An approach for the design and installation of geomembranes on the upstream face of rockfill dams

Colmanetti, J.P.
Geotechnical Consultant, Italy

Assis, A.P. & Palmeira, E.M.
University of Brasília, Brazil

Keywords: geomembrane, seepage barrier, rockfill dams, design aspects

ABSTRACT: The present work approaches the use of geomembrane as seepage barriers on the face of rockfill dams, focusing in a general way on the characteristics, properties and behavior of PVC-P geomembranes and project aspects concerning this type of polymeric material applied on rockfill dams. In spite of their elongation properties, the job of the geomembrane as a seepage barrier in dams requires some attention. Proper care regarding quality control during installation, special care during seeming, attention to the various installation details, especially for anchorage and systems to protect the geomembrane post-installation, should be observed. These aspects, evaluated from a deeper study, including the emerging factors faced in the design, installation, laboratory studies and the analysis of exhumed samples from Italian reservoirs and dams, has resulted in the development of a series of recommendations for design and installation. In short, this paper seeks particularly to present for discussion, for planners' analyses and for installers a proposal with recommendations for geomembrane installations on the face of rockfill dams.

1 INTRODUCTION

Rockfill dams have been built since the end of nineteenth century and in the last years the technology has been used for structures of increasing height. In cases where the design requires an impermeable face, one of the concerns is the execution of a barrier system compatible with the nature of the rockfill. Concrete-facing, which is commonly used as seepage barriers in this type of dam, introduces an element of high rigidity compared to the underlying rockfill. This differential rigidity can cause cracking in the concrete facing when the rockfill settles. The technique of using a more flexible material such as a geomembrane liner, which can accommodate the deformations of the rockfill without rupture, has been demonstrated in Europe and US as an advantageous option. Some types of geomembranes can tolerate large deformations without rupturing and, when designed and installed appropriately, they can safely resist the deformations of the underlying rockfill with very high factors of safety against rupture. For this reason, during a research program these aspects were evaluated aspiring to present to the professionals of the sector some technical aspects that should be considered when this alternative is adopted for a project of an impervious face rockfill dam.

2 GEOMEMBRANE PROPERTIES INVESTIGATION

An essential and indispensable part in the project of a Geomembrane Facing Rockfill Dam (GFRD) is the knowledge of the geomembrane properties and characteristics to be used as a liner barrier. The determination of the geomembrane characteristics and project parameters can be performed at laboratory through identification and behavior tests.

The identification (or index) tests assure that the product delivered at field is in accordance with the specifications and that their quality was controlled during the manufacturing process. A good number of the index texts are used to determine the geosynthetic intrinsic properties and they are useful for design calculations and for comparison of materials from different manufacturers. The usual identification tests performed on geomembrane liners are those for determination of: thickness, density, hardness, mass per unit area and tensile strength. Tests to determine the flexibility at low temperatures, spectroscopy infrared, thermogravimetry analysis (TGA), thermomechanic analysis (TMA), chromatography and carbon black content are not so easy to carry out, however, they are important when it is necessary to identify the geomembrane raw materials.

The behavior tests determine the functional properties of the material. They are useful to determine the project parameters for design purposes. The tests procedures are defined taking into account the different types of products and also considering the construction type (Ex.: hydraulic works, environmental works etc.). It is important to note that three aspects should be considered when performing behavior tests: the geomembrane performance itself, the geomembrane welds and the geomembrane durability. These tests must demonstrate the capacity of the geomembrane to work as a liner barrier, subjected to stresses and different environmental conditions.

In order to determine the ability of the geomembrane to perform as barrier liners in rockfill dams, the following properties are usually determined: permeability, dimensional stability, tensile strength, tear strength, puncture strength, bursting strength and, in specific cases, the resistance against biochemical agents and the flexibility at very low temperatures. When the geomembrane is a part of a whole system formed by drainage, support and protection layers, the laboratory testing program must include an analysis of each singular material and the interaction between them. The anchor system, the weld quality, the possibility of settlements and the interface shear properties should be carefully observed in a GRFD design.

