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Geomembranes for masonry and concrete dams: State of the art report

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ABSTRACT: geomembranes are used as a waterproofing liner on the upstream face of masonry and concrete dams in rehabilitation projects, and as the watertight element at the upstream face of Roller Compacted Concrete dams since the design stage. The present report illustrates the state of the art of these types of applications.

1 BACKGROUND

Masonry and concrete dams are subject to deterioration due to environment aggression. In countries where construction of new dams has been restricted, the issue of rehabilitation and sometimes upgrading of old deteriorated mansonry and concrete dams is being increasingly addressed in recent years. Often the dams in these countries also face severe environment conditions, which increases the probability of deterioration.

For rehabilitation, initial impermeability, compromised over the service life of the dam, must be restored, and the facing must be protected from further environment aggression. Traditional methods, such as new concrete facings, gunite, resins, metal sheethings, have all experimented some disadvantages. In Europe, starting from 1969, when a repair on an Italian dam was first performed, introducing the use of a low permeability synthetic geomembrane, a new technology was born. Since then, the technology has been applied to provide impermeability to the upstream face of all types of dams, including masonry, concrete, and Roller Compacted Concrete (RCC) dams.

Waterproofing the upstream face of a masonry or concrete dam with a low permeability geomembrane provides many benefits as compared to traditional techniques, due to its durability, ease and quickness of installation, and reasonable costs, but it is also a very technically challenging task. Being that the membrane is always left exposed, materials with very high performance must be used, with a controlled design and installation. When these characteristics are met, an expected durability of 50 to 100 years can be achieved.

2 GEOMEMBRANES ON MASONRY, CONCRETE AND RCC DAMS: A BRIEF HISTORICAL OVERVIEW

As developments of the waterproofing systems were different for masonry and concrete dams, and for Roller Compacted Concrete dams, they will be discussed in two separate sections.

2.1 Masonry and concrete dams

All but two of the rehabilitations performed on existing masonry and concrete dams have used the same waterproofing synthetic geomembrane system. The system was developed in Italy over the years by one company, with only limited contributions from other companies. It has been installed not only on Italian dams, but also on all other masonry and concrete dams rehabilitated in other countries with waterproofing synthetic geomembranes, with the above two exceptions.

The evolution of this system began with the purpose to stop water infiltration through the dam upstream face. The geomembrane was glued to the existing upstream face of the dam. Experience was gained after the first applications, the observed weakness being the method of attaching the geomembrane to the dam facing.

Subsequent improvement of the system focused on collecting and discharging water present between the geomembrane and the dam face, to avoid further deterioration. The system developed eventually into a mechanically anchored geomembrane system. The concern for durability also changed the choice of the waterproofing material type: a long lasting, high quality geomembrane was necessary to guarantee a long service life.

The importance of water discharge, along with gained experience connected with the interactions between the dam body and the geomembrane, lead to the concept of dehydrating the dam body via a properly designed drainage system.

2.1.1 Italy

The first pioneering installation was accomplished on the 53 m high Lago Verde rockfill dam, in Italy, in 1969: the junction between the rigid concrete structure at the heel of the dam and the deformable dam body was waterproofed using a composite polyisobutylene-polyvinylchloride (PIB-PVC) geomembrane. After the successful installation, it was deemed possible to adapt the technique to waterproof the whole upstream face of dams. First installation was accomplished on a concrete dam in 1970, using a 2 mm thick polyisobutylene membrane (Lago Baitone dam, a 37 m high multiple arches dam). The same waterproofing method was used on the Pantano D'Avio dam, a 65 m high buttress dam, in 1974. Attachment of the waterproofing liner to the dam upstream face was made by glueing, which required an extensive and time consuming preparation of the existing surface. The initial performance was satisfactory, but long term susceptibility of the liner to environmental actions such as U.V. and temperature variations caused its progressive deterioration. The original membrane was eventually replaced with a PVC membrane.

Improvement of the system lead to the use of a material with higher performance: PVC was the chosen material in all subsequent installations. In 1976 waterproofing of an entire upstream face was accomplished using a 2 mm thick PVC geomembrane (Lago Miller dam, a 11 m high masonry dam in the Italian Alps, altitude 2170 m a.s.l.). An improved system of attaching the membrane to the dam face by metal batten strips was used. The perimeter seal was watertight, to avoid water passing around the liner. The PVC geomembrane was left exposed to the environment. Since then, the Owner of the Lago Miller dam has conducted testing on samples of the PVC geomembrane after service, and the PVC performance is very satisfactory. This has proved that the membrane can withstand environmental aggression, especially U.V action.

