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POLYVINYLCHLORIDE GEOCOMPOSITES AS A BARRIER TO SEEPAGE AND DETERIORATION ON OLD AND NEW DAMS

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ABSTRACT

The paper describes the state of the art of waterproofing drained PolyVinylChloride membrane systems, installed as a remedial measure on old dams of all types, or as a preventive measure in construction of new embankment dams or RCC dams.
The systems installs a waterproofing drained PVC liner over the entire upstream face of the dam, and mechanically secures it by stainless steel batten strips. Drainage allows to discharge saturation and infiltration water, thus accomplishing dehydration of the dam body. The system has documented long and maintenance free durability. Underwater installation is also feasible.

INTRODUCTION

All dams are subject to an "ageing" deterioration caused by action of the environment (temperature changes, wetting-dehydrating and freeze-thaw cycles, impact by ice, debris, transported materials, chemical action of water) or by abnormal behaviour of the structure (problems with foundations and differential settlements, expansive phenomena of concrete). With deterioration of the facing (cracks and decreased imperviousness) water infiltrates the dam body, and subsequent washing of fines may cause carbonation and clogging of the drains. As the drains cannot efficiently perform their function, seepage extends to the whole body of the dam and saturation of concrete occurs. Increase in pore pressure causes deviation from the initial design conditions, and stability of the structure may be at stake. Rehabilitation must stop water infiltration and further deterioration of the structure.

Traditional rehabilitation methods have evidentiated some drawbacks:

- new concrete layers - relevant construction times and costs, difficult adherence between old and new concrete, the new facing is subject to the same deterioration as the old one
- shotcrete - extensive and time consuming surface preparation required, adherence between existing surface and new revetment jeopardized by shrinkage and uplifts, poor resistance to freeze-thaw cycles
- resins - accurate surface preparation needed to guarantee a smooth, clean and dry surface, quality dependent on weather conditions, and shrinkage, expansions, uplifts may quickly jeopardize adherence
- metal sheets - expensive and difficult to install, subject to corrosion, must be protected with paint, which deteriorates and must be renewed
- bituminous coatings - can be installed only on gentle slopes, subject to cracking and to bacteria's attack.

Since 1959, when a synthetic geomembrane was applied as a waterproofing liner on an embankment dam in Italy, a new method was initiated. Since then, the use of low permeability synthetic geomembranes as waterproofing and protection liners has greatly developed and improved, especially in Europe.
According to the ICOLD Bulletin 78 (1), more than 55% of dams all over the world lined with geomembranes are located in Europe. As reported by Scuero and Vaschetti (2), out of all dams investigated by the European Working Group on Geomembranes and Geosynthetics as Facing Materials, 38 % is located in Italy. The state of the art system, a drained membrane system which will be illustrated in this paper, has been applied to 68 % of the above dams.

THE DRAINED PVC MEMBRANE SYSTEM: OBJECTIVES AND CONCEPT

Installation of a drained PVC membrane, while still pursuing the main objectives of restoring the impermeability of the structure's facing, and of protecting it from further deterioration, has a further major advantage: by drainage, water already permeating the dam body can be extracted and discharged, thus reducing pore pressure and presence of undesirable agent feeding AAR phenomena.

The technique installs a low permeability synthetic membrane as the only barrier to water intrusion on the upstream face of the dam. At present, the material with the highest record is polyvinylchloride (PVC). The state of the art system is a drained system: anchorage of the membrane is made by lines, so that a drainage gap is constructed between the synthetic liner and the dam facing. Water permeating the dam body, or coming from foundations, tends to migrate through the permeable concrete towards the warmer upstream face of the dam, especially when the reservoir is empty and under the action of solar radiation. The impermeable membrane stops the migration. As outside temperature changes, if water is not discharged it can turn into ice or vapor and exert a pressure behind the waterproof liner, with possible detachment. In case of a rapid drawdown, water behind the liner may build up excessive stresses, that may cause membrane system failure. With a drained system, on the contrary, water behind the membrane can immediately and continuously flow by gravity in the drainage layer to bottom discharge. Detachment is avoided, water in pressure does not act directly on the dam upstream face, the dam is progressively dehydrated of saturation water, and efficiency of the waterproofing liner can be controlled by monitoring the drained water flow. A drained membrane system is superior to an undrained membrane system.

