Underwater repair of a 113 m high CFRD with a PVC geomembrane: Turimiquire

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SYNOPSIS. The paper discusses repair of Concrete Faced Rockfill Dams (CFRDs) with geomembranes, with emphasis on a project where a geomembrane system is being installed underwater in 2010, at Turimiquire, a 113m high CFRD in Venezuela, designed by Barry Cooke. An exposed polyvinylchloride (PVC) geomembrane is being installed to restore imperviousness to the deteriorated facing where leakage has reached 9,800 l/s. The 2010 project will cover the area requiring immediate repair, and it is expected that the remaining parts of the upstream face will be lined in subsequent projects.

INTRODUCTION

Since the end of the 1950s synthetic prefabricated geomembranes have been adopted to provide imperviousness to fill dams. They have either been incorporated in the dam at the design phase, or have been used as a repair measure to restore imperviousness when the original water barrier, be it concrete or bituminous concrete, has failed.

The advantages that geomembrane systems can provide when compared to traditional waterproofing systems in the construction of new fill dams have been already discussed in previous BDS conferences (Scuero & Vaschetti 2004 and 2008). The same beneficial characteristics of these systems apply also when the geomembrane is used for a repair, and in particular for the focus of this paper, the repair of Concrete Faced Rockfill Dams.

GEOMEMBRANES IN REPAIR OF CFRDS

CFRDs require repair because their performance is often not as expected. Common problems are the deterioration of the face slabs and/or the deterioration of the waterstops. Deterioration can be caused by climatic factors (e.g. freeze-thaw effects on the concrete), by poor construction procedures (e.g. inadequate sluicing/compaction, defects in placement and embedment of waterstops), or by actions exceeding the resistance of the concrete slabs (e.g. settlement of the foundations, settlement of the dam body, seismic events). As a result, water enters through the damaged facing causing leakage that may sometimes reach unacceptable rates.

Traditional methods to reduce leakage such as plugging the cracks/voids with clay material or filling material, or grouting them, are generally not very effective and do not provide acceptable long term performance. Additionally, when the reservoir cannot be dewatered placement of the repair material may become impossible or extremely difficult, and the effectiveness further decreases.

On the other hand, the use of a synthetic geomembrane, and in particular of a polyvinylchloride (PVC) geomembrane, allows an effective long term repair to be achieved, as demonstrated by the numerous successful rehabilitation applications of concrete dams of all types. These applications include not only the rehabilitation of the entire upstream face, but also of those critical portions where most of the leakage was occurring, and in the form of external waterstops to waterproof large fissures or failing joints.

An additional advantage of an exposed PVC geomembrane system is that it can be installed underwater. Some aspects of underwater installation have also already been illustrated in a previous a BDS conference (Scuero & et al. 2000).

The critical issues in both dry and underwater repairs of CFRDs with synthetic geomembranes are

- The selection of the material, which must have suitable properties and a track record of providing good weathering and long-lasting imperviousness
- The development of an appropriate design with particular regard to those details of the anchorage system that are crucial for resistance to settlement and differential movements
- The selection of installation crews having specific experience and good craftsmanship.

UNDERWATER REPAIR OF TURIMIQUIRE CFRD

The dam

Las Canalitas, better known as Turimiquire, is a 113m high CFRD located in Venezuela. Owned by Ministerio del Poder Popular para el Ambiente of Venezuela, it is used for potable water supply. Barry Cooke was the designer; construction was made from 1976 to 1980.

The original design of the dam envisaged materials of four different gradings for the fill. The construction phase had several setbacks resulting in interruption of the works, delays, and modifications of parts of the original design. Eventually, the dam was constructed with quarry random fill, placed in 2m high lifts and compacted with vibratory roller. A 5m thick Zone 1, with grading 6.5mm to 180mm, was retained at the upstream side, placed in 0.5m high lifts and compacted with vibratory roller. The backfill with clay that was proposed at the upstream toe in the original design was discarded.

