AUTHORS

Alberto Scuero
Dr. Eng., Carpi Tech,
Via Passeggiata 1,
6828 Balerna, Switzerland
alberto.scuero@carpitech.com

Gabriella Vaschetti
Dr. Eng., Carpi Tech,
Via Passeggiata 1,
6828 Balerna, Switzerland
gabriella.vaschetti@carpitech.com

Marco Bacchelli
Dr. Eng., Carpi Tech,
Via Passeggiata 1,
6828 Balerna, Switzerland
marco.bacchelli@carpitech.com

ADVANCED GEOMEMBRANE TECHNOLOGIES IN NEW EMBANKMENT DAMS AND TAILINGS DAMS

Polyvinylchloride (PVC) geomembranes, with permeability much lower than traditional water barriers, have been used in embankment dams since 1959, for new dams and with covered geomembrane. The use of upstream exposed PVC geomembranes started at the beginning of the 1970ies, due to greater confidence acquired through using these relatively new synthetic materials, on dams having hard subgrades (concrete, RCC, asphalt concrete). Since the beginning of the new century, PVC geomembranes are used also on granular subgrades. Major assets of geomembranes in embankment dams are outstanding elongation properties allowing resisting settlements, differential movements, and earthquakes, which would destroy rigid water barriers such as concrete. Geomembranes are engineered against environmental aggression, and unlike clay cores are always available in the needed quantity/quality. The dam can be built on deformable foundations, with steeper slopes reducing the quantity of the fill, construction can be made in stages and completed in shorter times at lower costs. New patented anchorage systems employ extruded curbs with PVC anchor strips, or anchor trenches, or grouted or earth anchors. These techniques have been installed on more than 10 dams worldwide. This paper shows the new anchoring techniques, including a technology allowing installing geomembrane systems underwater, even with flowing water.

Keywords: Geomembrane, polyvinylchloride, waterproofing, fill dam, tailings dam, GFRD, GFED

1. INTRODUCTION

Geomembranes are prefabricated, practically watertight flexible synthetic materials used in hydraulic projects for more than half a century. They are engineered to ensure adequate properties that allow them sustaining the loads imparted during service; they are manufactured in the controlled environment of a factory, ensuring that the properties established by design are constantly maintained throughout the whole production lot by computer-controlled manufacturing processes, and constantly checked in the laboratory. At the job site, the properties, especially those crucial for good performance, such as tensile properties, are checked with standard methods to verify that they are compliant to specifications and have remained constant during transport and storage. Since properties of geomembranes are independent of weather conditions during construction, the characteristics of the geomembrane water barrier when the dam is completed are consistent and verifiable. In Concrete Face Rockfill Dams (CFRDs) or in dams with clay or asphalt concrete cores, the characteristics of the water barrier, on the contrary, are influenced by construction conditions, construction procedures, and workmanship.

Geomembranes are of particular interest when embankment dams are at stake. The major assets of geomembranes, in particular Polyvinylchloride (PVC) geomembranes that are by far the most used waterproofing material for large dams [2], are their outstanding elongation properties, which allow resisting settlements, differential movements, and seismic events, which would destroy more rigid water barriers such as concrete facings (CFRDs); the possibility of engineering them to resist environmental aggression, and their permanent, consistent quality over large quantities, enables high quality installations.

The seaming of PVC geomembranes enables the face to be one large continuous waterstop, eliminating the need for the multiple defence lines of waterstops needed for a CFRD. Furthermore, geomembrane connections to the ancillary concrete structures can be designed to accept large differential movements ensuring watertightness at the perimeter. A geomembrane facing allows for building the dam on highly deformable foundations, allows for steeper upstream face, which means less volume of fill, and a shorter, smaller diversion tunnel.