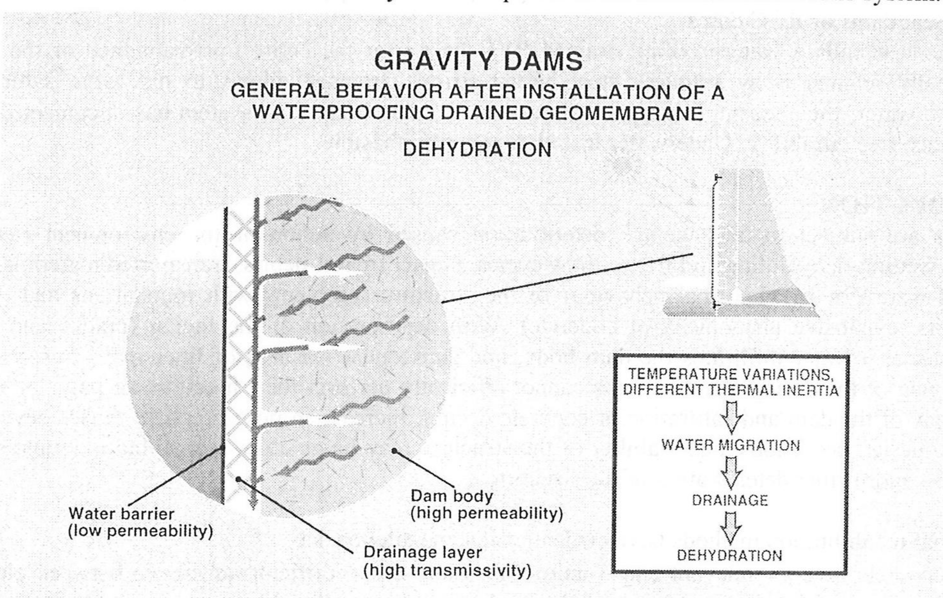


Figure 1. Advantages of a waterproofing drained geomembrane

THE DRAINED PVC MEMBRANE SYSTEM ON CONCRETE AND MASONRY DAMS

A complete water barrier is constructed on the upstream face of the dam by means of an exposed, low permeability, flexible PVC membrane, with a drainage system behind. Watertightness is obtained with a very thin (in the order of mm) layer, and design can connect the synthetic barrier to the grout curtain, to construct a continuous water shield from crest to impermeable foundation, as illustrated in Figure 2.

The state of the art system was first developed in the rehabilitation of concrete and masonry dams, where waterproofing membrane liners are always exposed, requiring particularly accurate design, materials, installation (construction of a protection layer is more demanding on a vertical facing due to the need of a higher number of anchorage points and watertight fittings, detachment of deteriorated protection layer can damage the membrane).

Main elements of construction are the drainage system, the anchorage system, the waterproofing liner and the perimeter seal.

