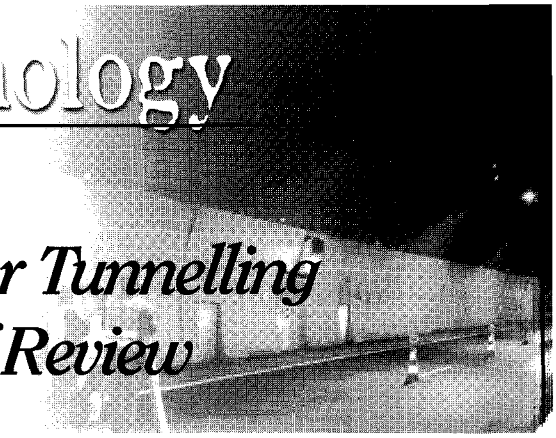

The Decision Aids for Tunnelling (DAT) - a Brief Review

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1. INTRODUCTION

Tunnelling, similar, but more so than other geotechnical endeavors, is characterized by the influence of uncertainty. Owners, planners, designers, contractors and other parties involved in tunnelling need to consider these uncertainties in their decisions since they affect tunnel construction cost and time as well as the required and produced resources. The DAT, developed by the author of this article together with many colleagues and students, allow one to assess all these uncertainties. Development and use of the DAT have been going on for many years. The reason for this article is to provide the Korean readership with a summary review based on other articles which have been and are being published and which are referenced for more detailed information.

The article will continue with a brief description of the DAT, then devote most of the content to a description of various applications before ending with "conclusions and outlook".

2. THE DECISION AIDS FOR TUNNELLING (DAT)

The Decision Aids for Tunnelling consist of an interactive computer program with which tunnel construction cost and time as well as required resources such as construction materials and produced resources such as muck can be computed. The DAT work with standard information used by tunnel designers and contractors in form of geologic/geotechnical descriptions, geometric-, structural - and material characteristics of tunnel supports, construction parameters in the aggregate form of advance rates and costs per tunnel length or in more detailed form. Most importantly, the DAT include uncertainties in all these factors and the results will, therefore, be distributions of construction cost, time and resources. The DAT have been developed over a number of years and have been applied in a number of cases (Einstein et al, 1991, 1992; Descoeudres and Dudt, 1994; ISRF, 1997; Xu et al., 1998).

The DAT consist of two major components:

- Description of Geology
- Construction Simulation and Construction Management

The Description of Geology produces probabilistic geologic/geotechnical profiles. The input is based on geologic information provided by geologists and engineers obtained from typical geologic explorations. The profiles which indicate the probabilities of particular geologic conditions occurring at a particular tunnel location are usually obtained through a combination of objective information and subjective estimates of experts. Specifically, the average length of geologic (geotechnical) parameter states and their transition probabilities are estimated. For instance, for the parameter lithology, one estimates the average length of the parameter states 'granite', 'phyllite' and 'schist' as well as the probability that phyllite follows granite, schist follows granite, etc. Subsequently the DAT use this information to simulate a possible profile for each parameter. The profiles for all parameters are then combined in groundclass profiles. Figure 1 shows such a profile resulting from a single simulation. A number of such profiles (each being different) are simulated to represent the whole range of geologic conditions.

The Construction Simulation simulates the construction process through the ground class profiles. This involves relating geologic conditions (groundclasses) to construction classes or "tunnelling methods". Tunnelling methods define tunnel cross sections, initial and permanent support, as well as the excavation method which are best suited for a particular ground class. This and the relation between tunnelling method and construction cost and advance rates (construction time) have to be prescribed by the user, who can also include cost- and advance rate-distributions, i.e. cost and time uncertainties, for each tunnelling method.

The level of detail of the input depends on the project phase and can also be defined by the user. Usually, one simply associates advance rates and cost per linear meter with each tunnelling method (Fig. 2a). On the other hand and if desired, it is possible to describe each round with all activities

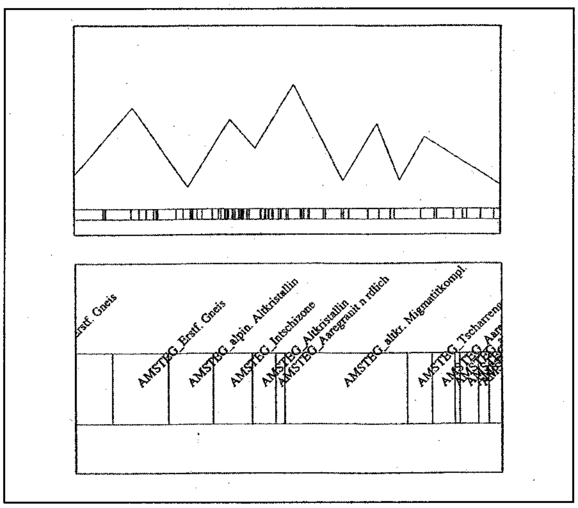


Figure 1. Simulated Ground-Class Profile for the Gotthard Base Tunnel.
Upper Figure: Profile of Entire Tunnel.
Lower Figure: More Detailed Profile of Northern (Left) Part of Tunnel.

