Underground Church of Saint-Emilion : Geotechnical challenges in light of heritage issues

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ABSTRACT

The underground church of Saint-Emilion in Nouvelle Aquitaine was carved in the early 12th century into a limestone facies. The subsequent construction of a 68-meter-high bell tower weighing nearly 5,000 tons has generated significant constraints, particularly on the four main pillars that support the load.

The underground church of Saint Emilion today exhibits pathologies and disorders, including hydrogeological problems, stone alteration, and vault cracking. After a short introduction to the site geotechnical context, this paper presents the reinforcement solutions already implemented and planned in the long term in relation with heritage conservation issues. The existing solution includes reinforcement with concrete pillars and metal strapping of the pillars. The forecast solution, based on the innovative technique of biocementation is then highlighted. This method enables calcification by biological precipitation of calcite obtained through the action of bacteria on a calcifying solution composed of urea and calcium.

The objective will be to share the feedback on the management of geotechnical risks in the context of the conservation of historical monuments, emphasizing the importance of reconciling structural safety requirements and heritage preservation issues.

1. GENERAL AND HISTORICAL CONTEXT OF THE CHURCH

1.1. Underground Quarries in Gironde

The expansion of Bordeaux in the 18th and 19th centuries led to the exploitation of more than 2,500 hectares of underground quarries in Gironde for the extraction of limestone construction materials. These quarries were most often located along the slopes closest to Bordeaux to facilitate transport by river or roads.

To date, nearly 1,400 underground quarries have been identified in the department. Most are abandoned and many of them are in a precarious state of stability. Although the exploitation of these quarries has stopped since the beginning of the 20th century, many abandoned quarries remain and pose a risk to the public. Many of them have several superimposed levels.

The limestone plateau where Saint-Emilion is located (see Figure 1) contains a large number of underground quarries ranging in size from a few square meters to several hectares. An inventory and diagnostic study of the underground quarries located within the city walls of Saint-Emilion was conducted by Antea Group in 2000, establishing a collapse hazard zoning map (see Figure 1). More than 150 quarries were inspected, on one to three overlapping levels, representing an area of over 12 hectares (70 hectares across the entire municipality). The underground church of Saint-Emilion, much older (excavation started in the 12th century), is located between all these quarries.

