Journal of Mining and Earth Sciences

Website: http://jmes.humg.edu.vn

Ground improvement by jet grouting and injection to control hydraulic conditions in the frame of Grand Paris Express Project, North-East section: methodology and quality control sequence

Tri Van Nguyen *, Pascal Chalivat, Alexis Liance, Jonathan Chazelle

Eiffage Infrastructure, Vélizy Villacoublay, France

ARTICLE INFO

Article history:
Received 08th Sept. 2021
Revised 15th Dec. 2021
Accepted 31st Jan. 2022

Keywords:
Groundwater conditions,
Injection,
Jet grouting,
Quality control,
TBM's departure and arrival gates.

ABSTRACT

The main tunnels of Line 16 Lot1 of the Grand Paris Express project are underway since 2019 using tunnel boring machines (TBM). They are drilled entirely in permeable strata (fine/silty sands, marls, and limestones) at a depth of 20÷30 m below the groundwater level. Groundwater inflow with high pressure is a major issue at the arrival/departure sections of the TBMs as well as during the excavation work of connection galleries between the main tunnels and maintenance or security shafts.

Line 16 Lot1 is located under dense urban areas with the requirement of minimizing the drawdown of the groundwater and water inflow in civil engineering works; the purpose is to avoid excessive settlements on existing facilities and dissolution reactivation process of gypsum-rich strata. In order to minimize these risks, different types of ground improvement technics (jet grouting and cement mixture injection) have been applied, where jet grouting is used in fine sandy soil and cement mixture injection used in fissured marly-limestone. In addition, both technics of improvement have been associated on the same site.

From a geotechnical point of view, the sands of Beauchamp are classified as coarse-grained soils (60% SM and 40% ML in the Unified soil Classification System) and Marly-limestone of Saint-Ouen and deep Marls as fissured soft to medium-hard calcareous rock.

This paper presents the geotechnical conditions, the ground improvement methodology and quality control during construction. The control sequence is performed by vertical and then horizontal drilling holes. The method of control work after excavation (horizontal control) allows to confirm the quality of the treatment blocks and specifically the bonding between the treatment block and the diaphragm wall.

*Corresponding author

E - mail: vantri.nguyen@eiffage.com

DOI: 10.46326/JMES.2022.63(3a).07

1. Introduction

The Grand Paris Express is a group of new underground rapid transit lines being built around Paris. The project comprises four new lines known as 15, 16, 17, and 18, plus extensions of existing metro lines (Lines 11 and 14). Line 16 Lot 1 is located in the North-East of Paris; it includes 20 km of new tunnels, five main stations, and twenty launch/maintenance/ security shafts with connection galleries. As shown in Figure 1, Line 16 Lot 1 extends between Saint-Denis and Le Blanc-Mesnil.

The main tunnels, 10 m in diameter, are drilled using tunnel boring machines (TBM) and are entirely located in permeable strata (fine/silty sands, marls, limestones) at a depth of 20 to 30 m below the groundwater level. Groundwater inflow with high pressure is a major issue at the arrival and departure sections of the TBMs as well as during the excavation work of connection galleries.

Line 16 Lot 1 is located under dense urban areas with the requirement of minimizing the drawdown of the groundwater and water inflow in civil engineering works; the purpose is to avoid excessive settlements on existing facilities and dissolution reactivation processes of gypsum rich strata.

To achieve these goals, different types of ground improvement technics (jet grouting [Harada et al. 2015, Lavassar et al. 2015, Njock et al. 2018] and cement mixture injection) have been applied. This paper focuses on the geotechnical conditions, ground improvement methodology, and quality control during construction.

2. Geological and geotechnical conditions

2.1. General overview of geological and hydrogeological conditions - geotechnical hazards

The average coverage height above the tunnels is around 20 m, except for some sites where the local coverage reaches a value of 30 m. On the tunnel alignment, the ground condition consists mainly of various sedimentary formations, which include marly limestone of Saint-Ouen (SO), fine silty sands of Beauchamp (SB), and Marls (MC). The sandy formation is positioned at an average depth of 15m from the ground surface and has a thickness of around 10÷12 m. It is a fine silty to clayey sand with a greenish-grey or blue-grey colour. It includes locally hard sandstone and gypsum inclusions. The underlying Marls have a thickness of 15÷18 m; this formation is known to include more or less decomposed gypsum levels.

Four superposed aquifers are found all along with the project; from the top-down, they are named: Alluvial aquifers, Middle, Late, and Early Eocene aquifers. The piezometric survey indicates that the water table is located 5÷10 m below the ground surface.

Among the geotechnical hazards identified, gypsum dissolution is the most significant.

Figure 1. Plan layout of Line 16 Lot 1.

