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THE USE OF EXPLORATORY TUNNELS AS A TOOL FOR SCHEDULING AND COST ESTIMATION

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Abstract. Exploratory tunnels are commonly used for examining the geotechnical and structural aspects of proposed tunnel alignments. This paper explores the utilisation of exploratory tunnels as a project management tool for estimating the cost and duration of construction for the entire project. Data were collected from the Kaponig 2,75 kilometers exploratory tunnel, a part of a double-track high-speed railway development in Austria. This knowledge and experience was used to evaluate the risks associated with design details for the final tunnel enlargement (alignment and grade, support requirements and excavation methods). A deterministic model based on Monte Carlo simulation was developed capable of predicting potential outcomes of the total project in terms of cost, duration and their associated probabilities.

Keywords: tunnelling, project management, geotechnical rock-mass grade, risks, duration, construction engineering, management, economics, Monte Carlo simulation.

1. The Kaponig tunnel

A trial tunnel was mined as part of the geotechnical investigations for the Kaponig tunnel, a section of the double-track high-speed rail development between Salzburg and Villach, Austria. The Kaponig tunnel is 2,75 km long, and situated between kilometre 48,7 and kilometre 53,8 of the Dossen-Lindisch section. The building site is located in the federal state of Carinthia and the Kaponig railway station is in the municipality of Obervellach. The New Austrian Tunnelling Method (NATM) was used to mine an uphill section heading towards the mountainside tunnel portals. As illustrated in Table 2–10 for General Data for Rock-Mass Grade 1–9 [1].

2. The New Austrian Tunnelling Method (NATM)

The NATM is a flexible method, designed to take into account variable conditions encountered at the tunnelling process while mobilising whatever intrinsic strength the rock possesses. This flexibility allows engineers to adapt and optimise their designs while the construction process is taking place. The basic methodology of NATM is simple: sprayed concrete is applied immediately to the tunnel wall as a temporary support during tunnelling, and, if necessary, reinforced by rock bolts, wire mesh and/or lattice girders. These components are employed so that as much elasticity as possible is retained in the initial support. This allows the stresses within the rock to relax and establish a revised equilibrium around the man-made opening. Once this self-supporting equilibrium is reestablished, the ground will sustain the opening and maintain its integrity with the minimum of extra support. The final liner is installed once the tunneling process has been completed.

The NATM is a rock mass classification carried out after blasting. With respect to size-strength classifications, graphs are plotted according to point load strength versus block size. The International Society for Rock Mechanics (ISRM) classification includes the following parameters: discontinuous spacing, uniaxial compressive strength, and the angle of friction of fractures [2].

2.1. Exploratory tunneling

A. The knowledge of geotechnical conditions is the most important prerequisite in planning and executing a tunneling project. The more comprehensively the preliminary investigations are carried out and the more valid they are, the better is the basis for selecting a tunnelling method.

B. From the cited geotechnical values and an overall appraisal of geological and hydrogeological conditions of the subsoil, the following important technical data can be obtained including:

– stability of the face;
– nature and extent of the supporting measures;
– time lag between breaking-out and securing the open cavity;
– deformation behaviour of the rock;
– influence of underground and/or groundwater [3].

C. On the basis of the listed geotechnical values and construction data, including the environmental factors, it is possible to select the construction method. It is also possible to divide the tunnel over its route into tunnelling classes, which closely define the tunnelling method, identify the performance to be applied to tunnelling class and describe the degree of difficulties. Whereas the selection of the construction method is the prerequisite for allocation into tunnelling classes (laid down by the client), the choice of the machines should be left as far as possible to the contractor in charge.

Exploratory tunnels are built in such a way that engineers can use the Observational Method (OM), the tunnelling management and design system that facilitates the use of modern measurement techniques. The OM's strength is its flexibility; design and management procedures can be modified during construction. The proper use of exploratory tunnels can assist engineers and managers in a number of ways [4, 5 *et al*.].

