HENRI CAMBEFORT AND SOIL GROUTING

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Soil grouting is a group of techniques that aim to reinforce soils and or reduce water permeability by incorporating binder in the soil porosities. Henri Cambefort is one of the most important figures in the development and diffusion of soil grouting methods.

Soil grouting, principles and uses

“Grouting consists of introducing into the ground (soil or rock), a "liquid" material likely to fill the porosity, in order to reduce permeability and improve cohesion” (AFTES 2006)

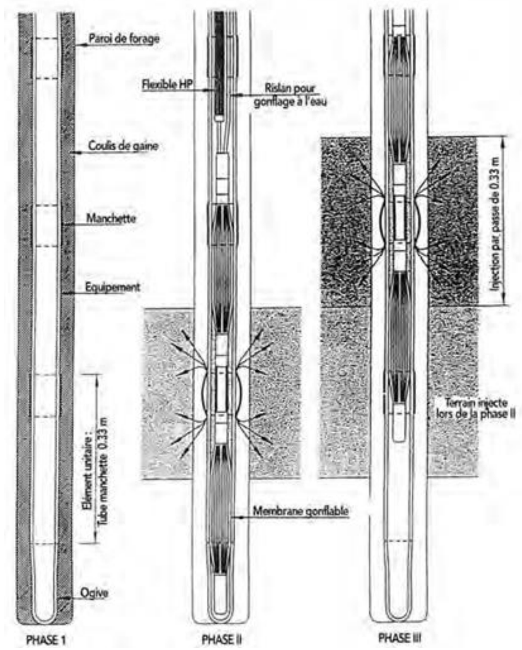
Soil grouting consists of modifying the soil by replacing the inter-particle voids with a binder that eventually forms a waterproof and more resistant matrix. The first documented use of this technique was in 1802 by Charles Berigny, where injected mortar grout was used to reinforce the foundations of locks in the port of Dieppe. The use of the method was essential for many worldwide large dam construction projects in the 1920s and 1930s. In fact, the method of injections filled the porosity of the ground by a grout, to reduce its permeability and to make waterproof layers of ground under the dams. This was otherwise impossible and the flow of water under the dams would affect their stability. Nowadays, grouting is used in many projects and is done using different methods for example shim grouting, compensation grouting, jet grouting, etc.

The treatment of a soil by grouting depends on the nature of the soil, but also on the depth of the grouting and the type of grout used. The current method is to use regularly spaced holes to reach the soil layers to be injected. They can be spaced between 1m and 10m depending on the permeability and the type of soil.

The grout is then injected, in successive plots, under pressure through the boreholes using a pump. The grouting can be done directly through the walls of the borehole, in the case of a cracked rock for example. But in most soils, the injection borehole is equipped with a sleeved tube which is a tube device with valves that open under the injection pressure and allow the grout to pass.

The grouting process is controlled by four main parameters, grouting volume, pressure, flow rate and the grouting phasing. The pressure and the flow rate are two related parameters whose control is important for the grouting mode and are fixed according to the depth and the stress state of the soil.

Two types of grouting can be noted: 1. grouting by impregnation which preserves the structure of the ground requiring relatively weak pressures; 2. crack grouting for which the pressure utilized is sufficiently high to break down the ground. Impregnation grouting is easier at depths where geostatic stresses are high while at shallow depths the risk of breakdown is more important.



The progress in grouting methods is closely linked to the evolution of the product used for grouting. While the first grouts were mortars, cement-based grouts are widely used today. Depending on the type of soil, cement-based grouts are added with various products. In the case of cracked rock or very coarse gravel, for example, mixtures of cement, bentonite and sand can be used. In the case of finer soils such as sand, mixtures of ultra-fine cement (over-moulded) and chemical additives allowing a better suspension in water and the deflocculation of particles are preferably used. Chemical based grouts are more expensive but allow the grouting of finer soils. They are also used to complete the waterproofing done by a cement grout. The most common additives are silicate gels which are formed by the reaction of soda silicate solution and acid. Other grouting materials exist, especially those based on chemical resins. Historically other materials have also been used such as asphalt on the Hales Bar Dam.

