SOIL IMPROVEMENT SYSTEM USING RESIN INJECTIONS IN SUBMERGED TUNNELS

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ABSTRACT:

The world of construction, and in particular the field of underground works, is immersed in a constant state of innovation and development. Numerous new variables are at work in this field, both in the improvement of the properties of materials and construction technology and in the new requirements and demands of users. Throughout history, civil engineering has had to offer support to the needs of comfort, aesthetics, sustainability and worker safety, among others. Of these, the latter is the most important and has become increasingly relevant in recent years. This research aims to offer an integral solution to the tunnelling process, under phreatic surfaces and in geological conditions of low cohesive strength and subjected to high pressures. The intention of this technology is to treat the ground by means of injections applied from inside a TBM to revise and replace the worn tools of its cutting wheel. The proposed solution consists of installing a high-frequency drilling unit in a hydroshield TBM. This new device is analysed to determine whether it offers a solution for the proposed requirements. The results obtained confirm a 15% improvement compared to existing solutions, greater efficiency and speed of execution, while proving to be a safer technique in terms of occupational risk prevention and respect for the environment.

Keywords: Subsea tunnel, Ground treatment, Water table, Injections, TBM, Hydroshields.

1.- INTRODUCTION

The development of maritime and terrestrial communications in recent years has required many societies to attempt to overcome the geographical accidents of their surroundings and adopt new solutions to maintain their competitiveness and the well-being of their citizens over time [1][2]. Although underground construction work has been around for a long time, the evolution of the requirements has given rise to a very precise field of engineering that demands the mastery of many techniques.

A tunnel is a type of infrastructure that adapts well to current communications requirements and society's environmental demands, and this infrastructure has evolved with time [3][4]. Tunnels are becoming more numerous, are becoming longer and are being built under conditions that are more difficult.

Building tunnels implies great complexity and a series of risks that must be managed, plus heavy investment in time, money and labour [5]. Currently, tunnelling machines play an important role.

In the past, the problems to be solved in the excavation of tunnels were complex and dangerous, but thanks to the fact that in the recent years there has been great growth and diversification in underground engineering [6] [7] we can now find multi-purpose underground constructions.

One of the problems to solve when drilling tunnels is that we always depend on thecharacteristics of the soil. When the tunnels are built in hard rock [8] the challenge is to pierce the rock mass by fracturing, excavating and extracting. Often, the excavation is self-supporting [9]. These days, however, it is customary to line the tunnel, even though many early tunnels had no lining and brick or stone linings were only added in areas that were weaker or fractured [10]. In the case of tunnels in soft soil, the main difficulty is to avoid collapse inside the tunnel [11]. Years ago, to perforate soft soil the normal method used manual excavation followed by elaborate shoring to support the trusses, the vault and even the front [12]. It must be noted that this system is not viable beneath the phreatic surface, so its use is considerably limited; it cannot be used, for example, to tunnel beneath rivers.

This traditional method of digging tunnels has advanced progressively, giving rise to shield tunnelling machines [13]. These machines are used to dig out full-size tunnels in soft soil; their mechanisms are confined inside a cylindrical shield, to protect them from the difficult soil conditions and possible cave-ins, providing immediate support while at the same time allowing a definitive tunnel lining to be constructed from inside them. After the shield tunnelling machine for soft soil came tunnelling machines with a completely circular section, with rotary heads for cutting solid rock [14]. Currently, complete machines used to excavate tunnels are normally known as TBMs (Tunnel Boring Machines), and refer to a series of machines capable of boring full-sized tunnels while allowing the installation of provisional or permanent shoring [15].

In addition, and depending on their specifications, tunnelling machines are divided into two main groups: rock boring machines and ground boring machines [16]. Both have specific features, depending on the type of rock or ground to be excavated and on the requirements for shoring or lining required by each type of soil. We should also mention moles, robust and relatively simple machines designed to excavate hard or medium-hard rock that does not require much support, and that operate by pushing hard metal disks against the soil, breaking it apart so that the rock fragments fall through the slots in the cutting head onto a conveyor belt that then either drops the waste onto another belt that removes it from the tunnel or deposits it in wagons for removal. Shoring normally uses conventional systems, i.e., studs, trusses and shotcrete. To absorb the shocks of the cutting head and move the tunneller forwards, TBMs use grippers to anchor the machine to the ground [17].

