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GEOTECHNICAL RISKS FOR PROJECT FINANCING OF TUNNELS IN NON-URBAN AREAS

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ABSTRACT: Physical as well as economical circumstances limit the amount of investigations and analysis, which can be carried out at design stage and even at any time before starting the construction of underground openings.
The knowledge of the ground, that is of the geological, geo-technical, hydro-geological and geo-mechanical conditions, to be actually met during construction will be always severely limited, at least as a rule.
Indeed, the set of data available will be the more vague and fuzzy the more the tunnel is long, at great depth, of large section and the more the overall environment is complex.
To found crisp legal and contractual clauses on such a fuzzy database is very prone to lead to sometimes quite dramatic situations.

1. INTRODUCTION

You may be happy to have to build an up to a dozen of kilometres long tunnel outside of the urban area. You may thus avoid a number of problems like the archaeological ones or the crossing of existing sewage ducts. And, when the tunnel is deep enough - let say a few hundred of meters below ground - you may also skip arguments with the inhabitants of the city on vibration and noises or problems of settlements of important buildings. If then by chance, the rock conditions are ideal, well known in any detail and fit exactly the requirements of the TBM-equipment you have on hand and further if any kind of problems with water or faults can be ruled out, then you will be absolutely happy and lucky. I would then be pleased to congratulate you for the excellent business you are about to do - provided of course you got also a regular price for. But, you will have to recognize that these conditions will be more likely to represent the great exception than the rule in tunnelling.

So, let us have a look on the main questions involved in said kind of underground works intended as tunnels for transportation, for the scope of conduction of water, any other type

of fluid or energy, or planned to accept in caverns any kind of human activities or finally to store any type of goods.
In doing so, we will take into account only engineering aspects of the construction, not considering the electro-mechanical equipments nor the operation of complex activities.

2. COMPLEXITY OF LONG DEEP TUNNELS

Deep tunnels are not just the extrapolation of shallow ones. New aspects arise.
A rock mass, which at shallow depths would behave in an elastically or, to some extent, in a plastically way, may show at depth completely different body-laws where viscosity or the so-called "softening" may play the most important role.
In other circumstances, the best rock on the ground may be affected at great depth by burst or spalling problems and may turn out to be a very bad one. In some cases the swelling of the rock mass, which is harmless at shallow depth may develop so to be a lot more harmful there.
Not to mention the increasing water pressure, but also the increasing temperature, which can be significantly less than very comfortable.

Also, in spite of a great depth, one cannot be absolutely sure to escape any environmental problem or argument with the inhabitants or owners in the region. Indeed, controversies on real or virtual problems cannot be ruled out. First of all, questions with the depressing of the ground water table and the drying out of springs, even if the tunnel is very deep, cannot be excluded in an absolute manner. But, one has also to remember the possibility of significant settlements due to the draining of the mountain by deep tunnels, which can affect some stiff structure on the ground like concrete dams. At the reverse, an excessive internal water pressure and losses from the tunnel may induce slides on the ground.

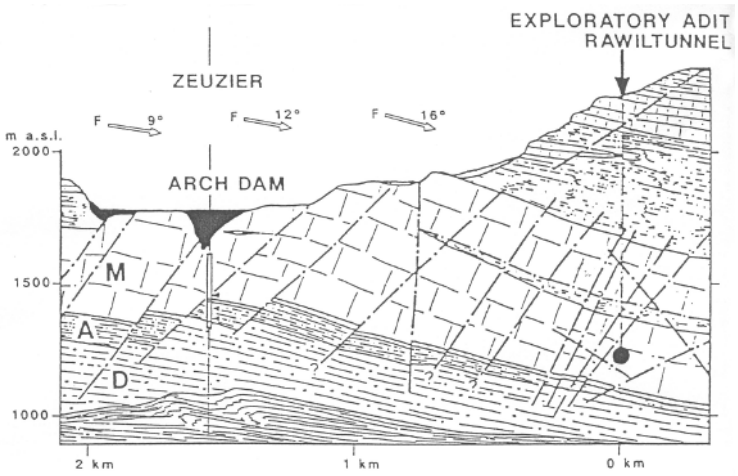

Figure 1: The excavation of the exploratory adit drained the ground water entrapped in layer D, caused the settlement of the region and damaged heavily the Zeuzier arch dam.