The upstream face of the dam, whose inclination is 1V:1.4H, is formed by 33 reinforced concrete slabs that are mostly 15m wide and 12.15m high, and whose thickness varies from 0.30m at crest to 1.00m at bottom. The construction joints are crossed by the reinforcement and have been designed with an embedded waterstop.

The dam has a spillway at the right abutment, a 111m high intake tower with six gated intakes, and a bottom outlet. Crest elevation is about 335m and the spillway elevation 328.8m. On the crest of the dam there are 30 measurement points for vertical settlement. Measurements were made in 1978, in 1987, twice in 1988, in 1990 and in 1994.

<u>The behaviour of the dam after impounding</u>

The dam commenced impounding in 1988. As reported by Suarez (2002), in July 1989 leakage reached 300 l/s which required lowering the water level and a repair by placing clay material, which reduced leakage to 60 l/s. However, leakage started increasing again and in 1994, when it had reached 2500 l/s, a second repair was carried out. The second repair was carried out after filming and a sonar study, and consisted of filling with material of two different sizes (3mm gravel and 0.4mm sand), in total 154.75m^3 of materials. According to some sources this repair was implemented with an impervious geomembrane covering the fissured zone (there is no definite evidence of it). As it had happened with the first repair, leakage initially decreased to 674 l/s but then started increasing again until in the second half of 1996 it reached 3,173 l/s.

In September 1996 a “natural repair” was carried out by a landslide that occurred at the left abutment and by covering part of the dam reduced leakage to 1,255 l/s. However, this “natural repair” also lost its efficiency over time. In September 1999 high leakage of up to 6,500 l/s was experienced. A fourth repair was made, by filling with material of four different sizes (304m^3 of 25mm gravel; 260m^3 of rough sand; 110m^3 of rough and fine sand; and 224m^3 of clay silt - in total 898m^3).

Between March and April 2000 a video inspection showed the problematic areas at the left abutment, and a fifth repair was carried out over an area of 450m², consisting of filling with granular material plus an impervious geomembrane; type XR5 by the Seaman Corporation. The geomembrane was placed on the left part of the dam, fixed at the top (elevation about 310m) and at the two sides with flat batten strips, and at the bottom with ballasting weights. The result of the geomembrane installation were very poor: due to the inadequacy of the anchorage system the geomembrane allowed an open path for water infiltration, became partially detached from the support, and was damaged.

In 2007 an analysis carried out within the Conservation Plan of the Cuenca Alta of Neverí River, of which Turimiquire is part, using non-toxic coloured markers, which concluded that there were three possible main areas of water infiltration, due either to cracks or to deteriorated concrete. The monitoring of the behaviour of the dam by the measurement system noted that settlement could be attributed to various causes, such as the geology of the site; the resistance of structural parts; the grading of the fill; the vibration and placement of the concrete, etc. Analysis of the leakage, occurring at about 15 m above the downstream pool and concentrated at both abutments, defined a phreatic level at about 8m above the downstream pool.

In September 2007, leakage reached 9,800 l/s, and even after lowering the water level it remained at about 7,800 l/s.

Further study was carried out by the Dirección de Estudyos y Proyectos – MARN (Direction for Studies and Projects of the Ministry), who commissioned a new sonar and video inspection by Corporacción ATM, who had already carried out investigations in 2007. Investigations by ATM were made first at separate points with a hydrophone, and then with multi-beam sonar scanning on the critical areas between elevations 250m and 280m. Before the investigation, a quantity of foreign material (trees and sediments of various compositions) was removed. The investigation showed that the area of damage had increased, especially at the right abutment, and that the main leak was not, as previously assumed, at the plinth. There seemed to be two epicentres, a crater of 4.1m² at slab 24 and one at elevation 270m at slab 9.