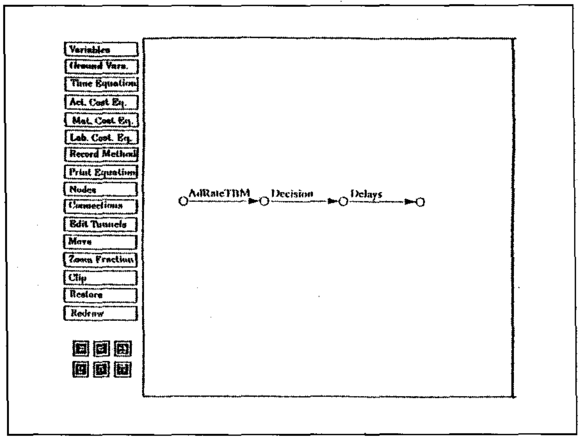


Figure 2a. Decision Aids for Tunnelling
Simple Construction Network

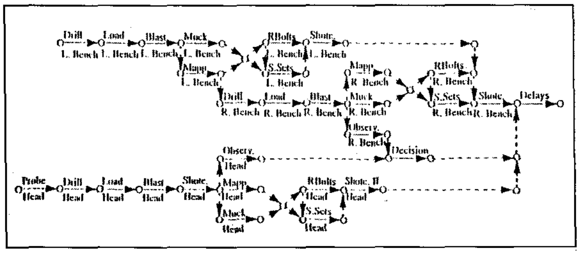


Figure 2b. Decision Aids for Tunnelling (DAT) Construction Network for Drill and Blast, Heading and Benching Construction

involved (e.g. drilling, loading, blasting, etc., Fig. 2b).

The simulation of the construction process is based on the Monte Carlo procedure. First, one ground class profile of the many probabilistically possible profiles is simulated and related to the corresponding tunnelling method profile. Construction simulation then proceeds round by round for drilling and blasting or cycle by cycle for TBM tunnelling through the ground class profile producing a total cost and total time for each simulation. The total costs and times for a particular tunnel simulation represent one point in Figure 1, the so called Time-Cost Scattergram as shown in Figure 3. This procedure is then repeated by simulating other geologic profiles and "constructing" tunnels through them to produce the complete scattergram. It is important to realize that this procedure allows one to consider different uncertainties, specifically geologic/geotechnical uncertainties and construction uncertainties. Geologic/geotechnical uncertainties are the most important uncertainties in deep lying tunnels. Examples of construction uncertainties which are independent of the geology, are operational variation in drill penetration, delays due to mishaps and similar causes. In shallow tunnels, such construction related uncertainties, particularly if they involve interference with activities on the surface are of equal or greater importance than the geologic uncertainties.

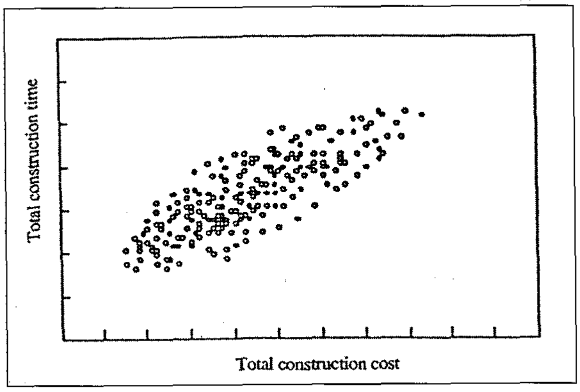


Figure 3. Time-Cost-Scattergram

Also, many other factors involved in tunnel construction such as delays caused by method changes, learning curves, delays caused by operational aspects such as rail placement or different shift arrangements (working and maintenance shifts) can be considered. Most importantly, and as will be seen in the examples, it is possible to model the construction of entire tunnel systems consisting of several tunnels, shafts and other features.

3. APPLICATIONS OF THE DAT

3.1 INTRODUCTORY COMMENTS

The best way to understand what can be done with the DAT is to look at a variety of applications. This will be done in the following with cases ranging from the transalpine tunnels, to other mountain tunnels and to tunnels under cities. Consequently, a variety of geologic and construction conditions will apply. This and the different objectives of the cases will provide an idea on the versatility of the DAT.

