Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)

A model for fair compensation of construction costs in TBM tunneling: A novel contribution

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ABSTRACT: TBM tunneling represents state-of-the-art excavation method for long alpine tunnels. This kind of tunnel construction is always associated with a considerable amount of uncertainty, having two major impacts on the TBM advance: various adverse occurrences at the tunnel face and imposing reductions of the achievable performance. The reduction is caused by the need to advance with sub-optimal operation parameters and the increased inspection and maintenance efforts. The second influence is given by the usage of additional measures in order to enable a safe TBM advance. The additional time required by encountering circumstances as described above can be hardly anticipated during the design phase. The model presented in this publication uses a very simple solution for the aforementioned issues: the construction activity during TBM advance is divided into three categories: regular advance, hindered advance and event-driven advance stop. A clear set of delimiting criteria is defined in the paper allowing a simple and objective identification.

1 INTRODUCTION

TBM tunneling represents state-of-the-art tunneling method for construction of long alpine tunnels, due to the intrinsic advantages of obtaining an almost finished tunnel by the end of the advance (in case of shield tunneling with pre-cast concrete segments), lower requirements on ventilation and fully mechanized, high-capacity logistics. The drawbacks, when compared to conventional tunnels, are also well known: possibly high performance is traded for lower flexibility, larger requirements on the ground investigation and risk of long standstills in case of TBM becoming trapped.

TBMs equipped with a hard rock cutterhead and without an active face support are generally used in alpine conditions. The desired performance is obtained only in case of a stable face, where intended regular chipping occurs, and stable extrados, where the filling of the annular gap is not hindered by debris in the annular gap. In case such conditions are not given, for instance in a jointed rock mass with high uniaxial compressive strength, this results in continuous dynamic loading of every disc, impact upon impact, and brittle damage to the discs (Figure 1).

In case of weak ground (tectonic faults), large displacements occur frequently and support pressure is mobilized already in the shield area, leading to an increased thrust force demand (Ramoni, 2010) and possible reduction of the performance. In larger tectonic faults perpendicular to the alignment, high volume overbreaks ahead of the face (Figure 2) can also be frequently observed, leading either to situations of “infinite mucking” or to cutterhead blockade. Both require substantial efforts on ground stabilization before an advance restart is attempted.

Figure 1. Left: Block rock mass. Right: damaged disc cutter, after operation in such conditions.

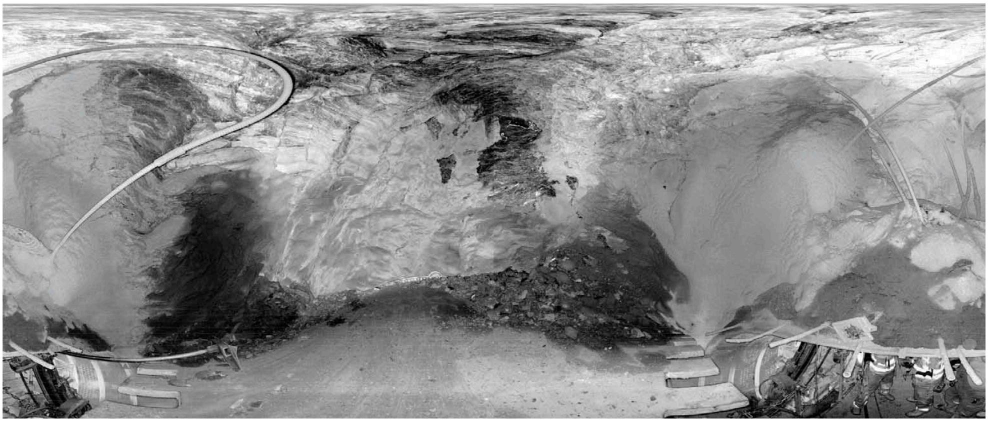

Figure 2. Laserscan of an overbreak please note the finger shield of the hard-rock TBM inside.

2 CONTRACTUAL CONDITIONS: STATE-OF-THE-ART IN MIDDLE EUROPE

The normative documents in Austria (ÖNORM 2203-2) and Switzerland (SIA 118/198) adhere to the desire for clear and fair separation of responsibility spheres in underground construction since more then 20 years. In their current and valid versions, they clearly assign the responsibility with regard to risks associated with the encountered ground conditions to the owner. In order to incorporate this into the daily site processes, the contracts have a flexible billing "mechanism" and enable straightforward billing of possibly changing conditions. Both standards split the contractual prices into material and time-dependent costs. Both informations have to be offered by the contractor in his tender bid: the contractor is obliged to estimate and enter his required time demand for each activity. The final payment is thus the result of the quantity of works and the time the contractor has offered for each activity. The described methodology has proven itself indispensable in conventional tunneling repeatedlyin the past decades.

