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DAMS, CANALS AND TUNNELS LINING

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BACKGROUND

Deterioration due to ageing is a process all hydraulic structures face sooner or later in their service life. The integrity of the original impermeable facing is affected by the environment and by service conditions resulting in mechanical and chemical aggression on massif "impermeable" concrete structures, on the concrete mortar filling the joints in masonry structures, on lining materials used to provide impermeability, and on the waterproofing of the construction joints.

Under high temperature gradients, wetting-dehydrating and freeze-thaw cycles, in the vicinity of the face the pressure due to ice formation in the pore system may cause dilatation of the concrete beyond its elastic limit. This results in superficial cracking and progressive disintegration of the surface, or to loosening and detachment of stone masonry. Other forms of mechanical aggression are the impact due to big floating and transported materials, the abrasion of transported sediments, the static pressure, the tear stress and the impact exerted by ice, the pressure due to uplifts.

Main chemical aggression is caused by soft or sulphate water, by reaction between water and aggregates, by UV rays whose energy can be prejudicial to some lining materials.

These agents cause formation of cracks and increase in permeability, which open a path to water penetration, further accelerating the deterioration process, and making the structure deviate from original design conditions. Obvious remedial measure is to restore the original impermeability of the structure. This has been done in the past with different waterproofing materials (new concrete facing, reinforced shotcrete, stone masonry facings, cement rendering, metal facings, bituminous liners, coating products). All these materials have experienced some disadvantages. The availability of geosyntetics, and the high pace at which the geosynthetics industry has been developing new and high performing materials and technology, provided a viable and dependable alternative to these traditional methods.

GEOSYNTHETICS AS WATERPROOF LININGS IN HYDRAULIC STRUCTURES

To the knowledge of the authors, since the late 1950s waterproofing geosynthetics have been installed on hydraulic structures as a remedial measure, or to provide impermeability in new structures (Roller Compacted Concrete dams, embankment dams). Applications include waterproofing of all types of dams, of forebay and afterbay reservoirs, canals, pressure tunnels, and lining and covering of reservoirs. Different types of geosynthetics were used in pioneer installations. Subsequent developments made designers and installers focus on materials which showed more dependable characteristics.

Now that more than 35 years have elapsed since the first applications, waterproofing with geosynthetic liners is no longer an experimental technique. Conceptually, two systems are available: the undrained system, by which the synthetic waterproof liner is glued to the surface to be waterproofed and protected, and the drained system, by which the liner is secured to the surface by mechanical anchorage. Undrained systems have a major disadvantage: the uplifting action exerted on the liner by water permeating the structure & migrating towards surface under temperature gradients. This uplift, in form of liquid or vapor, is detrimental to the stability of the liner when it is unbalanced, such as at reservoir drawdown or above water level in canals. The drained system, on the contrary, continuously discharges water present behind the liner, thus also avoiding that change in state of water may further deteriorate the surface of the structure. More extensive details on design and installation are illustrated in separate papers included in the Proceedings of this Conference.

The main assets of a drained geosynthetic lining system are

very low permeability - geosynthetics a few millimetres thick can provide a lower permeability (in the order of $k = 1x10^{-13}$ to $1x10^{-15}$ m/s) than several centimetres of traditional materials
durable watertightness - permeability is maintained over the years, as the system has proven in laboratory tests and in the field (see PERFORMANCE)
complete watertightness - as the liner covers the whole surface of the structure, all joints and existing cracks and discontinuities are bridged and protected from water infiltration.
capability of adapting to formation of new cracks - elongation properties of the liners allow to sustain stresses caused by seismic events, by settlements of incoherent soils, by piping, and by concrete swelling
reduced weight and volume - synthetic materials allow to achieve high performance by very thin and light materials, which dramatically facilitates transport to site (even transport by helicopter is economically feasible)
constant and controllable quality of the liner - liners are designed site specific, and produced in the controlled environment of a factory. Quality controls assure compliance and conformance of the material to the specified requirements
quick and constant quality of the installation - installation process is simple, accomplished with light equipment, and independent of weather conditions. Out of service time are minimised
monitored efficiency - by monitoring of drained water, or by specific leak detection systems
improvement of safety - by drainage, dehydration of the dam body, and of natural slopes in case of water conveyance structures
low hydraulic roughness - when installed on water conveyance structures, considerable increase in water flow can be achieved
cost effectiveness - as compared to traditional methods
underwater constructibility - by avoiding the need to dewater, costs and impact on the environment are minimised
minimum maintenance - field experience have showed that maintenance is seldom required, and it can be accomplished by simple patching.