3.2 SYSTEM AND ALIGNMENT STUDIES

Several new transalpine railroad tunnels are planned in the Central Alps, two of which, the Gotthard Base tunnel and the Lotschberg Base tunnel are located in Switzerland. During the early planning and design stages of these tunnels (1990/91) so called systems studies were conducted. In these systems studies, the construction cost and time of the three different tunnel systems (one double track or "two-track" tunnel and one service tunnel, two single track and one service tunnel, three single track tunnels) shown in Figure 4 were compared, resulting in the cost/time scattergrams shown in Figure 5. Figure 4 illustrates what was said earlier that complex systems and many interacting tunnels can be modelled. A number of interesting conclusions can be drawn from Figure 5.

- The time distributions of System 2 and System 3 are identical. This is so because construction time depends on the 'slowest' project component and since this slowest component is the same in either case, namely, a single track tunnel. In System 1, however, it is the double track tunnel which determines construction time and its distribution.
- While durations are influenced by the slowest component, costs have cumulative characteristics, i.e. every cost component will influence the total cost. This is the reason that the costs increase with the number of major components (System 3>System 2>System 1). What is particularly noteworthy is that the range of cost distributions increases correspondingly.
- Each system has three time-cost "clouds". This reflects consideration of the potentially very bad conditions in the Piora Zone with 0-length, (lowest cost), 1-20m length (medium cost) and 20-50m length (highest cost). The consideration of the Piora Zone and the reason why only an effect on cost but not on time occurs will be discussed in Section 3.3.

Figure 6 is an enlarged part of Figure 5 showing the scattergrams and the corresponding cost- and time histograms for System 1 (one double track and

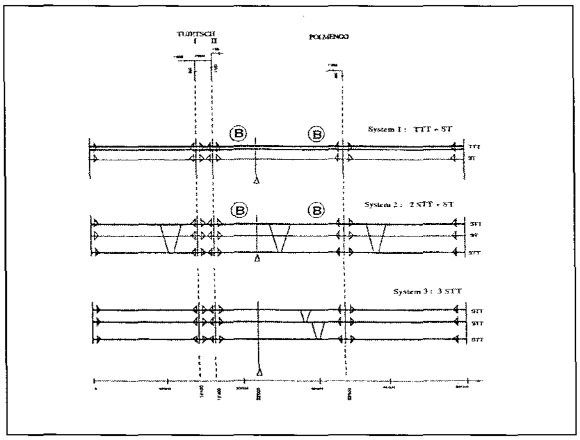


Figure 4. Gotthard Base Tunnel Systems –Tunnel Sections and Tunnel Advance Directions (TTT = Two Track Tunnel, STT = Single Track Tunnel, ST = Service Tunnel)

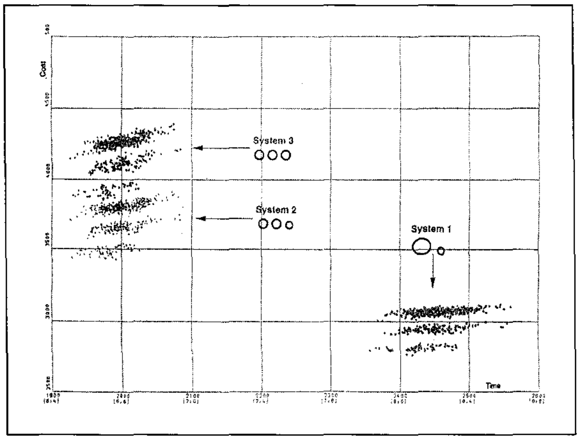


Figure 5. Gotthard Base Tunnel. Time–Cost Scattergram of the Three Systems (Time in working days and years: months; 1 year = 300 working days. Cost in million Swiss Francs)

one service tunnel). The cost–time points in Figure 6 have different symbols. As described in Section 2, several construction simulations are performed per geologic simulation (realization) to represent the distribution of advance rate and cost per linear meter for a "constant geology". Identical symbols in

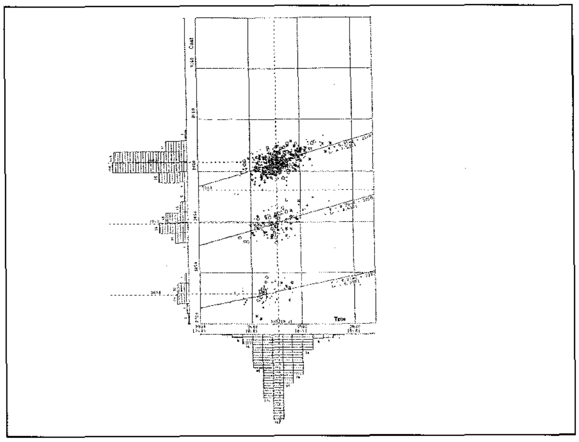


Figure 6. Gotthard Base Tunnel. Time–Cost–Scattergram and Corresponding Histograms for System1. (Time in working days and years: months: 1 year=300 working days. Cost in million Swiss Francs)

Figure 6 represent, in this case, three construction simulations per geologic simulation. It is quite evident that the distribution induced by geologic uncertainty is substantially greater than that due to construction uncertainties. As a matter of fact, the geologic uncertainties are between 10 and 70 times greater than the construction uncertainties.

