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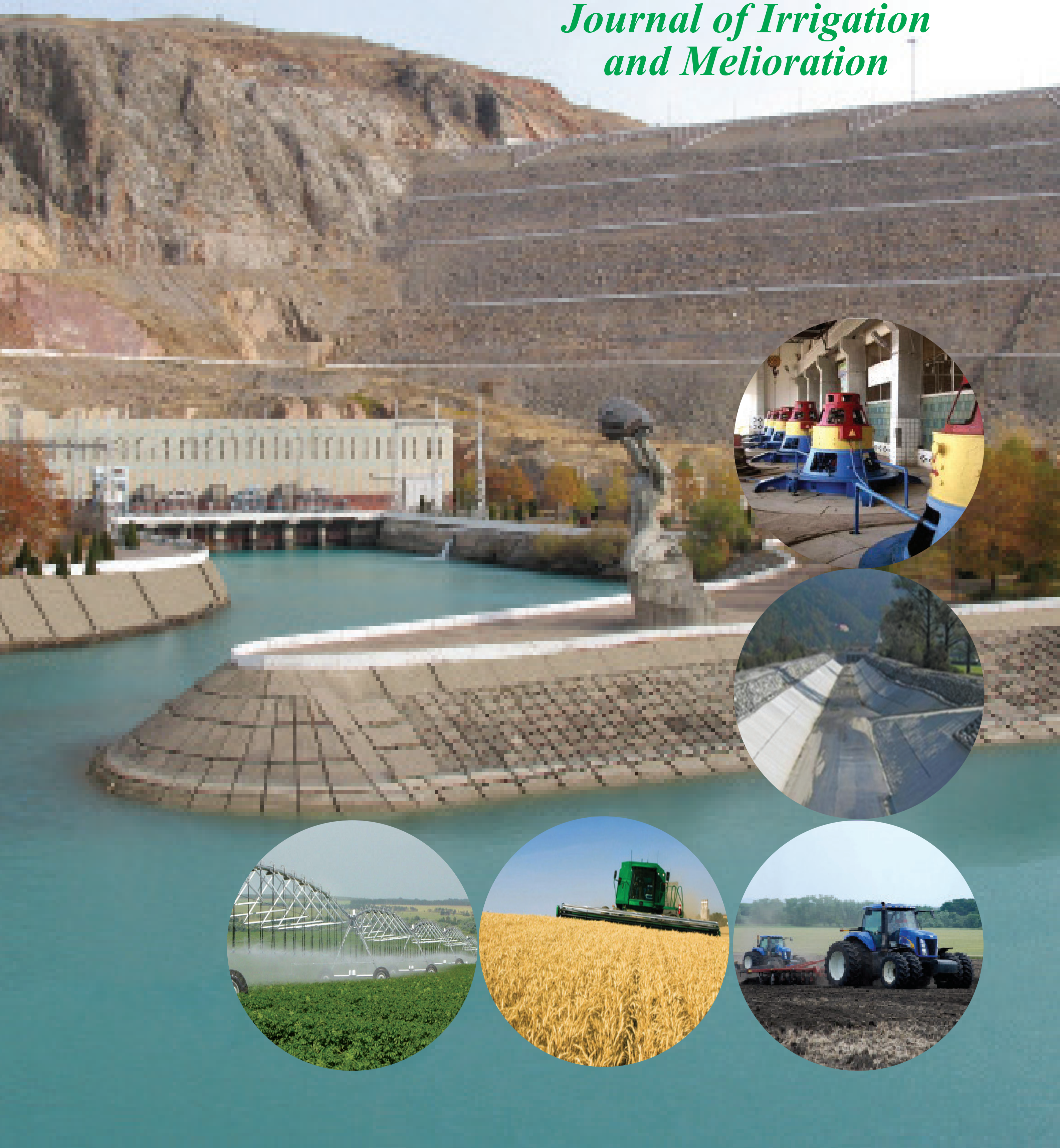

