BIM AND DIGITAL PROJECT: INNOVATIONS IN DESIGN, CONSTRUCTION AND MANAGEMENT OF CHALLENGING INFRASTRUCTURAL PROJECTS

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1 Introduction

Digital Project is the name given by SWS Engineering to the digitalization of civil infrastructures design processes.

Digitalization of design processes is a relatively new and revolutionary concept for civil infrastructure engineering, and clears the air to computer aided design approaches traditionally belonging to the mechanical engineering disciplines: multi-objective optimizations, sensitivity analyses, statistical analysis, process optimization.

BIM and GIS technologies are the key technological tools that, combined with robust procedures, allow to digitalize conventional civil engineering design, i.e. convert design input and output into 3D geo-referenced parametric geometries, and store non-geometric information in databases. Furthermore, IT technologies are nowadays accessible at a civil engineering design company level and boost conventional design processes and approaches.

The Digital Project has a fairly large applicability and the best way to convey its principles is presenting its implementations in tunnel design.

The paper will provide a definition of SWS Digital Project, highlight the importance of BIM and GIS technologies and present the application of the Digital project in a urban tunnel and in a deep rock tunnel. The two different applications will highlight the flexibility of the methodology to cope with different boundary conditions and different complex design goals. In particular, the Digital Project application in deep tunnels performs a detailed and extensive investigation of the rockmass response to TBM excavation according to the Monte Carlo approach, and exploits the results to support Contractor for TBM selection. The application of the Digital Project in urban tunnels applies an extensive and iterative stability, volume loss and settlement analysis to determine the optimal EPB pressure and to assess the residual building risk. For both examples the word “extensive” is used. With “extensive analyses” we mean a complete set of analyses performed along the entire alignment at a step ranging from 10m to 20m.

2 Digital Project

SWS names Digital Project a peculiar design approach which digitalizes relevant design input within a database and applies automatic design algorithms reading data directly from the database and storing results into the database with a minor, practically none, human interaction.

The Digital Project approach is particularly effective where input data present a large variability due to uncertainties (e.g. geotechnical parameters) and/or where more design scenarios shall be considered and compared in an objective way (e.g. different excavation equipment) pointing out a “Level of Residual Risk” for each different scenarios/solutions. SWS Digital Project framework is a combination of procedures, best design practices and IT tools. Digital Project is a process that converts conventional design inputs (drawings and reports) into 3D geo-

referenced models (BIM and GIS models) and stores their properties (materials, mechanical characteristics, dimensions, quantities) into a central database.
SWS is progressively converting its conventional analytical design approaches from the "old spreadsheets" to object oriented software codes able to gather data directly from a database. Digital Models retrieve data from the database, produce analysis and store results in the same database, enriching the information it contains.
Digital Project makes an extensive use of API available in most of commercial packages for Finite Element Analysis. Also in this case, automatic software procedures guide the data flow from the database to the FEM applications and then import results from the models to the database.
The results and the data contained in the project database are eventually elaborated to produce high quality deliverables.
Data exchange to and from database follows robust software procedures and it is automatic. This allows a series of highly important advantages:

- design performance is optimized: input data modifications are performed on BIM & GIS technologies by expert modellers and all changes are immediately available to analytical or numerical models that can be quickly re-calculated;
- data flow automation allows to perform optimizations or parametric analyses to fine tune design parameters and obtain the optimal combination (multivariate-analyses);
- the automation of data flow and analytical or FEM analyses allow to perform extensive statistical analyses providing the client a real feeling of the reliability of results and project related risks.