Further technical information concerning to the geomembrane properties, the selection criteria, the index and performance tests description regarding geomembranes applied to dams are reported by Colmanetti (2006). Some specific properties were also discussed by several researchers, such as Ingold (1991), Weiss & Batereau (1987), Fayoux et al. (1984), Giroud (1994), among others.

3 PROJECT ASPECTS

The rock or earth fill dams can be constructed considering two options for the membrane position: at the upstream face or as a central membrane.

The upstream geomembrane option is usually adopted for rockfill dams. In this case, aspects regarding the face stability; differential settlements; the connections to rigid structures and pipes; the support and protection layers and the installation of the geomembrane itself should be carefully evaluated. This investigation includes methods to analyze the cover stability layer, the geomembrane deformation mechanism subjected to differential settlements and the definition of the grain size and thickness of each layer of the waterproof liner system. The geomembrane installation, as well as the anchorage design details, are also discussed by installers and researchers.

4 TECHNICAL RECOMMENDATIONS FOR GEOMEMBRANE AS A SEEPAGE BARRIER IN ROCKFILL DAMS

The following topics describe some important technical aspects that should be taken into account during the design studies and installation of a plasticized polyvinyl chloride geomembrane (PVC-P) as a liner at the upstream face of rockfill dams. They present to the engineers and installers recommendations concerning the tests to be performed in each phase of the project, installation details and system liner monitoring.

4.1 *Face liner system design*

The recommendations have been separated in two phases of project: basic and executive studies. In the basic phase, the geomembrane type should be defined based on laboratory tests, in order to obtain the project parameters and to define the design criteria. During the executive phase studies, the whole system becomes integrated to the information from the previous stage: anchorage at the toe, crest and perimeter; disposition of the geomembrane panels; support and protection layers; seeming of the geomembrane and connections with concrete structures should be well evaluated.

The basic phase project includes studies of the upstream liner system barrier. The recommendations are assumed considering that the geomembrane as an impermeable barrier application on the rockfill dam was defined as a viable alternative in the previous phases of project studies. Therefore, in this phase, the following aspects should be evaluated:

- In-situ environmental conditions;
- General aspects as construction site, availability of construction natural materials;
- Mechanical and chemical stresses;
- Construction phases of the rockfill body dam;

- Geometrical aspects of the face.

Once all those data have been analyzed, it is recommended to choose the polymer type to be used as liner (PVC-P, HDPE, CSPE etc.), as well to specify the other components that will be part of the system. The selection geomembrane criteria are supported by the results of index tests, such as uniaxial tensile, tear, puncture etc., previously carried out on geomembrane samples candidates. The PVC-P geomembrane presents a good performance in hydraulic works, backed by several successful applications all over the world, mainly in Europe.

After the selection of the geomembrane or geocomposite type, a laboratory tests program should be elaborated and performed in a pilot sample in order to obtain the project parameters. During this phase the minimum requested values concerning the index and behavior properties of the geosynthetics must be established.

During the phase of executive project, detailed information on the whole system is required: toe and crest anchorage; perimeter joint anchorage; geomembrane installation and welds; support, base and protection layers; geomembrane or geocomposite fastening and connection with concrete structures or pipes. Furthermore, it is recommended that the project include the preparation of the following documents: control plan to receive the material at the work plant; installation plan (modulation and executive sequence); installation instructions and procedure for weld execution; installation quality control assurance; monitoring plan for geomembrane properties control; materials and work-men budget; a*s built* of the face liner system installation (support layer, geomembrane protection layer).

Table 1 presents the tests that should be carried out to obtain the geomembrane index properties and Table 2 shows some performance tests which can be required or not, according to the characteristics of each structure. It is recommended that these tests be carried out in the phase of the basic project and also during the reception control and installation.

4.2 *Main design aspects*

Regarding the project aspects of a waterproofing system of the upstream face of a rockfill dam, some issues deserve special attention, such as the transition layer thickness for the geomembrane support, the anchorage systems, the geomembrane placement and the stability analysis of the protection layer. The planner should observe the stability of the whole system constituted by base layer, support layer, geomembrane and protection layer, aiming to insure a good performance of the structure.