3.3 INVESTIGATION OF THE EFFECT OF MAJOR GEOLOGIC FEATURES

The geology of the Gotthard Base tunnel (Figure 7) is characterized by two potentially problematic zones, the "Tavetscher Zwischenmassiv" and the Piora Zone. The Piora Zone contains strongly disturbed dolomite which, if it were encountered in the tunnel at over 2000 m overburden and corresponding water pressures, would cause major cost increases and time delays. For this reason, an intricate exploration and treatment scheme (Figure 8) consisting of exploration tunnels, shafts and borings (see also Zuber, 1994, for details) was started. The purpose of this scheme was to determine if problematic geologic conditions exist at the tunnel level and if so, to use the pretreatment (grouting, drainage) to remove this zone from the critical path. In addition, the DAT were used to examine the impact on cost and time. Figure 9 shows the cost time scattergram for the Two-Single-Track Gotthard Base tunnel for the case with (Figure 9a) and without (Figure 9b) the problematic

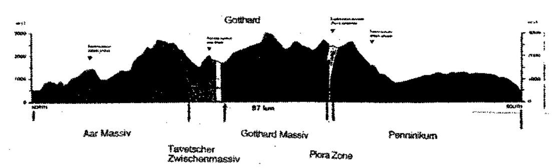
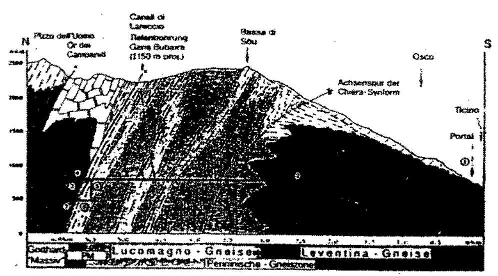


Figure 7. Geology of the Gotthard Base Tunnel (from Deep long tunnels... 1994)



PM = Piora-Zone
Stage 1: Portal Faido/Polmengo 1
Exploration tunnel (adit) 2
Test bores 3
Stage 2: Extension of the adit 4
Vertical shaft 5
Approach and cross shafts 6
Test bores 7

Figure 8. Gotthard Base Tunnel Exploration and Pretreatment Scheme for the Piora Zone
Note: Tiefenbohrung is the boring performed for the 1972 project (from Schweiz, Eisenbahnrevue, 1993).

ground conditions at the tunnel level. Figures 9a and b are at the same scale and a cursory look already indicates the important effect of the Piorazone. A few more detailed comments are warranted:

The two figures have no cost/time scales since the underlying numbers are still confidential. The differences in mean cost are roughly 500 million Swiss Francs and the differences in mean time are approximately 200 days. Most important are the larger uncertainties and thus risk in Figure 9a compared to Figure 9b.

At the time of this investigation with the DAT the pilot tunnel (No. 2 in Figure 8) had been constructed and an exploratory boring indicated that the problematic ground conditions exist in a 250 m wide zone at this elevation. This width of 250 m was, therefore, assumed to also be the maximum possible problematic zone width at tunnel elevation, 300 m below the pilot tunnel elevation. Figure 9a indicates that the problematic ground conditions have an effect on cost as was already shown in the systems study (Figure 5). In addition, as expressed by the upper inclined part of the scattergram, for lengths approaching the maximum of 250 m, there is also an effect on time which is in contrast to the assumption that the pretreatment eliminates any effect of the Piora Zone on the critical path.

There is a positive ending to this "story". Further exploration borings drilled late in 1997 and in the first half of 1998 indicate that no problematic ground conditions exist at the tunnel elevation in the Piora Zone.

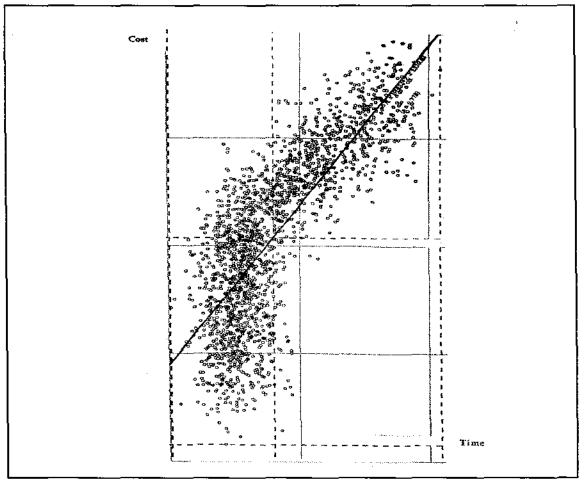


Figure 9a. Gotthard Base Tunnel. Time-Cost Scattergram. - With Piora Zone (From ISRF, 1997). Figures 9a and 9b are in the same scale.