From a construction standpoint, geomembranes have the advantage of reducing construction times, constraints and costs. In CFRDs, the installation/construction of the reinforced concrete face slabs, and the placement of copper and PVC waterstops, can have considerable impact on the overall construction schedule. In dams with clay or asphalt concrete cores, the construction of the dam body and the construction of the central core are strictly related. There are constraints imposed by weather conditions, or by disruption in placement of the filter material, or in placement/compaction of the impervious core. This affects the overall rate of construction of the clay or asphaltic core dam. On the contrary, installation of a PVC geomembrane system is practically unaffected by weather. The geomembrane system does not need to be a serial task in the construction process, and its installation can be done in parallel with other activities, so that it is independent of most construction or operational constraints of the dam. The geomembrane can be installed when the dam is completed, or installed on the lower completed part of the dam while construction of the fill is ongoing in the upper part. Geomembrane installations offer the additional benefit that if there are floods during construction, the waterproofed lower part of the dam will be a barrier against the flood, increasing the safety of the project.

The complexity of the techniques needed to construct the waterproofing system must be taken into consideration when evaluating the time and costs of embankment dams. Inadequate placement of the waterstops and inadequate construction of the connections to the ancillary concrete structures are critical, and can have highly negative effects on the future performance of the dam. Especially when the main contractor has little or no experience in construction of such dams, adopting a geomembrane system is “forgiving” and will avoid the problems related to inadequate construction, which could require future time consuming and expensive repairs.

Geomembranes were first used in construction of new embankment dams (1959 in Europe and in Canada). In these pioneering projects, when synthetic materials were relatively new to dam engineers, the geomembranes were covered. In the 1970s, once confidence in PVC geomembranes’ behaviour and reliability had increased, a cover layer was no longer mandatory and exposed geomembranes began to be used. At present, the use of PVC geomembranes in new construction includes facings for embankment dams, RCC dams, tailings dams, external waterstops for peripheral and vertical joints in CFRDs, and external waterstops for joints between monolith blocks in RCC dams. In rehabilitation, all kinds of dams have been waterproofed around the world, in both dry and underwater installations. This paper focuses on upstream exposed geomembrane systems applied to new fill dams to provide watertightness at the upstream face. Such dams have become known as Geomembrane Facing Rockfill Dams (GFRDs) and Geomembrane Facing Earthfill Dams (GFEDs).

2. THE GFRD AND GFED: CONCEPT AND COMPONENTS

Carpi upstream geomembrane systems for Geomembrane Facing Rockfill Dams (GFRDs) and Geomembrane Facing Earthfill Dams (GFEDs) are based on the concept of providing a flexible watertight barrier that can elongate well beyond the maximum expected deformations of the dam body. The flexible water barrier is anchored to the dam face with a site-specific anchorage system as described in this chapter and in the case histories that follow, and at boundaries with a perimeter seal designed to resist differential settlements while maintaining watertightness.

2.1 THE CONCEPT

In these dams, the water barrier is a flexible synthetic composite geomembrane, also called “geocomposite”, placed at the upstream face in exposed position. The geocomposite is anchored against uplift over the face of the dam, and is sealed at all peripheries by a continuous seal, which is watertight against water in pressure at submersible boundaries, and against rain, snowmelt, and waves at crest. The design of the anchorage and sealing system is conceived to be highly deformable, to accommodate all foreseen settlements that can occur in the dam body, and differential movements between the deformable dam body and the rigid concrete appurtenances.

The presence of the upstream geomembrane allows adopting a very simple layering for the dam:

- Dam body: zoning is not strictly required, a single fill material can be used

- Drainage layer: depending on the design of the dam, generally the thickness of this layer can be reduced

- Base/anchorage layer: this single layer acts as support to the geomembrane and incorporates the face anchorage system; depending on the design of the dam, this layer can also solve the function of drainage layer

- Waterproofing liner: the geocomposite.

2.2 THE WATERPROOFING LINER

The main issue when selecting the type of geomembrane for a GFRD is the tensile behaviour. A study by Giroud & Soderman [1] comparing the behaviour of different types of geomembranes subject to differential settlements has shown that an appropriate combination of tensile strength and strain is essential. This optimal combination depends on the shape of the tension-strain curve of the geomembrane; the co-energy, which is the area between the tension-strain curve and the tension axis, quantifies the ability of a geomembrane to withstand differential settlements. The larger the area, the more performing will be the geomembrane in this respect. Plasticised PVC geomembranes tension-strain curve exhibit by far the largest area as compared to High Density (HDPE) and Low Linear Density Polyethylene (LLDPE) geomembranes. Consequently, the factor of safety in respect to stresses associated with differential settlements is significantly higher if a PVC-P geomembrane is adopted.