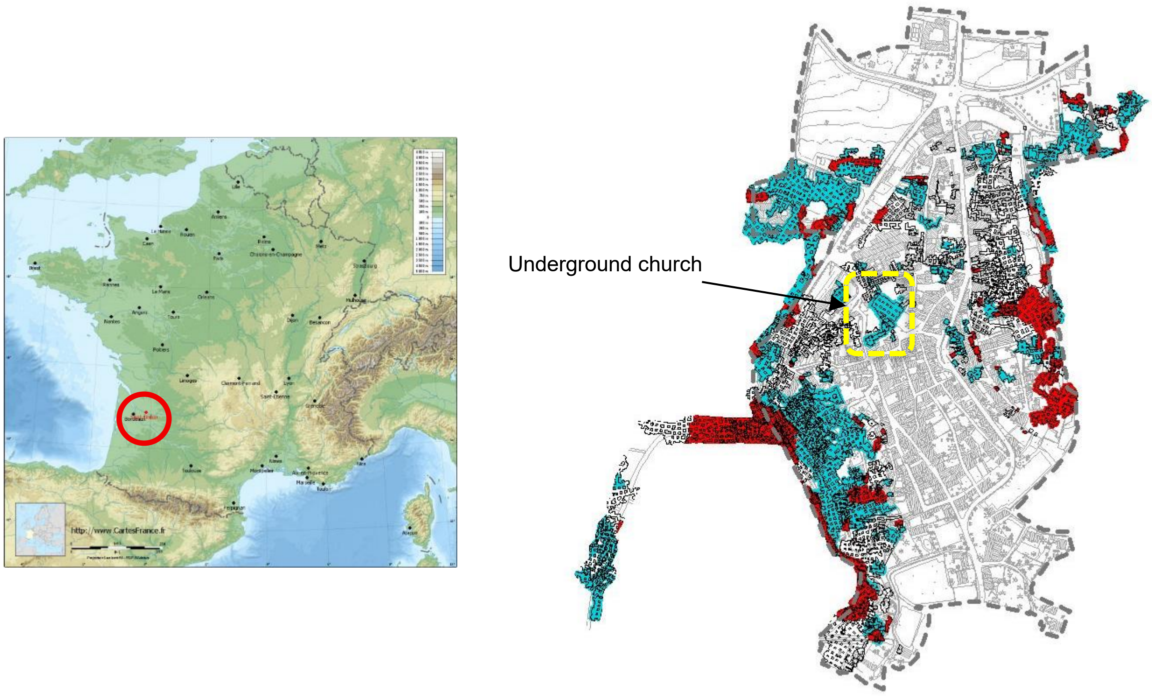

Figure 1. *Saint-Emilion location plan (left). Collapse risk zoning plan in the center of Saint-Emilion with the location of the church (right)*

1.2. Saint-Emilion underground Church

The Saint-Emilion underground Church is located in the centre of the city of Saint-Emilion in Gironde County Council (France), 30km north-east of Bordeaux (see Figure 1).

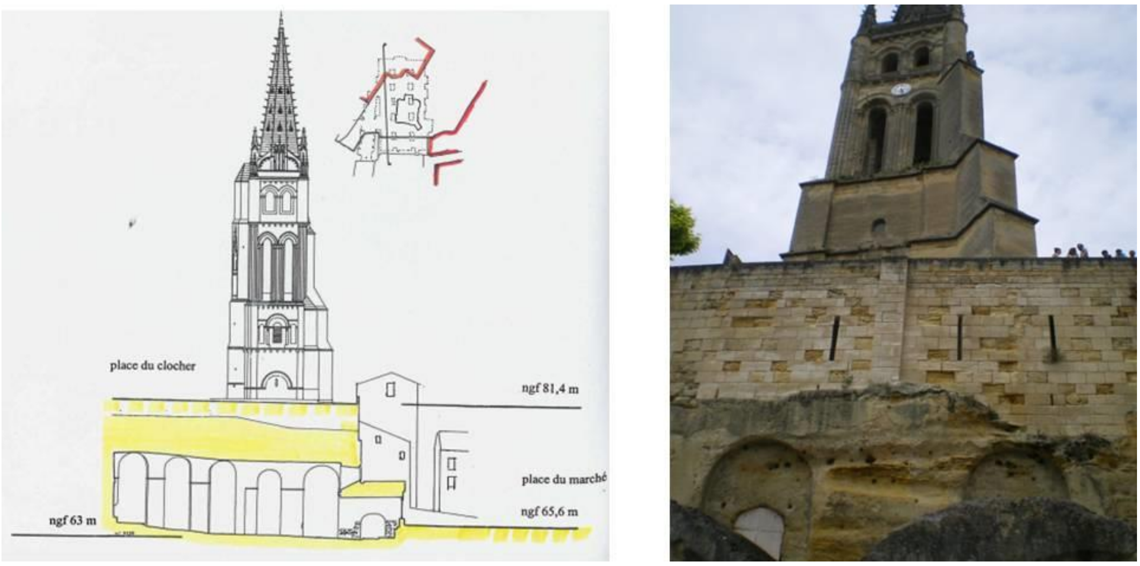

Figure 2. *Elevation view of the monolithic church of Saint-Emilion (Goutal M., 1999) (left). Photo from the lower forecourt (Antea Group, 2018) (right)*

The bell tower square forms a terrace which constitutes the "roof" of the underground church which is connected to the bell tower by a shaft dug through the rock about 5 to 6m thick. This bell tower, representing an overload of more than 5,000 tons, was built later, between the 15th and 16th centuries, on the upper square above the church (see Figure 2).

Measuring 38 meters long, 20 meters wide, and 10 to 11 meters high, the underground church consists of three parallel aisles of six bays, each with vaults of equal height. The pillars have an average cross-section of 2x3 square meters. The volume of the troglodyte church corresponds to the extraction of approximately 15,000 cubic meters of limestone.

