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Geomembrane barrier systems for construction and rehabilitation of embankment dams

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ABSTRACT: The main goal of this invited lecture is to discuss the use of geomembranes in embankment dams in order to understand and to evaluate the geosynthetic barrier function in different types of applications, both for the new constructions and also for the rehabilitation of existing dams. Presently, in more than 200 embankment dams worldwide, geomembranes are in fact the main waterproofing component, including the Contrada Sabetta rockfill dam in Italy, that dates back to 1959, being recognized from the international literature as the oldest geomembrane application in dams in the world. The use of geomembranes is generally associated with other types of geosynthetics performing various functions, as geotextiles for mechanical protection and local drainage, or also as geonets for more extended drainage, thereby forming a geosynthetic barrier system. In the invited lecture, the uses of geosynthetic barriers in the construction of new dams and also in the rehabilitation of existing dams around the world are critically reviewed. Design and construction aspects are considered, as well as selection and specifications of the various types of geosynthetic materials. In particular, the issue of sustainability matters on the use of geomembranes in embankment dams compared to the use of other traditional materials (as granular and cohesive soils, metallic blankets and bituminous concrete layers) is adequately treated. Finally, the durability aspects are extensively illustrated, with particular reference to the on-site behavior of applications in dams in the Alpine region.

1 INTRODUCTION

The design of embankment dams involves an adequate seepage and stability analysis of the dam's body (see for example Zhussupbekov and Mkilima 2022). Depending on the available materials on site, the embankment dam could be conceived with a central core or with a watertight upstream face (Jappelli 2002).

In particular, the use of geosynthetics as water barrier on the upstream face became widely use in the last sixty years, starting with the first application of Contrada Sabetta dam in Italy in 1959.

The first applications of geomembranes in dams took place in new embankment dams because many of these dams, being too permeable, required a separate element to provide imperviousness. In many cases, it appeared that geosynthetic barrier systems were more economical and easier to install than traditional impervious materials such as clay, cement concrete, bituminous concrete or even metallic blankets (ICOLD 1981).

Geomembranes were used in embankment dams before they were used in concrete or masonry dams probably for two reasons: (i) because geomembrane installation on the slope of an embankment dam is similar to installation on the slopes of a pond, an application where geomembranes has been used since the late 1950s; and (ii) because installation on a gentle slope is less demanding than installation on a vertical face (Cazzuffi et al. 2010).

As already mentioned, Contrada Sabetta dam, constructed in 1959 in Italy, is considered the first example of use of a geomembrane as the only water barrier in a dam (Cazzuffi 1987).

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Contrada Sabetta dam is a 32.5 m high rockfill dam with a crest length of 155 m. It is a dam of a special type: rocks were arranged as dry masonry, which made it possible to achieve very steep slopes, 1V:1H upstream and 1V:1.4H downstream. The geomembrane used was 2.0 mm thick and made of polyisobutylene, an elastomeric compound that is no longer used as a geomembrane today, not because of any performance problem, at least when it is covered, but essentially because modern geomembranes are easier to seam. A general cross section of Contrada Sabetta dam is shown in Figure 1 and a detailed cross section is illustrated in Figure 2. Special features of Contrada Sabetta dam included the following:

- The geomembrane barrier consisted of two layers of identical geomembranes placed on top of each other over the entire upstream face of the dam. (It is important to note that two geomembranes (or two liners of any type) placed on top of each other, without a drainage layer in between, do not form a double liner.) A total of 3900 m^2 of geomembrane were used on the 1900 m^2 upstream face. These two geomembrane layers were glued to each other along the edges.
- The lower geomembrane layer was glued using a bitumen adhesive on the 0.1 m thick supporting material made of porous cement concrete. The porous cement concrete rests on 0.25 m thick reinforced concrete slabs, resting on the dry masonry.
- The geomembrane barrier was covered by unreinforced 2 m x 2 m concrete slabs, 0.20 m thick, cast on site. The joints between adjacent slabs were left open, 1 mm wide, and were not filled by any porous material, to allow for free circulation of water and to provide some flexibility in case of settlement. There was also a sheet of bituminous paper-felt between the concrete slabs and the upper geomembrane layer to protect the geomembrane during the casting of the concrete slabs.

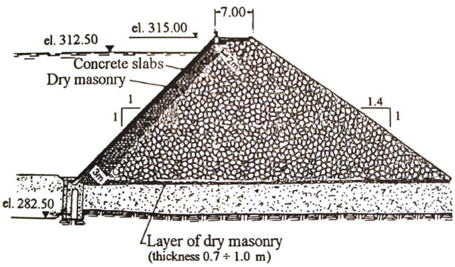

Figure 1. General cross section of Contrada Sabetta dam (modified after Cazzuffi 1987 and ICOLD 1991).

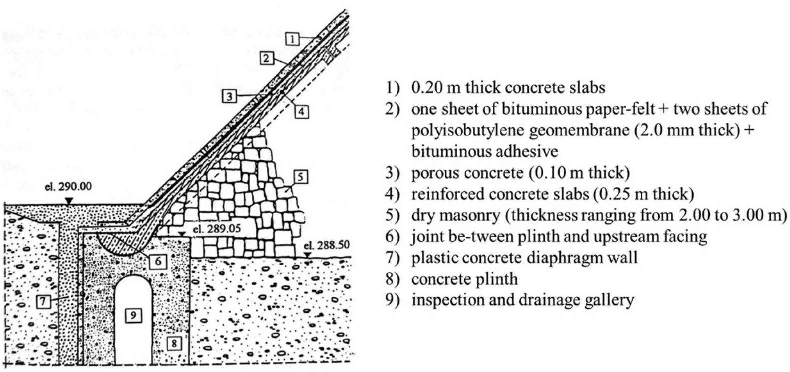

Figure 2. Detailed cross section of upstream toe of Contrada Sabetta dam (modified after Cazzuffi 1987 and ICOLD 1991).

In most of the early projects, the geomembranes were installed during construction of the dam on the upstream slope and covered. The first exceptions were: (1) the first geomembrane used inside a dam was a CPE (Chlorinated Polyethylene) geomembrane used in 1970 on a 1V:0.67H slope (56º) inside a rockfill dam (Odiel dam in Spain) with upstream and downstream slopes of 1V:1.3H; (2) the first geomembrane used for repairing a dam was a 0.9 mm thick PVC (Polyvinyl chloride) geomembrane installed in 1971 at Obecnice dam, an earthfill dam in the Czech Republic; and (3) the first geomembrane used exposed on the face of an embankment dam was a 4 mm thick bituminous geomembrane installed in 1973 at Banegon dam, a 17 m high earthfill dam in France. It was also the first use of a bituminous geomembrane in a dam.

