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The NTNU model 1976 – 2016

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Abstract

This paper studies the historical development of the NTNU prediction model from 1976 to 2016 and its impact related to the development in hard rock TBM technology during the same period. Tunnelling with TBM machines has become an important used method in the tunnelling industry and the advancements in TBM technology have expanded its applicability to a broader range of ground mass conditions. The interaction between the TBM machine and rock mass is highly complex and the prediction of performance and cutter ring life, especially in hard rock conditions involves large risk assessments. The NTNU prediction model for hard rock TBMs combines several parameters to estimate time and costs in TBM tunnelling e.g. net penetration rate, cutter ring life in addition to advance rate and excavation costs. The model has been updated several times since the first edition in 1976 and the last version was published in 2016. Advancements in TBM technology over recent decades, along with the possible impact of previously unconsidered parameters, necessitate model revisions to enhance prediction accuracy.

Keywords

NTNU prediction model, hard rock TBM technology, prediction accuracy, model revisions.

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1 The NTNU prediction model

In the tunnelling industry, TBM machines have become an important method, with advancements in technology expanding their applicability to a broader range of ground mass conditions. The highly complex interaction between the TBM machine and rock mass, especially encountered in hard rock conditions, involves large risk when predicting performance and cutter ring life. This paper studies the development of the NTNU prediction model from 1976 to 2016 in relation to the advancements in hard rock TBM technology during the same period. The NTNU prediction model for hard rock TBMs estimates time and costs in TBM tunnelling by combining several parameters, e.g., net penetration rate, cutter ring life, advance rate, and excavation costs. The model is based on on-site project studies, combined with statistics and analysis from tunnelling projects carried out in Norway and abroad, including more than 40 sites and more than 300 kilometres of tunnel. Over recent decades, advancements in TBM technology, combined with the potential impact of previously unconsidered parameters, necessitate model revisions to enhance prediction accuracy. The study includes a calculation example illustrating the development of the net penetration rate (m/h) and cutter ring life (h/c) in hard rock, based on the drillability category: Low, medium and high, in hard rock.

2 Historical model development

The development of the NTNU prediction model for hard rock TBMs started in the mid-1970s, with its initial version published in 1976 (Johannessen et al., 1976). The model has been successively developed since the first edition and Table 1 provides a historical overview of previous editions of the NTNU model to date (Bruland, 2000a, Macias, 2016).

Table 1. Historical overview of the NTNU prediction model for hard rock TBMs based on (Bruland, 2000a, Macias, 2016).

Edition	Year
1st	1976
2nd	1979 (published in 1981)
3rd	1983
4th	1988
5th	1994
6th	2000
7th	2016

The further description will provide an overview of the main features of the model development from 1976 – 2016 and provide some comparison of prediction results.

2.1 1976

The 1976 model (Johannessen et al., 1976) estimates the net penetration rate (m/h), cutter costs (NOK/sm³), weekly advance rate (m/week), and excavation costs (NOK/m). Utilizing the Drilling Rate Index (DRI) to quantify the intact rock's penetration capabilities, the model classifies fracturing into three levels: spacing ≥ 20 cm, ≈ 10 cm, and ≤ 5 cm. This classification does not account for the type and orientation of fractures. Net penetration rate is derived from the DRI and the degree of fracturing, assuming optimal machine parameters for the rock conditions. Cutter costs, and consequently cutter life, are determined by the Bit Wear Index (BWI) (Bruland, 2000f), with no consideration given to the rock's quartz or mineral content. The 1976 edition remains a comprehensive tool for estimating time consumption and costs. It offers an intriguing comparison between tunnel boring and drill-and-blast tunnelling in terms of excavation costs. The comparison concludes that tunnel boring is economically viable only for cross-sectional areas ≤ 12 m² and under the most favourable rock conditions, characterized by high DRI and fracture spacing ≤ 5 cm (Bruland, 2000b).