But, these are just a few of the special conditions, which may be met in a deep long tunnel. The third dimension, that is the axis of the tunnel needs also to be looked at. This refers to the extension of each particular zone of the rock mass and thus of the number, frequency

and distribution of the changes as well as to the relative position and orientation of the various domains to be encountered, showing different properties, state of stress or degree of alteration.
All the possible combinations - including obviously the most adverse ones - are to be duly considered and only few of them can be ruled out before hand. The same story can be told on water, its flow rate, pressure and chemistry.

3. UNCERTAINITIES

Except special cases - so when one is drilling a tunnel paralleling an existing one at reduced distance provided of course similar methods of construction are to be used as for the former one - an extremely great number of uncertainties are to be accounted for and introduced in the reasoning before starting with the design of any important underground work.
If you have for example the splendid opportunity to overfly the Alps in a clear sunny day, especially in wintertime, you may be impressed by the overwhelming beauty of the landscape, but you may also become aware of the extreme morphological complexity of this mountain chain, whose shape includes a number of fractal aspects. And, if you think that this extraordinary landscape just represents a kind of simple geometrical expression or interpretation of the actual geo-technical complexity hidden below the ground - which interpretation is governed by the relatively simple rules of the free field gravitational equilibrium - you may get an idea of what a tunneller may encounter, excluding of course the magnificent wide view you can enjoy from your comfortable seat in the plane.
The problem for the tunnel designer can be stated nevertheless in a very simple way and can be easily solved. He has simply to express the synthesis of this complexity by two possibly very precise numbers that are "Cost and duration of the construction". Well! This is at least the opinion of the people who have to wait for the tunnel and to pay the cost.

4. REDUCING THE UNCERTAINITIES

The main task for the designer is thus to try to reduce said uncertainties.
First aid is coming from the geologist looking down from the surface to the future underground opening. Obviously, the deeper the tunnel, the weaker is the sight and the more use of psychologically coloured intuition is required and cannot be avoided.
A certain support may possibly be found in former studies, investigations and construction records, but quite soon specific new investigations will be needed. Boreholes, shafts and adits may be of great help, provided they can be really carried out and are not impeded by some environmentally founded restrictions, specifications and conditions difficult, or even impossible, to fulfil, no matter whether they correspond to the reality or are an alibi.
There is for sure no need to list here all the geological, geophysical, physical, chemical, hydraulic and mechanical methods and devices that can be used to define in the best possible way, the geological, geo-technical, hydro-geological and geo-mechanical conditions to be expected during construction.
Fortunately or unfortunately - depending of the point of view - there is always somebody on charge of some legal rule intended to limit the expenses due to such investigation programs.
More exactly, the officially declared intention is to establish an optimal costs-benefit balance. How risky this exercise can be is due not that much to the fact that their costs may be underestimated, but to the fact that the benefits of the investigations are undefined, by definition. Or, if you prefer the problem is an implicit one. This means that, you often can de-

cide whether the investigation was worthwhile to be done or not, only after having carried it out.
Of course, to drill even an only hundred metres long borehole with the aim of just finding out how intense the jointing of the rock in a short tunnel section is, may be considered a waste of money, because at the end of the day the result will not change the amount of rock supports actually required and placed.
At the contrary, the excavation of a kilometres long investigation adit may result to be a relatively small investment, if it allows to avoid great difficulties during construction of the tunnel for example in slightly modifying its layout. The qualification of the rock mass remains a difficult task.

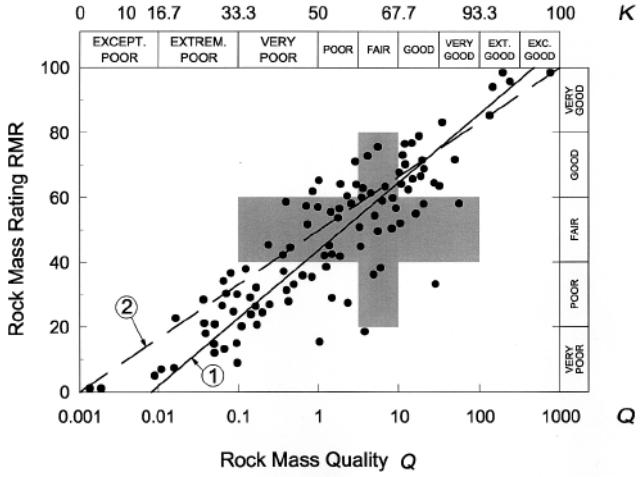

Figure 2: Different definition of the rock classes by two formulae.