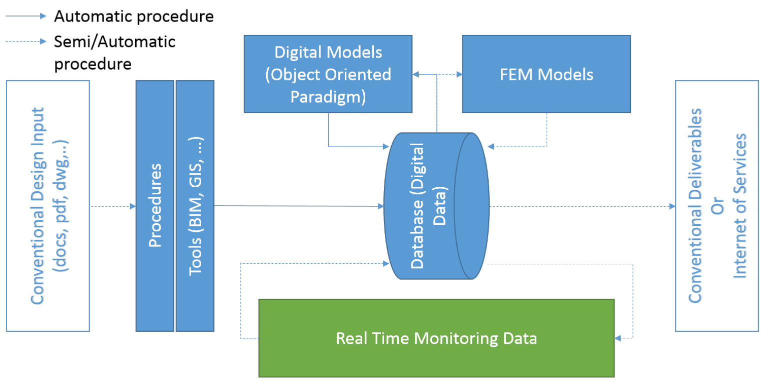

Figure 1: Schematic of Digital Project workflow

The automation process of the Digital Project allows to perform an extremely large number of simulations in a reduced timeframe. It allows for a very fine spatial resolution of the analyses and to iterate analyses to consider geomechanical parameter variability or to fine-tune operational parameters.
The purpose of the Digital Project design methodology is not to provide a black-box tool promising fast solutions to complex problems, but to provide an efficient tool to support decision making:

- Saving time during brute analysis phase for making sound analysis assumptions and for critically assess results;
- Providing extended information along the entire domain considering all (reasonably) possible combination of events.

3 BIM and GIS Technologies

To be able to apply extensive automatic analysis is extremely important to digitalize the relevant characteristics of each available design input, i.e. to convert the conventional design input in 3D geo-referenced objects and store their properties in the Digital Project database.
This process requires advanced skills with GIS & BIM technologies and processes, Database design and object oriented programming.
BIM technologies are emerging approaches which allow to model 3D geo-localized project geometries, and to enrich them with information including materials properties and construction schedule. BIM software packages store the entire set of information within built-in databases which not always allow for a direct inspection. Therefore, SWS has developed procedures and tools to gather the required information from BIM models and store them within the Digital Project database.

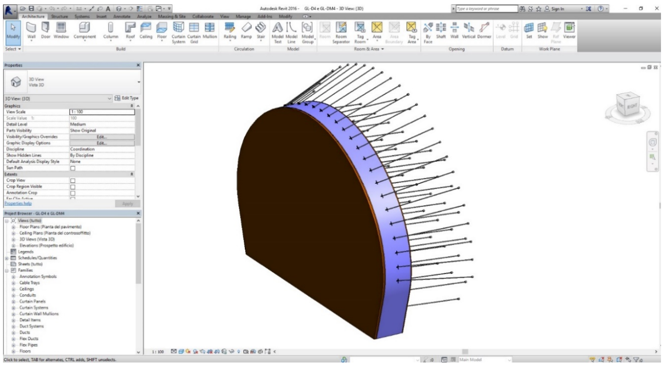

Figure 2: Digitalization of excavation with BIM technologies

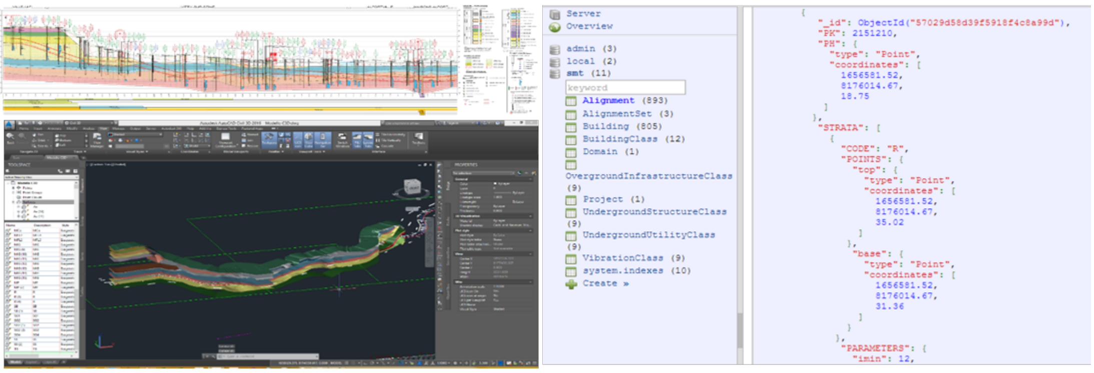

Figure 3: Digitalization of geological profile with BIM technologies

GIS technologies provide valuable open data sources regarding soils and buildings. At the same time, GIS are easy-to-use tools to quickly visualize information on large areas like metro lines. A typical use of GIS technologies is, for example, the retrieval of geometrical information

