An application of the Observational Method to deal with sudden water level changes: the 4 tunnels for the extension of the line 1 of the Milan subway

G. Iagulli[1], M. Silvestri[1], L. Messineo[2] and A. Antiga[3]
[1]*De Sanctis Costruzioni S.p.A., Roma, Italy*
[2]*A.T.M. S.p.A., Milano, Italy, (previous: De Sanctis Costruzioni S.p.A)*
[3]*AF Consult Italy S.r.l., Milano, Italy*
E-mail: andrea.antiga@gmail.com

ABSTRACT: The extension of the line 1 of the Milan Subway to the N-E outskirts of city involved the execution of 4 bored tunnels for a global length nearly 2 km in difficult geotechnical and hydrogeological context. The tunnels are built using conventional tunneling systems with a partial-face excavation. The work was found to be extremely complex for the presence of incoherent soil (sand and gravel) in an extremely variable hydrogeological context with water table level suddenly changing of some meters in a few months.
In order to overcome these critical issues and assure greater safety and continuity of the works, the Contractor and its Consultant developed a Detailed Design based on the Observational Method, which considered several possible hydrogeological scenarios and staged excavations over small stretches.

KEYWORDS: underwater excavation, observational method, soil improvement, groundwater, incoherent soil

1. INTRODUCTION

The growing need for transport infrastructures has led to a stronger and stronger growth in the use of underground spaces in highly populated contexts.
The common presence of soils with poor mechanical characteristics, groundwater interfering with excavations and pre-existing structures has led to major improvements in the construction technologies, in the design techniques and in the construction materials. In these areas, that is in the cases in which the conditions of stability and water tightness of the excavation can be guaranteed only using important stabilization systems, there has been the exponential growth of the "mechanized" excavation systems, in particular in the equipment field with face stabilization systems (EPB Shield, Slurry Shield).
At the same time, despite the technological advances made in the field of soil consolidation and waterproofing systems, the "traditional" excavation systems have been relegated, to interventions of reduced extension, that is to the cases in which for economic reasons the road of the mechanized excavation.
Cases of urban excavation under difficult geotechnical conditions made with traditional excavation systems are increasingly rare.
An interesting experience of the application of the conventional tunneling systems with a partial-face excavation is presented below; it relates to the realization of the extension of the line 1 of the Milan Subway in difficult geotechnical and hydrogeological context.
The work was found to be extremely complex for the presence of incoherent soil (sand and gravel) in an extremely variable hydrogeological context with water table level suddenly changing of some meters in a few months.
The presence of some important road infrastructures in operation and several existing buildings next to the excavations, completed the project framework.
In order to overcome these critical issues and assure safety and continuity of the works, the Contractor and its Consultant developed a Detailed Design proposal based on an observational approach, which considered several possible hydrogeological scenarios.

2 GENERAL DESCRIPTION OF WORK

The project to extend line 1 of the metro from Sesto FS to Monza is part of a broader framework for strengthening the public transport system in the north of Milan.
It is aimed at ensuring a valid alternative to the strong private traffic currents coming from the Brianza and important road axes such as the A4 motorway and the SS n. 36 and.
At the same time, serve areas for which a strong urban development is expected.

The extension of the M1 subway line in a northerly direction beyond the current Sesto FS terminus represents the most qualifying and functional element of the reorganization of the public system in the hinterland areas that most directly insist on the Milan-Monza route.

