XVIII Brazilian Conference on Soil Mechanics and Geotechnical Engineering
The Sustainable Future of Brazil goes through our Minas
COBRAMSEG 2016 — 19-22 October, Belo Horizonte, Minas Gerais, Brazil

The Geomembrane Facing Rockfill Dam (GFRD): an Advantageous Proven System to Construct Safe Dams

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SUMMARY: Polymeric geomembranes, having permeability some orders of magnitude lower than traditional water barriers, have been used in fill dams since 1959, at first in construction of new dams, in covered position. Since the beginning of the 1980ies, due to greater confidence in the use of these synthetic materials, geomembranes in fill dams are used upstream, in exposed position. The major assets of geomembranes in fill dams are their outstanding elongation properties, which allow resisting settlements, differential movements, and earthquakes that would destroy more rigid water barriers such as concrete facings. Geomembranes can be engineered to resist environmental aggression, and are always available in the needed quality and quantity (which for example does not apply to clay cores). The dam can be built also on deformable foundation, steeper slopes can be used, reducing the quantity of the fill, and construction can be made in stages and completed in a much shorter time. The concept of a GFRD is that of providing at the upstream face of the dam a flexible watertight barrier, an exposed PVC geomembrane, which can elongate well beyond the maximum expected deformations of the dam body. The geomembrane is fastened to the dam by a flexible anchorage system, and sealed at boundaries with a perimeter seal designed to resist differential settlements while maintaining watertightness. Such overall flexibility grants the system a capability to resist high settlements and differential deformations that would destroy the watertightness of "traditional" systems. The paper discusses the three current state-of-the-art options: exposed geomembrane placed on extruded porous concrete curbs and anchored by a patented geomembrane anchor strips system, exposed geomembrane placed on granular material and anchored by a patented trench system, and exposed geomembrane placed on granular material and anchored by patented deep anchors inserted in the fill.

KEYWORDS: Geomembrane, PVC, GFRD, waterproofing, fill dams.

1 INTRODUCTION

Geomembranes are thin flexible synthetic materials that due to their extremely low permeability since 1959 are increasingly and largely used in hydraulic structures to prevent or stop water leakage. They have been applied for this purpose to new construction of fill dams and RCC dams, and to rehabilitation of all types of dams.

Geomembranes are engineered products, designed to have the properties needed to sustain the service loads of each project. They are manufactured in the controlled environment of a factory; the properties established by design are maintained constant and computer-controlled throughout the production, and periodically checked in the laboratory. These procedures guarantee that the designed properties are constant for a whole production lot. At site the properties of the geomembrane, especially those crucial for good performance, such as watertightness and tensile properties, are checked according to standardised methods to verify that the material is compliant to specifications.

The properties of geomembranes are not altered by weather conditions during construction, and the watertightness of all components of the system, and therefore of the final water barrier, is checked with standardised methods. On the contrary, in CFRDs or in dams with impervious cores the characteristics of the water barrier can be influenced by construction conditions, procedures, and workmanship, and cannot be controlled.

In fill dams, the elongation properties of geomembranes can make possible projects that with other systems would not be feasible in terms of safety factors, due to foreseen deformations that could exceed the strength of the water barrier (concrete slabs) or of the waterstops, or because of lack of suitable materials at acceptable costs (clay cores). A geomembrane simplifies design because the multiple defence lines of waterstops needed for a CFRD can be reduced or eliminated; the connections to the ancillary concrete structures are designed to allow checking watertightness of the system at the connections, and to accept large differential movements between the fill and the concrete structure. A geomembrane facing permits to build the dam on highly deformable foundations, allows for steeper upstream face, which means less volume of fill, and for shorter and smaller diversion tunnel.