In following installations, from 1980 to 1988 (Lago Nero dam, concrete gravity, 43 m high, 1980; Lago Molato dam, multiple arches, 55 m high, 1986, Piano Barbellino dam, concrete gravity, 66 m high, 1987; Cignana dam, concrete gravity, 58 m high, 1988), the system evolved in time, incorporating additional features increasing its performance:

- improvement in the materials: the original PVC single membrane was heat-coupled during the manufacturing process to a non-woven polyester geotextile, creating the geocomposite currently employed. The geotextile backing provides an anti-puncture layer, thus giving the possibility to reduce the surface preparation required before membrane placement, and is also an extra assett for the dimensional stability. In addition, the geotextile allows in-plane water transmissivity: this is connected with the concept of providing drainage behind the membrane, which designers involved in these projects consider a very important issue for a good long term performance
- improvement in anchorage methods: the batten strips used were adapted to provide better perfomance, as will be thoroughly illustrated in the part discussing the state of the art.

Since 1988, the technique has furtherly evolved: starting in 1989, at Publino, a double courbature, 40 m high dam, the employment of a higher transmissivity material behind the membrane has improved drainage performances. In 1993, at Camposecco, a 27 m high masonry dam, the use of a very thick, anti-puncture transition geotextile allowed the installation of the membrane over a very rough stone pitching facing, without the need of extensive surface preparation.

2.1.2 France

In France, the first installation was accomplished on the Migoelou dam, a 29 m high concrete gravity dam, in 1989. The liner was made of a PVC geocomposite, of the same type used on the Publino dam in Italy. The same system was installed at Chartrain (masonry, 54 m high, 1993), La Girotte (multiple arches, 48 m high, 1994), Chambon (concrete gravity, 136 m high, 1993 to 1995), Les Bouillouses (concrete gravity, 25 m high, 1996), all waterproofed by the same Italian company. At Tregat (concrete gravity, 20 m high, 1995), a similar material and a mechanical anchorage which does not allow pretensioning of the liner were installed.

Fig. 1. Pracana Dam

2.1.3 Portugal

In Portugal, only one concrete dam membrane installation is recorded at this time. Pracana dam is a 65 m high buttress dam, waterproofed in 1992 using the same system developed in Italy, with a very efficient and sophisticated drainage system using an accurate design, allowing the membrane to adapt to any formation of any new fissures occurring in the dam body over time. On this dam, drainage water collection and discharge was divided in separate sections, allowing the evaluation of the waterproofing liner performance by independent monitoring. Fig. 1 shows the installation.

2.1.4 Germany

In Germany, in 1974, a 3 mm thick PVC geomembrane was installed on the Heimbach dam, a 7.5 m high concrete gravity dam. Anchorage of the membrane was made by non-ferrous nails. No more cases have been documented.

2.2 Roller Compacted Concrete dams

In the field of RCC dams, there are two different systems available, one with protected liner and one with exposed liner, the former having been developed in the U.S., the second one being an evolution of the system illustrated above for rehabilitation of existing dams.

The oldest case histories of RCC dams waterproofed with a protected synthetic geomembrane refer to the United States dams, the first one being Winchester dam, now known as the Carrol E. Ecton dam, constructed in 1984/1985. In all other RCC dams constructed since then in the United States and adopting a geomembrane as the waterproofing element, a protected membrane system has been used.

In 1990, in France, the first RCC dam built by EDF (the French National Power Board) used an exposed membrane system: the Riou dam, 30 m high, was waterproofed with a 2.5 mm thick PVC geomembrane installed during its construction. The same system was applied in 1990 to the Concepcion dam in Honduras, 70 m high, and is in 1996 under construction at Nacaome dam in Honduras, with a height of 55 m.

3 THE STATE OF THE ART

Rehabilitation applications on masonry and concrete dams, and applications on RCC dams are illustrated separately due to the different techniques adopted.

3.1 Masonry and concrete dams

At present, the technology for rehabilitation of masonry and concrete dams foresees construction of a complete water barrier using an exposed, low permeability, flexible synthetic geomembrane. For an efficient performance, the barrier must be continuous, that is no discontinuity should exist from the crest of the dam down to the grout curtain, as this would allow points of potential water infiltration.

