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Some geological and geotechnical factors affecting the performance of a roadheader in an inclined tunnel

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Abstract

The factors affecting the performance of 90 kW-shielded roadheader is investigated in detail in a tunnel excavated for Nuh Cement Factory. The first part of the tunnel is horizontal and the second part is inclined with 9° and excavated uphill. Tunnel passes through a formation of the Upper Cretaceous age with nodular marl, carbonated claystone, thin and thick laminated limestone. Water ingress changes from 0 to 11 l/min. In six different zones it is found that the rock compressive strength changed from 20 to 45 MPa, tensile strength from 1 to 4 MPa, specific energy from 11 to 16 MJ/m^3, plastic limit from 15% to 29%, liquid limit from 27% to 43% and water absorption from 4% to 18% in volume.

Detailed in situ observations show that in dry zones for the same rock strength the inclination of the tunnel and the strata help to increase the instantaneous cutting rate from 10 to 25 solid bank m^3/cutting hour. The effect of water on cutting rate is dramatic. In the zones where the plastic limit and the amount of Al_2O_3 is low, instantaneous cutting rate increases from 34 to 50 solid bank m^3/cutting hour with increasing water content from 3.5 to 11 l/min. However, in the strata having high water absorption characteristic and high amount of Al_2O_3, cutting rate decreases considerably due to the sticky mud, causing problem to the cutterhead. Excavation, muck loading and support works are performed separately due to safety concerns in the wet and inclined sections which reduced the machine utilization time from 38% to 8%. The information gathered is believed to form a sound basis in contributing the performance prediction of roadheaders in difficult ground conditions.

Keywords: Tunnel excavation; Roadheader performance prediction; Core cutting test; Specific energy

1. Introduction

The application of roadheaders in difficult ground conditions, in recent years, has increased considerably in both civil and mining engineering fields. The prediction of instantaneous (net) cutting rate and machine utilization time, determining daily advance rates, plays an important role in the time scheduling of the tunneling projects, hence, in determining the economy of tunnel excavation.

Although many roadheader performance prediction models were published in the past, the published data on difficult ground conditions such as the effects of tunnel inclination, water ingress, excessive fracture zones, etc. on daily advance rates were quite scarce. Sandbak (1985) and Douglas (1985) used a rock classification system to explain the changes of roadheader advance rates at San Manuel Copper Mine in an inclined drift at an 11% grade. They concluded that for a performance prediction model, engineering aspects of the roadheaders had to be also incorporated with the geomechanical factors. Field data on roadheader machine performance in inclined tunnels were also published by Unrug and Whitsell (1984) for a 14° slope in Pyro Coal Mine, by

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Navin et al. (1985) at 13° and 15° inclines in oil shale mine and by Livingstone and Dorricott (1995) in Ballarat East Gold Mine.

The majority of performance prediction models were developed for horizontal tunnels. Bilgin (1983) developed a model based on specific energy obtained from drilling rate of a percussive drill. Models for widely jointed rock formations were described by Schneider (1988), Thuro and Plinninger (1998, 1999), Gehring (1989, 1997), Dun et al. (1997) and Uehigashi et al. (1987). They reported that for a given cutting power, cutting rates of roadheaders decreased dramatically with increasing values of rock compressive strength. Copur et al. (1997, 1998) stated that if the power and the weight of the roadheaders were considered together, in addition to rock compressive strength, the cutting rate predictions were more realistic.

Another concept of predicting machine instantaneous cutting rate was to use specific energy described as the energy spent to excavate a unit volume of rock material. Farmer and Garrity (1987) and Poole (1987) showed that for a given power of roadheader, excavation rate in solid bank m^3/cutting hour might be predicted using specific energy values given as in the following equation,

$$\mathrm{SE} = \frac{\sigma_c^2}{2E}, \tag{1}$$

where SE is the specific energy, σ_c is the rock compressive strength and E is the rock elastic modulus.

Widely accepted rock classification and assessment for the performance estimation of roadheaders is based on the specific energy found from core cutting tests (McFeat-Smith and Fowell, 1977, 1979; Fowell and Johnson, 1982; Fowell et al., 1994). Detailed laboratory and in situ investigations carried out by McFeat-Smith and Fowell (1977, 1979) showed that there was a close relationship between specific energy values obtained from core cutting tests and cutting rates for medium and heavy weight roadheaders separately. They reported also that tool consumption might be predicted from weight loss of cutter used in core cutting test.

