DETERMINATION OF RELIABILITY IN GEOLOGICAL FORECASTING FOR TUNNEL PROJECTS: THE METHOD OF THE R-INDEX AND ITS APPLICATION ON TWO CASE STUDIES

By

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Why is a reliable geological model so important in tunnel projects?

1. Definition of a geological model is one of the first steps before pursuing in tunnels design
2. Knowledge of geological conditions is one of the most important aspects for risk assessment in tunnel works
3. Geological models imply a variable degree of uncertainty, due to the complexity of the natural settings
4. Underestimation of uncertainty is probably the main reason for economical loss, construction problems and of possible claims and arbitrates
5. Quantifying the reliability of a geological model is a hardly attainable objective: in the practice it is necessary to define which parameters are determinant for the evaluation and, more important, which consequences a bad or good quality of geological forecasts may have on the construction of the structure

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The Method of R-Index (Reliability Index)

A relatively simple computational method that allows to quantify the range of variability of geological/geomechanical conditions along tunnel alignments

OBJECTIVES

1. **Define an index (R-Index) able to express the quality of the interpretation for individual discrete stretches of a tunnel**
2. **Attach to this index a significance in terms of possible variations with respect to the forecasted situation**

The Method of R-Index (Reliability Index)

The R-Index is computed on the base of two main kinds of parameters which may be recognized as influencing the reliability of geological forecasts:

1. ***Investigation Parameters***, **i.e. parameters which define the quality of the investigation methods used in order to explore the rock volume to be excavated**
2. ***System Parameters***, **i.e. parameters which define the geological complexity of the rock volume and therefore the system to be investigated**

By analysing the interactions between these parameters it is possible to understand the process which leads to the construction of a geological model

This consequently allows to reach a quantification of the reliability

Investigation Parameters

In tunnelling, the investigation parameters typically comprehend three different methods of investigation:

1) geological mapping

2) bore-hole drilling

3) geophysical investigations

Each one of these investigation parameters is in its turn influenced by a certain number of variables

Investigation Parameters

Drillholes	Geological Mapping	Geophysical investigation
Number of available drillholes	Mapping scale	Number of available geophysical cross sections
Type (recovery of the core, destructive, BHTV etc.)	Extension of the mapped area	Quality of the survey (e.g. high vs. low resolution etc.)
Average distance from the examined stretch	Detail reached by the investigation technique	Average distance of the sections from the examined stretch
Depth reached by the investigation	Outcrop percentage	Depth reached by the investigation
	Depth of the tunnel in the examined stretch	

