

PREVENTION OF GAS INVASION RISKS DURING TUNNEL EXCAVATION WITH FAVOURABILITY FUNCTIONS

LONGO, SIMONE

PhD student at the Mining and Geo-Resources Engineering Department, I.S.T Technical University of Lisbon. simone.longo@ist.utl.pt

DINIS DA GAMA, CARLOS

Professor and Head of Geotechnical Center, I.S.T Technical University of Lisbon. dgama@ist.utl.pt

ABSTRACT

In order to establish a correct balance between safety and cost reduction around underground structures such as tunnels, research and analysis of factors that during construction contribute to increment the hazard of dangerous accidents are described, with the intent to reduce or eliminate them. For several tunnels typical hazards are explosive gas invasion, like methane.

In this paper the development of a risk classification is described, using Favourability Functions, to create maps with different risk classes regarding the possibility of gas invasion during the excavation of a tunnel. This classification was first applied to a real case study, the system of galleries for high-speed trains construction between Bologna and Florence, Italy.

To develop the Favourability Functions models, the Bayes theorem and the Fuzzy Logic were used, which are well adaptable to a predicting study. To process the geographic data for this study, a Geographic Information System called ILWIS was used.

1. INTRODUCTION

This study deals with the problem of methane invasion in tunnels under construction with a risk analysis process based on Fuzzy Logic and bayesian probability models.

The models calculate on the same geographic area and with the same database, different degrees of probability related to the event to be predicted (in this case the event is “methane invasion in tunnels”) and they may be called Favourability Functions.

The geographic area involved in the study is limited at north by the city of Bologna and at south by Florence. This area was subjected to excavations for the construction of various tunnels belonging to the complex project of high-speed trains.

The input data was prepared at two different levels: firstly, the various hypothetical causes of methane creation and accumulation (lithology, faults, anticlines and synclines) and secondly the evidences of methane existence (cited in the literature and registered during preliminary geological studies, investigations by drill holes, previous tunnel excavation and geological studies).

The study purposes a final map where the investigated area is divided in 20 risk classes, in which the zero of this classification means that a very low predisposition of ground for having methane, and values around 20 mean that the probability is consistent.

2. FAVOURABILITY FUNCTIONS

These functions associate, for every element of a studied area domain, a number that is related to the predisposition of that domain for the event under prediction. The favourability of an event to occur is the possibility for the event to become real in the area in which it is defined.

Thus, some concepts may be defined:

A:= Domain for the generic Favourability Function F.

A can be the set of points belonging to the analyzed geographic area, or even the whole pixels belonging to a raster map of the area.

K:= [1,2,...,m] is the set of layers with the characteristics related to domain A.

m:= number of *layers of characteristics*, which is the number of thematic maps, in digital or paper format, each one containing an attribute considered to condition the event that is being analyzed.

[1,2,...,n_k] := set of the attributes (*characteristics*) related to layer K.

V_k:= *Attributive Partition Function* (Pistocchi, 1997), given by:

$$V_k : \mathbf{A} \longrightarrow [1,2,\dots,n_k] \quad (1)$$

This is a function that for every element of **A**, associates an attribute (or characteristic) of Layer K. A more important function may be defined as:

$\forall k \in K$

$$R_k : [1,2,\dots,n_k] \longrightarrow [a, b] \quad (2)$$

where [1,2,...,n_k] := set of the previously defined characteristics; [a, b] := numeric interval, with a < b; R_k is associated to every class of attributes in which layer K is subdivided, a numeric value between a and b, and it is an index of inclination of the event to happen.

Thus, the definition of Favourability Function is:

$$F_k := R_k \circ V_k \quad (3)$$

$$F_k : \mathbf{A} \longrightarrow [a, b],$$

F_k is defined as a composite function of R_k ∘ V_k and is a function that, relatively to each layer K and for each point p of domain **A**, quantifies the inclination (in numerical form, as a number in the [a,b] interval) that the same point has in relation with the event to be predicted.

2.1 Bayes Theorem

T_p is the following proposition:

T_p:= "*in the p point there is methane*"

$$\text{Prob}\{\mathbf{T}_p \text{ is true} | V_k(p)\} \quad (4)$$

This is the conditional probability of **T_p** to V_k(p) and it means that (4) is the probability of **T_p** to happen if V_k(p) is true.

