Underwater installation of a waterproofing geomembrane at Lost Creek arch dam

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ABSTRACT: The use of geomembranes and geocomposites as repair measure to restore watertightness at the upstream face of ageing dams is an established technique. To install these revetments, total dewatering of the reservoir was required until the mid 1990ies. Following the most recent development in design and installation techniques of geosynthetics, a system that can be installed totally underwater is now available. The system, conceived and developed in Europe, was tested and approved by the US Army Corps of Engineers Waterways Experiment Station. In 1997 the system was selected for underwater installation on Lost Creek arch dam in northern California. The Lost Creek dam project was the first underwater installation in the world of a synthetic geomembrane as impermeable revetment on the entire upstream face of a dam. The paper reports on development of design, on analysis of available alternatives, including life cycle cost, and on final design and installation of the system.

1 INTRODUCTION

1.1 *Ageing of dams*

Dams age due to the aggression of environment (freeze-thaw cycles, wetting and dehydrating cycles, temperature differentials etc), and to a range of phenomena that may occur during service (differential movements, settlements, chemical reactions in concrete, seismic events etc). Ageing results in deterioration of the upstream facing, leading to formation of cracks, increased permeability, possible deterioration of joints and clogging of drains. Infiltration of uncontrolled water in the dam may result in decreased safety, and even when safety is not at sake, the appearance of seepage at the downstream face can arise concern in the population affected by the dam.

1.2 *Synthetic geomembranes as repair method*

Synthetic impervious geomembranes are a remedial measure to restore impermeability in ageing dams, that has been increasingly adopted due to good performance of pioneer installations in the late 1950ies and early 1960ies. In these applications, the impervious geomembrane is generally installed as a new liner on the upstream face of the dam. The main elements that have fostered the use of synthetic geomembranes in hydraulic applications are the following

- a synthetic geomembrane has very low permeability as compared to traditional materials
- a synthetic geomembrane, being much thinner and easier to install than traditional materials, minimises costs related to transport, site mobilisation, installation
- a synthetic geomembrane provides uninterrupted watertightness, obtained with the same material, over the entire lined area. This avoids the need of waterproofing the joints with a different material subject to a different ageing process (no waterstops that deteriorate over time)
- a synthetic geomembrane provides durable watertightness
- a synthetic geomembrane system is practically maintenance-free, and very cost effective.

Among the various geomembranes used since pioneer projects, the best current practice favours the use of polyvinylchloride (PVC) geomembranes. According to the findings of the ICOLD – International Commission on Large Dams - European Working Group for Geomembranes and Geosynthetics as Facing Materials, who are now preparing the new revised edition of the Bulletin on watertight geomembranes, PVC has been used for the vast majority of the dam lining projects all over the world (Scuero, Vaschetti 1998).

1.3 *The need for an underwater system*

Until a few years ago, synthetic geomembrane systems could be installed only in the dry. Therefore, in the event that the reservoir could not be completely dewatered, due to structural or operational characteristics, or because dewatering implied serious economic, social and environmental consequences, it was not possible to exploit the benefits associated with the use of a geomembrane system.

Consequently, in all cases in which the reservoir could not be dewatered, repair had to be accomplished either internally or downstream, with traditional and more expensive methods. Alternatives were internal grouting with chemicals or microfine cements, internal drainage by drilling from the crest, or construction of a new downstream facing/buttress. These solutions were not always reliable and durable, and/or very expensive and with high environmental impact.

Hence, the development of new waterproofing methods that could be accomplished without completely dewatering the reservoir was of significant interest to dam owners.

2 DEVELOPING DESIGN AND PROCEDURES FOR UNDERWATER INSTALLATION

CARPI, the company who had conceived the state of the art, drained PVC geomembrane system that had already proven its reliability in dry installations since the early 1970ies, was performing research to develop an underwater system. In 1994 the US Army Corps of Engineers Waterways Experiment Station, to ascertain the possibility of adapting that system to underwater installation, awarded a two-phase research contract to CARPI and to Oceaneering, one of the largest and most experienced underwater services companies in the world.

2.1 *First phase: testing*

The first phase of the study focused on testing of materials, of components of the system, and of installation procedures. Testing included large scale testing on 8 geomembranes selected as the most promising ones:

- PVC
- PVC with backing reinforcement (PVC-R)
- ChloroSulphonatedPolyEthylene with scrim reinforcement (CSPE-S)
- CSPE with backing reinforcement (CSPE-R)
- PolyPropylene (PP)
- PP with backing reinforcement (PP-R)
- EthylenePropyleneDieneMonomer (EPDM)
- HighDensityPolyEthylene (HDPE).