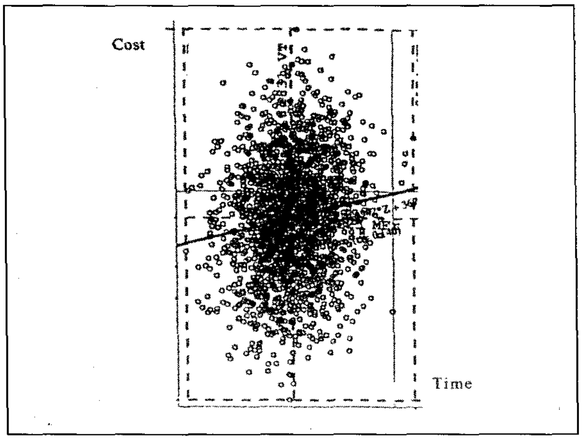


Figure 9b. Gotthard Base Tunnel. Time-Cost Scattergram. - Without Piora Zone (From ISRF, 1997). Figures 9a and 9b are in the same scale.

3.4 RESOURCES MODELLING

The resource model which can also consider uncertainties has been used in the context of the Swiss transalpine tunnel studies to examine materials management. Given the large volume of muck (e.g. over 8 million cubic meters from the Gotthard Base tunnel alone), the limited disposal space available in Switzerland, and the detrimental environmental impact of transportation and disposal it is desirable to reuse much of the excavated material.

Reuse of muck for concrete and shotcrete aggregate as well as for embankments is possible. What reuse is feasible depends on the characteristics of the muck which in turn depends on the geologic conditions and on the excavation method; TBM's produce smaller muck grain sizes than drilling and blasting. What type of muck is produced at a particular location is subject to two categories of uncertainty, the geologic uncertainty discussed earlier and an additional uncertainty as to what type of muck is produced by a particular combination of geology and excavation method. Four muck categories were identified:

1 : Muck reusable for concrete aggregate, coming from Drilling and Blasting operations

2 : Muck reusable for shotcrete aggregate, coming from TBM operations

3 : Muck reusable for embankments and other fills

4 : Muck not reusable for construction purposes.

The results can be presented in a variety of ways. A particularly useful one is in form of time-volume plots at shaft or portal locations as shown in Figure 10 for shaft Sedrun. In this plot the demand for concrete aggregate C1 and shotcrete aggregate C2 is also shown; the demand is also subject to uncertainties. One sees in Figure 10 that for material Type 1 there is always sufficient supply and one can

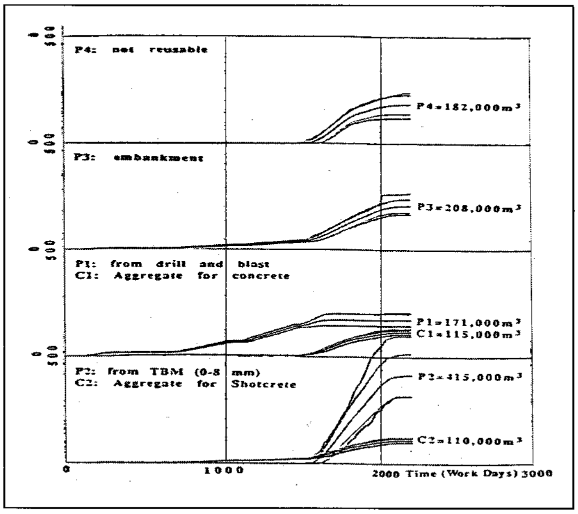


Figure 10. Gotthard Base Tunnel. Muck Production (P) and Concrete Aggregate Consumption (C) at Shaft Sedrun

determine the maximum storage size needed for this material. For material Type 2, there is an initial deficit followed by a large surplus. The uncertainties expressed in the curves allow one to calculate the risk of particular deficit – or surplus volumes.

Another interesting result of the materials management study was the effect of mixing rather than separating the material categories. Transportation of muck through the long shafts would be facilitated by mixing different muck types. The study showed, however, that such a mixing would lead to a loss of 50% of the reuseable muck. As a consequence, the designers decided not to allow such mixing to take place.

At present (fall, 2001) both transalpine tunnels in Switzerland (Gotthard, Lötschberg) are under construction. Sophisticated materials management systems have been implemented. The one used in the Lötschberg tunnel is being investigated with the DAT in the context of a Master of Engineering Thesis at MIT (Kollarou, 2002).

3.5 COMPARISON OF DIFFERENT CONSTRUCTION METHODS

Two cases are described in this context, the first involves a Metroproject while the other one deals with the effect of innovating tunneling technology.