Further investigations using a Remotely Operated Vehicle (ROV) with multi-beam sonar and a ROV with video showed a large zone with fissures and cracks without a definite orientation and up to 7m of length, a continuous accumulation of sediments between 260m and 280m (up to 6m at the toe), an influence of the settlements detected at the crest on the deep slabs. The concrete showed scales and loss of cementitious material in several places (honeycombs). The crater was plugged by tree logs that had penetrated the slab (video evidence). In addition to the erosion on the slabs at elevation 275m to 285m there was a permeable area below the geomembrane placed in 2000. The geomembrane had been locally displaced and formed large undulations and folds. Part of the perimeter anchorage had also been displaced. Foreign material found during the investigation included tree logs and sediments of different types with a solid spongy consistency.

Figures 1 and 2. Various sediments during underwater inspection

To ascertain the magnitude of the risk involved, MARN analysed and compared leakage to that of similar dams, with two different calculation criteria. A Memorandum issued in March 2008 suggested a phreatic level inside the fill of 40m to 55m above the toe of the dam. The Memorandum reported that the leakage occurring at that time seemed to be the highest recorded in a compacted rockfill dam, fully validating the decision to make urgent repairs to the main leakage paths, and in the future to make permanent repairs to the other damage. The Memorandum also gave recommendations on how best to carry out further investigations to find the exact locations of the leaks and the rate of water infiltration. On the other hand ATM, in an investigation report issued in April 2008, considered the phreatic level inside the fill, as assessed by the calculations, superior to that of any other structure in the world. The report identified the heavy consequences that emptying the reservoir to carry out repair works would have on the local population, and recommended underwater repairs.

Bathymetric measures carried out in summer 2008 to investigate the thickness of sediments and other materials could not fully ascertain the existing conditions along the entire perimeter of the dam, but suggested that on top of the plinth the sediment thickness should be in the range of 2m to 3m, while on the upstream toe it was likely to be >5 m, especially at the left abutment. A lower thickness was estimated at slabs 24/25 and 28/29 at the right abutment.

The inspections and the analysis provided unquestionable evidence of the deterioration of the concrete facing, and of the very poor outcome of all repair measures previously adopted. In May 2008 a preliminary decision was taken to install an impervious polyvinylchloride (PVC) geocomposite over the critical areas shown in Figure 3. The residual leakage estimated by the owner after installation of the geomembrane on the critical areas was around 3,000 l/s.

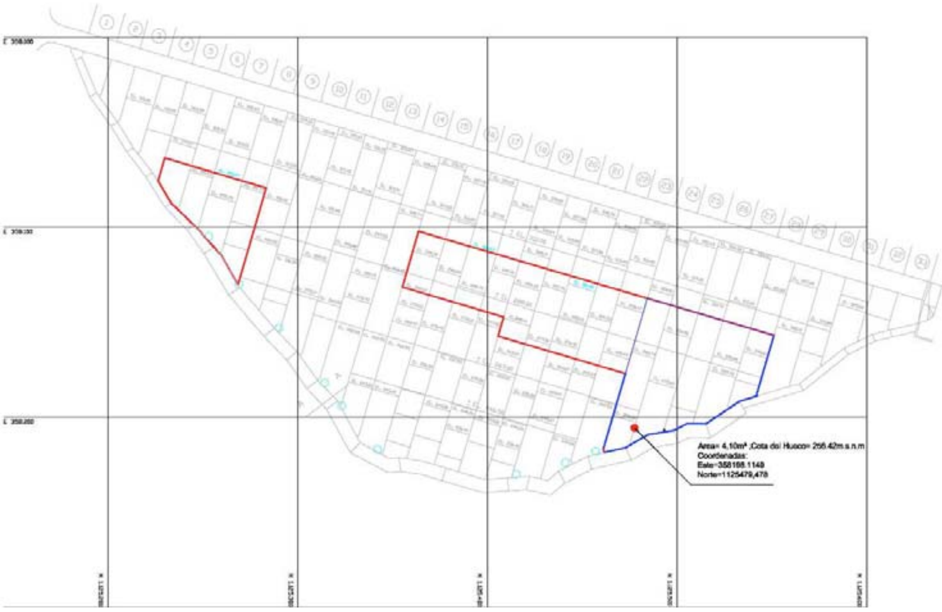


Figure 3. The critical areas to be waterproofed according to the preliminary decision

