GRAND PARIS EXPRESS METRO PROJECT – LINE 15 – GEOPHYSICAL INVESTIGATIONS OF TWO EXISTING STRUCTURES IN INTERACTION WITH THE TUNNEL UNDER THE SEINE RIVER

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ABSTRACT:

The western section of the line 15 of Grand Paris Express is located at the South of Paris between the future stations Pont de Sèvres and Villejuif Louis Aragon. The project consists of 12km of tunnel excavated using three Tunnel Boring Machines and includes three crossings under the Seine River.

This paper presents the investigations carried out to locate the remains of two existing structures potentially in interaction with the tunnel under the river:

- A wastewater network abandoned in 1983 because of sudden water inlets that occurred during the boring. The sewer is situated at the depth of the tunnel but the collapsing position is unknown;
- The foundations of the provisional "Pont de Sèvres" bridge built in the 1950s. Originally founded on wooden piles, it was strengthened several years later by steel piles maybe driven at the tunnel depth.

The main risk is blocking the TBM cutting head which would require long and unsafe human interventions. The aim of the investigations is to identify the real obstacles in order to define preventive measures for removing this risk.

The geophysical surveys were conducted from vertical boreholes drilled from a barge in the Seine. Using electric and magnetic methods, sensitive to conductive and ferromagnetic elements respectively, metallic elements in the area of the boreholes were detected and positioned. Radar waves were used to image and confirm the presence of structures.

The use of these complementary methods enabled structural remnants that were present on the path of the TBM to be characterized and positioned. This study was a means of assisting decision making in relation to risk management associated with the presence of such obstructions.

INTRODUCTION

The Grand Paris Express project (GPE) consists of a vast programme of public transport development around the French capital. It includes the creation by 2030 of 200 km of driverless automatic metro lines and 68 new stations which will connect the major demographic and economic nodes of the Parisian urban area. Every day, 2 million of passengers will use the new GPE network.

The main objective of the project is to improve and modernise the transport abilities to answer the large rise of traffic expected in the next decades. The new metro will reduce the travel time between suburbs and relieve the current network by creating peripheral lines around Paris, like the line 15.

In this kind of urban project, the interaction with existing structures represents a crucial aspect of the tunnel design and the risk management. To estimate the consequences of this interaction, it is essential to have a maximum of information about the structures.

This paper deals with the investigations, mainly geophysical measures, implemented to locate and characterize two no longer used structures situated under the Seine river and potentially in the tunnel section of the line 15-south. The aim is to know if they represent real obstacles for the TBM progress.

1. THE LINE 15-SOUTH: A PART OF THE NEW GRAND PARIS EXPRESS NETWORK

1.1. DESCRIPTION OF THE PROJECT

The line 15-south is situated in a very dense urban environment close to Paris. It corresponds to an underground section of 33km that will be the first part of GPE to be put in service (Figure 1).

