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Extract (pp.124-138):

TUNNEL CONSTRUCTION TIME AND COST PROBABILISTIC EVALUATION WITH THE SYSTEM DAT (DECISION AIDS FOR TUNNELING)

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1. INTRODUCTION

It is a characteristic of underground works that technical and economic decisions have to be considered under conditions of uncertainty. This uncertainty arises from the inability to form a complete structure of the medium, the rock mass, in terms of geological and geomechanical properties before construction, limitations of the existing methods of rock-excavation interaction analysis as well as from the variability in human and equipment performance and political and economical factors. All these factors result in a highly risky environment.

Practitioners in the field of ground engineering have been dealing with this “risky” environment using their experience, often resulting in expensive and conservative design solutions. Probably, up until recently, this was acceptable, but under the current global conditions of budget restraint, highly competitive markets, and society’s awareness of risk, an evaluation of risk is often explicitly required.

In other fields of science and engineering, decisions under uncertainty have been routinely addressed using Bayesian updating (1763; Harr, 1987) but only occasionally dealt with in tunneling due to the complexity of the medium and a lack of suitable and effective tools for performing such an analysis. Decision Aids in Tunneling, DAT, is a tool that was especially developed to respond to this challenge.

2. DECISION AIDS IN TUNNELING (DAT)

DAT was developed by Massachusetts Institute of Technology and Ecole Polytechnique Federale de Lausanne (Einstein et al., 1992), and applied by Geodata to actual tunneling situations. DAT is designed to cope with the inherent uncertainties related to geologic and geomechanical parameters and to duration and cost of construction operations.

DAT is a sophisticated software that provides an important step towards decision management under conditions of uncertainty in underground works, and therefore has the potential for assisting in the planning of underground operations. DAT elaborates geologic and construction data in a probabilistic manner by using an articulated sequence of calculations. In this manner, it is possible to provide the time and cost predictions for individual construction phases, highlighting the uncertainty in these predictions.

DAT assists in the decision-making process in several ways:
- by interpreting probabilistically the partial knowledge related to the medium (ground conditions), and the uncertainty related to the geologic-geomechanical model;
- by updating the parametric values of a project on the basis of information integration coming from the site investigation phase and observations during construction, simultaneously evaluating the variation in the preliminary model;

- by realistically modeling any design alternative; by changing for example the excavation method and direction, the number of excavation phases, and immediately providing a probabilistic estimate of construction cost and time figures; and
- by providing a basis for comparison of different design solutions in terms of time/cost and their associated confidence limits.

DAT can be applied in all project phases: from preliminary and feasibility studies to detailed design during construction. DAT is a useful decision-making tool for all parties involved in the project - owner, contractor, and designer - in scheduling and allocating resources including time, during all the phases of a project.

2.1 DAT Structure

DAT develops a series of probabilistic possible profiles, each of them composed of a succession of “ground classes” (see section 2.2) These “ground classes” are coupled with design solutions which are associated with construction time and cost that are entered in the model in the form of a statistical distribution. Each simulation corresponds to a geomechanical profile giving as an output a point in the time and cost diagram. The generated scatter cloud depicts the uncertainty and variability of geomechanical and construction related parameters. In particular, the modeling of the construction process allows for the statistical simulation of:

- the main excavation methods (conventional and mechanical);
- the different modes of excavation-advancement orientation (one or more excavation faces, adits, etc.); and
- the variability of time and cost of the different construction operations (including scheduled and unplanned delays, also as related to the distance from the face).

Depending on the actual project phase the simulation can be performed for each construction task.

DAT consists of two modules, the geology and construction ones.

2.2 The “Geology” Module

DAT represents, in a probabilistic manner, the geologic and geotechnical data assuming a Markov process (1912; Harr, 1987) where a parameter state depends only on its most recent condition.

In the “Geology” module all relevant variables (geological and geotechnical) whose states combinations define technical classes (which are referred to as “ground classes” in DAT and hereafter) are input in the program in a probabilistic form. A certain design, defined by a method of excavation and support measures, is coupled with a technical class. In summary, the process of a probabilistic profile generation (see Figure 1), in terms of allocation of ground classes to the tunnel alignment, consists of the following steps:

1. Subdivision of the alignment in homogeneous zones defined by similar geological and geomechanical conditions. The length of these zones can be given in a triangular distribution form [min, mode, max].