Rock cuttability classification based on core cutting test is usually criticized as that the effect of rock discontinuities are not reflected in performance prediction. Bilgin et al. (1988, 1990, 1996, 1997) developed a performance equation based on rock compressive strength and rock quality designation as given below

$$\mathrm{ICR} = 0.28 \times P \times (0.974)^{\mathrm{RMCI}}, \tag{2}$$

$$\mathrm{RMCI} = \sigma_c \times (\mathrm{RQD}/100)^{2/3}, \tag{3}$$

where ICR is the instantaneous cutting rate in solid bank m^3/cutting hour, P is the power of cutting head in hp, RMCI is the rock mass cuttability index, σ_c is the uniaxial compressive strength in MPa and RQD is the rock quality designation in percent.

Dun et al. (1997) compared the models described by Bilgin et al. (1988, 1990) and McFeat-Smith and Fowell (1977, 1979) in a research work carried out at Kumbalda Mine where a Voest Alpine AM75 roadheader was utilized. Two distinct groups of data were evident. The data grouped around Bilgin line was strongly influenced by the jointing and weakness zones present in rock mass. The other group of data on the line produced by McFeat-Smith and Fowell corresponded to areas where less jointing and fewer weakness zones were present.

One of the most accepted method to predict the cutting rate of any excavating machine is to use, cutting power, specific energy obtained from full scale cutting tests and energy transfer ratio from the cutting head to the rock formation as in the following equation (Rostami et al., 1994; Rostami and Ozdemir, 1996)

$$\mathrm{ICR} = k\frac{P}{\mathrm{SE_{opt}}}, \tag{4}$$

where ICR is th instantaneous production rate in solid bank m^3/cutting hour, P is the cutting power of the mechanical miner in kW, $\mathrm{SE_{opt}}$ is the optimum specific energy in kWh/m^3 and k is energy transfer coefficient depending on the mechanical miner utilized. Rostami et al. (1994) strongly emphasized that the predicted value of cutting rate was more realistic if specific energy value in equation was obtained from full-scale linear cutting tests in optimum conditions using real life cutters. Rostami et al. (1994) pointed out that k changed between 0.45 and 0.55 for roadheaders and from 0.85 to 0.90 for TBMs.

Bilgin et al. (2000) showed in their experimental and numerical studies that performance of mechanical miners was affected upto a certain degree by the earth and/or overburden pressure and stress. Copur et al. (2001) showed that specific energy obtained from full-scale linear cutting tests in optimum cutting conditions was highly correlated to rock uniaxial compressive strength and Brazilian tensile strength.

The effect of tunnel inclination, water ingress and the presence of clay on roadheader performance was not clearly shown in the above-mentioned works. The main objective of the research study described in this paper is to contribute the performance prediction models in difficult ground conditions. Hereke tunnel is chosen for this purpose. The first 50 m of the tunnel is horizontal. Later 225 m is inclined with 9° and excavated uphill. There is excessive water ingress and clay in some sections. Detailed in situ observations are made during the tunnel excavation and rock samples are collected for testing in the laboratories of the Mining Engineering Department of Istanbul Technical University for ground characterization. Instantaneous cutting rate of the roadheader used in the project is explained by some geological and geotechnical factors. Factors affecting machine utilization time is also explained in detail.

2. Description of the tunnel project

The Hereke Tunnel, located in Turkey in the city of Kocaeli next to Istanbul, was constructed for material transportation between the Nuh Cement Dock and Nuh Cement Plant. Tunneling was the best choice to avoid traffic disruption, since there was a railway, highway and freeway on the surface. The contractor firm STFA Co. was awarded the tunneling project. The tunnel included 50 m of horizontal section (chainage 0–50 m), where excavation started up, and 225 m of 9° inclined section (chainage 50–275 m). The excavation was performed in a horizontally straight alignment through sedimentary formations including dry (chainage 0–50 and 150–275 m) and wet sections (chainage 50–150). Excavation was performed by using a shielded roadheader, Herrenknecht-SM1 with 90 kW of cutter head power, in the excavation diameter of 3.48 m. Two shafts were sunk in the plant side of the tunnel. The first shaft was planned to be used for cement transportation from the plant to the dock via steel pipe line and the second shaft for coal transportation to the plant via a belt conveyor and skip haulage system.