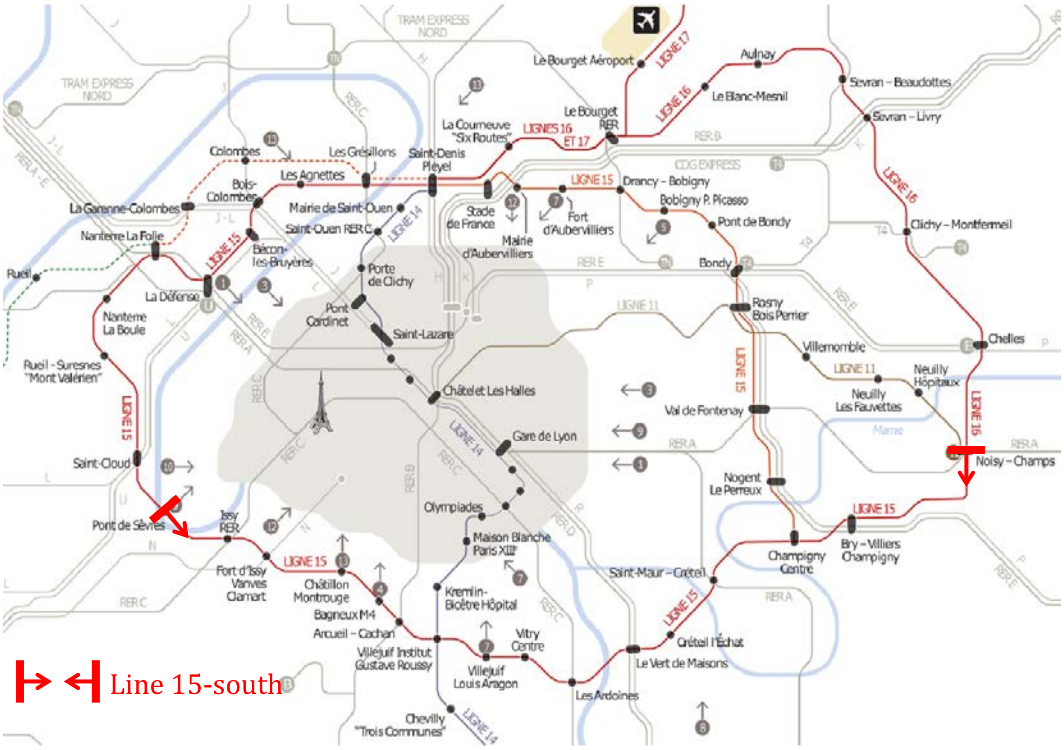

Figure 1: Map of the new GPE network

The consortium Setec/Ingérop was selected by the Société du Grand Paris (project owner) to supervise the civil engineering works of the portion located between the future stations "Pont de Sèvres" and "Villejuif Louis Aragon". Ingérop was particularly involved in the preliminary and detailed design of the western part that includes:

- 4km of a 9,8m external diameter tunnel dug with a TBM. This section concerns essentially the Seine valley and presents three crossings under the river;
- the "Issy RER" and "Pont de Sèvres" stations;
- the entry shaft of the TBM;
- 3 ventilation and emergency shafts and their junctions to the main tunnel.

Géos carried out the geological analysis and the geotechnical conception on behalf of Ingérop. The mission covered the studies of the interaction with existing structures too.

1.2. GEOLOGICAL CONTEXT OF THE PROJECT

The geology of the GPE is typical of the Parisian Basin. This area is characterised by a horizontal piling of sediments that was preserved since the basin formation thanks to a weak tectonic activity.

In the Seine valley (western part of the line 15-south), the Senonian chalk emerges under a thin alluvial layer (Figure 2). This stratigraphic particularity is due to the erosion of the Meudon anticline which presents an axis near to the route of the line 15.

The alteration profile of the chalk varies along the project. It is mainly developed on the right bank of the river where the thickness of the degraded layer is superior to 20 m. The analysis of the available surveys leads to distinguish three states of alteration:

- disintegrated and soft chalk, named Ca1;
- intermediate level less soft but very fractured, called Ca2;
- hard and compact chalk, named Cs.

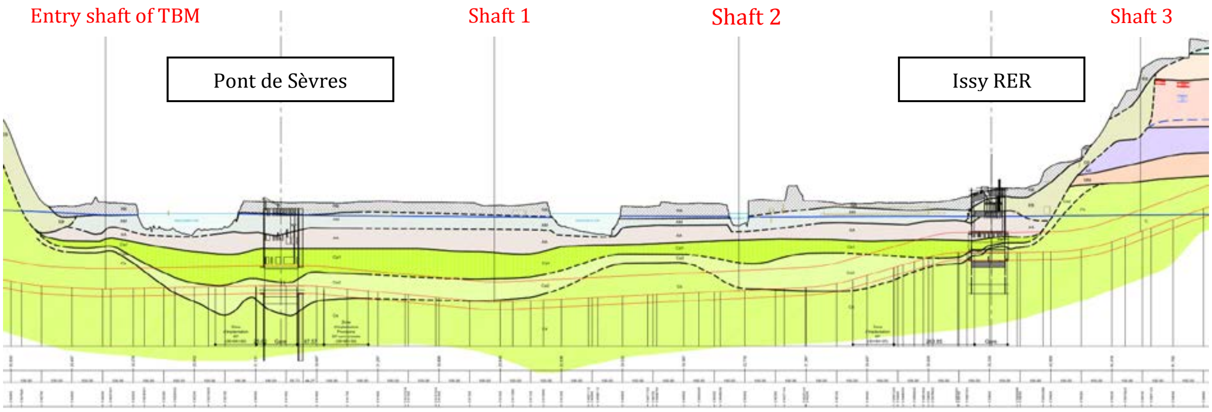

Figure 2: Geological profile of the « Seine Valley » part of the line 15-South

2. PRESENTATION OF THE STRUCTURES IN INTERACTION WITH THE TUNNEL UNDER THE SEINE

Two structures, no longer used today, are located under the Seine bed between the entry shaft of the TBM and the Pont de Sèvres station:

- an abandoned wastewater network of SEVESC company;
- a group of steel piles of the provisional Pont de Sèvres bridge built in the 1950s.

Géos realized the documentary investigation concerning these structures.