Mission dam (now called Terzaghi dam), a 55 m high rockfill dam constructed in 1960 in Canada, is a special case for both historical and technical reasons. It is a special case for historical reasons because Karl Terzaghi was the designer and because it was one of the first dams including a geomembrane. It was a special case for technical reasons because the geomembrane application was not typical. A detailed description of the construction of the dam was provided by Terzaghi & Lacroix (1964) and a description of the geomembrane installation was provided by Lacroix (1984).

Special features of Terzaghi dam relevant to the geomembrane application are the following:

- The water barrier in the dam was a 1.5 m thick clay layer covered by 2 m of rubble fill.
- Large differential settlement was expected and the clay layer was designed to be convex in order to remain in compression when settlement occurs.
- However, at the transition between the 15º slope and the quasi-horizontal area near the toe of the upstream face, the clay layer was necessarily concave.

In this 10,000 m^2 transition zone, a geomembrane was used to prevent the clay from cracking. The function of the geomembrane can be described as follows. The geomembrane, placed on top of the clay, ensures that a uniform pressure equal to the hydrostatic pressure is applied on the clay. The hydrostatic pressure being higher than the compressive strength of the clay, clay cracking is prevented. Furthermore, if some cracks develop, in spite of the normal pressure applied by the geomembrane, water does not penetrate into the cracks and, therefore, no hydrostatic pressure is applied within the cracks.

In contrast, without geomembrane, as cracks tend to develop as a result of differential settlement, water would penetrate in the cracks. The hydrostatic pressure, acting on both sides of cracks, would open the cracks and cause the cracks to propagate through the entire thickness of the clay layer, thereby impairing the clay barrier function of the clay layer.

A PVC geomembrane was selected because of its large elongation before rupture. The PVC geomembrane selected was 0.75 mm thick, which was considered, particularly in North America, to be a very thick PVC geomembrane at that time. It was smooth on one side and embossed on the other side.

Clearly, Terzaghi dam is an interesting use of a geomembrane in a dam, which can provide an example for some applications in the future. However, it cannot be considered as a precursor of modern applications of geomembranes in embankment dams.

2 EMBANKMENT DAMS

2.1 *Geomembranes and other barriers*

Until 2010, geomembranes have been used in 171 large embankment dams, according to the ICOLD database (ICOLD 2010), both for new construction and for rehabilitation purposes. (Scuero and Vaschetti 2009). In embankment dams, geomembranes are in competition with traditional barriers such as: clay or bituminous central cores, or upstream facings made of cement concrete slabs or bituminous concrete layers or even metallic blankets (Bertacchi et al 1988).

2.2 *Advantages of geomembranes*

Geomembranes are increasingly used because they have numerous advantages over traditional barrier materials: imperviousness, cost, construction, sustainability issues and practical considerations (Cancelli and Cazzuffi 1994).

Geomembranes are significantly less permeable than all other barrier materials. This geomembrane property is essential for the containment of liquids that could contaminate the ground or the ground water, but typically is not considered essential in dams. However, with the growing emphasis on water conservation due to the climatic change, it is likely that the superior imperviousness of geomembranes will be considered to be a significant asset of geomembranes in the future.

Some geomembranes can undergo large strains (e.g., 100% or more) without rupture. A geomembrane with a high elongation capability will maintain watertightness in presence of differential settlements and movements that could cause: (1) cracking of concrete slabs in concrete face rockfill dams and, in extreme cases, could cause failure of the waterstops; and (2) disruption in the connection of the bituminous facing to the concrete structures in the case of bituminous concrete face embankment dams. Concerning dams with clay core, the imperviousness of the core heavily relies on construction quality (too often influenced by weather conditions) and on the skill of the contractor. It can therefore be said that geomembranes can improve safety of embankment dams because they are engineered to maintain imperviousness in presence of events that could impair the performance of other waterproofing systems eventually used in embankment dams.

Geomembrane waterproofing barriers can provide substantial advantages in the construction of embankment dams as compared to traditional waterproofing barriers, because they avoid problems such as lack of suitable materials and deterioration of waterstops. Also, they simplify construction by eliminating the need for installing multiple lines of waterstops and by being easier to connect to ancillary concrete structures than clay cores or bituminous concrete layers.

Construction times and constraints are reduced when geomembrane barriers are used. With traditional barrier materials, the impact that the installation/construction of the face slabs, or the placement/compaction of the impervious core, can have on the overall construction schedule, and the complexity of the techniques needed to construct the waterproofing system, must be taken into consideration when evaluating times of completion. In dams with a central core (made of clay or bituminous material), a crucial point is that, being the construction of the dam body and the construction of the central core related, the constraints imposed by the weather conditions, or any disruption in the placement of the filter material, will affect the rate of construction of the entire dam body. On the contrary, installation of a geomembrane barrier system can be scheduled in function of the general schedule of construction and is not significantly affected by weather.

A variety of types of geomembranes are used in embankment dams (Table 1). Based on the ICOLD database, geomembranes have been used in a total of 171 embankment dams (ICOLD, 2010). In particular, PVC geomembranes have been adopted in 48.5% of dams, while PE (polyethylene) geomembranes (LLDPE, HDPE, CSPE, CPE) have been installed in almost 30% of dams and bituminous geomembranes have been utilized in about 12% of embankment dams.

Table 1. Embankment dams: geomembranes (GM) by types of constituent material.

Type of GM	N	%	Tot exposed	Tot covered	Unknown
PVC	83	48.5	23	57	3
LLDPE	27	15.8	0	26	1
Prefabricated bituminous	20	11.7	7	13	0
HDPE	15	8.8	3	11	1
Elastomeric	11	6.4	5	4	2
CSPE	7	4.1	3	4	0
PP	6	3.5	3	3	0
CPE	2	1.2	0	2	0
Total	171	100.0	44	120	7

PVC: Polyvinyl chloride; LLDPE: Linear Low-density Polyethylene; HDPE: High-density Polyethylene; CSPE: Chloro-sulfonated Polyethylene; PP: Polypropylene; CPE: Chlorinated Polyethylene

3 CONSTRUCTION OF NEW EMBANKMENT DAMS

For new construction of embankment dams, it is possible to define two design concepts: location of the geomembrane and type of liner system.

In an embankment dam, two positions can be considered for the geomembrane barrier: (1) the geomembrane can be at the upstream slope, covered or not; or (2) the geomembrane can be internal, i.e. located inside the dam body, either inclined inside the upstream zone of the dam, or vertical or quasi vertical, in a central position.