The waterproofing liner used in GFRDs and GFEDs is SIBELON® CNT, consisting of a thick high quality, specifically formulated, PVC geomembrane, 2.5 to 4 mm thick depending on the projects, which provides watertightness, and of a backing geotextile, mass per unit area 500 to 700 g/m^2, heat-bonded during manufacturing to the geomembrane. The geotextile provides anti-puncture protection, enhances thermal stability and stability on inclined slopes, and provides some drainage capability. SIBELON® CNT geocomposites are produced with a proprietary formulation under ISO 9001 certification. Large thickness is required to increase service life and survive mechanical loads during construction and operation.

2.3 FACE ANCHORAGE

The face anchorage system maintains the waterproofing liner stable of the dam face, resisting uplift by backpressures, uplift by wind, and variations of water level and waves. The face anchorage system is different depending on the methodology of dam construction and on the type of base layer on which the geocomposite is laid.

If the upstream base layer is made by extruded porous concrete curbs, the anchorage system consists of PVC anchor strips embedded in the extruded porous concrete curbs. This system is described in chapter 3.

If the upstream base layer is not made with curbs, depending on site-specific construction method and on the type of uppermost layer, the anchorage system can be of two types: PVC anchor strips embedded in trenches excavated in the base layer at site-specific spacing, as described in chapter 4.1, or deep anchors that are driven into the embankment after it has been completed, according to site-specific patterns, as described in chapter 4.2.

All the anchorage systems described in the paper are Carpi patents.

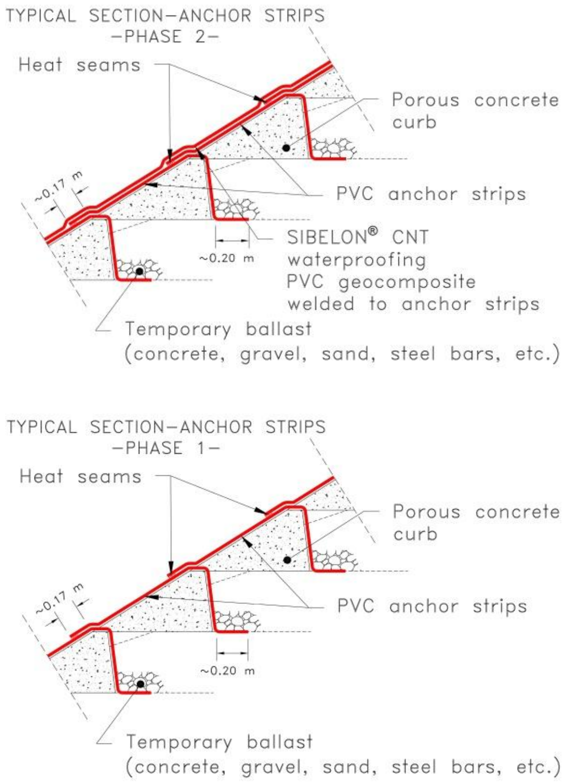
2.4 PERIMETER SEALING

At all peripheries, the SIBELON® CNT geocomposite is anchored by perimeter seals to avoid water infiltrating behind the liner. If made on concrete, the perimeter seal is of the tie-down type, which has been tested to water pressures exceeding 800 meters. If made on less cohesive material such as clay, the seal is of the embedded type, generally made laying the geocomposite in a trench then filled with impervious material. The case histories that follow will describe how the seal was designed in function of the underlying substrate.

3. FACE ANCHORAGE BY PVC STRIPS EMBEDDED IN CONCRETE CURBS

This system applies to new construction of embankment dams where the dam body is raised placing the fill against extruded porous concrete curbs that form a draining finishing layer at the upstream face of the dam. A PVC anchor strip fixed to one curb overlaps the PVC anchor strip fixed to the preceding curb, and the overlapping strips are heat-welded to form continuous anchor lines (Figure 1a). The distance between the anchor lines is designed in function of the design uplift loads. The waterproofing geocomposite is then deployed over the PVC anchor lines and watertight heat-welded to them (Figure 1b).