THE USE OF GEOMEMBRANES TO INCREASE EFFICIENCY, RELIABILITY AND SAFETY OF HYDROTECHNICAL STRUCTURES

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Abstract

Geomembranes are thin, flexible sheets with very low permeability. They are manufactured in a controlled factory environment starting from a mix of polymeric resins and additives, which is extruded to form the sheets. Performance properties of the final product depends on the characteristics of the single components, on the specific material design, and on the manufacturing method. Critical properties of a geomembrane for lining hydraulic structures are: imperviousness, which must be maintained over the whole service life of the structure; strength and elongation capability, which must enable the geomembrane to withstand deformations of the underlying support; resistance against ageing, so to enable an acceptable service life. Leakage through a hydraulic structure can affect its efficiency if not become a threaten for its safety. Geomembranes with proper performance properties can be essential in ensuring efficiency, reliability and safety of hydraulic structures. This paper describes a fewamong the >250 projects that have been performed by the affiliation of the authors.

Key words: Geomembranes, repair, new construction, dams, reservoirs, hydraulic tunnels, shafts.

Introduction. Polymeric geomembranes have been usedsince the late 1950s in the new design of embankment dams. Starting from the late 1970s, their use has been extended to rehabilitation of concrete and masonry dams. These successful installations helped to build up trust in these synthetic materials and their use was extended to construction of Roller Compacted Concrete (RCC) dams and to their rehabilitation. Nowadays, geomembranes are increasingly being selected in alternative to more traditional linings in embankment dams because they show to be a safest and surely more cost-effective solution. The geomembrane can be screened with a cover layer or maintained exposed. The last set-up has the major benefit that the geomembrane can be easily inspected and potential damages can be easily repaired. In the unlikely case of damage, the geomembrane can be repaired by patch work, namely cutting out the portion of damaged geomembrane and placing patches of geomembranes that are heat-seamed or fixed with stainless steel profiles to the rest of the lining, so to restore its continuity. Methods have been developed for installing geomembranes underwater, which bring the additional benefit of eliminating or minimize operation disruption. Performance properties of a geomembrane system depend on the physical and mechanical characteristic of the geomembrane, but also on the design and installation. A material with potential optimal characteristics will still perform faulty if the geomembrane system is not properly designed and installed. To this purpose, ICOLD has published a Bulletin in 2010 [1], which provides guidelines for designing geomembrane systems. The case studies descried in the following sections are all projects where the adopted waterproofing material is a SIBELON® geocomposite, obtained heat-bonding a SIBELON® geomembrane to a non-woven needle-punched virgin fibres geotextile. SIBELON® is the trademark for polymeric geomembranes produced exclusively for Carpi, and the geomembrane systems are mostly patented.

Concrete and RCC dams: the cases of Chambon and Susu dams

Chambon (France) is an outstanding example of how geomembrane systems can give a major contribution in extending the life of a dam. Chambon is a 137-m high concrete gravity dam completed in 1935, affected by heavy Alkali Aggregate Reaction (AAR). Measures to guarantee safe operation of the dam until year 2000 were a series of slot cutting, and adrained exposed SIBELON® geomembrane system anchored to the dam face with a system of tensioning profiles (Carpi patent), which was installed in 1994 to provide waterproofing protection atthe upstream face. This system was deemed the most adequate as: 1) in the event of an earthquake, the deformable and elastic geocomposite would bridge the cracks already existing and new cracks that should form, maintaining water tightness and reducing risk of hydro jacking; 2) it could stop water infiltrating into the dam body and feeding the AAR; 3) it would avoid the risk of uplift, thus maintaining the stability of the dam; 4) it would easily restore water tightness after slot cutting, providing reliable protection of slots; 5) efficiency could be monitored on a continuous basis due to the full face drainage system placed behind the waterproofing liner. In 2013, the owner EDF decided to carry out new slot cutting, and to makestructural reinforcement by an upstream system of tendons and carbon bands, which requiredremoving the geocomposite. The

Fig.1. Installation of the SIBELON® geomembrane system at Chambon dam

same geocomposite system was installed again, to protect the damfrom seepage feeding under pressure. Rehabilitation works were successfully completed in 2014,granting a further extension of service to Chambon.