The figure below (Figure 3) shows a plan view of the outline of the church and its pillars, and the outline of the bell tower (light blue outline) positioned just above. This bell tower rests mainly on 4 pillars (dark blue outline) which therefore support significant forces.

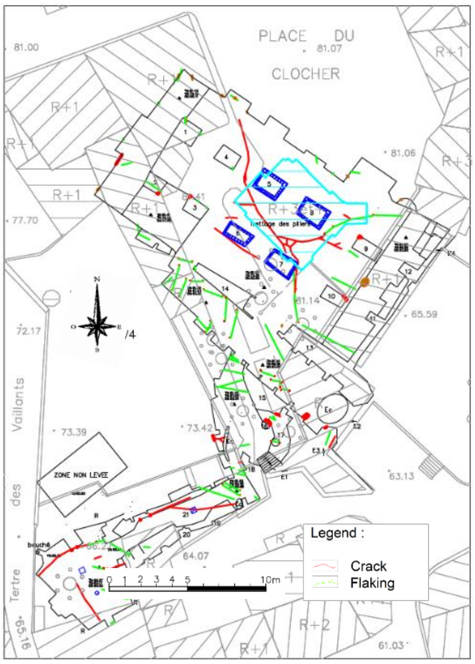

Figure 3. *Plan view of the monolithic church of Saint-Emilion with cracking position (Antoinet, 2013)*

2. GEOLOGICAL AND GEOTECHNICAL CONTEXT

The limestone plateau of Saint-Emilion is crowned by cliffs formed by the so-called Asteria limestone, dating from the Stampian period of the Oligocene (Cenozoic), which can reach 50 meters in thickness.

This horizon presents carbonate, biodetritic facies, with decimeter to meter thick clayey layers and marls at the base. The monolithic church of Saint-Emilion was carved out of coarse-grained limestone (cross-bedded deposit) more or less well cemented. The entire plateau surrounding Saint-Emilion has been exploited in underground quarries.

The softer underlying geological strata consist of Sannoisian and Upper Eocene Molasses.

2.1. Construction History of the Monument

Archaeological evidence suggests that excavation likely began in the 11th century, as indicated by the current configuration of the site. The 12th century saw the completion of the remarkable monolithic church carved directly into the rock. Later, in the 16th century, a bell tower was constructed above the structure, marking a significant addition to the original medieval ensemble.
Note: The catacomb adjacent to the church dates from between the 7th and 11th centuries.

2.2. Mechanical Properties of the limestone

Numerous laboratory tests were conducted as part of previous studies (1998).

The material is highly heterogeneous across layers (cross-stratification), with significant variability in the results and, therefore, in the material's characteristics (see Table 1).

Table 1. *Laboratory tests carried out by Antea Group (Antoinet)*

Antea Group tests	Unit	Tests number	Average	Standard deviation	min/max
Volumic weight γ_h	kN/m^3	74	19.3	1.4	16.9 / 23.2
Dry volumic weight γ_d	kN/m^3	41	16.6	1.6	14.1 / 20.2
Water content	%	73	16.1	3.8	9.4 / 23.9
Saturation	%	41	70.0	9.0	48.5 / 85.3
Porosity	%	29	41.2	5.6	33.0 /50.6
Uniaxial compressive strength UCS	MPa	45	2.9	1.8	0.9 / 9.8
Brazilian tensile strength BTS	MPa	29	0.43	0.25	0,06 / 0.90
Elasticity Modulus E	GPa	5	5.9	3.6	3.7 / 12.2

Influence of the Saturation State: UCS (saturated) / UCS (dry) = 0.6
Influence of sample orientation: UCS (vertical) / UCS (horizontal) = 1.4

These data are based on a small number of samples and are therefore indicative only, but they highlight:
- a limestone with very low mechanical characteristics,
- an important influence of the saturation degree and water content on the rock’s strength (see Figure 4), particularly linked to its high porosity (41%),
- the influence of sample orientation (strong Rc anisotropy).