The advantage of adopting extruded porous concrete curbs is that the curbs allow constructing in a short time a regular slope not erodible by rainwater, which can be steep and has constant characteristics. The curbs also provide a stable and regular base layer for the waterproofing geocomposite, and allow using a simple face anchorage method that is constructed by the waterproofing contractor concurrent with raising of the fill by the main contractor. In such a way, when the fill is completed also the face anchorage system for the waterproofing geocomposite is completed.



Figures 1a and 1b. Face anchorage with PVC anchor strips embedded in curbs

An outstanding recent project adopting this technology is Nam Ou VI rockfill dam in the Lao PDR, which is part of the Nam Ou VI Hydropower Project with a total installed capacity of 180 MW. The scheme includes an 88 m high rockfill dam, designed as a GFRD and the highest of its type in the country. The only water barrier is an exposed SIBELON® CNT geocomposite. The dam body consists of slate rockfill for the whole cross-section except for the bottom drainage facility. The upstream slope inclination is 1.6H/1V, the net upstream face surface is 38,000 m^2.

The original design envisaged a polyethylene geomembrane sandwiched between two anti-puncture geotextiles, placed on a 3 m wide granular base layer, and covered by precast concrete elements. A study carried out by the designers of the dam showed that the net expected settlement and horizontal displacement due to the embankment load and the reservoir hydrostatic head would be in the order of 100 mm vertical and 80 mm horizontal. Such expected deformations could exceed the resistance of a concrete cover, possibly causing damage to the polyethylene geomembrane. The initial solution was modified, eliminating the concrete cover and leaving the geomembrane exposed. To ensure long-term successful performance in an exposed position, instead of a polyethylene geomembrane, a SIBELON® CNT geocomposite was selected, consisting of a 3.5 mm thick PVC geomembrane, heat-bonded during fabrication to a nonwoven, needle-punched, continuous filament polypropylene geotextile, 700 g/m^2. The final design substituted the granular base layer with an extruded porous concrete curbs facing, on which the SIBELON® CNT geocomposite was placed in exposed position, and anchored to the dam body by the above described system using SIBELON® PVC anchor strips embedded in the curbs, forming parallel anchorage lines at 6 m spacing, as shown in Fig. 2.

Figure 2. Nam Ou VI GFRD: The SIBELON® PVC anchor strips placed on the extruded curbs

The SIBELON® CNT geocomposite was then deployed over the face of the dam and anchored by heat-seaming it to the anchor strips. Adjoining SIBELON® CNT geocomposite sheets were watertight heat-seamed, forming one watertight facing.

Figure 3. Nam Ou VI GFRD: Seaming of SIBELON® CNT geocomposite to anchor strips and of adjoining geocomposite sheets

A double mechanical seal of the so-called tie-down type confines the geocomposite at the peripheral plinth. Watertightness against water in pressure is attained by compressing the geocomposite unto the concrete subgrade with a flat stainless steel batten strip secured by stainless steel anchor rods embedded in chemical phials at regular spacing. Regularising resin, rubber gaskets, stainless steel batten strips and splice plates are used to achieve even adequate compression necessary for watertightness. The design of the peripheral sealing system is such as to grant the capability of following the differential deformations between the dam body and the concrete plinth.

The dam was constructed in three separate stages, two for the dam body and one for the parapet wall. Construction of Stage 1, embedding the face anchorage system, started on July 23rd 2014 and was completed on November 2nd 2014, immediately followed by installation of the geomembrane system, completed in 24 days for about 13,700 m^2 of upstream facing, a fraction of what a concrete facing would have required. Construction of Stage 2 started on December 12th 2014 and was completed on April 14th 2015, immediately followed by installation of the geomembrane system, completed in 28 days, on about 23,000 m^2. The settlements that occurred during construction of Stage 2 of the dam body were sustained by the deformable geocomposite.

