International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Current practice D&B tunnelling versus the NTNU prognosis model for D&B blast design – a case study

S. Gjengedal & P. D. Jakobsen
The Norwegian Geotechnical institute, Trondheim, Norway
sondre.gjengedal@ngi.no *(email of corresponding author)*

H. Nilsen
Leanhard Nilsen AS, Risøyhamn, Norway

Abstract

The Norwegian University of Science and Technology (NTNU) has a long tradition for publishing prediction models for estimated time consumption, production rates, and costs for drill and blast tunnelling (D&B tunnelling). Since the early development of the NTNU models the tunnelling industry has continuously improved and the NTNU models have been updated on several occasions. The current version of the NTNU model is from 2007, but has recently been reviewed, and unofficially updated. The model was in need of an update to better fit the current practice of tunnelling in Norway. Updated drill lengths, the contour requirements, the tendency to include the longitudinal ditches in the main blast were suggested as the main enhancements in the new version. This new unofficial version of the NTNU model is in this paper supplemented with additional data from two recent tunnel projects in Norway. These tunnels intersect geological formations consisting of Gneisses, Marble, Shale and Limestone, rock types traditionally associated with medium and good blastability, thus supplementing the data portfolio in the database. A total of 353 individual blast are presented. The results demonstrate that the current practice in D&B tunnelling employ more charged drill holes and specific charging per blast round than predicted by the current NTNU model 2007 version. The findings suggest that the current practice of tunnelling has seen a doubling in explosives consumption per solid volume of rock since the early 2000s. This increase cannot be attributed to an increase in number of charge holes alone. Some possible explanations are provided, where the contractual specification might be one possible cause, favouring high production rates and low cost for the projects, rather than obtaining a certain degree of fragmentation of the rock.

Keywords

D&B tunnelling, Specific charging, Number of charge holes, Performance, Blastability

1 Introduction

Since the early 1970s, the Norwegian University of Science and Technology (NTNU) has published prediction models for estimated time consumption, production rates, and costs for underground blasting, full face tunnelling with tunnel boring machines (TBM) and rock works. The NTNU models has been developed to provide an independent tool and methodology for economic dimensioning, choice of excavation method, equipment selection, time planning, cost analysis, tender, budget and risk control. The NTNU models are presently being updated to better fit the current practice tunnelling approach in Norway today and a recent review of the drill and blast (D&B) tunnelling model has been published by Jakobsen et al. (2024). Their work demonstrates how the current NTNU model, most recently updated by Zare (2007) and Rønn (1997), performs versus the current practice drill & blast (D&B) tunnelling design used by the industry today.

The study of Jakobsen et al. (2024) highlights how the current practice in Norway for D&B tunnelling utilize more drill holes and specific charging than reflected by the NTNU prediction model. The aim of this paper is to supplement the data portfolio in Jakobsen et al. (2024) with two new datasets and further elaborate on the variations in number of charge holes and specific charging used in current practice D&B tunnelling in Norway. The new data will be presented in more detailed than in previous published work and the new data will be compared to the current official NTNU model of Zare (2007) regarding tunnel sizes, drill hole diameter, blast depth, and type of explosives.

2 The NTNU D&B tunnelling prognosis model

The current version of the NTNU model determines the number of necessary charged 48 mm or 64 mm drill holes per blast round for various tunnel cross-sections and SPR values. The SPR value, namely the blastability index originally classified by Johannesen (1973), is a key input parameter for the NTNU model, and signify that different rock types require different specific charging to obtain similar breakage. The NTNU prediction model proposes charge hole spacing based on the three rock blastability categories, poor–medium–good.

The parameters to be determined prior to estimation by the NTNU model are the rock mass blastability (SPR), drill hole specifications (length and diameter), skill level of the tunnelling crew, and tunnel cross-section (m^2). Blast design details, encompassing tunnel cross-section shape, cut design, drilling pattern, ignitor sequence and contour rows are not directly needed as input parameters, but they are incorporated in the empirical framework of the model, and this is reflected in the output number of necessary charged 48 mm or 64 mm drill holes (Rønn, 1997)

The output from the NTNU model is shown in Fig. 1 for both specific charging (kg/sm^3) and necessary number of charge holes for a standard blast round. The default input of the model uses 48 mm drill holes and the 5.0 m drill hole length as standard, whereas the 64 mm drill hole model is also available but rendered in the results section of this paper. A correction factor (K_{bf}) is used to compensate for the other drill hole lengths. For 48 mm holes the correction between 3.0 and 5.5 m lengths is available. An additional correction is also suggested for crew skill level.

The designated output from the NTNU model thus gives a single blast round design, that can then be further used for estimation of construction capacity in the supplementary NTNU models, e.g. by allocating meters of tunnel produced per week on average, and subsequently the total construction time and cost estimates for the whole tunnel length.