2.2 1979

The 1979 edition (Johannessen and Johansen, 1979) predicts the same four output parameters as the 1976 edition. However, several modifications have been made on the input side. Cutter thrust level is now incorporated in the estimation model for net penetration rate and cutter costs. The applied cutter thrust is related to the degree of fracturing within the rock mass. Additionally, the cutter coefficient has been introduced to evaluate if the machine will be torque limited. Geologically, rock mass fracturing is classified into four classes (corresponding to today's Classes I to IV) and considers the angle between the tunnel axis and the planes of weakness. Fractures with an average spacing of 40 cm (Class I) or less are believed to significantly impact the penetration rate. The influence of fracturing increases for low DRI values and decreases for high DRI values. The classification distinguishes between joints and fissures, although it is unclear how fissures are treated since the model applies to continuous fractures (joints). For cutter costs, TBM diameter is used as a correction factor. The excavation cost model is more detailed but basically remains similar. It provides a comparison of excavation costs, with conclusions consistent with those of 1976 (Johannessen et al., 1976) (Bruland, 2000b).

2.3 1983

In the 1983 edition (Johannessen et al., 1983), distinctions were established between fissure and joint classes, and Fracture Class 0 (non-fractured rock mass) was introduced. The principal effect of rock mass fracturing on the penetration rate was modified so that the optimal angle is around 60° for fracture spacing of 10 cm or more, rather than the previous 90°. The penetration rate model also included the cutter diameter (305 mm to 432 mm). Marked Single Joints were incorporated into the classification of rock mass fracturing, and a model was presented to account for penetration rate increases due to such joints. For the first time, based on the new index CLI, the cutter life in h/cutter was estimated for 356 mm and 394 mm cutters. The rock quartz content in % was used as a correction factor. Additionally, the cutter life estimate included correction factors for cutterhead RPM and cutterhead diameter. A new model for machine utilization was presented, consisting of six sub-operations in the tunnelling process. The excavation cost model remained even more detailed (Bruland, 2000b).

2.4 1988

In terms of geology, the 1988 edition (Johannessen et al., 1988) was nearly equal to the 1983 edition (Johannessen et al., 1983), with mica and amphibole included in addition to quartz in the rock mineral content correction for cutter life. The influence of Marked Single Joints was again included in the Fracturing Classes. The influence of rock porosity was also acknowledged, though only as a tentative correction factor. The penetration rate modelling approach was now based on the penetration curve, essentially the same approach as currently used. The model included the influence of the average cutter spacing and covered cutter diameters from 356 mm to 483 mm. The introduction of the cutter constant aimed to assist in estimating the cutter coefficient, as well as the required torque or installed cutterhead power. The updated estimation model for cutter life now distinguishes the correction factor for cutterhead diameter into two categories: one for domed cutterheads and one for flat cutterheads. The machine utilization model retained the same sub-operations, but now it estimates time consumption in h/km for each sub-operation. The overall machine utilization is then derived from the time required for boring. The cost model retained its previous structure without any modifications (Bruland, 2000b).

2.5 1994

The 1994 edition (Blindheim et al., 1994) introduced practical changes to the penetration estimation process, although it remained based on the penetration curve. The model's coverage for cutter size was increased to 500 mm. The influence of rock mass on the penetration rate was aggregated into the equivalent fracturing factor, and the machine parameters' influence was aggregated in the equivalent thrust. The Marked Single Joints were reintroduced with a separate penetration rate addition. For rocks with porosity exceeding 2%, the influence was integrated into the equivalent fracturing factor. The cutter life estimation was now based on quartz content, aside from the CLI, as the sole influential rock mineral. The time consumption for machine utilization, including TBM and Backup repair and maintenance, as well as the aggregated sub-operation Miscellaneous, was determined to be a function of the net penetration rate. The excavation cost model remained largely unchanged (Bruland, 2000b).