The barrier must give the possibility to drain any water behind the waterproofing geomembrane. Experience has shown that the presence of water behind the geomembrane, due to migration of water already present inside the dam body and set in motion by temperature gradients, or to infiltrations from the reservoir caused by failures or by discontinuity in the water barrier, are detrimental to the waterproofing system. Temperature variations may change the water state, thus exerting ice or vapor pressure behind the membrane, and in the case of a rapid drawdown the presence of high quantity of water may build up excessive stresses on the liner, that causes membrane system failure.

If an efficient drainage system is constructed behind the geomembrane, a series of benefits can be obtained. All water can be continuously collected and discharged, thus avoiding the above inconveniences, and also avoiding that water in pressure acts directly on the dam upstream face. A further benefit is the possibility of exerting a continuous dehydrating action on the dam body, due to temperature gradients and to different thermal inertia and transmissivity of the concrete and of the geomembrane. Water already permeating the dam body after seepage from the reservoir, or coming from foundations, migrates towards the warmer upstream face of the dam. As temperature drops

Fig 2. Installation of the membrane system

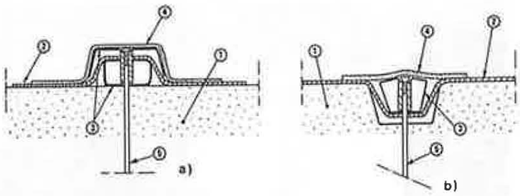

Fig. 3. Horizontal Sections through Steel Rib Fastening System

overnight, water condensates against the liner and is conveyed by the air gap, consisting of high in-plane transmissivity of a suitable synthetic drainage layer, towards a bottom collection and discharge system.

Drainage also provides control of the efficiency of the waterproofing liner when monitoring of drained water is performed.

To allow drainage, a gap must exist between the liner and the existing upstream facing, where a high transmissivity material is placed: for this reason, the primitive technology of glued geomembranes has widely been overcome by a technology using linear anchorage, by which the gap can be created. The geomembrane is thus fastened to the dam upstream facing by vertical metal profiles. Fig 2 illustrates a typical installation.

The original batten strips for mechanical anchorage have developed into coupled profiles with a more sophisticated geometry which allows not only anchorage, but also tensioning of the sheets to prevent folds which can be a dangerous feature in case of drawdown. A further benefit is offered by the profiles' capability of acting as free-flow, vertical conduits which collect and convey the drained water to a bottom collection and discharge system. Configurations include profiles installed above the existing surface, and profiles which have been embedded when extensive rehabilitation works asked for a new layer of concrete or shotcrete (see Fig.3, which is a reproduction of the profiles as illustrated in the ICOLD Bulletin 78).

At the heel of the dam, at spillways, intakes, and wherever water can by-pass the installation, the anchorage is watertight. Current practice achieves the watertightness by compression of the liner against the dam surface by suitably designed profiles, gaskets and epoxy resins.

Drainage materials are either geotextiles or 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, as this allows quicker and more correct placement of the two layers, and improved performance. Geonets, which have a very high transmissivity and a lower possibility of clogging, have been frequently used in the last years, and are installed either on the entire facing or as an additional drainage layer at the heel of the dam.

The material used on all installations mentioned is PVC. This is due mainly to the fact that the installation company, as already mentioned, was always the same, but in two cases. This material, with a specially designed formulation, was chosen because of

- its constructibility, meaning by it its flexibility, which allowed adaptability to difficult geometries, its dimensional stability, its ease in seaming, the reliability of the seams, its suitability to repair in case of damage during construction, its easy handling
- its resistance and durability : it has proved to have an expected service life of at least 50 years, with a possible trend up to 100 years
- its being not flammable

As the system always leaves the geomembrane exposed, the material must have a very high resistance to environment aggression (HYDRO QUEBEC - IREQ 1995). The geomembrane must be manufactured with high quality resins, must be suitably designed by the point of view of additives and plasticizers. Homogeneous membrane materials are to be

Fig. 4. Scais Dam

preferred to multilayers materials, to avoid that a lower quality layer should be exposed to the environment in case of accidental superficial abrasion of the liner. Comparison with the techniques adopted on embankment dams shows that PVC geomembranes with higher thickness are used on concrete and masonry dams, due to the fact that a higher thickness guarantees higher performance (mainly durability), provided it is compatible with good constructibiliy. Fig. 4 shows installation of the system on Scais dam.

It is important that the geomembrane material be thoroughly tested in respect to its resistance characteristic. The state of the art now foresees not only traditional standard testing, but also large scale, multi-axial testing which allows to predict more accurately the future service behaviour of the material. Puncture and burst resistance, resistance to opening of cracks are relevant tests used. As for resistance to ageing, thorough testing must be performed, always however considering that, because of lack of mathematical correlation between laboratory results and behaviour in service, a long and successful field experience is the best of indicators.

