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Recent underwater geomembranes solutions for dams and canals

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SYNOPSIS Underwater geomembrane technologies to stop or minimise leakage and grant safe and efficient operation started being adopted on dams in 1997, and have since been used to repair the full face of the dams, specific leaking areas, or failing joints. In the 2010s the combined expertise in waterproofing dams underwater and canals in the dry led to the development of a patented geomembrane system for underwater repair of canals in flowing water. Sibelonmat® is a watertight, factory prefabricated mattress formed by two geomembranes which are interconnected to form a void space, deployed underwater on site, to line the entire cross section of the canal or parts of it, and joined underwater to the adjacent mattresses by heavy duty watertight zips. The mattresses are then filled with cementitious grout to permanently ballast the bottom geomembrane that provides watertightness, while the top geomembrane confines the grout. This paper presents the state-of-the-art technologies in still water and in flowing water through two recent underwater projects: Studena, a 55m high buttress dam in Bulgaria, and the Kembs embankment, part of the Grand Canal d'Alsace navigation waterway in France.

INTRODUCTION

Ageing of hydraulic structures is almost always associated with decreased watertightness, which over time may jeopardise the efficiency of the structure, and ultimately its safety. To allow the structure to continue operating safely and efficiently, seepage must be stopped or minimised. Geomembrane systems are a proven method to restore watertightness in ageing dams since the beginning of the 1960s.

Until the early 1990s, to install a geomembrane system the dam had to be dewatered, which is sometimes impossible, or possible at unacceptable financial and/or operational, environmental, and social costs. Research carried out in the years 1995 and 1996 led to the development of a Carpi geomembrane system that could be installed underwater without impacting on the operation of the reservoir, and was followed in 1997 by a real project on a dam in USA, presented at a BDS Conference (Scuero et al, 2000). Many underwater projects have been completed since then, and different systems have been used depending on the extent of the areas to be waterproofed, i.e. the whole upstream face of the dam, or one or more areas where unacceptable leakage had been detected, or local damages (failing joints, cracks, holes). All such systems have in common the fact that the geomembrane has been installed at the upstream face of the dam, in still water conditions.

A new challenge came at the start of the 2010s, when the issue of ageing canals was addressed. Ageing of canals always entails decreased watertightness, hence loss of water, and at times reduced flow, which is magnified by the often-long path from the source to the users. Many studies have been performed on water losses in unlined and lined canals, especially for irrigation canals (Giroud and Plusquellec, 2017; Plusquellec, 2019). Other studies conducted across the globe have shown different values for the average amount of water losses, depending on the regions; overall it can be said that the water loss can exceed 35%. To reduce water loss, unlined canals must be lined, and lined canals where the lining has deteriorated must be repaired. For durable repair, the canal must be dewatered, which can be unfeasible, or feasible only at unacceptable inconveniences and costs. Since the underwater technologies then available were not applicable in most canals, because divers can safely operate only in still or almost-still water (water velocity less than 0.5 m/s), the objective was to develop a geomembrane system that could be installed underwater with the canal in full operation.

The geomembrane system for canals in full operation is the outcome combining the experience gained in underwater projects in dams, the lessons learned in projects executed in dewatered canals, and the knowledge acquired in studies and testing executed in flowing water conditions. The resulting system, Sibelonmat®, has been adopted in three pilot projects in canals. The paper presents the research, the solutions, and the two most recent applications, carried out by Carpi for underwater geomembrane systems in still and in flowing water conditions.

UNDERWATER GEOMEMBRANE SYSTEMS IN DAMS

Advantages and peculiarities of underwater geomembrane systems

When design is adequate and installation is carried out and controlled in a proper way, the quality of a geomembrane system installed on a dam underwater is comparable to that of a system installed in the dry, hence the technical assets are the same: capability of granting long-term safety and efficiency, because geomembranes are practically watertight and maintain watertightness over time, have no defective joints or cracks through which water can infiltrate, and, furthermore, can accommodate settlement, differential displacement, opening of joints, and opening of new cracks, thanks to the tensile properties that allow an elongation largely exceeding that of other traditional remedial measures.