The investigates properties were impermeability, tensile behaviour, tear and puncture resistance, specific gravity, seamability and dimensional stability. Evaluation included the overall constructibility, the references of previous applications, the durability, availability, repairability and costs.

The result of the evaluation was that PVC-R was the highest ranking material, followed, in order of decreasing suitability, by PVC, CSPE-S, EPDM, CSPE-R, PP-R, PP and finally HDPE (Christensen et al. 1995).

The first phase of the research produced a conceptual design of a tentative geomembrane system for underwater installation.

2.2 *Second phase: underwater constructibility demonstration*

In the second phase of the project, the solution developed in the first phase was further refined to produce a geomembrane system to be tested for underwater constructibility. A reinforced concrete structure was built for this purpose, and the constructibility and efficiency of the designed system was verified by its complete underwater installation on the test structure. Underwater installation was successfully performed under the supervision of the US Army Corps of Engineers (Christensen et al. 1996).

Figure 1. The “L” shaped, reinforced concrete wall constructed for the second phase of the research for the US Army Corps of Engineers. The wall incorporates rough and smooth parts, fissures, joints, corners, protrusions and depressions, to replicate as much as possible all features to be encountered in an underwater installation. Approximate dimensions of the longer side of the wall are 4.8 m x 3 m height, of the shorter side 1.5 m x 3 m height

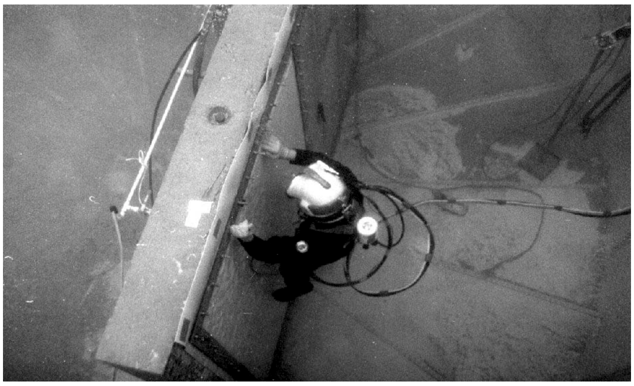

Figure 2. The wall was lowered in a tank, at a depth of 6 m, and the designed system was installed underwater. After underwater installation, a suction corresponding to 8.4 m of hydrostatic head was applied to the back of the liner. The geocomposite liner conformed to the subgrade, and no leaks were detected, demonstrating that an effective seal had been achieved. The Army Corps project demonstrated the feasibility of underwater installation, and allowed to refine design of the various components of the system, and of underwater installation procedures.

3 APPLICATION OF THE NEW UNDERWATER TECHNIQUE TO REDUCE REHABILITATION COSTS: THE LOST CREEK DAM PROJECT

In 1997, the system approved in the research period had its first application in the field.

3.1 *The situation*

Lost Creek dam is a concrete arch dam, 36 meters high, with a crest length of 134 meters, situated at an elevation of approximately 970 meters a.s.l. in the mountains of Northern California. The dam, completed in1924, forms a 6,969,213 m^3 storage and diversion reservoir of the Oroville-Wyandotte Irrigation District (OWID) Project on the South Fork of the Feather River and its tributaries.

The construction techniques, design and materials used at Lost Creek produced a concrete somewhat porous, through which water seeps in along the entire upstream face (not just along lift joints and cracks). In a thin arch dam subject to freeze-thaw as Lost Creek, infiltration water has a shorter path to reach the downstream face, seeping water freezes on the downstream face and, because of the expansion, spalling occurs. At Lost Creek, deterioration of the concrete on the downstream face was already noted before the 1960's, and proceeded so that in 1985 a thickness of 30 cm of concrete had been lost in the most severe areas.

Loss of concrete due to spalling can be of more concern in thin arch dams than in gravity dams. From 1985 through 1994, investigations were carried out to verify the conditions and strength of the concrete, and the stability of the dam. The investigations showed that the dam, though structurally adequate under all static operating and seismic conditions, had a small margin of safety for seismic conditions. As further deterioration could render the dam only marginally safe, methods to stop it were investigated.