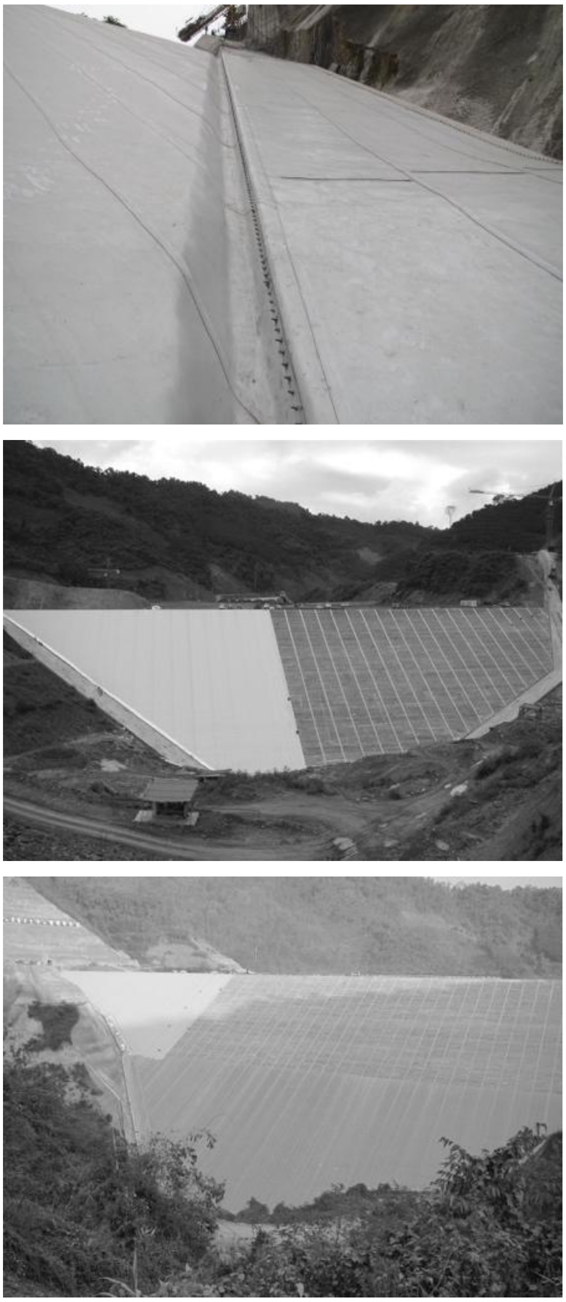


Figure 4. Nam Ou VI GFRD: Watertight perimeter seals at plinth, and Stage 1 and Stage 2 waterproofing

Impoundment of the reservoir started after completion of Stage 2, in the afternoon of June 17th 2015, less than eleven months after construction of the dam body had started. Lining of the parapet wall started on April4th 2016 and was completed on April 26th 2016. In 2017 the owner reports [3] "*After one year's operation, especially after Oct 2016, the dam has come to the longterm operation at normal storage level or high water level. The parameters from the monitoring devices show the dam deformation tends to be stable and dam performs well. … construction is speeded up greatly by the application of geocomposite*".

The same system was installed at the upper part of Runcu GFRD in Romania (2015) and in three mining projects, at Sar Cheshmeh tailings dam raising in Iran (2008), at Ambarau hardfill dam in DR of Congo (2017), and at an ongoing tailings dam project in South America where the geomembrane system is reaching a height of 118 meters, with an expected total height of the dam of 230 m.

Figure 5. Geocomposites on extruded curbs: at left Runcu GFRD in Romania, at right a tailings dam in South America

4. FACE ANCHORAGE IN GRANULAR SUBGRADES

When the base layer for the waterproofing geocomposite is not made with curbs but with granular materials (e.g. roller-compacted soil, or gravel stabilized with lean concrete and compacted with a vibratory plate, or cemented material), the anchorage can be made by PVC anchor strips embedded in trenches, or by deep anchors driven into the granular layers.

4.1 FACE ANCHORAGE BY PVC STRIPS EMBEDDED IN TRENCHES

This method can be adopted with different types of base layers, provided they are stable and with a regular surface. The trenches, of site-specific dimensions and spacing, in function of the foreseen loads, are formed or excavated in the base layer, and PVC anchor strips are placed inside the trenches, to form parallel PVC anchor lines, like the system with the extruded curbs. Configurations are site specific depending on the construction procedures adopted by the main contractor. The trenches are generally backfilled with porous concrete, or concrete, or granular material, to provide the right amount of ballast needed to keep the anchor strips in place against wind uplift. The waterproofing geocomposite is then deployed over the anchor lines and watertight heat-seamed to them, as for the extruded porous concrete curbs method.