Underwater installations on dams must on the other hand consider the almost always poor visibility, the need of limiting the time of each dive when diving in deep water, and the increased security/safety measures. While any diving depth can be attained, if depth regularly exceeds 50m, saturation diving and therefore a decompression chamber permanently in operation are required. Consequently, underwater works do not proceed as quickly as dry works, and they are more expensive for obvious reasons.

Performing underwater works can be a necessity, or a choice based on the evaluation of the costs, not only financial, of dewatering, and of the benefits deriving from continuing operating the dam, which in hydropower dams means revenues that can balance the higher underwater costs. The extent of the underwater works is another choice to be made: full-face underwater repair minimises the possibility of leakage coming from any unlined upstream portions of the dam, but may be unpractical, especially when large surfaces, great depths, and high diving costs, are at stake, or when leakage comes from a relatively small portion of the dam. The solutions can be to identify the areas leaking most and select the surface to be lined which maximises the benefit of the geomembrane system, or to line the dam in separate stages planned to meet the operational or budgetary needs of the owner. Bulletin 135 (ICOLD, 2010) discusses underwater issues and presents the applications existing at that time. Since 2010, projects of underwater repairs of failing joints and leaking areas have adopted the same or similar systems. An outstanding example is Llyn Teifi spillway in UK, a very demanding project due to the extremely complex geometry, with multiple convex and concave corners in very narrow spaces. The exposed geomembrane waterproofs the concrete spillway and the southern wing wall, extending beyond the two leaking side joints of the spillway, and downstream over the ogee weir, to cover the horizontal joint between the spillway and the new concrete constructed downstream.c The project was completed in 2016; performance data from the owner, dated October 2019, testify to the continuous good performance of the system.

Underwater installation at Studena, Bulgaria 2018

Studena, a 55m high and 259m long buttress dam in Bulgaria, crest elevation 845m, is a recent example of an underwater repair adapted to maximise the efficiency of the geomembrane system while meeting the operational needs of the owner. It is also the first example of an improved tensioning system for underwater installation, as described below.

Studena is a multipurpose dam used for potable and industrial water supply, for irrigation, for regulating the water of the Struma River and its tributaries, for protecting the arable land and settlements downstream of the dam against floods and for power production. The dam is located in the European-Continental climate zone, in a mountainous climate region where snowfalls begin in mid-October. The snow cover persists from 100 to 200 days depending on the altitude, and the snow depth can be from 1m to 3.4m. There are frequent ice formation and freeze/thaw cycles, and this harsh climate required protecting the concrete with a shotcrete layer. Nevertheless, after about 50 years of operation the dam and its appurtenant structures were badly deteriorated, with blistered shotcrete no longer attached to the concrete (Figure 1), cracks on working joints, vertical cracks, and damaged structure of the concrete, visible in the zones where the shotcrete was detaching. An inspection carried out by experts ascertained that water was penetrating the dam through damaged expansion joints that needed repair, and that the clogging of drain holes and piezometers in the gallery made it impossible to obtain true information about seepage at the dam and about the water level rise along the wall-foundation contact.

Although the dam wall was stable and no significant leakage seemed to be occurring, given the importance of the structure and to prevent a critical situation that could later threaten water supply and require more expensive works, the Bulgarian Government decided to implement a complete rehabilitation project to extend the functional life of the dam by at least 50 years, ensuring water supply and safety of the structure, which is in a seismically active region. The project, financed by the World Bank, had as its most relevant part the rehabilitation works to protect the dam concrete. A tender for the dam rehabilitation was issued by the Ministry of Regional Development and Public Works under the World Bank rules. The tender required as waterproof protection liner a 2.5mm thick polyvinylchloride (PVC) geomembrane heat-bonded at fabrication to a 500g/m^2 nonwoven needle punched anti-puncture geotextile, to be placed on a 2,000g/m^2 cushion geotextile protecting the liner against excessively aggressive rough areas. The geomembrane had to be secured to the upstream face with stainless-steel vertical steel shapes and components, clamps and anchors secured to the dam body. The geomembrane system had to be drained, with seepage water discharging into the gallery via two transverse pipes; acceptance criteria were seepage not exceeding 0.9 l/s for the whole dam, or 0.5 l/s for one drainage pipe to the gallery.

