Excavation of the Evouettes Tunnel – Lessons Learned from a jet grouting soil stabilisation support method

G. Questi[1], S. Minon[1], E. Garin[1], C. Carron[2], S. Lonfat[3] and V. Pellissier[3]

[1]*BG Ingénieurs Conseils SA, Lausanne, Switzerland*
[2]*PRA Ingénieurs Conseils SA, Sion, Switzerland*
[3]*Canton Wallis Department for Mobility, Sion, Switzerland*

E-mail: giorgia.questi@bg-21.com

ABSTRACT: The Evouettes Tunnel is a bidirectional, single-tube, 657 m long road tunnel under construction in Wallis, Switzerland. The encountered ground conditions, comprising loose material, makes the implementation of a classical pipe umbrella stabilization method very difficult. The decision was taken to design and specify a sub horizontal jet-grouting umbrella, which allows for full-face excavation, thanks to the presence of 45 jet columns around the excavation perimeter and 13 in the face itself. This advance stabilization method requires a big investment in terms of time and costs, and continuous adjustment of the injection parameters.
The jet-grouting technique remains unusual for sub horizontal tunnel support. This is why the lessons learned from such a project have to be shared among the tunnelling community and are necessary to establish a design methodology in terms of injection parameters, with the aim to optimize the obtained results and to mitigate the potential drawbacks.

KEYWORDS: Tunnelling, jet-grouting, loose material, monitoring.

1. INTRODUCTION

The Evouettes tunnel is a bidirectional single tube road tunnel under construction in Switzerland, close to the border with France. It is part of the main road project linking St. Gingolph to the motorway entrance at Villeneuve (see Figure 1).

The main interest of creating this connection underground is to bypass the village of Les Evouettes, which currently suffers from heavy traffic at peak times.

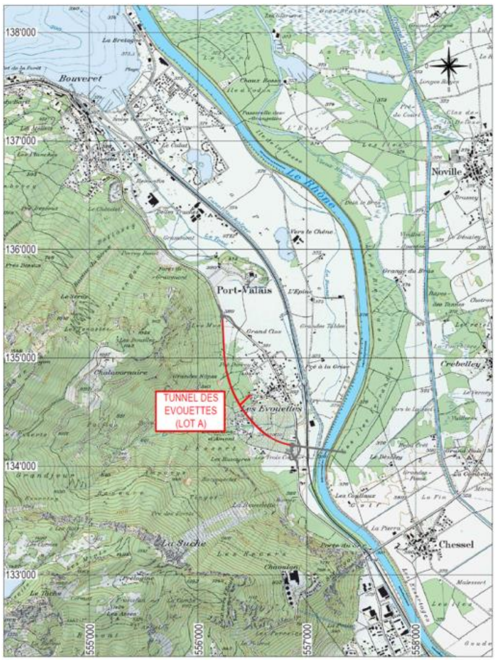

Figure 1. Project location

2. PROJECT DESCRIPTION

The project represents 1.4km of roadway: 635m in the open, 100m in cut-and-cover and 657m in tunnel, as shown in Figure 2.

The tunnel axis is a curve with a radius of 1000m. The longitudinal profile, from north to south, is initially rising with a slope of 5%, then falling with a slope of 2.5%. The inner gauge is constant, with two 3.75m traffic lanes. The radius of the tunnel lining is 5.30 m.

The structure includes a 150 m long pedestrian gallery as an emergency exit.

Two thirds of the tunnel are located below a forest area and the remaining third below vineyards. The passage under the village of Les Evouettes d'Amont, which is made up of individual houses, is about 150 m long.