Based on the ICOLD database, in approximately 90% of the dams where a geomembrane is used, it is at the upstream slope and in approximately 10% it is internal. Among the geomembranes used at the upstream slope: 70% are covered, and 30% are exposed.

When a geomembrane is used on the upstream slope, it can be exposed or covered (i.e. "protected") by a layer of heavy material such as soil, concrete, etc.

The design of a dam with a liner (any type of liner) should be such that the seepage resulting from a major breach in the liner should not cause the rupture or a major distress of the dam. Therefore, the various zones that constitute a dam should comprise adequate filters to prevent internal erosion of the dam. This is particularly important when the liner is an exposed geomembrane because this type of materials can be breached accidentally. In fact, geomembranes are significantly more waterproof than concrete or clay, but they can be damaged by some mechanical actions.

If the dam does not meet the conditions indicated above and is sensitive to internal erosion in case of seepage, a possible solution consists in minimizing the rate of leakage through the liner system, even in case of a breach in the geomembrane. Two possibilities for minimizing leakage are the use of a double liner, and/or the use of a composite liner.

Even if there are some examples of use of geomembranes in a central position of an embankment dam (Cazzuffi et al 2010), the present invited lecture illustrates mainly the case of applications on the upstream face, both for exposed geomembranes and for covered geomembranes.

3.1 *Upstream exposed geomembranes*

Exposed geomembranes account for approximately 30% of the geomembranes used at the upstream slope of embankment dams, e.g. Bilancino cofferdam in Italy (Figure 3); and the geomembranes used at the upstream slope of embankment dams are approximately 90% of the geomembranes used in embankment dams.

Geomembranes exposed on the upstream face of embankment dams are subjected to a variety of potentially detrimental actions:

- Mechanical damage by ice, floating debris, rocks falling, animals, vandals, and traffic.
- Degradation by exposure to environmental agents (oxygen, UV, heat).
- Displacement by wind, wave action, fluctuations of water level, and gravity (causing creep).

Geomembranes can be used exposed if they have appropriate strength and composition to resist mechanical damage and degradation. Precautions must be taken to prevent or reduce geomembrane displacement by wind, waves and gravity. Generally, the main risk is displacement by wind. Therefore, geomembranes must be anchored against wind uplift.

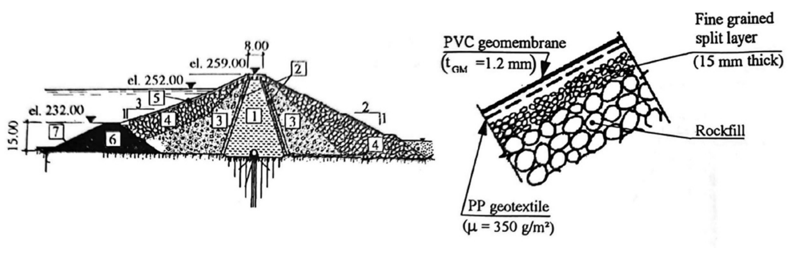

Figure 3. Bilancino zoned embankment dam in Italy, 42 m high, with a cofferdam lined with an exposed PVC geomembrane (modified from Baldovin, 1993): 1. Clayey silt core; 2. Filters, 3. Transitions; 4. Rockfill; 5. Rip-rap; 6. Cofferdam (with upstream face 1V:2H and downstream face 1V:1.5H); 7. PVC geomembrane (t_{GM} = 1.2 mm) and PP geotextile (μ = 350 g/m^3).

3.2 *Upstream covered geomembranes*

If a geomembrane is left exposed on the upstream face of an embankment dam, it could be subjected to a number of actions that could damage it. The reasons for geomembrane protection by a cover layer are:

- Protection of the geomembrane against mechanical damage (by ice, floating debris, rock falling from the sides, animals, vandals, traffic).
- Elimination of exposure to environmental agents (oxygen, UV, heat) that in some cases could cause degradation of the geomembrane.
- Prevention of geomembrane displacement by wind, wave action, gravity (causing creep).

Mechanical protection of geomembranes on slopes is typically ensured by covering the geomembrane with a layer of heavy material such as cement concrete or soil. Considering all of the potentially detrimental actions, a majority (70%) of the geomembranes used at the upstream slopes of embankment dams are covered, based on the ICOLD database.

Several systems have been used, or could be used, to cover geomembranes:

- Interlocking concrete blocks;
- Articulated concrete blocks;
- Concrete slabs;
- Shotcrete on geotextile;
- Geocells or geo-mattresses filled with concrete;
- Soil and rock protection layers.

It is important to note that improperly designed or constructed cover layers can eventually damage a geomembrane during construction or operation. Therefore, a thick needle-punched nonwoven geotextile is generally used between the geomembrane and the cover material.

The placement of the cover layer is possibly the most critical part of construction of a covered geomembrane system. Construction quality assurance activities should not stop after placement of the geomembrane. It should continue during the placement of a geotextile protection layer on the geomembrane and then, during the following placement of the cover layer.

The important role of the geotextile layer during operation is illustrated by the fact that the geomembrane was not damaged despite extensive displacement of articulated concrete blocks at L'Ospedale dam in France, that was built in 1978.

At Codole dam, always in France, a cost analysis at the design stage showed that the solution adopted was cost-effective compared to other solutions even if the geomembrane and the overlying cement concrete slabs had to be re-placed after 25 years of service. Codole dam was built in 1983 and is still in service without any further replacing of cement concrete slabs (Figure 4).

At Codole dam, the cement concrete slabs were reinforced with traditional steel bars. This proved to be a potential problem. Great precautions had to be taken during construction to avoid damaging the geomembrane with the reinforcing bars, in spite of the presence of a geotextile layer above the geomembrane.

Bovilla dam in Albania, is a 91 m high rockfill dam built in 1996 for water supply, flood mitigation and hydropower (Figure 5). The original design of a concrete face rockfill dam was changed to a geomembrane face rockfill dam for the following reasons: (1) concerns about the final quality of the reinforced concrete face and its potential for future cracking; and (2) need to reduce construction time and costs as the project was behind schedule (Sembenelli et al. 1998).

The upstream composite geomembrane installed in 1996 is the only element providing watertightness to the dam: the composite geomembrane consists of a 3 mm thick PVC geomembrane laminated to a 700 g/m^2 polyester geotextile. It was placed directly over a porous cement concrete layer constituted by gravel stabilized with cement slurry (Figure 6). The geomembrane covers the entire upstream slope, from the crest to the massive toe block, i.e. over a difference in elevation of 54 m. The upstream slope is 1V:1.55H in the upper 40% and 1V:1.6H in the lower 60%.