The works had to be carried out in such conditions as to guarantee the safety and the proper technical operation of the dam and of its appurtenant structures while providing continuous water supply, which meant that most of the works had to be carried out underwater, and without affecting the quality of the supplied water. During the tender procedure the decision was taken not to extend the waterproofing system down to the entire damaged area (elevation 802m), to avoid working in the sediment layer and creating turbidity. The waterproofing geomembrane system was installed from elevation 843.3m to elevation 814.0m, with underwater works from elevation 838m downwards (Figure 2).

Figure 1. Deteriorated upstream face at Studena dam

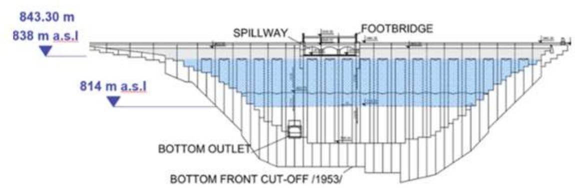

Figure 2. In grey, area lined in the dry, in blue, area lined underwater

The tender was awarded to a consortium of companies. Our company designed and installed the geomembrane system. As required by the specifications, the waterproofing liner, Sibelon® CNT 3750, is a 2.5mm thick plasticised PVC geomembrane heat-bonded to a 500g/m^2 non-woven needle punched polypropylene geotextile. The waterproofing liner has a drainage system behind, consisting of the drainage gap created by the anchorage system between the waterproofing liner and the dam face, and of a bottom drainage collector consisting of a longitudinal 500mm high band of a highly transmissive drainage composite formed by a cuspated drainage geonet thermally bonded on both sides to a non-woven polypropylene geotextile acting as a filtering layer to avoid clogging of the geonet. Two discharge holes drilled from the gallery to the upstream face, equipped with discharge pipes with a valve at the downstream end and with an upstream anti-intrusion stainless-steel plate, and four ventilation pipes at crest, to balance the air pressure beneath the waterproofing geomembrane in case of sudden changes in the atmospheric pressure, complete the drainage system.

The complex geometry of the dam required a complex face anchorage system, comprising (Figure 3) tensioning profiles (1) in the convex corners, point anchors (2) in the triangular recesses in the buttresses, batten strips (3) in all concave corners, and mechanical peripheral seals watertight against water under pressure (4) at the top and bottom peripheries of the sealing system. All fastening components are stainless-steel.

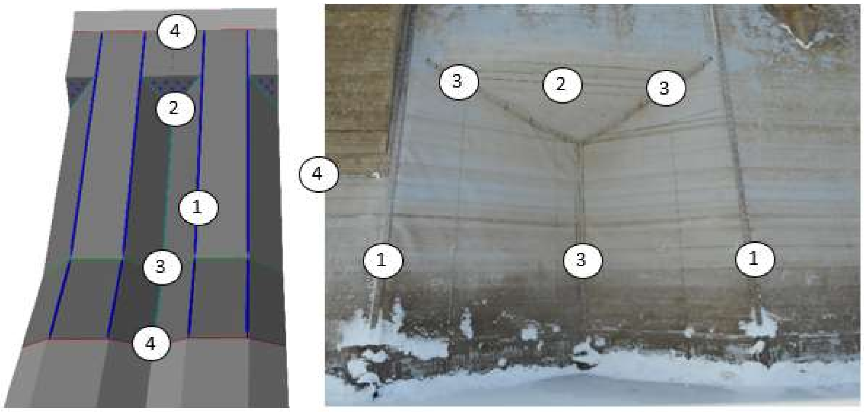

Figure 3. Tensioning profiles (1, in blue), point anchors (2, in black), batten strips (3, in green), and perimeter seals (4, in red)