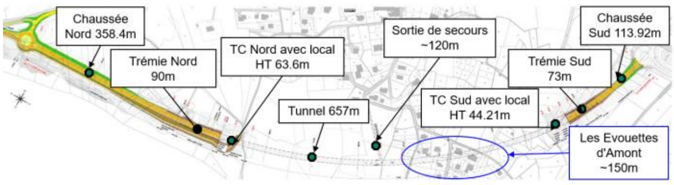

Figure 2. Parts of the project

3. GROUND CONDITIONS

The Evouettes hill is entirely composed of loose soil: local moraine, torrential alluvium (alluvial cone) and scree at the beginning and end of the structure. The longitudinal profile is shown in Figure 3.

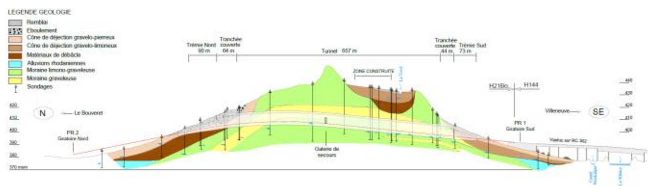

Figure 3. geological longitudinal profile

The main characteristic of these formations is the presence of blocks of the same lithology: limestone, dolomite and schist from the Grammont. Despite the matrix, which can be more or less silty, the large quantity of blocks, which can vary from a decimetre to several metres in size, makes these soils poorly cohesive and loose in places.

The Evouettes tunnel is situated just above a water table which varies greatly according to rainfall. Perched water tables, fed by the flooding of the river during rainfall, have also been observed in the boreholes.

4. TECHNICAL CHALLENGES

The poor cohesion of the existing ground is a technical challenge for the construction of the tunnel. When designing the stabilisation of the surrounding soil, the main priority was the safety of the workers during excavation. For this reason, a conventional advance support consisting of a pipe umbrella was considered unsuitable. Indeed, the spacing between tubes generated a potential for collapse of the non-cohesive formations between the tubes. A jet grouting crown on the other hand ensures the continuity of the advance support.

In order to improve the overall cohesion of the face, jet-grouting columns were also prescribed to facilitate site logistics.

The use of the jet-grouting technique also makes it possible to manage the problem of settlement, thanks to the rigidity provided to the excavation perimeter and the face.

The presence of large boulders is a risk during excavation, especially if they straddle the excavation perimeter. The presence of a boulder can cause an interruption of the jet column. Furthermore, the presence of these blocks represents a significant factor in the assessment of geotechnical characteristics by in situ and laboratory tests. The representativeness of the tests carried out is influenced by the size effect as well as by the strong heterogeneity of the massif, both at the scale of the specimens and of the in-situ test tools (pressuremeter, plate load tests).

It should be mentioned that the jetting vault also constitutes an effective screen against the infiltration of water and liquefied materials, thus blocking the development of voids in non-cohesive sandy-gravelly materials.

For these reasons, the final choice for the project was a jet-grouting advance reinforcement, despite the fact that it is a more expensive solution which is technically very dependent on local ground conditions.

5. TUNNEL

The geometric and geological constraints of the site led to the tunnel being constructed by conventional excavation in a single attack from the north.

The same standard profile (Figure 4) is applied throughout the tunnel. The excavation section is 105 m^2 at the beginning of the stage and 135 m^2 at the end of the stage, each excavation stage being 9 m long.

The advance reinforcement jetting consists of 45 crown columns and 13 face columns of 12 m length, with diameter of 80 cm and overlap of 3 m at each stage (see Figure 5).

The support is composed of heavy invert struts and reticulated arch struts, with polypropylene fibres reinforced shotcrete. The spacing of the arches is 1 m. Immediate safety is ensured by a 5 cm layer of fibre-reinforced shotcrete on the periphery of the excavation and at the face. At the beginning of each stage, the thickness of this layer at the face is increased to 10 cm in order to withstand the stresses induced by the jetting on the one hand, but also to ensure stability over a longer period.