Design verification: designs can be checked and adjusted during excavation in order to ensure stability and cost issues.

Quality control: engineers can determine if the tunnel is being constructed in accordance with the appropriate standards and stipulations.

Warning system: exploratory tunnels allow engineers to detect potential collapses with the provision that the site is being continuously monitored.

Exploratory tunnelling, through the use of the OM, allows engineers to take advantage of their own personal experience and also gain the first-hand information about a particular site. This knowledge, coupled with a proper understanding of standard tunnelling procedures, can potentially reduce costs as well as provide an indication as to the safety of a particular site. Project managers using exploratory tunnelling systems have the ability to alter the construction process in accordance with the specific features on the site.

This paper provides a brief description of the Kaponig tunnel, the drill and blast construction method as well as the Monte Carlo simulation approach. Analyses of productivity values observed during the tunnel construction are presented.

Table 1. Bill of materials for Kaponig tunnel [1]

Number of track supports	2,125
Grouting concrete	5,125 m^3
Concrete	860 m^3
Reinforced concrete	355 t
Surface area	3,810 m^2

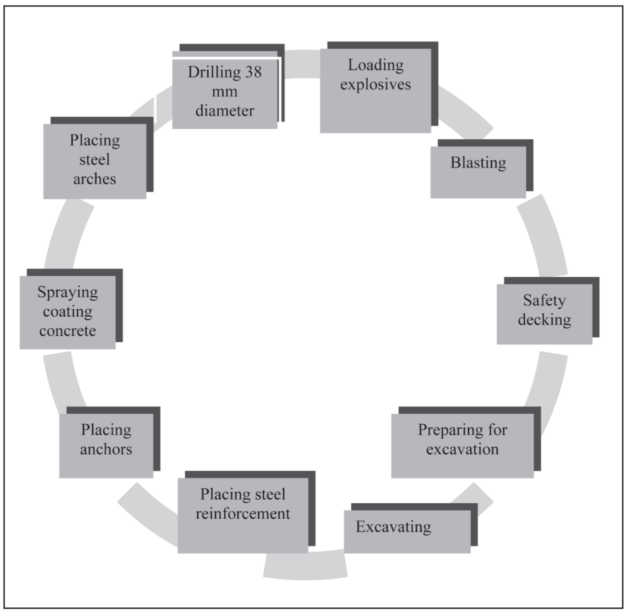

Fig 1. A generic flow diagramme of the construction cycle [1]

3. Kaponig tunnel

The Kaponig tunnel is located in Austria, on the Tauernstrecke between the municipalities of Schwarzach/ Saint Veit and Drava Lane. The project duration of second phase was completed in 1996–1999, and consisted of a 5 km tunnel extension with an internal diameter of 11,61 m. The tunnel intersects the 113 m long Kaponig bridge, and covers an elevation difference of 150 m. The tunnel supports a rail system with a design speed limit of 120 km/h, as this was required to accommodate the 2,8 % uphill slope. The smallest radius of curvature for the railway is 640 m and the largest radius of curvature reaches 1,005 m. The superelevation ranges between 75 and 124 mm. The estimated cost of this project was approx $85 million US. A summary of the materials list for the project is given in Table 1. In the Kaponig tunnel a system of reinforced concrete ties was used as track supporting panel. It provides an increased riding comfort for passengers. Construction equipment allocated for the exploratory tunnel included a CAT D6 bulldozer, mobile crane and a CAT 966 wheeled loader (PORR-Topic, 1997). The total time required to excavate the Kaponig tunnel was initially estimated to be 403,5 working days plus 28 working days for unexpected ground infiltration water problems (≅14,40 months). The exploratory tunnel was completed between October of 1992 and December of 1994 and was 2,75 km long and 11,61 m in diameter. Fig 1 shows a generic flow diagram of the construction cycle which was repeated approx every 3 m of the tunnel length.

