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Geomembranes in new pumped storage schemes

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SYNOPSIS Construction of pumped storage schemes is increasing to balance electricity networks and to maximise the energy coming from wind and solar sources. The reservoirs of such schemes must be lined with durable watertight facings to prevent water loss, ensure structural safety, and minimise maintenance, involving outage and heavy revenue losses. Geomembranes have been used in pumped storage schemes since the 1990s to restore watertightness of dams forming the reservoirs, and since the middle of the 2010s geomembrane were considered for new pumped storage reservoirs, substituting concrete or bituminous concrete facings. The advantages of geomembranes are numerous, the most important ones being the capability to resist settlement; differential displacement; joint openings; their maintenance-free durability and their repairability, also underwater. Several pumped storage scheme reservoirs have or will have a watertight flexible geomembrane facing, with different site-specific anchorage systems to maintain stability under varying hydraulic and wind loads. The paper presents design concepts, advantages, available systems, and related installation aspects of exposed flexible geomembranes through case histories recently completed or ongoing: Kokhav in Israel and Pinnapuram in India, with geomembranes anchored in trenches, and Abdelmoumen in Morocco, where a lacquered geomembrane was adopted to enhance durability in an environment with high UV radiation.

INTRODUCTION

The accelerating transition to clean energy produced an extraordinary worldwide increase in construction of new wind and solar plants. Wind and solar output, however, is not constant, and needs a storage system. Pumped storage schemes (PSSs) are at present the most dependable and mature storage technology to compensate for the intermittency of wind and solar energy. Consequently, pumped storage schemes are also dramatically increasing, either using and transforming existing powerplants and reservoirs, or creating entirely new schemes.

To provide the needed output to the grid almost instantaneously, a PSS must be kept safe and efficient, and an important role for safety and efficiency is played by the watertightness of its reservoirs: loss of water may initially entail only loss of profitability, but may also, in the long term, jeopardise the safety of the scheme if leakage continues. Since new reservoirs are mostly formed by earth or rock embankments and by excavation in semi-permeable soils, they require a facing system to ensure their watertightness. Due to the deformable nature of embankments and foundations, the facing system must be capable of resisting settlement, accommodating differential displacements where the embankments intercept concrete structures (intakes, spillways), and repeated loading and unloading cycles that can increase the potential for settlement and displacement, and aggressive environments. An additional issue is maintenance: facings that experience local or widespread failures due to the above stresses need frequent maintenance, and maintenance almost always implies outage. Due to the nature of these schemes frequent outage is unacceptable from a financial standpoint.

Geomembranes have been used for many decades to provide or restore imperviousness to dams and reservoirs, and the challenges posed by such structures have been successfully faced and solved. In particular for pumped storage, since the 1990s the application of geomembranes was related to restoring the watertightness of ageing dams forming one of the reservoirs. Only in the mid 2010s were geomembranes applied in new PSSs, and in 2016 what can be considered their first application in a PSS started operating: the 18 Water Saving Basins of the Third Set of Locks of the Panama Canal Expansion, lined with an exposed Carpi geomembrane liner to minimise water losses (Vale et al., 2018), with an average of 5 to 6 filling/emptying cycles per day, have to date undergone more than 15,000 filling/emptying cycles, equivalent to more than 40 years of operation of a PSS with 1 cycle per day.

There are at present 20 pumped storage schemes on which Carpi geomembrane systems have been installed, either as a waterproofing liner in new schemes, or as rehabilitation measures for leaking areas or joints, in the dry or underwater. This paper focuses on new PSSs, and in particular on the new reservoirs forming such schemes.

DESIGN CONCEPTS

The design of geomembrane systems for the reservoirs of new PSSs is based on previous experience in embankment dams and hydropower reservoirs, and on the additional issues to be considered for these plants: repeated loading/unloading, with the associated higher impact on slopes stability, cyclic daily exposure of the liner to UV and wind uplift, higher potential for fatigue phenomena, and the reversibility of the water current, which can amplify the formation of wrinkles and folds. Design parameters are the type of embankment and subgrade, and the loads acting on the geomembrane (varying water levels, wind). The type and thickness of the geomembrane, the drainage system, and the type and pattern of the anchorage system, are selected in function of such parameters.