Since the reservoir is critical for water supply the water level cannot be lowered, but must remain high to meet the supply requirements, the owner decided to perform the works on the most critical area with the water level at 295m. Most of the repair work therefore had to be carried out underwater. A contract for the design of the waterproofing system was awarded in July 2008 to Carpi Tech based on the experience acquired by the company in both dry and underwater application of impervious geomembrane systems on dams (Scuero & Vaschetti 2006).

<u>Developing the final design</u>

The design choice, dictated by the owner and based on the idea of using the available budget to install the geomembrane over the easily accessible areas rather than to spend money on expensive sediment removal, has been to perform the waterproofing works in separate phases, according to the seriousness of the damage indicated in the reports of all investigations carried out up to date, and to the urgency of repair. As a result:

- Areas 1, 2, 3, 4, 5 and 6 (see Figure 4) are to be lined first, under the same contract, from elevation 304m down to elevation 245m. The total acceptable residual seepage is not to exceed 3,000 l/s.
- Areas 7 & 8, being less crucial, are to be lined in a subsequent phase, under a separate contract.

Installation will be carried out in the dry in areas 2, 4 and 6, by technicians working from travelling platforms suspended from the crest, and working underwater in areas 1, 3 and 5 by divers based on floating pontoons moored in the reservoir.

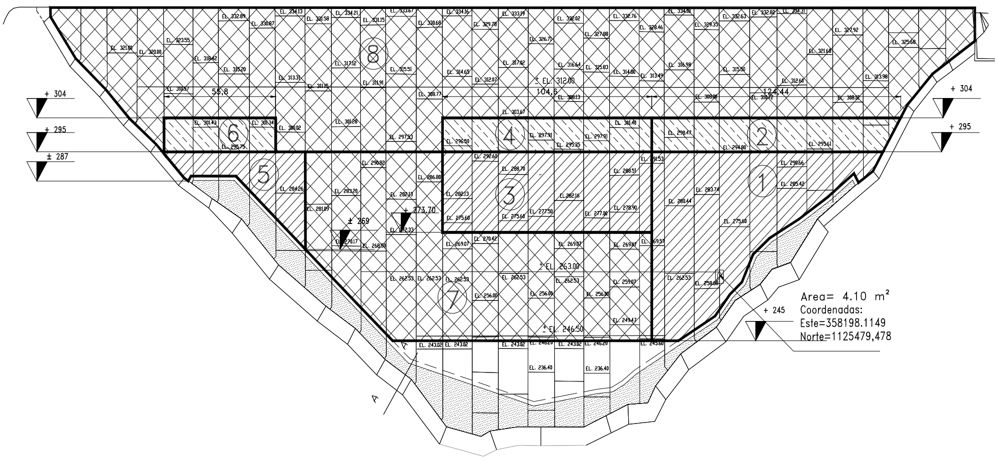


Figure 4. The areas to be waterproofed according to the preliminary design

Prior to the final design an underwater inspection was performed, with a multi-directional sonic probe and with multi-beam Sonar Konsberg 974. The survey showed that the thickness of the sediments varied with depth from a zero value a few metres below the normal water level to a maximum of 5m at some locations on the plinth, as shown in Figure 5 (the survey was in an orthogonal direction, with the real thickness derived trigonometrically).

