Supervision of tunnelling constructions and software used for their evaluation

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Abstract. Supervision is a common instrument for controlling constructions of tunnels. In order to suit relevant project's purposes a supervision procedure is modified by local conditions, habits, codes and ways of allocating of a particular tunnelling project. The duties of tunnel supervision are specified in an agreement with the client and they can include a wide range of activities. On large scale tunnelling projects the supervision tasks are performed by a high number of people of different professions. Teamwork, smooth communication and coordination are required in order to successfully fulfil supervision tasks. The efficiency and quality of tunnel supervision work are enhanced when specialized software applications are used. Such applications should allow on-line data management and the prompt evaluation, reporting and sharing of relevant construction information and other aspects. The client is provided with an as-built database that contains all the relevant information related to a construction process, which is a valuable tool for the claim management as well as for the evaluation of structure defects that can occur in the future. As a result, the level of risks related to tunnel constructions is decreased.

KEYWORDS: tunnel supervision, tunnel software, excavation performance, construction schedule, claim management, construction quality

1. Introduction

Tunnels are being constructed in an environment whose parameters are explored in details only locally priory to the commencement of construction. Therefore, changes to the expected geotechnical conditions are not rare when constructing a tunnel. Contractors adopt an excavation method and rock support as per given conditions in order to construct a tunnel in time manner and quality as per the contract's conditions. The final product, a tunnel, must serve without defects for its entire service life.

There is a large amount of data related to tunnel excavation, geotechnical conditions and rock support obtained a during tunnel construction period. These data are essential not only for the prompt evaluation of rock mass conditions, the determination of excavation and rock support measures and payments, but lately they form a base for the claim management as well as the analysis of possible defects of the structure.

The defects of a tunnel structure or the necessity of its improvement may appear during the operation of a tunnel. The knowledge of an excavation process, geotechnical conditions, used rock support and any complications that happened in the course of tunnelling are vital for choosing a correct remedial action. The later analyses of the conditions are more difficult because tunnel lining covers the surrounding rock mass. The experienced clients incorporated an obligation to provide a database of as-built information into their contract with the supervision and/or the contractor.

2. Supervision scope of work

Supervision work in tunnelling projects, based on the contract between clients and supervisions, can include, but is not limited to, the below listed tasks:

- Check of quality and quantity of contractor's tunnelling work including excavation process and installed rock support
- Regular evaluation of tunnel excavations and contractor's performance
- Geological mapping
- Determination of excavation classes and/or instructions of rock support
- Check of health and safety and compliance with environmental regulations
- Quality tests of construction material
- Design check, proposal of design improvements according to actual conditions; exceptionally designing
- Check of the contractor's technical documentation including method statements, as built drawings etc. and proposing improvements
- Financial matters – regular check of payment applications, claim management and quasi-arbitrator
- Client's representation
- Regular and ad hoc reports and analyses, Final Report
- Holding meetings

Some of the above listed tunnel supervision activities are described in more details in the following chapters. Tools used by a supervision to perform the tasks are presented, including the example of an on-line software system specialized in tunnel supervision purposes.

3. Excavation classes

According to contract conditions the supervision role can include the mapping of geological conditions, the determination of excavation classes and the check/control of rock support to be installed. It is of extreme importance to carry out this work properly because of health and safety reasons, technological reasons and not least economic reasons.

Clients pay contractors for the actual provided work as per contract conditions. In case of tunnel excavations the payments are often made as a cost per linear meter of a tunnel for a particular excavation class. The excavation classes are specified by their excavation methods and used rock support according to geotechnical conditions. There are two kinds of classes – expected (prior to construction) and actual (as built). The construction schedule is based on the expected excavation classes. The difference between expected excavation classes and actual excavation classes has significant influence on both project cost and schedule. Refer to Table 1 for an example which presents the difference between actual and expected excavation classes of a 4km long railway tunnel in the Czech Republic and its influence on project cost.

Table 1. Example: The difference between actual and expected excavation classes in a 4km long railway tunnel and the approximate impact on project cost.

Excavation class	Length [m]	Approx. cost for excavation class per	Approx. cost per excavation class [EUR]	Approx. construction time based on	Daywork - additional approx. cost

			linear meter [EUR]			bid advance speed [days]		for extended time [EUR]
1 - expected	650		2,413	1,568,450		33		---
1 - actual		950			2,292,350		48	---
2 - expected	1,641		2,849	4,675,209		99		---
2 - actual		658			1,874,642		40	---
3 - expected	868		2,855	2,478,140		60		---
3 - actual		200			571,000		14	---
4 - expected	169		4,466	754,754		12		---
4 - actual		316			1,411,256		22	---
5 - expected	784		4,870	3,818,080		63		---
5 - actual		1,988			9,681,560		159	---
Sum - expected				13,294,633		266		585,674
Sum - actual	4.1km		---		15,830,808		282	
Add. cost in total				**estimate:**	**+ 3,121,849 EUR**			**(+ 23.5%)**

When the actual geotechnical conditions lie within the limits specified in the contract, it is usually relatively easy to agree on a difference/change between expected excavation classes and actual excavation classes. The impact on construction schedule and cost is then automatically evaluated according to predefined conditions. However, when geotechnical conditions are outside the limits of the contract, then the agreement on additional work and its payment is sometimes difficult to reach, taking into account the fact of not predefined influence on construction schedule and cost.