Susu (Malaysia) is an RCC dam of 90 m height, which is part of the Ulu Jelai Hydroelectric project. Susu is an example how a safer and more cost-effective solution can be achieved when the upstream face of an RCC dam is lined with an exposed geomembrane. The geomembrane placed over the upstream face of an RCC dampermanently waterproofs the bulk material, the lift and construction joints, and any cracks that may develop. The cement content can therefore be reduced, pozzolan or fly ash can be reduced or eliminated, and

Fig.2. View of Susu dam during impoundment

requirements for placement and quality control of these materials can in general be relaxed. Lower cement content entails lower hydration heat production, thus the need of controlling temperature with expensive cooling devices is reduced. GEVR (Grout Enriched Vibrated RCC) or GE-RCC (Grout Enriched RCC) can be removed from the design and horizontal joint treatment or bedding mix of lift surface areas can be reduced. Vertical waterstops and drains can also be eliminated, because they are included in the geomembrane system. The overall result is that construction costs and construction time can be remarkably reduced, and filling of the reservoir and operation of the facility can move up. The original design of Susu dam conceived an RCC mix with a content of 100 kg/m3 cement and 80 kg/m3 fly ash, and a PVC geomembrane attached to pre-cast concrete panels used as formwork to place the RCC. This design was changed for an exposed, drained SIBELON® geomembrane system anchored to the dam face with the same patented system of tensioning profiles as at Chambon dam, which allowed a lower cement content in the mix of 95 kg/m^3 and enabled removal of the fly ash. Placement of the RCC, for a total of 731,000 m^3, started in March 2014 and was completed in September 2015. Installation of the geomembrane system, which was planned so to match the construction schedule of the dam, started in June 2015 and was completed in January 2016. The reservoir was impounded shortly after the waterproofing works were completed.The same geomembrane system has been used also in rehabilitation of RCC dams. Examples are Grindstone Canyon (2015) and San Vicente (2013), both in USA. At San Vicente, the geomembrane was placed on the nearly 36 m heightening of the dam, the highest dam raising in the world using RCC. The primary design objective was for the dam to survive a large seismic event, remaining fully operational to provide an emergency supply of water to the San Diego region.

Embankment dams: the cases of Nam Ou VI dam and Rogun cofferdam

Nam Ou VI is an88-m high rockfill dam, whoseconstruction started in July 2014 and was impounded just eleven months after. The reason for choosing a geomembrane facing instead of another type of facing was that large settlements were expected at the end of construction and during service life, as result of the poor mechanical characteristics of the foundation and of the material forming the dam body. In the original design the geomembrane was a covered polyethylene geomembrane. However, this type of geomembrane would not have been suitable for applications such as at Nam Ou VI dam and, for this reason, it was replaced with an exposed SIBELON® geomembrane. The adopted solution is much safer, as it canaccommodate the large settlements predicted

Fig.3. Nam OU VI rockfill dam after completion of the second stage installation of the exposed SIBELON® geomembrane system

for this dam, it has required a shorter construction time, and is overall a very cost-effective solution. At Nam Ou, the SIBELON® geocomposite liner is fastened,by heat-seaming,to anchorage lines embedded in the subgrade. The anchorage lines, also made of SIBELON® geocomposite, were constructed simultaneously to the dam body: after each raise of the embankment, a curb of high-permeability concrete was constructed at the upstream face of the dam, using an extruding machine; then, after strips of SIBELON® geocomposite were placed on top of the curb, at regular spacing, the embankment was further raised. Finally, the overlapping strips of SIBELON® geocomposite were heat-seamed to form continuous anchorage lines. This system is patented by Carpi. At Nam Ou VI dam, the geomembrane system was installed in stages, following construction of the embankment. The same system chosen for Nam Ou VI dam is currently being installed in a tailings dam under construction at 4,000 m a.s.l in the Andes. This dam, whose finall height will reach 230 m, with its 120 m height is currently the highest dam in the world with a geomembrane as only waterproofing element.