Moreover, the tests showed lower mechanical characteristics at the base of the pillars, which also exhibited the highest saturation levels due to capillary rise from the floor, with the groundwater level less than 1.5 m below the church floor (see figure 4).

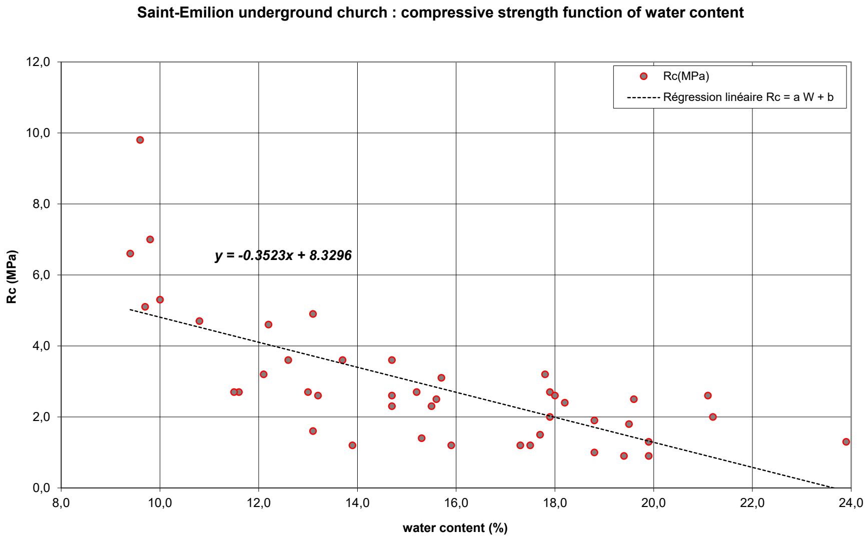

Figure 4. *Compressive strength evolution according water content (Carpentier, 2015)*

In addition, a crack survey was carried out, revealing mechanical cracking in the vault beneath the bell tower (red line on Figure 3) probably related to the overload of this construction.

3. PREVIOUS STUDIES AND WORK - REMAINING ISSUES

3.1. Emergency Shoring

In 1985, significant deterioration of the limestone was observed in the southeastern half of the underground church, causing flaking of slabs on the pillars and the roof. In addition, localized subsidence of the fill covering the floor was identified, apparently linked to water inflow.

In 1986, a university hydrogeologist warned the Chief Architect of Historical Monuments of the building's instability, even though no structural damage had appeared inside the church, aside from water infiltration. Following this inspection, emergency reinforcement work was carried out between 1990 and 1991 without a proper stability study. This temporary shoring consisted of 38 steel columns, 60cm in diameter, supporting the vault around the four main pillars beneath the bell tower (see figure 5).

The concrete columns completely disfigured the church, prompting calls to remove these temporary supports and find more elegant, less visible permanent solutions, especially as the monument was about to be listed as a UNESCO World Heritage site (officially done in 1999).

Note:

- Between 1988 and 1992, visual stability assessments did not show any evolution of the structure. This was confirmed by the fact that the temporary props were passive (no contact between the top of the pillars and the vault).
- The first geotechnical investigations were carried out starting in 1992.

Figure 5. *Emergency reinforcement by concrete pillars (1991 – Pierre Regaldo Saint-Blancard)*

3.2. Pillars reinforcement solutions considered

In 1998, at the request of the new Conservator of Historical Monuments, in consultation with the Chief Architect of Historical Monuments (Mr. Goutal), Antea Group was commissioned to conduct a detailed geotechnical study of the structure. The objective was to assess the real stability of the building and to propose alternative reinforcement methods that would both ensure safety and restore the church's original appearance.

This study concluded that short-term stability was assured (no visible signs of degradation), but with a low safety factor (1.1 to 1.3) at the four pillars supporting the bell tower. It recommended precautionary reinforcement measures before removing the columns and proposed several technical solutions.

Two categories of reinforcement work were considered:
1. Transferring all or part of the bell tower loads to reduce vertical stress on the pillars.
2. Reinforcing the four most loaded pillars, either by banding (fretwork) or by improving the rock's strength through treatment of its weaker zones over several meters in height.