The geomembrane was covered with unreinforced concrete slabs that were placed on an 800 g/m^2 geotextile. The slabs are 6 m long in the slope direction and 3 m horizontally. The slabs

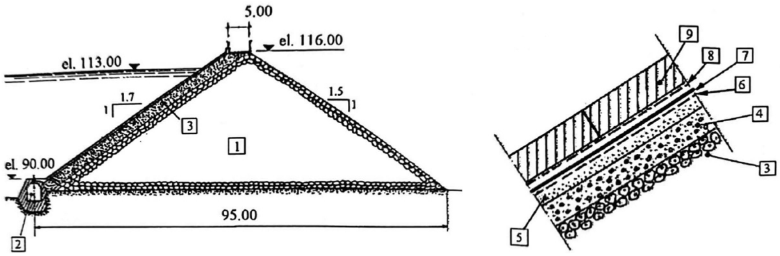

Figure 4. Codole rockfill dam in France, 22 high (modified from ICOLD, 1991): 1. Rockfill (up to 1.00 m size); 2. Inspection and drainage gallery; 3. Sand and gravel layer (2.00 m thick, 25÷120 mm grain size); 4. Gravel layer (0.15 thick, 25÷50 mm grain size); 5. Cold premix layer (50 mm thick, 6÷12 mm grain size); 6. Geotextile (μ = 400 g/m^3) bonded to geomembrane; 7. PVC geomembrane (t_{GM} = 2.0 mm); 8. Geotextile (μ = 400 g/m^3); 9. Cement concrete slabs (0.14 m thick, 4.5 x 5.0 m^2 size).

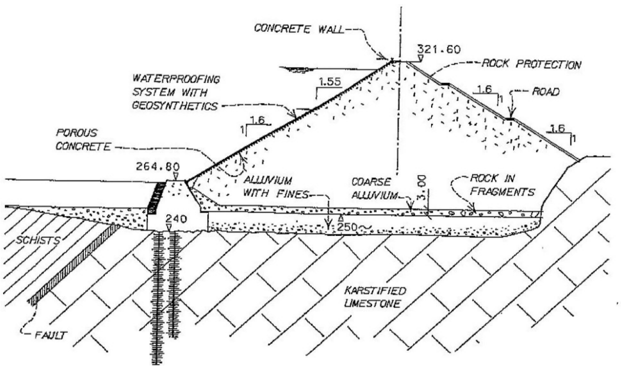

Figure 5. General main cross section at Bovilla dam in Albania.

are 0.20 m thick. The geotextile had a double function: providing anti-puncture protection to the geomembrane against casting of the slabs, and act as a light reinforcement for the slabs themselves.

Figure 6. Bovilla dam: composite geomembrane placing over the porous cement concrete layer.

The decision to adopt cast in place concrete slabs rather than prefabricated concrete blocks was taken because casting slabs was considered less aggressive on the PVC geomembrane than the placement of prefabricated concrete elements, and also considering the problems with articulated concrete blocks previously registered at L'Ospedale dam in France.

At Bovilla dam, the bottom seal of the geomembrane on the toe block was designed to be able to accept differential movements and settlements one order of magnitude larger than the estimated ones. Extra material and protection/decoupling layers were placed for this purpose over the layer of geomembrane at the seal.

La Galaube dam, 43 m high, a rockfill dam built in France in 2000, is one of the highest dam waterproofed with a bituminous geomembrane (Gautier et al,. 2002). The bituminous geomembrane, 5 mm thick, has been laid on a 0.10 m thick cold asphalt mix placed over a layer of non-bounded gravel impregnated with bitumen on the 1V:2.0H slope. The bituminous geomembrane is protected by a geotextile layer (Figure 7) and the final cover layer is constituted by a 0.10 m thick cement concrete slab reinforced with PP (Polypropylene) fibers.

The bottom anchorage is made on the concrete plinth and is of the tie-down type. Installation of 22.000 m^2 of bituminous geomembrane was completed in 2000.

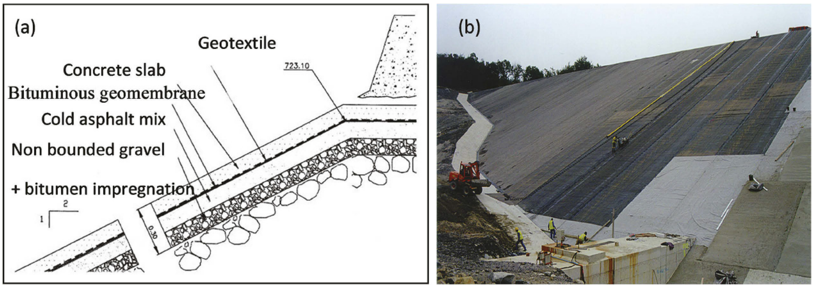

Figure 7. La Galaube dam in France: (a) typical cross section at the top (after Gautier, 2003); (b) placing of geotextile protection layer (in grey) over the bituminous geomembrane layer (in black).

Geomembrane covers using a soil layer cannot be used on the steep slopes typical of rockfill dams because they would not be stable. Soil layers should only be used on slopes less steep than 1V:2.0H, preferably on 1V: 2.5H slopes and less steep. It is essential to check the stability of the soil cover under rapid drawdown conditions, the worst conditions for static stability. In relevant areas, the seismic stability should also be checked.

At Worster dam, Colorado, USA, 22 m high, 215 m long, lined with a 1.5 mm textured HDPE (High-density Polyethylene) geomembrane, the 0.3 m thick soil cover bulged at the toe of the 1V:3.0H slope at the first drawdown of the reservoir, as it was uplifted by water entrapped between the geomembrane and an old concrete slab located a few meters behind the geomembrane.

4 REHABILITATION OF EMBANKMENT DAMS

Geomembranes have been used also for the rehabilitation of embankment dams, and in particular for cement concrete face rockfill dams and for bituminous concrete face rockfill dams.

4.1 *Rehabilitation of cement concrete or bituminous concrete face rockfill dams*

In the rehabilitation of cement concrete face rockfill dam dams or bituminous concrete face rockfill dams, the design should take into account that both are hard surfaces to which geomembranes can be attached. Therefore, the anchorage system of the geomembrane to the dam face is designed depending on the type and strength of the existing facing (cement concrete or bituminous concrete): consequently, the geomembrane is typically left exposed, and maintained to the dam upstream face by face anchorage and perimeter anchorage.

4.2 *Rehabilitation of cement concrete face rockfill dams*

For cement concrete rockfill dams, face anchorage in the past has be made by gluing or by mechanical fixations.