Sandstone levels in the sands of Beauchamp are also a strong constraint for ground improvement.

2.2. Geotechnical parameters

Based on numerous field and laboratory tests, the geotechnical parameters of the main strata were chosen. Pressuremeter modulus has been used to subdivide each formation according to its deformability (Table 1).

Table 1. Pressuremeter modulus Em for each formation and subdivisions.

TT	Formation	Em (MPa)
1	SO(1)	<25
2	SO(2)	25÷50
3	SO(3)	50÷100
4	SO(4)	>100
5	SB(1)	<80
6	SB(2)	80÷130
7	SB(3)	130÷200
8	SB(4)	>200
9	MC(1)	30÷100
10	MC(2)	100÷200
11	MC(3)	200÷350
12	MC(4)	>350

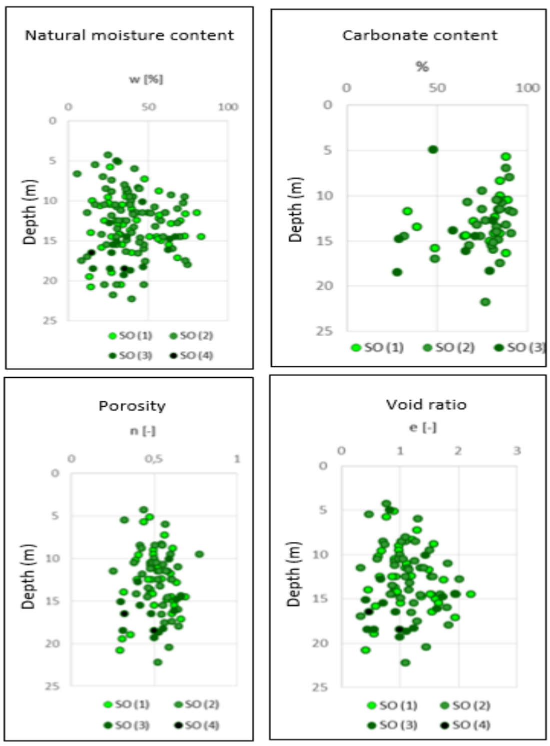

Figure 2. Results of lab tests for Marly limestone of Saint-Ouen (SO).

Figures 2÷5 present the results of identification tests for each formation and its subdivisions.

The Sands of Beauchamp are classified as coarse-grained (SM in the Unified soil Classification System) for 60% of the samples and fine-grained (ML) for 40%. Marly limestone of Saint-Ouen (SO) and deep Marls (MC) are classified as fissured soft to medium-hard calcareous rock.

Table 2 summarizes the hydraulic characteristics (permeability and anisotropy) issued mainly from large pumping tests.

Table 2. Hydraulic properties for each formation.

TT	Formation	Horizontal permeability Kh (m/s)	Anisotropy (Kh/Kv)
1	Marly limestone of Saint-Ouen (SO)	7.6E-05 to 1.0E-04	2.5
2	Fine/silty sands of Beauchamp (SB)	9.1E-05 to 1.4E-04	7.5
3	Marls (MC)	6.2E-05 to 1.0E-04	2.5

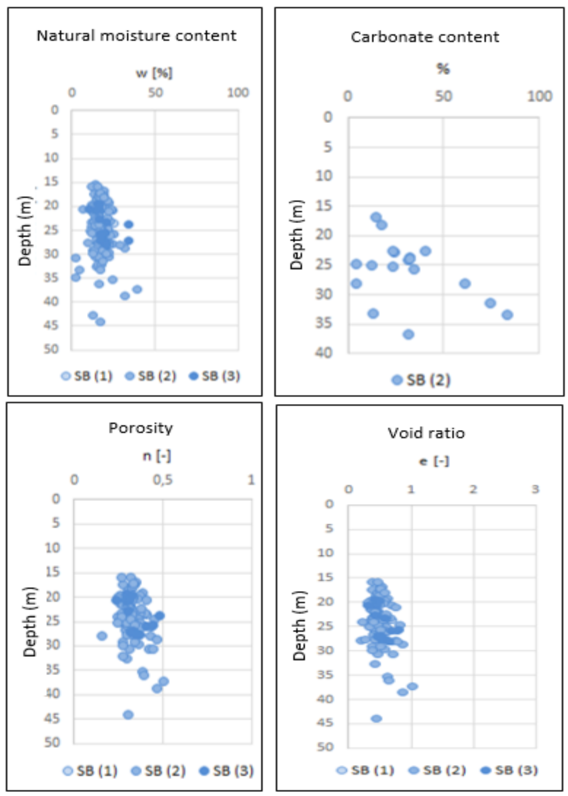

Figure 3. Results of lab tests for fine/silty sands of Beauchamp (SB).