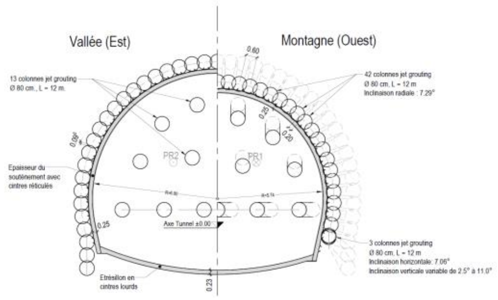

Figure 4. standard profile

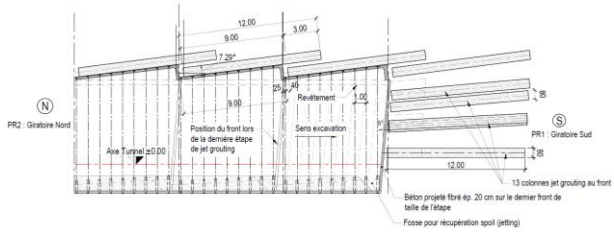

Figure 5. excavation advancement at the tunnel axis

6. CALCULATION METHOD

The design of advance reinforcement, the support and the final lining was carried out with the help of 2D and 3D finite element models. This type of model not only allows careful modelling of the soil-structure interaction, but also takes into account the successive phases of construction and the analysis of the reaction of the face.

On the basis of soil mechanics tests carried out in situ and in the laboratory, an HSS constitutive law was calibrated to represent the behaviour of the surrounding soil. These parameters are recalibrated throughout the construction of the tunnel, according to the observations made on the deformations. In the basic models and for the gravelly moraine, cohesion of 1kPa and friction angle of 34° were used.

It was essential to develop a three-dimensional model, not only for the design of the column cover length according to the extent of the plastic zone in front of the face, but also to reliably estimate the deconfinement rate of the excavation section (Figure 6).

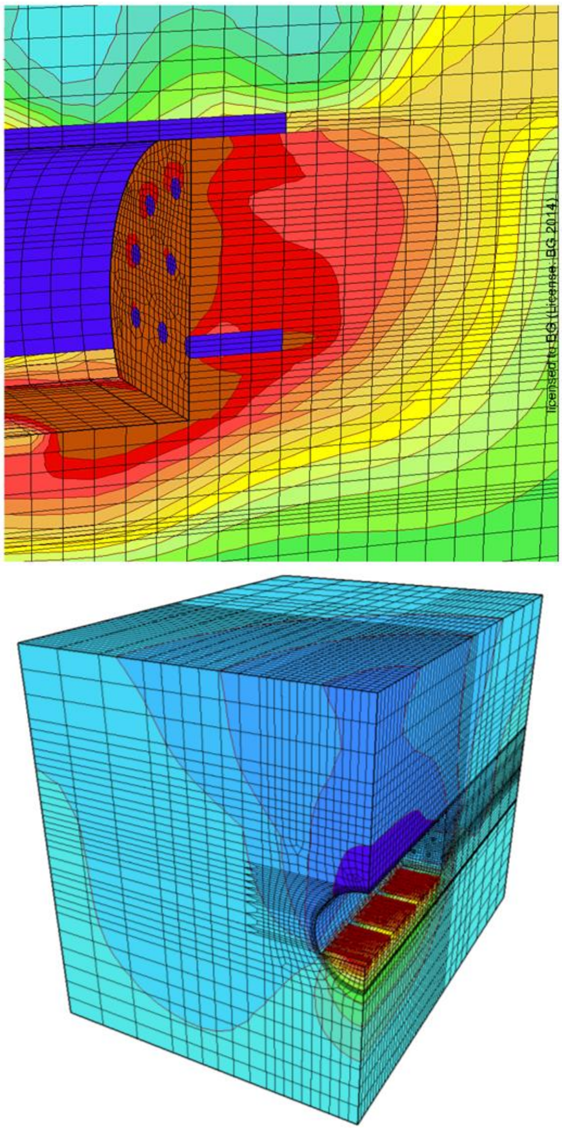

Figure 6. Extent of the plastic zone shown in red in front of the face (top) and deformations (bottom) with a maximum surface settlement of about 3.5cm

Indeed, the calculation of the deconfinement rate allows the elaboration of 2D models, in which the mesh can be refined without increasing the calculation time disproportionately. A fine mesh allows for a quality result in terms of forces and deformations in structural elements, such as supports and lining.