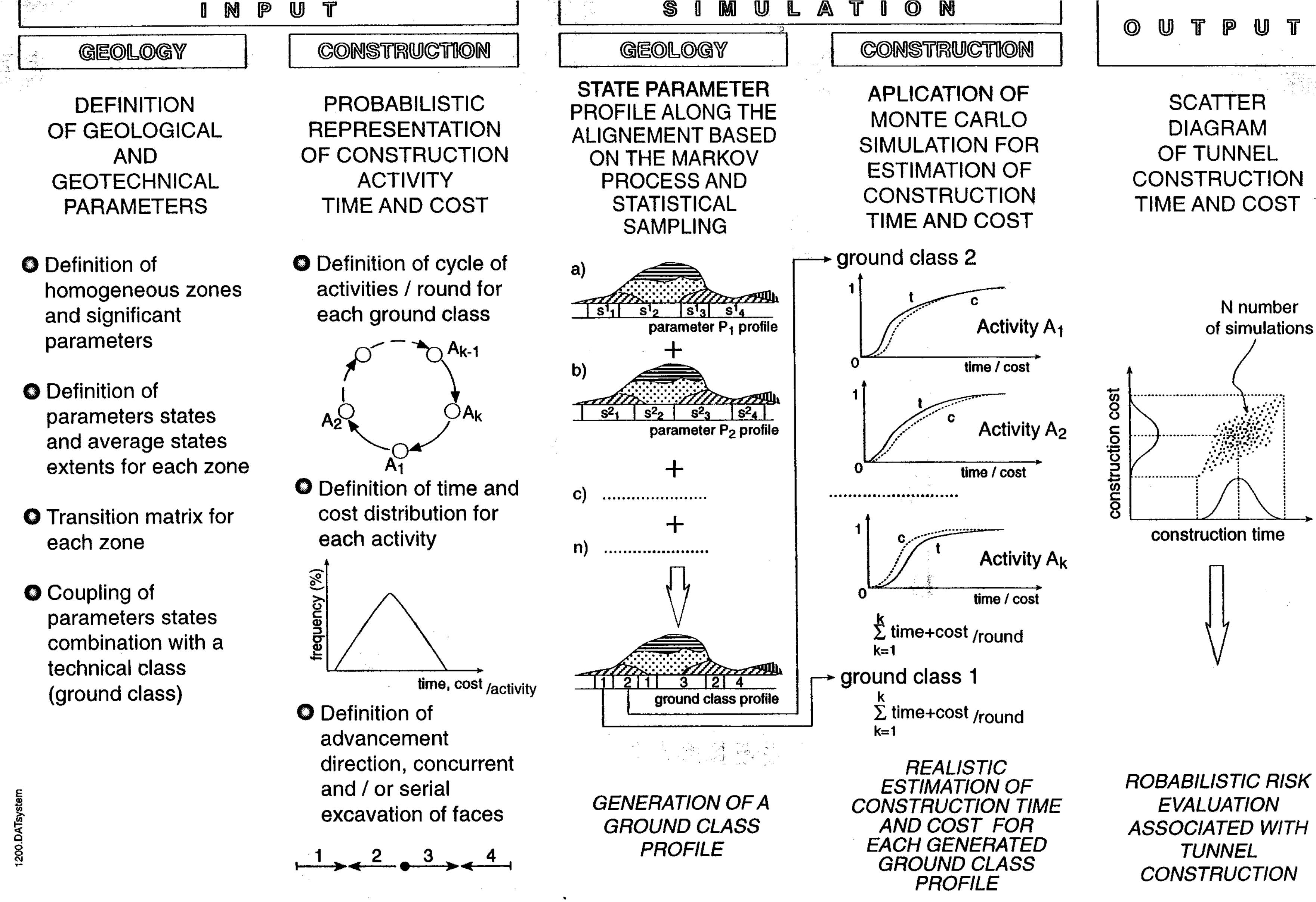


FIG. 1: *Schematic representation of the DAT process*

2. For each homogeneous zone, the geological and geotechnical parameters that control the excavation method and determine support measures are defined also in terms of their possible (parameters) states.
3. For each parameter the average state extent and the transitional matrix are provided. Parameters states can also be assigned deterministically along the tunnel alignment.
4. Combination of parameters states provides the ground classes.

An example is given in Table 1 for a certain homogeneous zone (see Section 5) as defined by five parameters and their associated states.

Table 1. Example of a possible set of parameters and associated states for a homogeneous zone

Parameter / State	p_1 (MPa)	p_2 (%)	p_3 (mm)	p_4 (*)	p_5 (MPa)	p_6
s_1	<25	<25	<60	0	<1	yes
s_2	25-50	25-50	60-200	10	1-3	no
s_3	50-100	50-75	200-600	20	>3	-
s_4	100-250	75-90	600-2000	25	-	-
s_5	>250	90-100	>2000	30	-	-

Note: p_1: Uniaxial compressive strength of the rock material, Co; p_2: rock quality designation, RQD; p_3: discontinuity spacing; p_4: discontinuity condition; (*) ratings according to RMR system (Bieniawski, 1989); p_5: lithostatic pressure; and P_6: presence of groundwater.

Given this input data, the program then assigns parameters states to segments of the zone according to Markov theory and sampling from the relevant distribution. The lengths of these segments are distributed according to a negative exponential distribution which is defined by the average extent of a state parameter.

The process is repeated until the cumulative length of the parameter states segments is equal to the zone length for each zone, for each parameter. In this way the program produces an alignment profile for each parameter. It is important to note that, if precise information is available, such as data coming from the site investigation phase of a project, it is possible to entered the data in the model in a deterministic way.

The program continues by combining the parameters profiles according to the parameters states combination to ground class matrix allowing for the generation of a ground class profile as shown schematically in Figure 2.