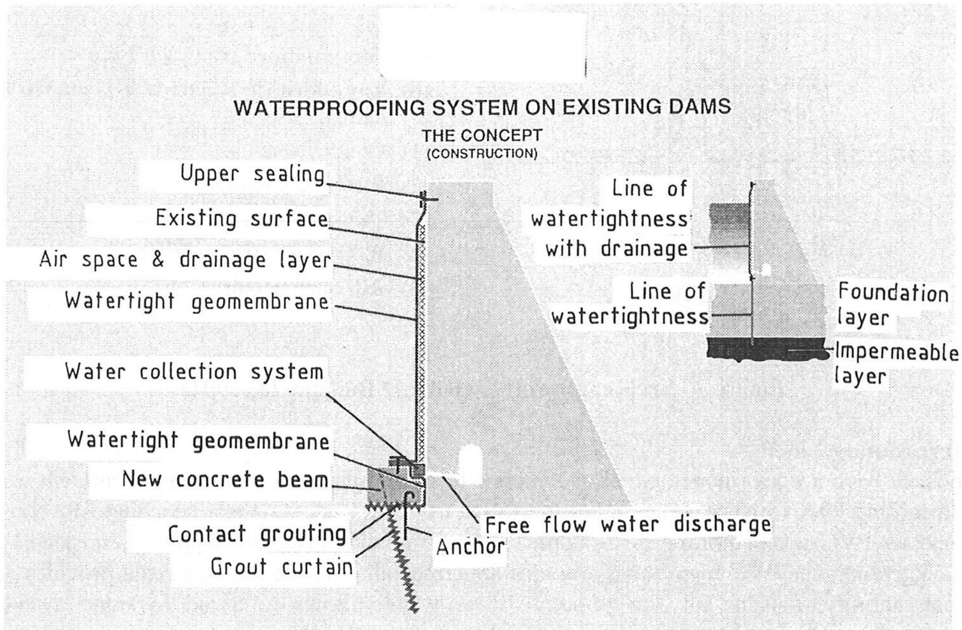


Figure 2. The drained PVC geomembrane system

The Drainage System

Construction of the drainage system includes construction of a collection and discharge system, installation of a drainage layer, installation of conduits for drained water flow.

The water collection and discharge system is positioned at the heel of the dam, downstream and upstream discharge can be designed. For more refined control of the liner's efficiency, drainage can be divided in compartments, and separate drainage can be constructed for water coming from the upstream face and for water coming from the foundation area.

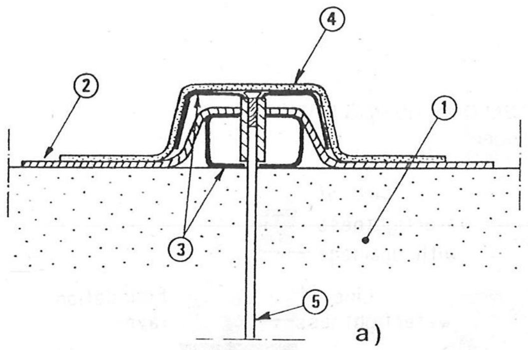
The drainage layer must have high in-plane transmissivity to facilitate water flow and avoid clogging. Drainage materials are geotextiles and geonets. In the case of geotextiles, the current practice is to use geocomposites in which the geotextile is heat-coupled to the low permeability membrane during manufacturing. High transmissivity geonets are installed on the entire facing or as an additional drainage layer at the heel of the dam. Drainage geonets can also provide planarity on small irregularities.

Drained water conduits are the vertical anchorage profiles illustrated herein. Ventilation of the drainage system improves water flow towards bottom discharge.

The Anchorage System

Anchorage is made by vertical stainless steel batten strips secured to the dam facing. The state of the art system, as reported by ICOLD Bulletin 78 (Figure 3), adopts an assembly of two profiles whose coupling allows to perform a triple function: soundly secure the sheets to the dam face, tension the sheets to provide perfect planarity, and construct free-flow conduits which convey the drained water collected by the drainage layer to the bottom collection and discharge system. Two configurations are available, a configuration installing both profiles over the existing dam facing, and a configuration embedding the profiles when a new concrete layer is envisaged. The embedded configuration has different profile's geometry but the same conceptual scheme and anchorage, tensioning and water conveyance functions.

The internal profile of the assembly (3) is secured to the dam facing (1). Two adjacent waterproofing membrane sheets (2) overlap over this profile, to be covered by the external profile of the assembly (3), which is fastened by a three components device (5) to the first profile, to secure the sheets to the dam. A PVC cover strip (4) is welded on top of the assembly, to avoid any water intrusion through the fastening device (5).



(a) Face-mounted rib (Lago Nero dam).
(b) Embedded rib (Cignana & Piano Barbellino dams).
(1) Concrete.
(2) PVC geomembrane.
(3) Two-part steel rib.
(4) PVC cover strip over rib.
(5) Rib anchor bolt.