3. Geology of the project site

The Hereke Tunnel passes through a formation of the Upper Cretaceous age. The formation exhibits fractured and folded structure with the direction of 48–52°N and the dip of 30°NE. The strata types encountered in this relatively shallow tunnel (3–21 m of overburden) are nodular marl and thin and thick laminated clayey limestone, carbonated claystone and thin laminated silisified limestone. Some levels of laminated limestone (chainage from 50 to 150 m) form a fractured aquifer causing water ingress in the tunnel. The tunnel is divided into six sections according to their structural and geotechnical differences. Fig. 1 presents the general layout of the tunnel and shafts and the geological cross-section along the tunnel route.

4. Construction method

Mechanical excavation method was chosen to minimize the ground disturbance beneath the railway, freeway and highway located between the Nuh Cement Plant and the Dock. Based on the geological and geotechnical information of the project site, a double-shielded roadheader cutter boom was considered to be well suited for the job.

Segmental precast concrete linings were used as final tunnel support. The segments were cast in site next to the tunnel entrance located on the dock side, transported to the tunnel by a monorail system with lifting capacity of 500 kg and placed by an erector and bolted behind the tail shield after at least every 75 cm of roadheader advance. A complete ring included six pieces of segments. Grout injection was applied through the holes in the segments to fill out the void between the tunnel wall and the rings.

Excavation, muck loading and ring installation works were performed simultaneously in the horizontal section of the tunnel (chainage 0–50 m). While installing the rings in the inclined section (chainage 50–275 m), excavation had to stop due to safety concerns.

Ventilation was performed by using flexible ducts and two fans, one of which was suction and the other exhaustive (blower). The suction fan was placed in front of the roadheader operator. The exhaustive fan was placed in front of the roadheader motors.

Muck coming through the chain conveyor and tail conveyor of the roadheader was dumped to muck cars (wagons) of 4 m^3 capacity, with the average loading rate of 5–7 min, and transported by a battery locomotive in

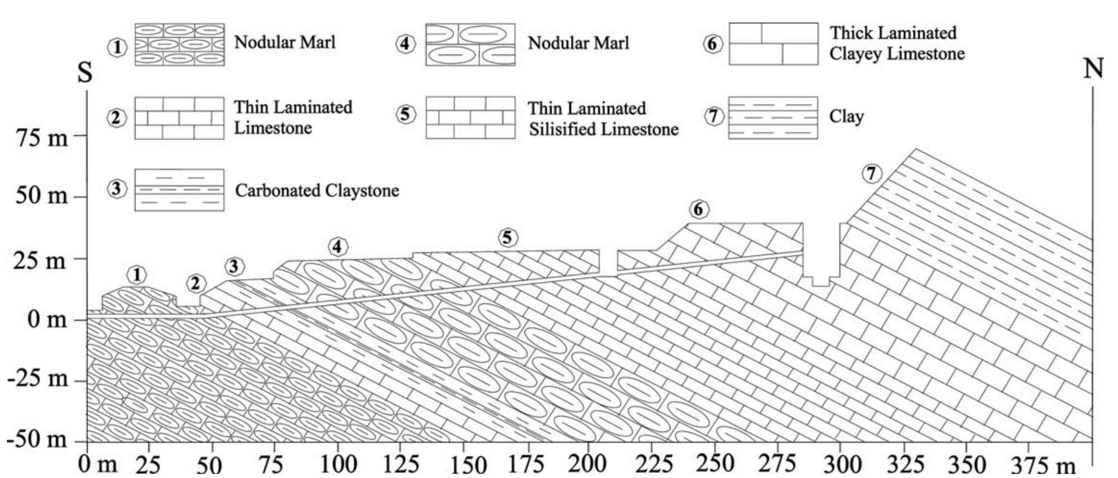

Fig. 1. Geological cross-section across the tunnel layout.

Fig. 2. General view of the roadheader used in the Hereke Tunnel.

the horizontal section (chainage 0–50 m) and by a wire rope haulage system, with an average haulage speed of 11 m/min, in the inclined section (chainage 50–275 m). The loaded muck cars transported to outside of the tunnel on the dock side were dumped to a 30-ton capacity track, which took it to the stockyard of the Nuh Cement Plant to use as raw material for cement production, by a portable crane.