Indeed, I know only few cases where, after construction, the investigations were considered having been excessive, but many more cases where more investigations would have been very useful in making possible a reduction of the total cost and of the duration of the works.
In spite of such quite theoretical exercises of optimisation, there is generally a "common sense" or intuition led by experience - which may at the end show to be right or wrong - that leads to decisions going from a minimal number of short boreholes at the portals, to the drilling of a pilot adit all along the tunnel, depending on the supposed degree of uncertainties and on the aim of the investigation campaign possibly related to tendering and contractual aspects or procedures.
But, no matter what you do as designer, at the end of the game the geological and geotechnical diagnosis and prognosis will always be considered - by the owner or by the contractor- as having been wrong. Again, some help will be offered by the geologist, who will be pleased - I hope so - to share the responsibilities. Quite likely the engineers and geologists will be supposed to be responsible - at least morally - for any cost and time overrun, no matter what they did decide, propose or only suggest.
In any case, there is obviously a reasonable limit to the investigations and the analyses, which can be carried out or developed at design stage, so that as a rule, the knowledge of the ground the designer can base on, will be severely limited and the number and amount of remaining uncertainties will be significant, if not considerable.

5. FUZZY DATA BASE

Additionally, the data available are always known only with some approximation, so one can consider them, without any doubts, as being quite fuzzy, or better said, as forming a "fuzzy data set". On this fuzzy set a supposingly final design has to be based, which should lead to an exact definition of the costs and the duration of the construction.
No wonder thus, that geo-engineering - which by the way includes not only tunnels, but also dams and similar works - was called the "fuzziest of all the engineering branches".
By "geo-engineering" one may in fact understand the branch of civil engineering where the ground is not to be considered only as one of the boundary conditions, let's say the underlying one, like the foundation of an usual building, but as a constitutive element or material of the entire project itself.
This is obviously especially true for tunnels.
At the end of the day, and as a rule, said set will remain fuzzy in spite of so many efforts undertaken to reduce its fuzziness by field investigations or office computations.

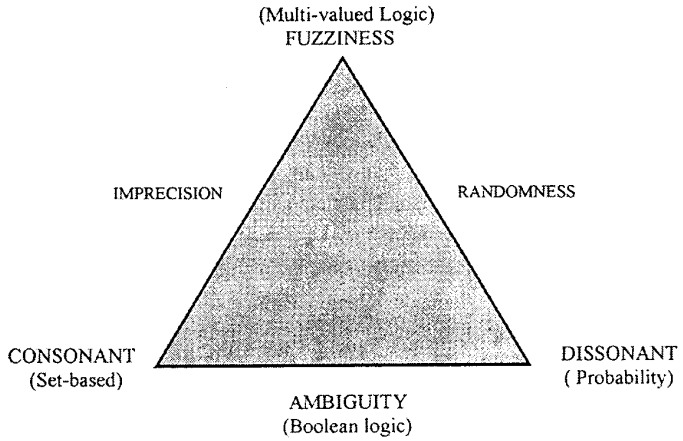

Figure 3: The uncertainty triangle (by. Prof. Alberto Bernardini)

The consequence of this situation is that both design and construction methods must include a great amount of flexibility as well as adequate provisions in order to face unexpected conditions under the ground.

6. MONTE CARLO ANALYSIS

With few exceptions, the data forming the set are independent each from another. A small exception is, for example, the fact that the lengths of the single stretches must sum up to the total length of the tunnel. Further, one may assume that for each type of rock only a certain set of geo-technical parameters can apply. At the contrary there is no reason at all, that, for example, the width of single faults correlates in any way with the friction angle in the discontinuities of the rock mass of other tunnel sections, while both values will of course influence, in the one or the other way, the total cost of the tunnel and the construction schedule.