The methods of soil grouting are now widely used and have been the subject of recommendations published by the AFTES in 2006 written by the working group 8 under the direction of M Chopin. Before that, it had been the subject of first recommendations also published by the AFTES in 1975 (updated in 1987), and the publication of a reference work "Injection of soils" (in two volumes) by Henri Cambefort.

Henri Cambefort (1912-1995)

Henri Cambefort, born in 1912, is considered one of the most important figures in soil grouting methods, although he is not the inventor.

He graduated in 1936 as a Civil Engineer from the *Ecole Nationale des Ponts et Chaussées*. He then began his career at the *Compagnie Nationale du Rhône*, and after a journey at the *Laboratoire du Bâtiment et des Travaux Publics*, he joined the SEC company in 1943, which became *Solétanche* in 1948, where he finished his career in 1975. He became the technical director in 1946. Henri Cambefort was behind most of the techniques developed at that time for foundation work: sleeve tubes for injections, cast walls, drilling bars and muds, silicate-based gels, re-injectable anchors, atmospheric preloading, triple-shell corer, micromoulinet for measuring water currents in drillings, etc. He worked in many countries, starting in France on the Castillon dam site, passing through North Africa and Mexico.

He was famous for his expertise during his career and was also known to give particular importance to experience, observation, and field work, rather than to theory and mathematical work.

He taught at the *École Spéciale des Travaux Publics* from 1949 to 1975. In an atypical way, he described the cases of building sites on which he intervened, more particularly those of dams and grouting works at the building sites of the Aswan or Tashkent dams and works of soil stabilization or rock reinforcement.

He is the author of numerous reference works, most of them have been translated into many languages, including Spanish, Russian, German and Japanese

- Drilling and soundings (1955, republished in 1966)
- *Reconnaissance des sols et fondations spéciales* (1963)
- Geotechnics for the engineer (1970)
- Introduction to geotechnics (1971)

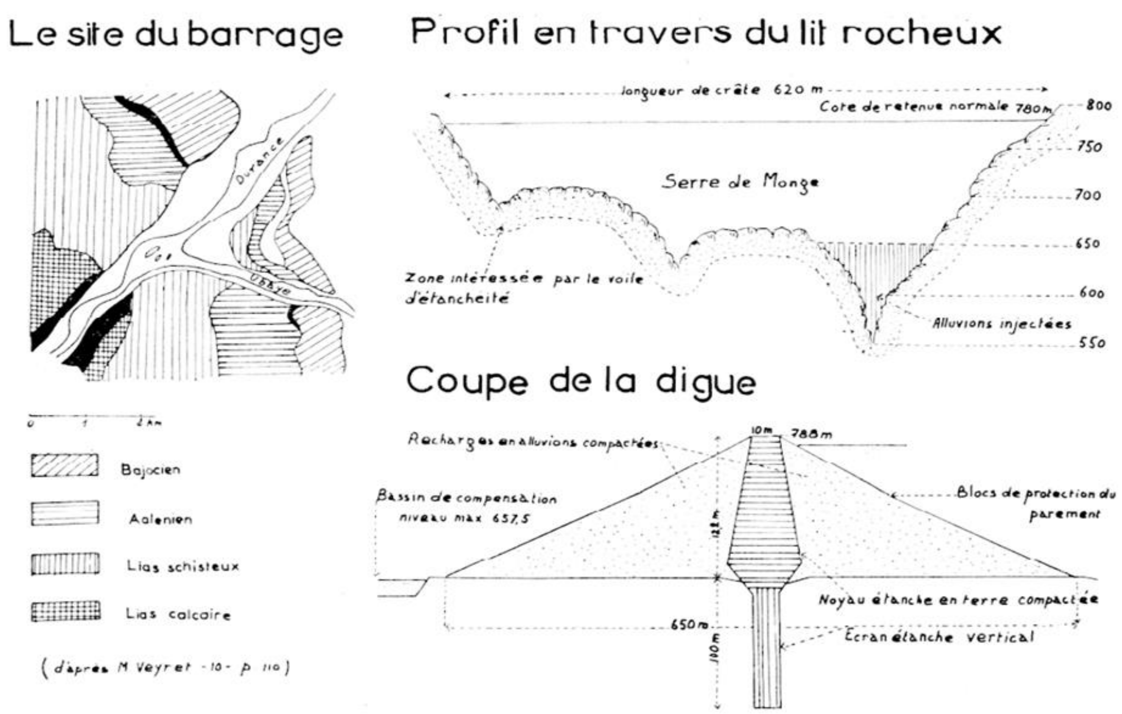
More particularly, he is the author of the book "Injection des sols (two volumes)" (Eyrolles edition, 1964). In the first volume, he describes the cases in which the grouting methods were used, the theory, the principles. He also details the technical aspects related to the objectives and the concerned soils, as well as the different materials and grout types. In the second volume, he not only details numerous case studies where grouting has been used to seal or consolidate cracked rock and alluvium, but also for masonry and for levelling and compensating for settlements.