However, in case of TBM tunneling, the occurrences described in the introduction chapter lead to major problems and cost overruns, since the required time cannot be estimated in the tender phase. This holds true even in case of excellent ground investigation: even if the location and the quantity of the stretches featuring blocky ground or massive overbreaks is known, the associated performance prediction for tunneling in such circumstances in not possible. The reduction of the performance parameters (thrust, penetration, cutterhead rotation rate) is a product of interaction between observed tool damage, conveyor belt loading, TBM heading stability and subsequent further face instabilities due to overload during excavation. The situation in case of additional stabilization measures, or – in an extreme case – excavating auxiliary bypass tunnels to free the trapped TBM is the same: neither the amount of material required for stabilization injections nor the duration of the entire endeavor can be anticipated in a reliable manner. These circumstances and the contractual problems frequently accompanying them have been the starting point to develop a novel billing model for TBM advance.

3 NOVEL BILLING MODEL

3.1 *Goals*

The new billing model has the following goals in mind:

1. Improving the contractual fairness and demanding only things from the contractor which can be really determined;
2. Improvement of transparence and flexibility for site implementation. Occurrences not described by the contract and the underlying geological prognosis must be coverable without additional mediation support and/or expertise by external experts;
3. Using TBM machine data as an integral part of the billing, due to the high information density.

3.2 *Activity classification*

The first step towards clear contractual structure is the clear classification of all technically possible activities on the TBM into three distinct categories:

1. Regular measures, composed of activities which are conducted always during the advance. These can be: advancing of the TBM for one stroke, regular inspection of key components, erection of one ring and backfill of the annular gap (in case of a shield TBM), rock bolt and steel arch installation (in case of hard rock, TBM type) etc.
2. Additional measures, composed of measures which are conducted on demand and based on the observed system behavior. These measures do not require installation of any additional equipment on the TBM (everything required must be already installed) and no additional, specialist personnel. Examples are shield skin lubrication by continuous bentonite pumping, silicate foam injections to fill overbreaks and cavities, steel connections and/or additional steel arches for increased capacity of steel segments, etc.
3. Special measures encompass such activities which require additional equipment installation on the TBM and/or specialist personnel, and are conducted only in case of major and extraordinary events and/or situations associated with high risk. Typical examples would be pipe roof umbrella installation with subsequent grouting, drillings for systematic water table drawdown campaigns etc.

The technical tender documents must clearly separate the TBM equipment into these three groups and give them clear assignment along the reasoning presented above. In addition, bill of quantities and time-dependent cost tables must accommodate the same structure as well.

The first principle of the new billing system is: the contractor is obliged to deliver contractually binding "time required" estimates only for activities belonging to the "regular measures". Only in exceptional cases the contractor can estimate beforehand the required times for activities belonging to "additional measures", while "special measures" are explicitly realized as non-calculable. A fair compensation for such activity is therefore found by splitting the tunneling works into regular advance (comprising regular measures), hindered advance and "advance halt".

3.3 *Definition of "regular advance"*

Regular advance represents the envisioned majority of the TBM operation – if this is not case, either the ground model is severely wrong or an inadequate TBM is being used. It is defined by following criteria:

1. Only regular measures (see above) are being used.
2. A stable face is present, with tight contact between the disc cutters and the face, is systematically present. No face instabilities are occurring, leading to either premature damage to the discs and/or cutterhead or requiring reduction of operation parameters (thrust, cutterhead rotation, etc.).
3. The flow of material is constant and no reduction of operation parameters is required in order to prevent conveyorbelt overload;
4. The mucked material does not cause damage to the conveyor belt immediately after the cutterhead;
5. The shield friction is so low that the capacity of the hydraulics system does not pose a limiting factor for the performance;
6. No premature damage to the disc cutters is occurring, only abrasive wear is observable;

The stability of the face is validated by the following criteria:

1. Visual inspection of the face during cutterhead inspection;
2. Usage of cutterhead cameras (Schuller et al., 2015, Gaich & Pötsch, 2016);
3. Usage of disc cutter monitoring systems (Entacher & Galler, 2013)
4. Usage of TBM data to determine the stability of face (Radoncic et al., 2014).

The consequence of the above criteria is that the performance of the TBM becomes solely dependent on the penetration and contractor's logistics in case of "regular advance". Both of them can be calculated in the bidding phase and can be handled in a straightforward manner: in case a large variability and/or uncertainty with regard to the intact rock strength are present, several penetration classes, with different time-dependent costs attached, can be defined to address this. The contractor's logistics remain entirely in the responsibility sphere of the contractor, and all time dependent costs based on such delays are contractor's responsibility entirely.