3.1. Analysis of tunnelling conditions

Due to the presence of extensive rock-mass grades 1 and 2 instead of the expected rock mass grades 3, 4, and 5 (based on geological and geotechnical investigations) and corresponding ground water inflow up to several hundreds of liters per second, the tunnelling process needed to be interrupted frequently. Large water intake during tunnelling required an enlargement of the sediment basin in order to handle the higher than expected sediment loading. Frequently the locomotives derailed and dumped their load on the tracks making track repair work necessary. High track maintenance requirements delayed the excavation activities repeatedly. A tunnel of this size was expected to affect the groundwater conditions [4].

3.2. Blast technology

The tunnel blasting technology consists of 3 components:

1) handling explosives,
2) detonators,
3) loading/charging the bore holes.

There is a wide range of commercial explosives available for use in tunnel blasting; however, pumpable site sensitised emulsion explosives are commonly used in modern

Table 2. General data for rock-mass grade 1

Excavation face	13,35 m^2
Preclusion of hammer	2,80 m
Borehole depth	3,00 m
Number of boreholes	45
Drilling distance	144,00 m
Volume of excavation soil	64,08 m^3
Full excavation cycle	
Drilling	
Gross drilling capacity (dia 38 mm)	1 m/min
Drilling	144 min
Loading	35 min
Blasting	15 min
Safety deck	10 min
Prepare rock excavation	10 min
Rock excavation	96,12 min
Time required	258,12 min
Cycle duration	4,30 h
Daily performance	16,73 m/working day

Table 3. General data for rock-mass grade 2

Excavation face	13,35 m^2
Preclusion of hammer	2,80 m
Borehole depth	3,00 m
Number of boreholes	45
Drilling distance	135,00 m
Volume of excavation soil	59,81 m^3
Full excavation cycle	
Drilling carriages tool	15 min
Drilling	
Gross drilling capacity (dia 38 mm)	1 m/min
Drilling	135 min
Loading	35 min
Blasting	15 min
Safety deck	10 min
Preparation for rock excavation	10 min
Rock excavation	89,72 min
Supporting	
Spray concrete coating	Layer thickness = 5 cm
Placing steel reinforcement	64,45 kg 24,17 min
Placing anchor	15,4 min
Time required	332,19 min
Daily performance	12,14 m/working day

Table 4. General data for rock-mass grade 3

Excavation face	13,35 m^2
Preclusion of hammer	2,30 m
Borehole depth	2,50 m
Number of boreholes	45
Drilling distance	112,50 m
Volume of excavation soil	49,13 m^3
Full excavation cycle	
Drilling carriages tool	15 min
Drilling	
Gross drilling capacity (dia 38 mm)	1 m/min
Drilling	112,50 min
Loading	40 min
Blasting	15 min
Safety decking	10 min
Rock excavation preparation	10 min
Rock excavation	73,70 min
Supporting	
Spraying concrete coating	Layer thickness 10 cm
Placing steel reinforcement	53,50 kg 20,06 min
Placing anchor	12,95 min
Time required	319,89 min
Daily performance	10,35 m/working day

Table 5. General data for rock-mass grade 4

Excavation face	13,35 m²
Preclusion of hammer	2,00 m
Borehole depth	2,20 m
Number of boreholes	45
Drilling distance	99,00 m
Volume of excavation soil	40,05 m³
Full excavation cycle	
Drilling carriages tool	15 min
Drilling	
Gross drilling capacity (dia 38 mm)	1 m/min
Drilling	99,00 min
Loading	45 min
Blasting	15 min
Safety deck	10 min
Preparation of rock excavation	10 min
Rock excavation	60,08 min
Supporting	
Spraying coating concrete	Layer thickness 15 cm
Placing steel reinforcement	66,40 kg 24,90 min
Placing anchor	18,75 min
Time required	318,79 min
Daily performance	9,03 m/working day

