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A SYSTEMS APPROACH FOR EVALUATING SPRINGS DRAWDOWN DUE TO TUNNELLING

A. DEMATTEIS
SEA Consulting, Turin, Italy

G. KALAMARAS, A. EUSEBIO
GEODATA S.p.A., Turin, Italy

ABSTRACT: the forecast of the extent of springs and/or wells drawdown is necessary for the evaluation of the hydrogeological risks related to tunneling. A method is proposed that considers all fundamental variables, defined by cause-and-effect relationships, that are related to the aquifer itself and to the behavior of the tunnel. These variables are combined through an interaction matrix using the approach of the fully coupled model to provide the drawdown-hazard-index that consists in the probability of drawdown in a specific spring and/or well. The application of this approach to a current case showed a very good correlation between the predicted and the observed drawdown.

1 INTRODUCTION

The construction of an underground tunnel in a mountain regions may have a significant impact on the regional hydrogeological system. After all, drainage galleries are considered the most effective means of subsurface drainage. Water drainage through a tunnel is likely to cause a drawdown of the hydrostatic level and a decrease in the discharge of springs and/or wells ("water-points" hereafter), a phenomenon that can persist after the construction of a tunnel if the final lining is not completely water-proof. The drawdown impact can be in terms both of groundwater quantity and quality, and its effects can be manifested on the surface by modification of the vegetation, instability of slopes, chemistry of thermal waters, and discharge of the hydrogeological basin.

The impact of groundwater on tunneling has been extensively discussed in literature, but only recently studies on the impact on the hydrogeological basin have been included in tunnel design projects (Monjoie 1990, Olofsson 1991, Pelizza 1991, Cesano 2001). The above mentioned studies refer to specific systems. Therefore, every statistical correlation established between observed behavior and input variables refer to these systems only, and cannot be extrapolated to other cases to predict the impact of tunneling on the hydrogeological basin.

A new approach that aims to give a general methodology for evaluating the impact of tunneling on the groundwater flow is proposed. Its basis is the systems approach applied to rock engineering (Hudson, 1992). Fundamental variables of the aquifer–tunnel system are considered on a binary level through cause-and-effect relationships. The approach of the fully-coupled-model (Jiao, 1995) was used in this study to quantify the impact of a variable change on the drawdown hazard index (DHI), an index that describes the likelihood of a specific water-point drawdown.

After a brief introduction on the systems approach as a decision-aid tool, the system aquifer-tunnel is described in terms of its principal variables and interactions between them. The proposed approach was tested on a real case where data on water-points discharge were recorded before and after the tunnel construction.

2 ROCK ENGINEERING SYSTEMS

The Rock Engineering Systems (RES), as they were developed by Hudson (1992), are described through the concept of an interaction matrix, where system variables interact through *cause-and-effect* mechanisms. The development of this approach comes from the complexity of the interactions between the rock mass and the construction domains. Numerical and analytical techniques can only model a small part of these interactions. Therefore, another approach had to be developed to allow the quantification of the fully-coupled character of the system. Due to the cause-and-effect character of these interactions the system is dynamic in character, i.e. a change in a parameter level may cause, through a process of consecutive changes, a follow-up change in its level, which will cause a subsequent change to the level of other parameters. This process will continue until the system, that is the rock mass- groundwater-construction domain, has reached an equilibrium.

The quantification of the dynamic behavior of the system, together with the introduction of an end-index, that summarizes the system behavior in terms of a decision variable, can give a decision tool that combines the benefits of empirical and analytical approach to design and the well-known fact that the system in reality behaves in a dynamic manner.

In implementing the RES approach, the following stages need to be observed (based on Hudson, 1992 and Jiao, 1995):

a. definition of the conceptual scheme of the system with the principal mechanisms identified;
b. definition of the system variables and their application ranges, followed by the definition of an end-system decision variable;
c. identification and quantification of cause-and-effect relationships between the system variables and the assemblage of the binary matrix;
d. definition of the system global mechanisms using mechanism path analysis; the result is the global interaction matrix (GIM) which reflects the global effect of a change in the level of a parameter; the GIM combines the fully-coupled character of the system;
e. evaluation of the system response, i.e. performance of the system with regard to changes in variables levels; and
f. back-analysis of existing cases, tuning of the system by using adjustment factors.