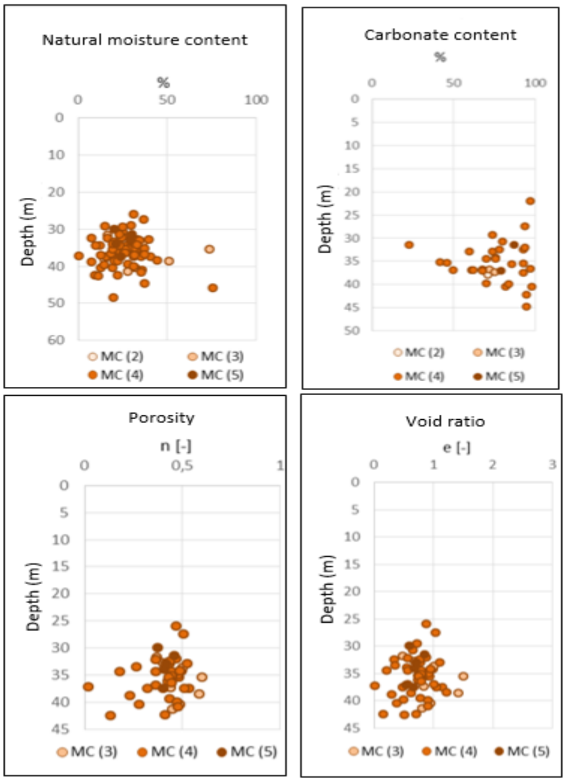

Figure 4. Results of lab tests for Marls (MC).

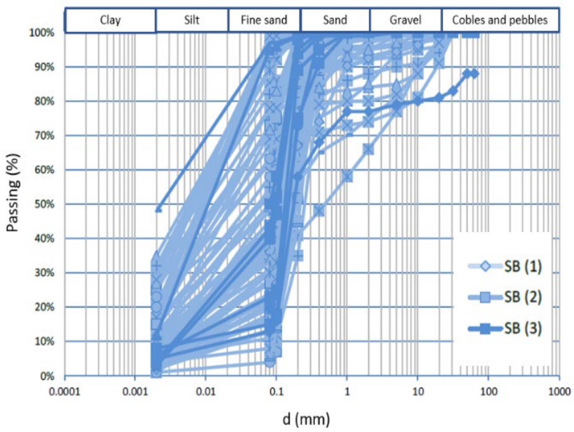

Figure 5. Granulometric data for fine/silty sands of Beauchamp.

3. Dimensions of ground improvement blocks and required permeability

In light of the current geotechnical profile, TBMs with earth pressure support were chosen. The TBM uses a confining pressure at the excavation face in order to prevent ground collapse and also to balance the hydrostatic water pressure.

In practice, at the arrival and departure sections, the pressures at the excavation face of TBM must be gradually reduced (arrival) or increased (departure) until zero at the level of the diaphragm wall. Therefore, in order to prevent groundwater inflow and also to limit surface settlement behind the diaphragm walls, ground improvement is necessary (Figure 6). The same improvement techniques were also selected for the areas around the connecting galleries which were excavated using the traditional method.

These blocks of improved ground can be carried out before or after the diaphragm wall. The dimensions of these blocks are:

- 15 m x 15 m x 15 m for the entrance and departure gates of TBMs,
- The dimensions of the connecting gallery increased by a thickness of 3 meters in all directions.

In order to avoid a significant groundwater inflow into excavation areas, the criteria adopted for the permeability of the improved ground was 5.E-07 m/s. This value was chosen following the results of the first in situ tests on the improved ground and based on a parametric study of the predicted leakage rates using numerical modelling.

4. Ground improvement types

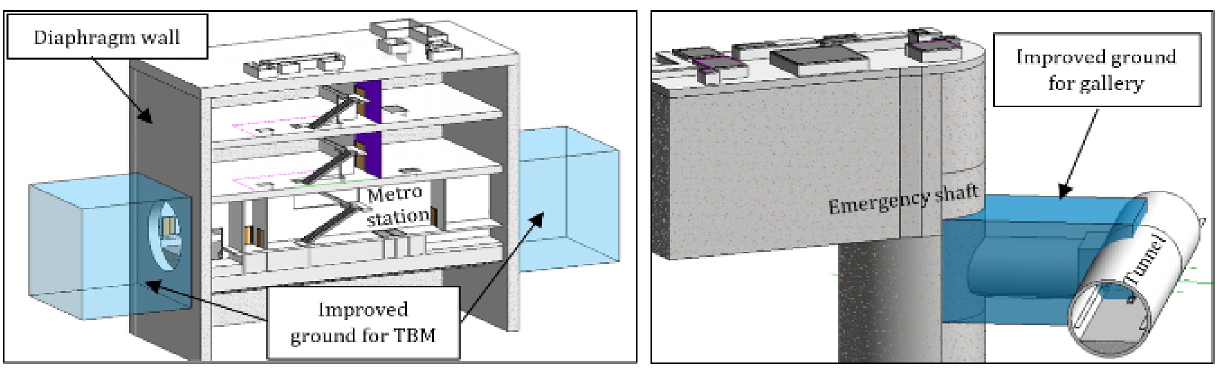

Figure 6. 3D view of the treated block.