Job organization consisted of two shifts of 12 h/day and 7 days/week. The number of labor working on the face was usually seven in a shift including one foreman, one roadheader operator, three ring montage staff, one loco operator and one crane operator.

Herrenknecht SM-1 double-shielded roadheader cutter boom was used in the Hereke Tunnel to fulfill the excavation job, Fig. 2. It was a refurbished machine of 3.48 m in excavation diameter and had a cutter boom with the length of 3.5 m attached to a beam inside the front shield. It had a new (unused) axial type cutterhead having an installed cutting power of 90 kW (120 hp), a variable rotation speed of up to 51 rpm and 36 conical cutters laced on a double-spiral pattern. It had a telescopic double-shield system allowing for excavation without any stoppage for segmental lining montage; in other words, excavation, muck loading and ring installation could be performed simultaneously. The front shield in 2.9 m length and the tail shield in 4.1 m length had a weight of 37 and 48 ton, respectively. Thickness of the shields was 30 mm. The front shield included five breast shields located on the upper front part, with the stroke of 85 cm, as a precaution to any face collapse condition. The machine had its thrust force from the last ring placed by using 11 hydraulic rams, each of which could thrust 12 MPa.

5. Geotechnical properties of the rock formation

Samples are collected by the authors of this paper from the six zones encountered on the tunnel alignment (Fig. 1) for testing in the laboratories of the Faculty of Mines of the Istanbul Technical University. These tests include chemical analysis, uniaxial compressive strength, Brazilian tensile strength, water absorption, plastic limit, liquid limit and specific energy (core cutting) tests.

Chemical analyses are carried out on the samples collected from six different zones to well understand the cutting behavior of the roadheader. The results of chemical analysis are presented in Table 1.

Uniaxial compressive strength tests are performed on core samples having a diameter of 33 mm and a length to diameter ratio of 2. The stress rate is applied within the limits of 0.5–1.0 MPa/s.

Brazilian tensile strength tests are conducted on core samples having a diameter of 33 mm and a length to diameter ratio of 1. The tensile load on the specimens is applied continuously at a constant rate.

Water absorption, plastic limit and liquid limit tests are carried out according to related ASTM standards.

Specific energy is obtained as described by McFeat-Smith and Fowell (1977, 1979). The test involves instrumented cutting tests on a 76-mm diameter core at a cutting depth of 5 mm, cutting speed of 150 mm/s, with a tungsten carbide chisel-shaped tool having 8% cobalt by weight, 3.5 μm nominal grain size, rake angle of $-5°$ and tool width of 12.7 mm.

The results of geotechnical tests are presented in Table 2.

6. Roadheader performance analysis in different zones

Excavation of the Hereke Tunnel was completed in 2 months with an average daily advance rate of 4.6 m. During this period, related field data, including machine performance and geotechnical parameters, were recorded by the authors of this paper. Performance of the roadheader was continuously recorded, including instantaneous cutting rate, machine utilization time and all stoppages for the different zones in the tunnel route.

Instantaneous (or net) cutting rate (ICR) is defined as is the production rate for the actual (net) cutting time of the machine (ton or solid bank m^3/cutting hour). Machine utilization time (MUT) is the net excavation time as a percentage (%) of the total working time, excluding all the stoppages. Advance rate (AR) is the linear advance rate of the tunnel or drift excavation (m/shift, m/day, m/week and m/month) and is a function of ICR, MUT and cross-section area of the excavated face.

Water ingress and geological discontinuities in the tunnel face were also recorded.

The recorded instantaneous cutting rate, water ingress, RQD values of the face and machine utilization time values are tabulated for different tunnel zones in Table 3. Machine utilization, percentages of stoppages

Table 1
Chemical composition of the rock samples taken from different zones

Tunnel chainage (m)	Zone	SiO_2	Al_2O_3	CaO	MgO	K_2O	Fe_2O_3	LOI[a]
0–50	1. Nodular Marl	21.89	5.48	36.81	1.13	1.12	2.41	30.91
50–70	2. Thin Laminated Limestone	10.06	2.68	46.75	0.12	0.41	1.24	37.53
70–80	3. Carbonated Claystone	57.04	15.10	12.23	0.67	1.53	3.01	9.41
90–150	4. Nodular Marl	18.47	4.67	39.86	1.21	0.87	1.90	33.00
150–225	5. Thin Laminated Silisified Limestone	17.90	1.78	43.55	0.49	0.27	0.76	35.13
250–275	6. Thick Laminated Clayey Limestone	20.20	5.26	38.00	1.32	0.97	1.96	30.42

[a] Loss on ignition.