7. EXECUTION

7.1 Portals

The excavations in the portal areas were carried out using king post walls and secant pile walls for the deepest parts. At the North portal, the tunnel attack is made under a very low cover of about 5 m through a vertical jetting block which ensures the stability of the spandrel.

7.2 Tunnel

For the construction of the tunnel, the machine used for horizontal jet grouting is equipped with an arm, a gondola and a tool for recording drilling and injection parameters in real time (Figure 7). Progress is divided into one week of jet grouting and one week of excavation, for an overall rate of one metre per day. It took about four stages of advancement to reach this cruising rate, as planned by the designer.

Due to the nature of the surrounding soil, excavation is carried out using a mechanical shovel. The excavator used on this site is large (40 tonnes), given the large excavation section. The tunnel is excavated in full section.

Figure 7. jet-grouting operation

7.3 Jet-grouting

Jet grouting requires several specific installations.

All grout production is carried out on site to ensure high production flexibility. The estimated consumption of grout at the beginning of the project was 500 kg per cubic metre of column. Due to the high permeability of the soil encountered and to the problems of resurgence, the actual average consumption is approximately 700 kg per cubic metre of theoretical column.

The spoil is treated in a sludge filter press, which separates the water from the suspension and allows it to be discharged into the clear water network after pH correction. The dewatered sludge is deposited in a final repository. A picture of this installation is shown in Figure 8.

Figure 8. construction of the sludge filter press

During the execution of the project, the main problems encountered were:

- Obtaining columns of the right diameter and shape;
- Obtaining sufficient strength for the columns;
- The splitting of the shotcrete supporting the face;
- Grout resurgence on the surface
- Ground splitting;
- Over-consumption of grout;
- Grouting-induced settlements.

The chosen injection pressure is 450 bar. This pressure is only one of the many parameters that can be adjusted during the jetting process. The main parameters affecting the result of the grouting work are the rheology of the grout, the size of the grouting nozzles and the speed at which the drill string is raised. These parameters can be calculated according to the ground conditions and the desired result, but they need to be adjusted according to the observations made during the execution.

Empirically, the size of the column is proportional to the energy supplied to the ground during injection, which is evaluated with the following relationship:

$$En_s = \eta_{ug} \frac{\left(\frac{2 \cdot g \cdot P}{\gamma_1}\right)^{\frac{3}{2}} \cdot s \cdot \gamma_1}{2 \cdot g \cdot v_e} = \left[\frac{J}{m}\right] \quad (1)$$
:

Where :

En_s	Specific energy supplied to the ground
η_{ug}	Nozzle efficiency (function of the head loss)
g	Acceleration due to gravity
P	Injection pressure
γ_1	Specific weight of the grout
s	Cumulated nozzle section
v_e	Exit velocity

As the priority was to obtain columns with a consistent diameter, i.e. 80 cm, the first adjustment of the parameters was determined for this purpose. Empirically, the size of the columns is directly related to the energy supplied to the ground. The most direct way to access the result of the calibration of these parameters is to observe the columns of the face, as shown in Figure 9.