Jet grouting in sands of Beauchamp and cement mixture injection in marly limestone/marls have been used [AFTES-GT8R2F1, 2006; AFTES-GT8R1F2, 1975].

4.1. Jet grouting

4.1.1. Principles

The columns are conducted by double fluid jet grouting technique where the grout is pumped at high pressure, surrounded by a concentric jet of compressed air. The main parameters of double jet grouting are following:

- Injection pressure of cement slurry, P (bars)
- Air pressure (bars)
- Flow rate of cement slurry, Q (litre/min)
- Rotation speed (round/min)
- Lifting time, t (cm/min).

These parameters allow to calculate the energy, E, for each meter long in the ground, as shown in the following:

$$E = P * Q * t \frac{1}{10000} \tag{1}$$

Soil concrete columns were conducted by drilling holes of 120÷220 mm in diameter and respected a hole deviation maximum of 0.5%. In order to get a minimum of 3 MPa for compressive strength after 28 days, the properties of cement slurry are following:

- Ratio of cement to water (C/W) : 0.5÷0.75
- Density : 1.4
- Viscosity : 30÷40 seconds
- Decantation during 1 hour : 10÷15%

The controls were carried out in two phases: an initial phase of diameter control on several isolated columns, and the second phase of more exhaustive controls described in the following paragraphs.

4.1.2. Initial phase

Four isolated columns have been injected in the first step of each site with a different energy. The energy was in the order of 60÷90 MJ/ml where the parameters of injection pressure, injection rate, lifting time are 400÷450 bars, 300÷350 bars, and 17÷22 cm/min respectively.