The characteristics of the rocks that limit the operations of these machines are, as the upper limit, simple compression strength and the quartz content, and as the lower limit, the sustainability of the soil during excavation and its strength, so that the grippers can get a good anchor. In machines with shields, the basic principle of excavation is the same as for moles, but with the protection of a shield during the excavation that allows a prefabricated lining to be installed from inside it. There are single shields and double shields [18].

In the case of double-shield tunnelling machines [19], these are more sophisticated and can be used in many different types of soil, depending on the quality of the rock. In this type of machine, the shield is divided into two parts: the front part, where the cutting head is located, and the tail, where the lining rings are installed. These two sections of shield move independently, with the grippers located in a space between them, so that the head can continue excavating while the lining rings are erected in the tail shield. As a result, the performance that can be obtained with this system is greater than that achieved with a single shield. Systems of this type can be used in soil that can withstand the forces transmitted by the grippers. In other words, while the soil withstands the pressure of the grippers, it is possible to carry out the excavation and the shoring simultaneously, installing the tunnel lining while continuing to drill.

When the soil faces are unstable, EPB (Earth Pressure Balanced) shields are used [20]. Machines of this type normally work by compressing the earth, mixing the material excavated in the chamber for subsequent extraction with a screw conveyor, adjusting the pressure in order to maintain the stability of the face. They can also be used in open mode (without pressure) in regions with better-quality soil, allowing the material to be removed by conveyor belt rather than with a screw conveyor.

At present, tunnelling machines with hydroshields are being used [21] [22], in soil with low cohesion consisting of loose sand or sandy gravel. These are similar to earth pressure balanced shields, but with two main differences: excellent control over the earth pressure (mixing the earth with a water-clay slurry) and much lower energy costs [23]. The material is removed via a pipeline, pumping the mixture out of the tunnel. The disadvantage of this type of machine is the treatment of the material removed. Since it is mixed with slurry, it requires plants with a large surface area to separate out the finer particles.

Summarising the above information, the figure below illustrates the classification of TBMs based on geological and hydrological factors (Figure 1):

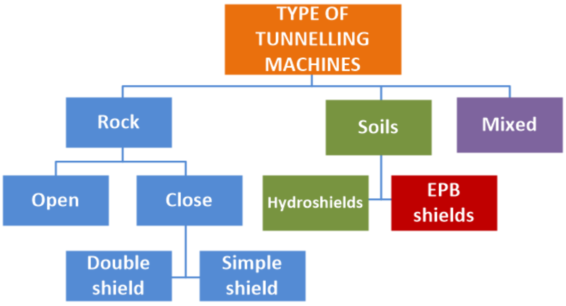


Figure 1: TBM classification by soil geology and hydrology.

When underground tunnels must be constructed at a great depth in soils with low cohesiveness, start-up and repair of the cutting head in the TBM is very challenging [24] [25], since a team of divers is required with expertise in subaquatic maintenance and repair operations at high pressures [26].

As a consequence, when evaluating underwater tunnelling activities at great depth and under adverse geological conditions [27], we can identify risk situations [28], since the area around the cutting wheel is directly connected to the sea bed [29] [30]. To solve this problem, we may consider the construction of a block of consolidated soil, to act as a barrier around the cutting wheel and part of the machine's shields, using injections from inside the TBM.

The main aim of this article is to develop this method of improving the soil around the head of the TBM with the addition of a hydraulic hammer. This method requires less time and fewer surface resources, has a lower environmental impact [31] and reduces labour-related risks considerably [32].

This research is intended to study the viability of adapting a drilling system operated from inside the hydroshield to change the cutting head when the machine is submerged under high pressure.

2.- MATERIAL AND METHOD

Since we are dealing with submerged excavations, a project located in the North of Spain is a case in point. Water is the main problem to be faced, since it influences the conditions for drilling, which can only take place when a continuous flow of water to the excavation site can be avoided. In the preliminary work, the idea is not so much to reduce the water level in the soil, but rather, to prevent water from circulating during the drilling.