A geomembrane system is by itself the most sustainable and resilient waterproofing solution, especially when compared to concrete and bituminous concrete liners: the small volume and weight of the components and of the equipment needed for installation make transport and site organisation easier, quicker and less cumbersome, resulting in a lower carbon footprint, and minimised environmental impact.

Geomembrane selection

All types of geomembranes, having permeability much lower than the permeability of traditional liners, are in principle very effective in providing watertightness. However, depending on the tensile properties and dimensional stability their behaviour in the field is very different. In the reservoirs of a PSS a geomembrane liner must be capable of resisting the action of an irregular subgrade under a varying water head, which can cause punctures and bursts; the stresses imparted by settlements in the subgrade; and by the differential displacements at boundaries (joints embankments/concrete structures).

Figure 1 compares the tension-elongation curves of a 3.0mm high density polyethylene (HDPE) geomembrane (in black) and of a Sibelon® CNT composite liner, formed by a 3.0 mm Sibelon® PVC geomembrane heat-bonded at fabrication to a 500g/m^2 non-woven geotextile (in red). For the HDPE, the curve is limited to the range of admissible strains in the field, i.e. below the yield point (at about 12% elongation), after which the behaviour of the geomembrane becomes plastic, the geomembrane thins down locally and elongates like gum, presenting a plastic elongation under essentially constant tension up to the elongation at break. For the PVC composite geomembrane, the curve is limited to the range below the breaking of the backing geotextile (at about 70% elongation), above which however the geomembrane keeps its functional integrity up to its elongation at break. The presence of a yield point may be crucial in hydraulic applications. According to ICOLD (ICOLD, 2010), "Mainly for HDPE, for a stress higher than the yield point, significant partially irreversible deformations (creep) occur after the stress has ceased." Therefore, HDPE geomembranes should be used only where the geomembrane elongation is well below the yield elongation, and with a substantial factor of safety. International literature (Seeger and Müller, 1996; Peggs et al, 2005) indicates that to be on the safe side the allowable elongation of HDPE geomembranes should not exceed 3% to 5%, and that for elongations greater than 3% the "creep" phenomenon is important and cannot be neglected. In the case of some textured HDPE geomembranes, even lower percentages should possibly be considered. Due to relatively poor dimensional stability HDPE geomembranes are also prone to the formation of high wrinkles and folds due to temperature variations. On the contrary, PVC composite geomembranes have no yield. They are characterized by a monotonically increasing tension-elongation diagram that has two peaks: the first peak corresponds to the breaking of the backing geotextile (Figure 1) and the second peak corresponds to the breaking of the geomembrane. Beyond the first peak, the material presents the characteristic behaviour of the geomembrane until failure. The presence of a backing geotextile further reduces the already low sensitivity to temperature variations and to the formation of folds.