In both cases – the actual geotechnical conditions are a) within or b) outside the expected limits – proper unambiguous specification of the excavation classes needs to be clearly stated in the contract. There are usually more aspects with the impact on determination of excavation classes. The determination of excavation classes must be carried out by experienced personnel in tunnelling.

Unfortunately, sometimes the definition of excavation classes is vague, ambiguous and unthorough. Furthermore, sometimes the specification of expected geotechnical conditions and their limits is incomplete and vague and/or with mistakes. It is wise to define expected geotechnical conditions and their limits in a special document. Such a document is often called Geotechnical Baseline Report (GBR) [2]. However, it is often a case that GBR or a similar document is not provided, especially when projects are located outside Western Europe and North America.

4. Construction schedule

The supervision shall monitor and evaluate the actual progress of tunnel excavations and should continuously compare it with the scheduled progress. It is an advantage when the supervision is capable of predicting of the future progress of excavations based on statistical methods. Such methods use data from the already excavated sections of tunnels and take into account the effects of actual encountered geological conditions, delays, maintenance periods, learning curve etc. It is a demanding task which needs a special software but when available, then the supervision is able to keep the construction schedule under tight, continuous and realistic control.

An example of construction schedule of a 4km long railway tunnel is shown in Figure 1. The excavation was commenced on February 2015. For the first three months the actual excavation progress was very slow. The status of excavation is related to the 30th of September 2015, when approximately half of the tunnel was completed. The chart presents the comparison of the actual tunnelling progress (2114m excavated) with the originally planned progress where planned excavation classes were used. The expected progress (2887m) – was updated for the actually encountered geological conditions, i.e. excavation classes. The predicted future progress is shown as an area of probabilistic distribution with the breakthrough date shifted from November 2015 to March 2016.

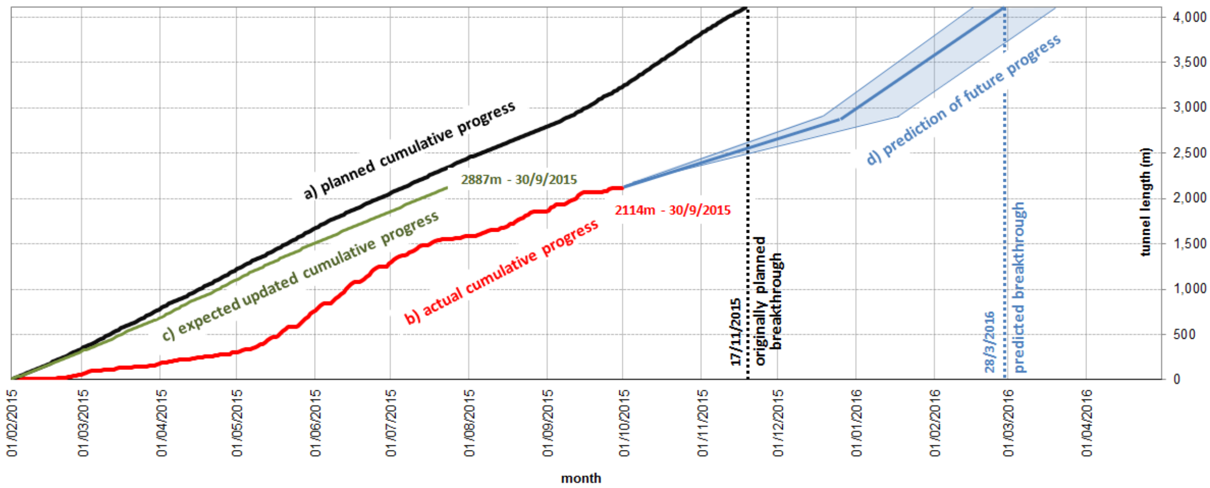

Figure 1. Construction schedule: a) black – originally planned excavation progress based on expected excavation classes; b) red - actual excavation progress shown till the end of September 2015; c) green – expected updated excavation progress based on actual excavation classes and advance rate as per bid; d) blue – probabilistic prediction of future excavation progress based on previous excavation data.