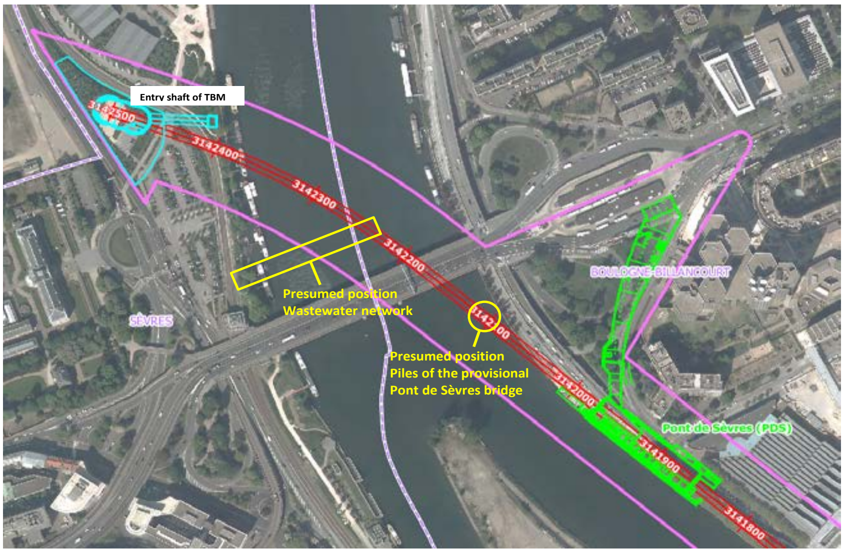

Figure 3: Localization of the remains of the two structures situated under the Seine bed

2.1. SEVESC WASTEWATER SEWER

Close to the Pont de Sèvres bridge, a wastewater network controlled by the SEVESC company (Société des Eaux de Saint Cloud et de Versailles) crosses the Seine by a siphon system. The sewer has a diameter of 1,6m and joins two wells placed on each side of the river. It is situated around 10 m under the line 15-south, so it is not impacted by the GPE project.

Nevertheless, the network owner (general council of the Hauts-de-Seine territory) informed us about the existence of another gallery located at the same depth of the GPE tunnel. Like the actual pipe, it was built through the chalk layer. However, sudden water inlets happened while its boring, approximately in the middle of the Seine crossing. The sewer was immediately evacuated.

Additional investigations were realized after the damage. They revealed that the collapse occurred because of the unfavorable evolution of the alteration profile of chalk from the left bank to the right bank of the Seine.

It was then decided to let the first gallery and to build another one 10 m lower in the hard chalk layer and from the same wells (bored more deeply to reach the desired depth). So, the old pipe should follow the axis of the actual network, but the exact position of the collapse is unknown.

Moreover, according to archive files, the retaining structure of the first sewer is composed of a wooden screen associated with steel ribs (Figure 4). The presence of these metallic elements represents a real risk for the TBM functioning.

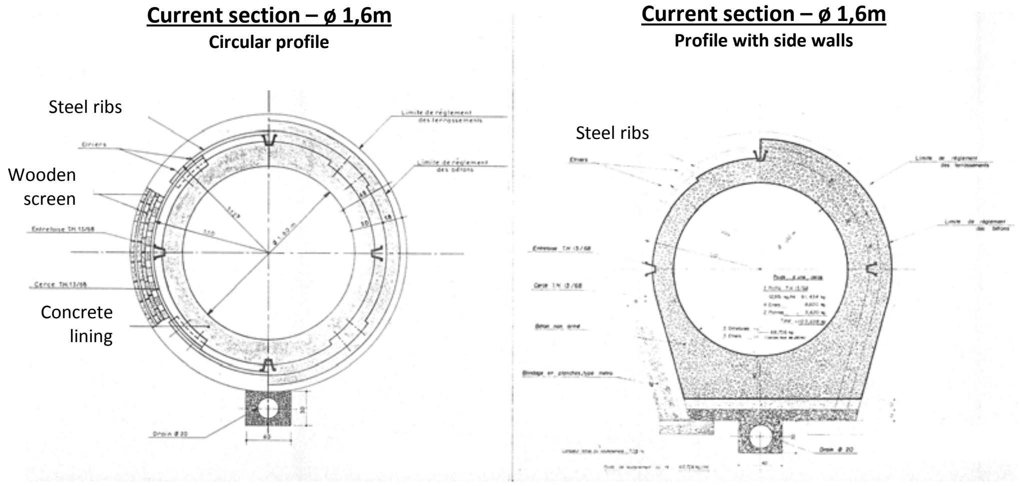

Figure 4: Current sections of the abandoned SEVESC gallery

2.2. PILES OF THE PROVISIONAL PONT DE SEVRES BRIDGE

A temporary metallic bridge was built in 1950 to maintain the traffic during the demolition of the former Pont de Sèvres bridge in stones (1820) and the building of the current bridge. The structure had ten piers founded on three lines of eleven wooden piles probably anchored in the alluvium.