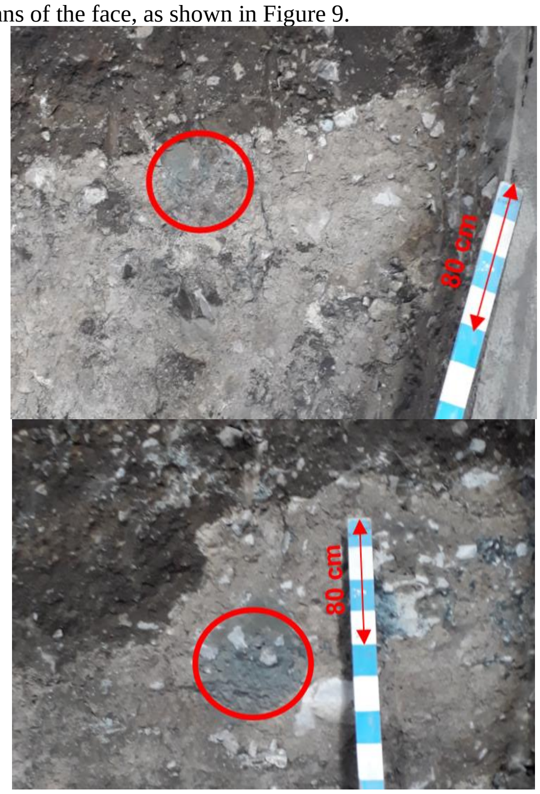

Figure 9. Observation of the face columns (small diameter on the top, good diameter on the bottom)

In a second step, cores were taken from the crown, which also allowed compression tests to be carried out to obtain the strength as a function of age (Figure 10).

Figure 10. core samples from the crown

<u>Splitting of shotcrete from the face</u>

Splitting of the shotcrete at the face was observed. This was due to the weakening of the shotcrete wall by the drilling and to pressure build-up as a result of the infiltration of spoil between the ground and the wall. They therefore occurred towards the end of the injection of the columns, when the grout under high pressure was approaching the face. An example is shown in Figure 11.

Although the detachment of shotcrete slabs did not constitute a safety risk (due to the absence of personnel under the face during jetting and a non-fragile breaking mechanism due to the presence of the fibres), it delayed the progress of the construction site as it was necessary to re-apply a layer of shotcrete in the area and wait for it to set before restarting the jetting.

Figure 11. Splitting of shotcrete from the face

Several solutions were studied and tested on site to solve this problem. The combination chosen was as follows: shifting the front columns by 3 m, i.e. increasing the drilled length of the columns to 15 m instead of the 12 m initially planned, stopping the injection 3 m before the front, and increasing the thickness of the fibre-reinforced shotcrete by 10 to 20 cm. The objective here is to maintain a 3 m overlap of the columns at the face between two stages (see diagram in Figure 12).

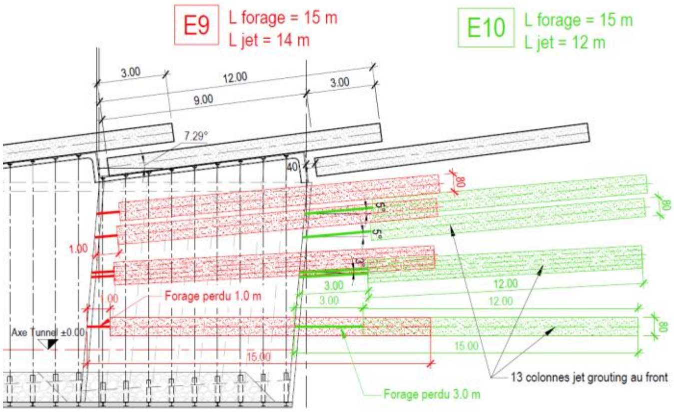

Figure 12. Adapting the position of the columns

<u>Grout resurgence on the surface</u>

An issue encountered in the jetting technique is the occurrence of grout resurgence on the surface.

Although the occurrence of these seepages has no negative influence on the stability of the excavation, it can be a major problem when they occur in a built or environmentally sensitive environment, such as a forest. Seepage of grout into pipes and networks as well as into buildings can cause significant nuisance and consequent restoration work. In addition, seepage is inevitably associated with significant additional consumption of grout and therefore additional costs for the construction site.

Figure 13. excavation face

During the construction of the first few metres of the tunnel, resurgences occurred with a relatively high frequency. According to the observations, these resurgences were mainly due to ground splitting combined with the low cover and the presence of a relatively deep forest fringe (2 to 3 m) with a large root network. These two phenomena create preferential channels for the grout to rise to the surface.