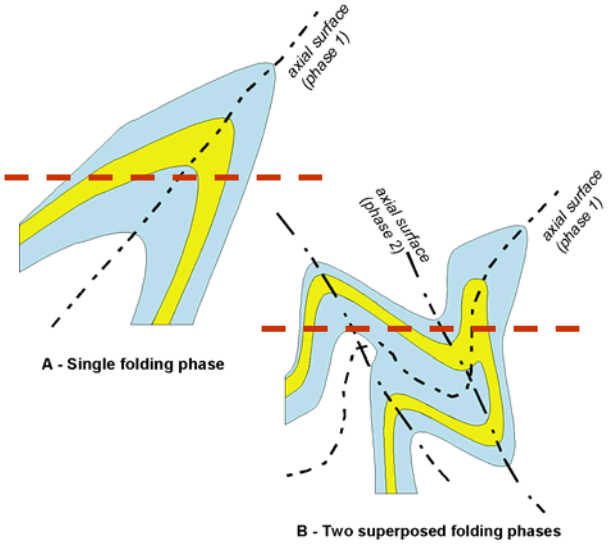
System Parameters

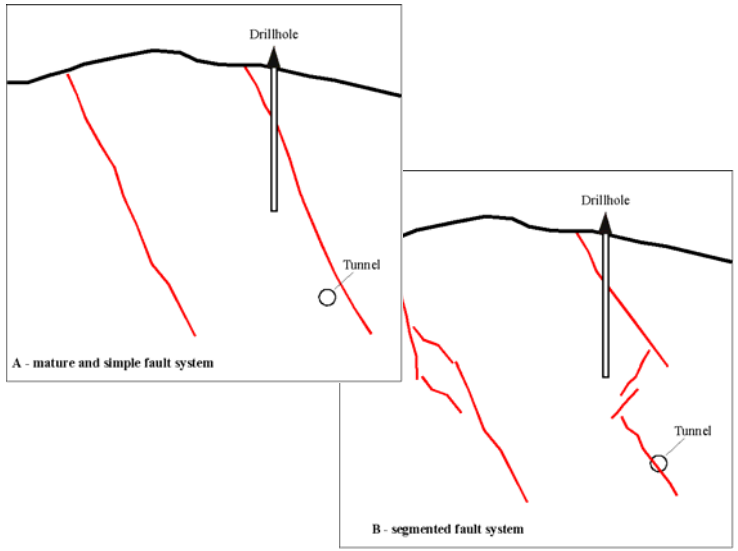
The system parameters depend from the geological setting of the underground structure and comprehend three different categories:

1) **Complexity of the lithostratigraphical setting**

2) **Complexity of structures related to ductile deformations**

3) **Complexity of structures related to brittle deformation**





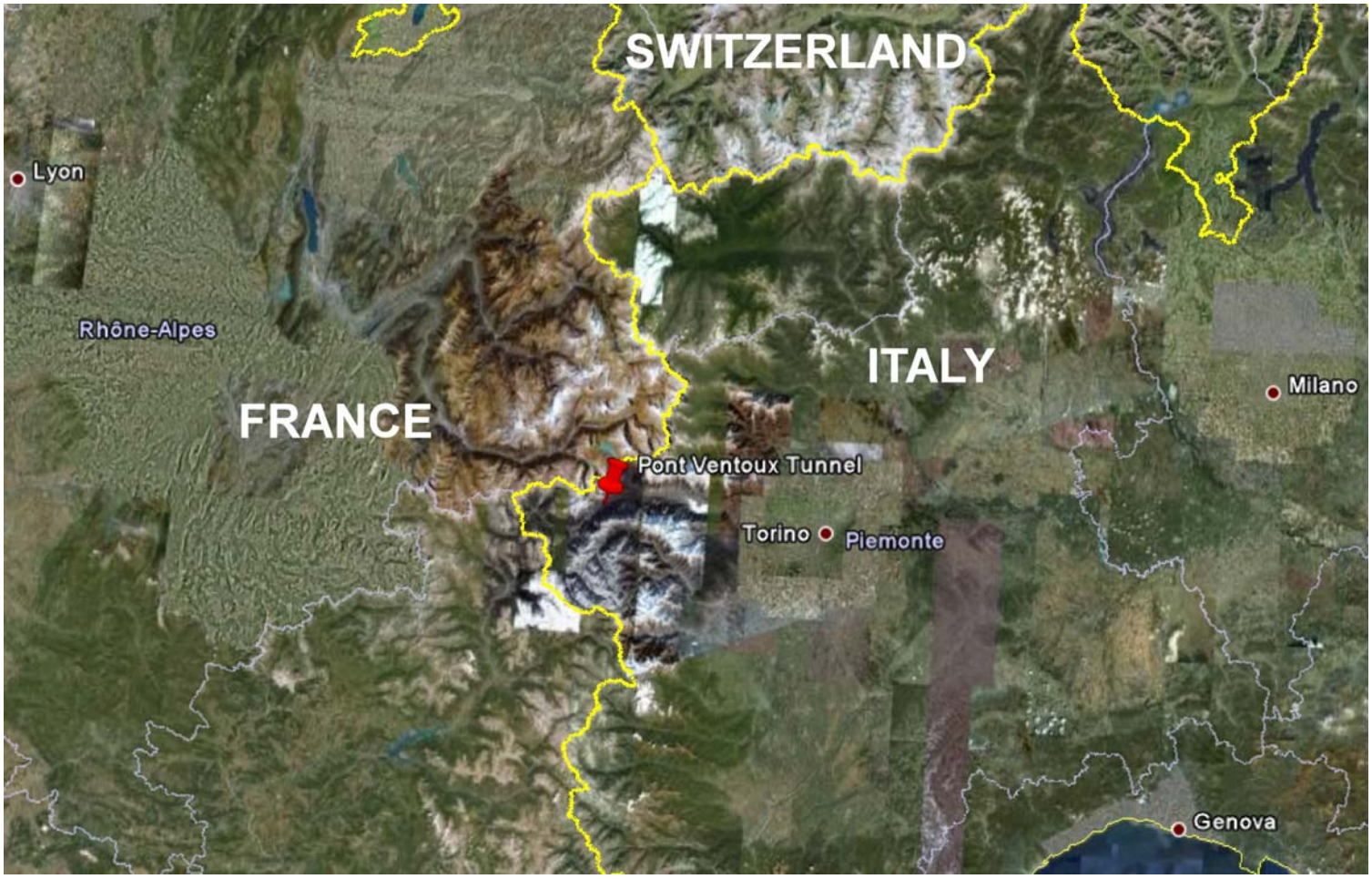
Significance of the R-Index

R-Index	Significance
10.0 – 7.6	***Good reliability*: the geological limits and faults reported in the stretch are certainly present and will be encountered within a range of ± 25-50 m; the thickness of lithological levels can have an error of 10-20%**
7.5 – 5.1	***Fair reliability*: the geological limits and faults reported in the stretch are certainly present and will be encountered within a range of ± 50-100 m; the thickness of lithological levels can have an error of 30-50%. Some minor fault out of those forecasted could be present**
5 – 2.6	***Poor reliability*: the geological limits and faults reported in the stretch are certainly present and will be encountered within a range of ± 100-200 m; the thickness of lithological levels can have an error of 50-100%. Some main fault out of those forecasted could be present**
2.5 – 0	***Not reliable*: the geological limits and faults reported in the stretch could be absents and other elements could be presents the thickness of lithological levels is unconstrained. Other geological elements out of those forecasted could be present**

The Pont Ventoux Tunnel

The Pont Ventoux tunnel is located in the Susa Valley in the Italian Western Alps

The tunnel is about 8 km in length and the overburden may reach about 850 metres

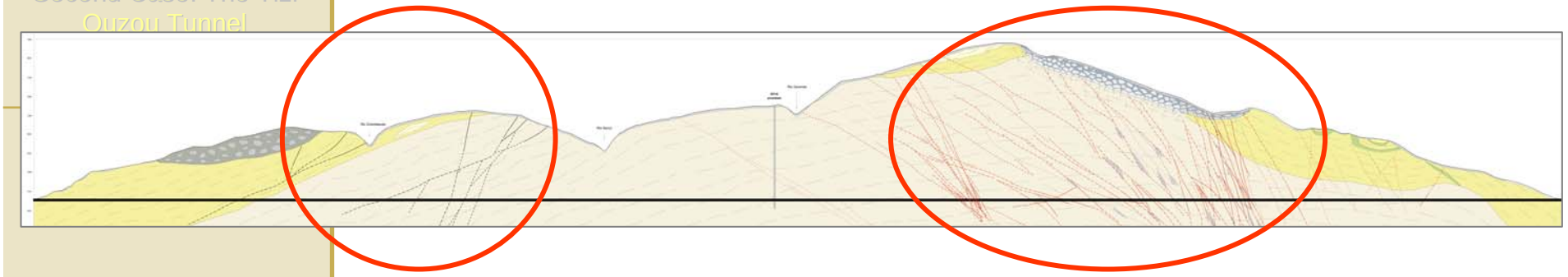


The Pont Ventoux Tunnel

1. **Lithology: a sequence of micaschist and gneiss with local minor layers of quartzite, of meta – conglomerate and of marble. The whole sequence underwent a polycyclic Ercinian and Alpine metamorphism**