Because of the significant delay of the Pont de Sèvres works, each pier had to be reinforced by driving steel piles to extend the working period of the temporary bridge. The number of the new foundations is not known, but several old photos seem to show a strengthening by two rows of three piles (Figure 6). Furthermore, we assumed that the driving piles had been stopped when hard chalk was met. On the right bank of the Seine, the GPE tunnel vault is situated in the degraded part of the chalk (Ca1). So, the presence of the steel piles into the tunnel section is highly probable.

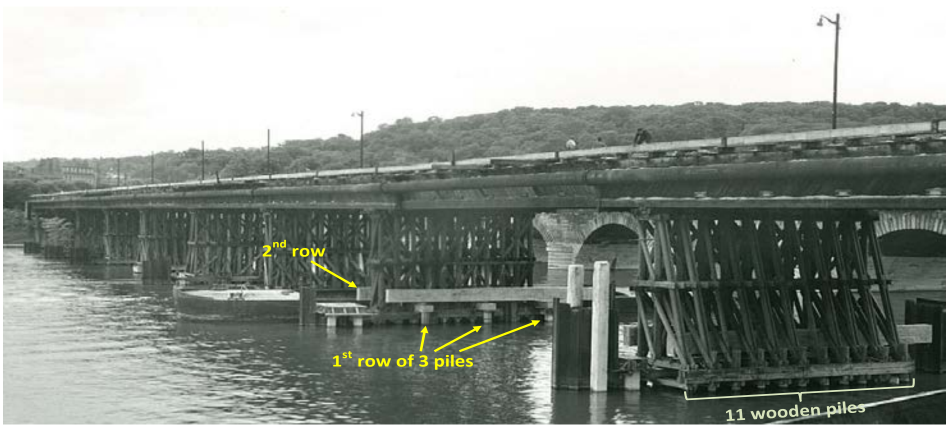

Figure 6: Photo of the provisional bridge

3. INVESTIGATIONS OF THE STRUCTURES FROM THE SEINE

3.1. AIMS OF THE INVESTIGATIONS

The main risk related to the presence of these structures is to block the TBM cutting head. Restarting the machine requires a very dangerous and complex human intervention in hyperbaric chamber. Besides, this operation will cause an important delay that will have a serious impact for all the line works. Indeed, the excavation of the Pont de Sèvres and Issy RER stations begins only after the TBM crossing for timing reasons.

Modifications of line route are not possible because of the proximity of the Pont de Sèvres station. Therefore, it seems imperative to check the presence of these structures into the tunnel section in order to define preventive measures if it is necessary.

3.2. PROGRAMME OF THE INVESTIOGATIONS

3.2.1 *SEVESC sewer*

The investigations were in two steps:

- the purpose of the first phase was to check the location of the pipe. Three surveys were realized on the river bank on the presumed position of the gallery. They are used for the calibration of the geophysical measures too,
- the second step consisted of searching the gallery. The surveys, essentially destructive boreholes, were realized close to the GPE line but not through its section to avoid blocking the machine into the tunnel. Then, geophysical measures were led into the boreholes to detect the presence of the sewer. The results were provided everyday in order to adapt the investigations programme. In total, twelve destructive boreholes and one core drilling have been made in three weeks.

3.2.2 *Temporary Pont de Sèvres bridge*

The campaign was in two steps too:

- first, a geophysical subaquatic investigation was carried out to locate the top of the piles
- according to the first phase results, six destructive boreholes followed by geophysical measures were implemented next to the assumed position of the piles.

3.2.3 *Présentation of the implemented geophysical methods*

In order to meet with success the aim of this study, three methods based on three different physical properties were implemented to determine the geometry of the existing structures.

This methodology increases the probability of obtaining relevant conclusions, even if one of the proposed methods reveals itself to be inefficient due to unexpected geological conditions, poor structure response, abnormal ambient noise, etc.

Surface based methods were not considered in this methodology: the important theoretical depth of the searched targets locations combined with their relatively small sizes would have made them difficult to detect with accuracy and certainty from the surface.

Single borehole methods presented themselves as the best way to detect the underground structures; as the resolution and accuracy of such methods are not influenced by the depth of the elements to locate but only by their distance from the borehole at their depths.

Due to site constraints preventing us from having two or more boreholes available at any given moment in time, cross borehole methods were not implemented during this campaign.