Figure 1 shows that that the actual excavation progress b) was delayed in comparison with the originally planned progress a) by 86 days (horizontal offset), which represented 1080m (vertical offset). However, due to aggravated geotechnical conditions, represented in higher/heavier excavation classes with slow advance rate, the progress was delayed by 20 days, which is a horizontal difference between the curves a) and c). The rest of the delay, i.e. 66 days, is on the account of unforeseen geotechnical conditions, unexpected events, learning curve, contractor’s delays including breakdowns and extensive maintenance etc.

When these delays are claimed by a contractor, it is up to a supervision to confirm or determine their owner. Having known the high cost of daywork – 66 days were equal to approx. 2.5 million EUR in the above mentioned project – it is of the critical importance to follow and record the activities and delays in details during the tunnelling.

Due to the amount of data it is necessary to use a special software application. One of such applications is mentioned in Chapter 7. The application analyzes events, i.e. activities and delays, for any time in the past. The Figure 2 presents a simple chart showing partition of main activities and delays during construction of a 14km long headrace tunnel in Iceland [1]. The tunnel was excavated by a 7.6m diameter hardrock open type TBM, see Figure 3. A noticeable amount of time was spent on the activity No. 7) Utilities, which included repairs of a conveyor belt. As the tunnel conveyor was getting longer, breakdowns in the conveyor belt happened more often and thus the excavation progress became considerably slower. The breakage of the conveyor belt was caused by an insufficient number of installed boosters. Having identified and quantified the true cause of the deceleration of the excavation progress, the issue could be further addressed.

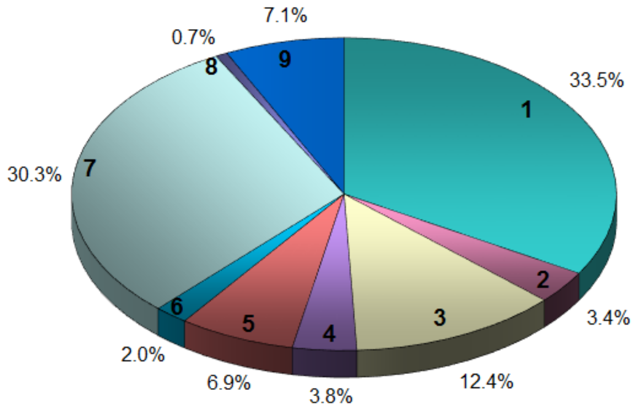

Figure 2. Actual TBM utilization after boring 14km long headrace tunnel.
1 – TBM boring, i.e. utilization – 33.5%
2 – TBM re-gripping
3 – installation of rock support
4 – cutter change and check
5 – TBM maintenance and breakdown
6 – back-up
7 – utilities including installing and repairing of tunnel conveyor – 30.3%
8 – probing
9 – others (downtime, holiday, grouting, etc.)

Figure 3. A 7.6m diameter hardrock TBM prior to the excavation of a 14km long headrace tunnel in Iceland.

5. Quality of tunnel structure

A tunnel structure should be constructed as specified in the design in order to fulfil its operational function during its entire service life. The final structure sometimes more or less varies in comparison with the design. There can be more reasons for the variation, such as for example the change in supplied materials, the different procedure of excavation, etc. It is necessary to have all the changes properly documented including the reasons for changes with all relevant records.

In cases when the variation in construction is not agreed, it is required to issue a special form called in many countries "Non-conformance Report" (NCR). The tunnelling industry regularly uses the NCR as a way to keep the track of deviation and work that fails to meet specifications and standards. A NCR should minimally include the information on what exactly went wrong and in which place, what the main reasons were, why the work did not meet specifications and what remedial action should be taken. A NCR is open until the time when the remedial works are undertaken and agreed, after which the NCR is closed. All NCRs shall be closed until a tunnel is handed over for operation to a client.

The remedial actions that are needed for closing NCRs are often time consuming and expensive. Refer to Table 2 and Figure 4 that present an example of time lost and money wastage due to the collapse of rock support and surrounded rock mass during the excavation of a 28km long headrace tunnel in Pakistan. The event happened because the contractor did not comply with rock support specifications. Having all relevant information including NCRs properly recorded the supervision was able to defend the client against the later false contractor's claim for "suddenly worsen geotechnical conditions". It is interesting to note that the direct cost of remedial measures is often much less expensive when compared with the estimated income from a project operation.

Item No.	Description	Additional time [day]	Daywork – approx. cost	Approx. direct cost

			for additional time [EUR]	for work [EUR]
1	Stoppage of excavation progress because of collapse and remedial works. Tunnel on critical project path. Two tunnel faces stopped and one partially affected.	22	520,000	---
2	Additional installed rock support – shotcrete, rockbolts, wire mesh, grouting etc.	---	---	63,000
Direct cost in total [EUR]		---	**583,000**	
For information purposes: Commencement of hydropower project operation delayed. Estimated price for generated electricity during 22days of hydropower project operation based on 90 EUR/MWh.		---	27.9 million	

Figure 4. An excavator buried by collapsed rock support and surrounded rock mass. The photo taken during time when rock was still falling and shotcrete lining was cracking. An excavator operator was pulled out alive.