Serre-Ponçon dam, a remarkable construction

This dam is iconic in the history of the grouting technics. Besides its unprecedented height and the importance of the soil grouting work conducted up to a depth of 100m, it is also the first project in which sleeved pipe grouting method was used.

The construction of this dam was a part of the hydraulic development of the Durance and the Verdon valley. The idea of building a dam on the Durance first appeared during the 19th century, following the exceptional floods of May 1856. The purpose of the construction of such a dam was to smooth the high flood levels of the river and to solve the problem of lack of water in dry periods. The project was delayed several times due to technical difficulties between 1897 and 1909. Finally, the engineer Ivan Wilhelm revived the project in 1919.

Twelve drilling campaigns were then carried out until 1927. These campaigns highlighted the difficulties linked to the geotechnical context: the bedrock was located at a depth greater than 100m and was topped by heterogeneous gravelly alluvium layer. High permeability of the alluvium layer (between 10^{-3} to 10^{-4} m/s) and its high thickness did not allow a concrete dam construction (which required a more resistant foundation soil. A compacted earth dam design was chosen for the first time in Western Europe.



A competition was organised by *Electricité de France* in 1948 for the design and the construction of the dam. The selected project was a compacted earth dam, with a height of 124 m, a length of 600 m and a width of 650 m. It resulted in a water retention of 1 200 million cubic meters. The dam construction started in 1952 and lasted until 1958.

The construction required the grouting of 100 m of alluvium to make it waterproof. The objective was to avoid the infiltration and internal erosion that could alter the stability of the dam foundations.

Grouting over such a large thickness required the development of adapted techniques that allowed grouting at very high pressure and reinjection by phases, as well as the use of fine binders that do not segregate too quickly over the injected thickness. Soil grouting was then conducted by Soletanche using sleeved pipes. This is the first use of this technique, developed by Soletanche particularly suitable for grouting soft ground. Soil grouting using this technique follows these steps:

- A borehole is drilled, into which a sleeved tube is inserted. The tube is sealed in the ground to prevent the grout from rising under the effect of the grouting pressure through the space between the tube and the ground.

A sleeved tube is (metal or PVC) smooth on the inside and perforated every 30 to 40 cm. At each perforation, rings with slots called sleeves are installed. These rings act as valves allowing the binder injection under pressure.

- Grouting is then carried out from the bottom to the top using an injection hose fitted with a stopper to prevent the binder from rising in the tube.
- At each depth, grouting is carried out in two phases: a phase of injection of a bentonite cement binder to fill the soil coarsely, followed by a phase where a more penetrating binder is injected to fill the soil finely.