regarding buildings, roads or railways, or the representation of the damage class of building interference by a metro line construction, or the representation of the induced settlement domain.
GIS advantages for the Digital Project are related to the automatic link established between the Digital Project database and the GIS database, and allow for dynamically changing views of the design result.

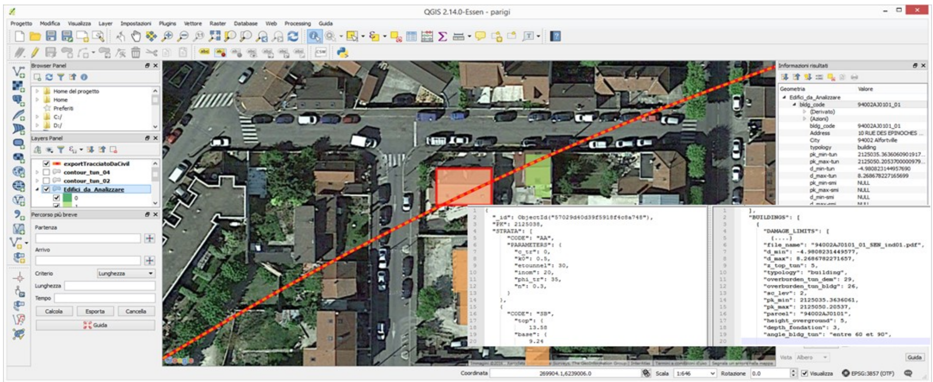

Figure 4: Digitalization of building information with GIS technologies

The application of the Digital Project to tunnelling requires the digitalization of at least:

- 3D alignment definition;
- Excavation geometries;
- Lining geometries and material characteristics;
- DEM (Digital Elevation model);
- Project geological stratigraphy;
- Water-table configuration;
- Geomechanical parameters of soils/rocks;
- Geometry and characteristic of ground treatments;
- Geometry of interference buildings and other services (underground or overground);
- Sensibility of buildings to settlements/Buildings conditions surveys;
- Damage class classification (for settlements and vibrations);
- Geometry and performance of EPM/TBM.

4 Quantification of construction risk in a deep rock tunnel

The main purpose of the study was to set up tools and procedures able to support the Contractor in comparing the ability of different TBMs to cope with a series of risks sources pre-identified by the Client. The aim of the comparison was to select the best TBM type and the manufacturer providing the best performing TBM. The best performance was defined as a balanced solution minimizing geotechnical risks (e.g. cutter head block, shield block etc.) and maximizing production rates.
The principal challenge of the study was to establish a robust methodology, as objective as possible, to be consistently applied to all available TBMs, able to take into consideration project

variability, and producing a simple scoring system where to consistently compare heterogeneous performances (e.g. geotechnical risk vs. production rate).
The operative solution adopted can be summarized in the following conceptual stages:

- Subdivide each alignment in segments of 10 m length and systematically analyse each segment;
- Treat input parameters variability through a Monte Carlo analysis;
- Apply analytical models to define rockmass behaviour to excavation;
- Apply analytical model to define TBM ability to cope with rockmass behaviour;
- Apply empirical models to define TBM foreseen production rate;
- Generalize geotechnical risk events and performance indicators within a unique scoring system;
- Assess the risk score for each event of risk;
- Sum risk scores for the entire alignment;
- Produce graphs to visualize performances along the alignment and synthetic graphs to compare risk scores of different TBMs.