In the following sections the above mentioned approach is developed as a mean to evaluate the potential of drawdown of water-points due to tunneling.

3 WATER-POINTS DRAWDOWN DUE TO TUNNELING

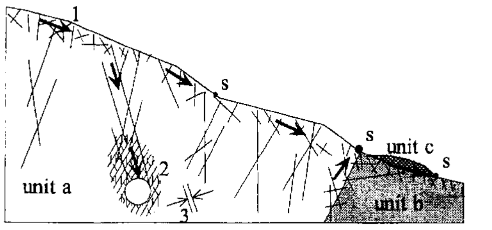
The systems approach for the evaluation of water-points drawdown was developed and tested during the planning and the construction of a 10km-long tunnel in a densely-populated mountain area. The development of the model followed the 6 stages listed in the previous section, that have been further elaborated in this section.

3.1 Setting of the area

The geological and structural setting of the area is complex, and many lithotypes, that underwent different degrees of metamorphism and history of deformation, are present along the tunnel alignment. On the surface, a thin sequence of quaternary deposits covers part of the massif. Contacts between geological units are of tectonic origin and generate steep shear and fractured zones including cataclastic rocks. The massif is fractured and contains two main groups of water-conducting fractures that are both sub-vertical and intersecting each other at high angles. The fractures are quite persistent: some of them extend from the surface to the deep part of the tunnel. During the excavation of the tunnel local groundwater inflow occurred in zones where the overburden was thicker than 100m. A few hours or days after the excavation the discharge decreased very quickly and reached a sort of steady state, as it was showed by a few liters per second or less, of inflow. The hydraulic conductivity of fractures is high, but the hydraulic connectivity of main fractures is low resulting in a limited recharge of the system and a complete hydraulic de-pressurization around the tunnel. This situation defines minor groundwater flow systems in the aquifer, unconnected or with low connection between each other. This suggests an heterogeneous drawdown of surface water-points, that was observed during the construction of the tunnel (more than 60 water-points were sensed having a mean discharge of less than 1l/s for each point). After the excavation in fracture zones with significant groundwater inflow into the tunnel, some water-points were dried up a few hours or days after, whereas others not far from the latter were not influenced and still have a discharge many years after the excavation.