2.3 The “Construction” Module

The ground classes are coupled with design solutions which are associated with time and cost. Construction parameters can be defined in a deterministic and/or probabilistic manner, where (in the probabilistic way) frequency distribution curves represent the uncertainty level associated with each activity. The level of detail in the input parameters and, as a result, the precision in the simulation output depends on the project stage phase. For

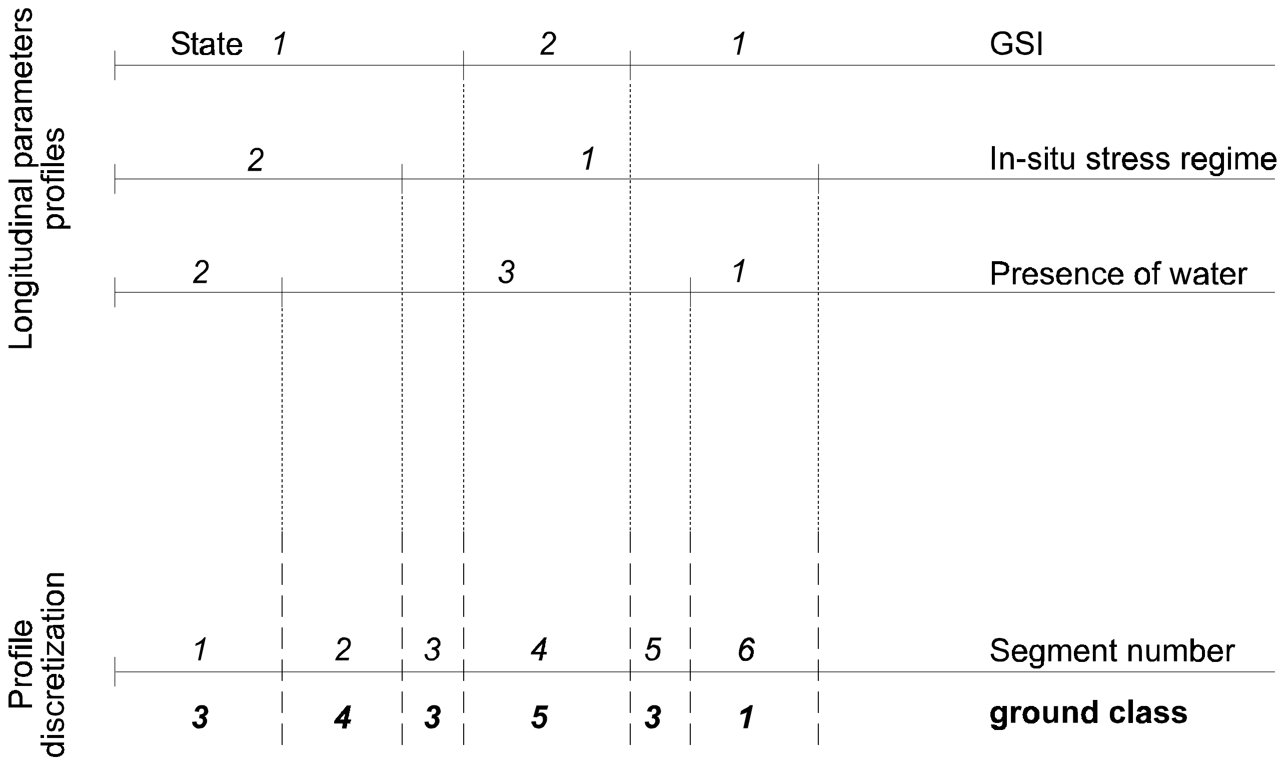


Figure 2 - Schematic example of ground class profile generation

example, in a detailed design stage it is possible to consider every single working activity and its variability.

The simulation of construction operations (Figure 1) is based on the Monte Carlo method (Metropolis and Ulam, 1949) and follows, round-by-round, the already defined ground class profile. For each round, the program samples a set of time and cost values from the relevant distributions of each operation in the excavation cycle. The procedure is repeated for all the segments of the profile adding up to a cost and time final value corresponding to that profile and to a point in the time vs. cost scatter diagram. This procedure is repeated for each profile generated by the “geology” module. To have a statistically significant result, it is usually necessary to do more than 200 simulation runs.

The program DAT allows to manage different tunnel excavation sequences such as multiple faces, excavated concurrently or in sequence, or simulate the construction of more than one tunnels in a project. DAT also allows for management of resources such as construction materials and personnel. Delays and/or scheduled interruptions in the working sequence can also be included in the construction simulation. The number of construction options as well as the integration of design and construction scheduling aspects particular to a project are only limited by hardware constraints.

3. USING DAT IN THE DESIGN PROCESS

The potential of the system DAT in all the project phases is based on the designer’s ability to relate to each technical solution a corresponding combination of parameters states. In other words, it is necessary to depict the design process on DAT modules. This procedure can be relatively simple when using the empirical approach to design for which a combination of parameters states is associated with a design solution. Yet, this procedure can become complex when an elaborate design approach is used, like the one suggested by the National Project for Underground Construction Standards (1995, in development) under the section “Guidelines for Design, Tender and Construction of Underground Structures”. In respect to these Guidelines, a procedure of sequential studies has to be followed, (before the discretization of the profile in segments) on the basis of the following items:

1. Geotechnical-geomechanical characteristics
2. In-situ stress regime
3. Excavation geometry
4. Overburden
5. Lithological characteristics of the Formation
6. Hydrogeological condition
7. Design constraints

Based on this list of principal items it can be derived that the design solution has to be associated with different combinations of the listed parameters states. The input of the key parameters in the base modules of DAT can follow the conceptual scheme of Table 2.