The following methods were implemented:

- *Fluxgate magnetometry (FM)*, based on ferromagnetic properties of steel embedded in structures The borehole method is based on the fact that almost all deep foundations, except those made prior to the 20th century, have rebars, steel casing, or at least embedded steel wires. All these metallic elements are ferromagnetic and generate relatively strong induced magnetic fields. This method is generally implemented to detect various buried metallic structures.

- *Electric Cylinder™ (EC)*, is used to image the electrical resistivity contrasts of the elements located in the vicinity of the borehole. It is based on the difference of resistivity between steel and soil. This system provides a resistivity pseudo-section including a 4 to 5 meter radius cylinder of ground (depending on ground resistivity), showing the depth and the extent ground singularities (hard and soft beds, weathered and/or fractured zones, shear faults, etc.)

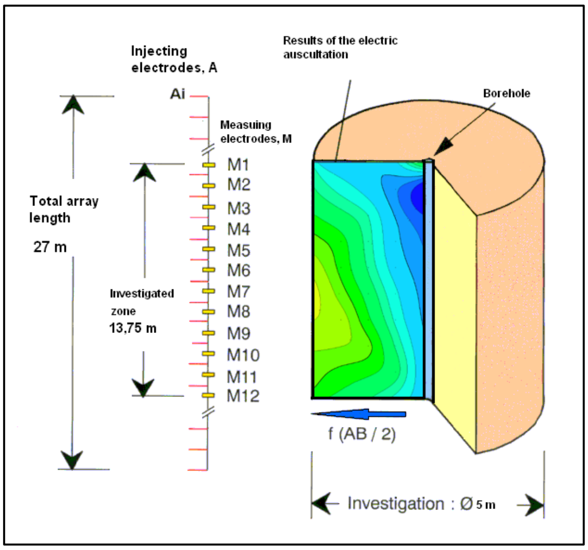

Figure 7: Electric Cylinder™ principle

- *Ground Penetrating Radar (GPR)*, this method was proposed to precisely locate reflective radar echos reflecting on structures. GPR technique is a non-destructive method used to image reflective structures in the vicinity of a borehole. It is implemented to detect buried structures and image subsurface. It is based on the transmission of an electromagnetic pulse into the ground. The wave propagates, is attenuated, and is partially reflected at each interface found. Each interface corresponds to a dielectric change of the environment. A receiving antenna records the different echoes reflected by the cavity.

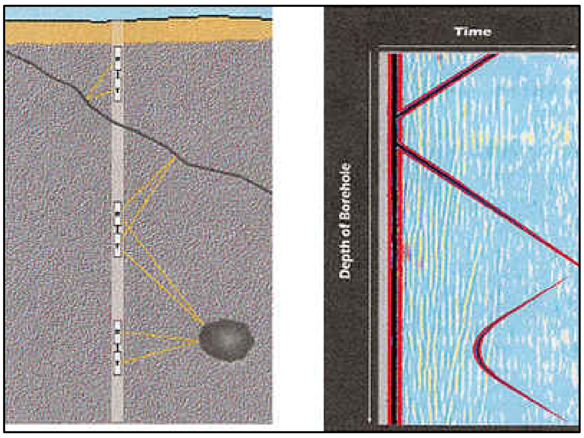

Figure 8: Borehole GPR principle (Gustafsson, 2008))

3.3. REALISATION OF THE INVESTIGATIONS

The intervention in the Seine navigation channel demanded a prior consultation of the waterway users launched by VNF (Waterways of France). The balance sheet was published on the internet. The purpose of this consultation was to seek the advice and suggestions on the operation and the selected device.

An authorization to work and a notice have been issued by VNF, dictating us the requirements to respect for the proper conduct of operations. Apart from complying with signaling and safety distances, we were forced to realize all parts of the operation the time of the year where the level of Seine reached its lowest point.

Also, it has been prescribed by VNF, in order to avoid polluting the bottom of the Seine (environmental respect), to recap all drilling holes not with grout cement but only with pellets of swelling clays (duranite).

These investigations (surveys and geophysical measurements) were undertaken by ERG teams and Soldata by using a SOCOMAFOR 5065, cantilevered from a pontoon of 3 metal piles. The investigations took place in advance.

Figure 9: Barge placed on the Seine river for the investigations of the SEVESC gallery

In consultation the project management company Géos, several scenarios have been established on the likely extent of the collapsed gallery. It is worth to know that it was asked to limit the number of investigations close the future path of the tunnel.

Also, in order not to intercept the underlying SEVESC gallery, still in service, the depth of the investigations was limited to 25 m below the bottom of the Seine (or -5 m NGF).