Rogun (Tajikistan) can be considered the Dam of Records: with its height of 335 m, it will be the highest dam in the world and the most powerful in the region, doubling energy production of the country and reducing the power shortages suffered during the winter months.The scheme includes a nearly 68 m high

Fig.4. Installation of the SIBELON® geomembrane system in the Rogun upstream cofferdam

upstream cofferdam up to 1,050 m a.s.l, a nearly 136 m high early production stage dam (also named Stage 1 dam) up to elevation 1,110 m a.s.l, waterproofed with an asphalt core, and a nearly 335 m high main dam up to 1,300 m a.s.l, waterproofed with a clay core. The upstream cofferdamwas conceived with an upstream geomembrane. The selected system is a heavy-duty SIBELON® geomembrane system, consisting of a 4-mm thick geomembrane and a 700 g/m^2 backing geotextile that has been installed in the period February-June 2017, for a total of 22,286 m^2. The SIBELON® geocompositewas placed on a supporting/drainage layer made of selected material and covered with a 50-m wide rip-rap layer, designed to conform to the stability requirements of the main dam. The waterproofing geocomposite is protected with a cushion of selected material and a 2000 g/m^2 anti-puncture geotextile. The important resistance of the geocomposite to puncturing has made possible to minimize surface preparation of the supporting layer. Installation proceeded in 6 m high stages to provide an increasing protection against floods and allow the simultaneous raising of the embankment while placing the backfill. Installation was completed according to schedule despite the veryharsh climate, with heavy rains and snow. To possibly achieve the goal of testing and commissioning of the first power unit of Rogun HPP within 2018, the SIBELON® is currently being extended up to elevation 1,065 m a.s.l, which corresponds to nearly 15 m heightening of the cofferdam.

Reservoirs: the cases of C.W. Bill Young reservoir and the Panama Extension Water Saving Basins

C.W. Bill Young, with a volume of 70 million cubic meters, provides water to Hillsborough, Pasco and Pinellas counties of Florida (USA). The reservoir, located in a county which is designated as a wildlife reserve, became operational in October 2005. The slopes of the reservoir were earthen embankment dams with a waterproofing geomembrane, soil-cement layer, a stair-step interior liner and an exterior grassed terrace. In 2006, abnormal cracks began to appear in more than about 40% of the reservoir's interior lining. Further investigations determined that the high pressure from water trapped in the soil wedge, below the soil cement, resulted in the cracking. Renovation of the reservoir started in 2012. A SIBELON® geocomposite was selected for a long-term repair, to replace the existing geomembrane. The adopted SIBELON® geocomposite is a 2-mm thick geomembrane heat-bonded at both sides to a 200 g/m^2 polyester geotextile at the back, and to a 500 g/m^2 polypropylene geotextile at the top. Installation, for a total of 417,000 m^2 geomembrane installed, wasmadebetween May 2013 and April 2013. The new reservoir ensures water supply, draught resistance and minimizes reliance on groundwater for customers today and in the future.

The **18 Water Saving Basins** that are part of the Panama Canal Expansion Project, which was

Fig.5. C.W. Bill Young reservoir in operation after rehabilitation, which included placement of a covered SIBELON® geomembrane system

inaugurated on 26th of June 2016, are of major importance for the project as these allow reuse 60% of the water in each transit. Therefore, watertightness is crucial to them. As this could not be granted only by concrete for the 100 years minimum functional life of the project, original design included a PVC geomembrane system covered with cast-in-place concrete slabs. The original design was changed in an exposed SIBELON® geomembrane system, designed to resist demanding load conditions that include: cyclic filling and emptying of the reservoirs up to 14 cycles a day, strong winds, large settlements, transit of vehicles, etc. Thanks to its flexibility, the system has undergone optimizations and changes to adapt to the specific site conditions. It consists of a SIBELON® geocomposite anchored in trenches, with tensioning profiles or with deep anchors, depending on the type and slope of the subgrade. Installation of the 591,600 m^2 geomembrane system has been completed in less than one year, in challenging weather and site conditions, fulfilling all contract requirements and passing all tests on completion. Selection of the exposed SIBELON® geomembrane system has resulted in a safer and cost-effective solution because of higher capability to maintain water tightness in presence of settlements and seismic events, of reduced amount of concrete involved, and shorter construction times.