The operational sequence proposed is therefore as follows:

a) Perforation of the soil
b) Consolidation of the soil
c) Generation of the bentonite slurry
d) Change of the cutting head

2.1.-Perforation of the soil

To commence this sequence, the first task was to select the most suitable drilling equipment, which was an adapted high-frequency hydraulic hammer for rock. We opted for a complete adaptation of this hammer, which is commonly used in jumbo-type machines. Tools of this type are used to drill conventional tunnels, and are mounted on hydraulically-operated arms to drill into the face (Figure 2). This hammer was selected given its excellent performance in rock tunnelling operations and its special characteristics that allow independent adjustment of the drilling length, impact energy and rotation.

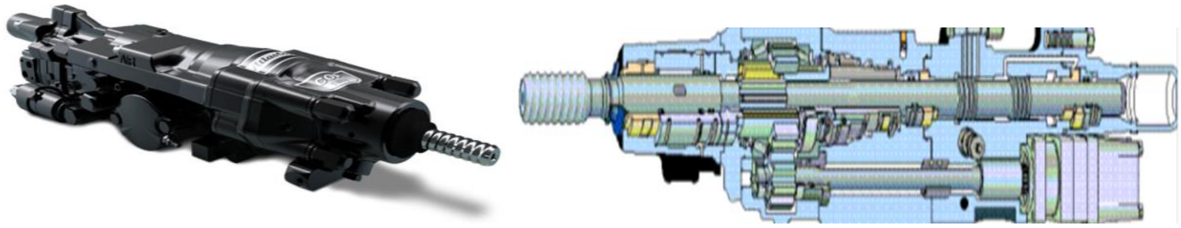


Figure 2: Hydraulic hammer drill [34].

This tool would allow us to drill the necessary holes for the installation of the BOP (Blow Out Preventer) valves required to seal, control and monitor the wells. BOPs were developed to manage the extreme and erratic pressures and the uncontrolled flow rates that are encountered during drilling. The thrusting or formation kicks can lead to a potentially catastrophic event called a blow-out. Apart from controlling the pressure, they prevent the drilling tube and the lining, the tools and the perforation fluid from being ejected from the shaft area when there is significant excess pressure.

The main functions of a blow-out system are:

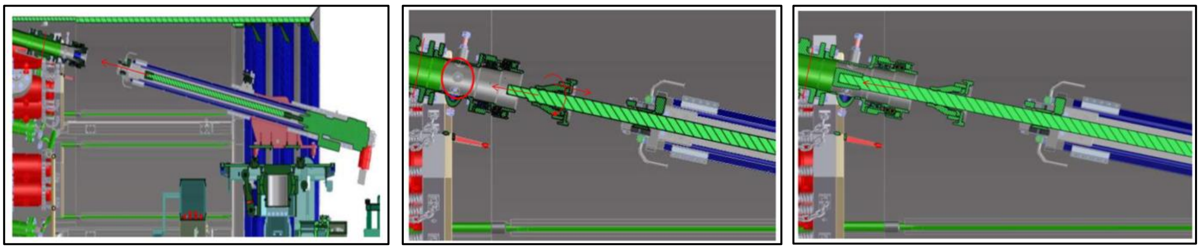
- To confine the drilling fluids inside the tunnelling machine.
- To provide the means to supply fluids to the drill.
- To remove controlled volumes of fluids from inside the tunneller.

When drilling a high-pressure borehole with the hydraulic hammer, as in this case, the drilling assembly passes through the BOP set into the soil. As drilling proceeds, drilling slurry or fluid is injected through the drilling assembly into the borehole. The slurry returns via the cylindrical space between the lining tube and the perforation tube. The column of perforation slurry applies a hydrostatic pressure that counteracts the opposing pressure of the formation and allows drilling to continue.