Given the random and strictly dependent nature of the formation conditions of the overburden, the control of resurgence remains difficult, all the more so as the setting of injection parameters is blocked in order to achieve the objectives in terms of shape, diameter and strength of the columns produced. Thanks to the increased cover and the less permeable nature of the surface soil, the resurgence phenomena disappeared after 190 m.

In May 2021, the state of progress was approximately 370 m, with a decreasing cover from 40 to 25 m, consisting of a silty-gravelly moraine on the surface and a gravelly moraine at greater depth. The face reaches the critical moment of the construction site, the passage under the village of Evouettes d'Amont. At this point, the moraine, of decreasing thickness up to 4 m, is covered by formations composed of debris flow materials at a depth of 11 m (natural accumulation of materials brought by water during floods and debris flows, or by landslides), which overlies a gravelly-silty alluvial cone at a depth of 9 m.

7.4 Monitoring of settlements and deformations

Monitoring of surface settlements and systematic measurements of the tunnel convergences are carried out throughout the construction period. This is of paramount importance for analysing the full-scale behaviour of the surrounding rock.

The surface levelling measurements are made in measuring sections 30 m long at the tunnel axis. Their measurement makes it possible to establish a settlement basin and to follow its evolution as the excavation progresses. The most delicate point consists of passing under the village of Les Evouettes d'Amont. There are currently 6 measurement sections set up before reaching the village. After the initial measurement, measurements are made for each stage of excavation before passing under the relevant section. After the passage of the section, the measurements continue until the deformations have stabilised (which occurs without delay according to current observations).

In the first measurement section, located about 70 m from the north portal in the forest, in scree and with very little cover, the maximum settlement measured at the tunnel axis was 13 cm. The 3D models developed during the study phases predicted a settlement of about 15 mm spread over a slightly wider trough than observed. A comparison of the theoretical and actual troughs is shown in Figure 14.

Following the in-situ observations, the parameters of the HSS behaviour law of the 3D model were recalibrated in order to obtain the real pit and to adapt the predictions for the continuation of the tunnel.

At Les Evouettes d'Amont, with the local geological and cover conditions, the models showed a maximum settlement at the tunnel axis of 3.5 cm spread over 70 m on either side.

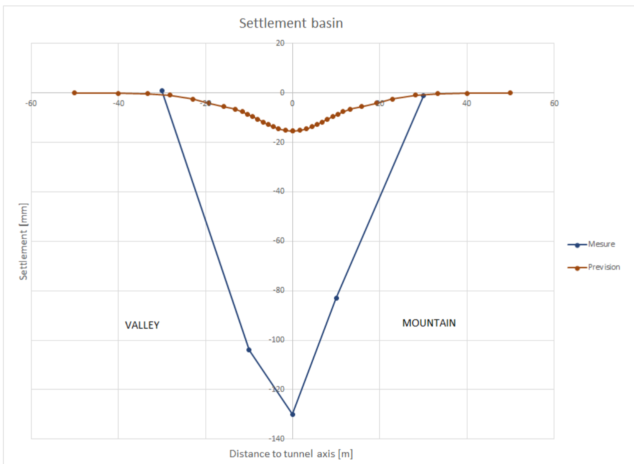

Figure 14. settlement basin

With the increasing cover thickness, the observed settlements present a decreasing tendency, up to 4 cm at the maximal overburden. As those values remained significantly higher than predicted by the computations, careful monitoring of the topographical survey revealed the unexpected fact that most of the deformation occurred during the jet-grouting phase.