The first step required was to digitalize, i.e. implement into the Digital Project database, the geometrical and mechanical characteristics of the alignments, rockmass, TBMs, excavation cross-section and lining. At the same time, geomechanical and statistical models were implemented in such a way to retrieve input data from and store results in the database.
Geomechanical properties were defined for each 10m-section and stored in the database as statistical functions. For example, the Gaussian density function was employed for rockmass unit weight variation, the truncated Gaussian was used to describe RMR values variability (a Gaussian density would have led to values lower than zero and larger than 100), and the triangular density was used to define the variability of the frictional coefficient of the TBM shield.
Risk assessment procedure adopted the Monte Carlo technic. At each section, a thousand iterations have been performed. At each iteration, geomechanical and mechanical variables were generated according to the relevant statistical distribution. Geomechanical models were applied to define rockmass behaviour indicators (convergence, rockburst, front stability, etc.). All TBMs, applicable to the analysed section, were tested against rockmass behaviour by applying the appropriate mechanical models. The likelihood of each event of risk was assessed and combined with its consequences to define the risk event score (according to AFTES 2012 recommendations). The entire set of data (inputs, geomechanical parameters, rockmass behaviour parameters, risks likelihood, consequence and level of risk) were systematically stored in the database for further processing and synthesis.
The study developed automatic procedures to produce different data representations depending on the parameters to be shown and the required level of aggregation:

- Rockmass behaviour and TBM performances were represented along a given alignment profile as statistical distributions valid for the selected TBM (Figure 5 to Figure 8);

- The risk of block of the TBM (for torque limits, thrust limits, or both) were represented along a given profile as histograms and showing one TBM performance or the comparison of two TBMS (Figure 9);

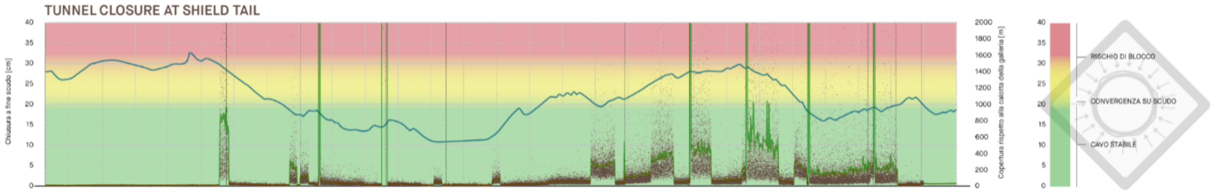

Figure 5: Statistical distribution of the tunnel closure measured at shield tail

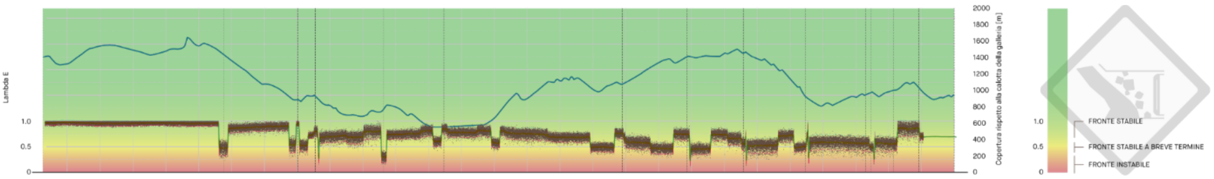

Figure 6: Statistical distribution of the front stability according (Panet)

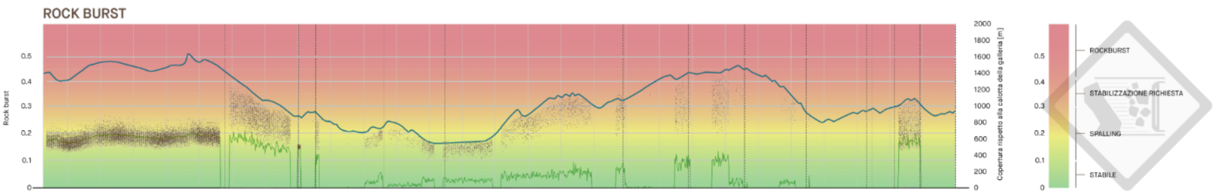

Figure 7: Statistical distribution of rockburst parameter (Hoek-Brown)