Figure 3. Anchorage profiles (ICOLD Bulletin 78, 1991)

The Waterproofing Liner
Geocomposites have a performance which is superior to performance of their components when separate. The waterproofing liner which has the highest performance record on dams is a geocomposite consisting of a homogeneous PVC geomembrane heat-coupled during manufacturing to a nonwoven, needle punched polyester geotextile. The PVC membrane provides impermeability, while the geotextile provides additional dimensional stability, acts as an anti puncture layer which allows to avoid to some extent surface preparation, and by high in-plane transmissivity facilitates water drainage.

PVC is chosen due to its high quality and performance. Resistance and durability, proven by laboratory tests with an expected service life superior to 50 years, and by experience acquired in the field, are main assets of the material. Further advantage is its constructibility, that is its dimensional stability, its flexibility, which allows adaptability to difficult geometry, the easiness and reliability of seaming, its easy handling. Finally, PVC has by far the greatest amount of favorable references in the field. In a recent study performed by IREQ [3], the Research Institute of Hydro Québec, the illustrated PVC geocomposite was deemed the most adequate material for waterproofing and protection of dams in cold climates.

The PVC geocomposite is designed site specific in respect to thickness of geomembrane, to type and weight of coupled geotextile. Quality and quantity of additives and plasticizers are chosen to manufacture a homogeneous membrane material. Higher thickness guarantees higher performance (mainly durability).
The geocomposite is supplied in sheets, with custom made length to accommodate the whole height of the dam and avoid transversal junctions. The sheets are unrolled from the dam crest, adjacent sheets overlap and are welded, to be subsequently tensioned and secured by the described profile assembly. PVC cover strips welded over the profiles guarantee construction of a continuous waterproof liner. Figure 4, from left to right, illustrates a typical installation.

In case of highly demanding substrates, such as on rock masonry dams, thick geotextiles have been installed to provide extra puncture resistance as an alternative to extensive surface preparation.
The Perimeter Seal
At the heel of the dam, at outlets, spillways, intakes, and wherever water may by-pass the liner, the perimeter anchorage must avoid water intrusion behind the geomembrane. A watertight perimeter seal is achieved by uniform compression of the liner against the dam surface by profiles and gaskets. Planarity of the subgrade, size and stiffness of profiles and gaskets, distribution of compression stresses at profiles' junctions are the features to consider.

The system is particularly suitable for rehabilitation of dams subject to alkali-aggregate reactions, as decreasing the humidity in the dam body is considered important to slow or stop the reaction [4]. The system also allowed to accommodate slot cutting campaigns for tension relief accomplished over the years, by assuring complete protection from water intrusion after slots had been accomplished.

The current technology conceptually described has been applied to all types of dams and appurtenances, even in the case of irregular geometry or substrates, in very different and aggressive environments. Out of a total of 22 masonry and concrete dams reported as having been waterproofed with a synthetic geomembrane by the European Working Group, 20 have been waterproofed with the illustrated system.