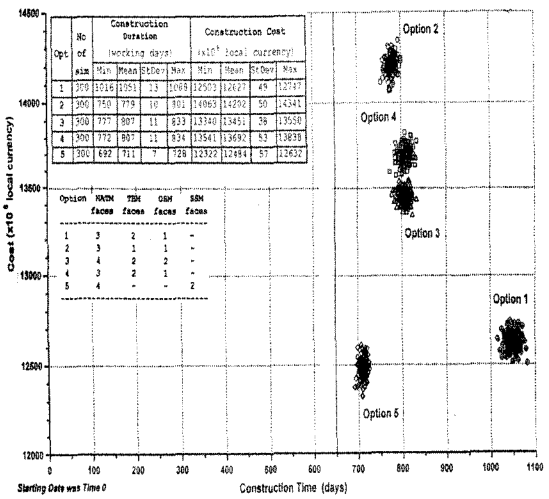
Metro Project

This case has been described in detail by Xu et al, (1998). It involved the investigation of several construction methods to bring construction of a Metro tunnel back to the originally planned schedule. A number of different options (TBM, open shield, slurry shield, NATM) were investigated, and the results of the DAT study are shown in Figure 11. The main use of these results is to estimate the time– and cost risk involved in completing the project. Also very interesting is the fact that there is a substantial overlap in the time distribution for options 2, 3 and 4. It is possible to give different weights to time and cost risks and base decisions on such a weighted assessment. (Note that this comment is purely theoretical in this case since option 5 is best both regarding time and cost.)

Innovating Tunnelling Technology

So far, uncertainties and risk were mainly related to geology and existing construction methods. Additional uncertainties enter the assessment when one considers the development and implementation of new technologies.

In a joint project of the departments of Mechanical Engineering and Civil Engineering at MIT, the University of Texas at Austin, the University of California at Berkeley, at the University of Missouri at Rolla (Nelson et al., 1992; Peterson and Einstein, 1993) the concept and details of a continuous tunnel boring machine were developed. While the principle of using a slipformed, continuous concrete liner behind a tunnel boring machine is nothing new and has been applied in practice, using the pumped concrete as a means to push the machine forward (Figure 12) is different from earlier concepts. What is equally important and innovative is the goal to develop a balanced system. This means that major components such as liner placement, cutting tools, and transportation have to have similar performance and reliability. In other words, developing extremely effective cutting tools does not



Cost vs. Time Scatter Plot for Construction of Metro Line (with indication of completion date) (From Xu et al., 1997).

Figure 11.

make sense if the transportation system cannot keep up with the pace. Also, innovative is the way in which the research and development was performed; namely, using the so called 'concurrent' approach. This approach is beginning to be used in industry with Japan leading; but it has not been used in university research. What it involves is that each contributor to the research, does his or her work while continuously receiving input from the other researchers. Otherwise expressed, the boundary conditions affecting one component are continuously updated reflecting development of other components. The research and development on the CTBM was assigned to: MIT Mechanical Engineering – TBM drive and conveyor systems; MIT Civil Engineering–ground structure interaction, concrete technology, DAT; U of Texas – factors affecting present day TBM performance; U of California and U of Missouri–cutter performance.

The balancing of the system development and the concurrent work were made possible by the DAT. For example, the major system components "boring", "liner placement", and "muck transport" have to be kept in balance. The DAT were used to compare the performance of these system components and to identify which component(s) were (was) lagging behind the other(s). This, in turn, provided the basis for the subsequent development cycle. The activity network introduced earlier (Figure 2) can be used for this purpose as shown in Figure 13. Note that the "delays" in this activity network do include maintenance, cutter changes, or breakdowns.

Applying the DAT-simulation then produces results such as those summarized in Table 1. Table 1 contains

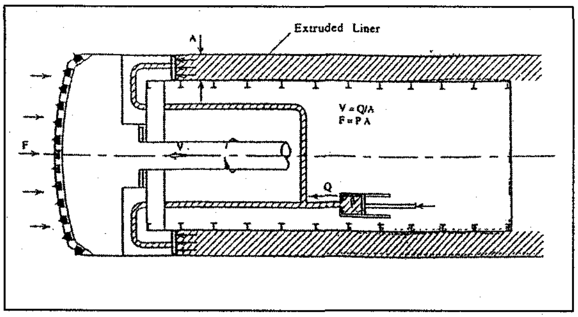


Figure 12. CTBM - Principle: Machine is moved forward by pumping concrete into continuously extruded liner.