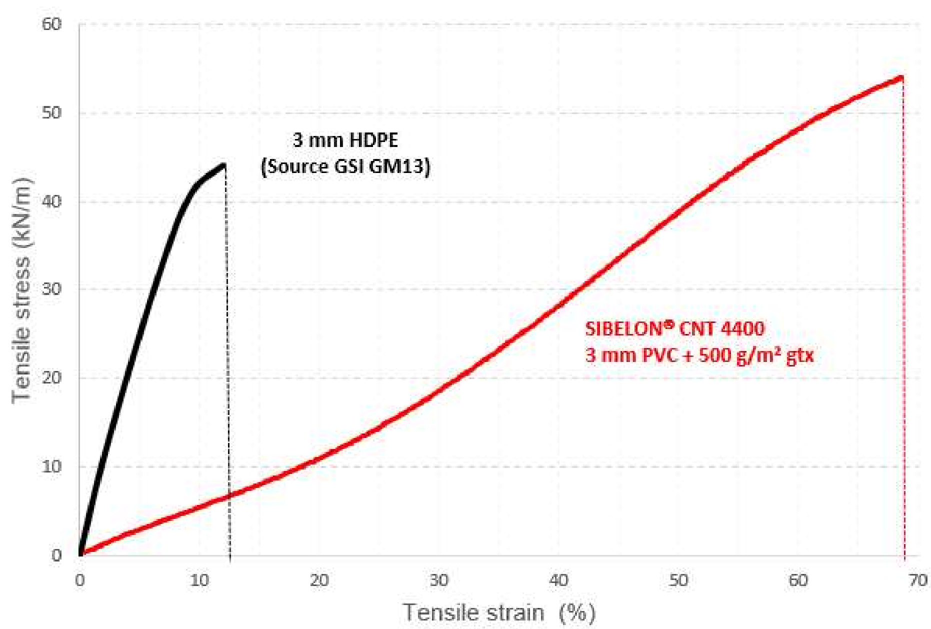

Figure 1. Tension-elongation curve of a 3.0 mm thick HDPE geomembrane (black) and of a PVC composite geomembrane (red)

Managing Risks for Dams and Reservoirs

The capability to withstand differential settlements at the junctions with concrete appurtenances can be ascertained following the Co-Energy concept developed by Giroud (Giroud, 2005). The Co-Energy is the area between the geomembrane tension–strain curve and the tension axis. A geomembrane can withstand a differential settlement when the required geomembrane Co-Energy, related to the stress-strain condition in the field, is lower than the allowable geomembrane Co-Energy. According to Giroud, geomembranes with greater Co-Energy can tolerate larger differential settlements.

The graph (Figure 2) comparing the Co-Energy of an HDPE geomembrane up to the yield point and of the composite geomembrane already considered up to the breaking of the geotextile, clearly shows that the maximum allowable Co-Energy associated with the PVC composite geomembrane (the grey area) is significantly greater than the Co-Energy associated with the HDPE geomembrane (the red area). As a result, the factor of safety with respect to a potential differential settlement is significantly higher for the PVC composite geomembrane than for an HDPE geomembrane of the same thickness. A different geomembrane thickness would not produce a different result.

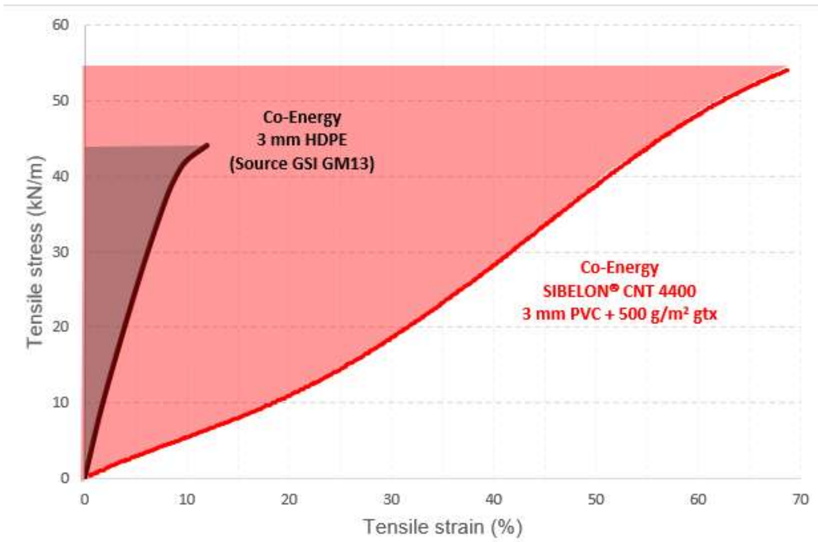

Figure 2. Co-Energy: comparison between the area comprised within the tension-strain curve and the tension axis of a 3.0 mm HDPE geomembrane and of a composite geomembrane (3.0 mm thick PVC geomembrane heat-bonded at fabrication to a 500 g/m^2 non-woven geotextile).

The thickness of the PVC geomembrane and the weight of the associated geotextile, which enhances the puncture resistance and the thermal stability, are selected based on the layers that will be in contact with the liner (subgrade, cover layer if any), on environmental aggression (basically UVs and temperature variations), and on required life span.