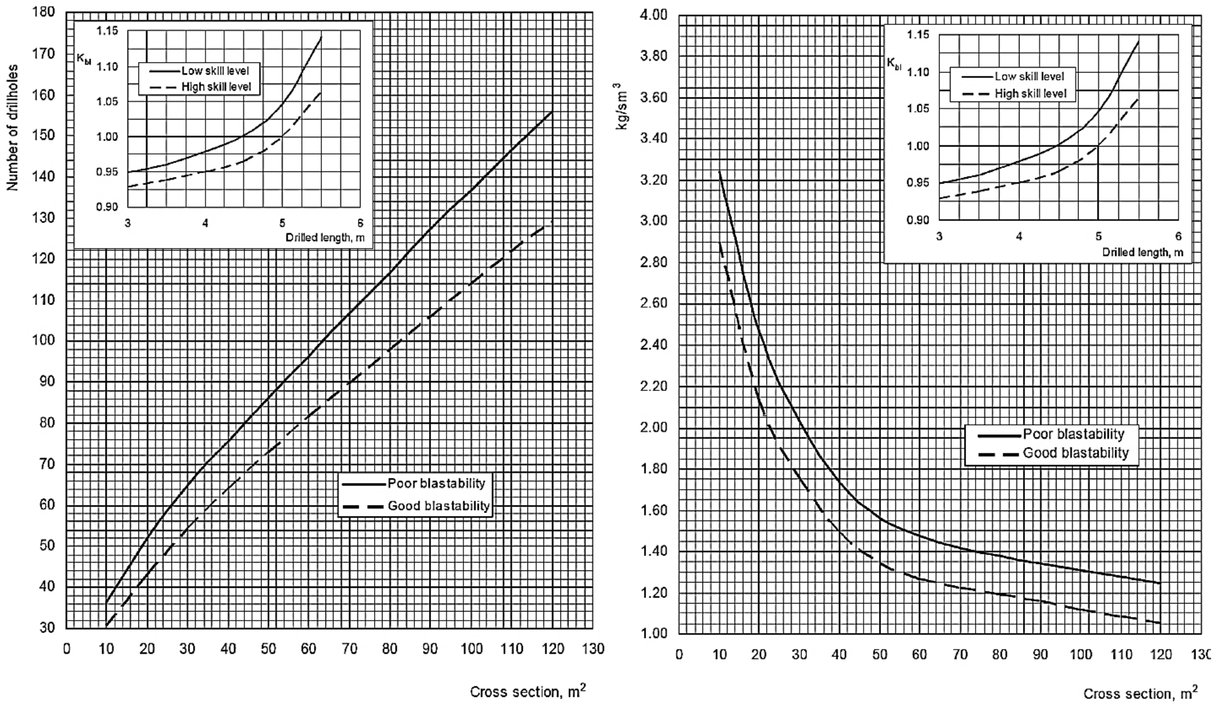

Fig. 1 The NTNU prediction model for D&B tunnelling (Zare 2007). Left) Necessary number of 48 mm drill holes versus tunnel cross-section, excluding large holes in the cut. Right) Necessary charging of ANFO in 48 mm drill holes for various tunnel cross-section sizes.

3 Research methods and project specific data

Two new projects, with specific charging data (kg/sm^3) and drilling data (number of charged holes per blast and cut design), are analysed similar as in Jakobsen et al. (2024). These two projects were selected with the aim of making available a new D&B conditions with different geology, equipment, operational crew, tunnel cross-sections, and face lengths. In addition, the detailed datapoints for project 12 and project 13 from Jakobsen et al. (2024) are included for comparison purposes. An overview of the project specific data er presented in Table 1 and 2.

Table 1 Overview of project specific data. Most frequent data points in each group are highlighted in bold font.

Project ID	**Tunnel type**	**Area type**	**Frequent tunnel cross-section sizes [m^2]**	**SPR**	**Dominant geological conditions**	**Drillhole diameter [mm]**	**Drill hole length [m]**
Pro. 12	Road	Rural	**80** – 115	Poor	Phyllite and Schist	**48**	2.98 -**5.80**
Pro. 13	Road	Rural	25 – **80** - 130	Poor	Phyllite and Schist	**48**	2.82 -**5.75**
Pro. 14	Utility	Urban	**30** – 45 – 100	Medium	Shale and Limestone	**48**, 64	2.5 – **4.6**
Pro. 15	Road	Rural	60 – **75** – 130	Good	Gneis and Marble	48, **51**, 64	2.0 – **6.0**

The datasets have been provided by the tunnelling contractors via their respective reporting system to the authorities. The specific charging is calculated from the total weight of explosives used in the blast round divided by the average solid volume of the blast round. If multiple explosive types have been used the dominant type, by weight (kg), is given priority in labelling.

All individual blast rounds are presented as individual datapoints, not averaged values. Thus, for comparison purposes with the NTNU model the datasets are fitted with a best-fit power regression curve to emphasis the general trend of the datasets. The correction factor (K_{bf}) is used to compensate for the other drill hole lengths. Table 1 shows that projects 12, 13 and 15 contain blast rounds that are outside the range the K_{bf} in Fig 1. A linear extrapolation of K_{bf} is then assumed to extend to 6.0-meter length, corresponding to K_{bf} = 1.15 for "High skill level crew".

Table 2 Overview of project specific data. Total number of individual blasts = 353.