TESTING

Thorough testing is required to guarantee successful results. Membrane material must be tested for relevant physical and chemical properties, such as impermeability, tensile and tear resistance, resistance to puncture, burst, impact, low temperature bending, dimensional stability, resistance to chemicals, to roots, to micro-organisms. The system in its entirety must be tested for anchorage resistance, especially in applications with water in motion (pull out tests, tests for resistance of embedded membranes), for efficiency of seals, for drainage capability, for subsidence and for friction properties in application on embankment dams.

Modern practice implements standard testing on small specimens with large scale, three dimensional tests on larger samples. Some of these tests have now become standards, others are performed on simulation structures, others on a real scale.

Among large scale tests, puncture and burst tests are a valuable help to designers, as they can fairly well predict resistance of a candidate membrane in service. This method was used to investigate suitability of various types of the membranes, during the first phase of a research project for the under-water application, granted by the US Army Corps of Engineers and performed by the teamed effort of the company who developed the drained membrane system, and of a US underwater services company. PolyVinylChloride (PVC) performed best in this project.

Simulation tests allow to ascertain efficiency of relevant features of the system. Typical examples are testing of the watertightness of the perimeter seal (in hydraulic pressure vessels where hydrostatic loads up to 250 m of head can be obtained), of the capability of the membrane and of the anchorage to accommodate sudden opening of new cracks (equipment simulating seismic events), of drainage capacity of various geosynthetics configurations (in large pressurised frames), of capability of the waterproof geomembrane system to adapt to sudden subsidence (a piping phenomenon can be simulated in large pressure vessels).

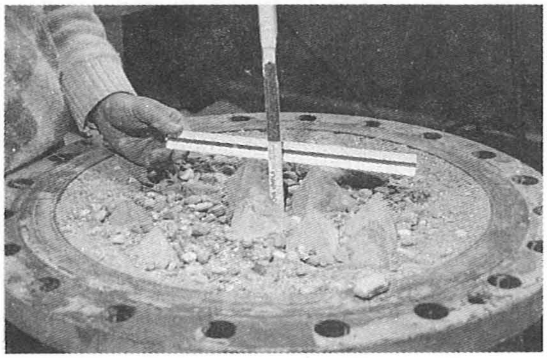


Figure 1. Large scale testing to ascertain puncture resistance of waterproofing geomembranes: a typical simulation substrate before loading in hydraulic pressure vessel

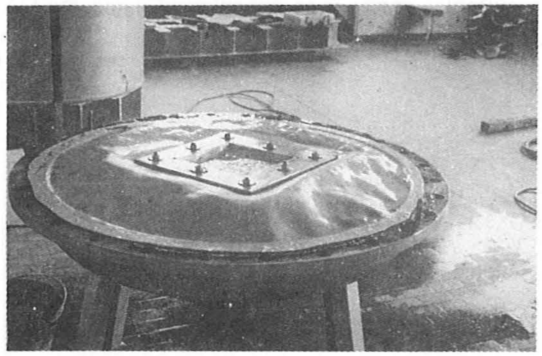


Figure 2. Hydraulic pressure vessels are used also to test efficiency of various elements of the system: the watertight seal is pictured after testing at 250 m of hydraulic head, with no leaks

Thorough simulation testing has also been performed by IREQ, the Research institute of the Canadian Hydro Québec, to investigate efficiency of all repair methods available for application to dams in cold climates. The research focused among others on simulation of resistance to freeze-thaw cycles, to low temperatures, and to the action of thick ice covers. Results of the research report the system illustrated herein as the most suitable for application to dams' repair in cold climates.