An efficient tensioning system was essential in view of the heavy snow and ice formation that could exert a dragging effect on the waterproofing liner if it were not perfectly tensioned. The underwater tensioning system used previous projects and presented in ICOLD Bulletin 135 was modified to improve the tensioning effect. The new tensioning profiles (1), intrinsically watertight, are a patented development of the system adopted in previous installations: while previously the tensioning effect was essentially achieved by the installation procedure, at Studena the tensioning effect is achieved by the geometry of the two profiles, as with the tensioning profiles used in dry installation. The point anchors (2) at the triangular recesses consist of long shaft anchors with a thick steel washer to distribute the uplift forces transmitted to the geomembrane liner by wind. Anchors are made watertight by a SIBELON® C 3250 geomembrane washer (the same geomembrane that composes the waterproofing liner, but without geotextile) placed on top of the steel washer and heat-seamed to the underlying waterproofing liner, which was possible because installation of such anchors was carried out in the dry. The batten strips (3) and perimeter seals (4) are made intrinsically watertight: the batten strips using two flat profiles and suitable gaskets to evenly distribute the compression that achieves watertightness, the perimeter seals spreading a resin bedding on the concrete to create a smooth surface and remove possible voids where the seal is placed, and using a rubber gasket under the profiles and splice plates at abutting profiles.

Works started in August 2017 with the civil works related to surface preparation, immediately followed by installation of the geomembrane system in the dry, which was completed by the inset of autumn 2017. The crew remained at site to prefabricate the 4m wide panels that would make underwater installation quicker, and to provide supervision for the underwater works. To minimise the amount, and consequently the costs, of such works, installation had to be carried out in the period of low water levels, which was a major challenge because it coincided with the coldest months, November through to February. In such months, diving often required breaking the ice in the reservoir. The maximum diving depth was 28m, i.e., 8m more than the contractual 20m depth.

The first underwater installation tasks were related to the drainage system: drilling the holes for drainage discharge; watertight fixing of a steel plate over the upstream area of the hole to prevent water flowing into the hole during drilling from the downstream; installing and fixing the discharge pipes; the anti-intrusion plates and a drainage band at the upstream side. The major surface preparation works consisted of the removal of the unbonded shotcrete by diamond saw cutting and high-pressure water jetting, followed by cleaning and by levelling of the roughest concrete with mortar. The rough concrete was covered by a 2000g/m^2 non-woven needle punched polypropylene anti-puncture geotextile fastened with impact anchors (Figure 4). Along the anchorage lines, the concrete surface was levelled with mortar. The same steps were performed underwater, where levelling of the rough concrete was made with resin. The geomembrane sheets/panels were then deployed on the upstream face (Figure 5) and connected and fixed with the Carpi patented face anchorage system described.

Figure 4. The 2000 g/m^2 non-woven geotextile is installed on the concrete after removal of the unbonded shotcrete, in the dry and underwater

Figure 5. Unrolling of a geomembrane sheet underwater, over the 2000 g/m^2 non-woven geotextile

Figures 6 and 7 are related to the tensioning profiles: the first profile is fastened to the concrete with mechanical anchors; the edges of two geomembrane sheets are overlapped at the profile; and the second Omega-shaped profile is positioned over the first one and tightly connected to it, thus forcing the waterproofing liner sheets into a new position that results in a tensioning effect.

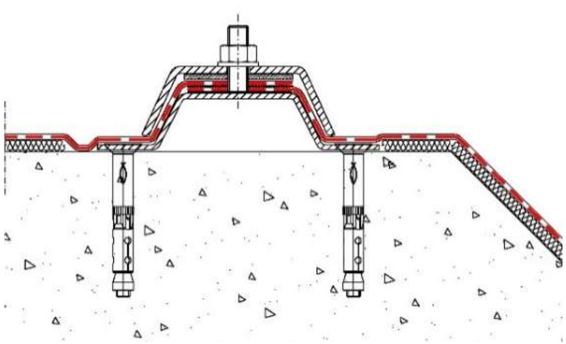

Figure 6. Scheme of the underwater tensioning profiles at Studena dam

Figure 7. Diver connecting the two tensioning profiles underwater

At completion of underwater works, the crew horizontally overlapped the geomembrane installed above water over the one installed underwater by the divers and welded on the overlapping a horizontal geomembrane cover strip, to make a watertight junction between the two geomembranes. Waterproofing works were completed within schedule despite difficult climatic conditions, on 27 December 2018. The total surface lined was 5,498m^2, of which 1,348m^2 was above water and 4,150m^2 under water. Total leakage from the geomembrane system, compliant with tender requirements, is shown in Figure 8.