Gluing has been done in the case of in situ geomembranes. In a number of these applications, gluing has resulted in failure, such as at Paradela dam in Portugal and Rouchain dam in France. These failures can be attributed to the nature of the in-situ geomembranes. But, they may also be due to a fundamental conceptual mistake. Two liners should not be located directly on top of each other, unless there is a sufficient load on them to counteract water pressure. Of course, there is no load on a geomembrane glued on a rigid support. Therefore, the ICOLD Bulletin (2010) recommends that gluing "should not be continuous over the entire face to allow drainage behind the geomembrane and release of vapor pressure which would result in uplift pressure which could detach and ultimately damage the geomembrane or the sup-porting layer. Rehabilitation of cement concrete or bituminous concrete facings with a geomembrane glued on the entire surface is not recommended." In fact, gluing has been abandoned since the late 1980s.

A simple mechanical fixation consists of nailing the geomembrane to the supporting layer. This has been done for the partial repair of Heimbach concrete dam in Germany. Conceivably, a nailed geomembrane (or a geomembrane with other types of punctual anchors) could be used for the repair or rehabilitation of cement concrete face rockfill dams.

Mechanical fixations are bolted to the dam with different methods depending on the characteristics of the face. Mechanical fixations are commonly used nowadays and they have the additional advantage of allowing a drainage system behind the geomembrane.

A remarkable example of rehabilitation on the entire facing of cement concrete face rockfill dam is represented by Midtbotnvatn dam in Norway (Figure 8). In this dam, the 2.5 mm thick PVC composite geomembrane was installed in 43 days instead of 2 full summer seasons as required by the second best rehabilitation option (morainic material): this fact is quite important for applications in cold regions where the rehabilitation works could be done only in the summer season.

Figure 8. Rehabilitation of Midtbotnvatn rockfill dam in Norway: placing of PVC composite geomembrane layer over the damaged cement concrete facing.

4.3 *Repair of bituminous concrete face rockfill dams*

If a geomembrane is used to repair dams having a bituminous concrete face, the anchorage system is designed in function of the particular characteristics of the subgrade, which being not a rigid material like concrete does not always allow using the type of anchors used on concrete.

For anchoring the profiles or batten strips that provide face anchorage, typically field testing is made to verify if chemical phials or grouted anchors or deep anchors must be adopted.

Chemical phials require a stronger and not very viscous subgrade. Grouted anchors and deep anchors (Duckbill/Manta Ray type) can be used in alternative.

At Moravka, a 39 meter high earthfill dam in the Czech Republic used for hydropower, potable water supply, and flood control, an exposed PVC composite geomembrane was placed on the bituminous concrete facing that despite several repairs, including a new bituminous concrete layer, continued to exhibit important leakage (Figure 9). An asset of geomembrane systems in this type of dams is that they do not require milling of the deteriorated bituminous concrete, which on the contrary is necessary if a new bituminous concrete layer is installed.

Pull out field testing was carried out at several locations of the facing to ascertain if chemical anchors could be used to fix the tensioning profiles for face anchorage. The tests were successful, but since the resistance of the bituminous concrete could vary over the year depending on atmospheric temperature, the conventional chemical anchors were modified to ensure stability.

Two bottom perimeter seals were installed at the concrete block where the drainage gallery is located (Figure 10). The primary seal confines the drainage system of the upstream face (geomembrane system); the secondary seal confines the drainage system for water coming from foundation/abutments/failing joints in the concrete. The two drainage systems discharge in the gallery with separate discharge pipes to allow a suitable monitoring of the system.

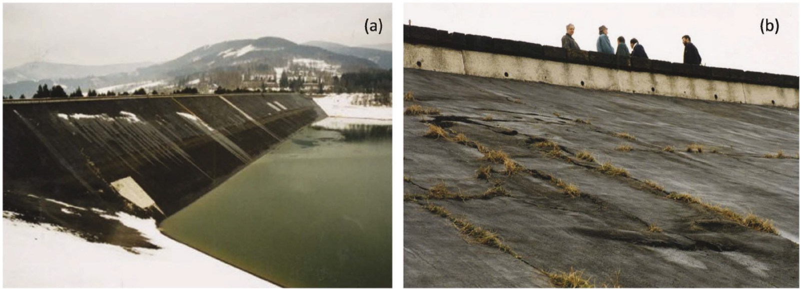

Figure 9. Moravka bituminous concrete face rockfill dam, Czech Republic: (a) original situation of the facing before rehabilitation; (b) detailed of the very important differential settlements in the facing.

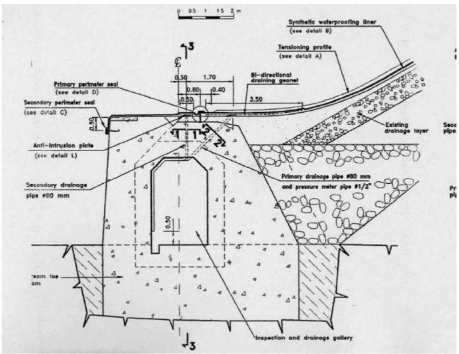

Figure 10. Moravka bituminous concrete face rockfill dam, Czech Republic: the two bottom seals.

The exposed geomembrane system was released in 2009 (Figure 11a). During the following years, the geomembrane system has resisted to important ice impact (Figure 11b).

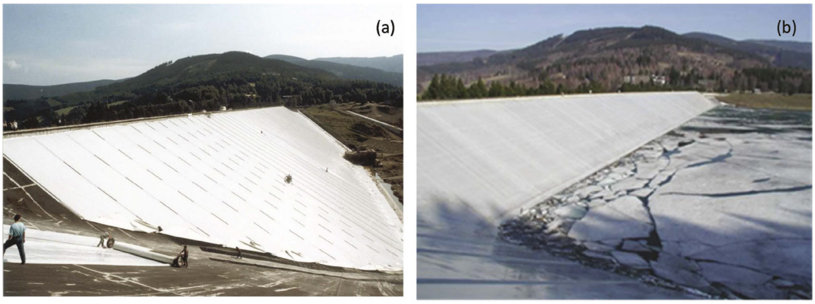

Figure 11. Moravka dam: (a) placing of PVC composite geomembrane layer 2.5 mm thick (b) heavy ice impact did not damage the exposed PVC geomembrane.