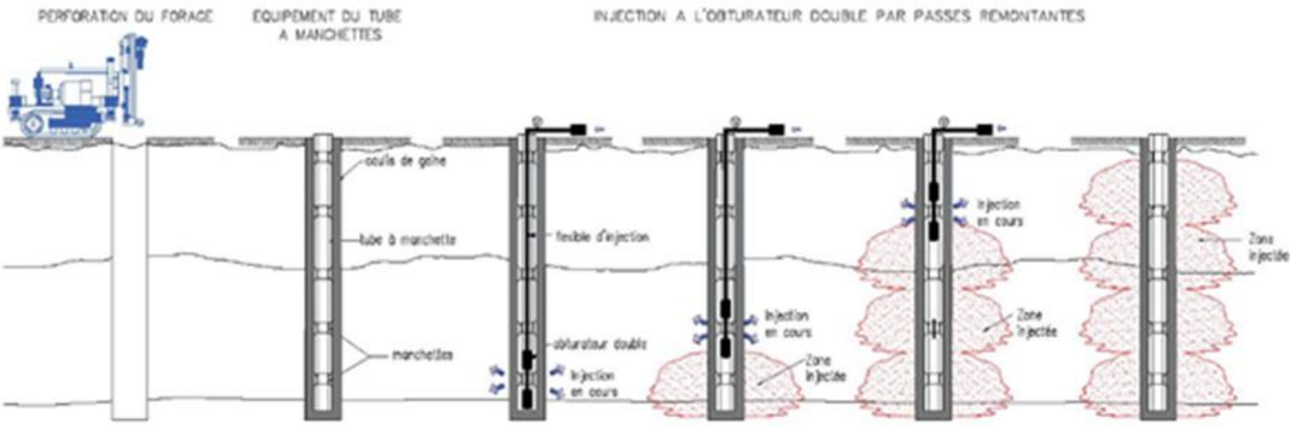


Figure n° 12 : principe de l'injection de claquage – séquence des opérations

The injections were carried out on a surface of 4200 m², with an in-depth width of 15 m and 35 m width at the connection to the dam. The grouting operation used a total of 10000 tons of fine slag cement and 20000 tons of Apt's clay. The volume of alluvium involved was estimated at 100000 m^3.

The usefulness of these injections has been confirmed through measurements. The maximum flow measured through the grouted zone was about 25 l/s and the alluvium permeability was reduced to approximatively 2.10^{-7} m/s.

Interview: Michel Chopin

After a remarkable career at *Solétanche* under Henri Cambefort's direction, Michel Chopin is currently working in KF International SA as a geotechnical consultant, specialised in special geotechnical work. He is known as a soil and rocks grouting expert and is the head of the AFTES working group in charge of the updates of the French soil grouting recommendations.

***Youssef and Thibault:* From your point of view, why is soil grouting such a particular technique in geotechnical work?**

Michel: For me, the use of soil grouting is to change soil property, reduce the permeability and increase the modulus, from a distance, including for rock masses. It is a relatively easy operation to carry out and, compared to other invasive methods or methods that require excavation, it allows us to transform the soil conditions in advance, and thus to carry out works in completely acceptable feasibility conditions.

***Youssef and Thibault:* Based on your experience what are the major advances in soil grouting methods since the beginning of your career?**

Michel: Progress in grouting technics can be divided into three parts. Firstly, the progress in drilling methods. Over the last 40 years, drilling techniques have evolved considerably. Today, we have machines that allow us to drill tubed boreholes very economically and with high productivity, which allow us to pass through difficult soils with much improved performance. Also, the recording of drilling parameters has become a usual way of processing and a very useful source of information.