Face anchorage system

The geomembrane is typically left exposed, and a face anchorage system keeps it stable against varying water levels and wind uplift. Anchorage at points is rarely adopted; unless loads are not very demanding and the anchors are very closely spaced, the stresses on the geomembrane at each anchor will be unacceptable (ICOLD, 2010). Face anchorage is made by lines, to maintain the geomembrane as tense and adherent as possible to the support layer, to avoid folds that can form during daily variations in water levels, as these folds are areas of stress concentration, potentially leading to more rapid ageing and fatigue phenomena in the geomembrane. The anchor lines can be longitudinal (at crest, berms, bottom) and/or vertical (at slopes, bottom), with spacing calculated with well-known methods (Giroud et al., 1995) depending on the effects of wind suction/variations of the water body. Face anchorage by ballast is possible, but it reduces the volume of impounded water and is generally restricted to areas with heavy traffic (access ramps, intake areas).

Face anchorage is designed in accordance with the type of embankment. In embankments constructed with soil (earthfill), characterised by mild slopes (e.g., 3H:1V), with a bedding layer for the geomembrane liner made of compacted cohesive material, face anchorage typically consists of geomembrane anchor bands embedded in trenches excavated in the bedding layer, to which the geomembrane liner is secured by heat-seams. A drainage layer must be provided under the geomembrane liner, which can be a granular material or a synthetic geodrain; the drainage layer is connected at the slope toe to the drainage network of the reservoir bottom. In embankments constructed with small rockfill (gravel, stones), characterised by relatively steep slopes (e.g., 2H:1V), with a bedding layer for the geomembrane liner made of compacted and selected gravel with sufficient drainage capacity to also act as drainage layer, face anchorage is made by heat-seaming the geomembrane liner to geomembrane anchor bands embedded in trenches, or embedded in the embankment as it is being raised. In embankments constructed with large rockfill (stones, cobbles, boulders), characterised by steep slopes (typically 1.6H:1V), the bedding/drainage layer for the geomembrane liner is made of porous concrete either in the form of a relatively thin layer (200mm-300 mm) or in the form of extruded kerbs (constructed with an extruding machine). Face anchorage is made by heat-seaming the geomembrane liner to geomembrane anchor bands embedded in trenches in the porous concrete, or to geomembrane anchor strips secured to the extruded kerbs; this method can increase void space in the reservoir which in turn has both short and long-term advantages to the overall project.

Perimeter seals

The geomembrane liner is sealed at all peripheries by a watertight perimeter seal. When made on concrete, the seal consists of stainless-steel flat profiles that achieve watertightness by compressing the liner onto the concrete with the aid of regularising resin, rubber gaskets and stainless-steel splice plates. Seals of the embedded type (embedment in top trenches, in slots) are adopted at deformable areas.

Designing for optimised advantages

The main advantages of geomembrane systems have already been outlined. Further optimisation is possible if the design is made in cooperation with the designers of the reservoirs. The face anchorage system and the drainage layers can be adapted to the design and the materials used for the embankments, possibly reducing the amount of granular materials/increasing the steepness of the slopes. Perimeter seals can be designed with an abundance of geomembrane liner, to resist large displacements, so avoiding stressing the geomembrane.

The geomembrane system can be conceived so that it can be constructed in sequence, organising the various tasks to meet faster construction schedules, achieving waterproofing at a much faster rate than would be achieved by using a concrete or asphalt concrete facing. Faster completion will allow earlier power generation.

Pumped storage schemes are structures where minimising outage is critical and selecting a liner that does not need routine maintenance can make a substantial difference for operation costs during the service life of the scheme. The geomembrane system can be designed for enhanced service life and minimum maintenance, and at its end, it can be recycled.

CASE HISTORIES

Earthfill embankments: Kokhav Hayarden reservoirs, Israel 2020/2021

At Kokhav Hayarden, which with an installed capacity of 344MW will be the largest pumped storage project in Israel, the upper reservoir was partly formed by a compacted earthfill embankment, and partly excavated in river deposits of clay and a clay-gravel mixture. The inclination of the slopes is 3.5H:1V and the water fluctuation is around 22m. The lower reservoir is formed by a continuous compacted earthfill embankment, composed of river deposits of clay and a mixture of silty clay and gravel. The inclination of the slopes is 3H:1V, the water fluctuation is around 21 m.