Canals: the cases of Pernegg and Tekapo canals

Pernegg is a 2.3 km long diversion channel power station on the river Mur, in Austria. The canal, originally with a concrete and bituminous concrete facing, presented seepage. An exposed SIBELON® geomembrane system was selected to provide long-term imperviousness to the canal. This consists of a SIBELON® geocomposite anchored to the subgrade with a system of stainless steel profiles placed parallel to the axis of the canal and fastened with short or deep anchors, depending on the quality of the subgrade. The geomembrane system was designed according to the guidelines issued by the Technical University of Munich

[2] and based on a research conducted at the same university [3], for a water velocity of 2.1 m/s. Among the benefits of the exposed SIBELON® geomembrane system is the increased hydraulic efficiency. This is a result both of the very low micro-rugosity of the material itself and of the low macro-rugosity. In fact, the face anchoring systems mentioned in this paper are all conceived to make the liner smooth between the anchorage lines, with no wrinkles or folds. Wrinkles and folds are in general deleterious to durability of a geomembrane as they are potential locations of stress concentrations and, in the case of canals or hydraulic tunnels, also reduce hydraulic performance of the structure. A requirement to the geomembrane system installed at Pernegg was its natural appearance: this

Fig.6. Aerial view of the Basins at the Pacific side upon completion of the waterproofing works

was obtained placing boulders in the upper part of the slopes. The SIBELON® geomembrane system was installed in a 2.1 km long section for a total of 48,000 m^2. Installation was completed in 3 months, in 2010. Up to date, the geomembrane system performs as expected.

Tekapo Canal, in the South Island of New Zealand, transfers water from the tailrace of the Tekapo A Power Station, on the edge of Lake Tekapo, to the head pond of the Tekapo B Power Station, which discharges into Lake Pukaki. The canal is 25.3 km long, has a capacity of 120 m^3/sec and a flow rate of 1.2 to 1.6 m/sec. Construction of the canal was completed in 1977, with an internal earth lining. In time, the canal developed excessive leakage and evidence of progressive internal erosion, which led to the need for repairs. Objectives of the remedial works were to manage deterioration of the existing canal lining and improve resilience of the canal to maintain the future viability of the hydropower asset. In addition, any solution had to be achieved with a high

Fig.7. Pernegg canal after completion of the waterproofing works

degree of assurance whilst minimising loss of generation. To minimise the canal outage and yet meet the onerous functional performance criteria, a major component of the remediation works included lining of selected canal reaches with a SIBELON® geomembrane system, which has specific material characteristics of strength and durability to meet the intended design life of not less than 50 years. One of the issues was that, being the canal in a seismic region, the lining should have the capacity to accommodate large elongations without breaking. This is a requirement perfectly met by SIBELON® geocomposites, which have an elastic behaviour until very large elongations. Typically, a SIBELON® geocomposite has elongations exceeding 65%, which correspond to break of the backing geotextile. However,

Fig.8. Tekapo canal after completion of the remedial works

the geomembrane composing the geocomposite can still elongate up to >250%. The waterproofing works where carried out in two campaigns, in 2013 and 2014, for a total of 349,415 m^2 surface lined in 74 days. Each campaign was completed 15 days ahead of schedule.

Hydraulic tunnels and shafts: the case of Tunjita pressure tunnel and shaft

Pressure tunnels and shafts are often excavated in mountain areas with unfavourable geological conditions. They are usually lined, to provide stability and watertightness to the natural excavation line, to avoid water infiltration into the ground, and to minimise head losses. Liners such as steel, and reinforced or un-reinforced concrete, are expensive, their construction is time consuming, and can be very complicated when the tunnel or shaft is in remote areas with difficult access. Over time concrete and steel liners may experience problems due to deterioration or to excessive stresses arising for example from ground movements. Loss of watertightness can have serious consequences on the surrounding soil, maintenance requires dewatering, and it can be quite expensive. SIBELON® geomembrane systems have proven to be able to provide long-term watertightness, both in rehabilitation and in new construction. The high flexibility and elongation of SIBELON® geocomposites allow bridging of construction joints and existing cracks, and accommodate opening of new cracks. By maintaining, despite unfavourable ground conditions, the watertightness for which they have been designed, SIBELON® geomembrane liners can thus increase safety of tunnels and shafts.As already discussed in the section on canals, in the exposed configuration, the low hydraulic roughness of SIBELON® geomembrane systems allows decreasing head losses. A recent example of application of an exposed SIBELON®