Depending on the reasons remedial actions could be paid solely by a contractor, a client or expenses can be shared between them. It is a supervision who has to guide this process. Contractors usually try to include the provided remedial works into claims regardless true reasons. Therefore, it is of a paramount importance to keep all the necessary relevant information related to NCRs. Furthermore, contractors are often directly penalized for any issued NCR according to contract conditions.

There can be plenty of information and documents related to any single NCR. Speaking of tunnels that are often several kilometres long and constructed for a period of couple of years, the amount of gathered data to be stored is vast. This imposes a necessity to involve software database solutions so that we could analyse the data efficiently even many years after the construction of a tunnel is finished.

6. Claim management

According to Reference [4] a construction claim can be defined as a request by either party of the contract, usually the contractor, for compensation for the damages caused by the failure of the other party to fulfil his part of obligations or for the change in expected conditions as specified in the contract. The compensation is usually in the form of an additional payment or an extension of time.

Construction claims are one of the most worrying and unpleasant events of a project. Hard competition forced contractors to submit their bids with minimum profits or worse underbid. In addition, projects are becoming more complex and risky. This put additional burden on contractors to construct increasingly sophisticated and risky projects with less resources and profits. As a consequence, the number of claims within the construction industry increases.

A large majority of claims involve delays in construction schedule. As could be seen in the examples above, refer to Tables 1 and 2, the cost for one daywork is significant. Therefore, it is of an extreme importance to understand what was happening in the tunnel all the time, as well as to know the true reasons for it. The causes of delays must be well described and the "owner" of a delay identified. When it comes to assessing claims, information and knowledge are vital in order to make the correct decision.

Special software applications, such as for example [3], are able to analyse activities and delays for any period of time and help to manage claims.

7. Software for tunnel supervision purposes

There exist only few on-line software applications or databases specialized in the tasks of tunnel supervision. The Tunnel Supervision [3] is one of such on-line applications which provides project participants with essential data from tunnelling. The Tunnel Supervision application manages and analyses data related to for example:

- Excavation classes
- Geological conditions and underground water
- Rock support and tunnel lining details
- Construction schedule
- Activities and delays
- Site diaries
- Site instructions
- Non-conformance reports
- Payments and claims
- Tests

The data of various fields of expertise are integrated and accessible all the time through one uniform environment. Routine reports are generated automatically, special reports are provided and statistics calculated as required. Refer to Figures 1 and 2 for examples where the application provided important information.

The application has been developed to provide support for:

- Certifying payments, defending or supporting claims
- Answering specific questions on excavation progress and construction schedule
- Passing data and information, i.e. enhancing collaboration in the team
- Reporting and graphic presentations
- Producing statistics as required
- Refining data for a wide spectrum of tasks that underground work generates

8. Conclusion

The construction schedules and costs of tunnel projects are often exceeded. Aggravated geological conditions are regularly proclaimed by contractors as the reasons for extra time and cost, although the true reasons often consist of combinations of factors, such as delays due to contractor's faults, construction mistakes and errors in design, poor contract conditions, poor geotechnical survey and worsen actual geotechnical conditions. The supervision should expose the true factors including mistakes, try to find and suggest solutions and do as much as possible to avoid mistakes. The supervision plays a very important role in tunnel construction industry, contributes to finish the project in required quality with time schedule and cost matching contract conditions.

During tunnelling construction a database of gathered data shall be established and managed in order to provide information and analysis. The input data include information such as for example geotechnical conditions, actual and expected excavation classes, installed rock support quantity and quality, other payment items, activities and delays during construction, deformation monitoring, photo documentation, etc. at any given place. Due to the amount of data and number of users with different rights to access them, it is wise to use a special on-line software application which provides ad hoc and precise analysis on the fly. A software database should be handed over to the client when the construction of a tunnel is finished. The client can use cross connected data and analysis any time e.g. for later maintenance or in case of some later structure defects.

Acknowledgements

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References

[1] Caravanas A, 2009 Tunnels for Kárahnjúkar Hydropower Project *Tunel 1/2009* pp 22-31

[2] Klee L, Hruška D, 2013 How to efficiently allocate the risk of unforeseeable physical conditions in underground construction? *Tunel 3/2013* pp 51-62

[3] www.tunnelsupervision.com

[4] Hadikusumo B, Tobgay S, 2015 Construction Claim Types and Causes for a Large-Scale Hydropower Project in Bhutan *Journal of Construction in Developing Countries* **15** pp 49-63