2.6 2000

The 2000 edition (Bruland, 2000a) introduced practical adjustments in the penetration estimation process, though the fundamental modelling approach remained unchanged. The estimation models are derived from a combination of on-site project studies, analyses, and statistics from tunnelling projects in Norway and internationally, including more than 35 sites and over 250 kilometres of tunnel (Bruland, 2000c). The rock drillability test methods are described in (Bruland, 2000f). The statistical distribution of test results for a large number of rock types are shown. For some rock types, the distributions have been modified with respect to e.g. mean values and percentiles. The graphs in

Bruland (2000h) are based on the database in Bruland (2000g). In the 2000 edition, the calculation of the basic penetration rate, one first computes the exponent b in the penetration rate equation, and M_1 is based on k_{ekv} from Figure 2.1, and the value of b is then found from the diagram shown in Figure 2.2 (Bruland, 2000c). In the 1994 edition, M_1 and b were integrated in the basic penetration rate prediction curves in Figure 2.9 and illustrated in Figure 7.5 showing a general penetration curve (Blindheim et al., 1994). The basic penetration rate prediction curves Figure 2.5 in Bruland (2000c) shows that M_1 and b prediction curves have been changed from the corresponding curves in Figure 2.9 of the 1994 edition (Blindheim et al., 1994). The increased basic penetration rate is increased more than 10 % for a high degree of fracturing.

The possibility to estimate the weekly advance rate for working hours other than 100 h/week was introduced by the advance rate model in the 2000 edition, see Figure 4.2 in (Bruland, 2000c). Only minor changes were introduced to the cost model (Bruland, 2000d).

2.7 2016

The 2016 edition (Macias, 2016) are based on data from five international projects involving TBMs ranging from 3.4 to 10 meters in diameter, as well as experience from the past decades. Detailed laboratory testing, geological back-mapping, TBM data analysis, and field trials have been conducted in adequate amounts. Based on the latest advancements in technology, the recommended TBM specifications have been updated and expanded (Macias, 2016).

For different TBM diameters (k_D), calculations have been made for the correction factors and for TBMs with diameters up to about 7 meters, comparisons with the previous version of the model (Bruland, 2000e) shows good agreement. However, for TBMs with a 10-meter diameter, the results exceed predicted values. Because of the limited number of available cutterheads, no variation has been implemented (Macias, 2016).

In response to the outcomes of in-situ trials (RPM tests), field data, and rock mass evaluations, the recommended cutterhead velocity (rpm) parameter has been modified. According to research results and the revised recommended cutterhead rpm, the penetration coefficient (b) and the predicted basic penetration rate have been adjusted. The rock mass fracturing factor has been redefined, with a unified fracture term, and a new classification system has been developed for low degrees of fracturing. The influence of the cutterhead velocity (rpm) on penetration rate has been discussed and based on cutterhead velocity testing RPM test, a factor describing the influence has been introduced. Procedure for RPM test has been proposed. The intervals for DRI and CLI category have been updated. The DRI correction factor has been updated (Macias, 2016).

A methodology has been established, and the basic cutter ring life has been updated. The predicted basic cutter ring life in the updated version has increased by up to around 20% compared with the previous version (Bruland, 2000c). This might be due to an improvement in the cutter disc quality over the last two decades. The updated version has been modified based on minimum cutter ring life values and data obtained from previous versions of the model. The same percentage increment in the basic cutter ring life has also been considered for cutter diameters of 432 mm (17 inches) and 483 mm (19 inches) along the CLI values (Macias, 2016).

A factor describing the influence of average cutter thrust on cutter life for very and extremely abrasive rock types has been introduced. Extra time consumption for tunnel activities related to the length of the tunnel has been included (Macias, 2016).

3 Theoretical calculation example

The historical development of the net penetration rate (m/h) and cutter ring life (h/c) are illustrated in a theoretical calculation example using the standard specifications of a 4.5-meter diameter TBM and medium range of rock parameters. The selected parameters in Table 2 and Table 3 are based on the 2016 edition of the NTNU model (Macias, 2016).

Table 2. TBM Machine input parameters based on (Macias, 2016).

TBM Machine	**Input parameters**	
TBM diameter (m)	4.50	
Cutter diameter (mm)	432	483
Cutterhead rpm (rev/min)	8.29	9.93
Numbers of cutters (N_o)	35	31
Thrust (kN)	7346.8	8756.4
F_N (kN/c)	209.9	282.5
Torque (kNm)	857.1	1113.8
Installed power (kW)	1312.62	1821.9
Cutter spacing (S) (mm)	64.29	70.90
Stroke length (m)	1.80	1.80

Table 3. Rock properties input parameters based on (Macias, 2016).