Here are the different phases and breakpoints that we have adopted for the realization of a borehole:

1) Moving and positioning of the pontoon (with a pusher) next to the borehole, in accordance with the theoretical coordinates defined by Géos (GPS implementation by topographic surveys, knowing that three topographical bases had been previously disposed on the banks and the Sèvres bridge)

2) Pyrotechnic security of the borehole (magnetometric sensor) by SITA Remediation approximately 6 to 7 meters / bottom of the Seine (2 phases of 3m)

3) Destructive borehole with parameter recording and PQ tubing in advance, up to 25 m depth / bottom of the Seine (about -5 NGF)

4) Laying of a full height 52/60 PVC inlet filter inside the casing.

5) Ascent of the casing

6) Geophysical measurements by Soldata (electric cylinder, radar, magnetometer) directly into the PVC tube

7) Filling the inside of the PVC tube, from the bottom, with clay pellets (duranite)

In order to meet deadlines (one drill per day), we preferred destructive boreholes rather than cored ones with the help of a tricone Advancer clamped to a PQ casing (corer cable with non-coring bit system).

It was also notified, in case of premature refusal because of steel ribs for example (in particular in the center of the collapsed gallery) that the drilling should stop and the borehole should be equipped with a PVC in order to confirm the presence of the gallery by geophysical measurements (including magnetic)

The theoretical position of the boreholes has been defined in advance by Géos according to the results of the geophysical measurements (Soldata Geophysic) which were communicated in real time. A first line, close to the future side wall of the tunnel (1 m) has been prospected (5 boreholes spaced at regular intervals of 2m). Then the mesh has been narrowed to 1m in areas of uncertainty. In total, twelve destructive boreholes and one cored borehole (control) have been undertaken by ERG next to the SEVESC gallery between 05/18/15 and 04/06/15.

In accordance with SGP, this methodology has been extended to the research of the length of six steel piles that have been drilled next to the eastern stack of the old Sevres Bridge (6 boreholes to a theoretical distance of 3 m maximum from the piles, down to -10NGf).

In this sector, the presence of a fiber optic cable in river environment required the intervention of divers in order to locate and materialize (using buoys) the actual path of the network towards the position of the future boreholes and the steel piles of the pontoon. A safety zone of 9 meters wide (relative to the path) was adopted.

3.4. GEOPHYSICAL RESULTS AND ANALYSIS

3.4.1 *Way of interpreting the results*

<u>Fluxgate magnetometry:</u>

The methodology to interpret magnetometry results consists in comparing synthetic signatures (calculated curves using forward modelling) with measurements (raw signal). The aim is to detect the structures magnetic signature located in the vicinity of the boreholes, if any.

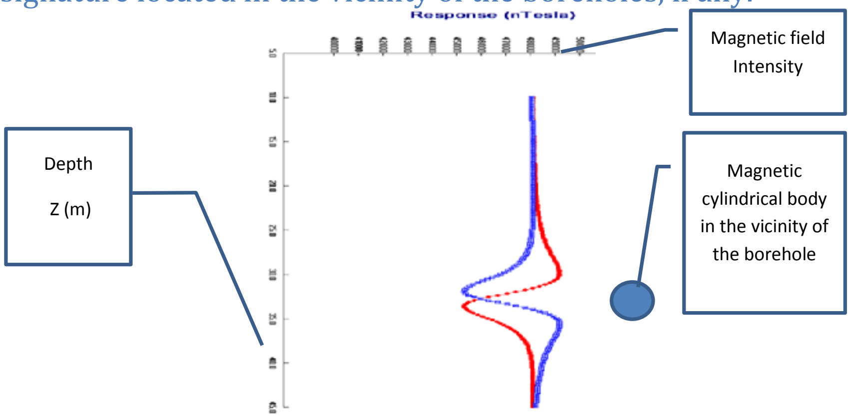

Figure 10: Case of a magnetic cylindrical body

<u>Electric Cylinder™:</u>

Electric Cylinder measurements enable a 2D representation of the resistivity values of the ground surrounding a borehole. In the absence of structure or heterogeneity (in this case, the structures being sought), the Electric Cylinder™ measurements represent the site geology by distinguishing the different geological entities on the basis of their electrical resistivity value.
To convert the resistivity picture into a geological picture, some knowledge of typical resistivity values for different types of subsurface materials and the geology of the area surveyed, is important.
Sedimentary rocks, which usually are more porous and have a higher water content, normally have lower resistivity values. Wet soils and fresh ground water have even lower resistivity values.

In the presence of a conductive body (which is the case of the reinforced structures being sought), the electric potential in the ground will be disturbed and will show a zone of lower resistivity compared with a measurement carried out in the absence of that structure.