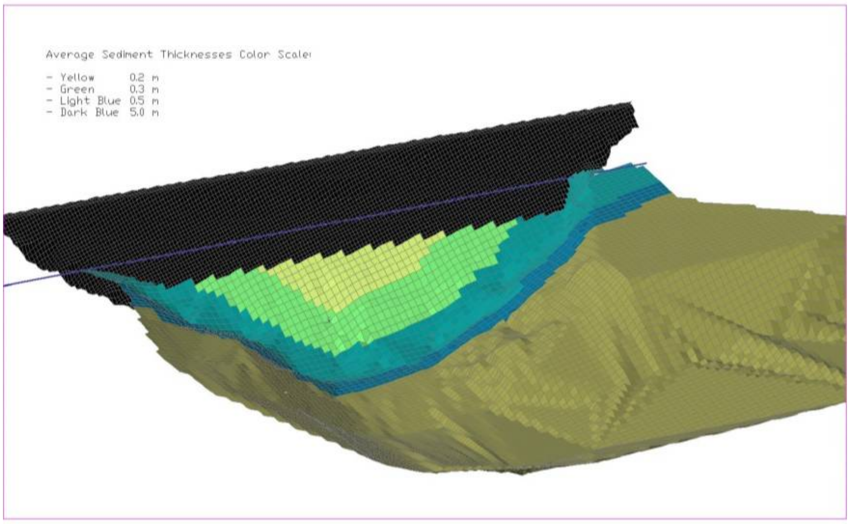


Figure 5. Distribution of sediments from the underwater survey

The sonar inspection was difficult due to a “background noise” that did not allow a totally accurate localisation of the patterns of water infiltration. Figure 6 shows the result of that inspection.

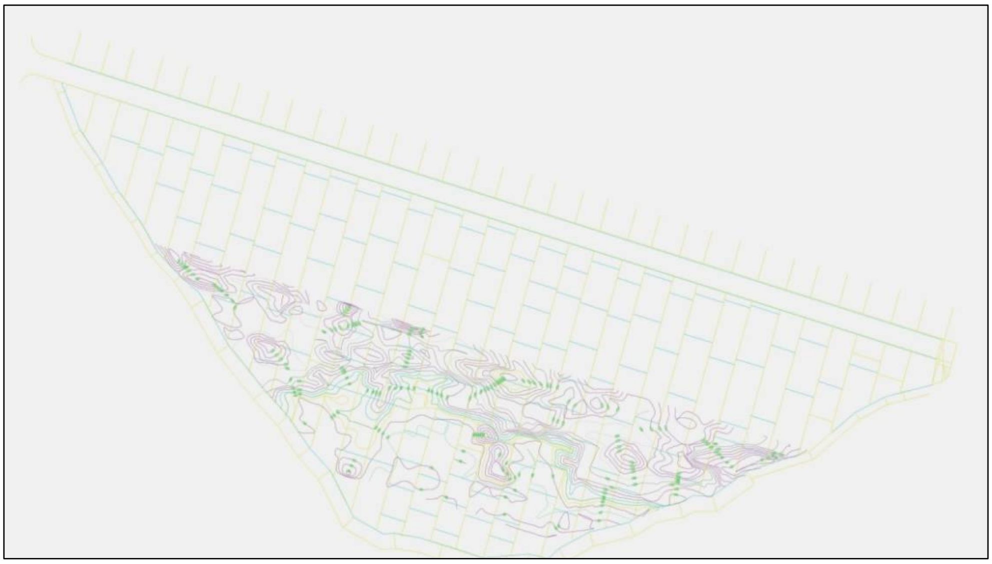


Figure 6. Leakage paths according to sonar inspection

In the preliminary design, the waterproofing system stopped along the line of the sediments, leaving the longitudinal joint between the face slabs and the plinth unlined. The longitudinal joint between the face slabs and the plinth is a critical zone where failures causing significant infiltration have occurred, due to the difficulties inherent to placement of waterstops. The final design envisaged a system that can in the future also allow lining of the critical longitudinal joint face slabs/plinth, in case the owner decides to remove the sediments. In areas 1 to 6 the PVC geocomposite will stop 2m from the line of the sediments. The 2m distance is based on the assumption that for the future removal of sediments drag-flow equipment is used that has an operational radius such that 2m is a safe distance that will avoid the geomembrane being is affected by suction due to the drag-flow equipment. Along the bottom perimeter of areas 1 to 6 an extra width of PVC geocomposite will be left beyond the perimeter seal; if in the future the owner decides to remove the sediments, this extra PVC geocomposite will be watertight welded to the PVC geocomposite that will be installed on the areas where sediments will be removed.