Table 2. Conceptual scheme for the definition of ground classes

Phase	Study	Principal items
A	Definition of geomechanical groups	1
B	Definition of behavior categories	1,2,3
C	Definition of technical classes	1,2,3,4,5,6,7

In phase A it is often useful to refer to classification systems that allow the determination of rock mass quality indexes (i.e. the Geological Strength index - GSI; Hoek et al., 1995 and the Rock Mass Index - RMi; Palmstrøm, 1996). Depending on the available information, it is possible to probabilistically quantify each parameter of the index or the index itself. In respect to phase B, Geodata has recently developed a classification system based on the predicted deformation of the excavated face and the tunnel using analytical and/or numerical in conjuction with the empirical approach to design (Figure 3). After the behavior categories have been defined; the eventual influence of other parameters in the definition of the ground classes is analyzed, phase C. The resulted ground classes are associated with different design solutions.

Table 3 depicts this three-phase procedure as it is applied for the parameters of Table 1. For each phase the relevant parameters are identified.

Table 3. Selection of significant parameters

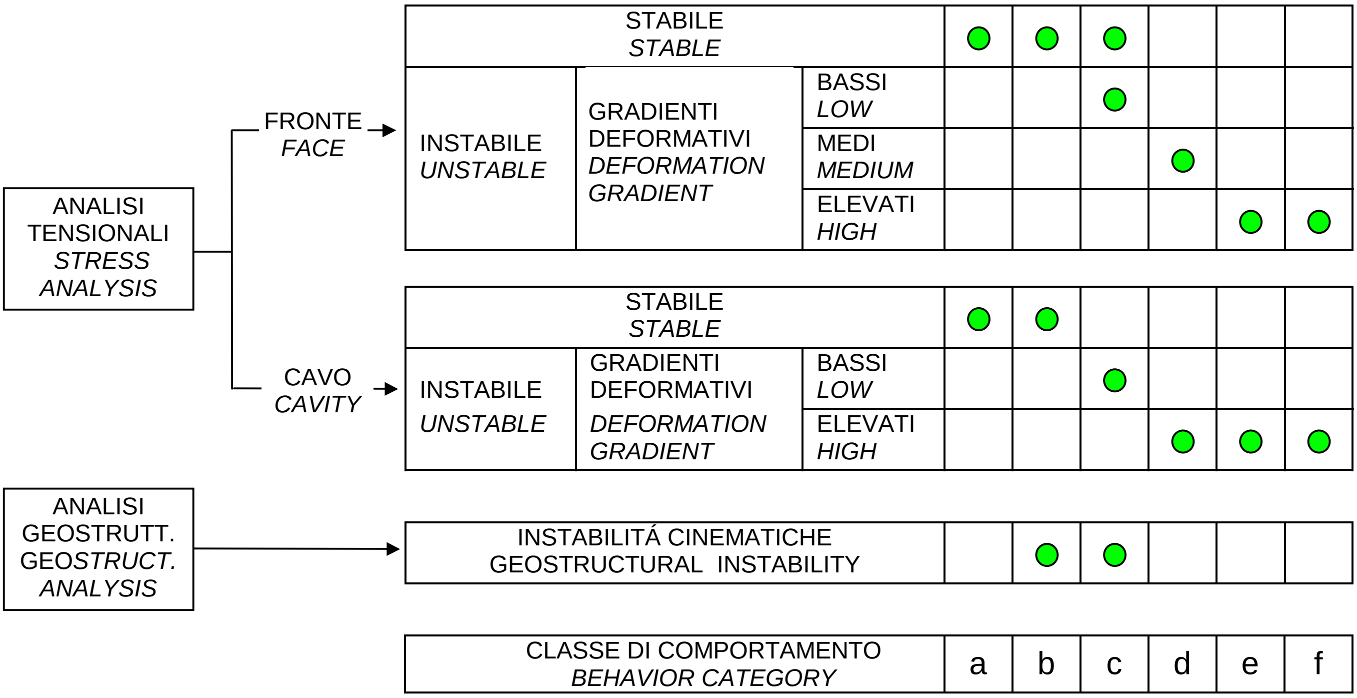
Phase	Selected Parameters
A	p_1,p_2,p_3,p_4
B	p_1,p_2,p_3,p_4,p_5
C	p_1,p_2,p_3,p_4,p_5,p_6

The total sum of the possible combinations of the parameters states to which a certain number of design solutions can be associated with is given by the product of the number of the possible states of each parameter (n_{pi}), Πn_{pi}. For the example of Table 1 the number of combinations is: $5\times5\times5\times5\times3\times2=3750$. DAT requires each of these combinations to be coupled to a design solution, (usually ≤10), a process which is extremely laborious. To overcome this, especially in phase A, the parameters states can be combined in a geomechanical quality index.

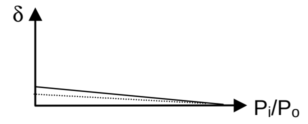
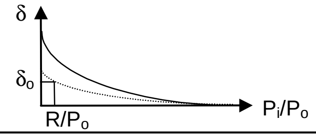
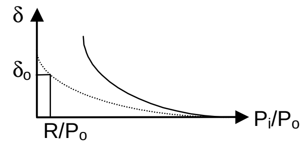
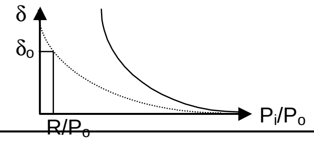
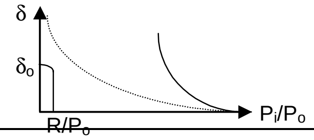
In the following sections the application of system DAT is demonstrated.