Testing on real scale was accomplished in the cited research project for the US Army Corps of Engineers, whose second phase consisted in a feasibility demonstration on a reinforced concrete structure submerged at a depth of 18 meters, on which a drained geomembrane system was installed completely underwater, to cover the whole submerged structure. In the domain of water conveyance structures, we can cite the case of a canal in Switzerland, where a trial section was waterproofed with the described system: cuts were made on the waterproofing membrane, and the canal was put back in operation for 4 days to verify efficiency of the system. Inspection after the test assessed that the liner and the anchorage had resisted the uplift of water and transported material intruding behind the membrane, and that capacity of the drainage system had been perfectly adequate.

THE STATE OF THE ART, DRAINED MEMBRANE SYSTEM APPLIED TO DAMS

Waterproof geomembrane systems were first conceived and later found largest application in Europe (more than 55% out of dams waterproofed by a geomembrane all over the world). In particular, Italy has pioneered these techniques and has at present the largest number of accomplished installations on dams and other hydraulic structures. According to data collected by the International Commission on Large Dams in 1991 (ICOLD Bulletin 78), out of the 70 dams waterproofed by a geomembrane all over the world, the first installations on embankment dams (Contrada Sabetta, 1959), on concrete dams (Lago Baitone, 1971), and on masonry dams (Lago Miller, 1976) were accomplished in Italy.

The ICOLD European Working Group on Geomembranes and Geosynthetics as Facing Materials, in operation since 1995, has been surveying all European dams incorporating a geomembrane as waterproof liner. Data collected among the Owners have showed that Italy, with 45 % of the total surface installed in Europe, has the highest record of works accomplished on large dams. PolyVinylChloride (PVC) is the material with the highest successful record on dams. Of all European dams surveyed by the Working Group, 77 per cent incorporate a drained membrane system.

The drained system cited by Bulletin 78 for rehabilitation of concrete and masonry dams, and as a suitable method for embankment dams, the CARPI system, now used on 34 dams in Europe, America and Asia, was conceived and developed in Italy.

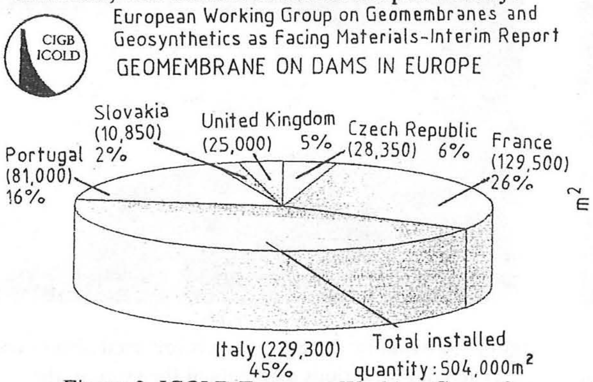


Figure 3. ICOLD European Working Group for Geomembranes and Geosynthetics as Facing Materials evidentiated that Italy has the largest record in waterproofing geomembranes applications

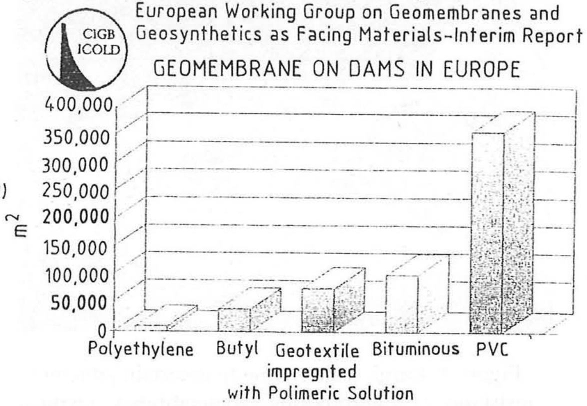


Figure 4. Data collected by the Group from all surveyed European dams showed that PVC is the most commonly used material. Satisfaction of the Owners in the drained membrane system amounted to 97.5%