Project ID	Tunnel excavation year	No. of bulk emulsion explosive datapoints	No. of cartridge explosives datapoints	Ignition type	Contractor ID
Pro. 12	2021 - 2023	125	-	NONEL	1
Pro. 13	2021 - 2023	64	-	NONEL	1
Pro. 14	2024	84	6	Electronic	2
Pro. 15	2022 - 2024	74	-	Electronic	3

The data for projects 12, 13 and 15 are gathered from road tunnels constructed in rural areas in Norway, with few or minor blasting restrictions, thus representing projects that do not regulate the unit charge quantity used in the blast design. Consequently, these projects only use bulk slurry emulsion explosives, which it the preferred explosives type in Norway today. The dataset of Project 14, however, is an urban utility tunnel with strict blasting restrictions, forcing the contractor to limit the unit charge. Thus, both cartridge explosives and slurry bulk emulsions explosives was used (Table 2).

4 Results

All of the projects provide a wide range of tunnel cross-section sizes, as a consequence of e.g. cross-adit sections and lay-bys occurring in the tunnels, but the main tunnel size is highlight in bold in Table 1 to emphasis the main origin of the data within each dataset. The benefit of presenting this range is that multiple tunnel blast designs are performed by the same tunnelling contractor and equipment. The blasting strategy of the contractor is thus reflected in the dataset (Table 2), even though the drilling patterns are not presented directly, nor the details on the cut design or the firing sequences. For instance, note that Pro. 14 has a small tunnel cross-section in the main tunnel (30 m^2 – Table 2), leading the contractor to limit the size of the drilling jumbo and, consequently, the maximum drill hole length available by the equipment (4.6 m). The other projects are not limited in the same way and all of them have selected drilling jumbos that can obtain 6-meter drill hole lengths.

4.1 Number of charged holes per blast round

The number of charged holes used per blast round for Pro.12 – Pro.15 is presented in Fig. 2 together with the output of the NTNU prediction model. There occurs a relatively large spread of the datapoints along the y-axis for a given tunnel size, for all of the four projects, which reveal the resulting variation due to adjustments of the blast design within a given tunnel project during the construction phase.

The results indicate that an increased number of charged drill holes is used in current practice blast design compared to the NTNU prediction model, regardless of contractor involved. The best fit trendlines of all four projects plot above their respective NTNU model. Jakobsen et al. (2024) suggested that some of these discrepancies are due to stricter contour requirements in road tunnel blasts. This seems a partly viable explanation, seeing that a large portion of the datapoints in the utility tunnel (Pro. 14) plot close to the NTNU model lines. In Pro. 14 these datapoints originate from blasts where blasting vibration requirements are not enforced. Still, several other datapoints in Pro. 14 plot well above the NTNU model with SPR poor, which show the effect unit charge requirements might have on the blast design.

One method for obtaining smaller unit charges in the blast is by drilling shorter boreholes. The distribution of the drill hole length is presented in Fig. 3. The figure highlights that, even though the unit charge might be smaller in shorter drill holes, the number of charged drill holes typically stay the same or increase slightly. This is somewhat counterintuitive in view of the NTNU model, which states that the number of charged drill holes should decrease with shorter drill length. Note also that the majority of the datapoints plot outside of the NTNU model range even though the variation in drill length is accounted for.