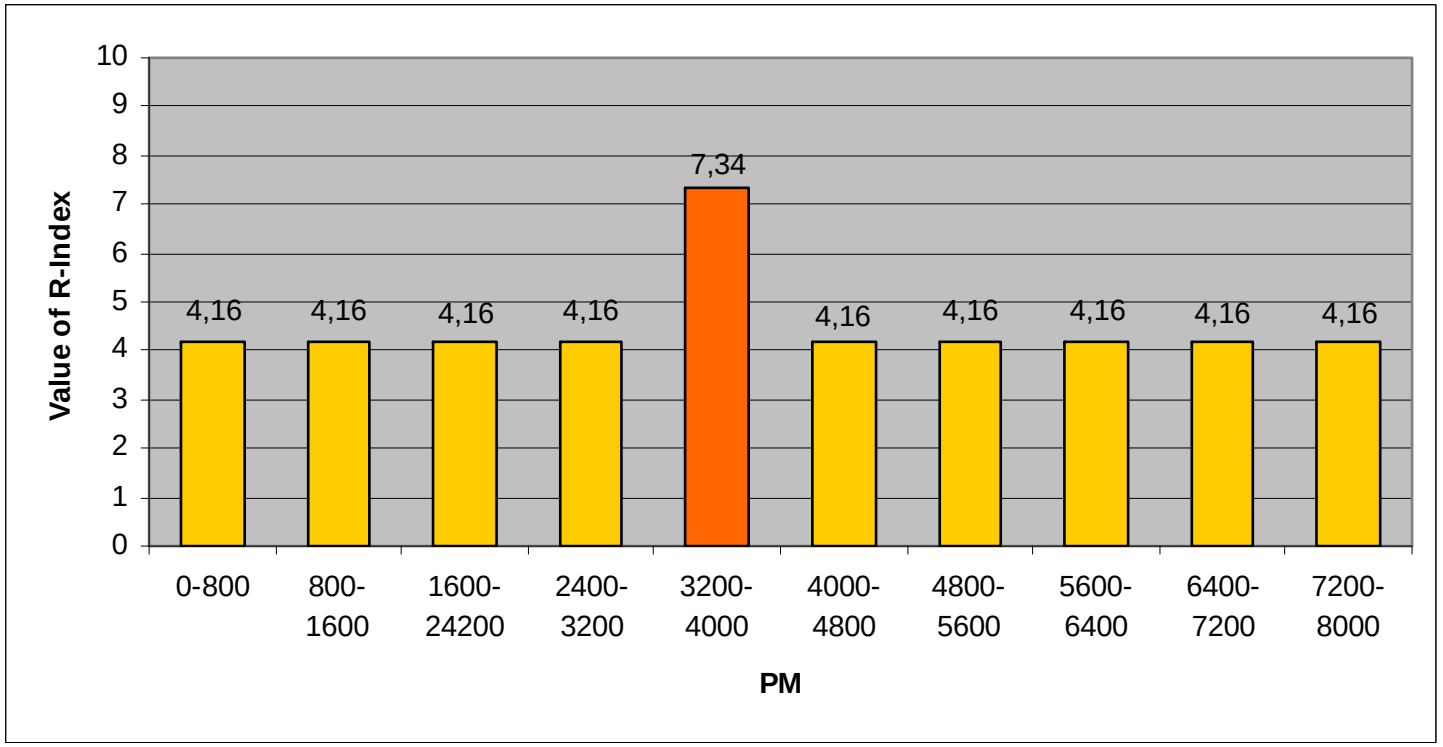
2. **Ductile tectonics: Three main superimposed folding phases.**

3. **Brittle tectonics: Two main systems of faults zones.**



Investigation program

- Analysis of aerial pictures
- Detailed geological and structural mapping at the scale of 1:5.000
- One cored borehole of about 550 m in length



- A higher number of fault zones than the foreseen ones has been encountered during the excavation
- In the 3200-4000 sector a good correspondence has been observed between foreseen and encountered conditions
- The occurrence of a higher number of fault zones than foreseen has been some way predicted by the R-Index method
- An increase of the reliability Index might be obtained by the execution of an higher number of boreholes. In this case a choice is possible on the base of a costs vs benefits criterion, since it might be possible to estimate the number of boreholes necessary to reach a fair or good level of reliability

The Tizi Ouzou Tunnel

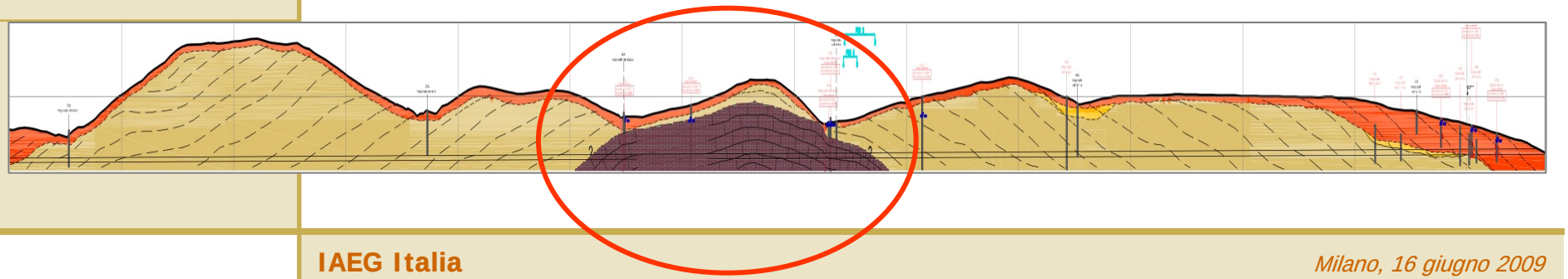
The second case study is represented by a TBM driven tunnel located in Algeria. The tunnel is of about 2,8 km in length and is characterized by low overburden, i.e. lower than 80 meters