The system installs a watertight liner, mostly a geocomposite consisting of a PVC geomembrane heat-coupled during extrusion to a nonwoven geotextile, on the entire upstream face of the dam. The PVC provides impermeability, the geotextile additional dimensional stability, additional puncture resistance, and in-plane transmissivity for drainage. A gap is provided between the watertight geomembrane and the dam's face, in which drained water can freely flow by gravity to a bottom collection system, and be

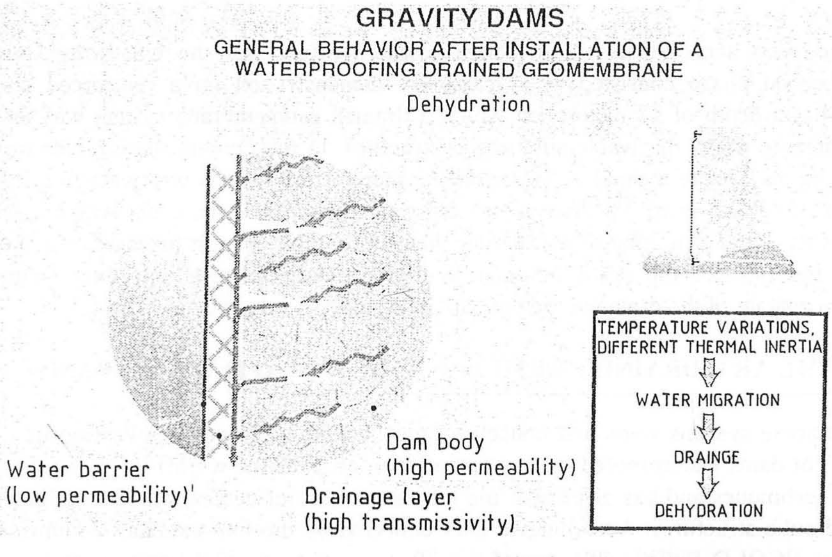


Figure 5. The drained membrane system exploits the reduced thickness, the low thermal inertia and the low permeability of the PVC membrane, as compared to the thermal inertia and permeability of concrete to decrease water content in the dam body

discharged in the inspection gallery, or downstream or upstream. Perimeter sealing avoids water intrusion behind the liner. The synthetic barrier can be connected to the grout curtain, to construct a continuous water shield from crest to impermeable foundations.

Design

The modern practice favours the drained system also due to its capability of dehydrating the structure, of impregnation water, and to the possibility of monitoring the efficiency of the waterproof liner by monitoring of the drained water.

After pioneering installation of different kinds of materials, flexible PVC is now established as the material of choice for application on dams. Additives, suitable thickness, and coupling to geotextiles, assure that the liner is capable of sustaining service and environment aggression, of providing the necessary flexibility, elasticity, and drainage capability. Geonets can be used for higher transmissivity. Recommended anchorage material is stainless steel. By accurate design and testing, very rough substrates can be accommodated, so that little surface preparation is required, thus shortening installation times and costs.

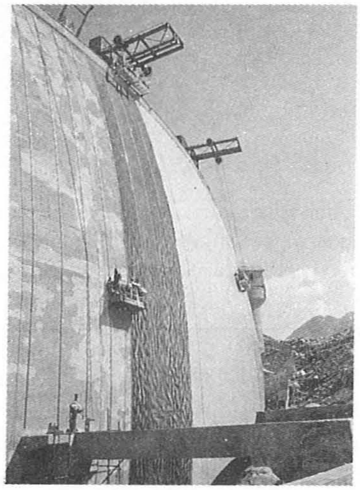


Figure 6. From left to right, installation of vertical anchorage profiles, of HDPE drainage geonet, of vertical membrane sheets

Figure 7. Profiles can also be installed of a very rough substrate, as on masonry dams waterproofed in Italy, France and Switzerland