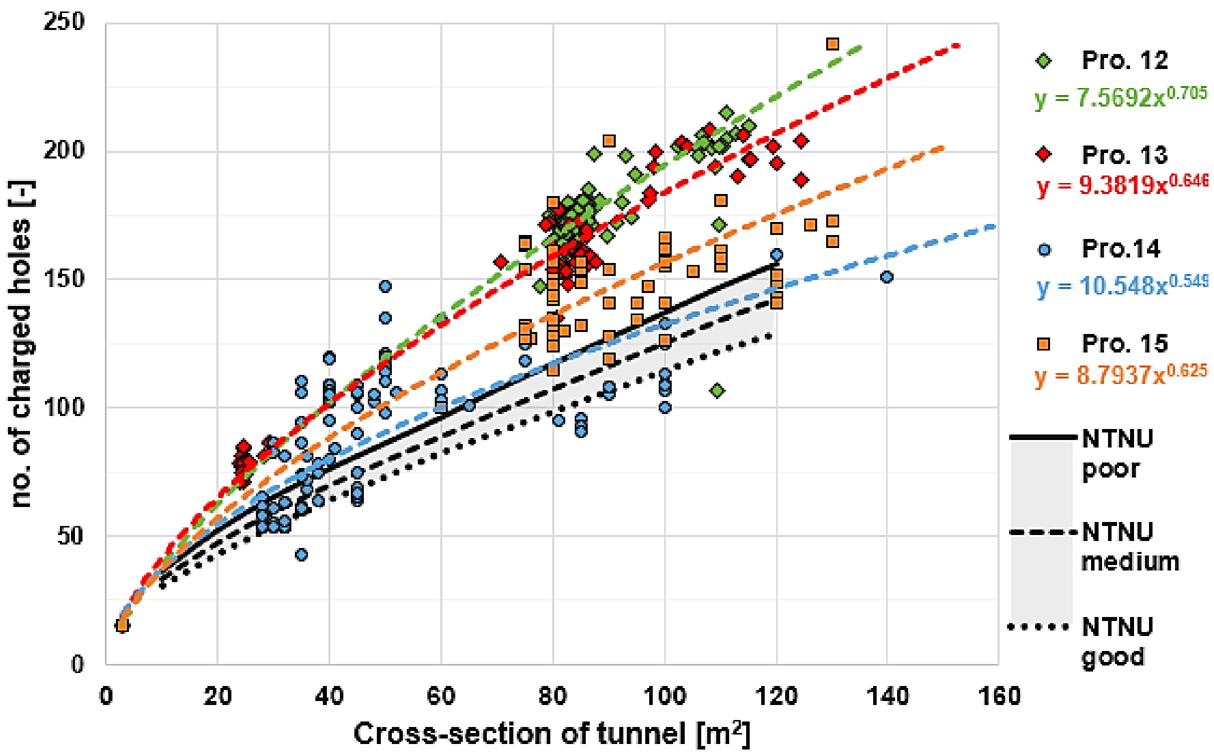

Fig. 2 Relation between number of charged drillholes and cross-section of tunnel. The NTNU models for good, medium and poor SPR are shown as trendlines for 5.0-m standard drill length and 48 mm charge hole diameter. Trendlines for Pro.12 – Pro.15 are best fit power curves, originating from the blast cut.

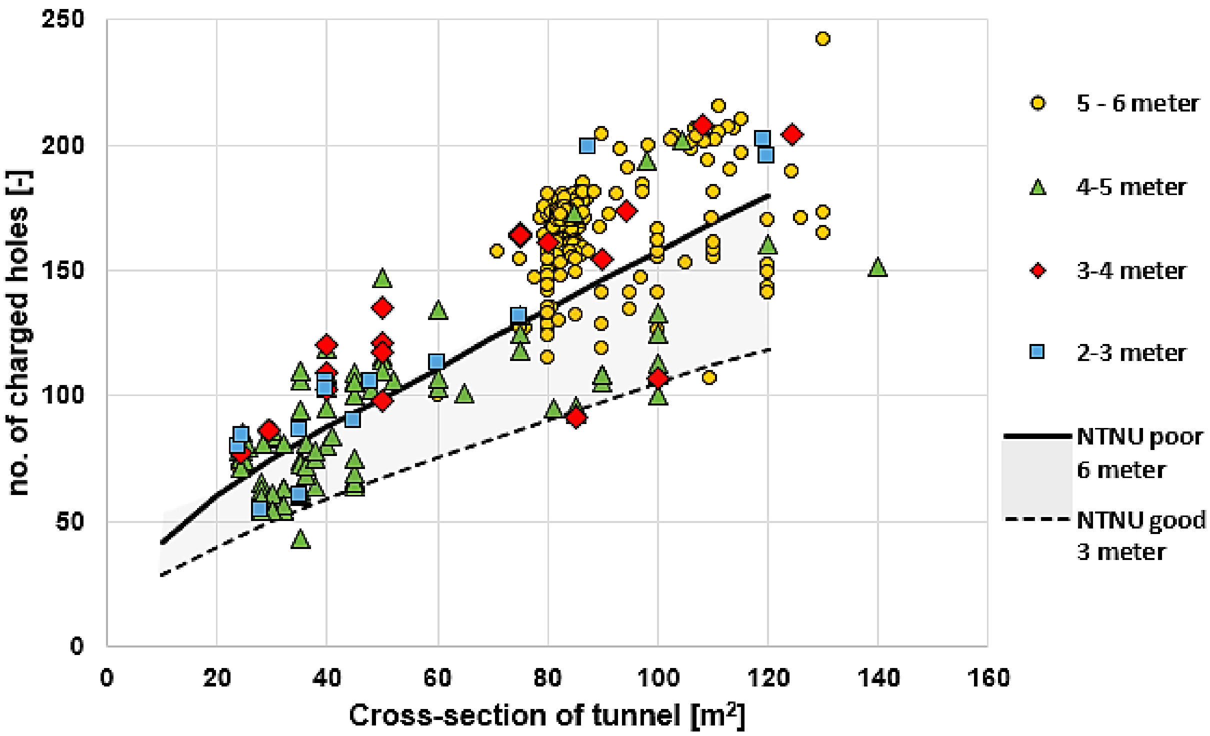

Fig. 3. Relation between number of charged drillholes vs. cross-section for different drillhole diameters. The NTNU model is rendered as the full range of possible plotting area for the various combinations of correction factor K_{bf}. and SPR values and 48 mm charge holes.

The spread of the datapoints in Fig. 2 are also in part an effect of the drill diameter used in the blast design. The distribution of the drill diameters used is presented in Fig. 4. The figure incorporates the 64 mm data from the NTNU model, and highlights that most of the datapoints plotting close to the 48 mm NTNU model lines, or below, originate from drill holes that are either 51 mm or 64 mm sizes. Still, compared to the 64 mm NTNU model, the data plot above the SPR poor line, showing similar trends.