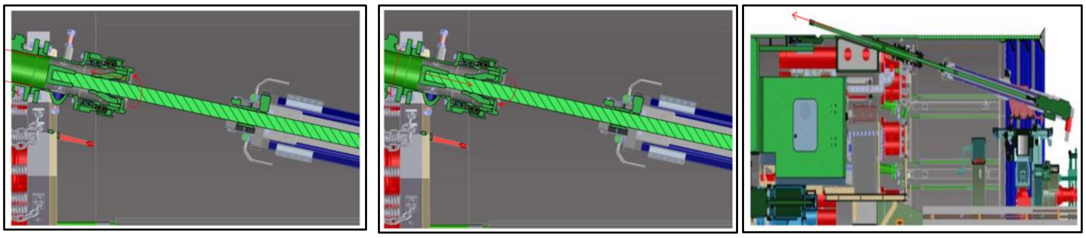
When the start of a blow-out is detected, the equipment operators or automatic systems close the BOP units, sealing off the cylindrical space in order to prevent the loss of the fluids inside the shaft area. Following this, higher-density slurry is injected through the drilling assembly, into the shaft area and up into the cylindrical space and the strangulation line in the base of the BOP and through the stranglers until the down-stream pressure is exceeded. If the integrity of the shaft is maintained, drilling can recommence. Alternatively, if circulation is not feasible, the shaft can be closed “by force”, i.e., by pumping heavier slurry at high pressure from above via the connection to the kill line in the base of the BOP. This is the least desirable option, since it requires greater pressure on the surface and because a great deal of the slurry that was originally in the cylindrical space will be forced towards the interior of the receiving formation in the unlined section of the shaft, below the deepest footing of the liner.

If the elements that prevent the blow-out and the column of slurry do not restrict the upwards pressure of the kicks in the shaft, the result will be a blow-out that could potentially shoot water violently through the tunnelling machine enclosure, damaging the drilling equipment and compromising the integrity of the tunnelling machine.

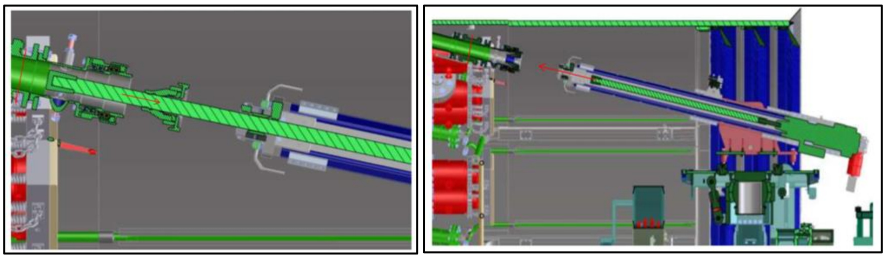
Once all phases for the installation of the BOP valve and the hydraulic hammer are completed, the drilling work for the treatment of the soil can commence in safety.



Phase 1: installing the hammer in the drilling position Phase 2: installing the “preventer” valve on the perforation barrier. Phase 3: installing the drilling head on the HERRENKNECHT drill.



Phase 4: Screwing the preventer valve onto the flange of the sounding tube, and opening the ball valve. Phase 5: Perforation of the sounding. Phase 6: After the injection, retract the drill, close the ball valve and unscrew the “preventer” valve. HERRENKNECHT,



Phase 7: Removing the preventer valve from the drill crown and the drill shafts. Phase 8: Positioning the hammer for a new perforation. HERRENKNECHT,

2.2.-Consolidation of the soil.

The first step in treating the soil is to reduce the water flow at the drilling face and thus to inject the resin as a containment barrier by injecting it outside the lining sections closest to the machine.

There are several ways of doing this:

1. Vertical injections from outside.
2. Injections from inside the hydroshield.
3. Injections from outside and from inside the hydroshield.
4. Injections in a previous area with secant piles.
5. Injections from a shaft constructed using a VSM (Vertical Shaft Machine).

In this specific case, the second method was chosen, since it is the cheapest and reduces the installation time, requiring fewer resources on the surface and reducing the social and environmental impact.

Planning was broken down into two phases. In the first, the retaining screens are constructed, by drilling two rings of perforations on the lining sections closest to the machine (valid for hydroshield diameters between 3.5 and 5 metres). The second phase is carried out from inside the machine, drilling a series of radial perforations with a conically truncated orientation with respect to the centre line of the tunnel, with a length of 12 and 9 metres and a triangular layout, so that the former extends beyond the position of the cutting wheel. Once these holes have been drilled, the drilling tool is removed and replaced by a hollow drill made of frp (fibre-reinforced polymers), through which the consolidation resins will be injected.