Table 6. General data for rock-mass grade 5

Excavation face	13,35 m²
Preclusion 0f hammer	1,50 m
Borehole depth	1,70 m
Number of boreholes	45
Drilling distance	76,50 m
Volume of excavation soil	28,04 m³
Full excavation cycle	
Drilling carriages tool	15 min
Drilling	
Gross drilling capacity (dia 38 mm)	1 m/min
Drilling	76,50 min
Loading	50 min
Blasting	15 min
Safety deck	10 min
Preparation of rock excavation	10 min
Rock excavation	42,06 min
Supporting	
Spraying concrete coating	Layer thickness 15 cm
Placing steel reinforcement	49,80 kg 2,80 min
Placing anchor	21,00 min
Placing steel arch	159,30 kg 47,79 min
Time required	346,66 min
Daily performance	6,23 m/working day

Table 7. General data for rock-mass grade 6

Excavation face	13,35 m²
Preclusion of hammer	1,20 m
Volume of excavation soil	22,43 m³
Full excavation cycle	
Drilling	
Safety deck	10 min
Preparation for rock excavation	10 min
Rock excavation	44,86 min
Supporting	
Spray of coating concrete	Layer thickness 20 cm
Placing steel reinforcement	40,66 kg 2,29 min
Placing anchor	18,00 min
Placing steel arch	169,92 kg 59,85 min
Time required	249,63 min
Daily performance	5,86 m/working day

Table 8. General data for rock-mass grade 7

Excavation face	15,00 m²
Preclusion of hammer	0,90 m
Volume of excavation soil	18,90 m³
Full excavation cycle	
Drilling	
Safety deck	10 min
Preparation for rock excavation	10 min
Rock excavation	37,80 min
Supporting	
Spraying concrete coating	Layer thickness 25 cm
Place steel reinforcement	75,98 kg 9,15 min
Placing anchor	27,60 min
Placing steel arch	223,60 kg 66,50 min
Time required	370,11 min
Daily performance	3,11 m/working day

Table 9. General data for rock-mass grade 8

Excavation face	13,90 m_2
Preclusion of hammer	1,20 m
Volume of excavation soil	23,35 m³
Full excavation cycle	
Drilling	
Safety deck	10 min
Preparation for rock excavation	10 min
Rock excavation	46,70 min
Supporting	
Spraying concrete coating	Layer thickness 15 cm
Placing steel reinforcement	40,05 kg 15,03 min
Placing anchor	37,60 min
Placing steel arch	177,00 kg 99,75 min
Time required	354,66 min
Daily performance	4,87 m/working day

Table 10. General data for rock-mass grade 9

Excavation face	14,60 m^2
Preclusion of hammer	0,90 m
Volume of excavation soil	18,40m^3
Full excavation cycle	
Drilling	
Safety deck	10 min
Preparation for rock excavation	10 min
Rock excavation	36,79 min
Supporting	
Spraying concrete coating	Layer thickness 20 cm
Placing steel reinforcement	60,98 kg 22,87 min
Placing anchor	32,40 min
Placing steel arch	177,00 kg 102,41 min
Time required	349,59 min
Daily performance	3,71 m/working day

Table 11. Excavation cycle [1]

Activities	Low value	Most likely value (MLV)	High value
Drilling 38 mm dia holes	38 min/m	48 min/m	57 min/m
Load explosive	10 min/m	12 min/m	14 min/m
Blasting	4 min/m	5 min/m	6 min/m
Safety deck	2 min/m	3 min/m	4 min/m
Preparation for excavation	2 min/m	3 min/m	4 min/m
Excavation	26 min/m	32 min/m	38 min/m
Placing steel reinforcement	6 min/m	8 min/m	10 min/m
Placing anchors	10 min/m	12 min/m	14 min/m
Spraying concrete coating	22 min/m	28 min/m	33 min/m
Steel arch placing	27 min/m	34 min/m	41 min/m

tunnels. Two emulsion components are pumped into the borehole and mixed by automatic means. The amount of explosive is volumetrically controlled by the degree of fill necessary to achieve the desired fragmentation.