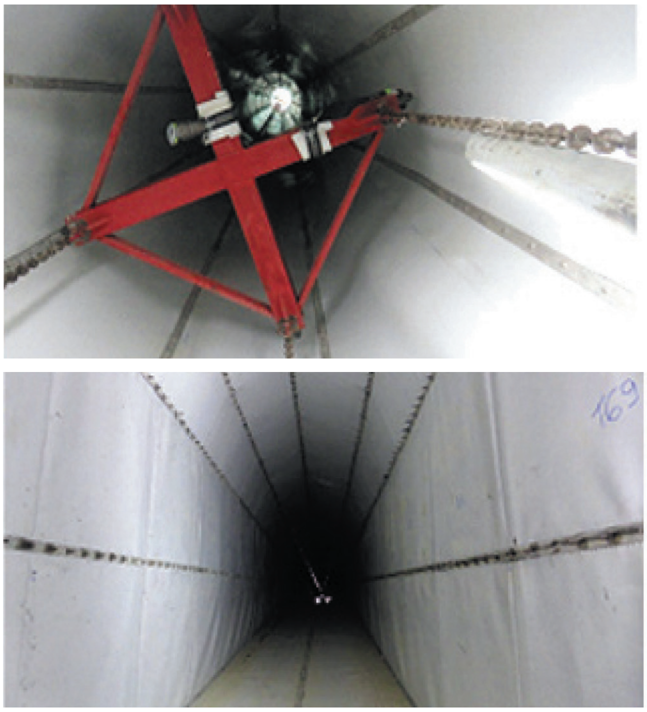

Fig. 9. View of the shaft (left) and of the pressure tunnel (right) after installation of the exposed SIBELON® geomembrane systemat Tunjita power plant

geomembrane system in hydraulic tunnels and shafts is at Tunjita power plant, in Colombia. During a routine inspection conducted at beginning of 2017 it was found that the existing concrete lining in the pressure tunnel and in the shaft that are part of the system conveying the water to the power house was heavily affected by cracking, with some parts of the lining detaching. An exposed SIBELON® geomembrane system was selected to prevent leakage through the cracks and ensure a safe and durable operation of the plant.To provide a regular support to the waterproofing geocomposite, a reinforcing geogrid was placed on the irregular concrete surface of the existing concrete liner. The geomembrane system was designed to resist pressures as high as 17 bar in the surge shaft and - 21.6 bar in the pressure tunnel, with 2.4 m/s velocity of the water.

Underwater installation: the case of Turimiquire CFRD

Turimiquire (Las Canalitas) is a 113 m high CFRD for storage of potable water, in Venezuela.

This is just an example of underwater installation of a SIBELON® geomembrane system, but very significative both for the criticality of the structure, where leakage is so high to potentially jeopardize safety of the dam, both for the very severe working conditions. This dam exhibited leakage since its impounding, in 1989. Several repairs were performed placing first clay material, then other material of different granulometry. Each time, the repair seemed to have mitigated the leakage, but this was only for a short time. Leakage eventually rose to 9,800 l/s. Extensive investigation carried out with sonar multi-beam scanning showed some craters in the concrete slabs, extensive cracking and erosion at several locations.In May 2008 a preliminary decision was made to install an exposed SIBELON® geomembrane system. Since several cities in the Nueva Esparta State rely on this dam for supply of potable water, it was not possible to empty the reservoir and installation of the geomembrane system had to be performed underwater. The most critical areas were identified with underwater surveys and it was decided in this manner where to intervene first, to maximize the benefits by minimizing remedial measures.

Fig.10. (Top) View of the upstream face of Turimiquire dam during the 1st campaign of the waterproofing works; (bottom left) the downstream face before the waterproofing works and (bottom right) after the waterproofing works

In 2009, a first installation campaign was conducted on a 30% of the surface, lowering leakage to 2,217 l/s, against 2,400 l/s set as target. After this successful installation, in 2011 the Venezuelan Government allocated new funds for a second intervention on an additional 11% of the surface. This intervention was delayed until 2017, due to the political and economic situation in the country. During this time leakage had again increased, up to 6,309 l/s, as result of the continuous deterioration of the concrete slabs in the parts of the dam that had not yet been treated. The repair conducted in 2017 has again lowered the amount of leakage.

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