3.2 *Selection of the rehabilitation method*

The impact that a rehabilitation project can have on the operation of the dam, and on the environment, is nowadays a particular concern for owners and communities involved in the exploitation of a dam. At Lost Creek, the need to maintain a fish flow downstream gave priority to rehabilitation methods that would allow the reservoir to be partially full during the construction/installation of the selected system.

All available repair methods were investigated. Due to the restrictions in lowering of the reservoir, only 3 methods were deemed worth of further investigation:

- Alternative 1 - Downstream drainage system covered with shotcrete: a layer of geodrain material would be placed on the downstream face and covered with three inches of reinforced shotcrete. This alternative could be accomplished without dewatering but, based on previous experience in cold climates, the shotcrete would be susceptible to freeze-thaw deterioration, resulting in short expected life of this alternative solution.
- Alternative 2 - Upstream synthetic geomembrane mechanically anchored to the dam: among several geomembrane systems evaluated, the most promising was the same for which underwater feasibility had been proven during the Army Corps project. All work could be done from platforms suspended from the crest of the dam, and from barges in the reservoir.
- Alternative 3 - Downstream roller compacted concrete (RCC) buttress: on the downstream side, an RCC dam would be constructed, with a drainage system between the existing dam and the RCC, to intercept the seepage. Although not requiring dewatering, this alternative would have high environmental impact caused by quarrying, hauling traffic, construction, and some additional concrete deterioration would still occur.

The life cycle cost analysis of the three alternatives provided the results reported in Table 2.

Table 2. Comparison of costs of the selected alternatives

Alt.	Price	Life	Amortisation (yearly, at 4%)	Environmental impact
1	$ 2,083,000	20 years	$ 153,271	Low
2	$ 2,053,000	50+ years	$ 95,568	Low
3	$ 4,569,000	50+ years	$ 212,688	High

The three methods described had differing benefits and therefore could not be directly compared based on cost alone. The Owner and their consultants concluded that Alternative 2, the upstream geomembrane system, offered the greatest benefits with respect to cost, and involved the least environmental impact.

Detailed design and installation plan of the selected alternative was developed by the same team that had accomplished the Army Corps research project, and was approved by the Federal Energy Regulatory Commission (FERC) and by the California Division of Safety of Dams (CDSD). The timing of the geomembrane installation was planned to coincide with the rewinding of the generator at the Woodleaf Powerhouse. This allowed significant drawdown of the reservoir without loss in power generation, resulting in reduction of dive depths, allowing longer time underwater per dive.

3.3 *The selected PVC geocomposite system*

The selected system consists of a PolyVinylChloride (PVC) flexible composite membrane (geocomposite SIBELON CNT 3750), lining the entire upstream face of the dam. The geocomposite is composed by a 2.5 mm thick PVC geomembrane providing impermeability, and by a 500 g/m^2 nonwoven geotextile for puncture protection, dimensional stability and drainage.

The system is a drained system, to intercept and discharge immediately and continuously water seeping from foundation, rain and snowmelt from the crest, and condensation water migrating from the colder dam body towards the warmer upstream face. The geocomposite is installed over a drainage geonet, to facilitate the flow of drained water to bottom collection. Bottom collection is made by an additional band of drainage geonet. Discharge is made through a pipe drilled to the downstream face of the dam at lowest elevation of the lined area. To enhance water transmission, the drainage layer is ventilated at 3 different points at crest.

The geocomposite is secured to the dam face by vertical stainless steel assemblies. In the part where installation was performed in the dry, the two profiles constituting the assembly are of the same type described by the International Commission on Large Dams Bulletin 78 on the state of the art of waterproofing geomembranes for dams (Corda et al. 1991). In the underwater part, the two profiles were adapted so that installation and joining of geocomposite panels could be executed mechanically, with no need for heat-welding.

The efficiency of the system is monitored by a water level indicator, positioned inside the vertical profile assembly left of the bottom outlet. The measurement of drained water flow, associated to the measurement of water standing behind the geocomposite if any, allow to ascertain if the geocomposite liner, and its associated drainage system, are performing correctly.

3.4 *Time frame and sequence of construction*

Construction was accomplished from suspended platforms anchored on the crest of the dam, and underwater from barges on the reservoir. Removal of silt and debris was followed by inspection of the surface. Surface preparation consisted of removal of loose concrete and local repair of cavities, performed with patches of geotextile or scrap geonet, or with concrete or quickset cement or grout above water, and with epoxy mortar underwater. Figures 3 to 13 document construction.