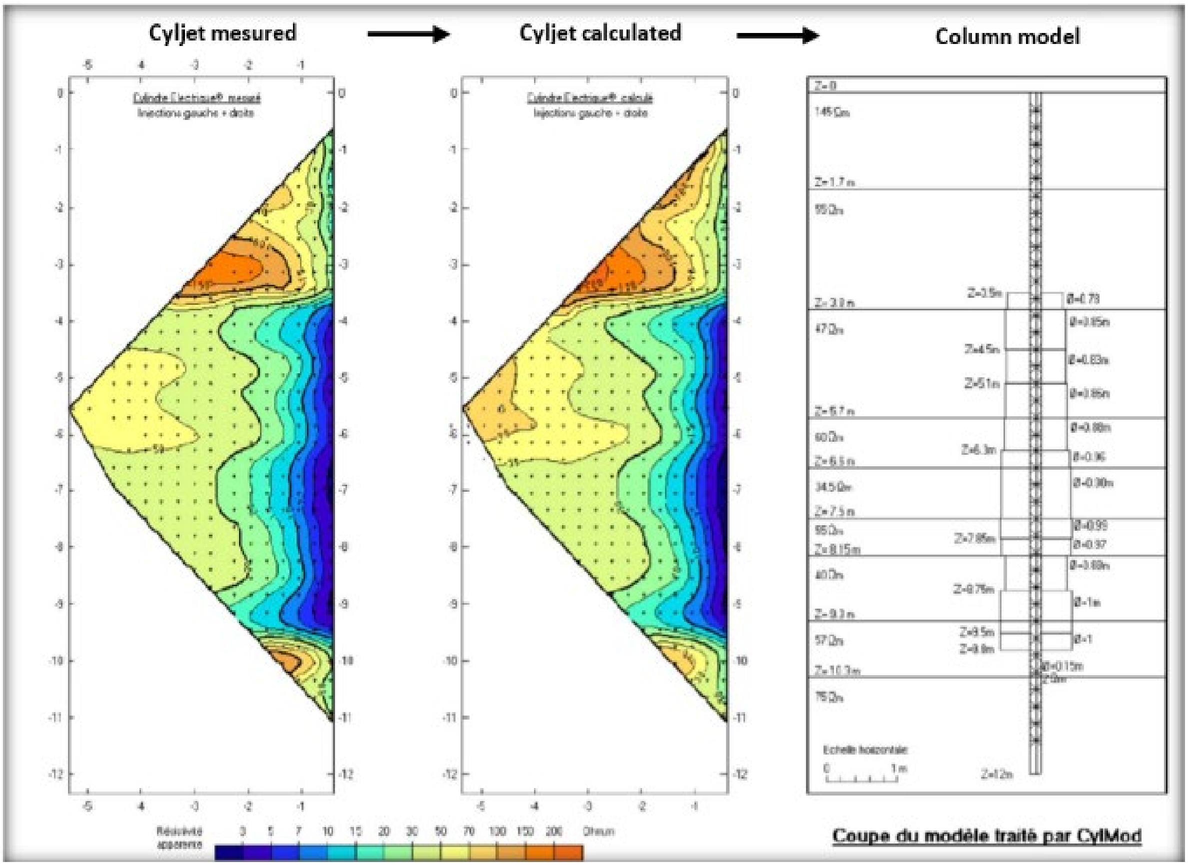

Figure 7. Column diameter measured by Cyljet method

The vertical deviation, diameter, and quality of the grout were checked.

The column diameter was controlled by the geophysical method so-called electrical cylinder method or Cyljet method (developed by the SIXENSE Engineering Company). The principle of the Cyljet method is to analysis the variations of electrical resistivity of fresh column (Figure 7). The energy level that allows reaching an average diameter of 1.5 m was chosen to fix the column spacing.

Coring was also performed in each column to assess the efficiency of the treatment.

4.1.3. Control during the production phase

A triangle mesh of 1.02÷1.14 m was selected. Five percent of columns have been controlled by coring and cyljet. Several permeability tests were performed in each coring.

Finally, the deviation records were used to create a 3D model to ensure that no untreated space remains within the treated block (Figure 8). If this was not the case, additional integrative columns were executed.

4.2. Cement mixture injection (TAM injection)

This technique was applied to the marly limestone of Saint-Ouen and more generally to the marls formations. Cement grout was injected under high pressure through sleeve pipes using double inflatable packers. The injection is carried out in successive phases; it is stopped at a given depth when stopping criteria in volume and pressure are reached. For each sequence of injection, the maximum volume of grout per sleeve pipe was scaled on ground porosity; the pressure was controlled by the type of sleeve pipe (Figure 9).

The following parameters were applied:

- Triangular mesh of boreholes: 1.75 m.
- Drilling hole diameter: 90÷114 mm.
- TAM pipe diameter: 40/48 mm.
- Injection flow rate: 10÷30 L/min.
- Injection pressure: 7÷20 bars.

The compositions of the grouts were chosen by experience and are widely used in the Paris area (Table 3):

Table 3. Slurry compositions.

Type	Water	Cement	Bentonite
Sleeve grout = slurry used to seal the tube into the ground	900 kg	300 kg	30 kg
Cement slurry	850 kg	350 kg	30 kg