3.4 *Hindered advance*

A "hindered" advance is present if the face (or, to a lesser extent: extrados) behavior forces a change of machine parameters towards reduced performance, or additional measures are conducted in parallel to the advance. If this occurs, the past 250 m (or any other length, as individually specified by contract) of advance are taken as a reference to determine the "would be" average performance. The reasoning is simple: the contractor reached a certain performance in this area, and all the intrinsic influences are incorporated (productivity, logistics, net penetration etc.) in it. This average performance is used to determine the hypothetical time required to advance through the area where the deviation from the regular advance is present. Subtraction of this time from the total time required for the advance through the area where hindered advance is present, yields "time difference" – TD – which has to be paid to the contractor in addition to the normal time-dependent cost.

The above reasoning is best presented when examining the exemplary chart, showing time, chainage and associated activities (Figure 3). It can be seen that from chainage 17.50 to chainage 30.0, the TBM stroke takes longer, and the advance rate does not reach the one observed before. The time difference "TD" awarded to the contractor is determined by extrapolating the past performance and subtracting it from the total time.

Analogous procedure is to be used when the stroke time is not affected, however additional measures (in this case: drillings for bedding improvement) are conducted systematically during the advance (Figure 4). The number of drillings and the time required to fully inject the loosened rock mass with grout or foam can vary from ring to ring, and the depicted determination over the entire stretch represents the simplest and fairest solution.

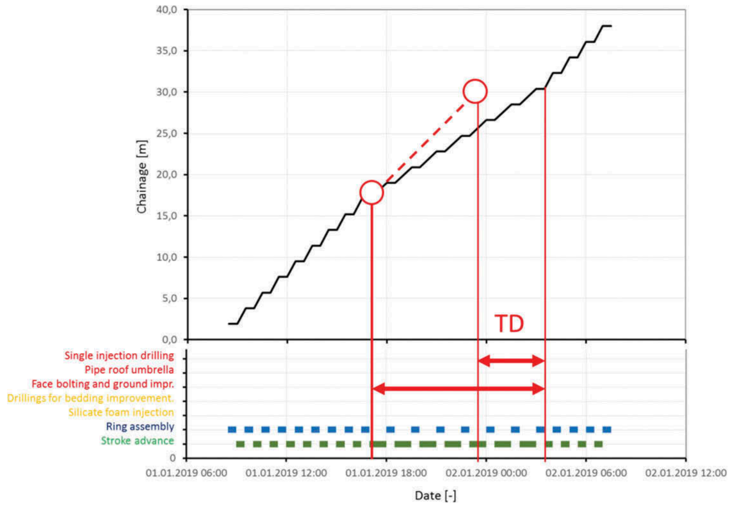

Figure 3. Exemplary time-advance plot showing the area of hindered advance due to face instabilities and the usage of the past performance to determine the additional time awarded to the contractor.

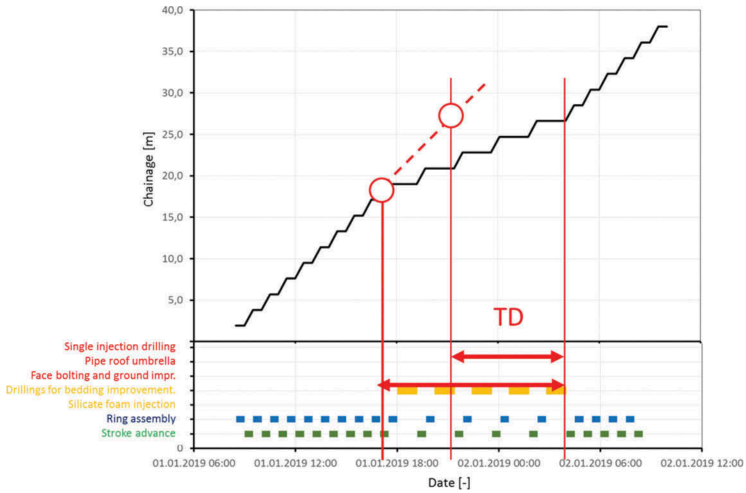

Figure 4. Exemplary time-advance plot showing the area of hindered advance due to additional measures and the usage of the past performance to determine the additional time awarded to the contractor.

