufte Rødberg, (2019) present drilling data from eight different tunnelling projects in Norway. A total of 55 individual blast rounds are included in his study with SPR in range from poor to medium. The datasets are included to show the potential spread of the input data from such tunnel projects.

The 13 new datasets are presented in Table 2 which summarizes the main specifications from the project sites.

Projects 1–11 represent averaged datasets for both specific charging and drilling, where the input values are averaged for the whole blast database. These datasets contain a single averaged value for the main tunnel blasts alone and are thus structured equal to that of the data of Zare (2007a, b) for comparison with older tunnelling data. Note that the specific charging is calculated from the total weight of explosives used in the blast divided by the average solid volume of the blast round (actual collaring area times drill hole length—including the volume due to the angle of the contour). The specific blast design is thus not presented and the details on the cut design, the firing sequences and tunnelling cost will not be elaborated and only mentioned in brief where relevant. The main bulk of the data originate from Norwegian road-tunnels that have a theoretical cross-section size of 80 m^2. Ideally, a more evenly distributed and wider spread of tunnel cross-sections would have been preferable.

Table 2 Overview of projects 1–13

Project #	Theoretical cross-section - tunnel purpose	SPR	Dominant geological conditions	Explosive type/ignitor type hole diameter/hole lengths	Data points
1	60 m^2 — Mine tunnel	Good	Limestone	Slurry emulsion/NONEL 48 mm/-	1*
2	80 m^2 — road tunnel	Medium	Basalt and porphyry	Slurry emulsion/NONEL 48 mm/-	1*
3	80 m^2 — road tunnel	Medium	Basalt and porphyry	Slurry emulsion/NONEL 48 mm/-	1*
4	80 m^2 — road tunnel	Medium	Basalt and porphyry	Slurry emulsion/NONEL 48 mm/-	1*
5	80 m^2 — road tunnel	Medium	Basalt and porphyry	Slurry emulsion/NONEL 48 mm/-	1*
6	80 m^2 — road tunnel	Poor	shale, phyllite, quartzite and greenstone	Slurry emulsion/NONEL 48 mm/-	1*
7	130 m^2 — railway tunnel	Good	Granitic rocks and porphyry	Slurry emulsion/NONEL 48 mm/-	1*
8	130 m^2 - railway tunnel	Good	Eugen gneiss and granitic rocks	Slurry emulsion/NONEL 48 mm/-	1*
9	130 m^2 — railway tunnel	Good	Eugen gneiss and granitic rocks	Slurry emulsion/NONEL 64 mm/-	1*
10	78 m^2 — road tunnel	Poor	Layered basalt	Slurry emulsion/NONEL 48 mm/-	1*
11	85 m^2 — road tunnel	Poor	Phyllite	Slurry emulsion/NONEL 48 mm/-	1*
12	80 m^2 — road tunnel	Poor	Meta greywacke, phyllites and schists	Slurry emulsion/NONEL 48 mm/2.98–5.80 m	125
13	80 m^2 — road tunnel	Poor	Meta greywacke, phyllites and schists	Slurry emulsion/NONEL 48 mm/2.82–5.75 m	64

*Average values for the main tunnel blasts in the projects (without lay-bys and cross-connections)

The data collection is also based on charge hole diameters of 48 mm, which is the industry standard at present.

Projects 12 and 13 are presented with more detail, including a differentiation between various tunnel sizes along these tunnel lengths. The actual collaring area for the drilling is normally slightly larger than the theoretical tunnel size due to the space requirement of the equipment and due to the angling of the drill holes. Furthermore, the tunnel size of cross-adits and emergency lay-bys within each tunnel project provide supplementary tunnel sizes even though the tunnel class is the same for most of the projects. These datasets are also averaged and structured like that of the data of Zare (2007a, b) for comparison. Projects 12 and 13 are both excavated in the same rock type and combined they contain a total of 189 individual blasts, distinguish into 17 cross-adit blasts, 139 main tunnel blasts, and 33 lay-bys blasts.