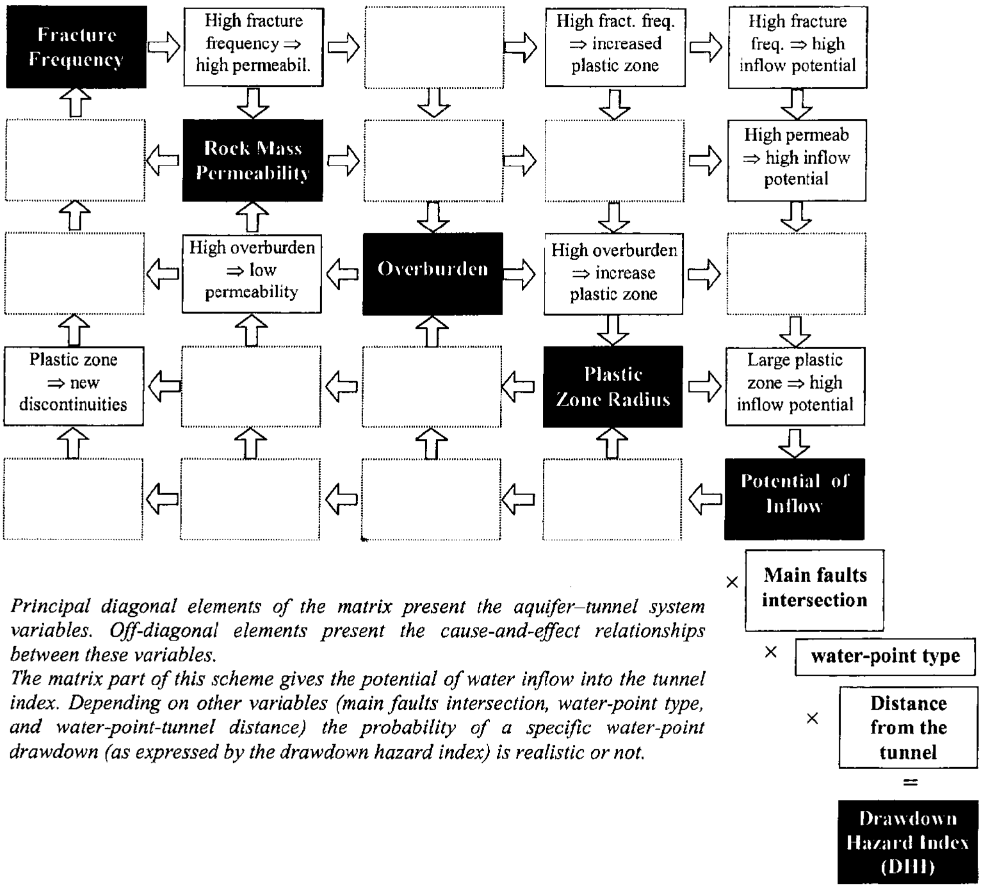
3.2 System definition

In simple terms, with regard to the geologic setting described in the previous section, water-points drawdown is caused by two principal and interrelated mechanisms that are shown schematically in Figure 1a. The first is defined by the intersection of the tunnel with discontinuities that conduct water from the water catchment area to the water-points network. The second is defined by the fact that tunnel construction cause the formation of a new fracture zone around the tunnel, increasing therefore the probability of intersecting conducting discontinuities. The way with which these mechanisms will cause water-points drawdown is a function mainly of: (a) the *in situ* stresses that reduce, in general, fractures conductivity because of the closure of the aperture; (b) the overburden factor as far as discontinuity condition is concerned: it is observed that with the increase of depth, discontinuities tend to be infilled resulting in lower conductivity.



The groundwater flow (1) direction and magnitude is determined by the discontinuities network and, around the tunnel, by the extension of the plastic zone (2); the contrast in rock mass permeability degree (medium to high in unit a, low in unit b and medium in quaternary deposits of unit c) define different types of springs (s); the in situ stress (3) increasing with deepness is accompanied by decreasing in hydraulic conductivity of fractures.

Figure 1a. Conceptual scheme of water-points drawdown



Principal diagonal elements of the matrix present the aquifer–tunnel system variables. Off-diagonal elements present the cause-and-effect relationships between these variables.
The matrix part of this scheme gives the potential of water inflow into the tunnel index. Depending on other variables (main faults intersection, water-point type, and water-point-tunnel distance) the probability of a specific water-point drawdown (as expressed by the drawdown hazard index) is realistic or not.

Figure 1b. Proposed matrix for water-points drawdown evaluation

3.3 Definition of system variables

The aquifer–tunnel system can be defined by a few fundamental variables. The definition of these variables, and their ranges is the first step in the RES approach. The following variables were identified for the system under consideration:

Fracture frequency (FF): it is well-established that the discontinuity density is a determinant factor of the rock mass permeability. Various indices can be used to describe the FF. In general, in tunneling the most available index to describe it is the RQD. However, from a permeability point of view, it is more appropriate to use the volumetric joint count (Jv) that derives from the number of fractures per linear meter (λ) for the discontinuity sets.
Rock mass permeability (MK): which describes the lithological units from a hydrogeological point of view. It can be argued that, by considering both FF and MK, the effect of FF is double-counted. However, by MK, in this case, is intended the effective conductivity of the rock mass as determined by discontinuities and rock blocks porosity. The four AFTES (1992) classes are used to describe the MK.
Overburden (OV): which, as it was noted in the previous section, an increase in overburden depth is likely to reduce the possibility of water inflow in a tunnel.
Plastic zone (PZ): which describes the effect of the tunnel excavation on the rock mass, i.e. the creation of new fractures in a zone surrounding the tunnel. It was decided to group the size of the opening, the construction techniques and quality in one variable, i.e., the thickness of the plastic zone, measured in excavation equivalent radius units.
Potential for inflow (PI): which describes the probability of water inflow to occur into the tunnel.