In the first category, three solutions were studied. All required heavy and tricky works, including underpinning the bell tower and significant reworking of the surrounding area over approximately 4 m of fill thickness. They also involved a pre-stressing phase to take part of the bell tower load - a complex and risky process for both the structure and the vault.

In the second category, the banding of the pillars with reinforced concrete jackets or with bolted, lightly pre-stressed ties were considered the safest, most effective, and least costly solutions. However, they altered the pillars' appearance. Other options - such as internal rock treatment by micro-drilling or hydroxyapatite resin injection via electro-consolidation - seemed promising but required prior testing and pilot projects, as these technologies were still at a research stage.

Finally, it was decided to **replace the props with a provisional and reversible banding technique**, less harmful to the monument than the existing columns.

3.3. Pillar banding works by metallic frames

The metallic banding works, through the application of lateral confinement, was implemented in 2000, allowing the removal of the unaesthetic temporary props (Figure 6). The system consisted of metal frames encircling the pillars, fitted with mechanical screw jacks exerting calculated pressure on distribution plates. To prevent surface damage, a layer of lime mortar was inserted between each plate and the pillar. Each pillar had five frames spaced one meter apart, with 12 to 14 jacks per level, depending on pillar cross-section.

The applied stress on the plates ($0.4\times0.4m^2$) ranged between 0.8 and 1 MPa. Force sensors on the adjustment screws allowed verification of the applied load. 3D modeling has been done to assess the behaviour of the pillar.

Due to the rigidity of the system and the pillars' geometry, it was difficult to apply a uniform force using mechanical jacks, so the nominal force was limited to **50%** of the initially targeted value.

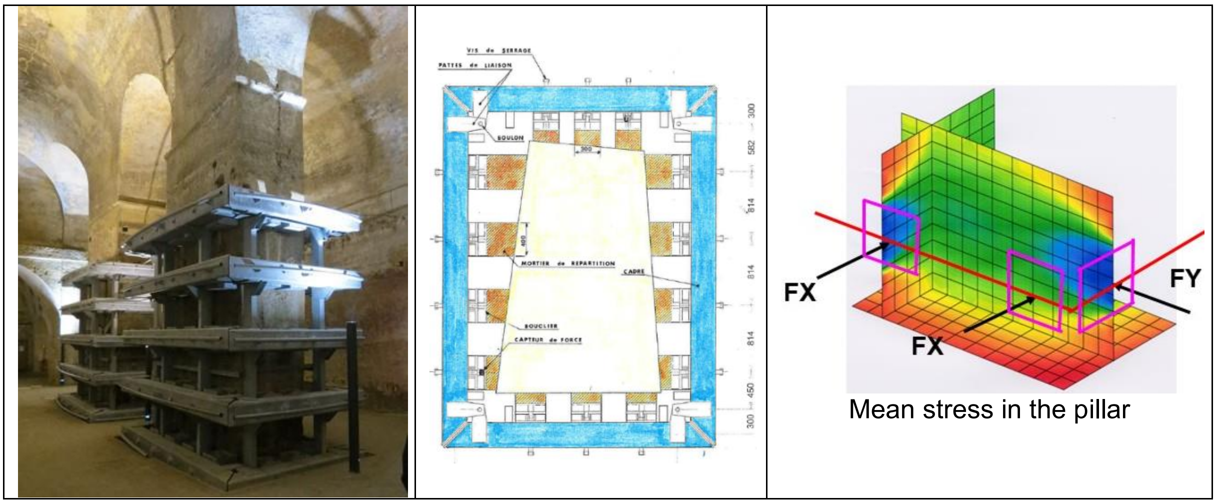

Figure 6. *Photograph of the banding system (left), plan view of a metal frame (center) and 3D numerical model (right)*

At the same time, drainage works (drain trenches) were carried out in the church floor to dry out the basement.