Strictly speaking, the chemical reaction starts immediately behind the lining, at the point of injection, although, given the low density of the resin, the expansion of the foam (which pushes the material around) and the injection pressure from the pumping system, allow it to move, completely filling the space behind the lining. Hydraulic fuses are incorporated into the hollow frp (fibre-reinforced polymer) tubes that act as shutters, activated according to the injection pressure or by the operator, to allow more precise control over the pressure and the filling of the micro-fissures of the soil. (Figure 3).

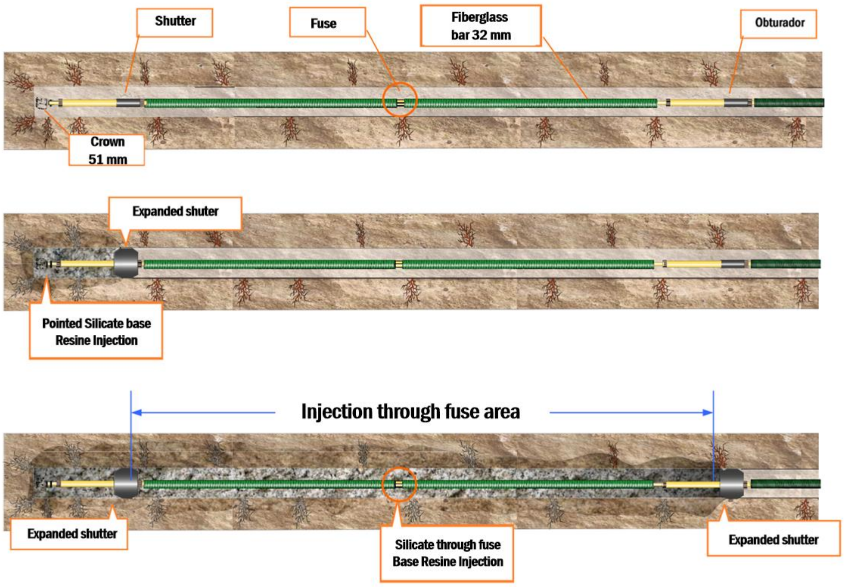


Figure 3: The assembly sequence proposed for this solution:

This will generate a network of injected material/filling for each point treated in the soil that improves its mechanical characteristics. The proposed sequence of injections by sectors at pre-determined distances allows us to provide greater stability to the soil, since the injections are carried out closer to the cutting head, which ensures homogeneity of the material injected and reduces as far as possible the risk of leaving unfilled gaps.

2.3.-Generation of the bentonite slurry.

Once the soil has been drilled and consolidated, the face of the excavation is sealed by adding bentonite slurry from inside the tunneller using the machine's pumping system, trying to achieve a density that will close the pores in the previously consolidated soil in order to maintain a constant pressure and so prevent the entry of material into the tunneller chamber. Once the pores in the soil have been sealed, the cake is replaced by a bubble of pressurised air so that the cutters can be changed from inside the machine.

In this section, we shall define a test procedure to analyse, in hydroshield tunnellers, the infiltration capacity of different configurations of modified bentonites in highly permeable soil. Specifically, we used the following reference: "Modified Bentonite Slurries for Slurry Shields in Highly Permeable Soils". P. Fritz et al. Division of Geotechnical Engineering, Swiss Federal Institute of Technology ETH, Zurich. Using this as a starting point, we have studied new bibliographic references to adapt the test procedure to the available resources.

2.3.1 Description of the test.

Elements required for the test.

To carry out these tests, the following laboratory equipment and materials are required (Figure 4):

1. Transparent tube (plexiglass or similar) 80 mm diameter, with a height between 30 and 40 cm.
2. Hermetic caps to close the tube, with a lower valve to remove water and an upper valve to introduce compressed air.
3. Filter for the water outlet.
4. A soil sample, simulating the real permeability conditions for which we are evaluating the infiltration capacity.
5. Modified bentonite slurries in the required doses.csdfzsdf
6. Precipitation flask (estimated size 500 ml)
7. Electronic scale.
8. Compressor, valves and connectors for the compressed air system.