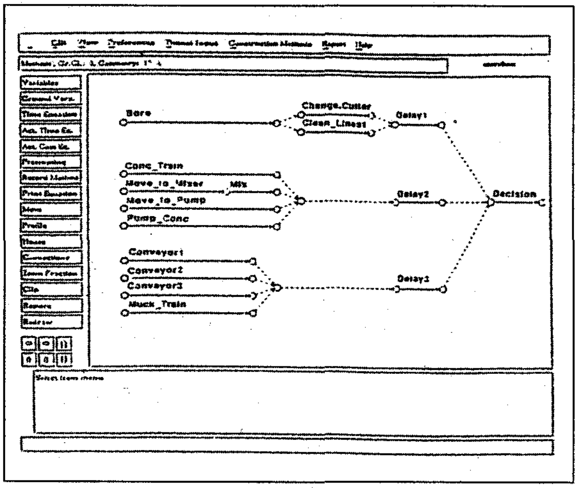


Figure 13. Network for a Continuous TBM Using Trains for Material Handling

a comparison of tunnels of three different diameters built by the CTBM using different muck handling systems. In addition to the CTBM, the DAT were also applied to simulate construction with a "conventional" TBM which uses prefabricated/segmented liners, the results of which are also shown in Table 1.

Another extensive use of the DAT to investigate the effect of innovative technology was in the context of freight tunnel systems under major US cities. The reader is referred e.g. to Sinfield et al., 1996.

3.6 EXPLORATION

One of the main effects of exploration is to reduce uncertainty. In a way, this has already been shown in the context of the cost-time determination with and without problematic material in the Piora Zone of the Gotthard Base tunnel.

A similar study was conducted by Dudt and Descoeudres (1993) using information from borings in the Tavetsch Zone of the Gotthard Base tunnel. Figure 14 shows that additional information reduces the scatter and thus the risk.

Table 1. Advance Rates in meters/hour for Continuous and Conventional T.B.M.'s

Muck Handling System		Diameter					
		3 meters		6 meters		12 meters	
		Length		Length		Length	
		1 km	10 km	1 km	10 km	1 km	10 km
Continuous Tunnel Boring Machine	Muck Pump	5.29	5.29	3.93	3.93	1.34	1.34
	Conveyor	5.32	5.32	4.27	4.27	2.27	2.27
	Trains	5.30	5.30	4.28	4.28	2.30	2.30
	Trucks	5.30	4.68	4.27	2.54	2.29	1.36
Conventional Tunnel Boring Machine		2.27	2.27	2.29	2.29	1.57	1.57

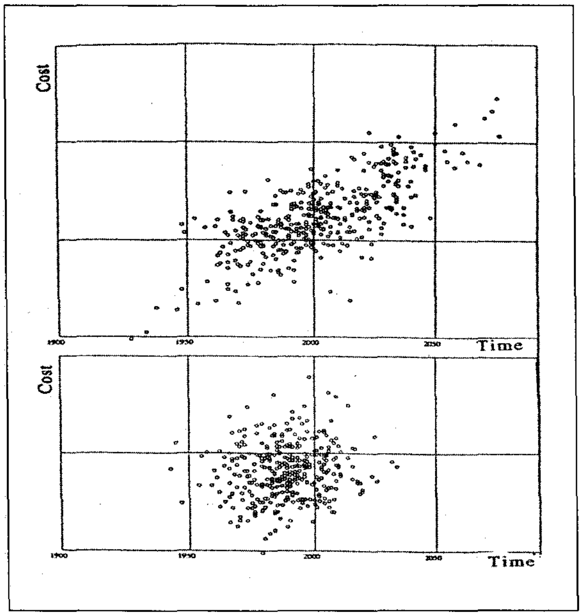


Figure 14. Effect of Additional Exploration on Scatter. Top: before–, bottom–, after exploration (from Descoeudres and Dudt, 1993)

The principle of reducing of uncertainty through additional information is well known in decision analysis (Raiffa, 1964). As a matter of fact, one can determine, prior to collecting more information, if the reduction in uncertainty is worth the cost of collecting this information, i.e. performing additional exploration. Several examples of this approach have been published (eg. Einstein et al., 1977, 1978).

3.7 UPDATING

Uncertainty is also reduced during the actual construction since one knows he actual geologic conditions and the construction cost and time. The uncertainty about the unexcavated part remains but becomes smaller as shown in Figure 15a. One can go

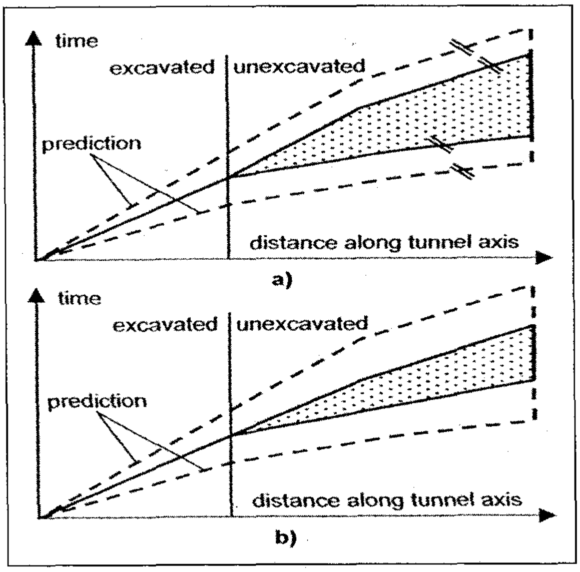


Figure 15. Reduction in Uncertainty (a) only by Replacing Predicted Progress with Actual Progress; (b) By Additionally Refining the Prediction Based on Observations.