Table 1 – Index tests proposed for geomembranes characterization for applications in Geomembrane Facing Rockfill Dams (GFRD), Colmanetti (2006)[1]

Test name	**Parameter**
Mass per unit area (EN 965)	Mass per unit area
Nominal thickness (ASTM D5199)	Thickness
Shore A Hardness (ISO 868)	Hardness
Density (ISO 1183)	Density
Uniaxial tensile strength (ASTM D 638)	Elongation at break
	Strength at break
Matter extractable by organic solvents (ISO 6427)	Plasticized content
Flexibility at low temperature[2] (EN 495-5)	Fissure or crack temperature
Tear strength (ISO 34-1)	Tear resistance
Dimensional stability (prEN 1107-2)	Long. and transversal dimension variation
Static puncture strength (EN ISO 12236)	Puncture strength
Dynamic puncture strength (UNI 8202)	Watertight loss
Water Vapor Transmission Ratio - WVT (UNI 8202/23)	Permeability

Note: 1 – Proposed test to PVC-P geomembranes; 2 – Usually not required for tropical climate regions.

Table 2 – Performance tests proposed to obtain design parameters of GFRD (Colmanetti, 2006).

Test	**Parameter**
Bursting strength (prEN 14151)	Strength and elongation at break
Direct shear (prEN ISO 12957-1/ASTM D5321)	Friction coefficient
Peel strength (UNI 8898/4)	Peel strength
Weld shear	Shear strength

4.2.1 Material transition between the base layer and the rockfill dam body

The support layer and the base layer should be designed to make the transition between the rockfill material and the impervious geomembrane face. ICOLD (1991) describes recommendations as grain size of the material and thickness of each transition layer. As this bulletin, the grain size of the first fine rockfill layer placed on the surface of the dam body, as well on the subsequent layers, should be established to respect the classic criteria of soil retention (protection against piping).

If a geotextile is used instead of a fine grained material layer, it is recommended to use a nonwoven product with mass per unit area not less than 500 g/m^2. In the case of adopting a support layer, it is admitted a lighter geotextile, preferably glued to the geomembrane. These layers do not have the purpose of increasing the rigidity near to the face watertight area, as usually done for the concrete face rockfill dams (CFRD), but intend to guarantee an appropriate support for the geomembrane or for the geocomposite layer.

4.2.2 Geomembrane (or geocomposite)

Regarding the choice of a geomembrane type, the planner has diverse options of products manufactured with different polymeric-base types (PVC, PE etc). According to the study conducted by Colmanetti (2006), it was observed that the PVC-P geomembranes have been more suitable mainly when the dams are of great height. Due to the flexibility, elongation, dimensional stability characteristics and its compatible durability with the dams' lifetime, the PVC-P geomembranes have been usually applied in high dams in Europe and even in the USA.

Moreover, the geomembrane must have appropriate additives to guarantee the minimum lifetime when exposed and the minimum thickness that assures compatible resistance against tears and punctures. It is recommended a geomembrane with thickness not lower than 2 mm for dams' applications.

The geomembrane installation begins after the conclusion of the rockfill body and the surface preparation. The classic method consists on laying the geomembrane panels from the dam crest and overlapping enough material for the welds. The planners should also avoid traversal welds in the face, mainly in dams of great height. Each roll should be ordered with compatible length according to the position that it will take in the face; it means with enough length to be extended from the crest to the anchorage dam toe.

4.2.3 Crest and toe anchorage

Several anchorage types can be adopted according to the dam dimensions and the geotechnical in-situ conditions. In the case of rockfill dams it is recommended that the anchorage be made in trenches as designed for Bovilla Dam (Figure 1).

Regarding to the toe anchorage, the possible options are: anchorage in a trench or in a concrete cut-off. As the rockfill dams present significant face deformations, it is advisable that the geomembrane be fastened in order to allow its elongation in the plinth zone. Figure 2 presents the details of the toe anchorage design for the Bovilla Dam.