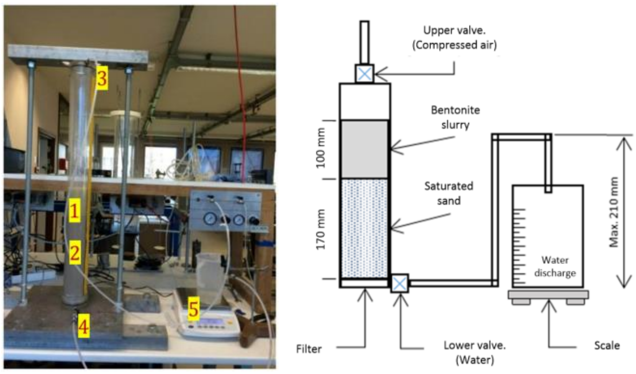


Figure 4: Photograph of the test column. 1, plexiglass tube; 2, material under study; 3, compressed air system; 4, water outlet; 5, system to measure the expelled water. (Xu, Dias, & Bezuijen, 2018).

The test procedure consists of the following passes (Figure 5):

1. Within the transparent tube properly attached to the base and with the valve closed, a thick filter is inserted that allows water to be expelled while removing particles that could block the water outlet valve.
2. A fine, saturated granulated material simulating the natural soil in which the slurry must be infiltrated is placed on this filter. This sandy layer should have a thickness of 170 mm.
3. On top of this layer, a layer of modified bentonite slurry 100 mm thick is deposited.
4. The assembly is then closed hermetically and connected to the compressed air system.
5. At the bottom of the test column, an outlet tube must be connected to the outlet valve, running into a precipitation flask on the scale, to register continuously the weight (volume) of water expelled.

   There should be an outlet tube connecting the system so that only the liquid part reaches the flask, leaving any solids at the bottom.

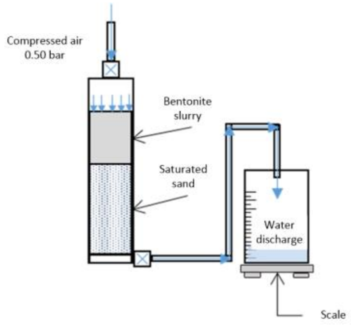


Figure 5. Schematic of the test procedure.

Test method.

At the start of the test, all valves in the measuring equipment must be closed.

1. Mount the transparent tube on the base of the test equipment and insert the filter paper.
2. Prepare the sand: The granulometry, density and optimum humidity of the sample of permeable soil used for the test must be known, since we need to know the porosity of this sample.

   The test procedure indicates that the soil sample should be inserted at 90% of its relative density until the layer is 170 mm thick. Once it is in place, determine the mass of sand inserted into the tube and its density. With these values (▯, %W), the porosity of the sample can be calculated.

   The sand is then saturated by adding seawater, simulating the conditions on-site, leaving the equipment to settle in order to guarantee total saturation of the sand sample.
3. Preparation of the bentonite slurry. The mixture of water, bentonite and additives should be stirred for at least 20 minutes to achieve a homogeneous fluid, and it should then be allowed to settle for 24h. After this time, the slurry can be added to the test column, on top of the saturated sand.

   The dosages for the bentonite slurries have been suggested by the team at the work site.
4. Close the test column and connect the compressed air system. Check that all valves in the system are closed.
5. Open the compressed-air inlet valve to pressurise the test rig. The test protocol indicates that the air pressure should be 0.5 bar. At this point, increase the compressed air pressure to 1-2 bars.
6. Once the pressure inside the test column has stabilised, open the lower outlet valve to start the test.
7. Readings of the amount of water expelled should be recorded every 30 s for 3 minutes. These readings should be plotted as the square root of time (√t) vs. volume of water expelled (Figure 6).

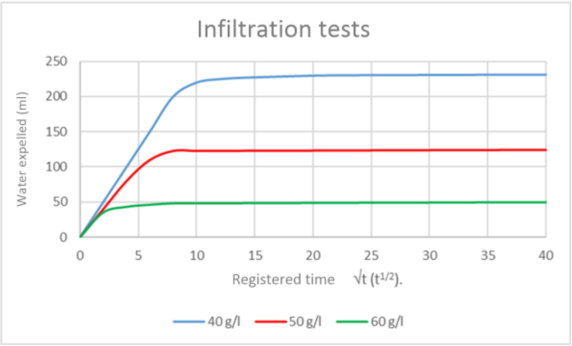


Figure 6. Example of graphs of test results for different dosages.