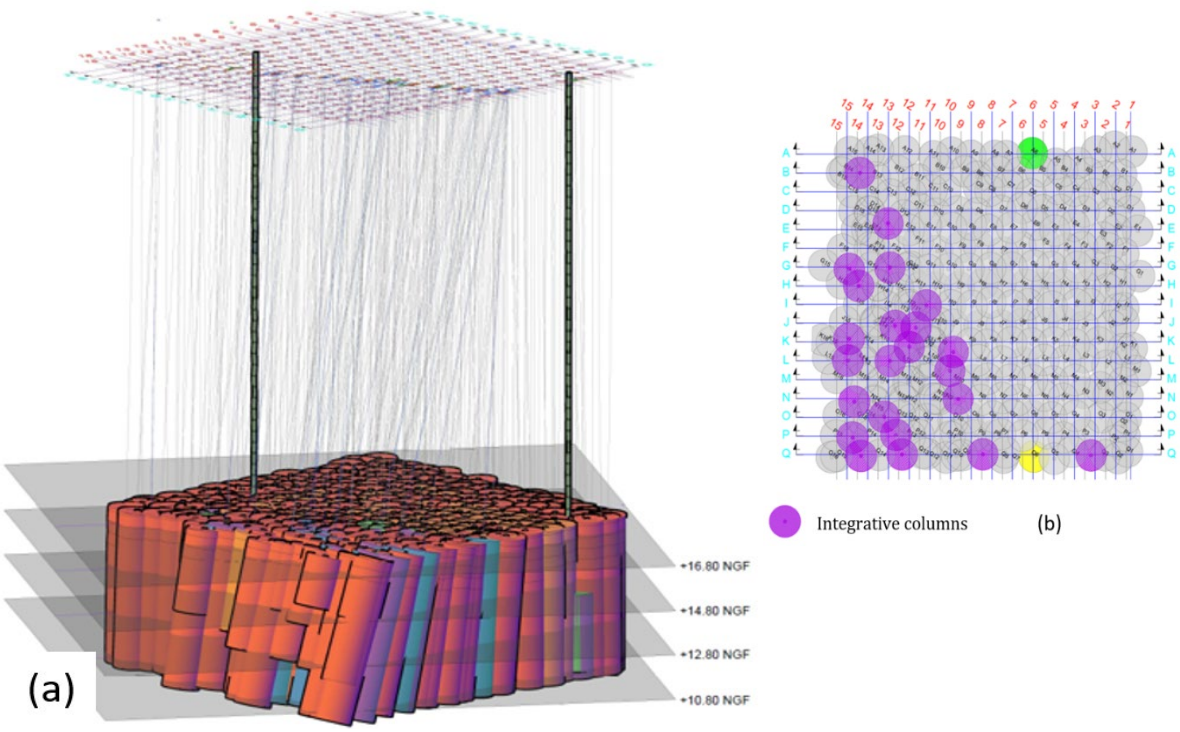

Figure 8. 3D model of the treated block (a) - view in 3D; (b) - plan view.

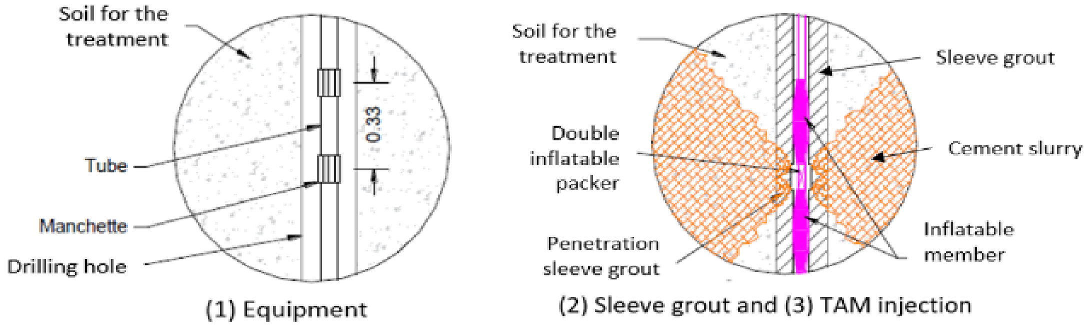

Figure 9. Detail of cement mixture injection (TAM).

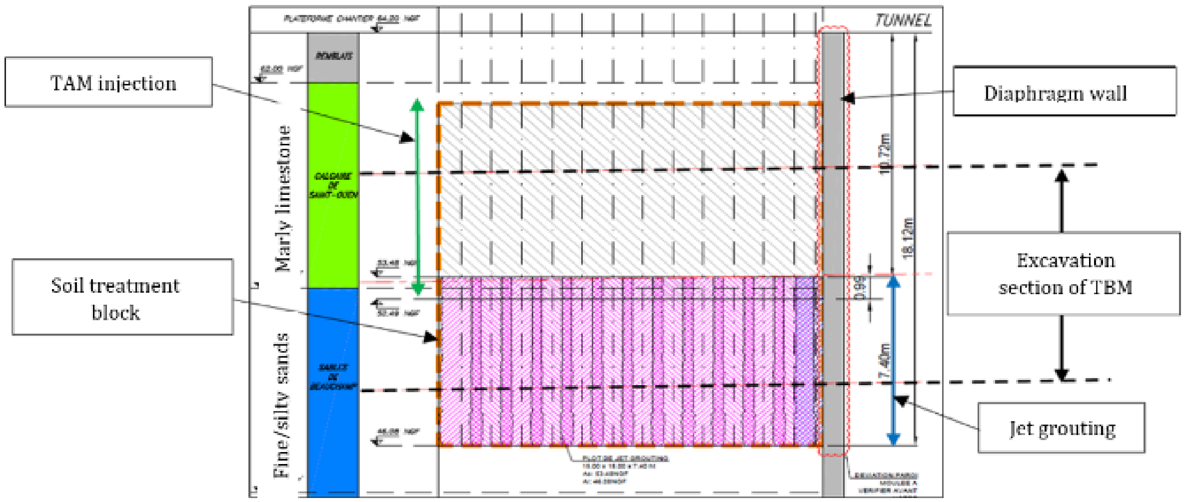

Figure 10. Longitudinal section of the treated block.

Finally, permeability tests were carried out over the full thickness of the treated block. The target that we met was 5.E-07 m/s.

4.3. Vertical cross section of the treated block

The blocks of improved ground are most of the time located at the interface between three different formations (Marly limestone of Saint-Ouen/Fine-silt sands of Beauchamp and Marls). Therefore, jet grouting and injection are performed together. An overlay of one metre between both types of treatment was used to ensure a safe transition at the interface between the two formations (Figure 10).

Ground improvement was generally performed after the diaphragm wall in order to make a good bonding between both parts. In some cases, because of particular scheduling, ground improvement took place before the diaphragm walls.