4.2.4 Protection layer (optional)

The available options to protect the geomembrane on the face can be: shotcrete layer, concrete ballast, rip-rap or soil cover. The shotcrete is an expensive alternative, while soil covers would demand very gentle slopes. The rip-rap protections require a transition between it and the geomembrane liner. Consequently, nowadays the better alternative to protect the face is to use prefabricated or *in situ* placed concrete slabs. The designer, however, should evaluate if is really necessary to protect the geomembrane. If the geomembrane remains completely exposed, subject to water and atmosphere conditions, the related disadvantages are the degradation due to the ultra-violet radiation action and the risk of damages by vandalism. If is possible to exclude these problems, several benefits by having the geomembrane exposed can be acquired, such as: fast and easy liner installation, lower global cost, the possibility of identifying damages with accuracy and effective repairs even under submerged operations. According to Colmanetti (2006), as the geomembrane degradation occurs mainly where there is oscillation of the water level or above it, where the geomembrane remains completely exposed, this option is certainly feasible. This study demonstrated also that the geomembranes manufactured specially for dam applications have a lifetime on average of 50 years when exposed and more than 150 years when completely submerged.

A proposition to solve the degradation problem can be to protect the geomembrane in the most critical area: exposed and on the oscillation water area; it means, from the crest down to the minimum water level of the reservoir, using a sacrifice geomembrane in this zone, welded to the underlying one, replacing it when necessary.

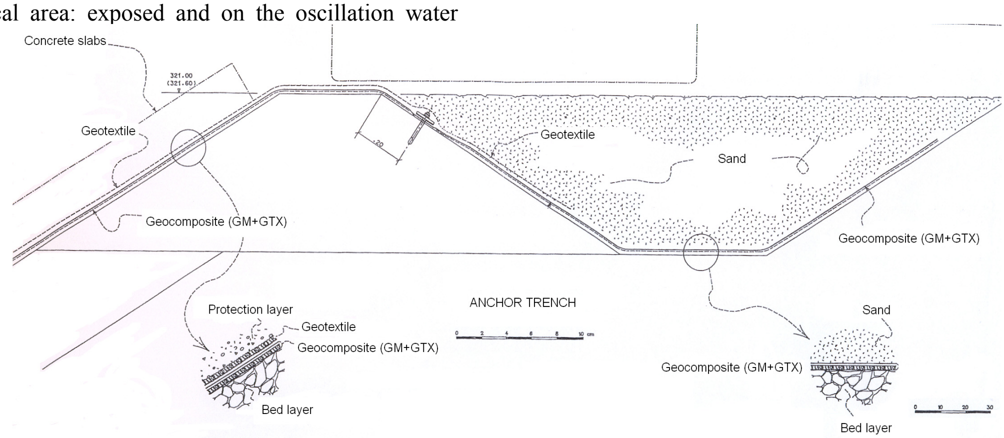

Figure 1 – Crest anchorage detail of Bovilla Dam (courtesy by Sembenelli, 1995)