Detonating systems used are either electric ignition or pyrotechnic tube ignition. Safety, simple installation, robustness, and accurate firing sequence of the individual holes are all highly desired attributes. Using proper detonators in the perimeter zone helps achievea high cross-sectional accuracy and a clean break along the contour with a low vibration and precise blasting.

Mucking refers to the gathering together of material from where it has been deposited after the blast. The size of the individual rock fragments and the volume excavated per length of advance are essential criteria for selecting mucking equipment. Muck haulage can be undertaken via trains, belt conveyors, or dumpers. Commonly, a crusher is used at the transfer point for feeding the conveyor belt or the train. A programme was undertaken. In May 1993 during the construction of the pilot tunnel, a large amount of water inflow was encountered, and some of the springs in the surrounding area experienced a decreasing discharge or were completely dried out. The decrease of discharge in some of these springs shows the influence of the tunnel construction on the hydro-geological conditions of mountain-groundwater body [7, 8 *et al*.].

4. The drill and blast tunnelling process

The drill and blast technique is a very common tunnel excavation method. The heading sequence, length of advance and the required temporary ground support at face and heading govern the cycle time of the tunnel excavation. Temporary ground support measures have to be undertaken in accordance with the specific requirements to protect the works at the face and in the loading area, and to stabilise the tunnel section. Support is achieved by rock bolts and/or steel mesh, shotcrete or, in the case of extreme conditions, the installation of heavy steel ribs and nailing or bolting the face. The working stages, which govern the coordination of the excavation and ground support operations, need to be balanced with respect to both their efficiency and their economic viability.

The drill and blast method employs a cyclic construction process with 4 key activity classes:

1. Drilling by a jumbo or otherwise;
2. Loading/charging of explosives;
3. Muck loading with tunnel excavators or side dumping loaders;
4. Installation of temporary ground supports such as

- Rock bolting,
- Erection of steel arch supports, and
- Shotcrete.

An accurate drilling is required for tunnel section and optimal fragmentation of the rock. The drilling cycle includes the positioning of the jumbo, checking that the proper drilling pattern is employed to match the position along the tunnel length (station location), positioning the drilling arms (booms), and drilling the holes. Positioning of the drill jumbo is done with the laser. Computerised systems are commonly used to program the drilling booms to achieve a specific drill pattern (horizontal, angle, depth, spacing).

5. Monte Carlo simulation

Statistical modelling, or the Monte Carlo method, is commonly used to solve a wide range of multivariate problems in engineering and other sciences. Monte Carlo simulation is a versatile method of risk analysis that can be applied to diverse applications. For the construction industry, Monte Carlo simulation can be applied to risk analysis of CPM schedules and range estimating. It is a valuable tool if the activities are well defined and distributions can be readily developed. Monte Carlo simulations can be easily set up in a spreadsheet application such as Microsoft Excel. The basic steps involved in the process are outlined below. Each activity that has a variable duration is described using a statistical distribution. This could be as simple as a uniform distribution between a minimum and maximum duration, a normal distribution described by a mean and standard deviation, or as complicated as a Beta or Exponential Distribution. The most common, and usually the easiest to generate is a triangular distribution made up of the pessimistic, most likely and optimistic durations. A random number is mapped onto the distribution to give the activity a possible duration for that run. After all the activities have been given a duration, the critical path is determined and a maximum duration of the project is calculated. This is repeated many times and the maximum duration is stored each time. This results in a distribution of the maximum duration of the project on which a risk analysis can be based. Depending on the distributions used for the activities, this distribution may or may not be normal, but it is usually reasonable to assume normality. In terms of cost estimation the same process is used except for the activity costs in an estimate are described using the distributions and the total cost of the estimate is calculated in each run.

Monte Carlo simulation can be summarised by the following algorithm:

1. Generate a random number on the interval [0–1].
2. Transform the random number into an appropriate statistical distribution (eg normal, beta, uniform); the resulting number is referred to as a random variate.
3. Substitute the random variates into the appropriate variables in the model.
4. Calculate the desired output parameters within the model.
5. Store the resulting output for further statistical analysis.