Table 2
Geotechnical properties of the rock samples taken from different zones

Tunnel chainage (m)	Zone no.	Tunnel inclination (°)	Compressive strength (kg/cm^2) ± SD[a]	Tensile strength (kg/cm^2) ± SD	Water absorption in volume (%)	Plastic limit (%)	Liquid limit (%)	SE[b] (MJ/m^3)
0–50	1.	Horizontal	200 ± 12	10 ± 0.6	5.4	17	32	11.0
50–70	2.	9°	210 ± 13	11 ± 0.5	3.8	15	27	–
70–80	3.	9°	200 ± 9	10 ± 0.4	18.1	29	43	–
90–150	4.	9°	200 ± 10	10 ± 0.6	5.0	18	32	–
150–225	5.	9°	210 ± 11	12 ± 0.4	5.4	–	–	11.2
250–275	6.	9°	450 ± 20	40 ± 2.0	4.3	–	–	16.3

[a] Standard deviation.
[b] Specific energy.

Table 3
Summary of the roadheader performance in six different zones

Tunnel chainage (m)	Zone no.	RQD (%)	Water ingress (l/min)	Net cutting rate (solid bank m^3/cutting hour)	Machine utilization (%)	Mean daily advance (m/day)
0–50	1	75	Dry	10	38	9.6
50–70	2	65	11	50	8	10.1
70–80	3	65	11	20	8	4.0
90–150	4	70	3.5	31	8	6.3
150–225	5	75	Dry	25	8	5.1
250–275	6	75	Dry	20	8	4.0

and other planned jobs such as ring montage, site surveying, etc. are presented in Fig. 3.

7. Discussion

The research results are discussed in two basis: instantaneous cutting rate and machine utilization time.

7.1. The effect of strata inclination

One of the most accepted methods for determining the roadheader cutting rate in horizontal and widely jointed rock formation is to use laboratory cutting specific energy obtained from instrumented core cutting test (McFeat-Smith and Fowell, 1979). As seen from Table 2, the samples taken from nodular marl, zone 1, have the specific energy value of 11 MJ/m^3, which corresponds to an instantaneous cutting rate of 8 solid bank m^3/cutting hour for non-inclined strata and medium weight roadheaders in the McFeat-Smith and Fowell's model. However, it is observed in the site that the inclination of the strata is in favor of the cutting action and the muck is easily coming out from the excavated area. The instantaneous cutting rate in this area (zone 1) is recorded to be 10 solid bank m^3/cutting hour.