So, using (4), the favourability function can be given by the function F_k:

$$\left. \begin{aligned} F_k : \mathbf{A} &\longrightarrow [a, b]; \\ p \in \mathbf{A}, \forall p \in \mathbf{A}, \forall k \in K (k = 1, 2, \dots, m) \\ F_k(p) &:= \text{Prob}\{\mathbf{T}_p \text{ is true} | V_k(p)\}. \text{ (Luzy, 1996)} \end{aligned} \right\} \quad (5)$$

The Bayes' theorem can also be written in the following form:

$$\text{Prob}_k\{\mathbf{T}_p | V_k(p)\} = (\text{Prob}\{V_k(p) | \mathbf{T}_p\} \cdot \text{Prob}_k\{\mathbf{T}_p\}) / (\text{Prob}_k\{V_k(p)\}) \quad (6)$$

Prob_k{V_k(p)} is the probability to have in layer K a particular attribute (or characteristic) independently from others factors. Prob_k{**T_p**} has a constant value for all p points in the K layer, because it is the probability that "*in the p point there is methane*" independently from the characteristics of p ∈ A.

Using (6), the favourability function F_k is then:

$$\left. \begin{aligned}
& F_k: \mathbf{A} \longrightarrow [a, b]; \\
& p \in \mathbf{A}, \forall p \in \mathbf{A}, \forall k \in K (k = 1, 2, \dots, m) \\
& F_k(p) := \text{Prob}\{V_k(p) | \mathbf{T}_p\} \cdot \text{Prob}_k\{\mathbf{T}_p\} / (\text{Prob}_k\{V_k(p)\})
\end{aligned} \right\} \quad (7)$$

2.2 Fuzzy Logic

A fuzzy set may be constituted of all p ($p \in \mathbf{A}$) for which the proposition \mathbf{T}_p is “likely true” (Wright, 1996), so the Fuzzy set is defined by a function m_s given by:

$$m_s: \mathbf{A} \longrightarrow [0, 1] \subseteq \mathbf{R} \quad (8)$$

μ_s represents the belonging grade or “compatibility grade” (Chung, 1993) of p to S .

μ_s can also be considered as a “possibility function” (Zadeh, 1978) that the proposition \mathbf{T}_p is approximately true in point p .

Therefore, a fuzzy set can be defined as the set of points $p \in \mathbf{A}$ for which the proposition \mathbf{T}_p is true in function of an established percentage for μ_s .

The advantage of using fuzzy logic for the predictions consists in the possibility of using a series of operations (fuzzy operations) that produce noteworthy results, especially under conditions in which uncertainty is present (Kosko, 1993).

The most commonly used fuzzy operations are:

- fuzzy AND: $\mu_{\text{AND}} = \min\{\mu_1, \mu_2, \mu_3, \dots, \mu_n\}$
- fuzzy OR: $\mu_{\text{OR}} = \max\{\mu_1, \mu_2, \mu_3, \dots, \mu_n\}$
- fuzzy SUM: $\mu_{\text{SUM}} = 1 - \prod_{i=1}^n (1 - m_i)$
- fuzzy PRODUCT: $\mu_{\text{PROD}} = \prod_{i=1}^n m_i$
- fuzzy GAMMA: $\mu_{\gamma} = (\mu_{\text{SUM}})^{\gamma} \cdot (\mu_{\text{PROD}})^{(1-\gamma)}$ (usually $\gamma = 0.7$)

3. THE CASE STUDY

The geographic area involved in this study was limited at north and south by the cities of Bologna and Florence respectively, in which many excavations were conducted for the construction of various tunnels belonging to the high-speed train project.

The eastern and western limits of the studied area were chosen by excluding zones at great distances from the Bologna–Florence axis, meaning that for distances greater than the chosen limits it is economically impossible the construction of tunnels. Thus the extents of studied area were 87 km in latitude and 59,3km in longitude.

According to the experiences gathered in previous construction of highways and railroad tunnels in that area, the probability of finding geological formations containing methane during the excavations was really high.

A synthesis of steps performed in this study to obtain the risk classification is presented in the following four phases:

- Research and selection of the necessary information
- Digitizing and thematic layers subdivision of all data
- Favourability models application
- Prediction rate analysis and sensitivity analysis

3.1. Research and selection of the necessary information

This was necessary to get the risk classification to assume particular importance in a probabilistic study. Useless information can trouble or worsen the results and for this reason in this study a sorting of data before the calculation with favourability functions was performed (especially following suggestions of geologists and methane emissions experts). More selections after the calculation were done, applying different sensitivity analyses and analyzing trends in the prediction rate.