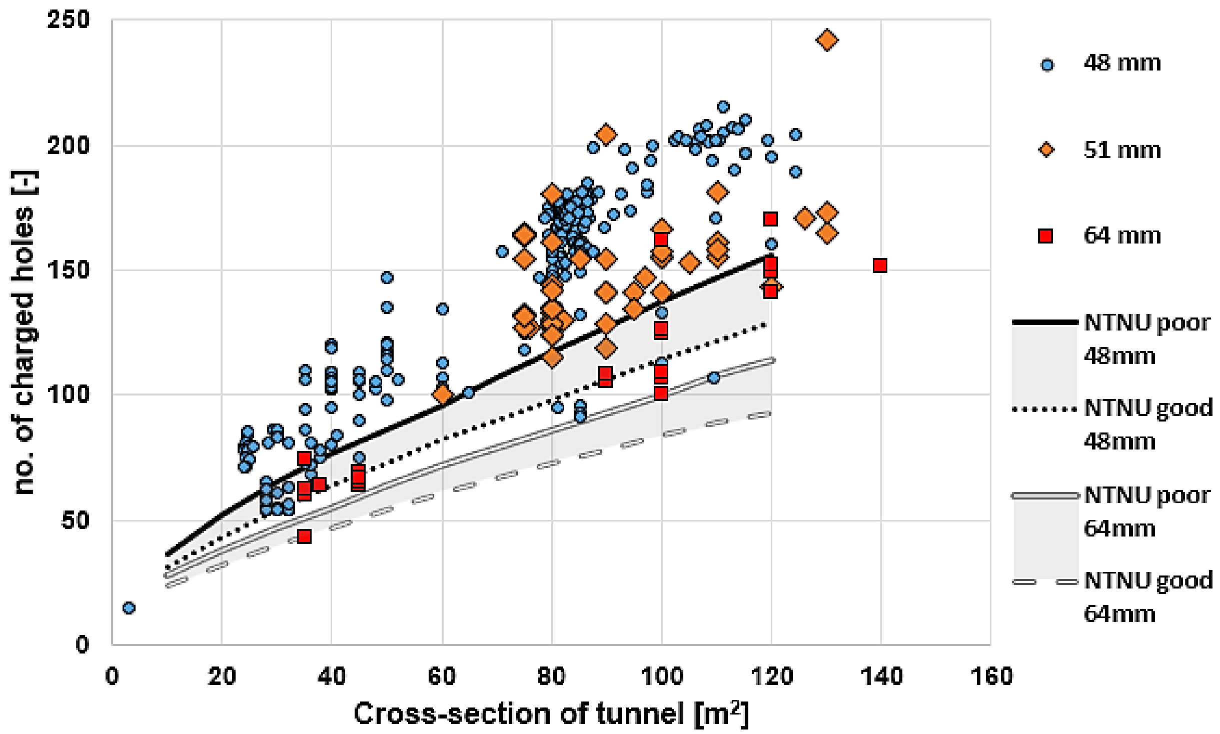

Fig. 4. Relation between number of charged drillholes vs. cross-section for different drillhole diameters.

4.2 Specific charging per blast round

The corresponding specific charge (kg/sm^3) used per blast round for Pro.12 – Pro.15 is presented in Fig. 5 together with the output of the NTNU prediction model for 48 mm and 64 mm diameter holes. The majority of the datapoints plot well above the NTNU model predictions. There occurs also here a relatively large spread of the datapoints along the y-axis for a given tunnel size, for all of the four projects. The result of this variation is a relatively wide variation envelope for the expected range of specific charging values utilized in practice.