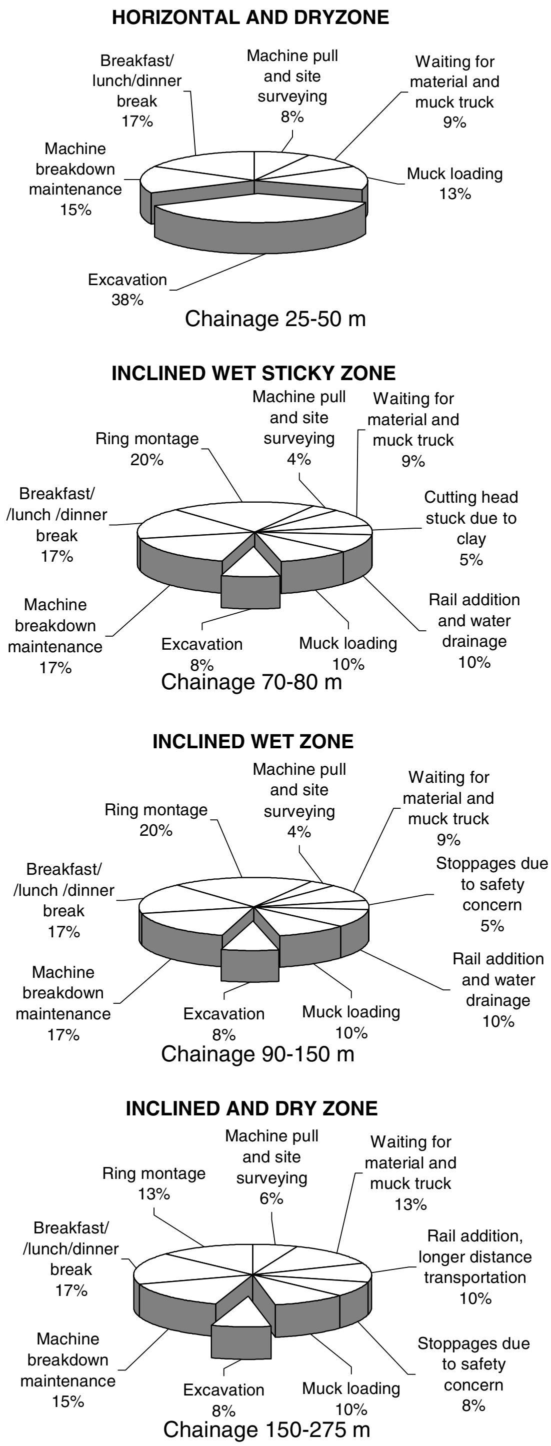

Fig. 3. Detailed roadheader performance analysis results for the Hereke Tunnel.

7.2. The effect of tunnel inclination

In zone 5, having the same compressive strength and specific energy values as in zone 1, the instantaneous cutting rate is more than double being 25 solid bank m^3/cutting hour. The inclination of the tunnel, hence, the gravity forces help the muck being loaded easily and coming quickly on the cut face preventing the muck recirculation within the cutting head and the face.

7.3. The effect of rock strength and specific energy values

Samples taken from zone 5 have compressive strength of 210 kg/cm^2 and specific energy of 11.2 MJ/m^3, and samples taken from zone 6 have compressive strength values of 450 kg/cm^2 and specific energy values of 16.3 MJ/m^3. This is reflected in instantaneous cutting rate values being 25 solid bank m^3/cutting hour in zone 5 and 20 solid bank m^3/cutting hour in zone 6.

7.4. The effect of water

The effect of water on the instantaneous cutting rate is dramatic. The water ingress in zone 2 is 11 l/min and zone 5 is dry, the samples taken from these two zones have the same compressive strength. However, the instantaneous cutting rate in the wet zone (50 solid bank m^3/cutting hour) is twice (double) more than in the dry zone (25 solid bank m^3/cutting hour). This might be due to the fact that the water reduces the strength of the strata and helps the muck coming easily from the tunnel face.

7.5. The effect of wet sticky zone

Water ingress in zone 3 is the same as in zone 2, being 11 l/min. The samples taken from zone 3 have the same strength as zone 2. However, it is observed in the site that the muck in zone 3 is sticky (muddy) and sticks the cutting head, hence, decreases the instantaneous cutting rate from 50 to 20 solid bank m^3/cutting hour. The samples taken from zone 3 have Al_2O_3 content of 15.1%, water absorption of 18.1%, plastic limit of 29% and liquid limit of 43%. XRD analysis show that the clay in zone 3 consists of nontronite and kaolinite. The pictures of the original (new, unused) cutting head (on top) and the mud on the cutting head after utilizing in the wet sticky zone (at the bottom) are seen in Fig. 4.

Zones 2 and 4 have similar geotechnical properties, although the water ingress in zone 4 is 3.5 l/min being one-third of the water ingress in zone 2. This is reflected dramatically on the instantaneous cutting rate value, which is 31 solid bank m^3/cutting hour in zone 4 and 50 solid bank m^3/cutting hour in zone 2.

7.6. The effect of lamination

It is considered that lamination affects the instantaneous cutting rate. Thin laminated limestone (zone 2) has a thickness varying between 2 and 0.6 cm. The instantaneous cutting rate in zone 2 reaches at an average of 50 solid bank m^3/cutting hour, which is the maximum