The utilized data had different origins, involving:

- Geomorphological maps, necessary to define the geological formations, their stratigraphy and also tectonics in the studied area (Longo, 2000);
- Maps containing information about methane emissions already happened in the area (Longo, 2000).

3.2. Digitalization of data

Six geological maps in 1:100 scale have been transformed from paper format to digital raster format. The geological maps were produced by IGM (Istituto Geografico Militare of Italy). A single map, containing information on six original maps was created with useful data only: point maps, segment maps and polygon maps with a GIS software called ILWIS (Integrated Land and Water Information System) based on this single map.

3.2.1. Geological information

From the geological raster map obtained by the six previous maps the following digital layers were obtained (see Figure 1a):

- 1 polygon map containing lithology of the studied area;
- 1 segment map containing geological faults;
- 1 segment map containing anticlines axis;
- 1 segment map containing synclines axis;

On each of these maps, excluding the lithology map, the operations “distance” and “stretching” were performed. With the first operation, maps were created where each point belonging to the map was characterized by its distance from the nearest discontinuity. With the “stretching” operation the pixels (or points) of the four distance maps obtained with the previous operation were divided in four classes of distance (see Figure 1b).

3.2.2. Methane emissions

For the information on methane emissions it was necessary to subdivide the work in two further phases:

- a) Digitizing the “*Emission map*” (a map containing all the known gas emissions).
A point map was created with all known emissions of gas and hydrocarbons in the studied area (Berry, 2000; E.P.G.N. ENI, 1963).
- b) Preparing two digital maps (*submaps E1 and E2*) from the Emission Map.
To verify if the Favourability Functions models correctly predict the risk classes in the area, a method for checking the calculation of the *Prediction Rate* was devised. This procedure imposed the subdivision of the emissions map in two submaps (*E1 and E2*), each one containing the *random* half of the emissions.
Therefore, the whole set of chosen maps considered for the study were:

- Lithology
- Faults
- Anticlines
- Synclines
- E1
- E2

3.3. Favourability Models application

The calculation models mentioned in chapter 2 have calculated the degree of inclination in the territory to contain methane and then subdivide their areas in twenty classes of risk.

For all models the following sentences were valid:

- A fraction of risk is assigned to every attribute of every layer of the studied area (meaning that a fraction of risk applies to every element of the segment maps (faults, lithology, anticlines and synclines). This attribution of risk fractions was done by using the previously described bayesian probability.
- The emissions of methane used in the models are only a random half of the known emissions; only in the final map, calculated with the best model, all the emissions are used.
- The assigned risk fractions are combined between them using the favourability functions. The favourability functions used by the models were: Probabilistic Interpretation Model (Bayes), Fuzzy And, Fuzzy Or, Fuzzy Gamma, Fuzzy Product and Fuzzy Sum.