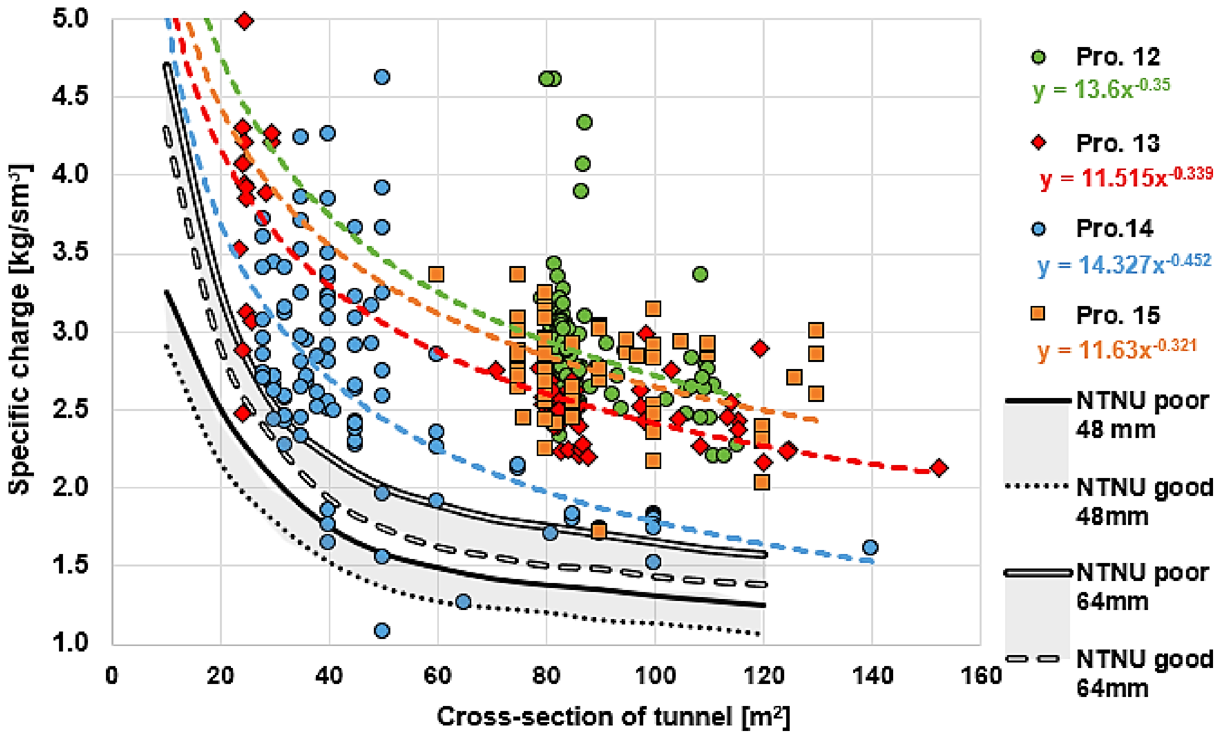

Fig. 5. Relation between specific charging and tunnel cross-section. The NTNU models for 48 mm and 64 mm drill holes are rendered as the full range of possible plotting area for the various SPR values and 5.0 m drill hole lengths. Trendlines for Pro. 12 to 15 are best fit power curves, originating from the blast cut.

All three road tunnel projects plot relatively similar trends in Fig. 5 and display an average specific charge roughly twice as large as the NTNU model, whereas Pro. 14 show a markedly lower trend, particularly for the larger cross-section sizes between 80 and 140 m^2. In this region the datapoints of Pro. 14 plot fairly close to the NTNU model for 64 mm drill holes, which fits rather nicely with the drill hole diameter used in that project in those cross-section sizes (Fig. 6). However, as shown in Fig. 6, the large variation envelope that occurs for all datapoints, regardless of borehole diameter, indication that the project specific trends in Fig. 5 might highlight differences in blasting strategy between different companies, rather than influences by specific drilling parameters.

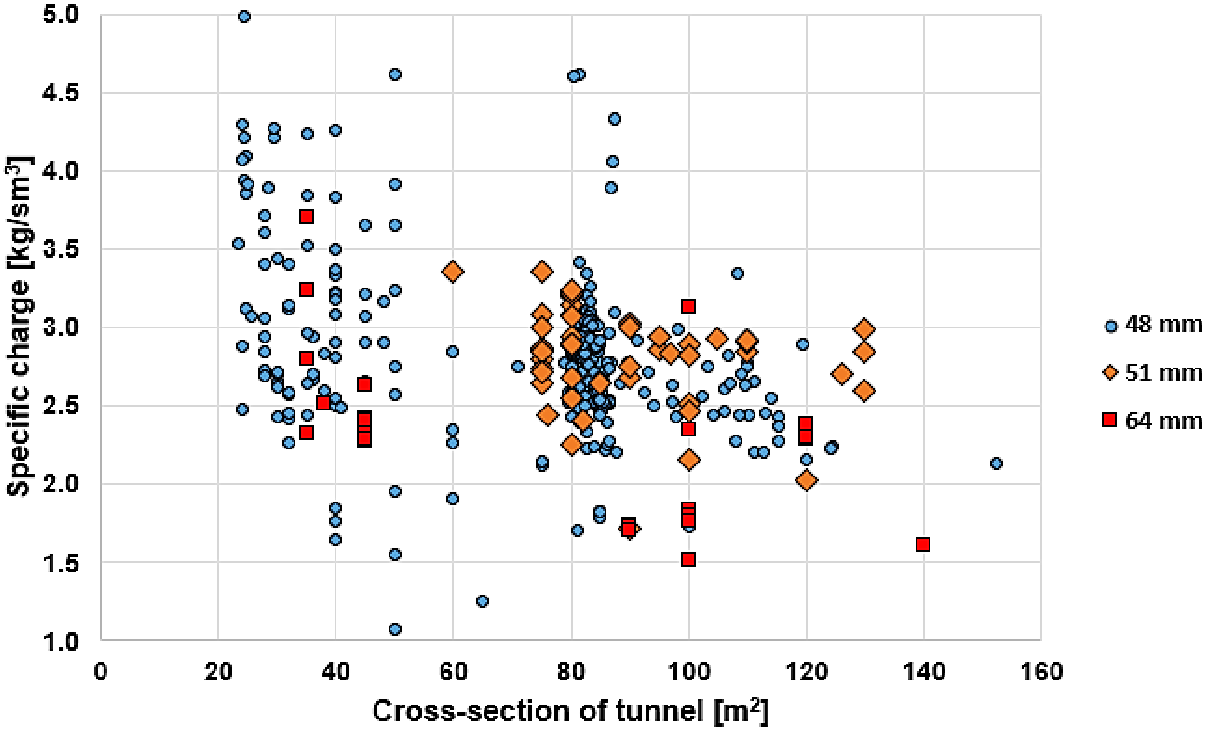

Fig. 6. Relation between specific charging and tunnel cross-section for different drillhole diameters for Pro.12 – Pro.15.

