KORREKT ERSÄTTNING AV KOSTNADER VID TBM DRIFT – EN NY MODELL BASERAD PÅ TBM DATA

FAIR COMPENSATION OF COST IN TBM TUNNELLING – A NOVEL MODEL BASED ON TBM DATA EVALUATION

Nedim Radončić, Thomas Jesel, Michael Rehbock, Amberg Engineering AG

Due to the usually strict construction schedules and considerable lengths of tunnel drives, TBM tunnelling represents state-of-the-art excavation method for long alpine tunnels. However, 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, such as mixed face conditions or structurally controlled face failure – "blocky rock mass", imposing reductions of the achievable performance. The reduction is caused either by the need to advance with sub-optimal operation parameters (reduction of rpm, thrust, et cetera) and/or increased inspection and maintenance efforts.*
- *Usage of additional and/or auxiliary measures in order to enable a safe TBM advance in the first place (e.g. various injections, shield smearing, installation of pipe roof umbrellas et cetera).*

As the additional time required by encountering circumstances as described above can't be anticipated, no realistic and fair construction time query can be made in the tender. 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. Each scenario is assigned a different accounting modality for time dependent construction cost.

The delimiting criteria defining the threshold between the regular advance and the hindered advance are based on systematic evaluation of TBM data, supporting visual inspections of the rock mass behaviour and allowing clear identification of possible face instabilities. Four different TBM tunnels have been evaluated in order to validate the relationships and thresholds presented in the scope of paper.

Finally, emerging technology of photogrammetric face surveying on a hard – rock TBM is briefly discussed. Its potential for future development and additional insights on the TBM process data is presented.

1. Introduction

TBM tunnelling represents state-of-the-art tunnelling 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 tunnelling 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 ad-vance restart is attempted.

Figure 1. Vänster: Blockig stenmassa. Höger: skadad skivskärare, efter drift under sådana förhållanden.

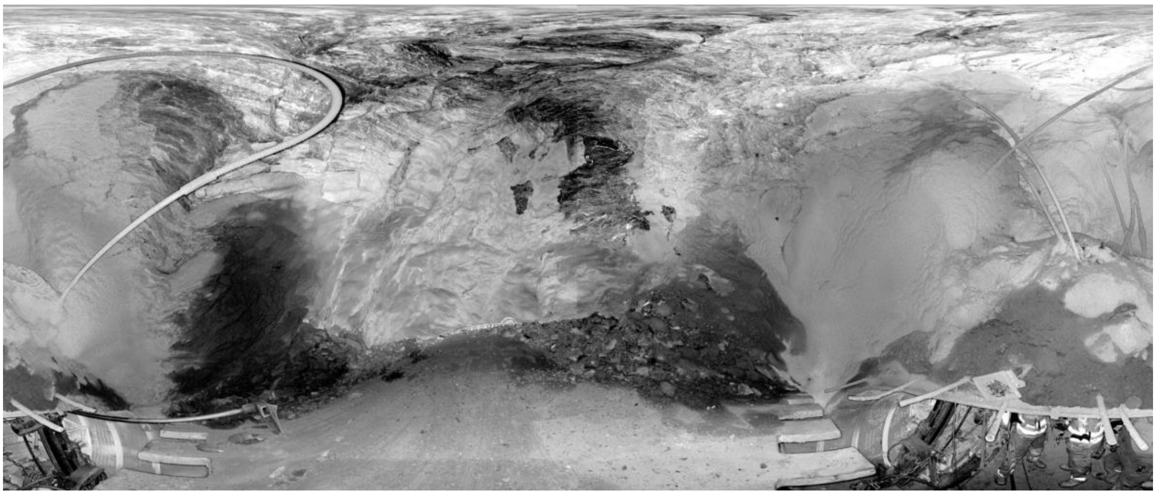


Figure 2. Laserscan av ett överbrott var vänlig notera fingerskölden på hårdrock TBM inuti.

2. Contractual conditions: state of the art in the 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 than 20 years. In their current and valid versions, they clearly as-sign 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 information 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 repeatedly in 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 over-breaks 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:

- Improving the contractual fairness and demanding only things from the contractor which can be really determined;
- 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;
- Using TBM machine data as an integral part of the billing, due to the high information density.