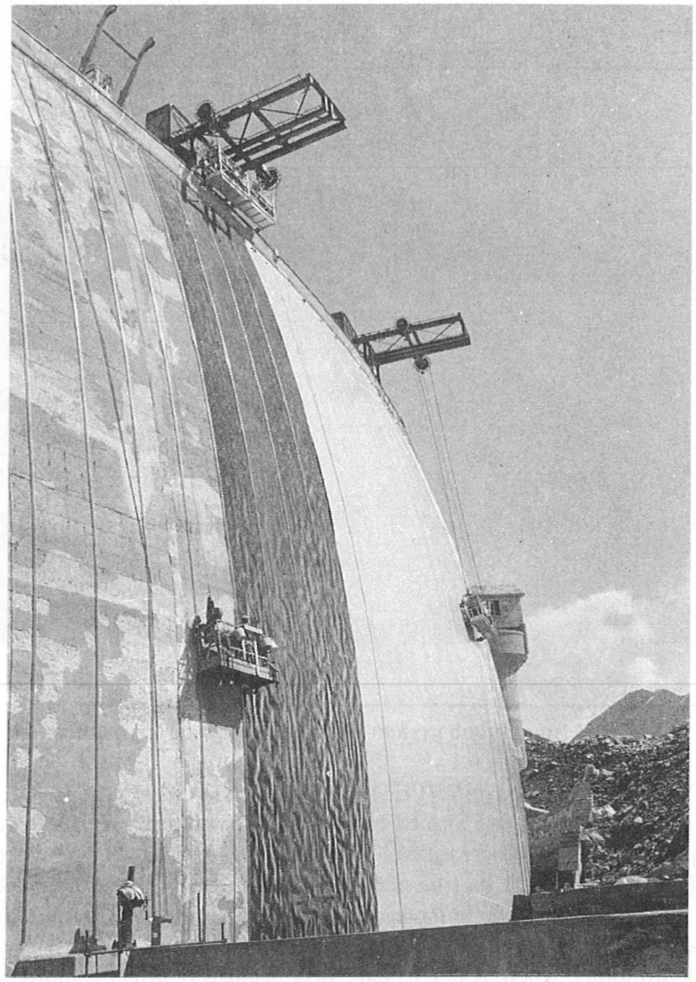


Figure 4. From left to right, installation of the internal profiles, of the drainage geonet, of the waterproofing liner, of the external profiles

THE DRAINED PVC MEMBRANE SYSTEM ON EMBANKMENT DAMS

The described system has been adapted to rehabilitate existing embankment dams, and to construct new embankment dams and cofferdams. The system then provides as additional advantages the capability of maintaining watertightness in presence of relative movements of the dam and of differential settlements of the fill, the possibility of construction when suitable traditional materials are not available, the capability of avoiding migration of fines, to prevent erosion and piping.

Exposed and covered membrane systems have been installed since the 1970's. Exposed membrane installations allow much easier inspection, while installation of a ballast or protection layer entails longer construction times and costs, additional precautions to avoid damaging the membrane, but may be necessary when the foreseen environmental aggression is very severe. A noteworthy ballasted membrane installation was accomplished at Bovilla, the highest embankment dam in the world using a geomembrane as the sole water barrier.

Bovilla, a 91 m high gravel fill dam in Albania, was waterproofed in 1996 with a PVC geomembrane, 3 mm thick, coupled to a 700 g/m^2 nonwoven, needle punched polyester geotextile, installed directly on a gravel drain 5-15 mm. A 800 g/m^2 nonwoven, needle punched polypropylene geotextile positioned over the geocomposite acted as transition layer for the cast in place, unreinforced concrete ballast slabs, 20 to 30 cm thick. Design addressed also the problem of seismicity and of foreseen differential settlements: large scale simulation tests were accomplished to previously verify behaviour of the membrane, extra slack membrane material and styrofoam elements account for movement of the liner and protection against relative movements of the slabs.