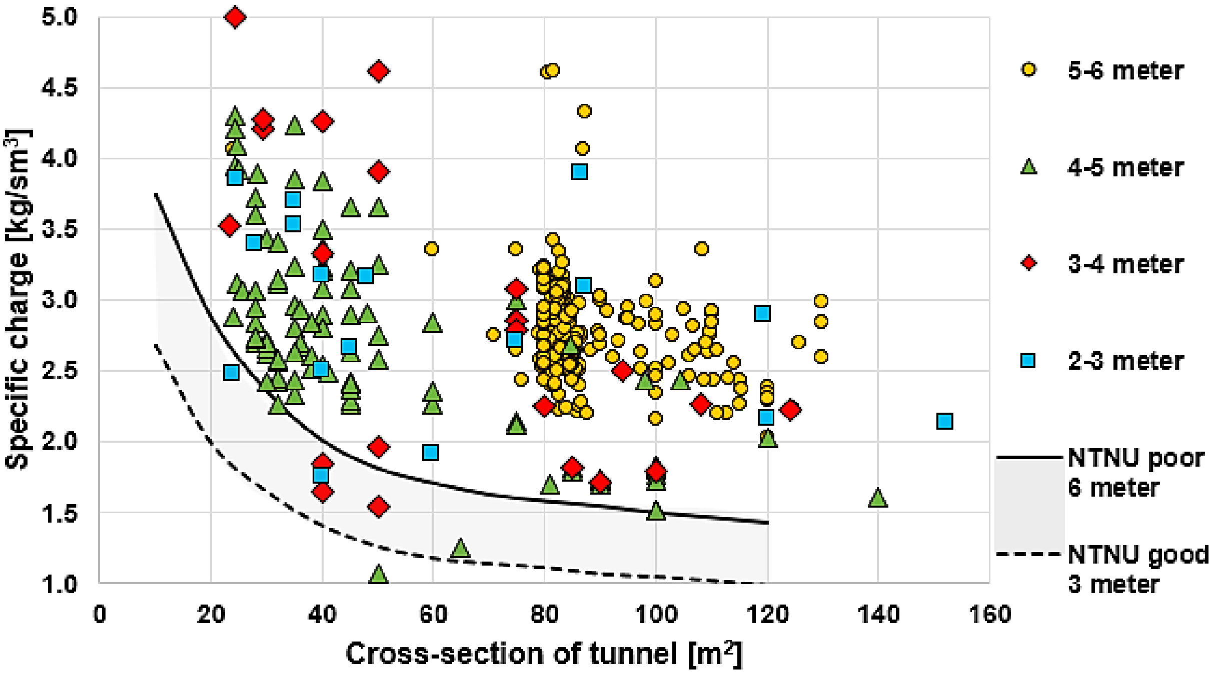

Fig. 7. Relation between specific charging and tunnel cross-section for different drillhole lengths for Pro.12 – Pro.15. The NTNU model is rendered as the full range of possible plotting area for the various combinations of correction factor K_{bf}. and SPR values for 48 mm charge holes.

The same observation can be said to apply if the datapoints are distributed according to the drill hole length of the blast, presented in Fig. 7. The figure highlights that, even though the unit charge might be smaller in shorter drill holes, the specific charge (kg/sm^3) of the blasts stay the same, or in some cases, increase slightly. This is somewhat counterintuitive in view of the NTNU model, which states that the specific charge should decrease with shorter drill length. The majority of the datapoints also plot outside of the NTNU model range even though the variation in drill length is accounted for.

The datapoints that obtain the best fit with the NTNU model (48 mm) is highlighted in Fig. 8 where the datapoints are distributed according to dominant explosives type. In this case the cartridge explosives plot in relatively fair agreement with the NTNU model.