The Tizi Ouzou Tunnel

1. **Stratigraphy: Two main terms, represented by Oligocene calcarenites and by marls of the Miocene. No metamorphic overprint**

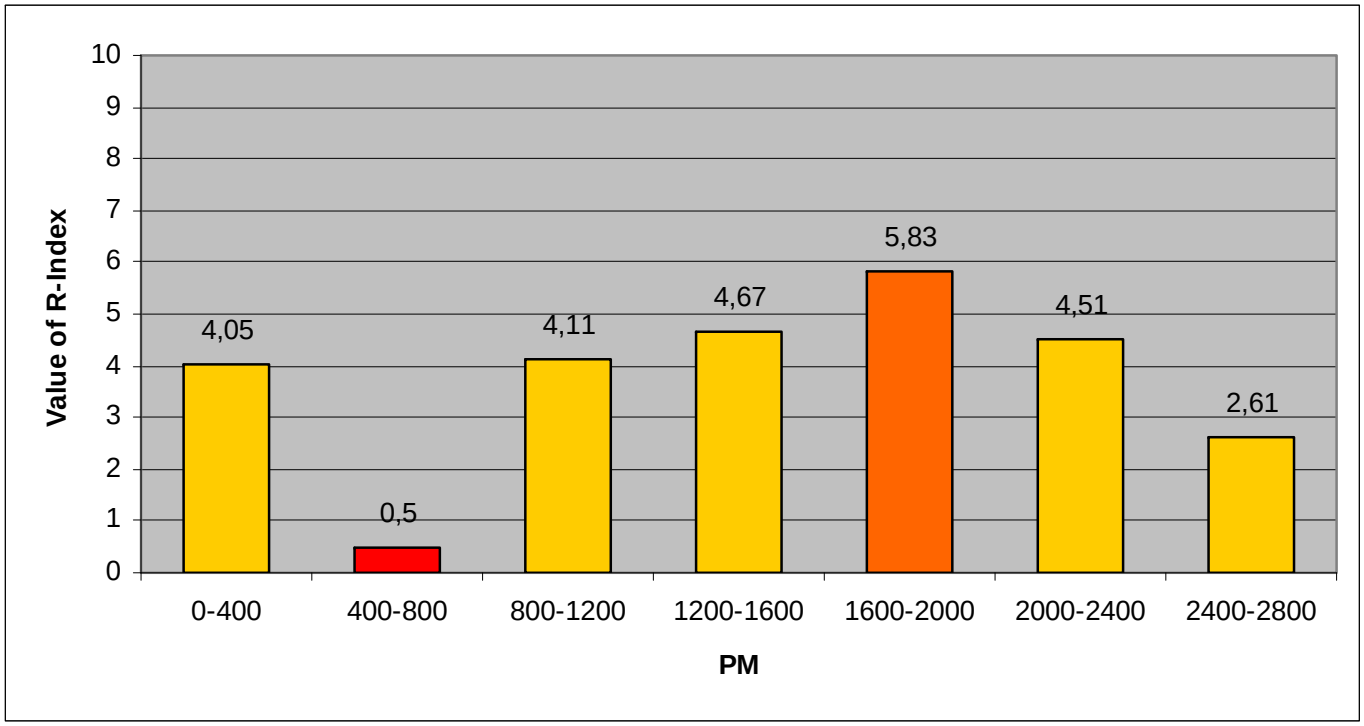
2. **Ductile tectonics: a single folding phase responsible of open folds at the kilometre scale**

3. **Brittle tectonics: three main systems have been identified, corresponding to minor fault zones or to fracture zones**