5 PERFORMANCE OF EMBANKMENT DAMS WITH GEOMEMBRANES

A typical rate of leakage per unit area observed in the case of large earthfill and rockfill dams constructed with a geomembrane liner on the upstream face and covered is of the order of 1 liter/hr/m^2 (assuming that monitoring is accurate, which is not guaranteed) for the best cases and up to 10 liter/hr/m^2 for dams that do not have the best performance. For the sake of comparison, one defect per 1000 m^2 with a diameter of 2 mm gives a calculated leakage rate of the order of 0.1 liter/hr/m^2 with a typical water head. It is possible that leakage at peripheral connections may explain the difference.

However, in the case of geomembranes anchored on a concrete face rockfill dam, the rate of leakage is of the order of 0.1 liter/hr/m^2 for the best cases. It appears that the typical leakage rate in the case of geomembranes anchored on a concrete face rockfill dam is an order of magnitude times less than the typical rate of leakage through geomembranes installed conventionally in embankment dams. This may be due to better installation on rigid surface.

5.1 *Safety in case of geomembrane failure*

Exposed geomembranes can be damaged by accidental exceptional events (vandalism, terrorism) or by repeated or occasional aggressions from the service environment (animals, ageing). Upstream geomembranes, exposed or covered, can be damaged by extraordinary causes such as earthquakes or falling aircrafts.

The design of a dam with a liner (any type of liner) should be such that the seepage resulting from a major breach in the liner should not cause the rupture or a major distress of the dam itself. Therefore, when a geomembrane liner is considered for an embankment dam, it is essential to check that the appropriate precautions have been taken.

First of all, it is important to monitor and maintain dams. Current defects in geomembranes generally have no detrimental consequences, because a geomembrane - with a small number of small punctures - is still less permeable than any other liners.

Significant defects in geomembranes, due to the exceptional causes mentioned above (earthquakes or falling aircrafts), should be repaired if they are likely to have detrimental consequences. Fortunately, it is generally easy to repair geomembranes. Damage repair, at least for geomembranes having suitable characteristics, is feasible by simple patching if in the dry, or by underwater installation. Of course, the damage repair could be easy for exposed geomembranes.

In the case of internal geomembranes (covered geomembranes), the only cause of significant damage to the geomembrane could be a major earthquake. Therefore, it is important - particularly in seismic areas - to design the dam structure accordingly and to use a geomembrane with high elongation capability and high puncture resistance, since the geomembrane could come in contact with rocks in case of malfunctioning of the protective layers. An internal geomembrane (covered case) with high elongation capability is probably the safest possible liner in case of earthquake.

In conclusion, with an appropriate dam design, and proper geomembrane selection, the geomembrane liners are very safe also in case of important earthquakes.

5.2 *Behavior of geomembranes as a function of time*

Durability is based on the weathering properties, and on the resistance of the geomembrane to specific loads during service (extreme temperatures, frost, freeze/thaw, ice, impacts by floating debris and boats, wind and waves, fauna and flora, vandalism etc.).

Taken for granted that not all geomembranes have the same behavior due to their chemistry, their basic ingredients and their manufacturing process, it is important for dam projects to select a type of geomembrane already adopted in several similar applications or eventually to design a new geomembrane that can best perform according to the type of environment in which it will be used, and that can provide adequate durability for the required application.

Standard accelerated ageing tests are available and are being used all over the world to predict the behavior of geomembranes in service. These tests, although accelerated, would however require too long time to give indication of long-term behavior.

The most practical way to ascertain if a geomembrane will be resistant in the long term to the environmental loading expected in a dam project, is to exhume samples of the same geomembrane that have already been in service, in a similar environment and project, for a period of time that should be as long as possible, ideally as long as the required service life of the geomembrane in the considered dam, and perform tests to determine to which extent their properties have changed. Testing of the physical and mechanical properties of the exhumed samples indicates if the geomembrane properties at the time of the test are within acceptable limits, and extrapolation allows the determination of the expected remaining service life.

This approach has been adopted for applications in the Alpine regions (Cazzuffi 1987; Cazzuffi and Gioffrè 2020; Cazzuffi and Gioffrè 2021; Giroud 2021), using data from several dams rehabilitated with exposed PVC composite geomembrane. The oldest reported application of exposed PVC geomembranes on dams dates back to the mid 1970s, and -since then- many dams have been rehabilitated with exposed geomembranes of the same type, which makes it possible to obtain dependable results. Furthermore, many of these dams are at high elevation (typically higher than 2000 m) where the UV radiation is relevant and the weather conditions are harsh. From this database, it has been provisionally concluded that the service life of PVC composite geomembranes in such extreme environment is around 50 years (Hsuan et al. 2008). It should be noted that geomembranes of the same type installed today are of better quality than the geomembranes installed about 40 years ago and included in the data base used to predict durability. Therefore, the durability of PVC composite geomembranes installed today may be even greater than the predicted durability of at least 50 years.

The approach just described for PVC geomembranes should be eventually used also with other types of geomembranes to evaluate if they have the appropriate durability for use in dams.

5.3 *Evaluation of the residual life of exposed geomembranes*

In order to evaluate the variation over time of the characteristics of the PVC geomembranes installed on 8 dams in Alpine regions, a remarkable number of samples have been taken some periods after application and all of them have been put through the same type of tests.

Samples have been taken both above and under the water level and in different parts of the upstream face, with the aim of studying the different behavior of the same geomembrane in different conditions of exposure.

In the determination of the life expectancy of a geomembrane, it is important to identify the more critical portion of the upstream face, as the first failure will affect negatively the whole waterproofing system. Therefore, here we will present the results of the tests made on samples exhumed above the water level, as this is the area which suffers most from the direct exposure to atmospheric agents. The results obtained are thus referred to the worse conditions for each geomembrane and this helped us to conduct a precautionary analysis of the geomembrane durability.

All the samples taken from the dams' upstream faces have been tested at the Geosynthetics Laboratory of CESI SpA in Italy. The different types of tests (Table 2) allowed the comparison among different samples during the degradation process of the geomembranes.

Table 2. Laboratory tests and reference standards for the evaluation of the determination of the long-term behavior of the exhumed PVC composite geomembrane samples.

Laboratory test	Reference standard
Plasticizer extraction	EN ISO 6427
Nominal thickness	EN 1849-2
Volumic mass	EN ISO 1183-1
Hardness (Shore A)	EN ISO 868
Cold flexibility	EN 495-5
Dimensional stability	EN 1107-2
Tensile properties	EN ISO 527-3
Water vapor permeability	EN 1931

The case of Camposecco masonry dam in Italy is particularly significant, as for this dam also the test results on virgin samples are available; knowing the material's initial conditions, the analysis is more precious as it allows to reconstruct the entire life of the geomembrane on the dam in which it has been applied for rehabilitation of the upstream face (Figure 12).