Figure 8. The works during a low water level period, and total leakage from the two drains

AN UNDERWATER GEOMEMBRANE SYSTEM IN FLOWING WATER CONDITIONS

Development of a new solution

Lining underwater a canal that is in full operation poses a critical challenge: the flowing water. Water in motion requires a robust anchorage system to keep the geomembrane stable, not only against the water flow, but mainly against uplift. Uplift can be caused by wind when the canal is empty, but higher uplift may occur if accidental damage in the geomembrane allows flowing water to infiltrate behind it. Many anchorage lines are needed to resist the uplift, in addition to those needed to join adjacent geomembrane sheets. Diving times become very long, costs increase, and the water speed may even impede diving and require outage.

The obvious answer to the problem was to change the anchorage concept, and instead of anchorage by lines conceive a system where the waterproof liner was incorporated into the anchoring system. Composite mattresses incorporating a watertight layer were already available in the industry, basically consisting of two textile layers, either containing a bentonite mixture in powder or granules, or confining a cement grout injected at site; the wetted bentonite, or the thickness and cement content of the grout, provided the watertightness and at the same time anchorage by ballast. These mattresses, however, have several drawbacks: to the knowledge of the authors, there is no experience of bentonite mattresses installed in flowing water, and they require a dead weight confining the bentonite so that the bentonite expansive reaction can be activated. Grouted mattresses can in fact be installed in a wet environment, but if grouting is not carried out continuously cold joints will form, the inevitable shrinkage of the grout will create cracks, and through cracks watertightness will be lost. Both types of mattresses entail the risk of water pollution by leaching cement components; the watertightness of the joints between adjacent mattresses is questionable; the connection to concrete appurtenances is tricky and not reliable in the long term, and they are prone to cracking if settlement occurs.

The solution was to create a mattress whose watertightness would be granted not by the material inside the mattress, but by a robust watertight geomembrane of the same type that has been successfully performing in canals for decades. The geomembrane has proven to be able to resist the rough subgrade of deteriorated canals, to be sealed watertight underwater to concrete appurtenances, and to resist differential displacements and settlements. The new patented mattress is formed by such a membrane, and by an impermeable system confining the inexpensive grout that is injected at site providing the required ballast without any risk of water pollution. The device that allows watertight joining of adjacent mattresses underwater was developed jointly with one of the leading zipper manufacturers in the world, and is an impermeable heavy-duty zip, integrated at fabrication to the mattress in a flexible way that allows it to adapt to the irregularities of the canal, compensating for possible misalignments between mattresses. The zip is generally pulled underwater using custom-designed equipment and unmanned procedures, while divers are employed when the water speed is low, for underwater control if needed.

The new mattress has been adopted for three pilot projects in canals, in Egypt and Italy for irrigation, and most recently in the Grand Canal d'Alsace navigation waterway in France, the subject of the following case study.

The Kembs embankment, France 2020

Kembs embankment is part of the Grand Canal d'Alsace, a 150m wide and 52km long navigation canal from Kembs to Vogelgrun, in the eastern part of France, whose construction started in 1932. Managed by EDF, Electricité de France, the canal started operating in 1959, and over decades of service deteriorated, with leakage occurring. EDF-CIH, the Centre of Hydraulic Engineering of EDF, deeming that traditional solutions for repairs such as concrete patching would not be satisfactory in the long term, especially at lower levels (the depth of the canal can reach 8m-10 m), explored the technical and economic feasibility of alternative long-term solutions. A pilot project was carried out at Kembs with two systems, one of which was the aforementioned mattress.