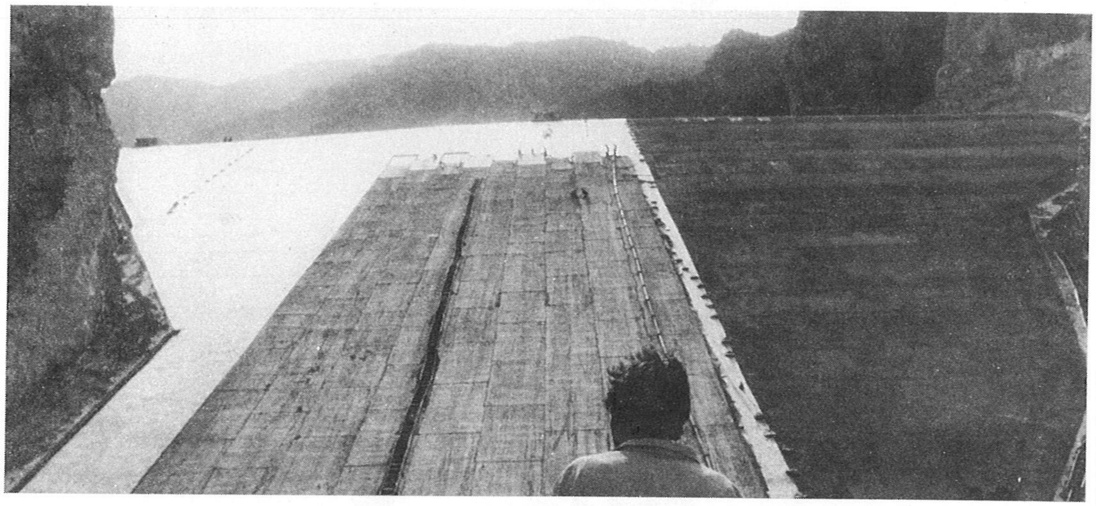


Figure 5. The PVC membrane system, with ballast slabs, installed at Bovilla dam

THE DRAINED PVC MEMBRANE SYSTEM ON ROLLER COMPACTED CONCRETE DAMS

On RCC dams, the static function is performed by concrete, in mixtures with a lower cement content and therefore lower impermeability characteristics. The concrete is placed in subsequent lifts, and then compacted with rollers. Construction can be accomplished in much shorter times than for conventional concrete dams, but the concrete mix characteristics, and the presence of lift joints, do not guarantee sufficient imperviousness. The issue of impermeability is of particular importance especially in correspondence of the lift joints, where water seepage may negatively affect stability at sliding.
The problem of impermeability can be solved in several ways, the easiest and quickest one being separation between the static function, performed by the RCC, and the waterproofing function, performed by the geomembrane. This permits to simplify design of concrete mixtures and construction procedures. Significant reduction in time and costs can be achieved, much in the philosophy of RCC dams. Two different geomembrane systems are available, both using a PVC membrane: a protected membrane system developed in the United States and known as the Winchester system, and an exposed membrane system which evolved at the beginning of the 1990's from the CARPI system.

The protected membrane system (Winchester) constructs the water barrier with prefabricated concrete panels embedding the PVC geomembrane. The concrete side of the panels faces the reservoir, the geomembrane is in contact with the dam body. The panels, constituting the permanent formworks for placing of the RCC lifts, are secured to the dam body by metal anchor bars embedded in the RCC lifts during dam construction. Anchor bars pierce the geomembrane with watertight fittings. PVC cover strips are welded over the junctions between the panels. The watertight seal at the heel of the dam is made by a PVC geomembrane strip welded to the main liner and laid horizontally in the dam body, to intercept water migrating from foundations. Disadvantage of this system is that any damage occurring during construction, or in subsequent service, cannot be easily located, and repairs can be very difficult, or impossible. On the other hand, an advantage is the possibility of limiting ageing due to U.V. action or environment aggression.

At present, technology in Europe is oriented more towards the exposed membrane system. The system is an adaptation of the illustrated system, conceptual design, elements of the system and installation being similar to those illustrated for concrete dams rehabilitation. The geomembrane constructs a continuous, drained water barrier from the crest to the foundation beam, where the perimeter seal is placed. In these installations, the internal element of the coupled vertical tensioning profiles is embedded in the RCC layers as construction of the dams proceeds. Configuration is very much similar to the one already illustrated in Figure 3. The PVC geomembrane, of the same type used for dam rehabilitation, is deployed on the dam surface after all RCC layers have been placed (see Figure 6), or during placement of the layers. The geomembrane is fastened and tensioned by the internal profiles, and cover strips restore total impermeability. Due to the characteristics of the RCC, the use of an additional high transmissivity geonet may not be required, as the irregularities in the RCC surface constitute a natural net of preferential paths for water present behind the liner.