4. EXAMPLE APPLICATION OF DAT

The study involves the preparation of tender design of a three-lane highway tunnel having a length of 3600m and an average excavation diameter of 15.0m under a maximum overburden of 150m.



					a	b	c	d	e	f
ANALISI TENSIONALI *STRESS ANALYSIS*	FRONTE *FACE*	STABILE *STABLE*			●	●	●			
		INSTABILE *UNSTABLE*	GRADIENTI DEFORMATIVI *DEFORMATION GRADIENT*	BASSI *LOW*			●			
				MEDI *MEDIUM*				●		
				ELEVATI *HIGH*					●	●
	CAVO *CAVITY*	STABILE *STABLE*			●	●				
		INSTABILE *UNSTABLE*	GRADIENTI DEFORMATIVI *DEFORMATION GRADIENT*	BASSI *LOW*			●			
				ELEVATI *HIGH*				●	●	●
ANALISI GEOSTRUTT. *GEOSTRUCT. ANALYSIS*		INSTABILITÁ CINEMATICHE GEOSTRUCTURAL INSTABILITY				●	●			
		CLASSE DI COMPORTAMENTO *BEHAVIOR CATEGORY*			a	b	c	d	e	f

Classe Category	Fronte *Face*	Cavo *Cavity*	Curve caratteristiche *CharacterIstic curve* al fronte - at the *face* (┈┈┈) e o distanza - *at a dist.* (───)	Interventi di stabilizzazione *Stabilization measures*: Funzione prev. *Primary function*	Interventi di stabilizzazione *Stabilization measures*: Tipologia *Type*
a	stabile *stable* $S>1$ (lievi instabilità di blocchi) (limited block instability)	Stabile *Stable* $S>1$ $R_p/R_o = 1$			
b	globalmente stabile *globally stable* $S>1$ (cinematisimi di blocchi) (wedge instability)	globalmente stabile *globally stable* $S>1$ (cinematisimi di blocchi) *(wedge instability)* $R_p/R_o = 1$		Confinamento *Confinement*	Radiale *Radial*
c	da stabile a leggermente instabile - *limit condition* $S\cong1$ (bassi gradienti deformativi) *(low deformation gradient)* $(\delta_o \leq 0.5\%)$	instabile *unstable* $S<1$ (poco spingente) *(light squeezing)* $R_p/R_o \cong$ 1-2		>Confinamento *>Confinement*	Radiale *Radial*
d	instabile: fronte plasticizzato ma stabilità non critica *not critical face instability* $(S<1)$ (medi gradienti deformativi) *(medium deformation gradient)* $(0.5\% < \delta_o < 1.0\%)$	instabile *unstable* $S<1$ (spingente) *(squeezing)* $R_p/R_o \sim$ 2-4		Confinamento e/o miglioramento *Confinement and/or improvement*	Radiale ed eventualmente in avanzamento *Radial and eventually in advance*
e	instabile: condizioni critiche *critical instability* $S<1$ (elevati gradienti deformativi) *(high deformation gradient)* $(\delta_o \geq 1.0\%)$	instabile *unstable* $S<1$ (spingente) *(squeezing)* $R_p/R_o > 4$		Miglioramento e confinamento *Improvement and confinement*	In avanzamento e radiale *In advance and radial*
f	instabile a breve termine *short term stability* $S<1$ (immediate condizioni di colasso) *(immediate collapse)*	instabile *unstable* $S<1$		Miglioramento e/o confinamento *Improvement and/or confinement*	In avanzamento e radiale *In advance and radial*

Note:

S=Rapporto di mobilitazione (resistenza/sollecitazioni)
strength-to-stress ratio
R=Resistenza mezzo nucleo - *strength of half nucleus*
δ=deformazione radiale (rapporto spostamento radiale /R_o)
radial deformation defined as the percent ratio of radial displacement (u_r) to R_o
δ_o=deformazione radiale scontata al fronte - *radial deformation at the face*
R_p=Raggio plastico - *plastic zone radius*
R_o=Raggio equivalente galleria - *equivalent tunnel radius*

Confinamento: Intervento teso ad evitare la decompressione della roccia e quindi il suo decadimento
Confinement: Measures to avoid relaxation and preserve the inherent rock mass strength
Miglioramento: Intervento teso a migliorare le caratteristiche geomeccaniche della roccia all'estradosso
Improvement: Measures to enhance rock mass characteristics around the cavity

Fig. 3. Definizione delle classi di comportamento - *Definition of behavior categories*

The tunnel crosses a series of slightly metamorphic formations, mainly sandstones of fairly massive and petitic schists. The site investigation, which was essentially based on surface mapping and borehole information, allowed to formulate a hypothesis regarding the geology/structural setting of the area.

4.1 Input parameters of the “Geology” Module

Based on the findings of the site investigation the tunnel alignment was subdivided in 9 homogeneous zones. Uncertainty related to the length of the zones was considered in the analysis by varying the zones extent by 10% of their length. This was decided in absence of more detailed information than the one coming from boreholes. The extents of the identified zones are given in Table 4.

To define the technical classes (ground classes), in accordance to the procedure described, the reader is referred to Tables 1 and 3. To facilitate the assignment of design solution to the different parameters combinations the Geological Strength Index - GSI[1] (Hoek et al., 1995) was used.