4 Results and discussion

The drilling data output of the NTNU prediction model is presented in Fig. 5 together with data from Projects 1–13, the data of Zare (2007a, b), and Tufte Rødberg, (2019). The number of applied drill holes per blast round reported by Zare (2007a, b), Projects 1–11 are shown in orange markers and the average values of Projects 12–13 are shown in yellow markers. The detailed data from the study of Projects 12 and 13 are differentiated for main tunnel blasts (white), emergency lay-by blasts (black) and for cross-adit blasts (grey). The over-all spread of the datapoints in Projects 12 and 13 demonstrate the resulting variation due to adjustments of the blast design within a given tunnel project during the construction phase. Figure 5 shows the NTNU model trendline used for estimating 5 m drill length in drill and blast tunnelling. The figure demonstrates that the development in Norwegian tunnelling practise over the recent years has resulted in an increased number of charged drill holes used in the blast design compared to the NTNU prediction model of Zare (2007a, b). This trend is indeed quite similar to the differences in the data of Zare (2007a, b) and Rønn (1997) in Fig. 2.

The lower bound of required charged drill holes is represented in Fig. 5 by the drill holes needed in the cut, here exemplified by two standard cuts (F and S) reported by Fauske (2002). These cuts typically contain 21–25 boreholes, of which 17–18 are charged. This lower bound seems to fit quite nicely with the trendline of the SPR—good data of the NTNU model. The medium and poor trendlines are seemingly given additional boreholes that cause a small vertical shift of the graphs. By comparison with the actual data, as indicated by Fig. 5, it is clear that the estimation of necessary number of charged drill holes in the NTNU model is essentially much lower than the majority of the new datapoints in Project 1–13 and also compared to the data of Zare (2007a, b) and Tufte Rødberg (2019). There are several reasons for this difference and some of the main factors are included in the trendline for the "new NTNU SPR–poor" model in Fig. 5.

One reason for this difference is partly due to the drilled length used in modern blast rounds. Common practice in modern blast design, as is the case for the Projects 1–13, is to utilize longer drill hole lengths than the baseline of the

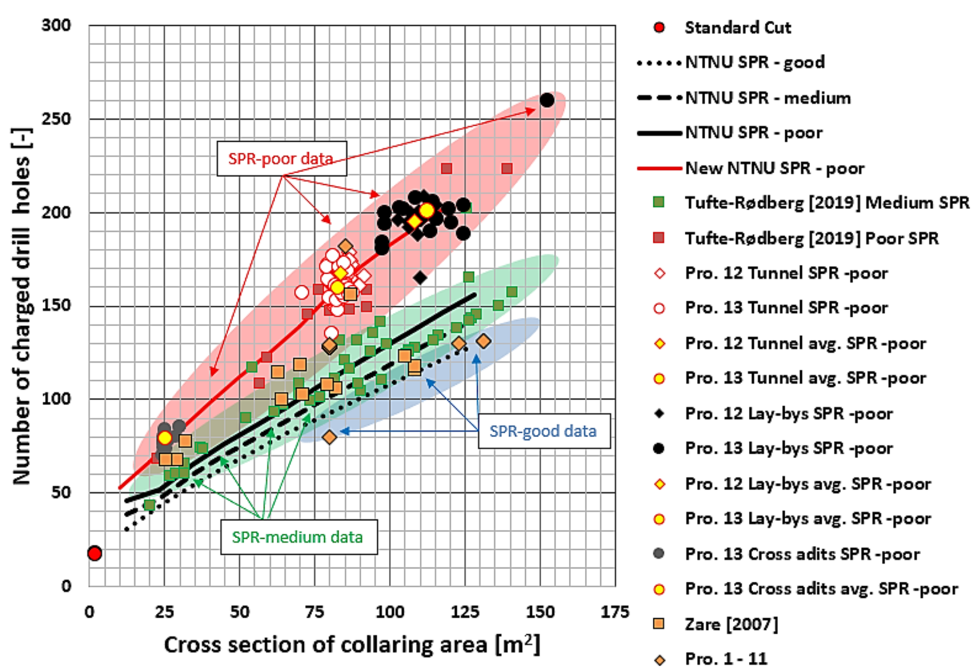


Fig. 5 Relation between number of required 48 mm charged drill holes per blast round and tunnel cross-section. The NTNU models for good, medium and poor SPR are shown as trendlines for 5,0-m standard drill length