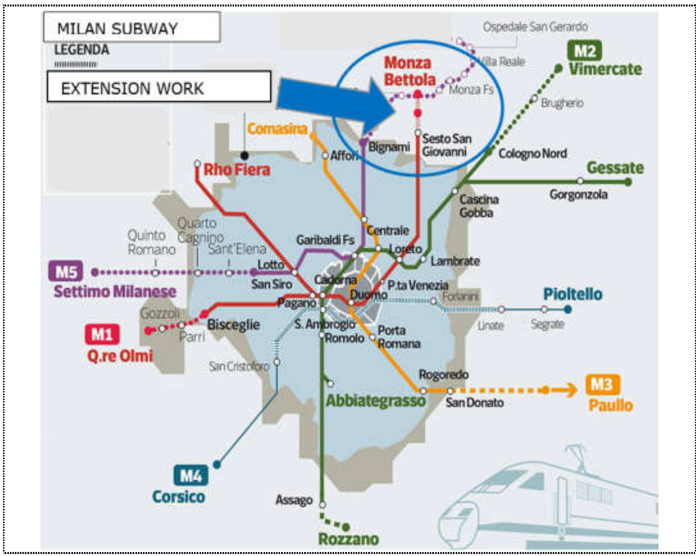

Figure 1. Milan Subway Key Map

From this point of view, the extension of M1 plays a dual and important role: on the one hand, it guarantees interconnections at the local level between areas of future significant urbanization and, on the other, contributes to improving the interrelations between the capital and the most representative poles of the northern hinterland.
The route covers the territories of the Municipalities of Sesto San Giovanni, Cinisello Balsamo and Monza.
The intervention extends for about 1800 meters and includes:

- 2 sections of cut-and-cover tunnel (total length: 300 m);
- 2 underground stations: Sesto Restellone e Cinisello-Monza;
- 4 bored tunnels (total length: 1207m);
- 5 shafts.

The route of the line in question intersects the planned extension of line 5 of the Milan Metro at the Cinisello-Monza station.
The amount of works is worth about 90.000.000 €.
The contract for the completion of construction works has been awarded in 2017 by De Sanctis Costruzioni S.p.A..
Contracting Authority: Metropolitana Milanese S.p.A. on behalf of the Milan Municipality.
In figure 2 it is showed a key plan of the extension works.

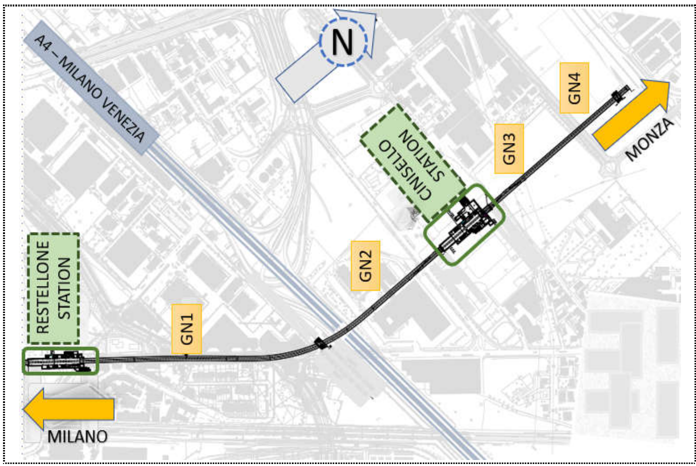

Figure 2. Key plan of the extension works

3 GEOLOGY AND HYDROGEOLOGY

The subsoil of the Milan area consists of alluvial deposits within which different zones can be recognized located at increasing depths and with different granulometric characteristics.

In the area of our interest, located just north of the city, a well-known lithological unit is present up to a depth of about 40 meters; it consists of a gravel-sandy granular deposits with diffused pebbles and occasional silty-sandy layers. The intercalations of silty-sandy lenses are limited to a thickness of few meters. The mechanical characteristics of this unit are characterized by a zero cohesion value and a moderately high friction angle. The mechanical characteristics are essentially well-known and uniform in the whole area.

In detail, below the backfill soil, with an average thickness of 0.50 m, we can recognize two layers of interest for the works in question, up to the maximum depth of interest (40 m):

Formation SLG (Silty sand with gravel) (0.5÷6.0 m b.g.l.)

19 ÷ 20 kN/m3	unit weight
30 ÷ 33 °	friction angle
c' = 0 kPa	drained cohesion

Formation GS (silty-sandy gravel) (6.0÷40.0 m b.g.l.):

20 kN/m3	unit weight
35 ÷ 38 °	friction angle
c' = 0 kPa	drained cohesion

The main and crucial theme in defining the geotechnical and hydrogeological framework is the level of groundwater to be taken as a design reference: this determines in a decisive way the safety conditions, the costs and construction times.