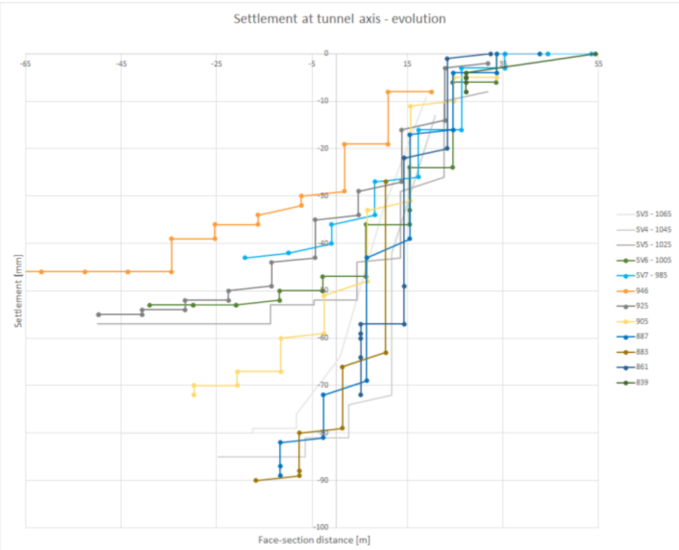

Figure 15. axis settlement considering face-section distance

As shown on figure 15, settlement begins about 25 m behind the face during n-2 jet-grouting phase. Only 10% of the total settlement occurs during the excavation phases, for a value of about 1 cm. Measurements made on a vertical extensometer installed in a borehole near the tunnel showed that most of the settlement occurred within about 5 m around the vault.

Such peculiar ground behaviour following jet-grouting operation had never been observed and is especially unexpected in consolidated coarse material. It could be caused by the dynamic compaction of the coarse soil with discontinuous granulometric distribution and high vacuum index, by the drilling and high-pressure injection activity. Voids could also be generated around the jet-grouting columns by the backflow of the grout during the drilling rods removing before closing the hole.

In order to understand the mechanism behind the settlements, the convergences of the tunnel section as well as their absolute position are also measured. The data collected showed only convergences and displacements in tunnel of millimetre order. The hypothesis that the surface settlements are mainly due to a face phenomenon can therefore be formulated.

Settlements started to increase as the face approached the village, in line with the decreasing overburden, up to 9 cm. As such values are not bearable without damage by the village houses, tests for effectiveness of potential countermeasures are currently being tested.

Variations in the jet-grouting process are evaluated, relating to the density of the grout, injection pressure, rods rotation and withdrawal speed, columns schedule layout, grout loss control during removing the rods using pinch valves.

If all those countermeasures prove ineffective, a stage of tunnelling using pipe-umbrella forepoling as auxiliary support measure could be implemented. Considering the very low cohesion of the moraine, 95 pipes should be drilled along the profile with average spacing of 25 cm in crown.

Implementation and evaluation of those countermeasures are ongoing at the time of writing this paper. Results and conclusions will be presented during the Congress.

8. CONCLUSION

Taking into account the feedback from the Evouettes tunnel, it appears that the horizontal jet grouting technique is very effective for the advance stabilisation of tunnels that are excavated in loose soil with little or no cohesion.

It allows safe driving even in the case of full-section excavation.

However, it is a complex working method, dependent on site conditions, which requires specialised and experienced design and construction staff. Experience is essential because of the high variability of the result depending on the progress of the tunnel. The application of the observational method is therefore necessary to obtain the required quality. For this reason, it is important to collect as much information as possible in order to build up good feedback for future projects.

An unknown phenomenon was observed implementing this method at the Evouettes tunnel. Jet-grouting induced settlement was found, leading to surface deformations far greater than planned. Dynamic compaction of coarse soil as collateral effect of this process, which has never been recorded before, deserves further investigations to understand its geomechanical origin so as better predict and prevent undesirable settlements.

The civil engineering contract is worth CHF 63 million (approximately 58 million €), including CHF 36 million for the tunnel (i.e. CHF 55 000 per linear metre of tunnel).

9. REFERENCES

Giuseppe e Giovanni Como (2005) Jet grouting: ceni teorici, campi d'applicazione e impiego quale opera di sostegno, pp.14-15

Zace (2018) ZSoil user manual: https://www.zsoil.com/v2018/