These variables interact with each other (Figure 1b). The state and the magnitude of the interactions determine the likelihood of water inflow into the tunnel, which can be real or minimal. However, tunnel water inflow does not necessarily result in drawdown of water-points. Other factors, referring to the specific water-point have to be introduced to take into account:

- the intersection of a major fault conducting water to the water-point with the tunnel (IF),
- the water-point-type (SP),
- the distance between the water-point and the tunnel (DT).

Three types of water-points were considered. Superficial water-points which are feeded by the local groundwater flow systems, and generally associated with low discharge (<1 l/sec). In this case, the groundwater flow system is supposed to be of limited thickness and it develope in the weathered zone of rock mass and in thin quaternary deposits. On the other hand, deep water-points are associated with deep flow systems that are in general more extended and associated with high water-volume reserve. An intermediate water-point type is also considered and defined as water-points that are feeded by both surface and deep systems.
The system variables, the adjustment factors and their ranges are presented in Table 1. Numeric values that allow the quantification of the system are associated to these ranges (scale: 0 - 1).

3.4 System interactions and evaluation of the system modeling response

At this point, the main diagonal elements of the water-points drawdown matrix have been described. The next stage is to quantify the degree that a change in a variable state causes to the other variables. This cause-and-effect relationship is described by the off-diagonal elements of the matrix. In doing so, empirical and analytical laws can be used. For example to evaluate the effect of the PZ on the potential for inflow (PI) the equation proposed by Goodman et al. (1965) was used. The same principle is used for the adjustment factors, as well. For example, the evaluation of the DT was based on historical data in the same geological context.

Table 1. Definition of variables and adjustment factors states, ranges and corresponding indices

Variable	Parameter						
FF - fracture frequency	λ (fractures/m)	0	5	10	15	20	
	index	0	0.25	0.5	0.75	1	
MK - rock mass permeability	Peremab. degree	very low	low	medium	high		
	index	0	0.33	0.66	1		
OV - overburden	thickness (m)	<50	50	100	200	>200	
	Index	0.9	0.5	0.25	0.1		
PZ - plastic zone radius	radius	0	10	20	>30		
	index	0	0.3	0.7	1		
IF - intersection of main faults	intersection with main conductive fracture connected with water point	NO	YES				
	index	0	1				
SP - spring type	type	superficial	intermediate	deep flow system			
	index	0	0.5	1			
DT - distance from the tunnel	distance (m)	>800	600÷800	400÷600	200÷400	100÷200	<100
	index	0	0.1	0.2	0.4	0.8	1

The result of this analysis is the binary interaction matrix (BIM) given in Figure 2a that describes the cause-and-effect interaction in a variable-to-variable level. In order to evaluate the *system* response to a change in a variable state, the technique of the fully-coupled model (Jiao, 1995) is used and its result is the global interaction matrix GIM given in Figure 2b. It shall be noted that the diagonal elements of the GIM are not equal to 1. This happens because, a change in the state of a variable, causes changes to other variables states which in turn may cause a change to the first variable that triggered off the system. Off-diagonal elements of the non-symmetric matrix represent the degree of change that one variable causes to the other.

To demonstrate the dynamic character of the system, as considered by the GIM, the following example is made for the effect of fracture frequency (FF) on potential of inflow (PI):

-on a binary level: a positive change in FF causes a change to PI of 0.5, i.e. 50% more inflow is expected;

-on a system level: a change in FF causes a change in rock mass permeability, extends the plastic zone around the tunnel increasing further FF; these changes cause a change to PI of 1.5: i.e. 150% more inflow is expected.

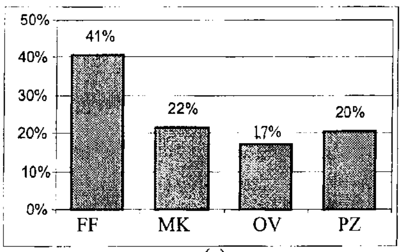
The effects of the system variables on the PI are given in the last column of the GIM matrix (Figure 2b).