3.4. Monitoring device

3.4.1. Survey of cracking

As part of the consolidation and restoration works, a monitoring system was installed, including 10 crack gauges fixed on the identified vault cracks. Monitoring showed small variations (less than 0.3 mm) correlated with temperature (pink line) changes (cf. figure 7):

- Cracks narrowing with higher temperatures,
- Cracks widening with lower temperatures.

Residual displacements over a yearly cycle were negligible (a natural "breathing" phenomenon of the rock mass), and no abnormal movement was observed. Therefore, the system was removed after two years of monitoring.

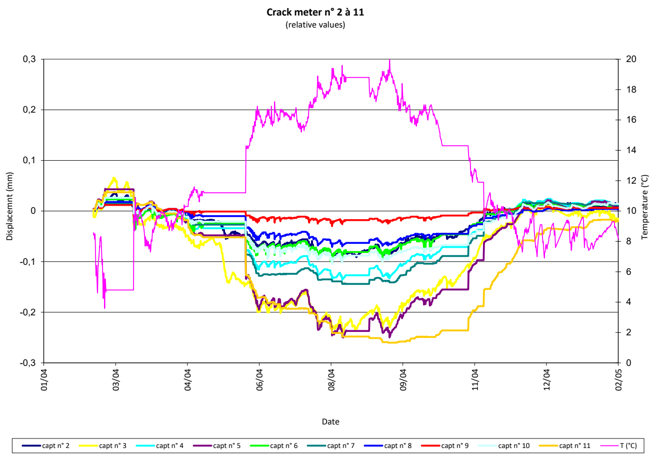

Figure 7. *Cracks monitoring on one year (2002)*

3.4.2. Monitoring of applied stresses in metal frames

A force sensor monitoring system was operated for about four years. Data analysis showed redistribution of stresses in the frames, with slight increases or decreases depending on sensor position. Unfortunately, recurring malfunctions (humidity, electrical issues, etc.) made data collection increasingly difficult.
Today, the instrumentation of the banding system is no longer operational (only 20% of the sensors are still in order), preventing assessment of the actual stresses in the pads and therefore of the system's efficiency (residual stress estimated less than 30% of initial stress after 15 years).

4. PROPOSAL FOR AN ALTERNATIVE RESTORATION PROJECT

Given the slow and continuous deterioration at the base of the pillars (see figure 8), partly due to capillary rise, and the reduction of banding stress, Antea Group explored new methods to improve the mechanical properties of limestone in depth. In this context, the Biocalcis process, developed by Soletanche Bachy, appeared as a potentially suitable solution.

Figure 8. *Pillars alteration at the base, between the metal frames (Carpentier, 2024)*

The Biocalcis process strengthens fine soils in situ through biological calcification, achieved by microbial precipitation of calcite. The crystals formed within the open porosity bind the soil grains together, increasing cohesion and mechanical strength.
Depending on the desired amount of calcite, the injection cycle of calcifying solution and bacteria can be repeated several times. The physical and mechanical properties of the treated soil are achieved within a few days of treatment and remain stable over time. A key feature of the process is that the porosity of the treated material is not significantly altered after treatment. This biological cementation is achieved through the action of bacteria on a calcifying solution composed of urea and calcium chloride (see Figure 9).

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^{+} + CO_3^{2-}$$
$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3\ (s)$$

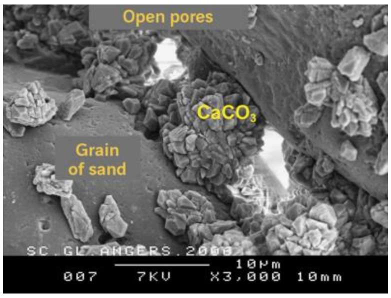

Figure 9. *Reaction principle (Soletanche Bachy, 2015)*

Soletanche Bachy conducted laboratory feasibility tests on limestone samples taken from an underground gallery adjacent to the Monolithic Church of Saint-Emilion.
After injection, a significant increase in mechanical strength was observed: between 2 and 5 times that of untreated limestone. The resulting mechanical strengths are remarkable, ranging from approximately 2.8 to >10 MPa to compare with values # 1 MPa before treatment (see Figure 10).