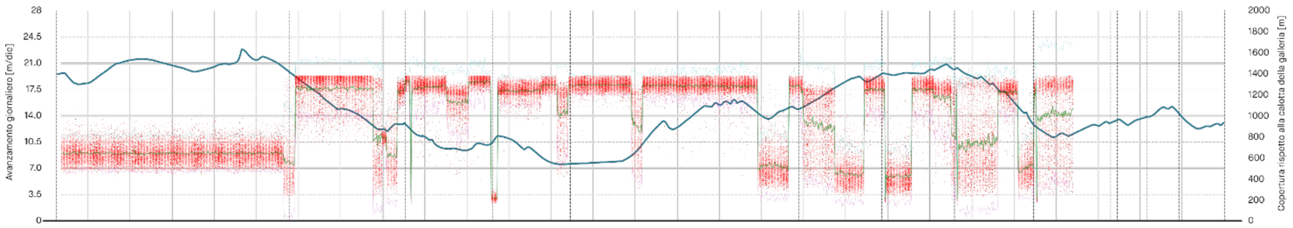

Figure 8: Statistical distribution of the expected advance rate considering actual rockmass conditions and TBM dotation

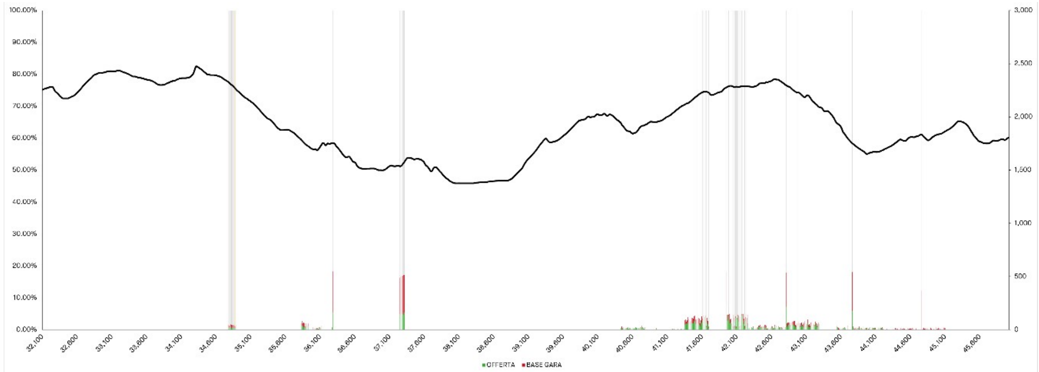

Figure 9: Diagram of the likelihood of block along one of the alignments. Two TBMs are compared (red Vs. green bars)

- The different risk score of all TBMs against a specific risk event were compared, for a given alignment, on violin diagrams (Figure 10). Each violin representing the density distribution for the risk score of each TBM, the risk score value represented on the y-axis;

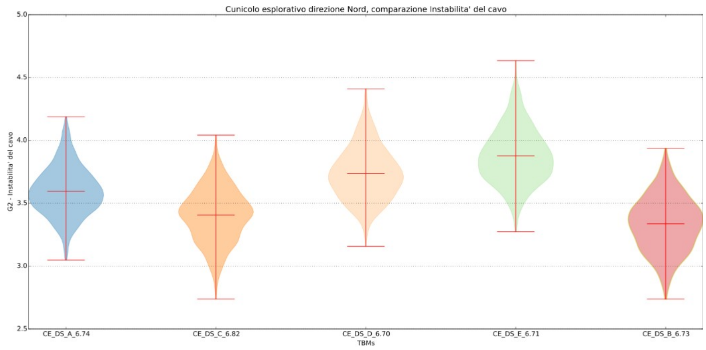

Figure 10: Example of comparison of TBMs performance on a given alignment: risk level results for G2 event of risk.