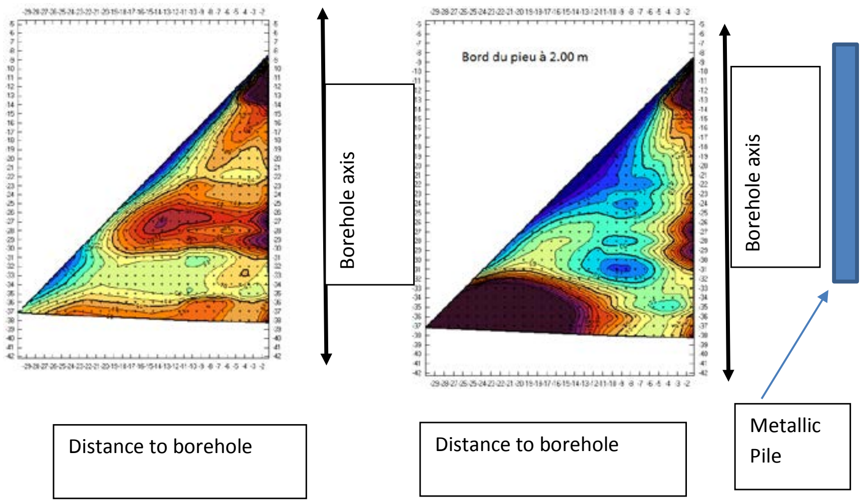

Figure 11: Case of a magnetic pile vs Natural ground (left)

Ground Penetrating Radar:

GPR final result is a section showing reflections amplitude as a function of distance/depth (X axis) and distance to transceiver (Y axis). It is also called radargram.

Signal amplitude corresponds to material changes. Amplitude remains weak in homogeneous materials. Amplitude becomes strong in case of high dielectric contrasts.

In that case, buried structures should be very reflective in a relatively homogeneous media.

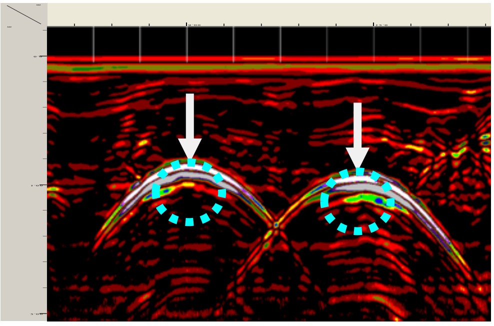

Figure 12: Example of two buried structures detected with GPR

3.4.2 *Obtained results – SEVESC pipe*

As a reminder, the purpose of the survey was to determine the location of the SEVESC pipe, and the position where it collapsed, as it could constitute an eventual obstruction for the future tunneling works.

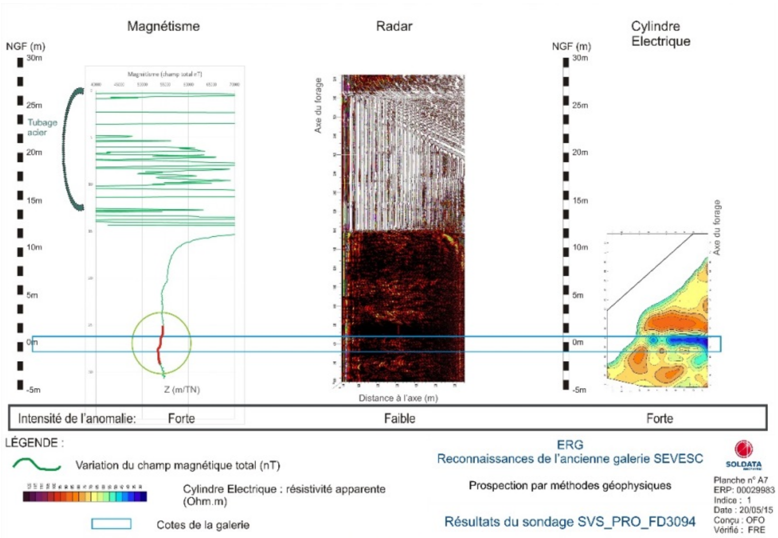

Figure 13: Case of a magnetic pile vs Natural ground (left)

Taking into consideration every results coming from the thirteen boreholes, a synthesis plan view was elaborated to visualize the location of the geophysical target beside the expected TBM path.

In absence of any other structures in the vicinity of the survey, this target was assumed to be the searched gallery.