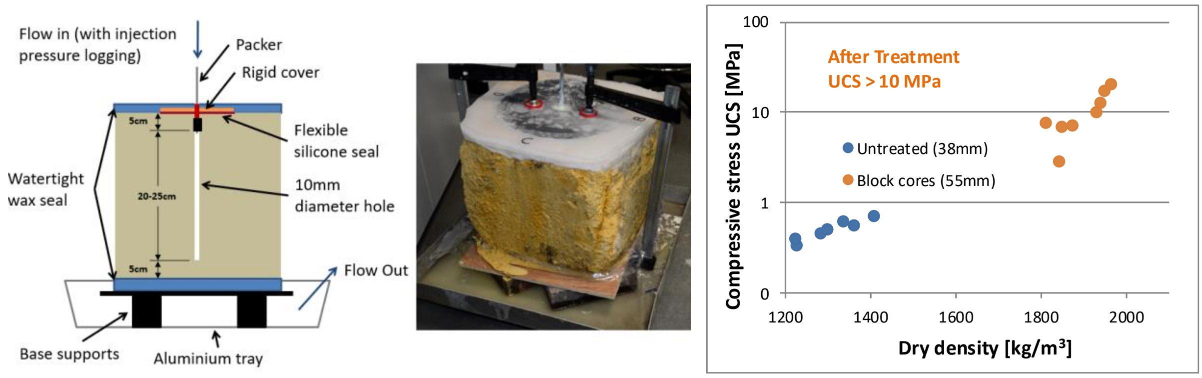

Figure 10. *Injection device in the block and obtained mechanical strengths (Soletanche Bachy, 2015)*

Test plot planned to validate the solution
To confirm these promising lab results and define in-situ implementation methods, it was recommended to conduct a trial treatment on a test pillar in a similar quarry to that forming the base of the Monolithic Church pillars.
The tests will consist of injecting a 3x3x3m pillar into a quarry in Saint Emilion, identified by Antea Group, under site conditions. The evolution of biocalcification will be monitored after a maximum of 4 treatment cycles to determine the optimum dosage for the desired resistance. The boreholes will be drilled on two parallel faces: 7 boreholes on one face and 8 on the other.

Soletanche Bachy will monitor biocalcification parameters, while Antea Group will monitor mechanical resistance and environmental impact: the aim is to test non-destructive methods that can be implemented once the reinforcement is carried out on the pillars of the monolithic church of Saint-Emilion. The objective is to combine two geophysical methods: seismic tomography and ultrasonic testing.
These non-intrusive tests, on a similar pillar near the monument, will be provided before and after the treatment, and in parallel with intrusive tests (borehole with mechanical tests in laboratory) in the aim to correlate with the geophysical methods.
Moreover, environmental analyses of the surrounding environment (bacteriological analysis) are considered, in order to study the risk of projection of the calcifying solution onto neighboring structures during the treatment phase and the possible impact of the implementation of the Biocalcis process on a possible modification of the bacteriological environment.

Today, the implementation of this technique suffers from a lack of references and feedback and the objective of this test is to establish a complete protocol to confirm the methodology and the effectiveness of deep bio-injection and not just on the subsurface as is usually done by spraying over a few centimeters.

5. CONCLUSION

Despite the completion of two phases of work, the stability of the church is still precarious, and the previous reinforcements carried out were only temporary. It is now time to undertake definitive reinforcement work which restore the pillars to their original state and ensure the structure’s long-term preservation.

A new interdisciplinary study of the two regional and similar underground church (Saint-Emilion and Aubeterre-sur-Drone) is underway in order to a better understanding of the degradation process and a complete structure modeling. At the end of this study, all the conditions will be in place to conduct full-scale tests and find a technically effective and definitive solution from both a technical and environmental standpoint with this promising bioconsolidation solution.

All that remains is a multidisciplinary team of scientists to lead this project and a political will from the French Heritage Authorities to secure the financial resources necessary to preserve this unique historical site in France, whose stability condition is inexorably deteriorating.

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