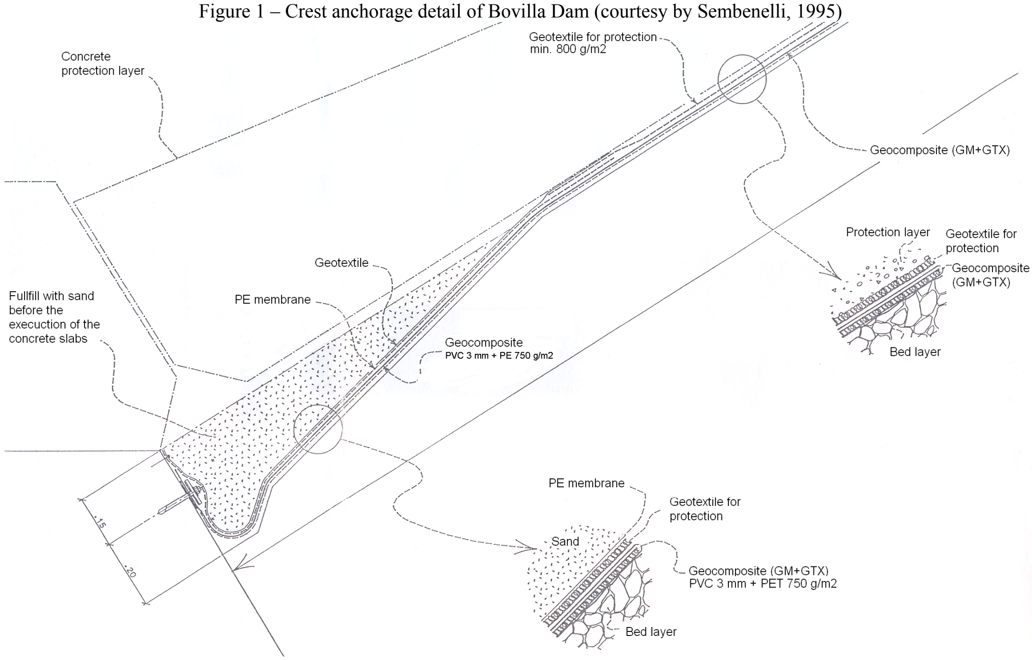

Figure 2 – Toe plinth anchorage at Bovilla Dam (courtesy by Sembenelli, 1995)

4.2.5 Geomembrane sampling program

The proposed monitoring program aims mainly to evaluate the conditions (physical and chemical aspects) of the geomembrane during the lifetime estimated for the structure.

The most critical situation is the option of an exposed geomembrane, submitted to the ultraviolet rays action, heat and to water (or other fluid type) contact. In this case, it is indispensable geomembrane sampling above the operation water level and in the oscillation water zone. The proposal is to perform samples exhumation in a smaller time interval during the first years (i.e., every 2 years in the first 10 years) to verify if there is a tendency of geomembrane properties changes. After these 10 initial years, the sampling could be made at each four years. Based on the study carried out by Colmanetti (2006) on exhumed geomembrane samples obtained from Italian dams, there is no need to extract samples in the submerged zone. However, if the liner system does not have a leak detection device, visually periodic inspections are recommended in order to verify the geomembrane conditions below the water level.

Colmanetti (2006) suggests the construction of "sampling pillars", built inside of the reservoir area and placed at the proximities of the face in which geomembrane samples are fastened for future exhumation. This would avoid the extraction of samples from the geomembrane installed on the face. It is also recommended to collect and to keep virgin geomembrane samples from different rolls during the installation phase, since it is important to determine the properties of the intact geomembrane for future comparisons with the aged ones.

5 CONCLUSIONS

A large bibliographic review, meetings with designers, manufacturers and geomembrane installers' and results from laboratory tests carried out on intact and samples exhumed from dams (Colmanetti, 2006) made possible to present some recommendations seeking to contribute to future projects of Rockfill Dams incorporating geomembranes (GFRD).

Besides the technical aspects already discussed other two deserve some attention to the good performance of the dam: the control of flow and deformation. Regarding flow control through the face, the installation of a downstream collector channel next to the perimeter joint of the dam is recommended to capture leakage through the geomembrane. The flow should be conducted to a traverse central channel, at a higher section of the dam, so that the water can be captured and the flow rate measure by appropriate devices. There are also leak detection methods based on electric conductivity principles (Sensor System) or transmissions by optical fiber cables to verify the integrity of the geomembrane liner (Colmanetti, 2006).

Furthermore, another important requirement is that concerning deformations of the materials of the dam. Since the geomembrane withstand quite high values of deformation, the usual techniques to measure deformations can not be applied. Therefore, future researches should address the development of new technologies to monitor geomembrane strains to contribute to a better understanding of GFRD behavior.

ACKNOWLEDGEMENT

The authors would like to thank the University of Brasília, CAPES/Brazilian Ministry of Education, CESI Milano and SC Sembenelli Consulting SrL for the support for the work described in this paper.

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