Secondly, in terms of equipment, following Henry Cambefort's idea, which he shared with G. Rodio, the development of the sleeved tubes method made it possible to equip and carry out impregnation work in granular and non-cohesive soils. What is regrettable, however, is the use of sleeved tubes in cohesive soils. In these soils, the fact of sealing a sleeve tube isolates the crack network and in order to reach it again, one is forced to push it through, which leads to the over-fracturing of these soils. And this over-fracturing is often harmful, or at least not useful. Moreover, it leads to conducting grouting work at pressures that include high losses and are, therefore, poorly controlled. So, for more than thirty years now, we have been developing the multi-packer system (MPSP), which uses a sleeved tube equipped with expandable bags (injectable separators) at a distance that is fixed in advance, and which makes it possible to inject directly without borehole grout, 2m, 3m or 5m of soil sections. This method allows a better management of grouting pressures and control of the flow rate, which will be higher than with sleeves tubes. This method has been widely developed recently in the Parisian soils, in the *Marnes et Caillasses* where it is not practical to use a sealed sleeves tube. On the one hand, the use of borehole grout fills the discontinuities that we wanted to treat with a different grout and on the other hand, passing the borehole grout will lead to over-fracturing of the marnes and will create high pressure losses and will not allow us to find a technically valid rejection pressure. So with the multi-packer system we can treat soils between 5 and 7 bars, whereas with the sealed sleeves pipes, it is common to use pressures of 10 bars or more. This makes a huge difference in terms of the quality of treatment and in terms of quantity and time. In fact, while using a pressure parameter, it will lead to inject quantities, to recycle, and to repeat injections several times. These choices on injection quantities and pressures are typically part of the design of the soil grouting works.

The latest development in equipment is the advent of self-drilling systems, but these are often prototypes. There are injection systems which can be adapted to self-drilling system which allow, in a single operation, to set up the drilling equipment, to inject, all through an airlock, so it's quite interesting when you face water pressures.

Finally, in terms of materials, I see three subjects. Firstly, the development of ultrafine cements, which has made it possible to treat fine soils beyond the limits we knew in the past, at permeability values around 10^{-4} m/s. This has made it possible to replace the hard silicate gel that was used in the 70s and 80s and which was susceptible to a phenomenon of syneresis. This is linked to the shrinkage of silicate ions when they are injected in high concentration. In the case of soil fracturing, the silicate gel will form a cluster which will disappear within 3 to 4 weeks and will results in a re-increase of the permeability after the grouting work. Secondly, in the 1990s, silicate gels with organic hardeners were abandoned and in parallel, nano-silicas were developed, which have nothing in common with silicate gels. They are pure silicon ions that are in emulsion and are broken up by a salt solution. This material has been used since the years 2000-2005 because of its expensive cost at the time. While injecting soils, it is problematic, since we fill 30% of porosity, but when we inject rocks it is much better since we do not fill more than 3% of porosity. Finally, there are few subjects on resins and polyacrylates which were widely developed in the 1990s. Those types of materials are not often used, except in particular cases. For example, when we want to make waterproof cores in fine sand, we can imagine a bilinear system with silicate lines and a central line in acrylate or polyacrylates

***Youssef and Thibault:* How do grouting techniques vary between different countries?**

Michel: The French-European grouting methods and North American methods are almost as dissimilar as the difference between Menard pressure-meter methods and Standard Penetration Test methods. They use a technology with a return line circuit that is not easy to understand. During the grouting work, a return line is used so that the pressure does not reach too high values and so that there is no blockage refusal at the pump. This technology is not in our way of achieving the refusal and estimating the quality of the grouting treatment. It's not very efficient and it's sometimes quite anti-productive. In my opinion, this system is can be improved, compared to our technics.

Claude Caron realised, and this was already an approach taken by Henri Cambefort, that very often people were unable to control the injection conditions because they did not take geostatic stress into account. But this is a basic parameter in grouting which will define the possibility of injecting or not at a given depth. The same soil with the same permeability may be injectable at a depth of 50 m or 100 m, but it is no longer injectable at a depth of 10 m, because the horizontal stresses are so low that the binder do not penetrate the soil porosity and simply break soil's resistance and form a cluster, so this is a purely wasteful work. And this is still a recurring problem on certain construction sites today.