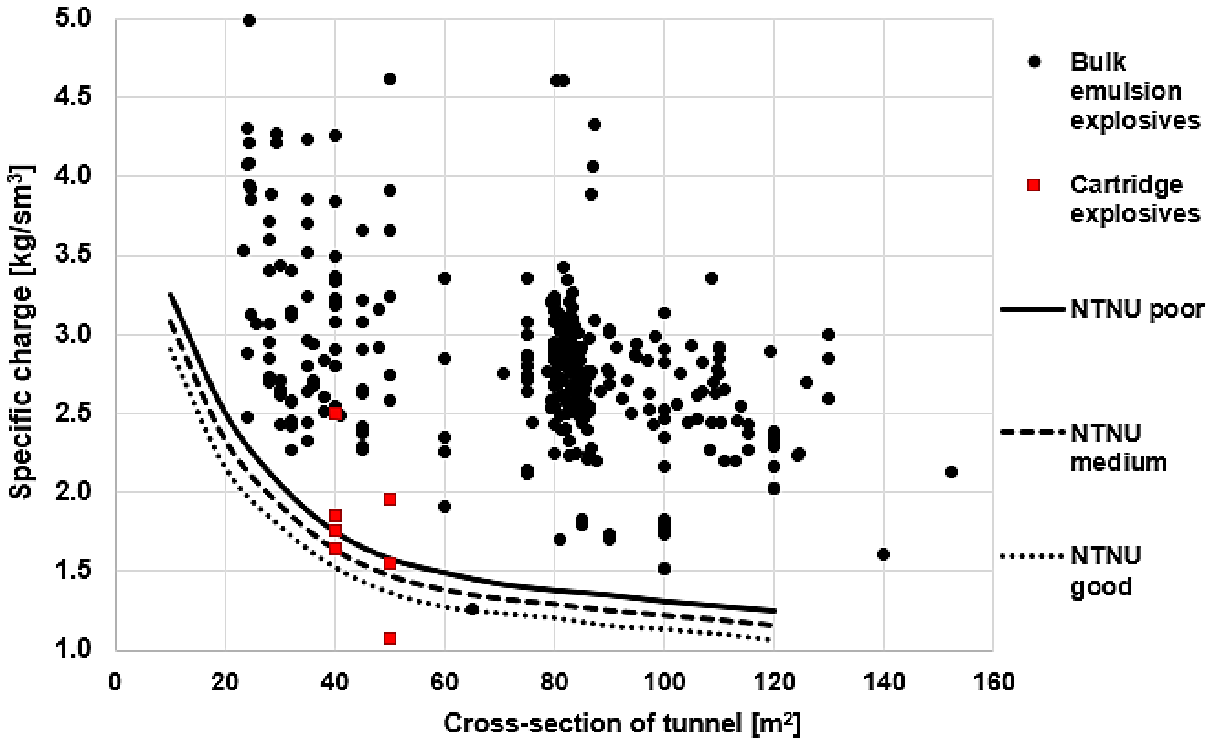

Fig. 8. Relation between specific charging and tunnel cross-section by explosive type. The NTNU models for good, medium and poor SPR are shown as trendlines for 5.0-m standard drill length and 48 mm charge hole diameter.

5 Discussion and conclusion

Data from a total of 353 individual and new blast rounds has been presented in this paper, displaying a rather large variation envelope for the actual D&B tunnelling data used in practise. This variation envelope is much larger than the possible output envelope offered by the current NTNU models. However, the NTNU model is based on average data from datasets and is not directly design to account for project wide variations. This should therefore be noted by practitioners or legal entities, for instance if the NTNU model is used for risk analysis or as a guideline in legal disputes in specific projects in the future.

Apart from displaying the large variation envelope for actual tunnelling data the data also highlight the same trends in the current practice in D&B tunnelling as pointed out by Jakobsen et al. (2024). The current practice tunnelling design seemingly deviate from the principles in the NTNU model by employing both more charged drill holes per blast round in addition to higher specific charging than predicted by the NTNU models. The reasons for this is in part allotted due to a mis-match in the prognosis model related to contour requirements by the road and rail authorities. Also, and perhaps more importantly, due to a significant increase in explosive usage compared to older reference data. The reason for this increase is not clear, and a variety of causes are currently discussed. The increase in specific charging goes beyond the quantity allocated to the increase in number of charged holes, indicating that the charge per hole today is higher than in the early 2000s. For road tunnels the increase in specific charge has in some project doubled, regardless of contractor, drillhole diameter, drill length or SPR.

One of the main hypotheses suggested by Jakobsen et al. (2024) was to be the explosive type used in Norwegian tunnelling today, namely bulk slurry emulsion, which is deemed more susceptible to unintentional over-consumption or waste than cartridge explosives, that were the dominant explosive type until the early 2000s. The new data presented in Fig. 8 seemingly support this statement, showing that cartridge explosive blasts plot much closer to the NTNU model. However, there are only six datapoints within this category in this dataset, and the large variation envelope in the blasting data in general necessitate that more datapoints must be included before a clear conclusion can be drawn.

Based on the new data of current practice D&B tunnelling in Norway today on observation becomes apparent. The current practice blast design seemingly does not regard the rock blastability index (SPR) as a matter of big concern for the blast design and the contractors elect to use more explosives regardless of rock blastability or rock type. Presumably this is due to how tunnelling contracts are organised in Norway today, favouring high production rates and low cost for the projects. The larger specific charge should result in higher degrees of fragmentation of the rock and easier loading conditions for the crew, presumably at the expense of the rock debris quality and its usefulness after excavation.

If this is the case, the prediction accuracy of the NTNU model could be the improved, with respect to current practice D&B tunnelling, by simply adjusting the SPRs used in the model to account for a higher degree of fragmentation. The current SPR index was originally selected so that 50 % of the size distribution of the blast debris is smaller than the 250 mm diameter sieving size. By investigating the size distribution of current practice tunnelling blasts this might be included as a correction, as is the case for surface blasts (Olsen, 2009). This should be investigated in future work.

References

Jakobsen, P.D., Grøv, E., Bruland, A.; Gjengedal, S. (2024) Validity of the NTNU Prediction Model for D&B Tunnelling. *Rock Mech Rock Eng* **57**, 781–791.https://doi.org/10.1007/s00603-023-03585-9

Johannesen, O. (1973) *Steinproduksjon. Ytelser og kostnader*. Institutt for anleggsdrift. Norges Tekniske Hoyskole (NTH). (**InNorwegian**).

Olsen, V. (2009) *Rock Quarrying – Prediction Models and Blasting Safety*. PhD Thesis 2009:96 [1], Norges tekniske-Naturvitenskaplige Universitet (NTNU). pp. 183

Ronn, P-E. (1997) *Konvensjonell drift av tunneler*. Doctoral thesis 1997:6. Norges Tekniske-Naturvitenskapelige Universitet (NTNU). (**In Norwegian**).

Zare S, Bruland A (2006) *Comparison of tunnel blast design models*. Tunnel and Underground Space Technology 21 (5) : 533–541

Zare, S. (2007a) 2A-05 *Drill and Blast tunnelling – Blast design*. PhD Thesis 2007:129 [2], Norges Tekniske-Naturvitenskapelige Universitet (NTNU). pp. 73.

Zare, S. (2007) *Prediction Model and Simulation Tool for Time and Cost of Drill and Blast Tunnelling*. NTNU Trondheim.