Table 4. Zone subdivision

Zone #	Overburden (m)	Extent (m)
1	<50	25
2	<50	220±10%
3	50-100	670±10%
4	50-100	600±10%
5	100-150	720±10%
6	50-100	30±10%
7	50-100	1000±10%
8	<50	310±10%
9	<50	25

Table 5. Selected parameters and corresponding states

Parameters States	P_1(*)	P_2 (MPa)	P_3
s_1	65-84	<1.3	no
s_2	45-64	1.3-2.6	yes
s_3	25-44	>2.6	-
s_4	<25	-	-

(*) available data indicate that P_1, GSI < 85; P_2: lithostatic pressure, P_o, at tunnel level; and P_3: presence of groundwater.

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[1] The GSI value can obtained by adding 10 to the sum of the ratings assigned to the first four parameters of the RMR system ($p_1 ... p_4$; Table 1).

Table 6. Average extents and transition probabilities (matrix) of parameter P_1, GSI, for each zone

Zone #	Parameter state	Extent (m)	Transition probabilities			
			s_1	s_2	s_3	s_4
1	s_4	refer to Table 4	Deterministic attribution			
2	s_1	100	0.0	1.0		
	s_2	100	1.0	0.0		
3	s_1	50	0.0	0.7	0.3	
	s_2	100	0.5	0.0	0.5	
	s_3	30	0.2	0.8	0.0	
4	s_1	90	0.0	0.9	0.1	
	s_2	120	0.3	0.0	0.7	
	s_3	30	0.1	0.9	0.0	
5	s_1	130	0.0	1.0		
	s_2	200	1.0	0.0		
6	s_4	refer to Table 4	Deterministic attribution			
7	s_1	60	0.0	0.7	0.3	0.0
	s_2	100	0.4	0.0	0.5	0.1
	s_3	70	0.1	0.4	0.0	0.5
	s_4	20	0.0	0.2	0.8	0.0
8	s_1	100	0.0	0.8	0.2	
	s_2	150	0.4	0.0	0.6	
	s_3	50	0.2	0.8	0.0	
9	s_4	refer to Table 4	Deterministic attribution			

In Table 6, the average state extents and the transition probability values (matrix) are given for parameter P_1, GSI. These values have been calculated analyzing statistically the state variations of the parameter using available data (from boreholes and geostructural survey in the surface).

For the determination of behavior category (Phase B), as it is derived from the combination of parameter P_1 (GSI) and P_2 (P_o) the analytical method of “convergence-confinement” was used in conjunction with the GSI-based geomechanical parameters. Phase C, follows, where parameter P_3, presence of water, is considered in the analysis. Tables 7 and 8 provide the correspondence of the possible parameter state combinations to specific design solutions.

Table 7. Determination of behavior categories

GSI P_o (MPa)	65-84	45-64	25-44	<25
<1.3	b	c	d	f
1.3-2.6	b	c	e	f
>2.6	b	d	e	f

Table 8. Determination of technical classes and assignment of corresponding section types (given in parentheses)

Behavior Class / Presence of Water	b	c	d	e	f
No	1 (B)	2 (C1)	4 (D)	5 (E)	6 (F)
Yes	1 (B)	3 (C2)	4 (D)	5 (E)	6 (F)

4.2 Input parameters for the “construction” module

To the different technical classes (ground classes) shown in Table 8, correspond design section types characterized by preliminary support/stabilization measures, and by a final concrete lining. Section types are characterized by an increasing support capacity, with Section B consisting of only a radial reinforcement scheme to Section F characterized by systematic support interventions and proportionally increasing construction time and cost.

The simulation involved a drill-and-blast operation of four faces. Two of these faces were accessed by an adit (Figure 4). A planned delay of 30 days was considered for initiating the excavation of the second front, while a 60-day delay was allocated to the access adit excavation.

In order to incorporate in the analysis the uncertainty related to the construction operations a triangular distribution was used for advance rate. Cost per meter was represented deterministically, in a normalized form in respect to the most common section type, D. In Table 9, the values used are summarized.

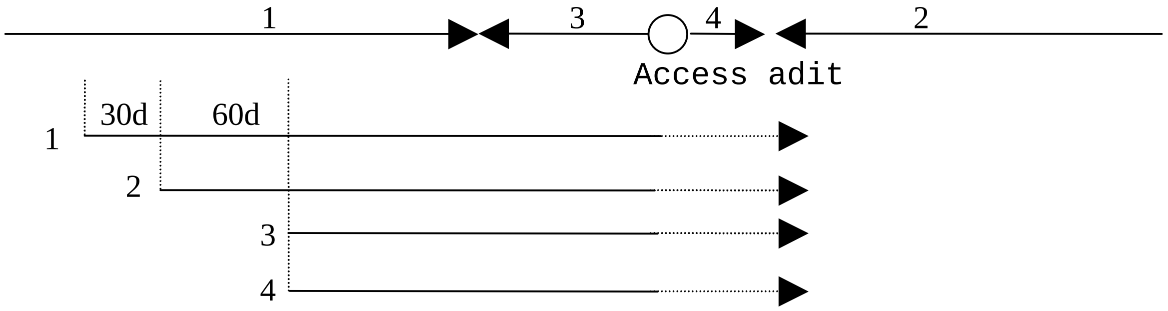


Figure 4 - Geometry of excavation face and scheduling of tunnels excavations sequence

A total of 300 simulations were performed, each producing a couple of construction time and cost values, represented by a point in Figure 5. The uncertainty associated with the geologic and construction parameters is depicted in the scatter of time and cost predictions of Figure 5.