***Youssef and Thibault:* Do you have a remarkable construction where soil grouting was determinant for the success of the project?**

Michel: A typical construction site where typical materials have been a technological breakthrough and a subject of interest is the Lötschberg tunnel in Switzerland. It was the first combined rail-road tunnel to be put into operation in 2007.

This Lötschberg tunnel was built in a rather interesting technical way. There was one technical subject, at the southern entrance at Ferden. There is a geological incident which is a cusp of the Triassic liasses which are subvertical at the emergence of the Alps. In this accident, there is a surface exploitation of mineralized water (thermal spring). This thermal spring is fed from within the incident zone. And the tunnel crosses the incident zone twice at 150 m intervals.

The environmental conditions imposed by the operator of the thermal spring and by the courts were to take a maximum of 2 l/s from the two incident zones. So, it was necessary to carry out investigations (as the tunnel was being built) to detect the position of the geological incident zones and the importance of the aquifer. The goal was to treat these discontinuities that were subvertical. To achieve this objective of 2 l/s max, we carried out this grouting work with long-distance drillings equipped with metal standpipes and we had to achieve a permeability of $5x10^{-8}$ m/s, which is not very common. To achieve this, the cracking was injected with a series of ultra-fine binders and then complemented with a nano-silica-based grout. This was the first application of nano-silica on a large scale. The operation was very successful; the system was very effective and is still works.

***Youssef and Thibault:* In your opinion, how did Henri Cambefort play a decisive role in the development and diffusion of the technique?**

Michel: Henri Cambefort was one of the first to carry out a vulgarisation operation which consisted of organising the design thinking from factual elements, a very careful analysis of the data and measurements made in situ and the behaviour of the injection. He was one of the first to try to rationalise the behaviour of grouting by numerical application and he was largely helped in this task by Brillant who tried to extract all that was possible from underground hydraulics in order to use it to interpret the behaviour and give examples of the behaviour of hydraulic binders during their grouting.

We can also largely recall that Cambefort worked on the grouting of fissured media. There are many applications in his book which explain how we can get rid of the treatment of cracks, residual pressure loss in cracking

So, this book is quite interesting because it has made it possible to popularise but also to explain many things and to give mathematical and numerical elements capable of supporting grouting operations (of soils and cracked rock masses) and to explain how they can be organised, designed, and stopped when satisfied with the outcomes.

Another of Cambefort's contributions was the introduction of the sleeved tubes.

Finally, after his retirement, Cambefort published papers in the annals of the IBTP, such as "Soil grouting and its limits", which is a work done with Claude Caron. In this work, there is a theory on how to predict soil failure as a function of stress. This theory makes it possible to predetermine the conditions in which grouting is possible or not in fine soils, only from one flow regime calculated by taking into account the geostatic stress.

***Youssef and Thibault:* The updated version of *"Recommandations de l'AFTES relatives à La conception et la réalisation des travaux d'injection des sols et des roches"* [Recommendations for soils and rocks grouting works] will be published under your supervision this year 2022. What are the major updates of this version?**

Michel: They were clearly missing something in the 2006's recommendations.

First of all, it should be noted that grouting works are a special geotechnical work according to the standard. They are possible under certain conditions that must be defined in advance, specified and evaluated at the preliminary design stage. When the client starts to look at his project and assess its feasibility, he has to look at its environmental impact. And if we realise that, for the construction to be possible, it will require soil grouting, this part of the construction work must be integrated into the design and preliminary work plan and achievability must be checked.

If this is not achievable, the risk must be managed by the project owner during the preliminary design studies. This risk approach is associated with the establishment of a risk register. This register must be communicated to the project owner at the time of contracting with the design offices, so that everyone is aware of the progress of risk management, particularly with regards to grouting work and environmental risk in general. Then, this approach continues to be managed throughout the study period: preliminary project, project, and contractor consultation phase. At the time of contracting with the building company, it should take a position on the risk register and either refuse, contest or accept it.