Test results.

The parameters obtained in each test include graphs of the volume of water expelled as a function of time, where time is expressed as its square root. This data allows us to calculate the infiltration thickness via the expression (1):

$$x_t = \frac{V_{pw}}{A_{IC} \cdot n} \qquad (1)$$

Where: x_t is the infiltration depth; V_{pw} is the volume of water expelled; A_{IC} is the area of the test column; n is the porosity.

To estimate the infiltration speed, expression (2) is used.

$$V_{slurry} = \frac{a}{(a+t)^2} x_{max} \qquad (2)$$

In this case, time "a" is estimated based on the test results, taking it as 50% of the maximum infiltration thickness ($t(x_t/2)$). The maximum infiltration speed is identified at the start of the infiltration, with t=0, so the expression is reduced to the following:

$$V_{slurry} = \frac{x_{max}}{a} \qquad (3)$$

With the set of infiltration graphs and the numerical results obtained from the calculations (Maximum infiltration thickness x_t. and maximum infiltration speed $V_{slurry,0}$), we obtain the results required to study the behaviour of bentonite slurries.

Tests required to study bentonite slurries.

1. Soil typing tests:
    a. Granulometry;
    b. Specific weight of the soil particles;
    c. Standard Proctor test to determine 90% of the relative density;
    d. Permeability test.
2. Characterisation of the bentonite slurries: Viscosity (Fann-type viscometer). 1 measurement should be made per dosage.
3. Characterisation of the bentonite slurries: Infiltration tests.

This part of the tests includes characterisation tests for the selected slurry and four alternatives with different dosages. In view of this, the following battery of tests is proposed (Table 1):

Solution	Theoretical composition of the slurry	Number of determinations
APPROVED	60 kg/m^3 Berkbent 100 (TOLSA) + polymer.	2
ALTERNATIVE 1	60 kg/m^3 Berkbent 100 (TOLSA) + polymer	2
ALTERNATIVE 2	50 kg/m^3 Berkbent HY (TOLSA)	2
ALTERNATIVE 3	50 kg/m^3 Bentonil CF (CLARIANT) + polymer.	2
ALTERNATIVE 4	50 kg/m^3 Bentonil XR (CLARIANT) + additives.	2

Table 1: Alternative dosages more optimal to be tested.

Taking into account the number of tests suggested and considering the volumes required for the tests, two litres of slurry will be prepared for each determination, so we will need at least 2 kg of each type of bentonite, plus a sample of the additives and polymers that will be used.

At least 20 kg of the sand used as the infiltration material will be required, plus 20 litres of sea water.

Once we have obtained the final results of the tests, we will be able to determine the optimum dosage in terms of mechanical behaviour of the soil and optimum costs. We can then use this dosage in the cake and proceed to the final phase, the substitution of the cutting elements on the front of the tunnelling machine.

2.4.- Changing the cutting tools.

Given the solution adopted in this article, it will be possible to inspect the cutting head/wheel and the cutting tools from inside the machine using hyperbaric techniques. During this inspection, possible damage must be evaluated, plus critical zones that require immediate intervention by technical divers, to carry out the appropriate changes (both in the cutters and in the crusher). Once the preparatory actions to prepare the face have been carried out, these changes can be carried out using conventional techniques.

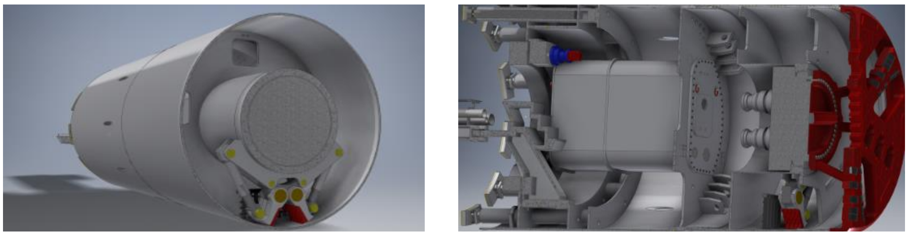


Figure 7- General view of the cutting tools of the hydroshield.