Adaptation of the described system allows, by a unique impervious element:

- to waterproof construction joints in correspondence of RCC horizontal lifts, induced vertical joints, random fissures and cracks, connections between RCC and traditional concrete blocks
- to construct a water barrier without interfering with RCC placement and accomplishing overall construction of the dam in shorter times
- to easily inspect efficiency of the waterproofing liner

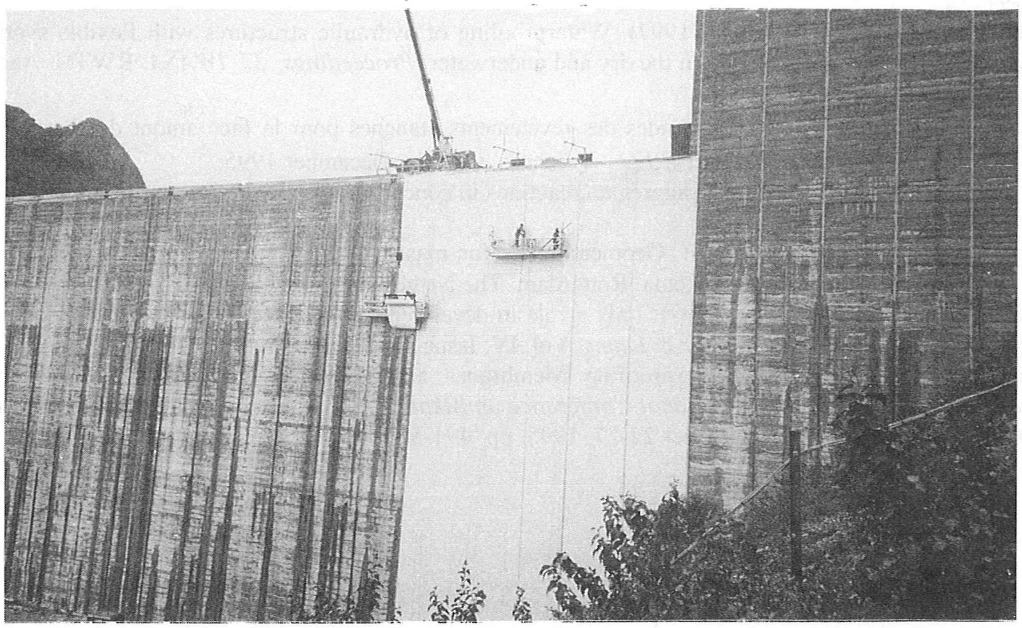


Figure 6. Installation of the unprotected PVC system on Nacaome RCC dam

UNDERWATER INSTALLATIONS

After a two phase project granted by the U.S. Army Corps of Engineers, and accomplished by the teamed effort of the company who developed the described system and by one of the largest underwater services companies in the world, underwater installation is now feasible. Constructibility has been proven in a real repair on a Portuguese dam and on a dam in USA. A new complete underwater installation of the system will start in USA, shortly after this paper is finished.

CONCLUSIONS

The techniques for waterproofing and protecting the upstream face of masonry and concrete dams, of embankment dams, and of Roller Compacted Concrete dams, with drained PVC flexible geomembranes, has reached a high degree of sophistication and reliability. The main benefits of the system are the following:

- it constructs a continuous waterproofing liner on the whole upstream face, bridging also construction joints and cracks
- it constructs a waterproofing liner which can provide a complete water barrier from crest to deep impermeable foundations

- it constructs a waterproofing liner which can resist opening of even large cracks in case of differential settlements, of seismic events, of concrete swelling
- it can perform dehydration of the structure from saturation water
- it relieves uplift pressures
- it is durable and reliable, and a standard quality, not dependent on weather and on skill of labor, can be achieved
- it has 20 years of maintenance free history
- it has a low costs/benefits ratio
- installation is quick, easy, independent of weather conditions
- should repairs be necessary, they can be done by simple patching

At present, range of applications is fairly large, and results of installations performed according to what has been described as the state of the art have all been satisfactory.