Installation

The system has been installed as a remedial measure on all types of dams. Typically, membrane sheets are installed vertically, adjacent sheets overlapping and being secured to the dam face by an assembly of two stainless steel batten strips which also tension the liner and construct vertical free flow conduits for drained water. However, as installation proceeds with very simple sequential steps, different site and

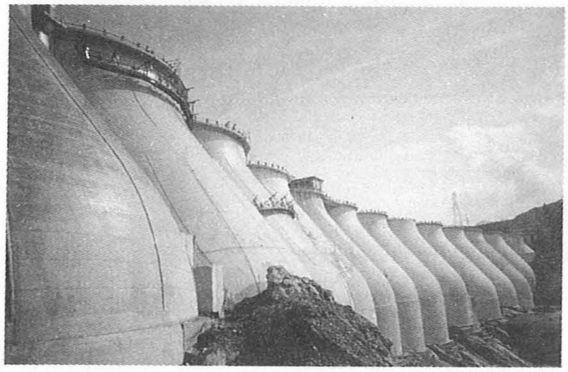


Figure 8

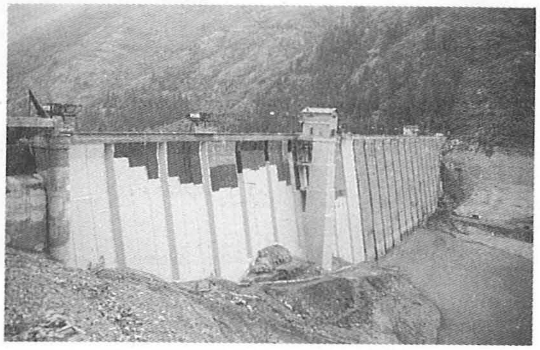


Figure 9. To minimise impact on operation, large panels are prefabricated and installed horizontally, to follow the raising of the reservoir

operational requirements can be easily accommodated. Waterproofing can be accomplished in separate campaigns, or proceed horizontally, from the heel of the dam upwards, to follow raising of the reservoir.

Exploitation of favourable characteristics of geosynthetics further minimises surface preparation, such as in the case of masonry dams, where a thick transition geotextile substitutes traditional materials used for smoothening the surface, thus reducing weight and volume of materials to be transported to site. Recent developments now allow complete underwater installation, such as it is being accomplished in these days on a dam in northern California.

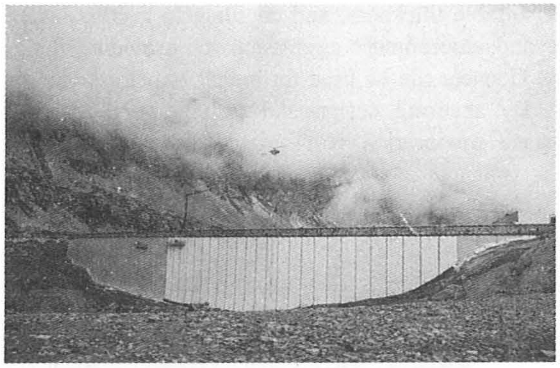


Figure 10. A thick transition geotextile installed over the masonry facing avoided smoothening of the surface and allowed to transport all material by helicopter, to reach a site with no access road

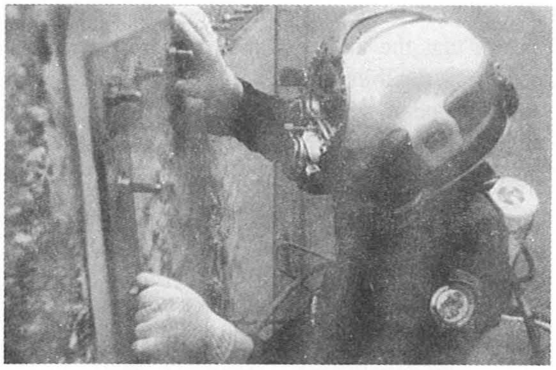


Figure 11. The system was modified to allow adaptation to an underwater working environment. Complete installation is accomplished, with no need to dewater

The system has also been adapted to construction of embankment and RCC dams. On embankment dams, PVC has proven a reliable and long lasting alternative to bituminous materials and to stiffer materials whose technology had been borrowed by the field of environment protection. The highest embankment dam in the world waterproofed by a geomembrane has been constructed with the described PVC system. As for RCC dams, prefabricated panels with embedded PVC membrane are used mostly in US, while the same conceptual exposed membrane system is used in Europe, Central America and Asia.