3.-RESULTS

The conventional response if the option of changing the tools from inside the machine does not work and it is necessary to access the machine from outside by constructing underwater screens in the middle of the bay can be divided into the following 6 phases, which consist on the following units:

1. - Auxiliary installations to disassemble the tunnel.
2. - Disconnect the machine's circuits (slurry circuit, electrical circuits, transport circuits, etc.)
3. - Preparatory work in the access shaft and inside the tunnel.
4. - Dismount the tunneller (lining tables, bridge, erector, pumps, etc.)
5. - Work on the shield.
6. - Work outside the tunnel.

It is estimated that 180 days are needed to carry out this work, in which the most critical phases involve the preparatory work for the access tunnel and the disassembly itself (phases 3, 4 and 5), which take up about 60% of the execution time and 70% of the assigned resources.

For this reason, other alternatives, such as that discussed in this article, are studied that require fewer resources and shorter execution times, attempting to change cutting tools from inside the tunnel and to minimise as far as possible the exterior work required on the sea surface. For this reason, the savings provided by this solution have been calculated, assuming an estimate of 15% of the material execution budget, since the disassembly time is reduced by 31%, which implies reduced C.D. and C.I. resources.

4.-CONCLUSIONS

Technological advances in construction of underground tunnels means adapting existing technologies in areas where they have not yet been used due to the technical, economic, social and environmental difficulties. For this reason, comparisons between different injection methods demonstrate that the method pursued here, with its characterisation and adaptation, and which consists in a new soil treatment based on injections from inside a TBM, allow worn tools to be revised and replaced on the cutting wheel with greater safety. In this specific case, the method employed is the best used to date for works of this type under exceptional geological conditions (water at high pressure) that make drilling operations to change cutting tools from inside the machine difficult and that require that the safety both of personnel and of the machine must be guaranteed at all times.

Although this method is ready for use, if a large number of actions are required, we should first define the assembly methods and the systems used to adapt the machine to the installation of the high-frequency drilling equipment, although in the prototype, it can be seen that an improvement can be obtained with respect to solutions available in the marketplace, from the cost point of view and also as regards prevention of labour-related risks.

In view of the above, and in summary, the main conclusions obtained in the course of this investigation are:

- Definition, testing and field validation of injections from inside a TBM that allow execution times to be reduced 15%, compared to other solutions on the market.

  In this case, the results corresponding to the development of an innovative construction process necessary for the disassembly of a hydroshield tunnel boring machine and extraction through the attack shaft are analyzed. Given the geological causes that arise from the continuity of the drilling, the serious deterioration of the cutting tools and the impossibility of being able to maintain a "bubble" in the front to be able to carry out the changes with hyperbaric works; the need arises to provide for the disassembly of the tunnel boring machine in an exceptional way (from inside the machine itself). For the reasons listed and given the complexity of building an extraction well in the middle of the bay, the traditional construction system has been discarded in such cases (making an extraction well using screens) whose planned project solution was valued at about 3 .5 M€, in said solution all the costs corresponding to the execution of the extraction well, the drainage for the execution of the jetty as well as the works of access to the bay will be improved).

  In this new line of action, an approximate calculation of the costs involved has been made; the resins, the valves and the anchors, estimating the total costs at around €300,000. This very low cost is due to the fact that a large part of the material used for its application already belongs to the company's assets, and has been amortized, for which reason said costs have not been allocated in this section, although it has been deemed convenient to mention it to obtain a global perspective of the project.
- Adaptation of drilling equipment used in other types of tunnelling (conventional tunnels using jumbos or scrapers) and reapplication of this high-efficiency equipment to a hydroshield TBM.
- A reduction in the environmental impact in the work area itself.

In the course of this work, we have developed our own equipment for soil treatment that allows us to review and replace worn tools in the hydroshield cutting wheel in a satisfactory manner, thanks to knowledge obtained from the construction sector and technological advances, achieving beneficial results in the pursuit of our objectives.

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