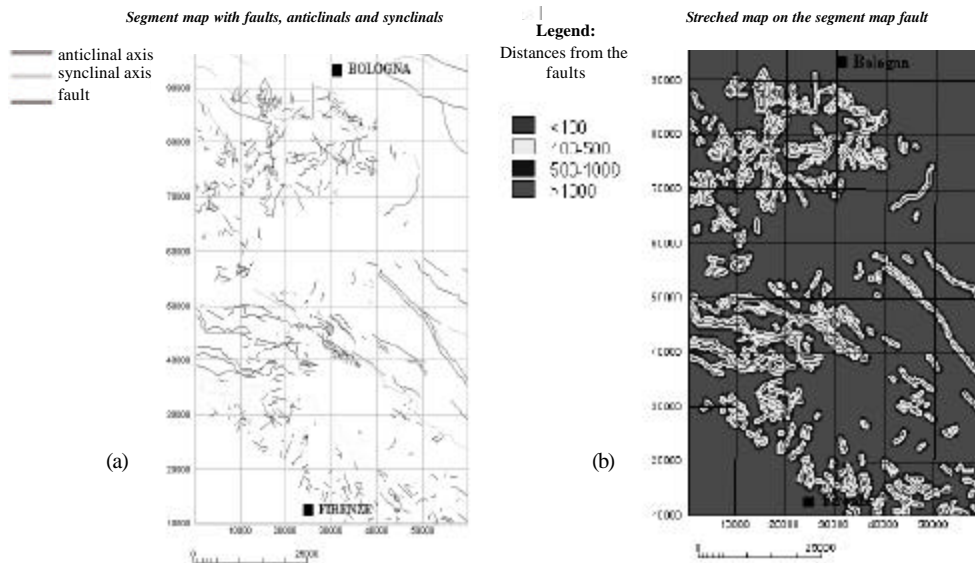


Figure 1 - (a) Contemporary representation of the segment maps: *Anticlines*, *Synclines* and *Faults*. With an operation of “masking” on this map it is possible to create more segment maps, with only a part of the characteristics of the map (for example only faults or only anticlines). (b) Example of map obtained after the application on the segment map faults of the “Distance” and “Stretching” operations

Six different risk maps were obtained (one map for each model) using the same input data.

A software program was also used (ILWIS, Integrated Land and Water Information System, produced by ITC, Netherlands), and a *script* in this program was created especially for this study. This script is a subroutine which use the commands and language of ILWIS to execute different operations, such as distance and stretching commonly used in GIS, and also apply the Favourability Functions to produce six risk maps.

The maps obtained with these models contained 20 different classes of risk of methane presence. In figure 2 it is schematically represented how the script runs.

Running it more times with favourability functions, it was possible to obtain a risk classifications even more reliable and fine.

To improve risk classification quality, operating in the following ways is recommended:

- Following expert suggestions by analyzing results and advising for alterations to apply to the script, referring to his experience and to his know-how;
- The prediction rate analysis
- The sensitivity analysis

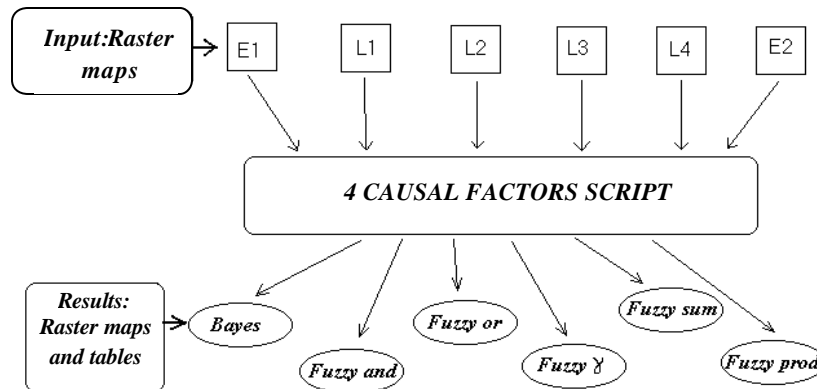


Figure 2 - The script uses 4 causal factors as input (L1,L2,L3 and L4 are the Anticline, Syncline, Faults and Lithology maps) and 2 raster maps containing the emissions (the map *E1* to calibrate the models and *E2* to verify the results). The program produce with this script 6 raster maps (each map using a single model) contain areas divided in 20 risk classes to find methane.

3.4. Prediction rate analysis and sensitivity analysis

3.4.1. Prediction

The Prediction Rate is the percentage of methane emission don't used to calculate the risk areas that falls inside every risk class. It means that in every area defined by a risk class (obtained only by using the emissions map *E1*) we observe and count the number of pixels of methane emissions of the map *E2*, and so we can measure the reliability and the quality of zoning the risk classes. With this procedure we calculate, in percentage, how many emissions don't used in the calculation falls in the areas with high, medium or low risk. If the predictors are working well, the number of emissions in the high risk areas is large and really few emissions exist in the low risk areas.

In Figure 3 the prediction rate is represented in a graphical form. The Y axis represents the cumulative explained emissions, that is the percentage of emissions of the map *E2*. Every curve

in the graphics represent the prediction rate of the corresponding model. Greater is the inclination of the curves respect to the $y=x$ straight line, better is the prediction that the model is giving.

3.4.2 Sensitivity Analysis

Sensitivity analysis is a methodology that permits to evaluate which causal factors are more influent for prediction in favourability models (Carranza, 1999). This analysis was applied in this study by excluding each time one of the four causal factors and creating at each exclusion six *difference maps*. The difference maps are generated subtracting in each point of the area, the value of risk obtained with three causal factors to the value of risk calculated with four causal factors in the same point.