Both reservoirs were originally designed with an HDPE geomembrane facing, placed over a drainage layer of compacted granular material, anchored at the crest by a longitudinal trench and at the bottom by the ballasting action of the water that would always be standing in both reservoirs. This design was deemed susceptible of improvement considering that in a PSS the geomembrane remains exposed for longer times to the potential adverse effects of wind uplift and wrinkle formation due to temperature variations. After a detailed review of the project, to provide higher performance, also in respect to possible large settlements of the subgrade, alternatives of different waterproofing liners were evaluated and a safer and more durable design configuration was approved for construction. The HDPE geomembrane was substituted for a Sibelon® CNT 3100 composite geomembrane (a 2.0mm PVC geomembrane heat-bonded to a 500g/m^2 non-woven polypropylene geotextile), which is more flexible and deformable, and less prone to formation of wrinkles and folds. The face anchorage system was made more robust by vertical anchorage trenches excavated in the embankments, where anchor bands of SIBELON® CNT 2300 composite geomembrane (1.5mm thick PVC geomembrane, heat-bonded to a 350g/m^2 non-woven polypropylene geotextile) were embedded and ballasted with compacted granular material, thus providing stable anchor lines for the waterproofing liner. Based on a maximum design wind velocity of about 150km/h (upper reservoir), an 8m trench spacing for the upper 1/3 of the slope and 16m spacing for the lower 2/3 of the slope were adopted for both reservoirs. The trenches in the upper 1/3 of the slope are larger due to the stronger effect of wind uplift towards the crest.

A synthetic drainage layer was installed over the compacted support on the slopes: it consists of a composite material providing drainage (its geonet component) and filtering (its geotextile component) functions. At the bottom, the drainage layer consists of selected gravel. The drained water is discharged through a network of perforated pipes.

At submersible concrete peripheries, the waterproofing geocomposite is watertight, sealed by a stainless-steel mechanical seal, 80x8mm. To further increase safety in respect of differential displacements, the seal is designed to limit stresses in the waterproofing liner by providing an extra length of geomembrane accommodated in a "settlement slot" that acts as a hinge between the embankment and the concrete structure.

Figure 3. Preparation of subgrade and anchor trenches at Kokhav Hayarden

Figure 4. Components of the waterproofing system

Installation of the geomembrane system in the lower reservoir started on 21 July 2021 and was completed on 29 September 2022. In the upper reservoir it started on 20 July 2020, and was completed on 17 December 2022. In total, 433,000m^2 of geomembrane was installed.

Figure 5. Kokhav Hayarden upper reservoirs' liner being completed

Figure 6. Kokhav Hayarden lower reservoir impounding

Impounding tests are ongoing. Data available at present for the lower reservoir show piezometer pore pressure curves with negative values and lower than the alert values, and for leakage values of 0 l/s in three compartments, and between 0.083 and 0.0183 l/s in the other four compartments. Only at the three compartments adjacent to the intake had the pressure increased, and leakage values were higher, the maximum being of 0.616 l/s. An underwater inspection ascertained that the increase in pressure was due to a leak coming from a local defect (puncturing) of the geomembrane in coontact of a vertical joint of the intake. The defect, found and temporarily repaired underwater, will be permanently repaired when the impounding tests are completed.

Small rockfill embankments: Abdelmoumen reservoirs, Morocco 2021/2023

Abdelmoumen, a PSS on the River Issen in Morocco, will have a 350MW installed capacity, exploiting a 500m water head. Both reservoirs are formed by embankments made of compacted granular material, with a slope inclination 2H:1V and a water level fluctuation of about 20 m. In addition to the usual challenges of pumped storage schemes, Abdelmoumen had two specific aspects: the geographic location required a waterproofing geomembrane capable of resisting particularly intense UV radiation, and the poor subgrade material available for the rather steep embankments could result in significant settlement and/or slope stability issues under the effect of repeated hydraulic loading. Therefore, the slopes had to be properly compacted, and the geomembrane had to be placed in a way that would not affect the slope stability and vice versa – the waterproofing system should not be affected by the settlement of the subgrade.