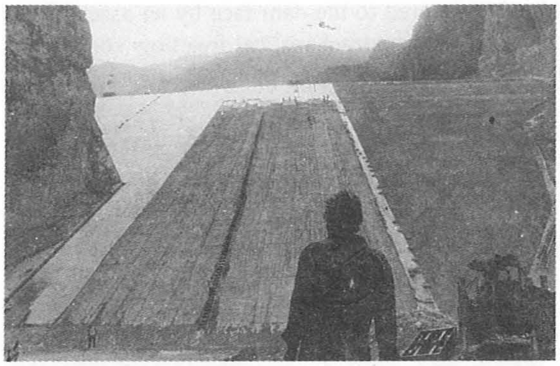


Figure 12. On the 91 m high Bovilla Rockfill dam, switching from original CFRD to the geomembrane system brought the project back to schedule and reduced costs

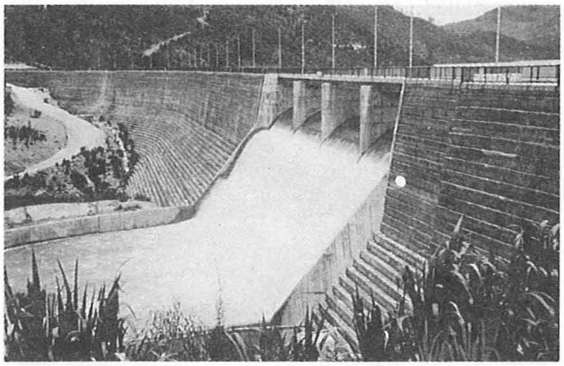


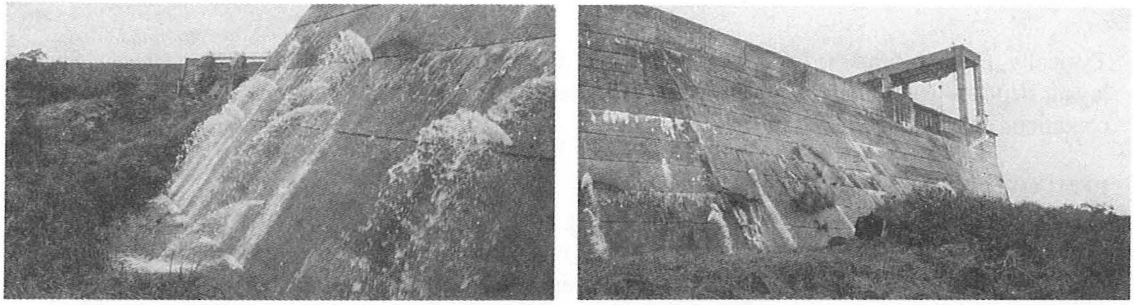
Figure 13. At Concepcion, the geomembrane system was installed in 1990, with significant time and cost saving. Actual total seepage, including foundations, is 0.4 l/s

THE STATE OF THE ART, DRAINED MEMBRANE SYSTEM APPLIED TO CANALS AND TUNNELS

The same conceptual system has been applied to waterproofing and protection of hydropower canals and pressure tunnels. In these installations membranes, anchorage and drainage must be designed according to the foreseen dynamic actions of water and transported material, and to entity of uplifts. Also in these structures, PVC has proven a reliable material and has been adopted on irrigation and hydropower canals of large or small size, with high water speed, and very different climatic conditions.

Design

The drained system is favoured also due to its capability of dehydrating the structure and the surrounding soil from impregnation water. This is particularly beneficial in case of canals and tunnels excavated in deep and incoherent slopes.