Figure 3. The drainage layer consists of a geonet with cross-diagonal grid pattern, anchored to the dam face by impact anchors. 3 ventilation holes at crest enhance water flow to bottom collection. Along the bottom perimeter of the lined area, an additional layer of geonet facilitates conveyance of water towards the bottom discharge system.

Figure 4. The bottom discharge consists of a transverse pipe inserted into a hole drilled through the dam body.

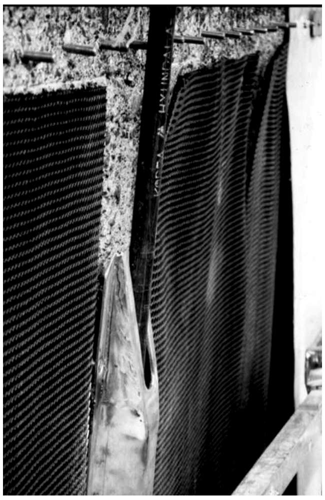

Figure 5. To monitor the efficiency of the system, a water level indicator is installed in one of the vertical profiles assemblies.

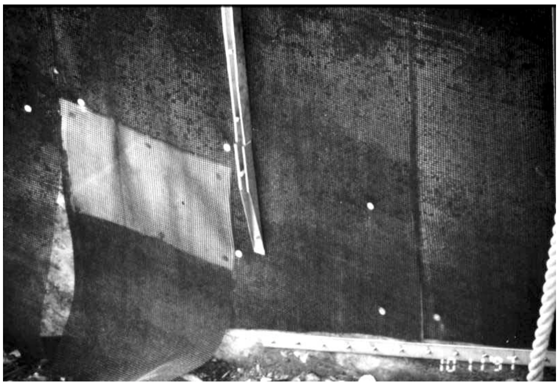

Figure 6. The geocomposite liner is mechanically anchored to the dam face along vertical lines, and along the perimeter. Perimeter anchorage is resistant to water in pressure at bottom and spillway, to rain and snowmelt at crest. To optimise installation underwater, standard 2.05 meters wide PVC geocomposite sheets were assembled to prefabricate wider panels. This allowed increasing standard interaxis between vertical anchorage assemblies from 1.80 meters to approximately 7.8 meters, reducing the amount of hardware and of underwater work necessary to secure the membrane on the dam face. Pictured are one of the vertical anchorage profiles and the batten strip that is part of the bottom seal. All anchorage lines are made with stainless steel.

Figure 7. The dry vertical anchorage assembly (patented system illustrated in ICOLD Bulletin 78 on waterproofing geomembranes) consists of one “internal” profile, which is positioned on top of the drainage geonet, and of one “external” profile, which is placed over the geocomposite. The connection between the two profiles secures the geocomposite to the dam face, and tensions it to assure that no slack or folds form.

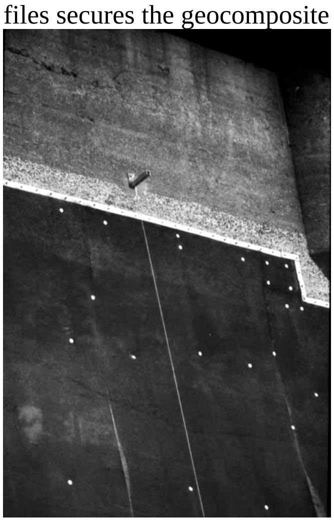

Figure 8. At top, the batten strip for perimeter anchorage at crest. The vertical line is one of the guide wires that were installed to assure proper alignment of the geocomposite panels, especially underwater, where turbidity limited visibility from nil to less than 1 m.

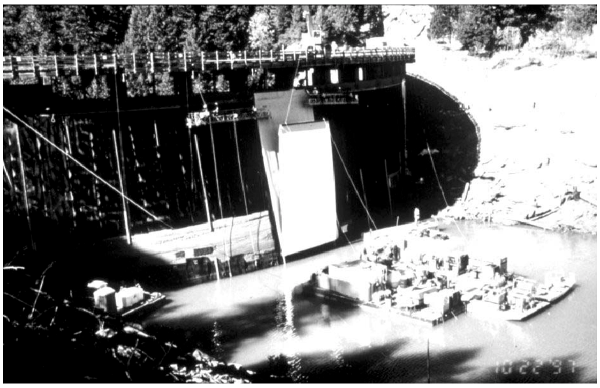

Figure 9. The geocomposite was prefabricated in 8 m wide panels, to optimise construction schedule while accommodating the need of underwater work. The panels were lowered from the dam crest into the water, to cover the entire face with no transverse junctions. Adjoining panels overlapped at the vertical anchorage profiles. In the dry, overlapping panels were heat-welded. Seventeen panels were necessary to cover the 2800 m^2 face of the dam.