Repeat steps 1–5 a number of times (note that the generated uniform random numbers must be different in each repetition). Analyse the collected sample of output and perform desired risk analysis

6. Monte Carlo simulation of excavation process

Evaluating the probability of different duration and cost scenarios is one of the principal reasons for using simulation to model construction processes. One of the primary objectives of using a simulation to model construction processes is to evaluate and compare the performance of alternative approaches and fleet configurations. A common mode operation is to construct a simulation model for each approach, conduct a limited number of simulation experiments (runs), and then compare the competing alternatives based on the resulting average measure of their performance. The basic methodology described in the previous section was used to develop a simulation system for comparing the duration of a project (days) and actual completion times for each rock-mass grade of the total project using the NATM. Based on 500 cycles, probability values associated with different duration and cost estimates were established. Another application of simulation is for optimisation of fleet configuration such as the number of muck cars or different mucking systems. In tunneling, most of the risk is due to geologic uncertainty, which is independent of the chosen construction method. Therefore, it is important that competing construction alternatives be compared under the same geologic conditions. Otherwise, the observed differences will be due to differences in the project geology rather than to the construction methods themselves. Conceptually, the solution to this problem is quite simple. The simulation runs for each alternative must be designed so that uncertainty impacts each construction method in a similar manner. Since all uncertainty in a simulation model is determined by random numbers, the key is to ensure that the random numbers used for each method follow similar patterns. This approach, however, may introduce bias into the analysis.

The tunnel is assumed to serve as a connector for two commuter rail systems and thus requires no intermediate stations. All excavation must be performed underground with no intermediate shafts, starting at one of the existing stations. The current analysis assume the same excavation (drill & blast) and muck methods (train muck haulage) were used in all sections, but differ in the system used for initial tunnel support. The simulation created to model this tunnelling process is described in the following.

A Monte Carlo simulation model was created in Microsoft Excel to generate the duration of tunnelling projects as a function of rock mass grade. The model uses a series of random numbers to act as variables that occur during the tunnelling process. The model first generates a random number to determine the rock mass grade that will be bored through. The rock mass grade is selected based on the percentages that rock hardness in the construction area as determined by the data collected from the pilot tunnel *Abdallah*. From the knowledge of rock-mass grade the length of time (referred to as base time) to complete the excavation of a segment 3 m in length can be determined. The base time is then altered by ±20 % to account for the various processes that must take place depending on the rock-mass grade, which is present. Another random number is generated to obtain the water intake range. The random number determines the intake range (l/s) based on the percentage of linear metres. By comparing the rock-mass grade to the water intake, a predetermined efficiency factor, which accounts for minor delays, that may occur during the tunnelling process. The model then divides the adjusted time by the efficiency factor to derive a final time required for the tunnelling process which is measured in time per 3 m of progress. The model then calls a macro to this process a desired number of times to accommodate the length of the entire tunnelling project being modelled. The result of this calculation yields the length of time required to complete any tunnelling project as a number of days. This process is then, again, repeated 500 times to produce the probability distribution function (PDF) shown in Fig 2 and cumulative distribution function (CDF) shown in Fig 3. The latter gives the probability of a tunnelling project taking a given duration.

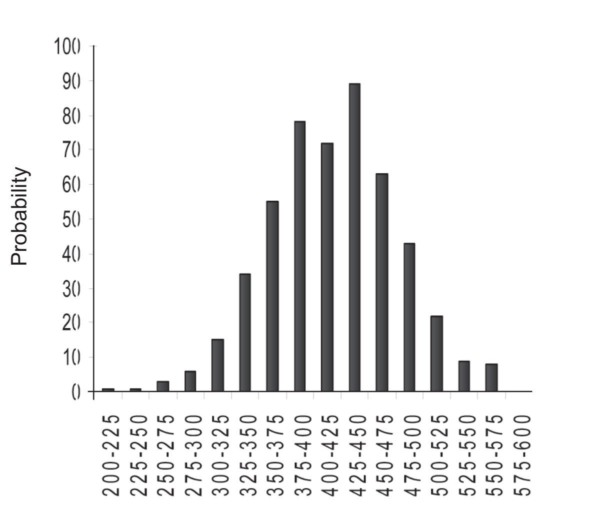

Fig 2. The probability distribution function (PDF) based on the results from the simulation model [1]