The material, which is manufactured in a homogeneous mass, in form of flexible sheets and usually heat-coupled during manufacturing to a non woven geotextile, is deployed on the dam face and fastened to it in by the tensioning profiles in correpondance of junctions. PVC cover strips restore impermeability on the junctions.

As already mentioned above for the Camposecco dam (Italy, 1993), very thick anti-puncture geotextiles, installed directly on the dam facing (see Fig. 5), now allow application of the system to very rough surfaces with little need of previous preparation of the subgrade.

Fig. 5. Camposecco Dam

The current technology conceptually described has been applied to all types of dams and appurtenances, even in the case of irregular geometries or substrates, in very different and aggressive environments. This has been possible not only due to the system design, but also to the type and quality of geomembrane materials used.

Out of a total of 25 masonry and concrete dams where waterproofing rehabilitation by a synthetic geomembrane was accomplished, 23 have been waterproofed with the system developed by one company, which adopts a drained system with pretensioning and anchorage of sheets by mechanical profiles (ICOLD,1991). Only in one case, at an arch dam in Italy (Cazzuffi & Sembenelli, 1994), the system adopted is completely different: the 2.5 mm thick PVC geomembrane is anchored to the dam facing by glueing along vertical strips, and only in the gaps between the strips a high transmissivity drainage material has been installed vertically to provide drainage. Both systems are covered by patents.

3.2 *Geomembranes as waterproofing element on RCC dams*

RCC (Roller Compacted Concrete) dams are constructed according to a fairly new technique, which dates back to the late '60'ies in the pioneer project of Alpe Gera, Italy, 174 m high. They are gravity dams which in mass and construction procedure are similar to embankment dams, but which adopt concrete as a construction material to reduce the mass of the dam body and shorten construction times.

In these 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. This problem can be solved in several ways, the easiest and quickest one being the installation of a low permeability geomembrane on the upstream face of the dam.

With this concept, the concrete performs the static function, the geomembrane performs the waterproofing function. Two systems are available, one which leaves the geomembrane in exposed position, and one which protects the geomembrane from the environment.

At present, technology in Europe is oriented more towards the exposed membrane system. The system is an adaptation of what has been illustrated in 3.1. The geomembrane constructs a continuous, drained water barrier from the crest to the foundation beam, where the lower watertight perimeter anchorage is usually 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 Fig. 3. The PVC geomembrane, of the same type used for dam

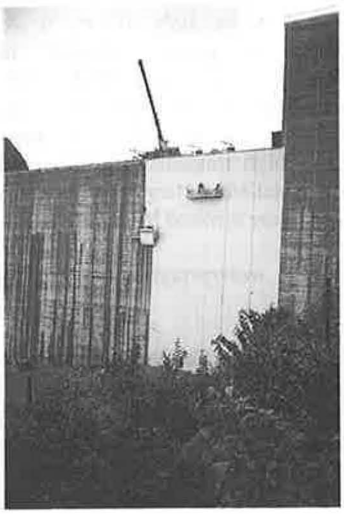

Fig. 6. Nacaome Dam

rehabilitation, is deployed on the dam surface after all RCC layers have been placed (see Fig. 6, illustrating installation at Nacaome dam). The geomembrane is then fastened and tensioned, 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. The vertical profiles convey water towards the bottom collection and discharge system, usually constructed at the foundation beam. Generally speaking, system features and construction are very similar to the ones described for rehabilitation.

The advantages of this technique are an easy and quick installation, and the possibility of easy detection and repair of any damage to the liner which should occur during construction and operation. This also implies that the system greatly facilitates later maintenance.

In the United States, a protected membrane system has so far been used. The advantage of this system is the possibility of avoiding environment aggression, be it mechanical damage due to vandalism, or ageing due to U.V. action. On the other hand, damages occurring during construction, or in subsequent service, cannot be easily located, and repairs can be very difficult, or impossible in case the reservoir cannot be dewatered.