Rock properties	**Input parameters**
Tunnel length (m)	12500
Fracture spacing (fs) (average, cm)	40.0
Dilling Rate Index, DRI*	50
Cutter Life Index, CLI*	12
Abrasive mineral content, Q (%)	30
Porosity, P (%)	2.0
Fracture Cass	$S_{f\,4}$
Rock mass fracturing factor k_s	0.90
Average angle, α’, °	35.0
Marked Single joints (MSJ)(m), 24(n)	154.24
MSJ orientation, α_{esp}, °	35.0

*The acronyms and trademark terms relating to the indices DRI™ (Drilling Rate Index™) and CLI™ (Cutter Life Index™) are unique to test results originating from the NTNU/SINTEF laboratory in Trondheim (Norway) (Dahl et al., 2012) (Macias, 2016).

The calculation example focuses specific on the cutter diameter (cd) 432 (mm) and the cutter diameter (cd) 483 (mm) where these are described in the different editions of the NTNU prediction model for hard rock TBMs. The rock properties are based on parameters of Dilling Rate Index (DRI), Cutter Life Index (CLI), Abrasive mineral content Q (%) and Porosity P (%) from the category: Low, medium and high, as shown in Table 4.

Table 4. Theoretical case rock properties based on (Macias, 2016).

Theoretic case	**Category**	**DRI**	**CLI**	**Q (%)**	**P (%)**
	low	37	7.0	20.0	0.2
Rock properties	Medium	49	12.0	15.0	0.5
	high	65	25.0	10.0	2.0

Based on the machine parameters in Table 2 and the rock properties in Table 3 and Table 4, Table 5 show results for the net penetration rate (NPR, expressed in m/h) and cutter ring life (Crl., expressed in h/c) in this specific theoretical calculation example.

Table 5. Theoretical calculation example based on the NTNU model 1976 – 2016 (Johannessen et al., 1976) (Johannessen and Johansen, 1979) (Johannessen et al., 1983) (Johannessen et al., 1988) (Blindheim et al., 1994) (Bruland, 2000a) (Macias, 2016).

Edition	Year	Category	DRI	CLI	Q (%)	P (%)	cd: 432	NPR (m/h)	Crl. (h/c)	cd: 483	NPR (m/h)	Crl. (h/c)
*1st edition	1976	Low	37.0	7.0	20.0	0.2	-	-	-	-	-	-
		Medium	49.0	12.0	15.0	0.5	-	-	-	-	-	-
		High	65.0	25.0	10.0	2.0	-	-	-	-	-	-
**2nd edition published in 1981	1979	Low	37.0	7.0	20.0	0.2	-	-	-	-	-	-
		Medium	49.0	12.0	15.0	0.5	-	-	-	-	-	-
		High	65.0	25.0	10.0	2.0	-	-	-	-	-	-
3rd edition	1983	Low	37.0	7.0	20.0	0.2	✓	2.19	1.61	-	-	-
		Medium	49.0	12.0	15.0	0.5	✓	2.85	3.48	-	-	-
		High	65.0	25.0	10.0	2.0	✓	3.66	8.84	-	-	-
4th edition	1988	Low	37.0	7.0	20.0	0.2	✓	3.44	2.23	✓	3.10	2.23
		Medium	49.0	12.0	15.0	0.5	✓	3.44	3.68	✓	3.10	3.68
		High	65.0	25.0	10.0	2.0	✓	3.44	7.93	✓	3.10	7.93
5th edition	1994	Low	37.0	7.0	20.0	0.2	✓	2.50	1.98	✓	4.43	2.65
		Medium	49.0	12.0	15.0	0.5	✓	3.32	2.92	✓	5.00	4.09
		High	65.0	25.0	10.0	2.0	✓	2.50	1.82	✓	5.42	4.99
6th edition	2000	Low	37.0	7.0	20.0	0.2	✓	2.80	2.23	✓	3.64	2.69
		Medium	49.0	12.0	15.0	0.5	✓	3.13	3.38	✓	3.98	3.85
		High	65.0	25.0	10.0	2.0	✓	3.72	5.39	✓	5.03	5.62
7th edition	2016	Low	37.0	7.0	20.0	0.2	✓	2.77	2.64	✓	4.09	3.13
		Medium	49.0	12.0	15.0	0.5	✓	3.13	3.69	✓	4.69	4.45
		High	65.0	25.0	10.0	2.0	✓	3.43	5.65	✓	5.22	6.78

*1st edition in 1976: Model limitation: Cutter diameters are not described.
**2nd edition in 1979 published in 1981: Model limitation, maximum 15 ½ cutters.