- The risk score grouped by risk family (G- Geotechnical, P-Production, V-Other) were represented on radar diagrams (Figure 11- the distance from the center representing the single risk event score);

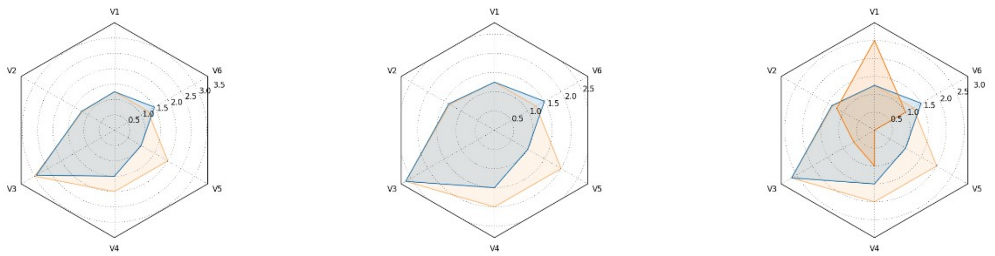

Figure 11: Example of comparison of TBMs performance on three project alignments: risk level results for the entire V family – other risks.

- The selection of best performing TBM type was supported by violin diagrams (Figure 12). The violin represents the sum of all risk scores of all TBMs belonging to a particular type;

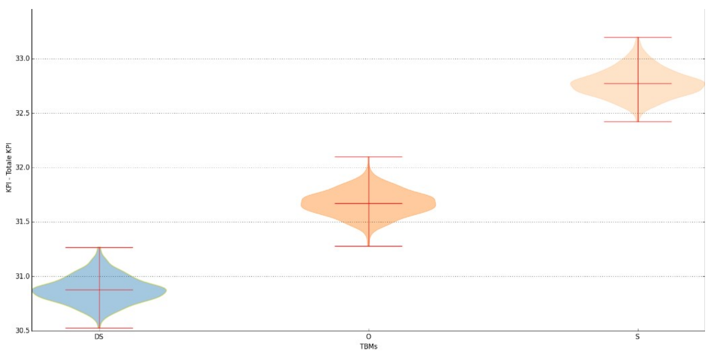

Figure 12: Example of graph supporting TBM type selection for a given alignment: DS- double shield, O-open, S- single shield

- Finally, the selection of the best performing TBM within a chosen TBM type was similarly represented with violin diagrams (Figure 13). The violin represents the density distribution of the sum of the score of all risks for a given TBM and a given alignment.

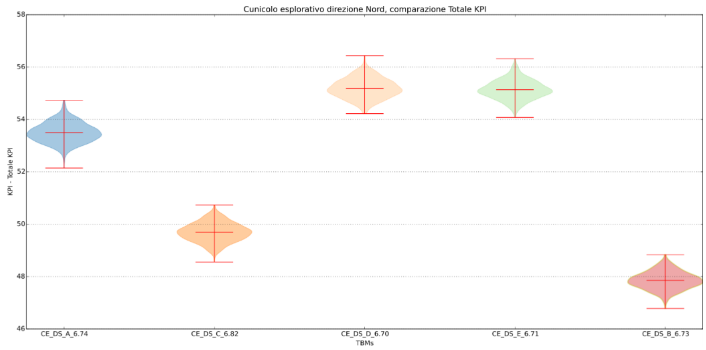

Figure 13: Example of graph supporting TBM manufactures selection for a given alignment and a given TBM type

After a setup phase, where risk analysis was agreed among stakeholders and the overall software framework was developed, the approach allowed to keep up with manufactures technical specifications evolution. Technical improvements were quickly reflected in updated graphs and performance indicators.
The graphs showing the statistical distribution of rockmass behaviour along the alignments' profile allowed to validate results and provided a powerful tool to locate potentially dangerous areas. Furthermore, the statistical analysis allowed to have a better representation of the likelihood of occurrence of risk events.
Similarly, foreseen productivity variation along the profile and its local variability due to geomechanical uncertainties was effectively validated and analysed to fine tune construction schedules.
Violin and radar graphs supported decision-making and provided synthetic representation of the compared performance TBMs over the entire alignment. Single event of risks or the sum of them could be easily represented to double-check where a particular TBM was more or less effective compared to the competitors.