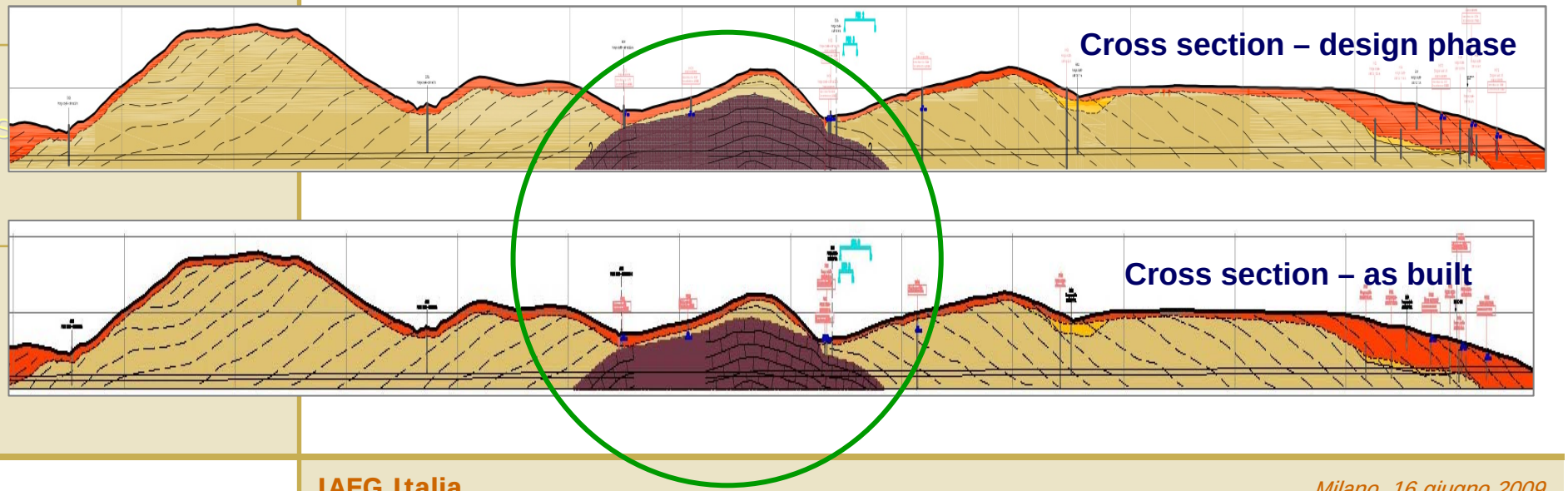


Investigation program

- Analysis of aerial pictures and of satellite images
- Local field observations on a few outcrops. No field mapping has been carried out
- N. 20 cored boreholes, although some boreholes have been realised at a certain distance from the alignment and not all the boreholes were driven until the tunnel depth
- N. 2 seismic profiles



- The results of the computation of the R-Index point to a poor to fair reliability along the tunnel axis
- The lack of boreholes in one sector leads to not reliable forecasted conditions whereas the occurrence of seismic survey allows to increase the value of R-Index in the PM 1600-2000 sector
- Despite of general poor reliability, the foreseen conditions were confirmed during the excavation with a high level of confidence. This is due to the simple lithological and structural setting and due to low overburden which enhance the definition of a reliable setting



Conclusions

- **In both case studies the R-Index allowed to properly assess the reliability of the foreseen geological conditions, whether high or low, by evaluating the complexity of the geological setting and the adopted investigation program**
- **The R-Index represents an important tool for the use of clients, design engineers and contractors for costs vs benefits analysis, to minimise both construction and economical risks related to tunnels excavation**
- **Clients can use the R-Index to establish if their investigation campaigns reach a satisfactory level and to correctly plan or optimize the investigation campaign**
- **Design engineers can use the R-Index to identify the more critical stretches**
- **Contractors can apply the R-Index to identify the main construction risks deriving from geological aspects. This consequently will allow a better calibration of the economical proposal or eventually a conscious acquisition of risks**

Conclusions

Whether by mean of the R-Index or of other methods, the determination of the reliability of geological forecasts is a key tool for Geological Risk Analysis

It is important to promote the development of an agreed method

***IAEG*: Italian National Group – Commission for Determination of Reliability of Geological Models for Underground Works**

***IAEG*: Proposal to 2009 Council meeting for initiation of new Commission - C28 Reliability quantification of the geological model in large civil engineering projects**

***AFTES*: Launching of Working Group 32 – Uncertainties and Geological Risks**

THANKS FOR THE ATTENTION!