At Murdhari 36 m high rockfill dam in Albania the design was modified from a dam with an asphalt core to a GFRD when the project had already started. The design was modified with the objective of making construction of the dam safer, faster, easier to build, and less expensive. Since construction of the fill was already ongoing, there was no possibility of adopting the curbs, so a system similar to the curbs was conceived: the base layer was made with porous concrete slabs, leaving a trench between adjacent slabs for placing the PVC anchor strips. Starting from the bottom and proceeding upwards, the trench was gradually filled by superimposed porous concrete blocks: after the first bottom block was completed, a PVC anchor strip was placed on it and permanently anchored by another porous concrete block placed on top, and so on up to the crest. In practice, instead of placing porous concrete horizontally by a curb extruder, porous concrete is constructed within the vertical trench, in superimposed small blocks embedding the PVC anchor lines. The waterproofing geocomposite was then deployed and heat-seamed to the anchor strips. Waterproofing works started on September 16th 2013 and were completed on October 19th 2013, a total of 6,770 m^2 of geocomposite installed in about one month.

At Bulga coal mine dam in Australia, a 460 m long and 17 m high zoned earthfill embankment, the base layer was granular material, where trenches were excavated to insert the PVC anchor strips and the backfilled. A drainage geonet was placed between the base layer and the geocomposite.

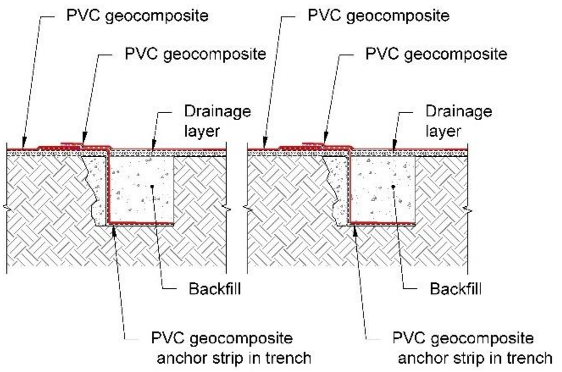


Figure 6. Geocomposite anchored by PVC anchor strips embedded in trenches at Bulga GFED (2016)

At the upstream toe, the PVC geocomposite extends into a trench providing perimeter anchorage and a positive cut-off for foundation seepage minimisation.

The same system was installed at the embankment forming the Kohrang head pond in Iran (2004), in the lower part of Runcu GFRD in Romania (2015), and at some of the slopes and invert of the 18 Water Saving Basins of the Panama Canal Expansion (2014-2015).

Figure 7. Murdhari GFRD (left) and 9 of the 18 Water Saving Basins of the Panama Canal Expansion

4.2 FACE ANCHORAGE BY DEEP ANCHORS

Deep anchors are adopted in base layers of granular material or cemented material, where they are driven into the embankment after it has been completed, placed in regular patterns, at spacing calculated in function of the loads acting at the dam face. Depending on the characteristics of the base layer into which they are driven, deep anchors can be of the grouted type, or of the Duckbill type.