Figure 10. Underwater, the joining of adjacent panels was made by the vertical anchorage assemblies, which have a special design conceived for underwater installation.

4 BENEFITS OF THE PROJECT

4.1 *Technical*

Seepage control: the monitored flow, after some initial fluctuations due to higher initial dehydration of dam body, has stabilised to less than 0,0631 l/s with reservoir at spillway level. The readings of water level indicator show that there is no water standing behind the geocomposite in the drainage system.

Concrete deterioration: the elimination of water passing through the dam has dried the downstream face eliminating the ascertained cause of deterioration. OWID will continue monitoring on a constant basis.

Longevity: the system installed at Lost Creek has now a proven successful record on more than 40 dams and a great number of other hydraulic structures, with installations exceeding 20 years. From testing performed on samples of the same geocomposite in service on 6 existing projects in cold climates at high altitude (Cazzuffi 1998), interpolation indicates that the PVC geocomposite will exceed 50 years. The system has been recognised as the most reliable rehabilitation method for concrete dams in cold climates (Durand et al. 1995).

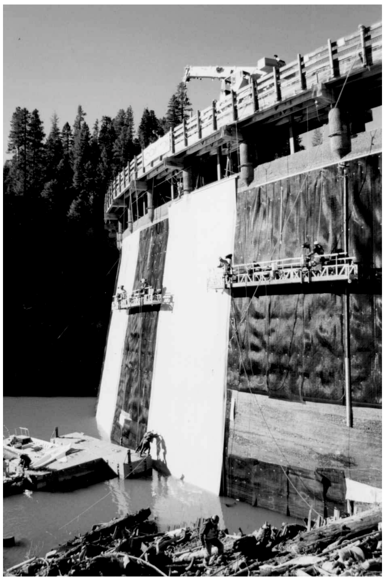

Figure 11. Dry and underwater installation proceeded at separate locations for security reasons. As workers install the geonet in the dry, from suspended platforms, the divers are securing the panels at bottom.

Figure 12. The vertical profile assemblies are all watertight. In the dry, to avoid that water seeps along the threads of the set screw/hex coupler assembly coupling the profiles, PVC cover strips are welded over the profiles. Underwater, the external profiles are connected to the internal ones by a watertight connection obtained by compression. At spillway, the upper seal is executed below the bottom of the concrete piers supporting the bridge deck.

4.2 *Cost effectiveness*

Adopting a new technique of underwater installation of a prefabricated geocomposite allowed a saving of approximately 37% on yearly amortisation of costs as compared with the next cheapest alternative considered (downstream drainage system), and 55% as compared with the RCC alternative. OWID saved more than US $ 2.8 million over the minimum life-cycle years of operations by selecting the geocomposite solution.

4.3 *Environmental impact and aesthetic value*

Installation of the geocomposite was accomplished without alteration upstream, nor impacts on downstream life. The geocomposite liner at Lost Creek will remain underwater for almost 90% of the time. When the geocomposite will be exposed during partial drawdown, its grey colour very similar to concrete will give the dam a natural appearance.

4.4 *Maintenance*

The upstream geocomposite system has not required any maintenance on any of the 40+ installations completed so far with the same system. Should repairs be necessary, both partial or total repairs can be accomplished quickly and easily, without need to dewater, as they require simple mechanical operations and do not involve civil works.

4.5 *Validation*

The Lost Creek project has been granted the following awards:

- 1998 West Region Award of Merit from the Association of State Dam Safety Officials (ASDSO)
- 1999 Hydro Achievement Award for Technology Solutions from the National Hydropower Association
- Federal Laboratory Consortium Award of Merit from the U.S. Army Corps of Engineers.

Figure 13. The installation was completed in Autumn 1997, in less than 3 months for a total lined area of 2800 m^2. The whole project was completed safely, without a single reportable or Lost Time Accident. Up to date, total documented seepage is less than 0.063 l/s, and there is no water standing behind the membrane.

5 CONCLUSIONS

The Lost Creek project itself is a validation of the suitability of the developed system for underwater installation. This installation represents a milestone in the history of application of geomembranes to the waterproofing of hydraulic structures. Underwater installation is now feasible and can provide substantial benefits to dam owners.

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