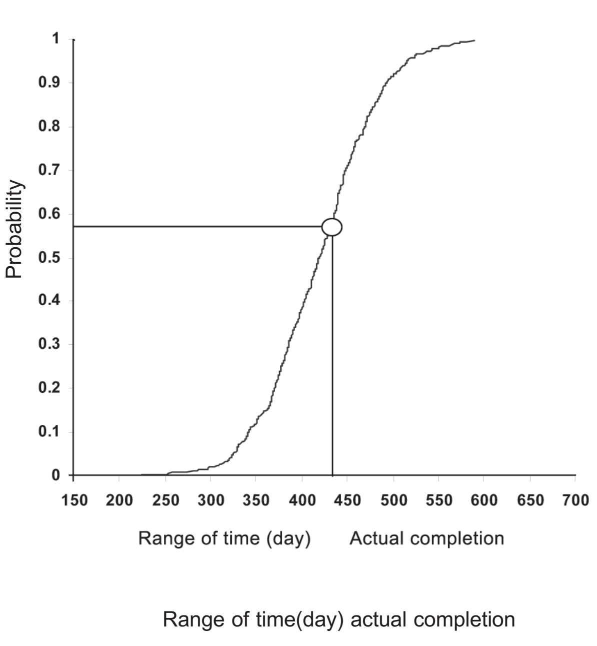

Fig 3. The cumulative distribution function (CDF) based on the results from the simulation model [1]

The excavation activity for construction includes drilling holes into the tunnel face and loading them with explosives. This is followed by "shooting" the rock (retracting the jumbo, wiring the detonators, and detonating the explosives). For simplicity, these times have been made part of the duration of the "excavation" activity and thus firing is assumed to take zero time. Detonating is followed by the ventilation activities to remove the smoke and toxic gases out of the tunnel. In order to bring back the jumbo and resume drilling again, all the debris resulting from the last shot must be removed. When mucking is done, excavation (ie, drilling and loading) and the installation of the initial rock support can start. Thus "excavation" and "support" can occur at the same time. In order to detonate again, the "excavation" for the next round (drilling and loading of holes) must be complete, and sufficient initial support must have been placed so that, after the rock is blasted, the length of unsupported tunnel is less that the maximum allowed for the current rock class. After the rock is blasted, the cycle repeats again.

The excavation progress cycle (drilling, blasting, and mucking) is called a round. The tunnel geology is modelled as a discrete-state, discrete-space process. The first step starts in rock-mass grade 1 and ends at rock-mass grade 9. The rock-mass-grade transition probabilities from step to step. The excavation advance rates are expressed as linear metres per day.

Comparison of alternatives

The probability distribution function (PDF) indicates that the project could take as little as 225 days or as long as 550 days, with the most likely completion date of 425 days. The cumulative distribution function (Fig 3) reveals that the actual duration of the project 432 days corresponds to a probability value of 0,58.

7. Conclusion

Exploratory tunnels are important monitoring tools for project managers. These tunnels indicate the appropriate construction method by providing information about geologic and hydro-geologic features. In the case of the Kaponig tunnel, the exploratory tunnelling work revealed that the initial estimates for ground water intake were misjudged, and a larger sedimentation basin and revisal, construction equipment configuration would be required. Clearly, if no exploratory work had been conducted prior to the final construction process, a significant amount of time and money would have been lost. The usefulness of exploratory tunnels could be further enhanced by combining productivity data, probability of encountering various geological and hydro-geological conditions and the Monte-Carlo simulation method to predict the probability values associated with duration and cost values for the remaining tunnelling project.