Geomembranes provide additional advantages in terms of reduction of 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 bituminous concrete cores, the construction of the dam body and of the core are strictly related and the constraints imposed by the weather conditions, or any disruption in the placement of the filter material, or in placement/compaction of the impervious core, will affect the overall rate of construction of the dam. On the contrary, installation of a geomembrane system is practically unaffected by weather, and can be scheduled in function of the schedule of construction and operation of the dam: the geomembrane can be installed when the dam is completed, or in the lower completed part of the dam while construction of the fill is ongoing in the upper part. In case of floods during construction, the already 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 rockfill dams. Inadequate placement of the waterstops, 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/no experience in construction of such dams, a geomembrane system is an "insurance" in respect to problems related to inadequate construction, which may require future time consuming and expensive repairs, as it occurred for several high CRFDs.

2 THE GFRD: CONCEPT AND COMPONENTS

2.1 The GFRD

In a GFRD (Geomembrane Facing Rockfill Dam) the water barrier consists of an exposed geomembrane placed at the upstream face and designed to be highly deformable, in order to accommodate all foreseen settlements and differential movements that can occur in the dam body and between the deformable dam body and the rigid concrete appurtenances. The water barrier is a flexible synthetic material, generally a composite geomembrane, also called "geocomposite". 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 able to accommodate differential movements.

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 of the design of the dam, generally thickness can be reduced
- Base/anchorage layer: this single layer acts as support to the geomembrane and incorporates the face anchorage system; depending of the design of the dam can it also have the function of drainage layer
- Waterproofing liner: the geocomposite.

2.2 Waterproofing liner

The main issue when selecting the type of geomembrane for a GFRD is the tensile behaviour. A study by Giroud & Soderman (1995) has shown that an appropriate combination of tensile strength and strain is essential. This optimum combination depends on the shape of the tension-strain curve of the geomembrane, and on the area between the tension-strain curve and the tension axis (i.e. the vertical axis). This area, known as co-energy, quantifies the ability of a geomembrane to withstand differential settlements. It must be said that only the continuously increasing portion of the tension-strain curve can be used in the determination of the co-energy. When the tension-strain curves of a Polyvinylchloride (PVC) geomembrane, of a Low Linear Density Polyethylene (LLDPE) geomembrane, and of a High Density Polyethylene (HDPE) geomembrane are compared, the co-energy associated with a PVC geomembrane is significantly greater than the co-energy associated with an LLDPE geomembrane, and even greater than the co-energy associated with an HDPE geomembrane. Consequently the factor of safety in respect to stresses associated with differential settlements is significantly higher if a PVC geomembrane is adopted.

The composite geomembrane used in GFRDs consists of a 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. With an elongation at break largely exceeding 230% according to EN ISO 527/4 standards, a PVC geocomposite can accommodate with a high factor of safety settlements and differential movements occurring at these dams.

2.3 Face anchorage system

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. All the anchorage systems described in the paper are patented by Carpi.

If the upstream base layer is made by extruded porous concrete curbs (ITA method, adopted in Brazil for the first time), 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

a) PVC anchor strips embedded in trenches excavated in the base layer at site-specific spacing. This system is described in chapter 4.1.
b) Deep anchors that are driven into the embankment after it has been completed, according to site-specific

patterns. This system is described in chapter 4.2.

2.4 Perimeter sealing

The perimeter seal is designed in function of the subgrade on which it is placed. If made on concrete, the seal is mechanical, of the so-called tie-down type. In tie-down seals, watertightness against water in pressure is attained by compressing the geocomposite unto the concrete subgrade (at plinth or intake tower or outlet or spillway) with flat stainless steel batten strips 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 (Fig.1).

Figure 1. Sar Cheshmeh GFRD, Iran 2008. Perimeter seal of the tie-down type at abutments.

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.

3. EXTRUDED POROUS CONCRETE CURBS AND PVC ANCHOR STRIPS

The advantage of adopting extruded porous concrete curbs against which the dam body is raised, 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.