The aquifer is characterized by high transmissivity and permeability values, equal to approximately 0,01 m^2/s e a 0,001 m^2/s. They determine its remarkable productivity, with specific flow values of (10÷25) l/s for lowering the aquifer level of one meter.

4 WORKS CHRONOLOGICAL HISTORY

Over the last decades the trend of the piezometric level in the Milan area has been strongly influenced by the social evolution. The level of the groundwater has been known since the beginning of the 50s thanks to the piezoelectric map of the Province of Milan drawn up in 1958 and subsequently constantly updated. From the late 1970s, we began to see an upward shift in the piezometric levels in conjunction with an exceptional period of rainfall combined with a reduction in industrial water withdrawals due to the reduction in industrial activity. Since 1976, a cyclical (still ongoing), slow and progressive climb has begun, with approximately fifteen years cycles, due to the closure or relocation of numerous industries with consequent relocation of the water withdrawal points in areas far from the urban center. This hydrogeological context has been causing a negative interaction between groundwater and underground infrastructures for decades.

It conditions, in a significant way, the construction of all underground works in the Milan area. This is also due to the possible sudden variations (pluri-metrical in one month) due to the high permeability and hydraulic transmission of the Milanese aquifer.

4.1 First Public Contract (2011)

In 2011, the firs Contract, for the L1 extension works, was awarded to a Joint Venture in a design-build contractual framework. Unfortunately, between the tender (2009) and the assignment of works (2011), the water table level increased for more than 4 m with a foreseeable increasing trend. Therefore, the Contractor had to deal with the actual recorded water table level. With the new water level configuration, the tunnel excavation was affected by significant water inflow. For this reason, the new design was characterized by important and massive ground improvement. The project was drafted and approved in 2011; tunnel excavation works began in 2012 after the excavation of the stations and shafts up to the excavation level of the bored tunnels.

4.2 Works stop (2014-2017)

When the works production had reached about 30% the financial difficulties of the JV Contractor, and the sudden further rise in the aquifer led to the termination of the contract at the end of 2014. The abandonment of the site, without the completion of the ground improvement treatments, followed the contract termination. This, combined with the endless increase of the water table, caused inexorably the flooding of the executed works (figures 3, 4).

Figure 3. Flooding of the executed works

In spring 2015, the groundwater level reached its peak, with a 5–6 m increase over year 2011 (year of the JV Detailed Design) values and 12–13 m increase over year 2008 (year of tender design final approval) values.

Figure 4. Flooding of the executed works

The period (2013-2015) was characterized by large fluctuations in the groundwater level. For all these reasons the Owner had to prepare an integration of the Final Design to reassign the works. The

Owner also stated to insert in the new construction contract the obligation for the new contractor to develop the new Detailed Design considering the actual groundwater levels and its foreseeable trends (this was because after the peak of 2015 the levels of groundwater recorded show a downward trend).

4.3 Second Pubblic Contract (2017)

According to the Italian law, in case of contractual termination of the awarded contractor, the works Contract can be entrusted to the second ranked company.
By this assumption the second ranked contractor manifested its availability for the completion of the work.
In June 2017 a new contract was signed between the Municipality of Milan (Owner, legally represented by Metropolitana Milanese S.p.A.) and De Sanctis S.p.A. (Contractor).