NTNU model, with typical drill length values in the range of 5.5–5.8-m. For the road tunnel profile of approximately 80 m^2 Fig. 5 show that the NTNU model estimates a need of 100–115 charged holes for a 5.0 m drill length blast in SPR medium–poor. If the drilled length is increased, the number of holes must be slightly increased to compensate for the drill hole deviation and larger burden in the deeper end of the blast (Zare 2007a, b). The baseline NTNU values must thus be increased by 10–15% to enable a comparison with the majority of the new datapoints of this study. This upscales the NTNU model estimates to 110–140 of 48 mm charge holes for a road tunnel profile of 80 m^2.

Another reason for this difference was disclosed by Tufte Rødberg (2019) whom emphasized that the average drilling collaring area starts outside of the theoretical cross-section contour, causing an increase of the tunnel cross-section size by 8% on average. This trend can be observed in Fig. 5 for the data of Project 12 and 13, whom both display an almost consistently larger collaring area (white shaded datapoints) than the theoretical 80 m^2 size the tunnel should have had. The spread of the white datapoint clouds shows that the collaring area for these two projects range from 71 to 95 m^2, with an average collaring area of 83,5 m^2 (4,3% larger than the theoretical). This increase of cross-section area has some practical implications for the blast design. Compared with the theoretical size, a larger collaring area essentially enlarges the tunnels from the theoretical specifications and produce a longer contour perimeter and a larger blast volume (sm^3), which increase the number of required charged drill holes in the blast design.

The effects of collaring enlargement especially influence road tunnel blasts in Norway, because the Norwegian regulations (Vegnormal N500, 2022) state that the contour hole spacing shall not exceed 0.7 m for normal contour conditions, and not more than 0.5 m for smooth blasting requirements, which contractually overrule the suggested spacing in the NTNU prediction model. The regulations also set requirements on blast holes adjacent to the contour (second contour), with shorter spacings and less charging density. These requirements oblige the blast designer to utilize additional charged holes in the blast design than what the NTNU model suggests. In Fig. 5, the white and black data points of the Project 12 and 13 the contour holes and second contour holes comprise 45–50 holes of the total quantity. This is some 10–15 additional drill holes than predicted by the NTNU model. The baseline NTNU values must thus be increased further, to 120–148 of 48 mm charge holes for a road tunnel profile of 80 m^2 in the SPR medium–poor range.

Another reason for the difference in number of charge holes is due to a common tunnelling practice in modern blast design in Norway. The road and railway tunnels have parallel drainage ditches along the entire tunnel length, as is the case for the Projects 1–13. These ditches are commonly included in the main blast to save costs and over-all construction time. Each ditch usually requires additional charged holes in the invert, typically in the range of 3–5 charge holes per drainage ditch. In the white and black data points of the Projects 12 and 13 datasets, the tunnels are designed with two such ditches, adding between 6 and 10 additional charge holes in each blast round. The baseline NTNU values must thus be increased to 126–158 of 48 mm charge holes for a road tunnel profile of 80 m^2 in medium to poor SPR rocks.