Table 9. Time and cost values considered in the simulation of the construction process

	Advance (m/d) and Relative Cost ( )		
Section type	Minimum	Mode	Maximum
B	10.0	11.0 (55)	14.0
C1	7.5	8.0 (70)	10.5
C2	5.5	6.0 (85)	8.0
D	4.0	5.0 (100)	6.0
E	3.0	3.5 (110)	4.5
F	1.0	1.5 (130)	2.0

4.3 Discussion of the Results

In Figure 5 the simulation results are shown in the cost vs. time plot. The frequency distributions of tunnel construction time and cost are also given. Table 10 provides a summary of some of the characteristic values of these frequency distributions. The deterministically calculated time (and cost) corresponds to the accumulated extent of each ground condition along the profile multiplied by the most probable value of time (and cost) which is then summed up for all ground conditions. The scatter cloud of time and cost points generated from DAT simulation surrounds this value. This type of results not only gives a complete picture of the potential total time and cost, but also allows for the evaluation of the probability of completing the project under specified time and cost. For example, there is a 48% joint probability to complete the project without exceeding the deterministically calculated time and cost values. The product of the probability of exceeding the deterministic values, 48%, with costs associated with not delivering the project in the specified time and cost (penalty and opportunity costs) represents the risk which either the ownner or the contractor must take.

Such information may be an additional criterion for bid selection as well as for selection of alternative solutions, since each technical solution deals differently with the variability of the ground properties and is associated with different variabilities in the time and cost of each operation. An example application is shown in Figure 6 where two design solutions are considered. It can be derived from this figure that alternative 2 is associated with mainly lessen total cost and similar total time when compared to solution alternative 1, but the latter is characterized by a lower variability. Information of this type can be the decisive factor in a complex selection process where similar solution alternatives are compared in respect to time and cost threshold values.

Table 10. Characteristics of the generated distributions of time and cost

Characteristic measure	Total time (days)	Total cost (normalized)
Average	366	1.000
Standard deviation	16.4	0.029
Coeff.of variation	4%	3%
Skewness coefficient	0.425	0.220
Median	364	0.998
Mode	375	1.007
Max	423	1.096
Min	328	0.930
Percentile 5% value	342	0.958
Percentile 95% value	396	1.049

One may argue that the possible range of conditions generated by DAT could have also been anticipated by sensitivity analysis where the worst and best possible scenarios in terms of geology, time and cost can be considered. Needless to say, that such an analysis is much simpler, requiring also minimal resources compared to the ones required for DAT. Such an analysis, although able to define trends, cannot reflect the stochastic character of variables which is so pronounced in the field of rock engineering. Adopting the probabilistic approach of DAT it is possible to depict in the end-results of the analysis the spatial and random variability of geologic parameters, subjective uncertainties arising from geological and geomechanical hypothesis, as well as performance variability for the tunneling operations. Only by combining the likelihood of occurrence (frequency distributions) of these different sources of uncertainty, a meaningful and realistic generation of the range of possible conditions can be obtained whre each condition is associated with a possibility of occurrence. Deterministic sensitivity analysis cannot provide this dimension of the trend in the cost vs. time plot.

Further on, unacceptable risk, reflected by the considerable scatter in the generated results, can be an indication for a more elaborate investigation scheme, modification and/or addition of activities (i.e. probing ahead of the face) to the cycle of tunneling operations. In some cases high variability in the tunnel cost and time projections can provide the basis for changes in the contract type.

5. CONCLUSIONS

It is a predominant characteristic of the geotechnical works and particularly tunneling, the uncertainty surrounding the medium where construction has to be performed. This uncertainty is related to the geologic complexity and spatial variation of geologic parameters as well as the practical limitations of the sampling scheme, current methods of analysis, as well as variability in resources and market dynamics. DAT allows for the