5 Definition of the optimal EPB pressure in an urban tunnel in soft soils

The main purpose of the study was to define the optimal EPB pressure for a 9 km urban tunnel. EPB pressure had to ensure front stability, avoid blow-up and minimize damage on existing buildings and structures. A map of the residual risk on buildings and structures was finally to be produced.
The Digital Project approach was chosen to perform an extensive analyses for the entire alignment able to capture the punctual variability of:

- Overburden;
- Geological profile;
- Water table;
- Buildings/Structures position, sensibility to settlements and to vibrations.

Furthermore, the Digital Project approach was preferred to overcome the difficulties related to the interdependency between EPB front pressure, volume loss, induced settlements and the damage expected on buildings.
The operational procedure followed can be summarized as follows:

- Digitalize and discretise project data in segments of 20 m length, and systematically analyse each segment;
- Define front stability pressure and blow up pressure;
- Retrieve interfering buildings/structures position, geometry and sensibility;
- Define volume loss, settlement domain and building risk assessment for increasing values of EPB pressure (comprised in stability - blow-up pressure range);
- Record optimal EPB pressure into the Digital Project database, i.e. minimal pressure minimizing damage on buildings/structures;
- Produce graphs and maps to visualize the optimal results.

For this study, GIS technologies provided a valuable support. Open data available for existing buildings allowed, combined with in-house procedures and tools, to quickly import in the Digital Project database more than 800 sensitive structures locations and plans and to cross-reference them with the Building Condition Survey information available in pdf format (Figure 14). The Digital Project database contained, for each 20m-section, a complete set of information regarding overburden, geology, water table, presence of buildings/structures, their relative distance from tunnel axis, foundation depth, sensitivity, structure type, etc.

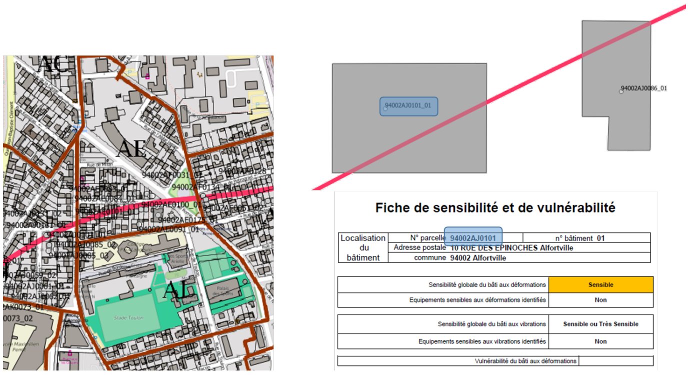

Figure 14: Building information exchange between open data sources and building condition survey

Furthermore, GIS technologies were employed for effective representations of the residual Building Risk Class (Figure 15) and contour plots of greenfield settlements (Figure 16). Standard graphs were automatically produced to represent the prescribe EPB pressure along alignment profile, expected volume loss values, maximum settlements, etc. (Figure 17).