The system embeds the PVC geomembrane in prefabricated concrete panels, shaped so as to be easily assembled. The geomembrane is provided with ribs for embedment in the concrete. The concrete side of the panels faces the reservoir, the geomembrane is in contact with the dam body. The panels constitute the permanent formworks for construction of the dam, and are therefore positioned and assembled as construction proceeds. A conventional concrete layer of small thickness is cast against the panels, then the RCC lift is placed, and construction proceeds by subsequent layers. The panels are secured to the dam body by metal anchor bars embedded in their concrete part during prefabrication, and subsequently embedded in the RCC lifts during dam construction. Anchor bars pierce the geomembrane with watertight fittings. To guarantee watertightness between the panels, PVC cover strips are welded at their junctions, all along their perimeter.

Watertightness at the heel of the dam is made by a PVC geomembrane strip welded to the main liner and subsequently laid horizontally in the dam body, to intercept water migrating from foundations. Additional horizontal strips can be placed in the lower part of the dam, with the same technique, to provide subsequent interception areas.

Both patented systems described above have as a great assett the capability of waterproofing the entire upstream face of the dam, including expansion joints, construction joints and horinzontal RCC lifts joints, which are always a potential point for water infiltration.

4 NEW FRONTIERS

When used for rehabilitation, the system described above, with a flexible PVC geomembrane, mechanically anchored to the upstream face of the dam and drained, has been installed in the dry. The need for installation underwater, however, was very much felt, especially in Europe southern countries and in North America, due to impossibility of dewatering very large reservoirs, or to site constraints, or to environmental reasons. As stated by Mc Donald (1993) "A geomembrane system that could be installed underwater would have significantly increased potential in repair of hydraulic structures".

To find a solution to this problem, in 1993 the U.S. Army Engineer Waterways Experiment Station, Vicksburg, U.S.A., started a research program to demonstrate feasibility of underwater installation of the system. The work was granted to the Italian company who developed the system in the dry. In the first phase of the program, material testing and evaluation were performed, and a conceptual system was designed. Results confirmed PVC as material of choice, also because of its sinkability and of its not requiring accurate surface preparation, which would be very time consuming underwater. The chosen system, now patented, was an adaptation of the system used in the dry, with mechanical anchorage and possibility of draining.

The second phase of the program aimed to demonstrate that the designed system could be installed underwater. A full scale simulation reinforced concrete structure was constructed for this purpose, and placed in a tank at a depth of 6 m. A diver performed underwater all phases of the installation of a PVC drained geomembrane on the whole facing of the concrete structure. The installed system was then tested under a simulated hydrostatic load of 20 m, and proved to be waterproof.

In 1994, a local repair has been performed totally underwater with the same system on a dam in Portugal. Results have been satisfactory. Research and field are both pointing in the same direction: therefore new frontiers are now open for the application of the system.

5 CONCLUSIONS

The techniques for waterproofing and protecting the upstream face of masonry and concrete dams, and of Roller Compacted Concrete dams, with synthetic flexible geomembranes, has reached a high degree of sophistication and reliability.

At present, experience is in the hands of a very small number of manufacturers and installers. The range of applications up to date is fairly large, and results of installations performed according to what has been described as the state of the art have been satisfactory. The main benefits are the possibility of waterproofing the entire facing, joints included, of protecting the dam from environment aggression, and of dehydrating it from permeating water, with a simple system that can be installed in the dry and underwater, quickly and at reasonable costs. Fig. 7 shows Camposecco dam back in service.

6 ACKNOWLEDGMENTS

A considerable contribution to the report has been given by the recent work performed by the "ICOLD European Working Group on Geomembranes and Geosynthetics as Facing Materials", which includes as member countries the Czech Republic, France, Germany, Great Britain, Italy, Portugal and Spain.

The group has assembled datas related to installations in the above member countries, including all types of large and smaller dams, and also some reservoirs and canals waterproofed with the same technologies. Although service conditions, especially in structures where water is in motion, are different, many issues are similar, and it was

Fig. 7. Camposecco Dam

deemed that the type of solution adopted on these structures would give further informations on the performance of geosynthetics as waterproofing materials, and enable to compare different installation solutions.

Informations are at the present date being inserted in a data base, by which the group aims to proceed to elaboration of some guidelines and recommended practice for these types of applications. It will certainly be a considerable improvement if all other European countries would join in this effort and provide a complete collection of datas of all case histories in Europe (Scuero & Vaschetti, 1996).

Further data collection worldwide, further development in materials manufacturing techniques, additional experience acquired during underwater applications, will provide further improvements, but it is most important that also designers and Owners are more aware and confident in this type of technology, that now has more than 30 years of experience.

A special aCknowledgment goes to those Owners and designers who, by being open to new tecniques and by accepting innovations that are not standard practice, have allowed development and improvement of these technologies.

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