5. Additional control work after excavation

Once earthworks and concrete rafts have been completed in our stations and shafts, a final sequence of control and additional injections took place.

5.1. Horizontal controls

Additional horizontal controls were performed to confirm the quality of the treated blocks and particularly the bonding between these blocks and the diaphragm walls in the silty sands of Beauchamp (Figure 11). The number of destructive and core-drill boreholes were defined following different criteria:

- Working sequence (grouting before or after execution of diaphragm walls),
- Geometry of the civil engineering structures (circular versus rectangular shape),
- Local geological conditions (sandstone elements in the sands of Beauchamp),

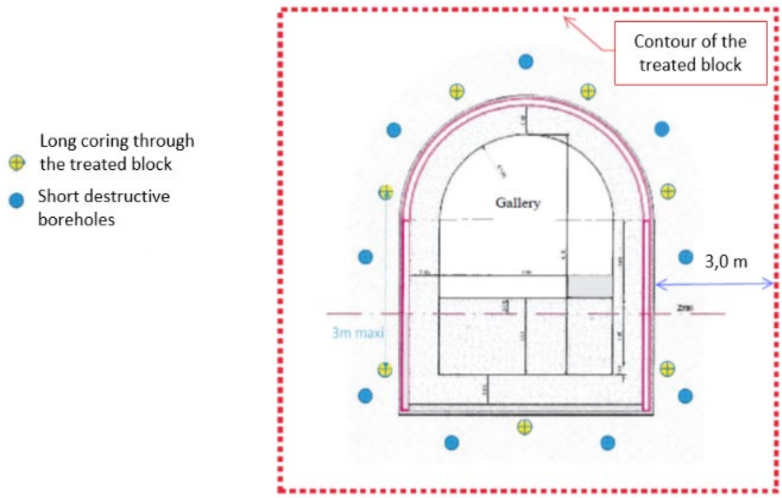

Figure 11. General guidelines for the location of horizontal controls.

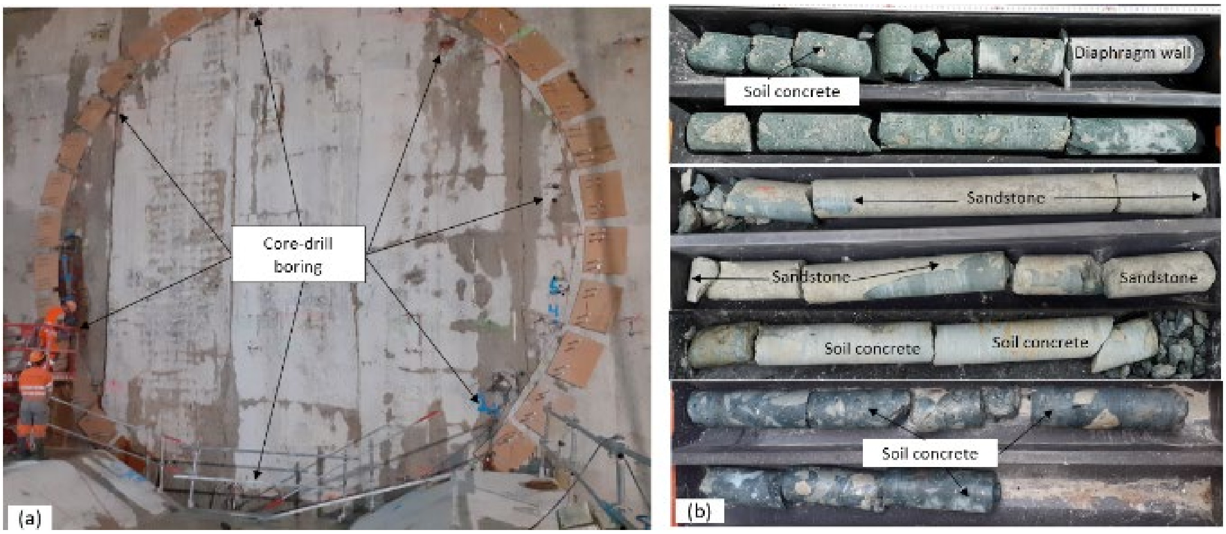

Figure 12. (a) final control before TBM arrival in a shaft; (b) horizontal core-drilling for a gallery.

- Geometry of the openings in the diaphragm wall,
- Geometry of the treated block,
- Results of the vertical controls.

The number and location of the additional boreholes were adjusted on a case-by-case basis:

Figure 12 illustrated this phase preceding gallery excavation and TBM start/arrival in the concrete structure.

5.2. Additional treatment

The treated blocks show an overall good quality; only one site required additional horizontal grouting because of the density and size of sandstone elements, which contributed to less efficiency of the jet grouting method.