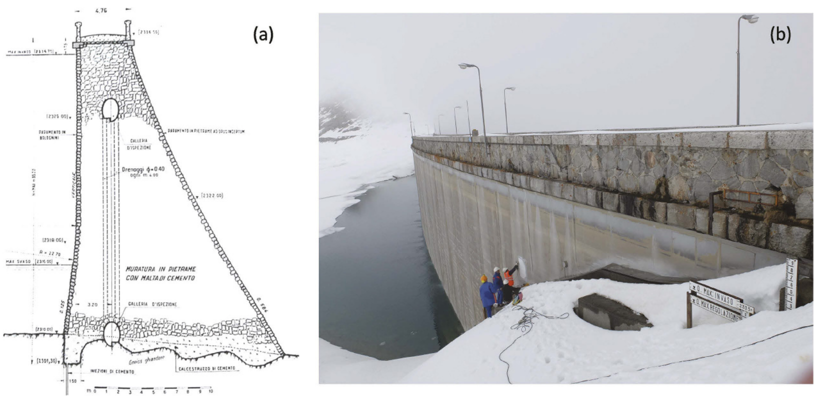

Figure 12. Camposecco dam in Italy: (a) Cross section; (b) PVC composite geomembrane sampling.

The results obtained show a constant small decrease of the plasticizers' content (Figure 13), while temperature of cold flexibility rises with time, and dimensional stability grows longitudinally and declines transversally in the years.

Mechanical parameters derived from the tensile tests show that the geomembrane get a little bit stiffer over time (Figure 14), with some increase of tensile strength and a small reduction of the correspondent strain, both in the longitudinal and in the transversal directions.

With regards to the waterproofing properties, the results of the vapor transmission tests demonstrate in general a negligible decrease of the permeability coefficient, thus a small improvement of the watertightness of the geomembranes, also due to some possible inclusion of particulates and sediments.

Long-term performance of PVC geomembranes depends on several aspects referred to the exposure environment and to the specific polymer and additive formulations. The service life of PVC geomembranes can be predicted based on experimental results. Through a careful monitoring of the variation over time of the characteristics of the PVC geomembranes in service, it was possible to define a methodology of lifetime prediction of the geomembrane installed in dams when the results on virgin samples are available. In particular, the plasticizer content plays a fundamental role particularly in terms of variation in physical properties of the PVC geomembranes (Giroud, 1995; Giroud and Tisinger, 1993).

In order to evaluate most critical service life of the PVC geomembrane, the curve of plasticizer content versus time is extrapolated until the end-of-service-life plasticizer content is reached.

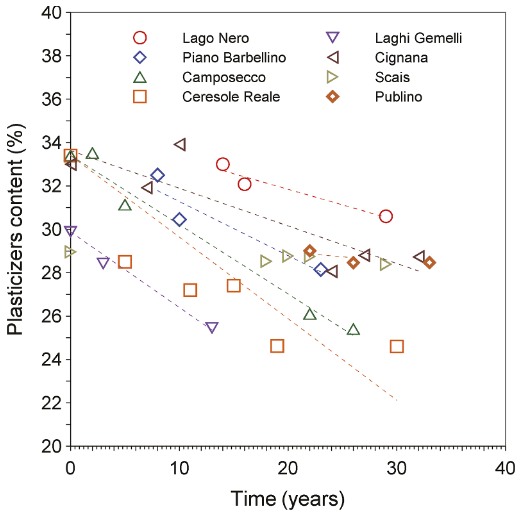

Figure 13. Plasticizers content evolution vs time for PVC geomembrane samples exhumed from different dams on Alps in Italy.

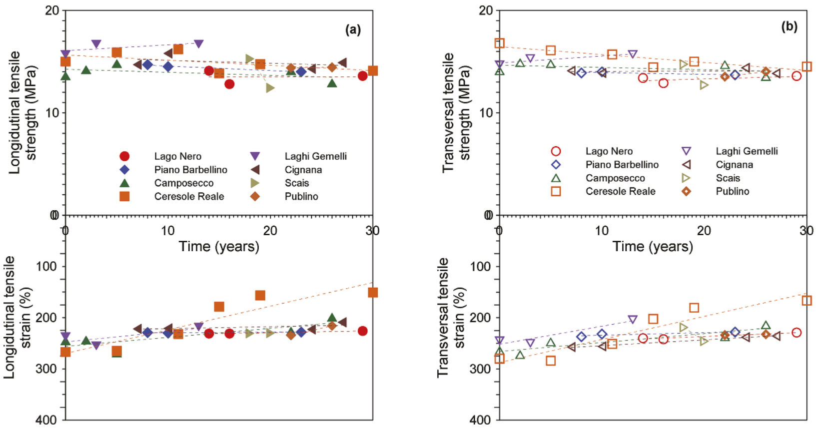

Figure 14. Tensile strength and strain evolution vs time for PVC geomembrane samples exhumed from different dams on Alps in Italy: (a) longitudinal direction; (b) transversal direction.

Based on laboratory tests (Luciani et al. 2019; Luciani et al. 2020) and on data from monitored structures, Giroud (2021) proposes, for the end-of-service-life criterion, a plasticizer content value of 17.5% for PVC composite geomembranes bonded to a nonwoven needle-punched geotextile (which are most frequently used in the considered dams).

Figure 15 shows lifetime assessment of exposed PVC geomembranes for Camposecco dam; vertical lines in Figure 15 shows that the lifetime assessment of the exposed geomembranes for Camposecco dam, assuming a linear decrease of plasticizer loss ratio over time, is approximately 48.5 years, based on the plasticizer content criterion.

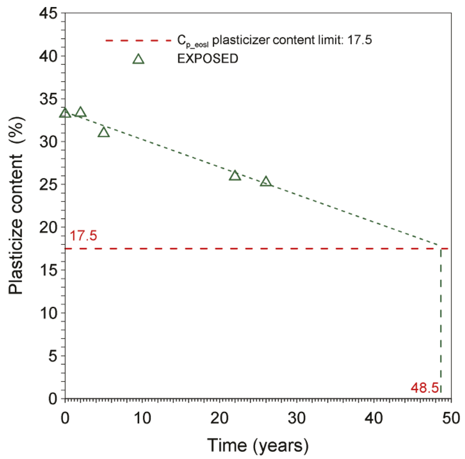

Figure 15. Camposecco dam: Lifetime assessment of exposed PVC geomembranes.

6 CONCLUSIONS

The range of possible applications of geomembranes as water barriers in embankment dams is quite wide. Geomembranes can be applied to all types of dams, in new construction and in rehabilitation.