The project requirements were to restore watertightness, with required permeability coefficient $k < 1 \times 10^{-9}$m/s, and to provide a new upstream concrete layer at least 120mm thick and capable of withstanding the expected stresses from self-weight, differential deformations, irregularities of the existing layer, hydrostatic and hydrodynamic pressure, flow speed up to 1.5 m/s, boat wash, flow variations due to tripping of a hydroelectric generation group, tidal range, wake, propeller swirls, and impact of anchors or shocks by boats in the event of an accident. The works had to be carried out without stopping the operation of the canal, which is also used for hydropower, or the navigation of barges (on average 60 convoys per day). Further constraints were the presence of a high-voltage electricity line to the right of the work area, and the presence of construction joints of the 4.75m x 5.30m concrete slabs lining the canal. To measure the performance of the new revetment, EDF-CIH required the installation of a system to detect and locate the leaks that could occur in the lined section, and to monitor the leakage rate.

The mattress designed for Kembs has as waterproofing liner a 2.5mm thick Sibelon® C 3250 PVC geomembrane, and as grout confinement layer SIBELON® C 2600 R, a 2.0mm thick scrim-reinforced PVC geomembrane. The monitoring and leak location system comprises a drainage layer, with measurement of flow rate, an inclined piezometer, temperature and pressure sensors, and an optical fibre cable (OFC) system. The innovation for Kembs was to integrate the drainage layer, the OFC system, and the grouting hoses with the mattress at fabrication. The drainage geonet and OFC are attached to the bottom of the waterproofing liner (Figure 9) and the grouting hoses are embedded between the two geomembranes, so that the panels leave the factory incorporating all these elements plus the underwater joining system (the watertight zips). This innovation reduces the diving time, and is consequently a safer installation method, and guarantees there is no loss of cement in the water.

Figure 9. At left and middle, integrating the OFC and drainage layer at the bottom side of a mattress. At right, rolled void mattresses ready for installation at Kembs crest. The drainage geonet is the black material, and the integrated zip can be seen along the edge of the panels

The stretch to be lined was about 50m long, spanning the existing deteriorated concrete slabs of one embankment from crest down to about elevation 236.3m, i.e. on about 28m of slope, covering 80 slabs and spanning 26 vertical and horizontal joints. Five mattresses, each 10m wide and 28.4m long, were prefabricated to waterproof the area, in total 1,445m^2.

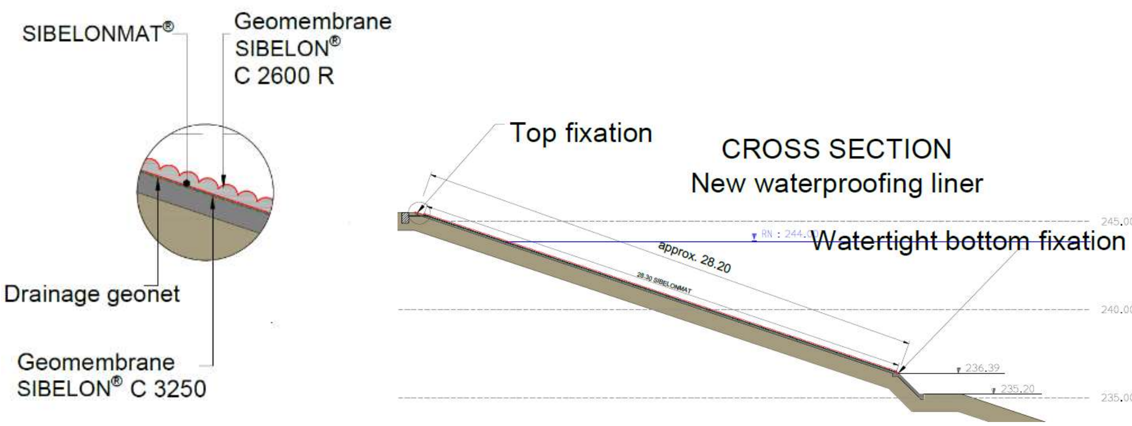

Figure 10. Cross section of the mattress and of the lined slope

The mattress is fixed at the top by a stainless-steel seal, watertight to rain and waves. The side peripheries have a standard watertight stainless-steel perimeter seal, the bottom perimeter seal is an L-shaped stainless-steel profile that also acts as support for the filled mattress. Special details were developed and tested in real scale for the underwater terminations of the zips, in a pressure vessel under water pressure of 40m for 144 hours and 60m for 48 hours.