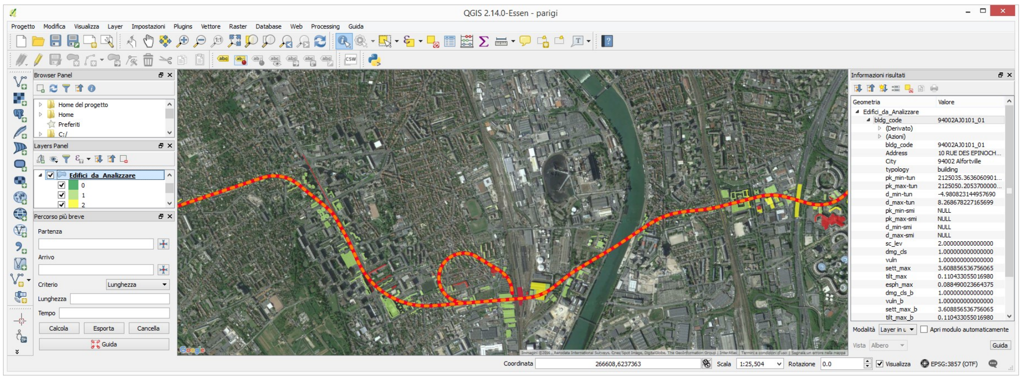

Figure 15: GIS representation of Building Risk Class along tunnel alignment

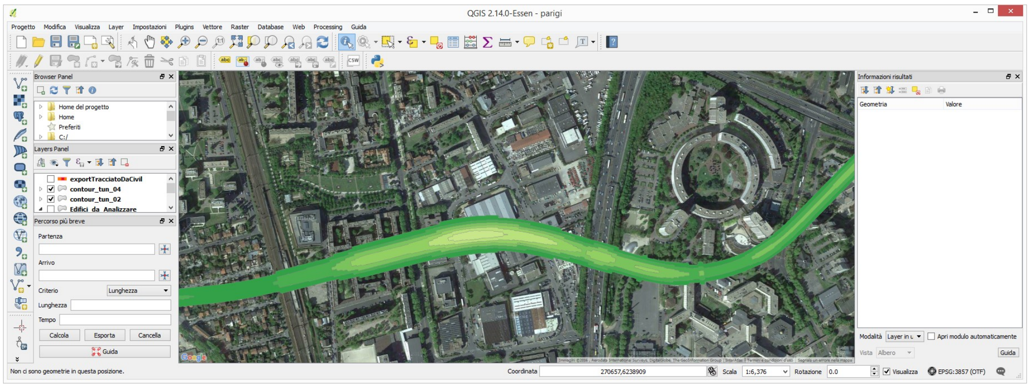

Figure 16: GIS representation of settlements induced by tunnel boring

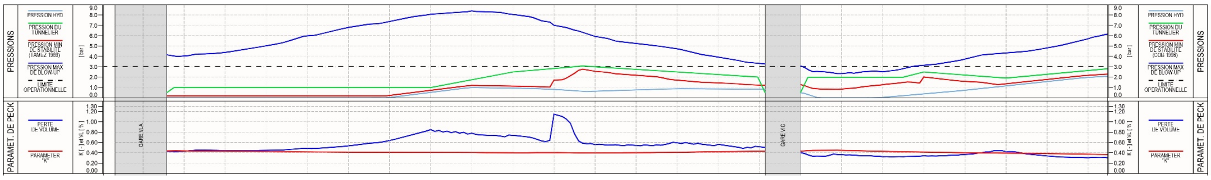

Figure 17: Digital Project graphs for front stability, blow-up, EPB pressure and volume loss

6 Conclusions

The paper has briefly presented SWS Digital Project concepts and applications to tunnelling. The Digital Project approach offers valuable advantages were design analyses shall be extensively and/or iteratively applied. Automatic access to project data, analyses execution and result representation allow for a quick execution of an extremely large number of simulations which would result highly un-economical with conventional design approaches. The proposed approach leveraged BIM and GIS technologies potential to strengthen the quality of both the input and the output stages and, at the same time, to improve the performance in case of frequent input data changes. The Digital Project application in deep tunnels applied Monte Carlo approach, simulated rockmass response to excavation and exploited the results to support Contractor for TBM selection. The application in urban tunnels applied an extensive and iterative stability, volume loss and settlement analysis to determine the optimal EPB pressure and to assess the residual building risk. The different application scenarios and design goals were chosen to highlight the flexibility of the Digital Project approach which can be specialized to support the Client with a deep and detailed design insight.