As known, any element of a fuzzy set is supposed to be defined by a minimum, a maximum and an "average", or most probable value, as well as by a density distribution of probabili-

ties from the minimum to the maximum value. In general, this distribution is supposed to be triangularly shaped with its peak at the assumed most probable value.

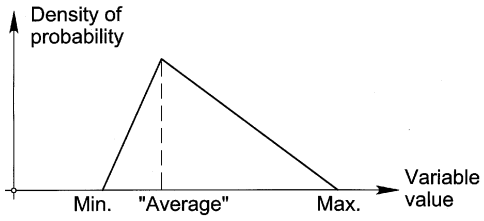

Figure 4: The usual triangular-shaped assumption for the density of probability for a Monte-Carlo simulation.

In this respect one has to underline the fact that these is no real reason at all for this distribution to assume that shape. Also one must be aware of the fact that, as a rule, both limits as well as the most probable value are just the result of a process of estimation or guessing.
Apart all the weaknesses of this statistical procedure, it appears however to be the only way out of a dilemma, and is a confirmation of the thesis that statistics are the most pleasant and efficient way to hide our ignorance and to escape the quagmire of fuzziness in singing a triumphant tune.

In fact, it is quite likely that one never will be unlucky enough so that all along the tunnel all the parameters will assume at same time the most unfavourable value. Or one may say, that the theoretically possible absolute worse combination is very unlikely to occur. In the same way, also the absolutely best combination of conditions cannot be expected. In the reality however, even a worse than the worst expected situation did occur from time to time!

Nevertheless, procedures based on a Monte Carlo algorithm can thus be used to define a plausible probability distribution of said overall costs and duration of the project considering the internal compensations, which are to take place. The scatter of the results around the average is reduced sometime to a quite astonishing degree; said compensation being of course the more likely and effective the longer the tunnel is.
The probabilities obtained in this way may be very useful for the steps to follow during the development of the project, but do not eliminate the fact that the base for design and construction remains always fuzzy.
Also a number of important aspects, like for instance:

- the degree of optimism of the designer,
- a psychologically distorted procedure in estimating some fundamental elements of the same set of pieces of information,
- a non-suitable method of interpreting the test results, or to compute the requirements of rock supports,
- the use of a non-appropriate method of construction,

cannot be detected in using these methods, which nevertheless can be very useful in assessing the most probable results.

7. COMPUTATIONS

During the recent decades, the computational methods to solve civil engineering problems and especially to analyse rock mechanic questions did develop very significantly. It appears that today no evident mathematical limitation exists any longer in this field.

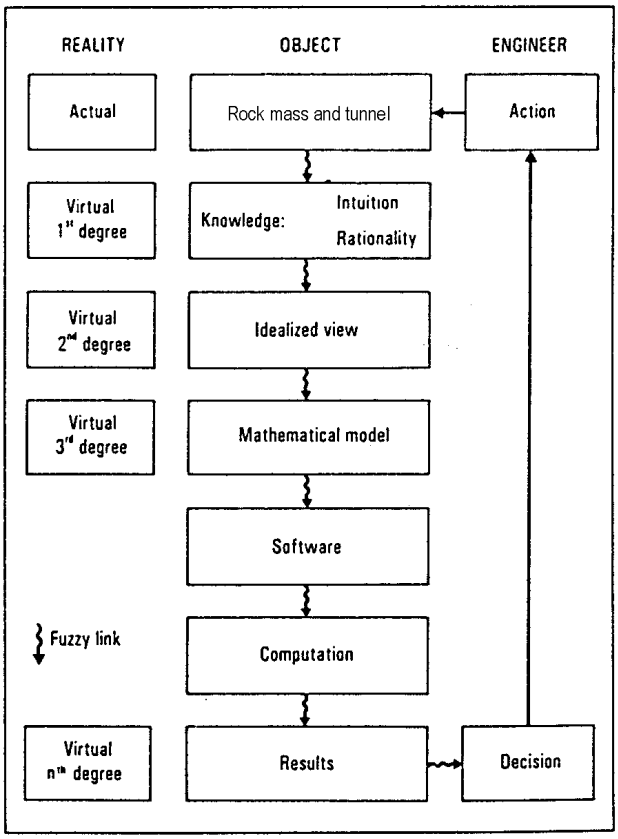

Figure 5: Flow chart of an analysis. Fuzzy data, fuzzy links and fuzzy results.