Installation was carried out in 2020, from 22 October to the end of November. The high voltage line made it necessary to take customised safety measures, and to adapt the procedure for conveying the rolls to limit the height of the handling equipment. Navigation management was carried out first by providing information to the navigation services, limiting the speed of traffic, then by placing buoys delimiting the work area. Despite these measures, the site suffered repeated wash from the passage of boats, which however did not disturb the smooth running of the waterproofing works. Water speed during installation was variable, with a maximum average speed of 1m/s inside the canal, and a little less along the embankment, which allowed the divers to perform their underwater tasks without shelter.

The divers checked the conditions of the slabs before executing the treatment at joints. As often happens, the real conditions of the subgrade were somewhat different from those anticipated. The thickness of the slabs was not uniform, at some points being only 30mm, which required adopting different types of anchors (mechanical, semi-mechanical, resin based). The vertical joints at the bottom did not exist, therefore joint treatment was necessary only for the horizontal joints, seven upstream and six downstream. The solution envisaged for joint treatment had to be modified, because when drilling started a strong suction was experienced, which indicated that the resin could possibly have been sucked into the holes. The divers treated the joints with a suitable underwater resin. Each rolled mattress was set on a customised unrolling device, temporarily anchored at the crest, and unrolled down to the bottom (Figures 11 and 12). The divers controlled the correct unrolling and joining of the panels, and executed the bottom and side perimeter seals, while at the crest the top fixation was completed by the above-water crew. Adjoining mattresses were joined by pulling the zip from the dry, under the control of the divers.

Figure 11. The empty mattress deployed to underwater placement

Figure 12. Navigation ongoing during underwater works

After the panels had been joined, using the integrated grouting hoses the hollow space between the two geomembranes was injected from the crest with cement grout (Figure 13), thus reducing the diving time, increasing the safety of the divers, optimising the cost of the solution and, by preventing loss of cement in the water, providing a solution totally respectful of the environment. Figure 14 shows the completed mattress.

Figure 13. Grouting the mattress

Figure 14. Mattress completed

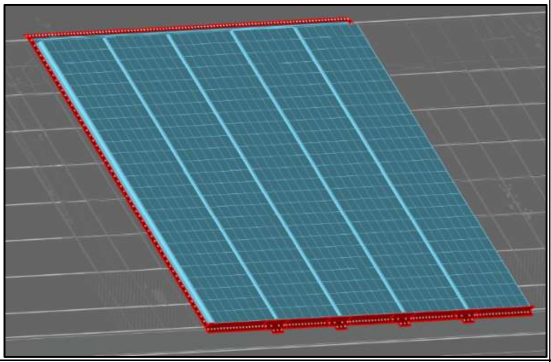

Figure 15. Scheme of the lined area

Figure 16. View of five mattresses

Cross-checking the results of the multiple monitoring means will be possible to obtain a better knowledge of the actual behaviour of the installed solution. EDF measured the monitoring data upon receipt of the experimental plot with the tested solutions, and plans to carry out regular measurements to check their efficiency over time. The first results are encouraging and confirm the interest in developing this kind of technique. An important improvement in watertightness has been observed and is monitored to evaluate with accuracy the performance over time.

In terms of cost, underwater solutions are still more expensive than dry solutions, but each project must be assessed considering also financial, social and environmental dewatering costs. Furthermore, research is continuing and other solutions are already at a good development stage, to reduce costs and make underwater installation more competitive.

CONCLUSIONS

Underwater projects with geomembranes are technically very well performing, are the most sustainable solution, and are becoming more and more interesting also from a financial viewpoint. Pilot projects like Kembs enable improved knowledge and foster development of environmentally friendly solutions.

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