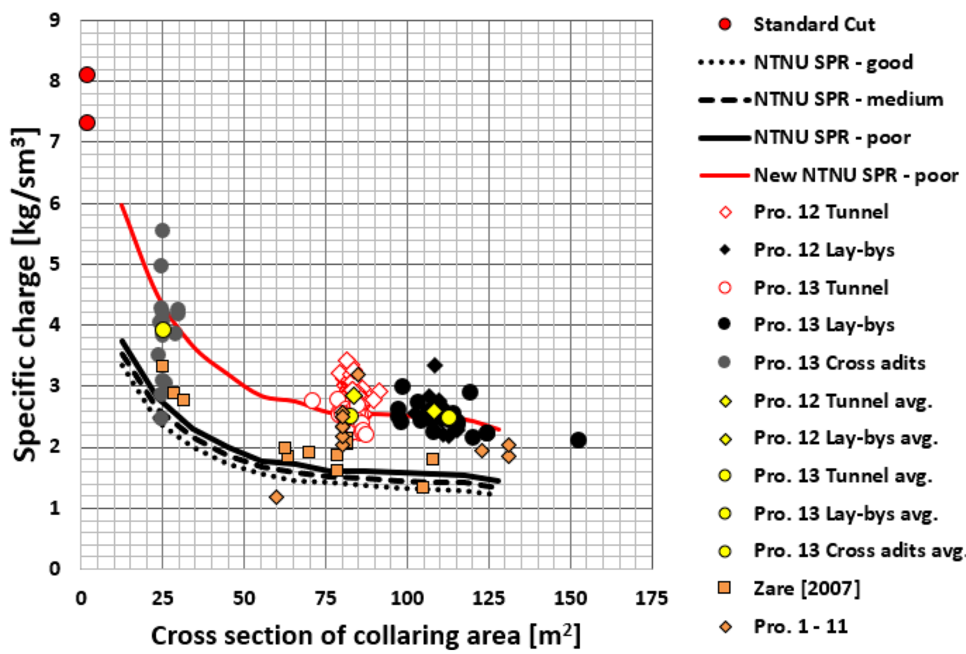
All three of the abovementioned factors are added to the SPR–poor model of NTNU to demonstrate the increase in number of drill holes that will result in the prediction model of the "new NTNU SPR–poor" should be updated to include these current trends in blast design. It is evident that the new NTNU SPR–poor trendline plot relatively well within the cluster of SPR–poor datapoints of Project 1–13.

The corresponding used specific charging values are plotted in Fig. 6. The upper bound of required specific charging is represented by the blast charge in the cut, here characterised for two cuts (F and S) reported by Fauske (2002). The average specific charging reported by Zare (2007a, b) and Project 1–11 are shown in orange markers, while the new data from the study of Projects 12 and 13 are shown in yellow markers for the average specific charging. The yellow marks, that represent the average values for each of the categories (white, black and grey), are comparable to how the orange data of Zare (2007a, b) and Project 1–11 are structured. The individual blasts for tunnel blasts (white), emergency lay-by blasts (black) and for cross-adit blasts (grey) are seen in the background. The over-all spread of the datapoints in Projects 12 and 13 demonstrate that there occur variations and adjustments in the blast design within a given project during the construction phase. The spread of the data for the tunnel blasts (white: 2.2–3.4 kg/sm^3) might e.g. be due to local variations in geology within a tunnel length, but also due to optimization efforts carried out by the tunnelling crew during construction.

The result of this variation is a relatively wide variation envelope for the expected range of specific charging values utilized in practice, as is evident in their data distribution in Fig. 7. For instance, in the Project 12 data, the number of blasts with specific charging is relatively "flat" within the range 2.5–3.1 kg/sm^3. The average value for all blasts might be given as 2.86 kg/sm^3 but due to the large range of variance the average value does not necessarily provide the best overview of the situation. This fact is important to consider when comparing the averaged values between various projects, e.g. Projects 1–13 in Fig. 6, or other datasets.