3.5 *Advance halt due to an unexpected event*

In case of major unforeseen events (such as a major overbreak and cutterhead blockade), the contractor is awarded on the strict cost plus fee basis. The reasons for this regulation are as follows:

- The entire duration in case of such circumstances is usually long and unforeseeable, and the “regular advance” duration becomes negligible;
- Usually numerous activities are conducted simultaneously (for instance: face stabilization grouting while drilling the pipe roof umbrella) and the determination of the critical path is complex;
- The activities are determined at different locations on the TBM, but in the same tunnel area. Best example is a passage through a major overbreak area, where the face and the

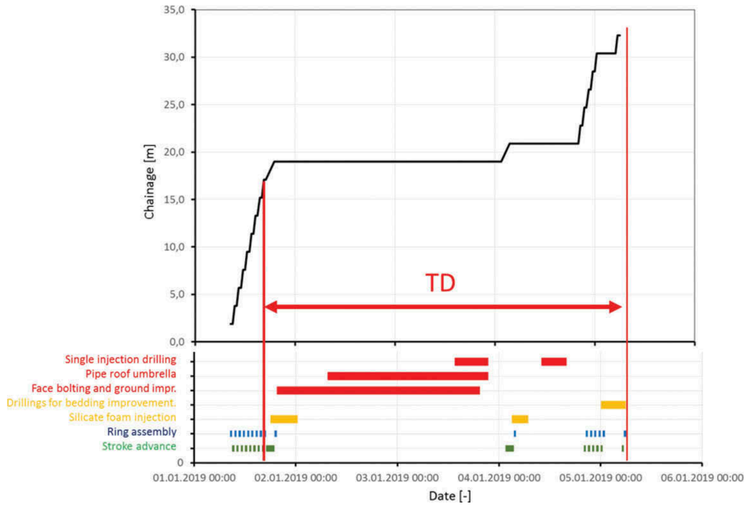

Figure 5. Exemplary time-advance plot showing the activities and billing in case of advance stop due to an unexpected, major event.

roof are stabilized and the advance is restarted. However, the annular gap in this area may require additional grouting injections, conducted from various positions on the backup trailer. Therefore, a single event at a constricted, singular location affects the advance over the length of the entire TBM with its backup trailer;

- Additional equipment and/or personnel are required for the execution of the requested measures ("special measures") and their respective time-dependent costs can not be foreseen and offered in the tender bid.

The contractor is awarded, apart from the actual material cost, time dependent costs for personnel (salaries) and equipment (depreciation) in the actual quantity. The personnel present at the site and the additional equipment used need to be logged meticulously by the site supervision to provide the basis for the accounting.

3.6 *Additional regulations*

The basis for the presented billing model is given by a clear differentiation between a regular advance and circumstances departing from it. In order to enable the presented model to work in real life conditions, additional regulations are required:

1. The contractor is obliged to define the required time for the activities resulting in longer standstills associated with the logistics. These are: main surveying campaign, conveyor belt extension, power and water extension, scheduled cutterhead and TBM overhauls etc. These will be smeared over the entire advance length and accounted for in the determination of the achieved past performance. Simply put, if a conveyor belt extension has been conducted in the past 250 m, not the entire duration of this can be associated with the 250 m.
2. If the past 250 m (or any other length used for determination of the performance in "regular advance") are also affected by the occurrence of hindered advance or major events, then the affected stretch is to be ignored and the entire length is to be increased by the same quantity. Simply put: if a hindered advance was present over 30 m in the past 250 m, then this part of the tunnel is to be ignored in the determination of the performance, and 30 m are to be added to the frame used for performance determination.
3. The contractor is obliged to offer his loan prices in the tender bid. When a major event occurs and cost and fee accounting is used, the contractor will be paid the true personnel

strength present with the offered loan prices. In this way, speculations regarding loans and personnel quantity are prevented.

4. Site supervision is required to take a proactive role, working together with the contractor from the beginning and logging all times and quantities meticulously.

4 CONCLUSIONS

The authors are fully aware that the presented models have certain drawbacks: the contractor may be inclined to reduce the productivity deliberately when knowing that the advance is currently not classified as "regular advance". The site supervision has the task of working closely with the contractor and maintaining high productivity in all circumstances. Furthermore, tunnel construction needs to be understood as a partnership endeavor, where fairness and transparency are of utmost importance. The presented model reduces the potential for speculation considerably, and ensures that reasonable prices are offered both for services within the scope of "regular advance" and for the ones outside of it. Only by a meaningful offer without speculation the contractor can be sure to earn money, because almost all unforeseen occurrences are covered by the presented model.

The authors have been involved with two tenders in Austria where such billing methodology has been used, and the presented philosophy is also being discussed within the Austrian standards committee, tasked with an update of the ÖNORM 2203-2 standard. We sincerely hope that the presented model will enforce meaningful prices in the tender phase and allow a generally fair and transparent financial rewarding for contractor's services, reducing the need for mediation and protracted discussions during construction.

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