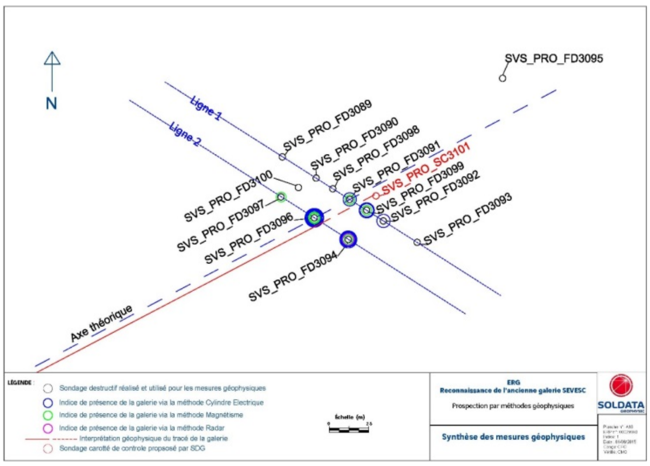

Figure 14: Synthetic results of the geophysical survey

3.4.3 *Obtained results – Former Pont de Sèvres Bridge*

A preliminary geophysical subaquatic campaign, not described in this article, was carried out from the Seine River, and allowed to locate the top of the remaining foundations of the former bridge.

As a reminder, the final purpose of the survey was to determine the length of the piles, to evaluate the obstruction risk of for the future tunneling works.

Following the preliminary survey, six boreholes were drilled to investigate the previously identified foundations area.

The three methods (EC, FM and GPR) were implemented in each borehole.

On the figure 15 below, typical geophysical results are presented and illustrate the signature of the piles that were searched for, in absence of any other structures in the vicinity of the survey.

Finally, the borehole geophysical survey allowed to determine the length of the structures aligned with the TBM path. Using this methodology, no distinction were possible between the different piles, but it was conclusive enough with regard to the survey purpose.

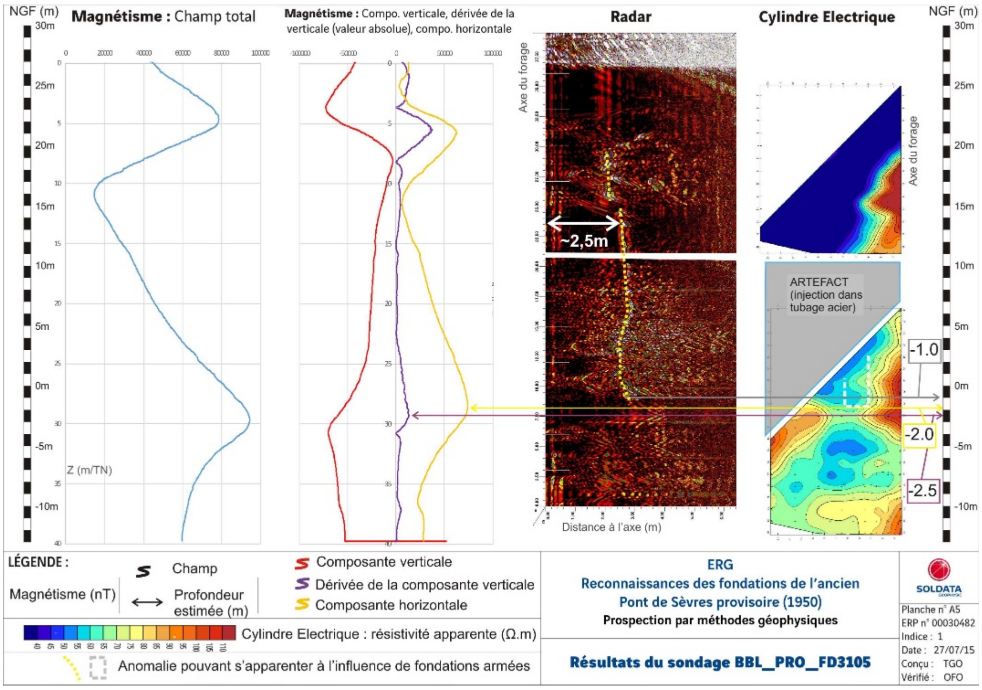

Figure 15: Synthetic results of the geophysical survey

CONCLUSION

This paper presents two examples of risk management carried out on the project of the line 15-south.

After a documentary research about the two structures presented in this paper, a campaign of physical surveys was implemented in order to determine the real risk for the tunnel.

The programme of the investigations was elaborated in association with the project owner (Société du Grand Paris). The type and the location of the encountered structures led to choose in priority geophysical methods.

The interpretation of the results showed that the SEVESC sewer was not in the tunnel section, contrary to the steel piles of the provisional Pont de Sèvres bridge. In that last case, it is proposed to extract the piles before the beginning of the tunnel works.