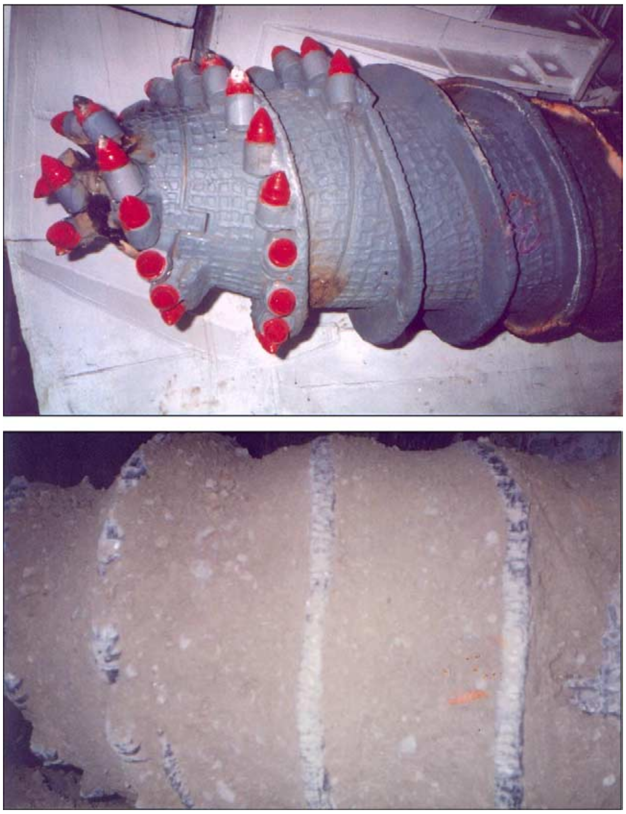

Fig. 4. Pictures of the new (unused) cutting head (on top) and mud on the cutting head after utilizing in the wet sticky zone (at the bottom).

rate among all of the zones, as seen in Table 3. On the other hand, the chemical composition of the excavated formations affects the instantaneous cutting rate, as well. Although the thin laminated limestone (zone 2) and thin laminated silisified limestone (zone 5) have similar thicknesses, the instantaneous cutting rate is lower in zone 5, being 25 solid bank m^3/cutting hour, which might be due to silisification, as well as being dry.

The thickness of thick laminated clayey limestone (zone 6) is greater than 60 cm. Therefore, it can be concluded that, based on previous researches (Bilgin et al., 1988, 1990, 1996, 1997), lamination does not increase the instantaneous cutting rate in zone 6. It is a known fact that discontinuity spacing smaller than around 10 cm increases the instantaneous cutting rate.

Joint type discontinuities affect similarly the all of the zones in the region. Since the RQD values are similar in all of the zones, Table 3, the effect of joints on the roadheader performance cannot be deduced.

7.7. The factors affecting machine utilization time

Machine utilization time is as important as instantaneous cutting rate, since daily advance rates are directly related to machine utilization time, daily working hours, tunnel cross-section area and instantaneous cutting rates.

The machine utilization time is 38% in the horizontal section of the tunnel (zone 1). Tunnel excavation and ring montage are executed simultaneously in zone 1. However, the machine utilization time decreases to 8% in the inclined zones 2, 3, 4 and 5 due to the difficulties related to the tunnel inclination, which is reflected in job organization. Tunnel excavation and ring montage are executed separately, which reduces the machine utilization time, in the inclined section of the tunnel due to the safety concerns. In other words, excavation stops during the ring montage. The ring montage takes 13% of the total working time in the dry-inclined section, while it takes 20% in the wet-inclined section.

In addition to the ring montage stoppages, some other stoppages coming from the job organization are encountered in the inclined wet and dry zones: 9–13% of the total time is spent to waiting for material and muck trucks. The cutting head sticks in the sticky zone due to the sticky mud, causing a delay of 5%. About 15–17% of the total working time is spent to machine breakdown and maintenance in the entire tunnel.

8. Conclusions

The prediction of instantaneous (net) cutting rate and machine utilization time, determining daily advance rates, play an important role in the time scheduling of the tunneling projects, hence, in determining the economy of tunnel excavation. The majority of the performance prediction models developed by different research workers were for non-inclined tunnels. The effects of strata inclination, tunnel inclination, water ingress and the presence of clay on roadheader performance were not clearly shown in those models.

Detailed in situ investigations during Hereke Tunnel excavation show that strata and tunnel inclination, water ingress to a certain extend increase the instantaneous cutting rate up to 2–5 times compared to a non-inclined tunnel. The inclination of the tunnel, hence, gravity forces help the muck being loaded easily and coming quickly on the cut face preventing the muck recirculation within the cutting head and the face. However, material cut in the wet zones containing nontronite and kaolinite sticks the cutting head and decreases the instantaneous cutting rate considerably.

Machine utilization time which is a very important parameter in determining daily advance rate is much effected by the tunnel inclination, decreasing from 38% to 8%. In Hereke Tunnel, in the inclined zone tunnel excavation and ring montage were executed separately due to safety reasons which reduced the machine utilization time.

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