5. DETAILED DESIGN 2017: TECHNICAL SOLUTION

In a broad perspective, in the development of the new Detailed Design (2017), the design and construction difficulties already examined in the previous phases had to be addressed. It is evident that the excavation of these tunnels is particularly difficult due to the simultaneous presence of four characters already singularly very unfavorable: loose soils, low tunnel depth, presence of buildings and road infrastructures, high groundwater level.
The construction procedure was designed in order to ensure tunnel stability and to reduce surface settlements to allowable limits, with respect to the urban environment. A “partial-face excavation” with a "top-heading" scheme was chosen for sections with an excavation bottom below the groundwater level.
The first phase excavation level is higher than the reference groundwater level to allow the first phase excavation to be carried out above the water table.
For the excavation of the upper part of the excavation section, sub-horizontal jet grouting columns are executed around the section and in the tunnel face in order to obtain a sort of shield, covering the soil to be excavated (figure 5).
It has the dual function of ensuring the stability of the excavation face and of reducing the deformation regime of the soil mass within acceptable values.
Working from the first phase excavation plan, a treatment of ground improvement is performed with injections of cement and chemical grout (figure 6, point 4).
The improvement treatment has the purpose of guaranteeing the stability and impermeability of the excavation bottom; it extends below the inverted arc and ends at the sidewalls at a height such as to allow the execution of temporary and definitive support operations in the absence of water.
In typological terms, in the tunnel sections interfering with the aquifer, the soil improvement interventions indicated remain the same (i.e. jet grouting sub-horizontal columns and sub-vertical chemical and cementitious injections).
In a quantitative point of view, the interventions are modulated in relation to the hypothesized groundwater level and to the possible presence of structures on the surface that require a severe limitation of induced deformations.
The level of the first phase work plan, the number and the overlap of the jet grouting columns, the thicknesses of the subvertical grouting, the lengths of the advancement fields and the maximum distances from the excavation face for of the inverted arc and of the internal lining are regulated accordingly.
The main point was that water table level was (and is) suddenly and unforeseeably changing.
To have an idea of this aspect, one must keep in mind that a possible 3 m variation of water table must be assumed over a 5-month period (please, see chapter 7).
The tuning of the ground improvement interventions highlighted above exponentially affects the overall cost of the work. This, obviously, considering the high cost and the time required to carry out soil improvement treatments.

If the maximum possible water table levels had been assumed a contractually unaffordable works cost would be resulted; on the other hand, the Detailed Design had totally to satisfy safety condition and had therefore to consider all the possible unfavorable hydrogeological conditions.
As already explained, the contractual framework is a “design and build” one.
So, the main issue for the Contractor was the management of the Contract risk in terms of costs and execution times.
The major complexity was represented by the necessity to balance a very difficult geotechnical and a suddenly changing hydrogeological context, with the Contractual obligation that imposed to adapt the Detailed Design to the actual water table level
For a typological section, the stabilization interventions and the executive phases are the following (figures 5, 6):

Top excavation (figure 5)

1. soil improvement intervention around the excavation section profile by means of sub-horizontal jet-grouting columns (800 mm) length 13.0 m (overlap to the previous field);
2. face stabilization by sub-horizontal jet-grouting columns (600 mm) length 14.0 m;
3. temporary lining: steel ribs 2 IPE160/1.0 m (eventual steel strut in inverted arc) + sprayed concrete (thk 0.20 m) reinforced with steel fibers; sprayed concrete (thk 0.10 m) reinforced with steel fibers in the excavation face.

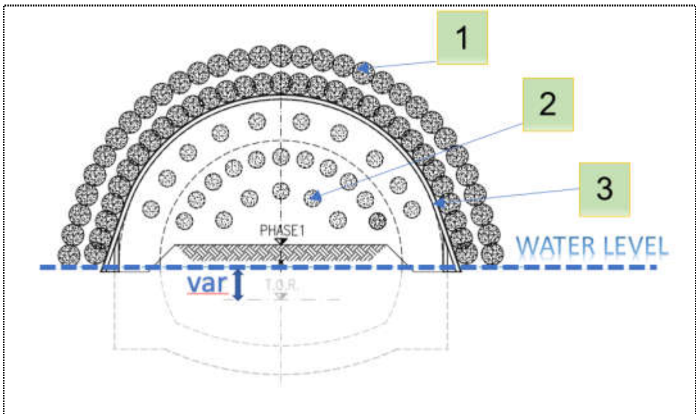

Figure 5. Top excavation

Bench excavation (figure 6)

4. ground improvement by grouting: creation of a strengthened zone of soil by means of cementitious and chemical injections, in correspondence of the sidewalls and of the inverted arch (thk 3.0 ÷ 6.0 m) up to the level of the bottom excavation;
5. excavation of the lower part of the face operating for segments;
6. temporary lining: completion of the lower part of the steel ribs + sprayed concrete (thk 0.20 m) reinforced with steel fibers;
7. inverted arch: reinforced concrete (thk 0.90 m);
8. internal lining: reinforced concrete (thk 0.50÷1.5 m.).