The reason to create this workflow is simple. If risk management is addressed at each stage of the project between the project owner, the project designer and the building company, it will be possible to establish a contract in which the company will be paid into three parts. The first semi-fixed main part corresponds to given quantities. The second secondary part corresponds to additional quantities in the event that these are necessary in view of the environmental variabilities. The third part is a flexible part that will allow for the payment of additional studies, and unexpectable changes in materials or equipment in case of particular conditions that would be manifested and that had not been demonstrated, found or identified during the studies by the risk register.

For the grouting operation itself, its characteristics, its extension and its quality must be precisely defined in the project. If a grouting work is used, it aims to obtain different characteristics from the natural ground. If a given permeability is required, this must be specified and it must be ensured throughout the project that the means used are appropriate to obtain this result. This includes making sure that during the design phases the project manager is aware of the means that will be needed to achieve these results and guarantee the objectives (the need for non-standard materials and equipment, for example).

We will try to push in this direction to avoid the project owner being afraid of soil grouting work in projects (because of the uncertainty of the time needed for this work and its usefulness) and the engineer not taking into account the injections in his calculations for safety reasons, because we are not sure if the treatment is homogeneous. We sometimes end up letting grouting work go ahead that no one really believes in, without really knowing why, because we have not defined a precise objective to achieve.

So, we have to get out of this problem, which makes no sense from a technical or financial point of view. To get out of it, we have to clarify the achievability of soil grouting and to describe the technical way in which we can imagine an improvement in the soil and how we can take it into account in the design. This should be addressed in discussions involving the project designer the client and the building company at the different stages of the process, initial design, project design and construction, in order to avoid possible disturbance in the programme and subsequently increasing of the project's cost. This is why it is important to know from the beginning of the project the relevance of the chosen method (if any), the reason of this choice, the target results of these work and the way to control they efficiency, in order to take it into account during the design.

And that leaves the technical part, which is in fact an update of the old recommendation, which is a best practice. This part will be reorganised in terms of the presentation of the arguments so that it is easier to read.

Furthermore, the organisation of the recommendation is totally different from the previous version. It is organised in 6 chapters, plus a technical annex. The document is organised like the chronological phases of the project. You start with the acquisition of data at the client level, the concerns of the client with its preliminary project and its objectives, as well as the sharing of the risks. Then you have the project design with all its studies and the way in which the grouting project is developed. Then you have the contracting phase with everything that it should mention to explain each party commitments and responsibilities. Then, there is the building section. It includes everything that involves the preparation and execution of the works, the necessary documentation, and the appropriate controls for each of the objectives. And finally, the appendix gives an overview on all the technical part, with tables and graphs. So it's a radical change compared to the previous version of the document.

On the other hand, we will take advantage of this update, as we do each time we publish an updated recommendation document, to include feedback on a few unfortunate experiences to prevent them from happening again. It may concern all sorts of operations, in order to avoid disasters and especially to avoid a bad perception of the design of the grouting works.

References

La conception et la réalisation des travaux d'injection des sols et des roches. (AFTES 2006), Tunnels et ouvrages souterrains, (194-95), 70-149.

Cambefort, H. (1964). Injection des Sols, Part I and Part II. Eyrolles.

Rock Grouting and Diaphragm Wall Construction, 1st Edition - February 1, 1989, Author: J. Verfel.

Grouting Deep Alluvial Fill in the Durance River Valley, Serre Poncon Dam, France, Marcel Haffen, Engineering Geology Case Histories Number 4, Geological Society of America, Volume 4.

Barrage de Serre-Ponçon. Gap (Hautes-Alpes). France (1960).

https://www.soletanche-bachy.com/fr/solutions/techniques/etanchement/injections.

Réparation et renforcement des fondations (guide STRRES).

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