3.2. 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:

- Only regular measures are being used.
- 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.).
- The flow of material is constant, and no reduction of operation parameters is required in order to prevent conveyor belt overload;
- The mucked material does not cause damage to the conveyor belt immediately after the cutterhead;

The shield friction is so low that the capacity of the hydraulics system does not pose a limiting factor for the performance;

- 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:
- Visual inspection of the face during cutterhead inspection;
- Usage of cutterhead cameras (Schuller et al., 2015, Gaich&Pötsch, 2016);
- Usage of disc cutter monitoring systems (Entacher & Galler, 2013)
- 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.

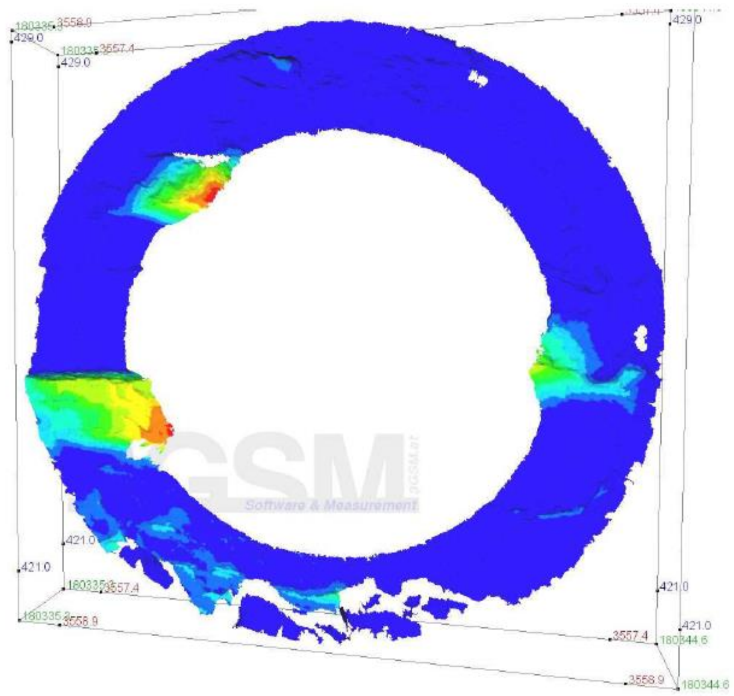
3.2.1. 3D face photos: an emerging technology

A large amount of research and development has been conducted in the field of making camera recordings and/or videos of the face during the TBM advance (Gaich & Pötsch, 2016, Schuller et al., 2015). The state-of-the-art is based on making "ring photos". Based on a viewable angle and position of the camera, an annulus of the face surface is recorded during an advance stop: the thrust force equals zero and only the cutterhead is turned for one revolution. The "stitching" together of the recordings is performed by applying techniques of computer vision, resulting in one continuous picture (Figure 3).

Figur 3. 3D-bild med bestämda kamerapositioner som färgade pyramider (taken from Gaich & Pötsch, 2016).

In the next step, the parallax occurring during the cutterhead revolution, paired with camera characteristics, is used to produce a 3D model of the recorded face annulus. Additional further evaluation options are possible after this step, allowing the determination of the overbreak depth (Figure 4) and discontinuity orientation measurement. Additional data which could be easily combined with this technology is the monitoring of disc cutter forces, allowing both a detailed measurement of the face conditions and the reaction of the TBM to it (Entacher & Galler, 2013).

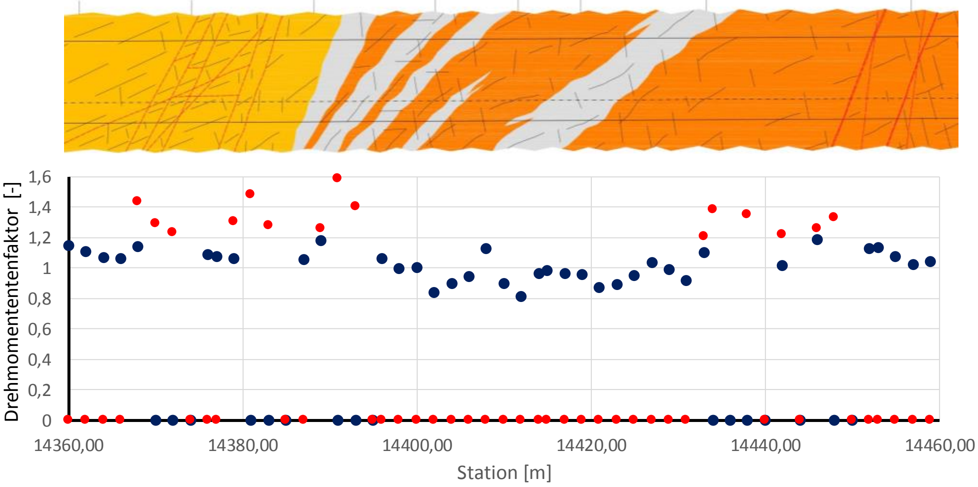
However, the recordings have up to now always been conducted by additional, 3rd party equipment retrofitted into the cutterhead and they are neither regularly conducted nor are the results used in a defined, practical manner. The tender documents of new projects in Austria require regular recordings of this kind (as a basis for contractual issues presented in this paper) and the recording equipment is required to be integrated in the cutterhead design from the beginning, including lens protection and lens washing equipment.