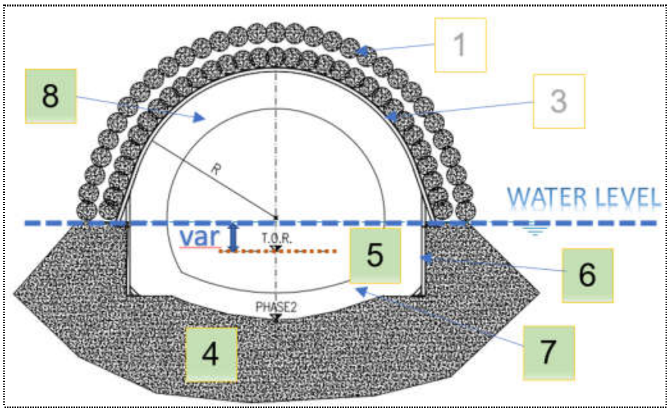

Figure 6. Bench excavation

6 DETAILED DESIGN 2017: OBSERVATIONAL APPROACH

All this considered, a technical table was opened which involved Client, Contractor and Designer to identify the design approach to be adopted in the Detailed Design.
In the light of the Client's Final Design, the contractual obligations and the actual variability of the hydrogeological hypotheses, the Contractor and his Consultant considered appropriate to study a proposal for a Detailed Design based on an Observational Method with the aim of reducing the risk in terms of time and cost of the project and increasing the safety factors of the tunnel works.
This was achieved by:

i. introducing a variability of the ground improvement interventions and of the execution phases;
ii. defining a rational and binding sequence of the work phases with well-defined activities to be completed in a well-determinate period;
iii. defining a realistic gradient increase of the water table level;
iv. using an "active monitoring system" during construction to combine the previous three points and adapt the design to the actual site conditions.

At the end, analyzing the actual groundwater conditions and simulating its possible increases based on the available historical data, it was agreed to develop the Detailed Design according to the basic principles reported below (except for a short section in which it had to work with soil improvement interventions from the ground level).
1) A "Basic Detailed Design" was drafted as a reference solution. The assumptions contained in the Final Design 2015 (groundwater level of January 2015) have been kept in the basic design and therefore the distribution of the basic interventions did not consider the groundwater levels recorded in 2018.
2) According to the principles of the Observational Method and in compliance with the obligations contained in the Contract, in the construction phase the Contractor with its Consultant will constantly monitor the levels of groundwater and on the basis of the data collected will proceed (route by route), to the choice of interventions more adherent to the effectively recorded groundwater levels.
In this way, the optimization of the economic aspects will be ensured in full compliance with the degree of security envisaged in the 2015 Final Project.
3) The Detailed Design contains (as an addendum), to allow the application of the Observational Method, an "abacus of the section interventions" which defines the possible interventions of soil improvement and support according to the likely variation of the groundwater level. With the sections contained in this abacus, one will therefore be able to cover all the possible levels of groundwater: from the maximum (2015) to those collected in 2018 up to a minimum groundwater that does not interfere with the excavation section.
4) It was established that during the execution of the works, through a constant activity of interpretation and analysis of the collected data (level of groundwater and increasing or decreasing trend) one will proceed to a continuous modulation of the Detailed Design adapting it to the conditions that will gradually manifest in executive phase.
For all sections, the continuous monitoring of groundwater levels must therefore be carried out in the construction phase.
Basically, according to the principles of the Observational Method, the examination of the groundwater level data collected allows the Detailed Design to be calibrated. This is done by issuing a specific "Detailed Design for Construction" for the various sections in execution.