Figures 14 and 15. The Itutinga canal picture before and after installation of the drained membrane system: imperviousness is integrally restored

Depending on the deterioration of the existing structure, flexible geomembranes, semirigid membranes, or concrete panels embedding a ribbed membrane have been used. Semirigid membranes are now being considered as a low cost method for construction of new canals. Ribbed membranes embedded in thin concrete walls are used as a self-regulating drained system when heavy canal rehabilitation is needed. Drainage discharge can be accomplished outside the structure, by longitudinal or transversal pipes, or inside it, by one-way valves activated by pressure differentials.

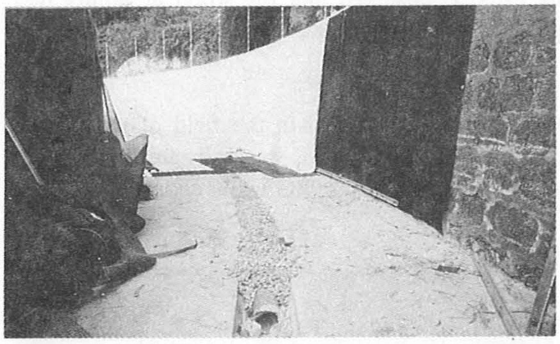


Figure 16. Longitudinal drainage pipe at the invert, HDPE drainage geonet, flexible PVC liner

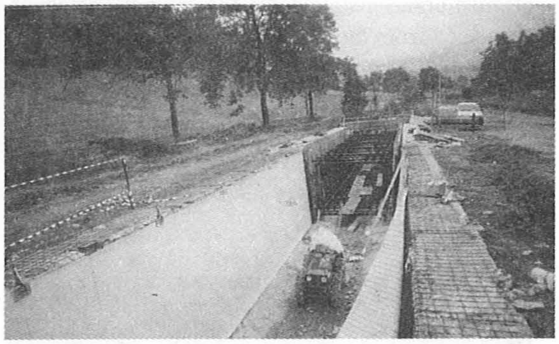


Figure 17. Ribbed PVC membrane positioned before embedment in new concrete walls

Anchorage and drainage are designed on the basis of the anticipated dynamic effects of water and transported debris, and on the possibility and entity of uplifts when the structure is empty. Anchorage can be linear, by batten strips, or extend to the whole surface, by a ballast layer, when vandalism, or high uplifts, or traffic inside the canal are foreseen. Tunnels, where high piezometric load is usually present, have more stringent requirements for anchorage and drainage.

Figure 18. Linear anchorage is increased where higher dynamic action is foreseen

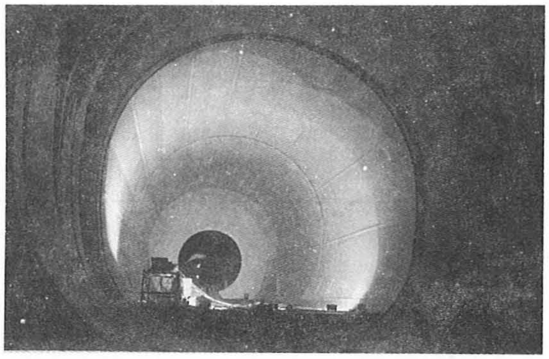


Figure 19. Tensioning profiles and adequate drainage system avoid uplift pressures build-up

Installation

Typically, the membrane is left exposed to exploit the low hydraulic roughness of the material. Sheets laying depends on the shape and size of the canal. Underwater installation is feasible, in adequate conditions of water speed and turbulence.

PERFORMANCE

As for any system, performance is best judged by results in the field. Among questions included in the Technical Form which the cited ICOLD European Working Group circulated among Owners, one referred to satisfaction in geomembrane systems. Affirmative answer accounted for 97.5% (dissenting data referred to bituminous membranes).