Design and installation systems of the various components of geomembrane systems according to the type of application have been discussed in this invited lecture.

Geomembrane selection and behavior of geomembrane systems vs. time have been also investigated based on various research projects, and on results from laboratory tests and tests on exhumed samples.

Data on the performance of dams rehabilitated using geomembranes have been provided. These data show a remarkable performance of geomembranes in embankment dams, even when geomembranes are directly exposed to atmospheric agents.

Therefore, this invited lecture could contribute to demonstrate that nowadays the use of geomembranes in embankment dams, both for new constructions and also for rehabilitation purposes, is a well-established technique all around the world, provided that good design, excellent application and careful monitoring are provided.

REFERENCES

Baldovin, E. (1993). New developments of filters in some recent Italian embankment dams. *Filters in Geotechnical and Hydraulic Engineering*, Balkema, Rotterdam, 321–330.

Bertacchi, P., Jappelli, R., Croce, A., Baccini, S., Baldovin, G., Catalano, A., Cazzuffi, D., Di Maio, S., Puccio, M., Sarti, L., Sembenelli, P., Silvestri, T., Tomasi, L., and Travaglini, B. - Working Group of the Italian National Committee on Large Dams - ITCOLD (1988). Embankment dams with impervious upstream facings: an overview of Italian practice, *Proceedings of the 16th International Conference on Large Dams*, Q. 61, San Francisco, USA, 415–454.

Cancelli, A. and Cazzuffi, D. (1994). Environmental aspects of geosynthetics applications in landfills and dams. Keynote Lecture. *Proceedings of the 5th International Conference on Geotextiles, Geomembranes*

and Related Products. Preprint Volume on Special Lecture and Keynote Lectures, Singapore, 55–95, and Vol. 4, 1998, 1299–1338.
Cazzuffi, D. (1987). The use of geomembranes in Italian dams. *Water Power and Dam Construction*, vol. 39, 17–21.
Cazzuffi, D. and Gioffrè, D. (2020). Lifetime assessment of exposed PVC-P geomembranes installed on Italian dams. *Geotextiles and Geomembranes*, 48(2), 130–136.
Cazzuffi, D. and Gioffrè, D. (2021). Reply to the discussion by Giroud on Lifetime assessment of exposed PVC-P geomembranes installed on Italian dams. *Geotextiles and Geomembranes*.
Cazzuffi, D., Giroud, J.P., Scuero, A. and Vaschetti, G. (2010). Geosynthetic barriers systems for dams. Keynote Lecture, *Proceedings of the 9th International Conference on Geosynthetics*, 9 ICG, Guaruja, Brazil, Vol. 1, 115–163.
Gautier, J.L., Lino, L. and Carlier, D. (2002). A record height in dam waterproofing with bituminous geomembrane: La Galaube Dam on Alzeau river, *Proceedings of the 7th International Conference on Geosynthetic*s, 7 ICG, Nice, France, Vol.3, 975–978.
Gautier, J. L. (2003). Etanchéification de masques amont par une membrane bitumineuse, *Colloque du Comité Français des Grands Barrages*, Paris, France. CD Rom.
Giroud, J.P. (1995). Evaluation of PVC Geomembrane Shrinkage Due to Plasticizer Loss. Geosynthetics International, *Special Issue on Design of Geomembrane Applications*, 2 (6), 1099–1113.
Giroud, J.P. (2021). Discussion on "Lifetime assessment of exposed PVC-P geomembranes installed on Italian dams" by D. Cazzuffi and D. Gioffrè. *Geotextiles and Geomembranes*.
Giroud, J.P. and Tisinger, L.G. (1993). The Influence of Plasticizers on the Performance of PVC Geomembranes. *Proceedings of the 7th Symposium of the Geosynthetic Research Institute*, Koerner, R.M. & Wilson-Fahmy, R.F., Eds., Philadelphia, USA, 169–196.
Hsuan, Y.G., Schroeder, H.F., Rowe, R.K., Müller, W., Greenwood, J., Cazzuffi, D. and Koerner, R.M. (2008). Long-term performance and lifetime prediction of geosynthetics. Keynote lecture, *Proceedings of the 4th European Geosynthetics Conference EuroGeo 4*, Edinburgh, UK.
ICOLD, the International Commission on Large Dams (1981). *Bulletin 38. Use of thin membranes on fill dams*, Paris, France.
ICOLD, the International Commission on Large Dams (1991). *Bulletin 78. Watertight geomembranes for dams – State of the art*, Paris, France.
ICOLD, the International Commission on Large Dams (2010). *Bulletin 135. Geomembrane sealing systems for dams – Design principles and review of experience*. ICOLD, France.
Jappelli R. (2002). Terza Conferenza Annuale A. Croce - Le costruzioni geotecniche per le grandi dighe in Italia (in Italian with English abstract). Third Croce Lecture – Earthwork Engineering for Large Dams in Italy *Rivista Italiana di Geotecnica*, Vol. 2, 17–79.
Lacroix, Y. (1984), Use of a geomembrane at Terzaghi Dam, *Proceedings of the International Conference on Geomembranes*, Denver, USA, Vol. 1, pp. 9–14.
Luciani, A., Todaro, C., Martinelli, D., Carigi, A. and Peila, D. (2019) Long-term durability analysis and lifetime prediction of PVC waterproofing membranes. *Proceedings of the WTC2019*. Napoli, Italy.
Luciani, A., Todaro, C., Martinelli, D. and Peila, D. (2020). Long-term Durability Assessment of PVC-P Waterproofing Geomembranes through Laboratory Tests. *Tunneling and Underground Space Technology*, Volume 103.
Sembenelli,P., Sembenelli, G. and Scuero, A. M. (1998). "Geo-synthetic System for the Facing of Bovilla Dam", *Proceedings of the 6th International Conference on Geosynthetics*, 6ICG, Atlanta, USA, Vol. II, 1099–1106.
Scuero, A.M. and Vaschetti, G. (2009). Use of geomembranes for new construction and rehabilitation of hydraulic structures, Keynote lecture, *Workshop on Advanced Methods and Materials for Dam Construction*. Skopje, North Macedonia.
Terzaghi, K. and Lacroix, Y. (1964). Mission dam, an Earth and Rockfill Dam on a Highly Compressible Foundation. *Geotechnique*, London, UK.
Zhussupbekov A. and Mkilima T. (2022). Stability analysis of an old earth Samarkand dam in Kazakhstan under rapid drawdown conditions. *Environmental Engineering - Inženjerstvo okoliša*, Vol. 9 No. 1–2.