With respect to bonding, supplementary grouting was systematized.

6. Exemple of an excavation for a connecting gallery

The feedback of the project showed that the ground strength was significantly improved (Compressive strength > 3 MPa). The horizontal boreholes showed also a low permeability that respects the conceptual requirements. Figure 13a showed an example of a heading face entirely in fine/silty sands of Beauchamp treated by jet grouting, represented by dark blue and light blue

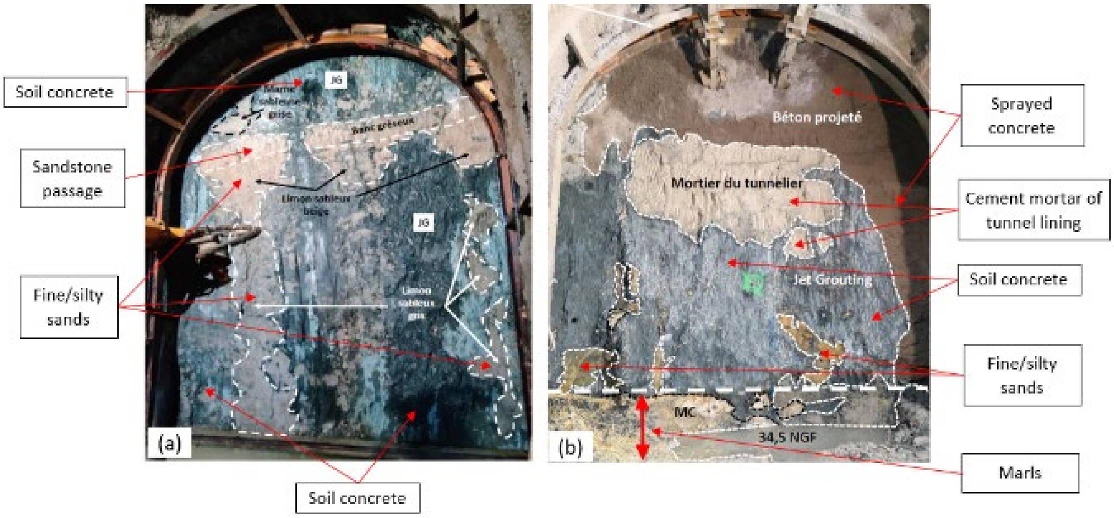

Figure 13. Gallery excavation works: (a) in fine/silty sands; (b) in fine/silty sands and marls.

colours. Grey sandstones near the top heading were clearly identified and no areas of poorly treated ground were observed. Figure 13b showed another example of a satisfactory work with a treated block including both Beauchamp sands in the upper part and marls in the lower part. Excavation works have been carried out with vertical heading faces in all cases simply using superficial protection by sprayed concrete [AFTES-GT24R1F1, 2008; AFTES-GT1R1A1, 2003].

7. Conclusions

Based on the results of tests in the improved ground, the requirements on permeability were respected. The permeability of sandy/marly formations was significantly reduced to 5E-07 m/s by injections or jet grouting.

Both technics of improvement have been associated on the same site and treated blocks can be executed before or after the diaphragm walls with successful results.

Author Contributions

Tri Van Nguyen - included data collection and analysis; Pascal Chalivat - included main idea and paper checker; Alexis Liance - included data collection and paper checker; Jonathan Chazelle - paper checker.

References

Harada, K., Ohbayashi, J., Matsumoto, J., Kubo, Y., & Akima, T. (2016). New ground improvement technologies under restricted conditions in Japan. *Japanese Geotechnical Society Special Publication*, *2*(32), 1165-1170.

Lavassar, C., Reeves, J., Gerondale, A., Blanding, M., Cowles, B., & Sally, J. (2015). Jet grout ground improvement for tunnel launch and retrieval lect. Rapid Excavation and ocations on sound transit’s northgate link extension proj. *Tunneling Conference 2015 proceedings*, 718-726.

Njock, P. G. A., Chen, J., Modoni, G., Arulrajah, A., & Kim, Y. H. (2018). A review of jet grouting practice and development. *Arabian Journal of Geosciences, 11,* 459.

Recommendations of AFTES (French Tunneling Association) - GT8R2F1. (2006). *La conception et la réalisation des travaux d’injection des sols et des roches*.

Recommendations de l’AFTES - GT8R1F2. (1975). *Travaux d’injection pour les ouvrages souterrains*.

Recommendations de l’AFTES - GT24R1F1. (2008). *Les reconnaissances à l’avancement.*

Recommendations of AFTES (French Tunneling Association) - GT1R1A1. (2003). *Characterization of rock mass useful for the design and the construction of underground structures*.