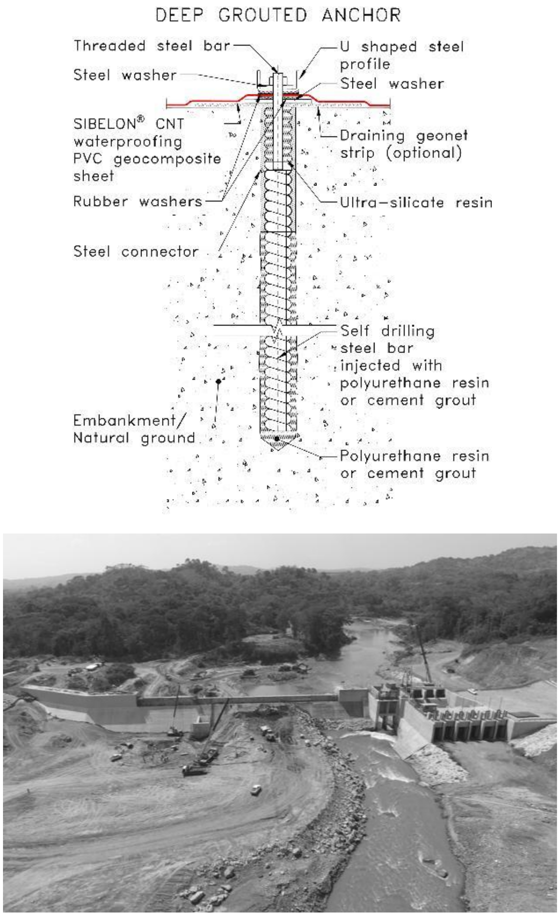


Figure 8. Deep grouted anchors used at the Panama Canal Water Saving Basins and at Ambarau dam

Regardless of the type, deep anchors are equipped with stainless steel anchor rods that stick out of the dam face. The waterproofing geocomposite is punched over the anchor rod, and covered by a watertight patented end piece. The end piece consists of a stainless steel disk, of an anti-puncture geotextile disk, and of a geomembrane cover patch, watertight heat-seamed to the geocomposite.

Deep grouted anchors have been used at some locations of the 18 Water Saving Basins of the Panama Canal Expansion and of Ambarau hardfill dam, and at Filiatrinos (Greece 2015) hardfill dam. Duckbill anchors have been adopted for the rehabilitation of Vaité earthfill dam in French Polynesia (2011).

5. UNDERWATER INSTALLATION

In the last few years, a totally innovative underwater waterproofing technology, SIBELONMAT®, has been developed to provide/restore watertightness in embankment dams and canals without impacting on operation. The system consists of two watertight geomembranes connected to form a mattress.

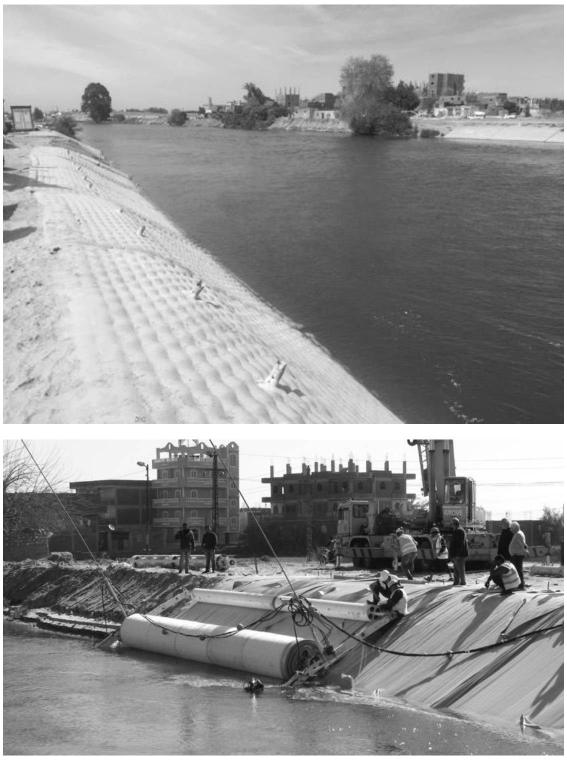


Figure 9. SIBELONMAT® installed underwater at Ismailia canal, Egypt 2016

The connection of the geomembranes is designed to allow injecting between the two a ballasting filling material such as inexpensive cement grout. The lower geomembrane provides watertightness, the grout provides the ballast to anchor the mattress, and the upper geomembrane provides containment of the grout, protects the ballast during operation, and in canals improves hydraulic efficiency. SIBELONMAT® is prefabricated in 10 m wide mattresses having custom-made length to minimise junctions and facilitate placement. Adjoining mattresses are joined by watertight heavy-duty zippers pre-attached to each mattress during fabrication. Installation can be performed totally underwater and without stopping operation or reducing water speed.

This new technology has already been successfully installed on two canals with no reduction of water speed. SIBELONMAT® can be considered also for new construction of embankment dams, to provide an impermeable upstream facing or an impermeable blanket even on very aggressive irregular subgrade.

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