7 HYDROGEOLOGICAL FRAMEWORKS FOR TUNING OBSERVATIONAL METHOD

In order to identify the optimal technical-economic solution, in relation to the actual hydrogeological situation, various scenarios have therefore been studied combining the possible design solutions with the possible rise of the groundwater expected in the construction period.
To this end, an in-depth analysis of the hydrogeological data available in the area relevant to the works was made.
In particular, the upward trend in groundwater over the last 10 years has been examined.
In order to identify the possible speed of growth of the groundwater level (mm/day), for a time period comparable with that of the excavation, the available piezometric data were analyzed.
The analyzes were carried out on the basis of the data available on the portal of the Environmental Information System (SIA) of the Province of Milan and those obtained from the piezometers installed in the works area.
The most significant aquifer wells were selected and the recorded trend in groundwater fluctuations over the last ten years (2004-2014) was analyzed. For wells, data after 2014 are not available, piezometers existing in the construction site since 2011 have been used for this time range.
In the dotted ellipse (figure 7), the period with the fastest growth rate is highlighted (2010÷2011).

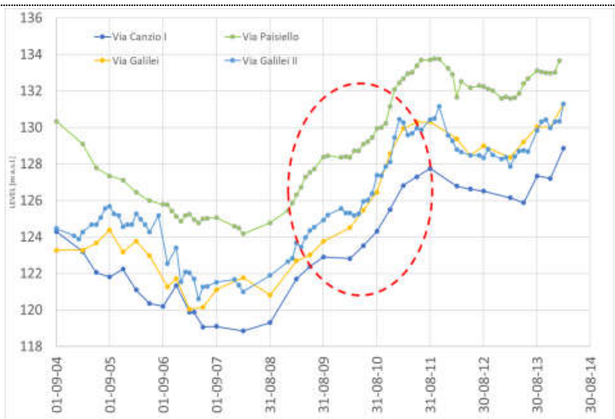

Figure 7. Groundwater fluctuations over the last ten years

Among the individual readings (performed with average monthly frequency) there are values of the groundwater growth up speed that are very high with a maximum peak higher than 40 mm/day (figure 8).
Although observing that in the analysis of the recorded increases it is more significant to refer to longer periods and therefore comparable with the duration of the works in the project, it should anyway not be overlooked that the peaks shown above may have a significant influence on the single workings.

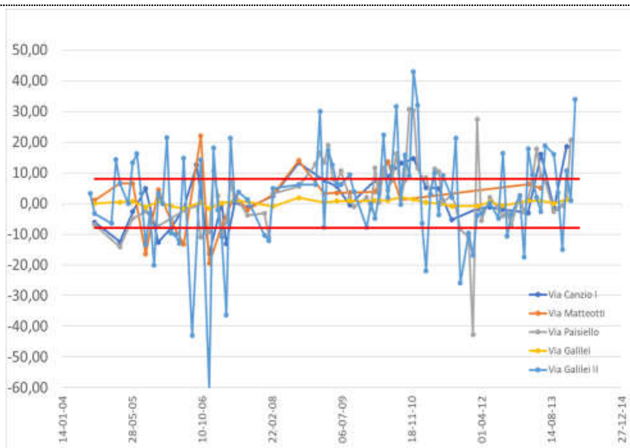

Figure 8. Groundwater level growth rate (one day average)

In order to obtain a significant parameter, periods of a duration of 18 months were analyzed; these are representative of the entire duration of the construction activities of the planned civil works; the most significant period is shown in figure 9.

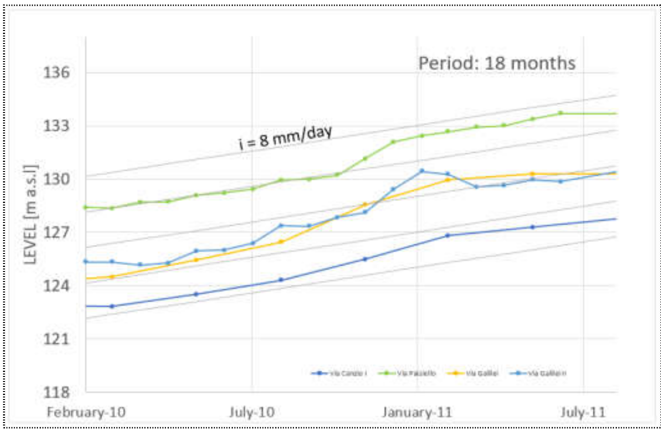

Figure 9. Groundwater level growth rate (18 months average)

Within the period of 18 months it is possible to highlight how the speed of increase are on average (averaged over the entire period) always above the value of 8 mm/day.
Analyzing time intervals of shorter duration (6 months), more representative for the excavation work in the project, it is also noted that significantly higher speeds were recorded (figure 10) with a maximum value of 20 mm/day (red line, figure 10).