	FF	MK	OV	PZ	PI
FF	0	0.8	0	0.5	0.5
MK	0	0	0	0	0.8
OV	0	0.3	0	0.5	0
PZ	0.3	0	0	0	0.3
PI	0	0	0	0	0

(a)

	FF	MK	OV	PZ	PI
FF	1.2	0.9	0	0.6	1.5
MK	0	1.0	0	0	0.8
OV	0.2	0.4	1.0	0.6	0.6
PZ	0.4	0.3	0.0	1.2	0.8
PI	0	0	0	0	1.0

(b)



(c)

Figure 2. Binary (a), global (b) interaction matrix, and weights of system variables (c) on the potential of tunnel water inflow

The normalized global interaction weights of the four system variables are expressed in percentages in Figure 2c. The result of the matrix-system is the potential of inflow index, that is the sum of the weights multiplied by the parameters states, for a given tunnel section.

$$PI=(41*FF + 22*MK + 17*OV + 20*PZ)/100 \quad (1)$$

Adjustment factors are added to this equation that gives the potential of inflow into the tunnel in order to give the drawdown hazard index (DHI):

$$DHI=(41*FF + 22*MK + 17*OV + 20*PZ)*(IF+1)*(ST+1)*(DT+1) \quad (2)$$

It shall be noted that the DHI is calculated for a single water-point on the surface. In deriving the states for the matrix variables, a 300m-tunnel segment is assumed to be representative in terms of geological and geomechanical context. This threshold value was defined by analysis of historic data.

3.5 Validation of the model

The model defined in the previous section was applied to an already excavated segment of the alignment where water-points census data and detailed geomechanical data were available. This permitted to tune the model in terms of interaction weights and adjustment factors (the values given in Table 1 and Figure 2 are the final values). The results obtained allowed for the definition of the following threshold values:

$DHI<0.2$	null to minimal drawdown was observed,
$0.2<DHI<0.6$	partial drawdown was observed,
$0.6<DHI<0.7$	partial to complete drawdown was observed,
$DHI>0.7$	complete drawdown.

4 WATER-POINTS DRAWDOWN RISK EVALUATION

The results obtained allowed to define two principal threshold values in terms of hazard probability:

$DHI<0.2$: null to minimal hazard (model reliability 100%), and
$DHI>0.7$: very high hazard for a complete drawdown (model reliability 100%).

The data indicated that for DHI between 0.2 and 0.7 the hazard is medium (partial drawdown). A linear function can be assumed between these two values to define the corresponding probability. Depending on the importance of specific water-point it is logical to assume that the closer the DHI value is to 0.7 the more is the need of further investigations.
In practical terms, the DHI can be considered as the probability that drawdown will actually take place. The decision to proceed to further studies and/or mitigation measures depends on the other component of risk, i.e. the social and economical cost of drawdown of a specific water-point. The fact that the drawdown index was developed for a specific water-point facilitates the evaluations of social and financial consequences of drawdown due to tunneling.

5 CONCLUDING REMARKS

A new approach was presented based on RES for evaluating first the potential of water inflow into the tunnel, and second the likelihood of water-points drawdown. Using this approach a model was defined for a tunnel in mountain region in a fractured medium where different water-point types are present. The aspects that differentiate this approach and, therefore, the model are the following:

- basic tunneling data that facilitates the integration of this approach to tunnel design is used;
- unlike statistical studies the proposed approach does not require the vast amount of variables data before the development of a model because it is based on description of physical mechanisms; on the other hand, unlike a numerical model it does not suffer from the current well-known scale limitations of modeling (e.g. calculating by a coupled numerical model the water-points drawdown caused by the construction of a 5m-radius tunnel found at 200m-distance is very computational-expensive, to say the least).

The proposed model concludes with the Drawdown Hazard Index (DHI) that presents that probability of the drawdown of a specific water-point. The results indicate a very good correlation between the DHI and the observed drawdown. Combined with evaluation of the social and economic cost of drawdown, DHI can be used for risk analysis. The simplicity of the model (one arithmetic operation) facilitates its integration with GIS models.

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