It is obvious however that no computation can be more valuable that the data used as input. It happens, unfortunately, from time to time, that this aspect is ignored and that the computation results are interpreted in a way intended to hide more than to put in evidence this point of weakness. Also the vague and fuzzy aspect of said input data-set is not duly taken into consideration in the computations themselves. This fact may lead to some additional distortion of the overall results of any risk analysis developed on the base of a Monte Carlo type method.

8. GAMBLING, INSURING OR TRANSFERRING?

In front of this fuzzy situation, which can be made less vague only to a quite limited extent, in carrying out additional investigations, more computations or Monte Carlo simulations, there are a number of positions, which can be taken. They may be called as:

- gambling with the risks,
- assuming them,
- covering the risks by insurance,
- sharing them with somebody else, or
- transferring them.

This always remembering that geo-engineering is one of the fuzziest fields in civil engineering.

There is of course nothing new, nor surprising when I say that nobody is very keen to assume more risks than obliged and that everybody would be happy to transfer them to other parties.
Also insuring the risks is indeed only another way to transfer them, while gambling with the risks was at some time more used as it is today.

The problem is thus simply the following one. Which is the best way to share the unavoidable risks between owners and contractors in order to optimise not only the project itself, but its overall economic impact, from a general point of view? This means that not only the direct financial expenses for the project should be minimised, but that the total real investment should be reduced to a minimum. For the general economy it makes not much sense to reduce the nominal disbursements for a tunnel or similar works, while at same time other costs are to be beard by the community like costs of accidents, damages, or unemployment due to a too irregular working load, or even the consequences of the bankruptcy of the contractors involved.
I know however very well that any attempt to solve such a kind of problem is a pure illusion!
The problem thus simplifies somewhat and spells: which is an acceptable, reasonable risks sharing policy?

9. CONTRACTING

Finally, this is a question of the contracting methodology.
Since a number of years a strong tendency may be noticed to transfer the risks to the contractor as much as possible and at the end all the risks, including the ones raising from unexpected geological conditions. This tendency may be due to some former bad experience, but it is also favoured, by the increasing number of economists, lawyers or accountants assuming management duties in the owner's organisations, replacing often experienced engineers.
To go that way is for the owners, and possibly also for the Engineer, an easy one, but it shows already some drawbacks.
The first question raised is how long it will take until the contactors will include in their prices an adequate premium for the risks they are supposed to assume or to insure?
If additionally the contractor has to take care even of the financing of the project, the role of the owner will turn to be a very pale one. I don't know whether many owners are really very keen to stay that much in the background.
The second question, which arises in the case the project may count on an economic return, is thus: what for do we need an owner any longer?
Indeed, you may have noticed that worldwide an increasing number of contractors turn to become owners themselves, for example, if toll-highways or powerplants are involved.

In doing so, they assume obviously in addition also the risks of operation, not only those of construction, but they achieve to simplify significantly the procedures.

I still believe therefore that in view of the real uncertainties and the remaining risk connected with any tunnelling activity, that an adequate way of sharing these risks must be looked for.
To try to include into contractual documents an endless list of special clauses reflecting any possible combination of conditions suggested by the century-long history of tunnelling is for sure not the right solution.

10. CONCLUSION

In conclusion, one must start from the principles that in any case contracts must be net, simple, precise, short and fair. But, that in our field of activity they must additionally be also as flexible as design and construction themselves are.
Extreme legal and burocratic complexity should hopefully be replaced by an open and honest cooperation based on simple rules, always remembering the limited predictability of the natural conditions under ground.
To try to found absolutely crisp contractual clauses on a fuzzy data base, is very prone to lead to quite dramatic situations resulting in less than optimal solutions, causing high economic costs and additional delays, as it could already be observed in an increasing number of cases. In some occasions also inadequate quality as well as risky operations were observed.
Due to ongoing legal procedures, such cases cannot be discussed nor presented here in a more detailed manner.
The main conclusion however is that great improvements of the present contracting praxis need be achieved if successful tunnelling, as well as a reduced activity in disputes, claims and lawsuits are desired.