3.1 Face anchorage: PVC anchor strips fastened to curbs

The face anchorage system consists of PVC geocomposite anchor strips nailed to the curbs and permanently anchored by the ballasting action of the fill against the curbs. The anchor strip fixed to one curb overlaps the anchor strip fixed to the underlying curb, and the two overlapping strips are heat-seamed to form continuous parallel anchor lines on the dam upstream side. The waterproofing geocomposite is then deployed over the face and watertight heat-seamed to the PVC anchor lines (Fig. 2), whose is designed in function of the design uplift loads. This patent is presented in ICOLD Bulletin 135 (2010).

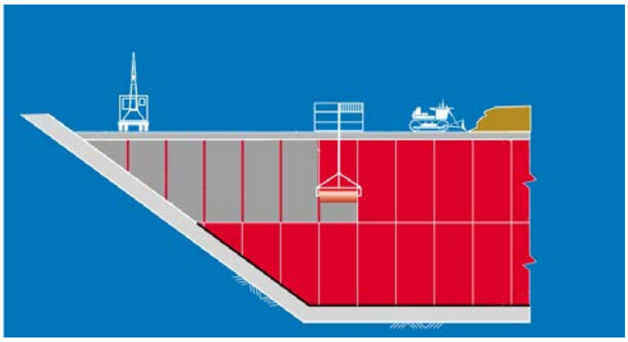

Figure 2. The red PVC geocomposite sheets and red PVC anchor strips (case of staged construction).

This system was first installed in 2008 at Sar Cheshmeh dam raising, where it is behaving very satisfactorily. The most recent completed example is Nam Ou VI rockfill dam in Lao PDR, discussed below. The same system is being installed at a tailings dam (name under confidentiality agreement) in South America that when completed will be 230 m high, at

Runcu 91 m high rockfill dam in Romania, at Bulga 17 m high dam in Australia, and has been approved for Dugald River dam in Australia.

3.2 Case history: Nam Ou VI rockfill dam, Lao PDR

Nam Ou VI rockfill dam is part of the Nam Ou VI Hydropower Project that will have 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 PVC 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 PVC geocomposite was selected, consisting of PVC geomembrane 3.5 mm thick, 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 PVC geocomposite is placed in exposed position, and anchored to the dam body by the above described system using PVC anchor strips embedded in the curbs, forming parallel anchorage lines at 6 m spacing. The dam body was constructed in three separate stages: Stage 1 from the bottom of the excavation, at El. 427 m, to a temporary work platform at El. 472.1 m, Stage 2 to from El. 472.1 m to a temporary platform at El. 512.1 m, and Stage 3, comprising a 3 metre high parapet wall, to reach El. 515.0 m. Construction of the dam body of Stage 1, embedding the face anchorage system, started on July 23rd 2014 and was completed on November 2nd 2014. Installation of the geomembrane system on the completed Stage 1 started on November 3rd 2014 and was completed in 24 days for about 13,700 m^2 of upstream water barrier, a fraction of what a concrete facing would have required.

Figure 3. Nam Ou VI GFRD, Stage 1. Dam body and anchor strips completed, PVC geocomposite under installation. Waterproofing system completed in 24 days.

The perimeter seal at plinth was designed with extra geocomposite material, to further extend the elongation capability of the system at the connection plinth/face. Construction of the dam body of Stage 2, embedding the face anchorage system, started on December 12th 2014 and was completed on April 14th 2015. The geomembrane system of Stage 2, identical to the one of Stage 1 and connected to it by watertight heat-seaming the geocomposites of the two stages, was installed starting April 15th 2015 and was completed in 28 days, for about 23,000 m^2 of upstream water barrier (Fig. 4).

The settlements that occurred during construction of Stage 2 of the dam body were sustained by the deformable geocomposite. 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.

Figure 4. Nam Ou VI GFRD, Stage 2. Waterproofing system completed in 28 days. The geocomposite of Stage 1, covered by dust, looks like concrete.

Stage 3, which will consist in covering the parapet wall with about 1,500 m^2 of geocomposite liner, will start at the beginning of April 2016. More details on this project can be found in a paper by Scuero et al. (2015).

4. ANCHOR TRENCHES AND DEEP ANCHORS

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 trenches

This patented method can be adopted with different types of base layers, provided they are stable and with a regular surface for installation of the waterproofing geocomposite.