Regardless of this fact, Fig. 6 demonstrates that the estimation of necessary specific charging in the NTNU model is significantly lower than the majority of the new datapoints in Projects 1–13. This trend is consistent with the additional number of charged drill holes actually used in Norwegian

Fig. 6 Relation between specific charging and tunnel cross-section. The NTNU models for good, medium and poor SPR are shown as trendlines for 5,0-m drill length



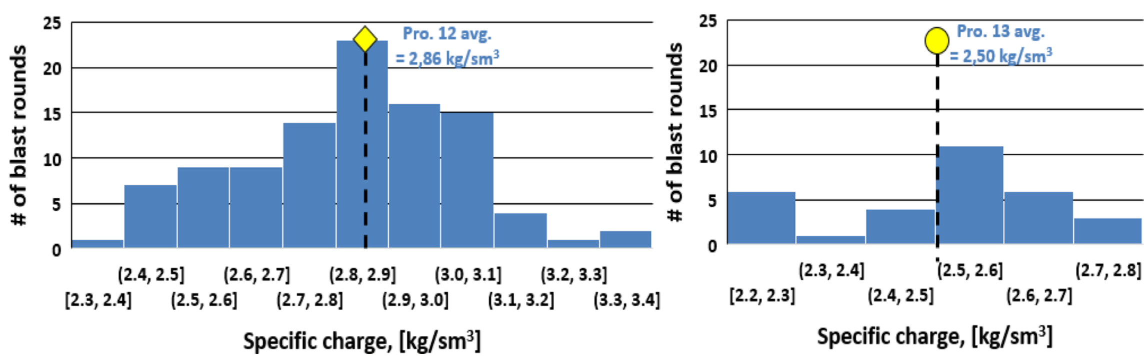


Fig. 7 Distribution of the specific charging data for the 101 main tunnel blast data in Pro. 12 and the 31 main tunnel blast data in 13. Pro. 12 (left: 2.3–3.4 kg/sm^3) has a larger spread than does Pro. 13 (right: 2.2–2.8 kg/sm^3)

tunnelling practise (Fig. 5) and suggest that the quantity of explosives used in modern tunnel blasts is much higher than the NTNU model predicts, regardless of the SPR.

Fauske (2002) reported on the early stages of use of emulsion bulk explosives in tunnel blasts in Norway and Sweden during the early 2000s. During that time, the 80 m^2 tunnel test blasts the cut, easer and invert holes were charged with 0.9 kg explosives per meter borehole, leading to a charge weight of around 4–5 kg per blast hole and a specific charge of 1.4–1.5 kg/sm^3, indeed very similar to the NTNU model. In Projects 12 and 13, it is evident that the main bulk of the specific charge data is within the range 2.5–3.1 kg/sm^3. Consequently, the main blast holes must be charged with much higher quantities of explosives than during the early 2000s for these figures to add up. The average charge weight per blast hole in modern blast design is evidently between 9 and 11 kg of explosives. The reason for the significant deviation of the NTNU model and the project data in Fig. 6 is, therefore, also due to a change in the charging strategy in tunnel blasts today, where the tunnelling blasts are designed with an "over-consumption" of explosives compared to older charging strategies. This is further supported by the "New NTNU model" in Fig. 6 visualizing the NTNU SPR–poor trendline with a 60% increase in explosive consumption. It has not been possible to determine why this occur, but several reasons might cause the observed increase of explosives consumption.

A minor part of the over-consumption can be explained by the explosive type used in the tunnel. In Norwegian D&B tunnelling most blast rounds are charged with slurry emulsion bulk explosives as the main explosive type. Zare (2007a) reported that, under the assumption of approximately the same charging density, the specific charging for emulsion is the same as for ANFO, and by charging with bulk explosives, there will be waste and unintentional over-consumption of explosives. This over-consumption is deemed to comprise a 10% increase in explosives consumption compared to the NTNU model.

Another reason might be due to a lack of blast-induced vibration regulations in some of the tunnel projects or in parts of the tunnel in given projects. A third reason might also be a desire to achieve higher pull percentage (ratio between drill hole length and achieved blasting depth) and to avoid re-blasts due to remaining rock within the tunnel profile. A fourth reason might be a desire to achieve smaller fragmentation sizes of the rock and thus easier loading conditions, which might yield over-all faster tunnelling rates. Further, it is seldom that the uncharged length exists in Norwegian D&B tunnelling, meaning that the holes generally are filled in their entire length. This, together with ignition system (NONEL vs. electronic detonators) should be investigated further.