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The choice of the low permeability membrane is based on resistance characteristics, on ease of installation, on successful application records. The use of a resistant and highly flexible material allows to bridge fairly large discontinuities in the substrate, so that deteriorated surfaces, construction joints, existing cracks, and cracks that may open in case of seismic events or of ground subsidence, can be accommodated. The possibility of coupling the membrane to a highly transmissive geotextile provides the further advantage of additional dimensional stability, of antipuncture protection, and of providing a drainage layer reliably associated with the low permeability layer. PolyVinylChloride (PVC), heat-coupled during extrusion to a nonwoven geotextile, has proved to be the most suitable material for hydraulic applications.

Anchorage of the membrane to the structure is made by metal batten strips, and must be designed to resist high water velocity and pressure. Presence of high uplifts requires particular care in design of the drainage system, and of ballast layers.

APPLICATION OF THE DRAINED MEMBRANE SYSTEM TO GANDELLINO PRESSURE TUNNEL

The Gandellino pressure tunnel is a power tunnel for the Val Sedornia Plant, located in the Italian Alps, near the city of Bergamo. The average inclination of the slopes is 25% and the 280 m long tunnel is not very deep into the ground. The natural slopes are of incoherent soil of highly different graded materials. The deterioration of the concrete structure of the tunnel, with subsequent loss of water, considerably affected the stability of the soil.

The Existing Conditions

The tunnel consisted of a concrete structure on the vault and on the walls. Over time, the concrete had deteriorated, and through large and diffused cracks water infiltrated the soil (see Figure 1). This resulted in loss of power and in increase of soil instability during operation. When the tunnel was empty, it acted as a drainage collector for water impregnating the soil.

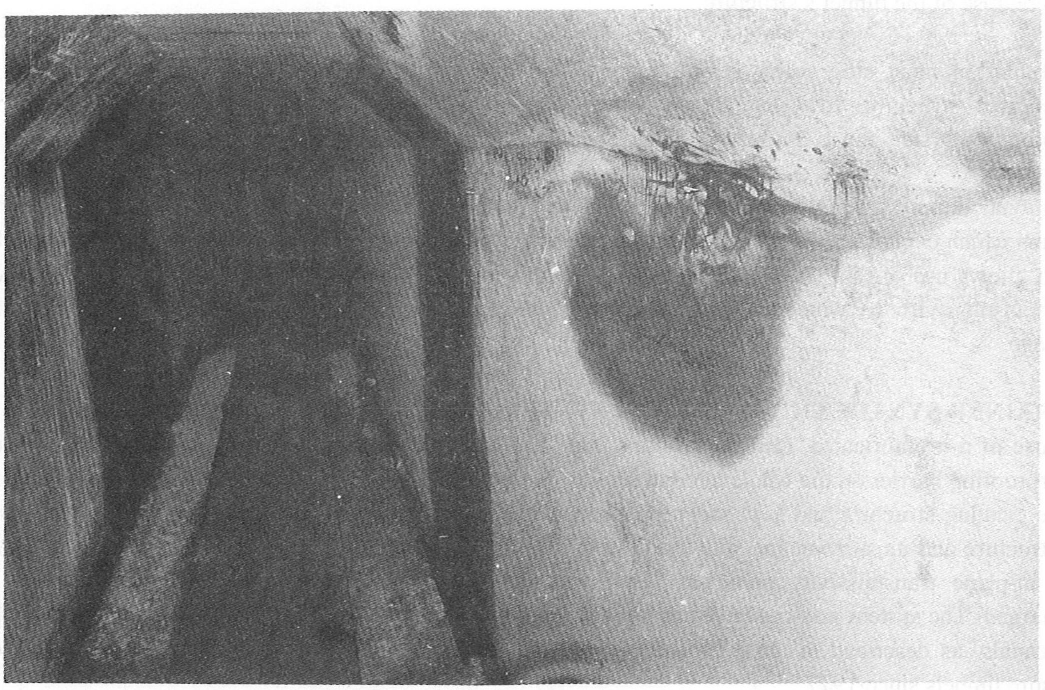

Figure 1. Gandellino tunnel before waterproofing intervention