a step further by using the observed geology and actual performance (time, cost) to refine the prediction for the unexcavated part. In other words, one uses the observed information to update the predicitons for the as yet unexcavated part which leads to a further reduction of uncertainty (Figure 15b).

A formal procedure to do such updating has been incorporated in the DAT based on research by Haas (Haas, 2000; Haas and Einstein, 2001). The results of applying the procedure are shown in Figures 16 a – c). In 16a, the cost–time scattergram for a tunnel before construction starts is shown. In figure 16b, the scattergram considering the encountered geology and performance but without updating for the unexcavated part is shown. In figure 16c full updating is applied, i.e. the predicted geology and

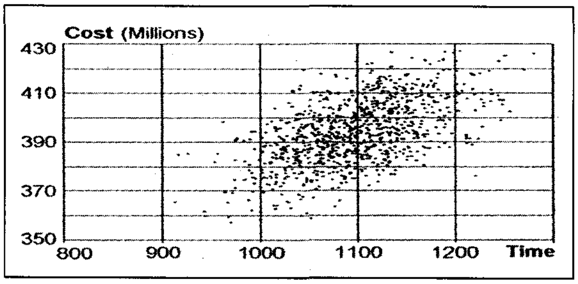


Figure 16a. Time–Cost Scattergram for Initial Input – Tunnel Before Construction Start

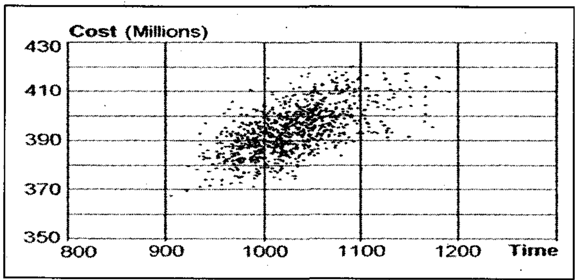


Figure 16b. Time–Cost Scattergram for Partially Updated Input. Tunnel After Some Excavation Has Taken Place; – Observed Information in Excavated Part Used Only There.

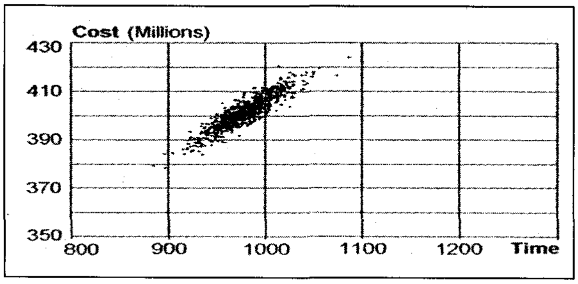


Figure 16c. Time–Cost Scattergram For Fully Updated Input – Tunnel After Some Excavation Has taken Place; Observed Information in Excavated Part Used to Update Unexcavated Part.

performance in the unexcavated part has been updated based on what was observed in the excavated part. It is evident that the scatter becomes smaller as one goes from 16a to b to c!

3.8 OTHER APPLICATIONS

The DAT have been applied to many tunnels in the sense reported in Sections 3.2 and 3.3 In addition, applications involved also the evaluation of different bids (ISRF, 1993). Simply using the logic but not applying it to a tunnel was the use of the DAT to model fire fighting in a house as was done in research performed at Worcester Polytechnic Institute. The latter shows that the DAT can lend themselves to simulations of any linear or networked process subject to uncertainties.

4. CONCLUSIONS AND OUTLOOK

The DAT are useful, whenever uncertainties affect a largely linear or networked processes. So far the applications are all related to tunnelling and they allow all parties involved in a tunnel to rationally determine the effect of uncertainties. This is important with regard to decision making in general and risk analysis in particular. Most large geotechnical projects and particularly tunnels require such decision making in today's engineering environment.

The methodology used for the DAT is widely applicable. In addition to other issues related to tunneling, such as effects on the surface or on the environment in general, safety during construction and operation can be considered. As mentioned several times, the methodology is also applicable to any other linear or networked system subject to uncertainties.

As a final point, it might be worthwhile to mention that the DAT development not only benefitted from the work of my collaborators at MIT and EPFL but from the input of the engineers and other decision makers who used this tool.

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