The selected geomembrane, Sibelon® CNT 4400 L, consists of a 3.0mm PVC geomembrane heat-bonded to a 500g/m^2 non-woven polypropylene geotextile, having a surface lacquered treatment (L) designed to increase the service life of the liner. Accelerated and specific weathering tests have shown that this treatment enhances the life of the material under intense UV radiation with respect to a non-treated liner of the same thickness, while keeping the remarkable flexibility and excellent tensile response of such PVC liners. To assess the effect of cyclic loading on the geocomposite and on a heat-seam, a real-scale testing campaign was carried out in the laboratory, simulating the conditions at Abdelmoumen. The simulation parameters included the Abdelmoumen subgrade material, the Sibelon® CNT 4400 L geomembrane liner, water pressure corresponding to the expected daily fluctuations, and number of fill/empty cycles compatible with the expected usage of the plant: with water pressure fluctuating between 0 and 2 bar during each cycle, we performed cyclic loading at the rate of 144 cycles per day for 127 days. This corresponds to 25 years in operation assuming two fill/empty cycles per day, or 50 years in operation assuming one fill/empty cycle per day. The tested sample and seam were then evaluated and compared with a virgin sample of the same material and seam by an independent laboratory in Germany, for thickness reduction, tension/elongation, and seam resistance to shear and peel. The test results demonstrated that the selected geomembrane liner can withstand cyclic loading with no quantifiable evidence of fatigue, showing no sign of damage or loss of watertightness, and variation of the mechanical properties less than 3% when compared to the ex-work samples.

The anchorage system at Abdelmoumen was based on the concept of avoiding constructing trenches, and of embedding instead rectangular geomembrane anchor strips into the embankments during construction. A specific procedure was developed to embed the geomembrane anchor strips while achieving a good compaction of the subgrade material. The result is a stable slope of compacted material, and effective robust confinement of the anchor strips. A continuous band of geomembrane was heat-seamed unto the strips to create a continuous vertical anchorage line, which distributes the stresses at placement and during operation. The design wind velocity was about 90km/h for both reservoirs, with a safety factor of at least 2.0. The resulting spacing of the vertical anchorage lines on the slopes is 8.0m, measured along the crest. Considering the possibility of a complete emptying of the reservoirs, a specific anchorage system is provided in the bottom, consisting of longitudinal trenches backfilled with concrete at 16m spacing.

Compaction of the embankments and installation of the geomembrane anchor strips started in April 2021 at the lower reservoir and in May 2022 at the upper reservoir. The geomembrane systems were completed in August 2022 at the lower reservoir and in January 2023 at the upper reservoir. Additional anchorage lines consisting of ballasting prefabricated concrete blocks were placed at some top locations of the upper reservoir where wind gusts stronger than expected were experienced (Figure 9). In total, about 195,500m^2 of exposed geomembrane liner installed. Both reservoirs are now impounding (Figure 10).

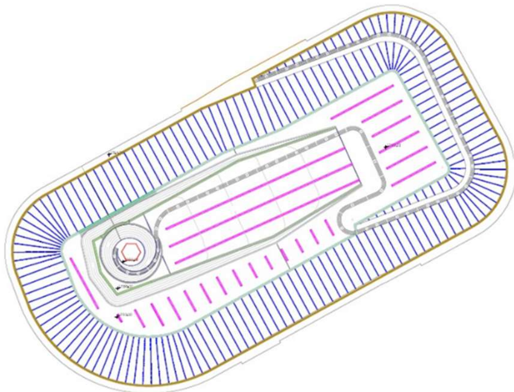

Figure 7. Abdelmoumen: layout of anchor trenches at upper reservoir

Figure 8. Abdelmoumen: anchor strips and anchor bands

Figure 9. Some additional ballast at Abdelmoumen upper reservoir

Figure 10. Upper and lower Abdelmoumen reservoirs impounding

Rockfill embankments: Pinnapuram, India, ongoing

Pinnapuram reservoirs, under construction in India, are part of the Pinnapuram Integrated Renewable Energy pumped storage project, which includes 1000 MW solar, 550 MW wind and 1680 MW of standalone pumped storage capacities. The scheme is a first-of-its-kind pumped storage project developed by Greenko, an independent power producer in India, whose second PSS, Gandhi Sagar, is starting now. The upper reservoir features a 6.5km long rockfill dam, forming a continuous embankment with a nearly rectangular shape in plan, and maximum height of about 40m. The lower reservoir is formed by three separate rockfill dams connecting existing natural slopes, with a total crest length of about 3.3km and maximum height of about 46m.