Figur 4. Konturplot av uppmätta utbrott i ansiktet. 1cm = 1 färg i konturplotten (taken from Gaich & Pötsch, 2016).

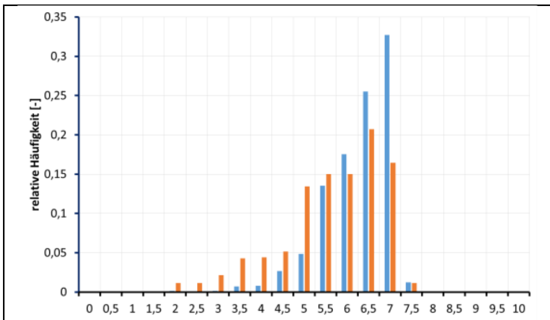
3.2.2. TBM data interpretation

Continuous TBM data evaluation and comparison to the observed behavior at the face have proven to be indispensable during the advance of the Koralmtunnel KAT 2 (Radoncic et al. 2014). Based on the findings, a “torque factor” has been developed (Radoncic et al. 2014) for determining whether the face is stable or not, and it is based on taking the present thrust force and penetration and determining the theoretical torque of the cutterhead based on this data (Anders, 2010). The analysis and calibration on three additional advances show that the face can be assumed to be stable if the torque factor is between 0.80 and 1.20 (Figure 5).

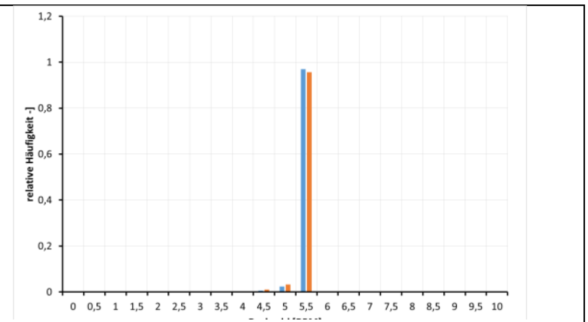


Figur 5. Jämförelse mellan vridmomentfaktorn och de geologiska förhållandena. Röda prickar betyder oregelbunden förskott (ansikte instabil), blå prickar representerar regelbundet förskott. Observera koncentrationen av röda prickar på platser av inspelade sub-vertikala spricker.

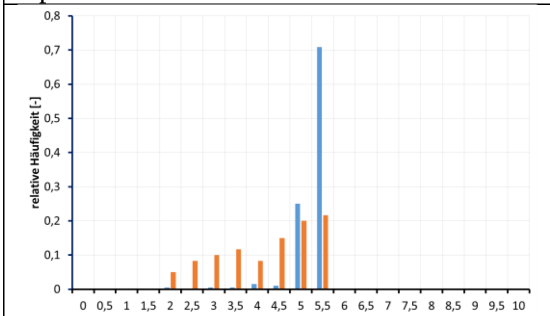
For further validation, three additional TBM advances with varying ground conditions and different cutterhead setups and machine types have been examined along the same criteria.