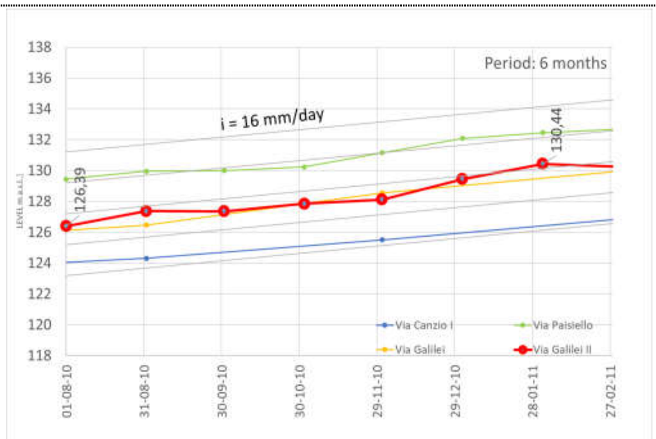

Figure 10. Groundwater level growth rate (6 months average)

Regarding the period between December 2013 and December 2014 (data not available on the SIA portal), the piezometric data made available in the Final Design and installed within the work area were analyzed.
We highlight (figure 11):

- over an interval of 12 months maximum values of the average speed of increase about 12 mm/day;
- over an interval of 6 months (June 2014-December 2014) maximum values of the average speed of increase of about 17 mm/day.

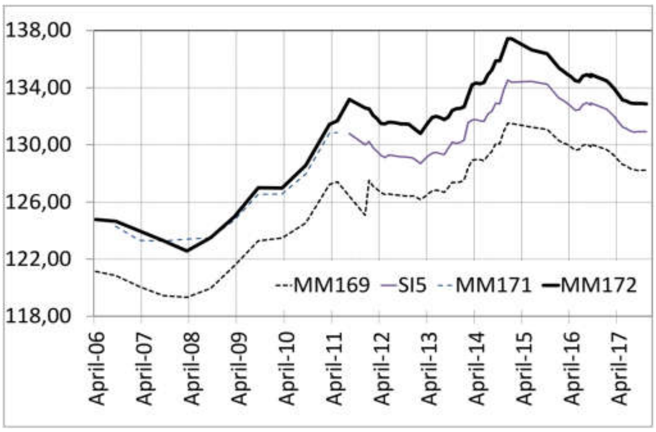

Figure 11. Groundwater fluctuations (2006-2017)

In summary, it is possible to highlight that the analysis of the available data has shown that, within the last 7 years, there were therefore two significant periods (each characterized by a time span of between 12 and 18 months) in which the rise of the aquifer had a rising speed medium high up to average values of 20 mm/day over a period of 6 months which is certainly representative of the excavation processes.
This value was taken as a design reference parameter for the application of the Observational Method.
The average growth rates found in the two periods analyzed would cause a rise in the stratum level exceeding 3 m over a 5-month period.
The strength of this hypothesis is confirmed by the fact that in the period June 2014-December 2014 the piezometers installed in the work area recorded increases in the groundwater level up to 3.10 m.

8 3D FINITE ELEMENT MODEL ANALYSIS

The study of the interaction of the structure (support and soil improvement interventions) with the soil and the aquifer, for the geotechnical and structural design of the excavation sections, was conducted by means of a FEM analysis with the Plaxis calculation code. 3D analyzes were performed with simulation of the main construction phases (jet grouting face improvement, jet grouting soil improvement around the excavation, excavation, provisional lining, inverted arch, final lining). These 3D analyzes allowed:

- the dimensioning of consolidations and the verification of the stability of the excavation conditions with reference to the conditions at the excavation face;
- determination of the expected deformation levels both tunnel face and tunnel cross section;
- the definition of the deconfinement curves for the calibration of 2D equivalent plane deformation models.

In addition, 2D analyzes were carried out to determine the Detailed Design stresses on the structural elements.