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, similar to 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. Fig. 5 shows an example where the base layer was compacted soil.

Figure 5. Kohrang dam and headpond, Iran 2004. PVC anchor strips embedded in trenches excavated in compacted soil.

At Murdhari 36 m high rockfill dam in Albania, the base layer was made with porous concrete slabs. The dam was originally designed with an asphalt core; when the project had already started, the design was modified to a GFRD. The change in design had the objective of making construction of the dam safer, faster, easier to build, and less expensive. When the design was modified, construction of the fill was already ongoing, so there was no possibility of adopting the curbs. 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 (detail of Fig. 6). 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, for a total of 6,770 m^2 of geocomposite installed.

Figure 6. PVC anchor strips embedded in trenches placed between porous concrete slabs at Murdhari GFRD, Albania.

A further development of the system consists in anchor trenches that also allow pre-tensioning the geocomposite, to avoid formation of slack areas and folds that can be points of potential higher stresses and quicker ageing of the PVC geomembrane. This configuration was adopted at some slopes and bottom of the 18 Water Saving Basins of the Panama Canal Expansion project, in 2015 and 2016. The PVC geocomposite was laid directly over the trenches, which were then filled with concrete that provided the face anchorage against uplift. The procedure followed for filling the trenches allowed exerting a tensioning action on the geocomposite, thus minimising fatigue phenomena in basins that are subject to 14 daily cycles of filling and emptying.

Figure 7. Tensioning anchor trenches at Panama Canal Expansion Water Saving Basins.

4.2 Face anchorage by deep anchors

Deep anchors are adopted in base layers in 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 Duckbill type, or of the grouted type.

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.

Anchors of the Duckbill type have been used for the rehabilitation of Vaité earthfill dam in French Polynesia in 2011. A Duckbill anchor consists of a stainless steel bar or wire, of a rotating Duckbill, and of a tendon, which are driven into the ground (Fig. 8). When the anchor is fully inserted, an upward pull on the tendon rotates the Duckbill into a perpendicular "anchor lock" position in the soil. At Vaité, the anchorage system has been designed to resist hurricane conditions, with wind speed u to 204 km/h.

Figure 8. Deep Duckbill anchors at Vaité earthfill dam.

Anchors of the grouted type have been used at Filiatrinos 55 m high hardfill dam in Greece, the world's first hardfill dam having a geomembrane facing. Hardfill dams have aggregates of poor quality together with low cement content (typically 50-80 kg/m^3), which achieve a mix of low strength that is sufficient for stability requirements, but is semi-pervious. To fulfil watertightness requirement the hardfill dam needs an upstream sealing, traditionally provided by upstream concrete slabs. The concrete slabs can be advantageously substituted by a PVC geocomposite, placed at the upstream face and drained underneath. The system can be part of the dam's design, or be retrofitted, as at Filiatrinos, where the geocomposite is secured to the hardfill by deep grouted anchors placed at 4 x 4 m spacing (Fig. 9).

Installation of the system at Filiatrinos was completed on August 8th 2015, in one month for a total of 10,200 m^2. The designer of the dam (Moutafis 2015) states "Replacing the foreseen reinforced concrete slab with a geocomposite implemented at Filiatrinos dam in Greece, improved the functionality and reliability of the facing watertight element, with a simultaneous reduction of construction time and cost. Construction procedures were greatly simplified by eliminating the use of a slip form for the construction of the slab, eliminating the requirement for a mix design, omitting the construction of multiple joints in the slab and the installation of elaborated waterstops foreseen, minimising potential sources of leakage, etc."

Figure 9. Deep grouted anchors at Filiatrinos hardfill dam. Waterproofing facing completed in one month.

5. CONCLUSIONS

GFRDs can sustain large settlements, allowing constructing safe dams with simple procedures accommodating demanding schedules. They allow completing the waterproofing system for the dam in a shorter time and at a lower costs than traditional water barriers.

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