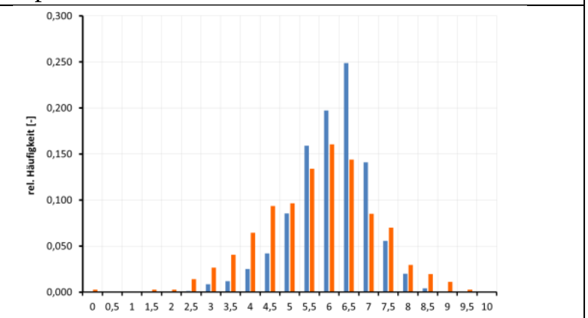
UCS average: 73 MPa
Open hard rock TBM



UCS average: 70 MPa
Open hard rock TBM



UCS average: 165 MPa
Double shield TBM



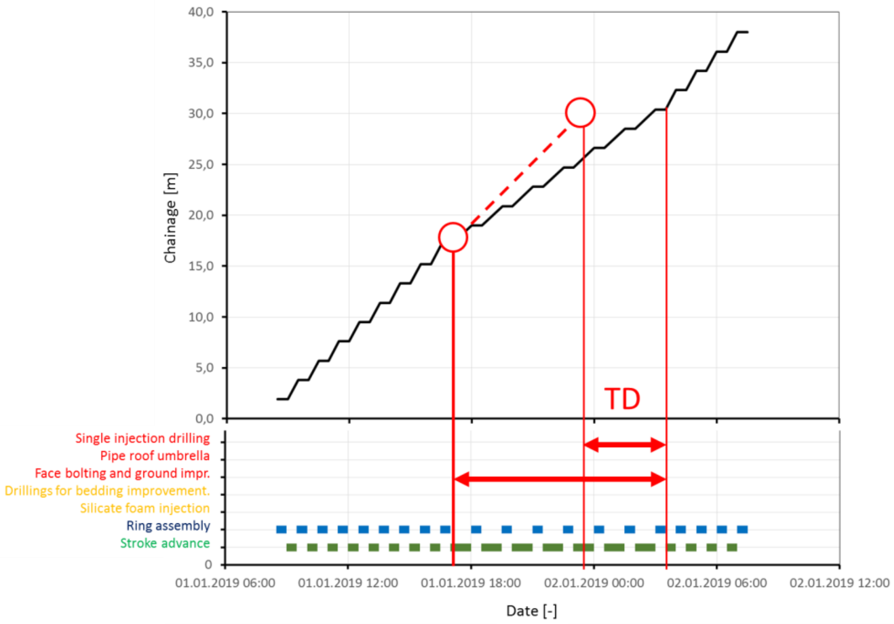
UCS average: 63 MPa.
Double shield TBM

Figur 6. Frekvenshistogram för rotationshastigheten hos skärhuvudet. Blå: vanlig förskott, röd: instabil ansikte (taken from Bach et al. 2018).

The evaluation of the applied cutterhead rotation speed shows a clear reduction of operational parameters in case of “irregular” advance, with the influence of the face stability rising with the encountered compressive strength of rock (Figure 6).

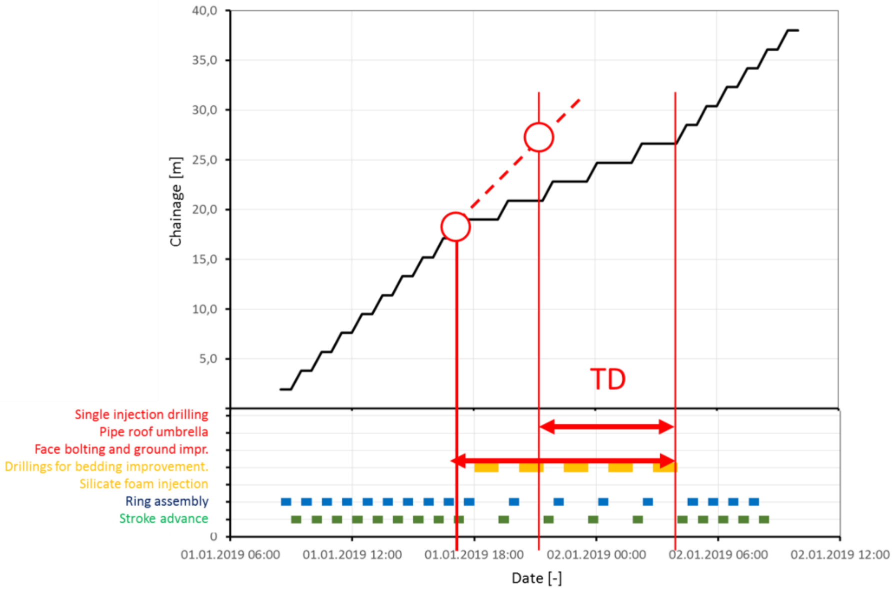
3.4. Hindered advance

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 deter-mine 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.