For Pinnapuram, avoiding/minimising water losses through the reservoirs is fundamental to the project: both reservoirs are far from existing natural river systems and have no/negligible catchment area, so water will be lifted once from the Gorakallu Reservoir irrigation system to fill them and to be used cyclically for energy production. Evaporation losses, if any, will be recouped periodically. A bituminous concrete facing was originally planned to grant watertightness to the dams forming both reservoirs. After further technical and economic assessment, the bituminous concrete was eventually replaced by an exposed geomembrane facing. The geomembrane liner selected for all dams is Sibelon® CNT 4400, the same material used at Abdelmoumen, but without surface treatment.

Managing Risks for Dams and Reservoirs

The layering at the dams, proceeding from the transition layer of rock fill material 3A-US/2B towards the upstream, consists of a concrete layer, needed for the Optical Fibre Cable system required by the owner to allow leak location, followed by a thin layer of porous concrete that constitutes the bedding layer for the geomembrane. The face anchorage system is made by geomembrane anchor bands embedded in trenches created by discontinuing the concrete and porous concrete layers, and then ballasted with concrete and porous concrete (Figures 11 and 12). The regular spacing between the trenches, calculated as usual based on the wind force, the resulting uplift, the water level cycles, is 16m. The porous concrete bedding layer has sufficient drainage capability to act also as full-face drainage layer under the waterproofing liner.

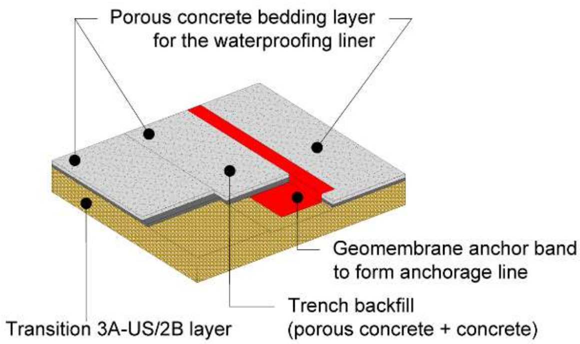

Figure 11. Scheme of anchor trenches at Pinnapuram lower dams

Figure 12. Geomembrane anchor bands embedded in trenches

The geomembrane system was installed in a sequential manner, following the deployment of civil works: earth works for the construction of the embankments, placement of the concrete and of the porous concrete bedding layer for the geomembrane system, concurrent with creation of the anchor trenches, installation and ballast of the geomembrane anchor bands in the trenches, deployment of the waterproofing liner and subsequent fastening to the anchor bands by heat-seaming (Figure 13). At the upper reservoir, to expedite works at the more than 6km long dam, the porous concrete bedding/drainage layer was substituted with a synthetic drainage layer (Figure 14), like the one adopted at Kokhav Hayarden.

Figure 13. Installation of geomembrane on porous concrete at lower dams

Figure 14. Installation of geomembrane on synthetic drain at upper dam

At present, the geomembrane is being installed at the dam forming the upper reservoir (Figure 15) while installation has been completed at the lower reservoir; waterproofing works are ongoing at the tailrace channel, where an exposed geomembrane replaced the bituminous concrete liner originally planned.

Figure 15. Pinnapuram pumped storage scheme: upper reservoir

CONCLUSIONS

Typically, the waterproof facing works represent less than 2% of the cost of a pumped storage scheme, but their efficiency is essential to make the investment profitable. Geomembrane liners propvide safety and efficiency of pumped storage schemes by preventing water loss through the two reservoirs, and by resisting settlement and differential movement. Reducing construction time and costs, and allowing earlier generation, are the assets of this sustainable technology.

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