CONCLUSIONS

The distribution of risk classes presents special features in all the models (Bayes, fuzzy and, fuzzy or, fuzzy gamma, fuzzy sum and fuzzy product): the areas containing clay called “*scagliosa*” and other areas located in the central part of the area under investigation are never with a low class of risk; in the south part of the studied area and outside the zone where that clay exists the expected risk is moderate.

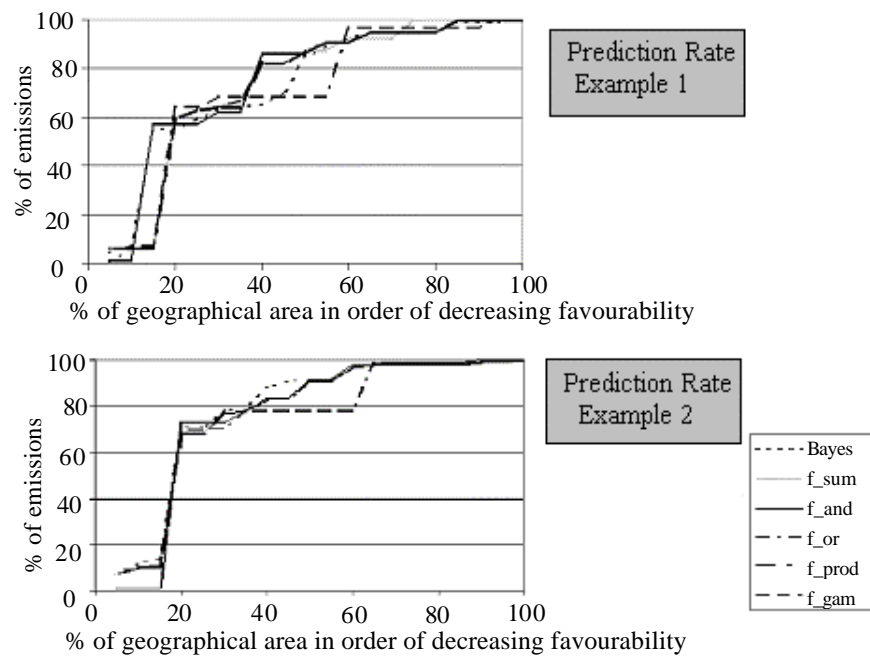


Figure 3 – Are represented two examples of Prediction Rate: the first was obtained with the combination of causal factors (using faults and the causal factor Lithology); the second was obtained with the combination of factors that resulted to be the best (using only the causal factor Lithology and increasing the influence of clay “*scagliosa*”).

Excluding the causal factor “lithology”, important changes are found: the prediction rate and the sensitivity analysis in this case are poor. This fact revealed that the most determining causal factor was indeed the lithology.

In the risk classification obtained excluding the causal factor Faults, the quality of the prediction revealed to be better.

It was found that in the area of this study geological structures like anticline and synclines have no influence on the risk assessment classification.

It may be concluded that the most important causal factor in this risk analysis is Lithology and the probability to find methane greatly increase where there is clay type called “scagliosa”.

The favourability model that demonstrated the best prediction was the Bayesian Model, with values of the prediction rate really high.

Further considerations can be added with respect to the sensitivity of the system: the favourability models react to the variations of input data (e.g. number, type and position of the emissions), and this means that *the classification, once the parameters and the database are introduced, is not definitive, but improbable*, meaning that it can be more reliable and precise if more new gas emissions are utilized (e.g. emissions found during excavations or drillings).

In Figure 4 the final map is represented with the best obtained risk classification. For this map, after having controlled what conditions and combination of data was the most appropriate, all the known emissions of methane were utilized, and not only a random half of them.

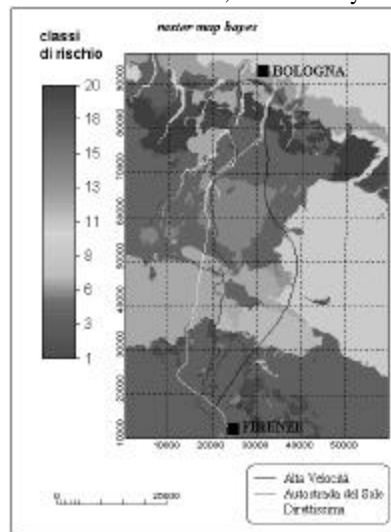


Figure 4 - Final map of prediction, obtained by using the causal factor lithology and all known emissions of gas

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