fig. 5 Risultati dell' analisi con sistema DAT
Results of the analysis using DAT

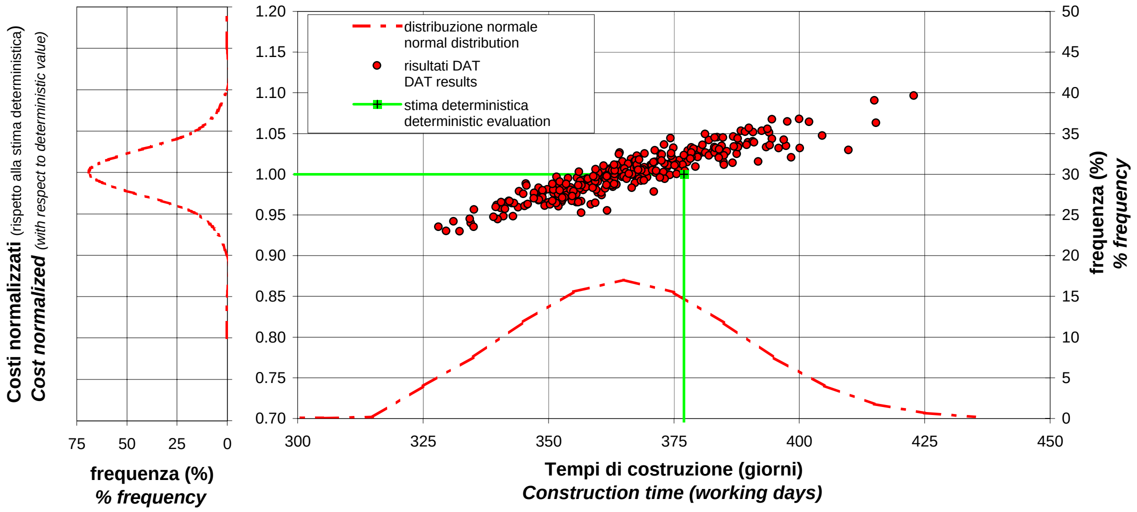
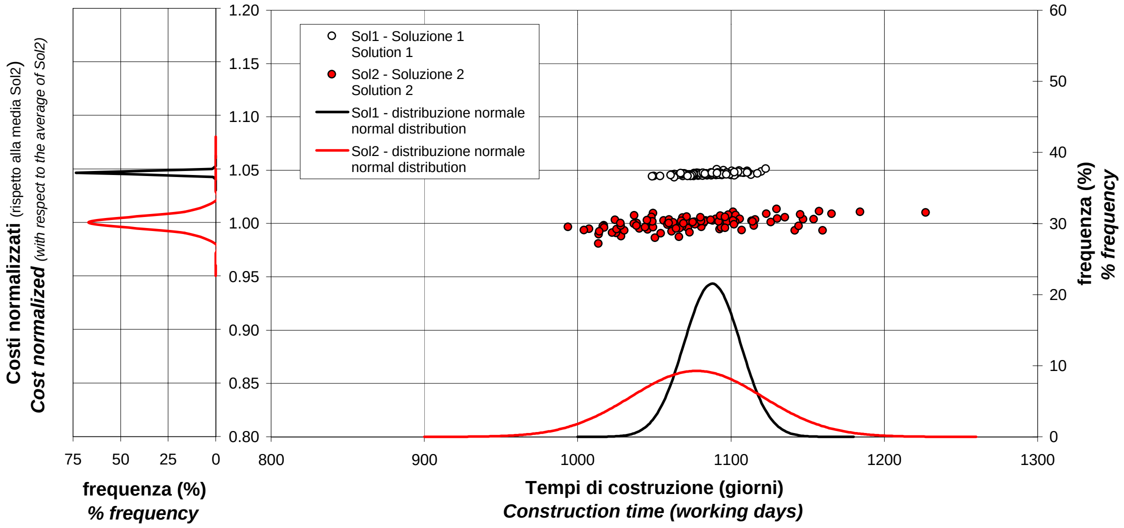


fig. 6 Analisi DAT per differenti soluzioni progettuali
DAT analysis of different design solutions



quantification of this uncertainty in respect to a design solution with benefits for all the parties involved. More specifically:

for the Owner

- to consider not only the bid quantities, but also the risk for the project exceeding these quantities;
- to define eventually threshold ranges for bid acceptability;
- to consider further exploration if a large scatter in the time and cost range is observed;
- to re-evaluate the type of contract;

for the Contractor

- to define the risk associated to the bid and the relevant position of the bid in the scatter time vs. cost diagram;
- to define better resources quantities and evaluate the adequacy of project financing;
- to examine what-if scenarios for scheduling, therefore allowing for identification of “bottlenecks” and a priori consideration of possible solutions; and

for the Designer

- to orient the design solution towards a more adaptable process (to the ground conditions), which also incorporates the impact of changing construction methods (constructibility principle);
- to identify and quantify the need in terms of extent and location for a site investigation program (as for the owner);
- to examine the effect of different design solutions on the range of total cost and time.
- to analyze the impact of a variation of a parameter on the total project time and cost rendering it non-critical.

Identification of risk is a necessary requirement for proper allocation of risk between client, contractor and designer resulting in benefits for all parties involved. Proper allocation of risk results in a fair contract: project is completed on time and at a fair price. DAT offers the potential for arriving in such a “win-win-win” situation.

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REFERENCES

Bieniawski Z.T., 1989. *Engineering Rock Mass Classifications.* J. Wiley, New York, 251 p.

Einstein H.H., Dudt J-P., Halabe V.B., and Descoeudres F., 1992. *Decision Aids in Tunneling - Principal and Practical Application*. Swiss Federal Office of Transportation - Project AlpTransit, Lausanne, 19p.

Harr M., 1897. *Reliability-Based Design in Civil Engineering*. McGraw-Hill, New York, 290 p.

Hoek E., Kaiser P.K., and Bawden W.F., 1995. *Support of Underground Excavations in Hard Rock*. A.A. Balkema, Rotterdam, 215 p.

Metropolis N., and Ulam S., 1949. “The Monte Carlo Method,” *J. Am. Statistical Assoc.*, Vol. 44, No. 247, pp. 335-341.

National Project for Underground Construction Standards, 1995. *Gallerie e Grandi Opere Sotterranee*, N. 46., pp. 21-27.

Palmstrøm A., 1996. “Characterizing Rock Masses by the RMi for use in Practical Rock Engineering, Part 1 & 2,” *Tunnelling and Underground Space Technology*, Vol. 11, No 2 & 3, pp. 175-188 & 287-303.