References

1. ABDALLAH, A. *Investigations in the Kaponig Construction of the Kaponig Railway Tunnel* (Carinthia, Austria). Research Report, Institute of Construction Management and Economics, Faculty of Civil Engineering, Technical University of Vienna, Vienna, Austria, 2006.
2. LECA, E.; CLOUGH, G. W. Preliminary design for NATM tunnel supports. *Journal of Geotechnical Engineering, ASCE*, April 2005, Vol 118, No 4, p. 558–575.
3. RAMSPACHER, P.; STEIDL, A.; STROBL, E. 2000. *Hydrogeological Investigations in the Kaponig-Dösen Area during Construction of the Kaponig Railway Tunnel* (Carinthia, Austria). Joanneum Research Institute of Hydrogeology and Geothermics, University of Technology Graz, Austria. 2000. Bd 51, 111–167.
4. PORR-News No 126. Report "Feste Fahrbahn und Masse-Feder Systeme am Beispiel der Bauvorhaben Feste Fahrbahn Zammer Tunnel und Kaponigtunnel". 1997.
5. GALL, V.; ZEIDLER, K.; MYERS BOHLKE, B.; ALFREDSON, L.; SAUER, G. *Optimization of Tunnel per-support- soft ground NATM at Washington, D. C. Metro's section F6B "North American tunneling"*. Published by American Underground-Space Association Newport Beach, California, February Melbye T., and Garshol K. 2000, 8th edition, Sprayed Concrete for Rock Support-A Particular specification, Nick Swannel and Tom Melbye, p. 229–236.
6. PALMSTRÖM, A. *RMI – a rock mass characterization system for rock engineering purposes*. PhD thesis, Oslo University, Norway, 1995. 400 p.
7. PALMSTRÖM, A. A new method to characterise rock masses for applications in rock engineering. In *International Conference at Oslo Bergmekanikkdagen*, Oslo, 1996. 27 p.
8. EISENSTEIN, Z. *Urban Tunneling Challenges & Progress*. International Tunneling Association; Challenges of urban tunneling in general, any tunneling project, 1992–1995. 1999.
9. MARTINEZ, J. C. *et al.* State- and Resource-Based Construction Process Simulation. In *Proceedings, ASCE First Congress on Computing in Civil Engineering*. Washington, DC, June 20–22, 1994.
10. GIRMSCHEID, G. and SCHEXNAYDER, C. *Drill and Blast Tunneling Practices*. Institute for Construction Engineering and Management, Swiss Federal Institute of Technology, Zurich, Switzerland article, 2005.

BANDOMIEJI TUNELIAI DARBŲ TRUKMEI PLANUOTI IR SĄMATOMS SKAIČIUOTI

A. Abdallah

Santrauka

Bandomieji tuneliai paprastai naudojami geotechniniams ir konstrukciniams tunelių tiesimo projektams tirti ir palyginti. Šiame straipsnyje nagrinėjami bandomieji tuneliai kaip projekto valdymo priemonė, nustatant bendrą tunelio tiesimo trukmę ir kainą. Buvo surinkti duomenys iš Kaponig – 2,75 kilometro ilgio bandomojo tunelio Austrijoje, kuris yra dviejų juostų greitojo traukinio linijos dalis. Šios žinios ir patirtis buvo naudotos vertinant rizikas, susijusias su projektavimo detalėmis, reikalingomis galutinai tuneliui užbaigti (tunelio ašies ir aukščio nustatymas, sutvirtinimo reikalavimai, žemės kasimo darbų metodai). Sukurtas deterministinis Monte Karlo modeliavimo metodas, kuriuo remiantis galima prognozuoti galutinį projekto terminą ir statybos kainą bei su tuo susijusias tikimybes.

Reikšminiai žodžiai: tunelių tiesimas, projektų vadyba, uolienų klasifikacija, rizikos, trukmė, statybos inžinerija, valdymas, ekonomika, Monte Karlo modeliavimas.

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