ENEL, which so far probably has the greatest number of dams waterproofed with this technique, has been periodically monitoring durability by testing samples taken on dams after several years of service. In 1995, samples were taken again from 10 dams and reservoirs where the described system had been in service, in some cases since the 1970s. The samples were tested for the content of plasticizers, for Shore A hardness, for tensile resistance and water permeability, to compare initial values with values over time. Results showed that all PVC geomembranes were performing well. For example, on the geomembrane installed for the longest period of time, ENEL observed that the strain at failure had decreased from the 280% value at manufacturing, to 258% after 9 years of service, to remain unaltered for 10 more years.

On water conveyance structures, the system has a considerable potential in the field of upgrading. Substantial gain in power supply can be attained. Flow capacity increase is generally in the range of 50%. Increase up to 90% has been reported, in a Portuguese canal where the walls underwent a 10% heightening.

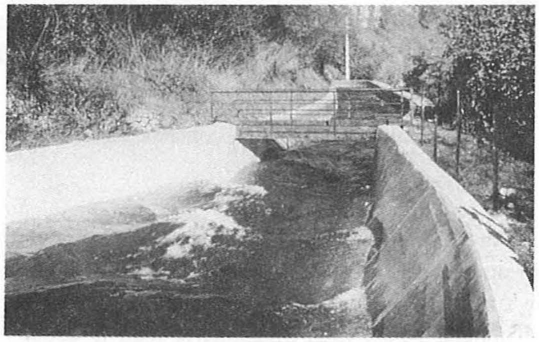


Figure 20. The system can sustain high water speed...

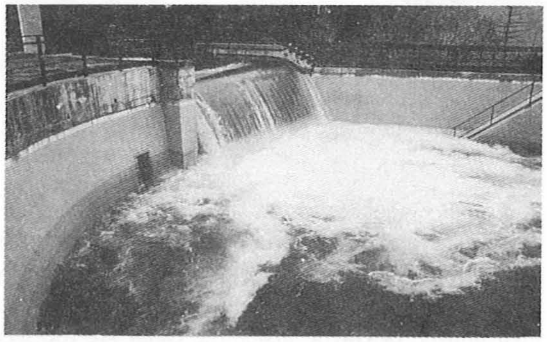


Figure 21. ... turbulence and suction

The described system has been applied in very cold climates, at high altitudes, as well as in tropical climates, on dams, canals and tunnels, and behaviour has been very satisfactory. In the majority of cases, tests carried out by ENEL were performed on samples manufactured before the mid 1980s. The rapid pace at which the geosynthetics' industry is improving the quality and performance of products means that even better behaviour can be predicted for the future, and consequently a much longer service life, for installations provided with modern geomembranes and geocomposites based on the latest technology.

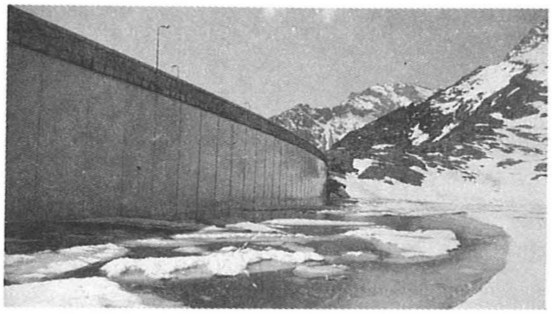


Figure 22. The system resists the cold climates, freeze-thaw cycles, UV exposure of high altitudes (2337 m)...

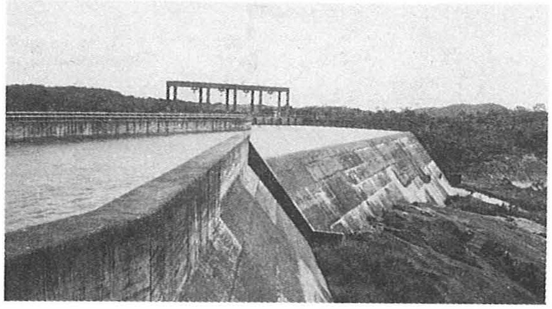


Figure 23. ... and environment of tropical climate with very severe UV exposure (canal in Brazil)