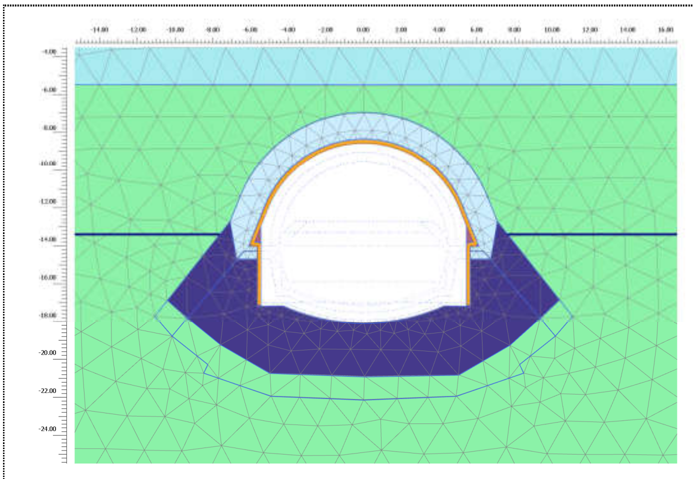

Figure 12. FEM Model

9 THE CONSTRUCTION PHASE

During the works, in order to validate the design hypotheses previously illustrated, it was necessary to constantly perform:

- monitoring of the groundwater level
- updating of the design and of the works program as works progressed to realign them with the actual measured groundwater levels and its predictable growth levels.

This resulted in greatest complexity for Contractor in terms of Construction Management and in particular for works planning and procurement.
The photographs below show some significant phases of the work.
First phase excavation and soil improvement intervention around the excavation section profile by means of sub-horizontal jet-grouting columns (figure 13).

Figure 13. First phase excavation – jet grouting columns

Ground improvement: creation of a strengthened zone of soil by means of cementitious and chemical injections, in correspondence of the sidewalls and of the inverted arch (figure 14).

Figure 14. First phase excavation – subvertical grouting treatments

Excavation of lower section part (figure 15).

Figure 15. Final excavation phase

The excavation work on the GN1, GN3, and GN4 tunnels ended respectively in January 2019, March 2019 and July 2018 in total accordance with the contractual deadlines (figure 16).

Figure 16. The excavation of tunnels is completed

No critical situation was register nor for underground work safety nor for external existing structures.
The GN2 tunnel (please see figure 2), which passes under the A4 motorway, will be built in 2020.
This is because the signing of a complex agreement is currently underway, between Owner, A4 Milano-Venezia motorway Concessionaire and Contractor to identify the responsibilities for the realization of this part of the work that insists under the busiest highway in Italy.

10 CONCLUSIONS

The Detailed Design 2017 based on the Observational Method, as developed by the Contractor together with its Consultant and approved by the Client, allowed to finish the excavation works on time and with no interruptions. It allowed the following main benefits:

1. to include in the design possible "most unfavourable" groundwater conditions and to absorb the hydrogeological uncertainties;
2. to rationalize the quantities and the dimensioning of the ground improvement treatments with a significant economical optimization of the works cost;
3. to offer greater guarantees and reliability in terms of risk management related to the execution of the project (timing of the work and execution costs) both for the Client and for the Contractor.

Therefore, in this case, the Observational Method has been a valid design support for the execution of a complex geotechnical and hydrogeological works and projects. The Observational Method has also proved to be a mostly suitable design criterion when dealing with situations in which the construction methods, operating sequences and the statics of the works are particularly related and the quantities are to be rationalized.
The potential optimization of the quantities, that the Observational Method offers, must necessarily be supported by detailed studies and verifications, which ultimately lead to greater reliability of the project, both in terms of cost and execution times.

11. REFERENCES

Antiga A., Chiorboli M., De Luca U.. The potential for use of the Observational Method in tunnel lump-sum contracts. World Tunnel Congress 2019 Napoli (Italy).

Province of Milan 2019. Direzione Centrale Risorse Ambientali. Sistema Informativo Falda (SIF). http://www.provincia.milano.it/ambiente.

Zekâi Şen 2014. Practical and Applied Hydrogeology 2014. – Elsevier.