Figur 7. Exempel på tidsfördröjningsplan som visar området för hindrad förskott på grund av ansiktsinstabiliteter och användningen av tidigare prestanda för att bestämma den extra tid som tilldelats entreprenören.

The above reasoning is best presented when examining the exemplary chart, showing time, chainage and associated activities (Figure 7). 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 8). 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.



Figur 8. Exempel på tidsfördröjningslista som visar området för hindrad förskott på grund av ytterligare åtgärder och användningen av tidigare prestanda för att bestämma den extra tid som tilldelats entreprenören.

3.5. Advance halt due to an unexpected event

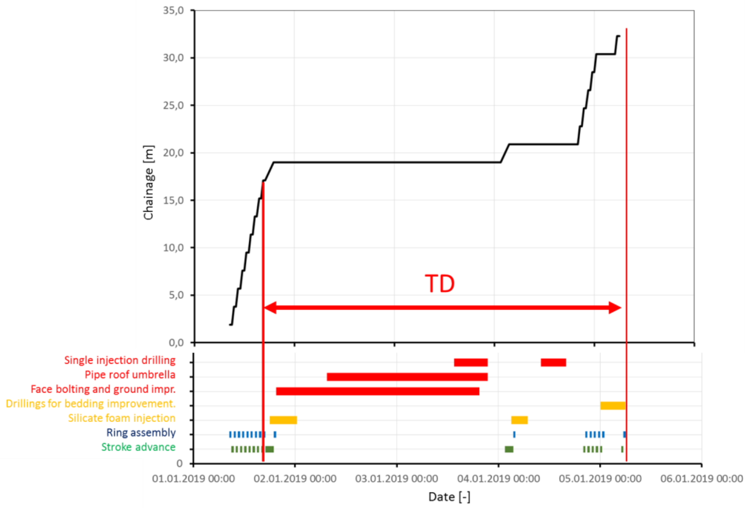
In case of major unforeseen events (such as a major overbreak and cutterhead blockade), the contractor is awarded on the strict cost plus fee basis (Figure 9). The reasons for this regulation are as follows:

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 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.



Figur 9. Exempel på tidsfördröjningslista som visar aktiviteter och fakturering vid förskott på grund av en oväntad större händelse.

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:

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 observed performance in the last 250 m, but only the weighted fraction.

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 endeavour, 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 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.

REFERENCES

Ramoni, M. 2010. On the feasibility of TBM drives in squeezing ground and the risk of shield jamming. Veröffentlichungen des Instituts für Geotechnik (IGT) der ETH Zürich, Doctoral Thesis, Zürich, ETH, 2010.

SIA 118/198. 2004. Allgemeine Bedingungen für Untertagbau - Allgemeine Vertragsbedingungen zur Norm SIA 198 Untertagbau – Ausführung.

Austrian Standards Committee. 2005. ÖNORM 2203-2: Untertagebauarbeiten - Werkvertragsnorm - Teil 2: Kontinuierlicher Vortrieb

Gaich, A. & Pötsch, M. 2016. 3D images for digital tunnel face documentation at TBM headings – Application at Koralmtunnel lot KAT2. Geomechanics and Tunnelling 9 (2016), No. 3, pp. 210-221.

Schuller, E., Galler, R., Barwart, S. & Wenighofer, R. 2015. The transparent face – development work to solve problems in mechanized hard rock tunnelling. In: Geomechanics & Tunnelling 8/3, pp 200-210. 2015 Elsevier.

Entacher, R. & Galler, R. 2013. Development of a disc cutter force and face monitoring system for mechanized tunnelling. In: Geomechanics & Tunnelling 6/6, pp 725-731. 2013 Elsevier.

Radončić, N. Hein, M. & Moritz, B. 2014. Determination of the system behaviour based on data analysis of a hard rock shield TBM. In: Geomechanics and Tunnelling 7/5, pp.565-576. 2014 Elsevier.

Anders, E. 2010. Adams modelling of contact forces between the cutter and the mount. Master Thesis, Department of applied mechanics, Chalmers University of Technology, Göteborg, Sweden. 2010.

Bach, D., Holzer, W., Leitner, W. & Radončić, N. 2018. use of TBM process data as a normative basis of the contractual advance classification for TBM advances in hard rock. In: Geomechanics and Tunnelling, v. 11, n. 5 (Oktober 2018). https://doi.org/10.1002/geot.201800042