The 1st edition in 1976 model limitation, cutter diameters are not described. The 2nd edition 1979 published in 1981 model limitation, maximum 15 ½ cutters. From the 3rd edition in 1983 cutter diameter (cd) 432 (mm) was included and in the 4th edition 1988; the 5th edition 1994; the 6th edition 2000 and the 7th edition 2016 cutter diameter (cd) 432 (mm) and cutter diameter (cd) 483 (mm) were included. Figure 1 show results for the net penetration rate (NPR, expressed in m/h) and Figure 2 show results for cutter ring life (Crl., expressed in h/c) from the 3rd edition in 1983 to the 7th edition in 2016 for the cutter diameter (cd) 432 (mm) and cutter diameter (cd) 483 (mm).

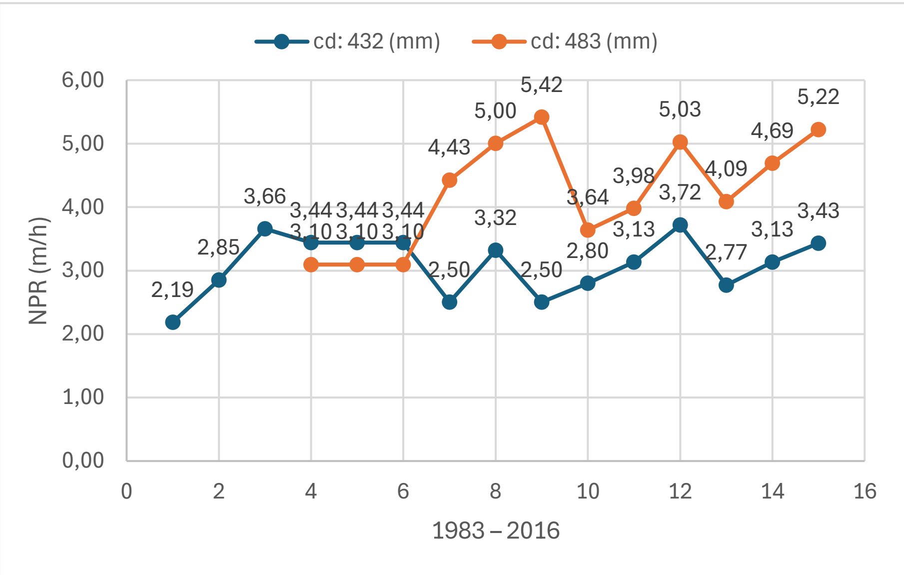

Figure 1. Results from theoretical calculation example presented in Table 5 for the net penetration rate (NPR, expressed in m/h) (Johannessen et al., 1976) (Johannessen and Johansen, 1979) (Johannessen et al., 1983) (Johannessen et al., 1988) (Blindheim et al., 1994) (Bruland, 2000a) (Macias, 2016).