Based on the data collected for this study, a new proposed specific charging classification is presented in Table 3. The classification is based on average values for the D&B tunnelling projects in Norway and is deemed applicable for cross-sections between 50 and 130 m^2. For these tunnel sizes, it is expected that the majority (80%) of D&B tunnelling projects would fall within 1.6–2.3 kg/sm^3 specific charging on average. Note that this is on average and it should be expected that the spread of the actual specific charging per blast round could vary significantly, as is evident in Fig. 6. The classification should not be used for smaller tunnel cross-sections due to large variation in the data catch from cross-sections less than 50 m^2, and an expectation of much higher specific charging levels should be considered.

Table 3 Classification based on percentile of bulk emulsion explosive consumption in Norwegian D&B tunnelling for tunnel cross-sections between 50 and 130 m^2

Classification for bulk emulsion explosive consumption	Percentile	kg/sm^3 (from)	kg/sm^3 (to)
Minimum	0	1.2	
Extremely low	5–10	1.3	1.6
Very low	10–25	1.6	1.9
Low	25–40	1.9	2.0
Medium	40–60	2.0	2.1
High	60–75	2.1	2.2
Very high	75–90	2.2	2.3
Extremely high	90–95	2.3	2.6
Max	100	3.2	

Quantities are given in total weight bulk emulsion per solid volume of rock [kg/sm^3]

5 Concluding Remarks

The NTNU prediction model has been validated versus data from ongoing and recently completed tunnelling projects in Norway. Input factors such as necessary number of charged drill-holes and specific charging has increased since the last revision of the model. However, the shapes of the trendlines are similar as in the 2007 version of the model. During the last decades the cost of explosives has been small in Norwegian tunnelling projects compared to the man-hour cost and machine cost. The increased number of charge holes and the quantity of explosives can be explained with the contractor’s desire for lower over-all tunnelling costs. The current cost incentives drive towards higher tunnelling rates; by achieving a higher pull percentage, few or no incomplete blast rounds, and to eliminate the probability of remaining rock protruding the theoretical profile of the tunnels, all of which leads to higher explosive consumption. If, however, the relative cost of explosives should increase in the future it is expected that this trend might change. With the current global trends and macro-economical perspective, with higher raw material cost, difficulties in distribution of consumables and lower purchasing power, an effect can be a leaner D&B performance in the future, also in Norwegian D&B tunnelling projects.

The presented study suggests that the NTNU prediction model for D&B tunnelling design is still a valid model and is still applicable for use in the tunnelling industry. The NTNU model may appear to be too optimistic as current tunnelling trends show both a higher drill hole usage and higher specific charging per blast round in most of the recent tunnelling projects. Some possible causes for these deviations are discussed above and a suggestion for further updates are suggested, e.g. including the ditch holes into the model, which provides better conformity with the actual tunnelling data. Still, the presented study suggests that the database does not cover the extremities on number of charge holes and quantity of explosives that may occur in geological conditions that are on the extreme side of poor blastability. The importance for the future would be to collect more data and improve the data base to represent the ever-developing improvements in tunnelling technology and to the current regulations in force.

One other possible way forward when it comes to improving the NTNU model is to further develop the SPR, or the way the qualitative assessment of "rock blastability" is incorporated into the model. The SPR does not consider directly rock mass properties, such as joint and fissure densities, nor their orientation along the tunnel alignment. In principle, it is expected that closed joints and fissures with moderate spacing (10–20 cm spacing) will act as crack propagators for the explosives. Rock masses with no fissures and joints will be more dependent on the brittleness of the rock than jointed rock masses. Rock masses with open joints and fissures will also act as pathways that evacuate the explosive gas, causing the rock mass blastability to become poorer. Incorporating such parameters into the model might improve the output and the accuracy of the model, and other blasting predictions.

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