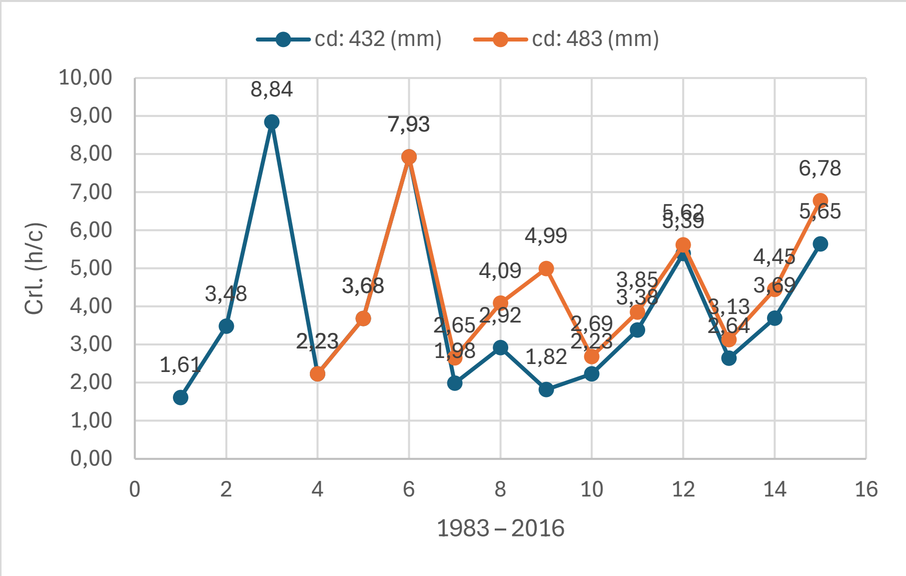

Figure 2. Results from theoretical calculation example presented in Table 5 for cutter ring life (Crl., expressed in h/c) (Johannessen et al., 1976) (Johannessen and Johansen, 1979) (Johannessen et al., 1983) (Johannessen et al., 1988) (Blindheim et al., 1994) (Bruland, 2000a) (Macias, 2016).

The calculation results presented in Table 5 based on the TBM machine parameters in Table 2 and the rock properties in Table 3 and Table 4 illustrates the historical development of the NTNU prediction model for hard rock TBMs from 1976 – 2016, as well as the technological advancements in TBM technology.

3.1 Further editions

The tunnelling and TBM technology are constantly improving, an important factor for continuous updating of the prediction models for performance and assessments of cutter life. More resources should be invested in improving of cutter technology e.g. bearing systems and cutter ring steel quality. Major improvements in machine efficiency can be achieved through the real-time monitoring of cutter thrust, cutter wear, cutter rolling, and temperature parameters for individual TBM cutter discs. This approach also provides a better understanding of rock-breaking and cutter wear processes. The influence of machine designs (e.g., cutter designs and cutterhead layouts) on machine performance and cutter life is not well investigated. Through small adjustments, greater efficiency could be achieved (Macias, 2016).

In relation to the prediction model e.g. integration of more data from large TBMs and/or shield machines. For open gripper and shield TBMs and/or large diameters, an investigation of the gross cutter thrust parameter may exhibit different characteristics. A classification of fractures including e.g. persistence, filling and opening, and the influence of tunnel diameters. Testing of RPM in combination with descriptions of geology, rock mass fracturing in a greater variety of geologies and drillability, rpm levels and cutter thrust as well as TBM types and designs. Research to investigate the opportunity and need to further develop the existing drillability testing. An analysis of the influence of additional parameters like rock stress and groundwater inflow. A study of the influence of cutter tip width and steel quality on tool performance and consumption. The analysis of the influence of cutter thrust on cutter consumption should be verified and expanded by first acquiring more data. The influence of cutterhead layout and design on cutter consumption (Macias, 2016).

4 Summary

This paper studies the historical development of the NTNU prediction model from 1976 – 2016 in relation to the advancements in hard rock TBM technology during the same period. Several parameters are combined in the NTNU prediction model for hard rock TBMs to estimate time and costs in TBM tunnelling, e.g., net penetration rate, cutter ring life in addition to excavation costs and advance rate. The highly complex interaction between the TBM machine and rock mass, involves large risk assessments when predicting performance and cutter ring life, especially in hard rock conditions.

Since the first edition in 1976, the model has been updated several times, with the last version published in 2016. Over the past decades, advancements in TBM technology, along with the possible impact of previously unconsidered parameters, have necessitated model revisions to enhance prediction accuracy. The calculation results presented in Table 5 based on the TBM machine parameters in Table 2 and the rock properties in Table 3 and Table 4 illustrates the historical development of the NTNU prediction model for hard rock TBMs from 1976 – 2016, as well as the technological advancements in TBM technology during the same period.

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