The same principle has been adopted along all the peripheries of areas 1 to 6: an extra width of PVC geocomposite will be left beyond the perimeter seals, to allow the connection of the waterproofing system of areas 1 to 6 to the waterproofing system of areas 7 and 8.

<u>The waterproofing system</u>

A design choice has been to have the same conceptual waterproofing system in the dry and in the underwater parts. The components of the system will be modified as required by the different working environments and operating conditions. Another design choice has been to minimize as much as possible surface preparation by extensive use of synthetic materials.

Surface preparation

The waterproofing liner has tensile properties that allow using and placing it under very demanding conditions, including rather rough subgrade, provided it is stable. Nevertheless, the deterioration of concrete slabs generally involves fissures and loss of cementitious material that may result in formation of large cavities, and in severe roughness of the surface. A support and anti-puncture system has been designed, to avoid the waterproofing liner collapsing inside the cavities/cracks, and to protect it against puncturing by excessive roughness of the subgrade.

The surface of the slabs, after removal of the sediments up to a thickness of 300mm and total removal of the geomembrane installed in 2000, will be cleaned by hydro-jetting. Then a two-layered geosynthetic system will be installed over the entire surface to be lined. This will comprise a support layer, comprising a geogrid with tensile characteristics to provide the required strength over the cavities, and an anti-puncture layer consisting of a 2000 g/m² polyester geotextile that will be installed on the entire surface on top of the geogrid. This configuration has already provided very successful performance in previous repairs, as shown in Figures 7 and 8.


Figures 7 and 8. Support geogrid and anti-puncture geotextile at Karagjol rockfill dam in Bulgaria

Two different geogrids are proposed for the face slabs; a standard one for the smaller cracks and a heavy duty one for the larger cracks and the cavities. In the zone of the crater, a stronger rigid support has been deemed necessary to guarantee that the divers can safely install the waterproofing system, and that the waterproofing liner is not sucked into the crater during operation. At this stage a strong steel structure equipped with fittings that will allow safe placement and operation has been foreseen.

The waterproofing liner

The waterproofing liner is SIBELON CNT 4600, a geocomposite consisting of a 3mm thick PVC geomembrane laminated during fabrication to a 700 g/m² nonwoven geotextile. The selection of such a robust geocomposite has been due to the high water head that it will sustain. The geocomposite has been manufactured under ISO 9001 certification and has been supplied in 2.10m wide sheets. For the underwater part, four sheets will be pre-welded at site to prefabricate 7.7m wide panels. Wide panels minimise expensive underwater operations.

Face anchorage

Face anchorage will have different configurations in the dry and underwater: in the dry, the patented Carpi tensioning system adopted requires welding a PVC geomembrane strip over the tensioning profiles to ensure watertightness. Since underwater welding is not feasible, the profiles will be modified to be intrinsically watertight, with a configuration like the one adopted at Lost Creek dam (Scuero et al., 2000).

The spacing between the vertical fastening lines will be different in the dry and underwater parts, due to the suction factor, which on inclined slopes (according to the calculation method used) is higher at the top and lower at the bottom of the slopes. The design has assumed that the face anchorage system in the lower areas (where the geomembrane will be installed underwater) will sustain no suction, being mostly covered by water, therefore the spacing between anchorage lines can be larger than in the dry section. This approach will also result in easier, quicker and more cost-effective installation of the system in the underwater section.

In the parts where the system will be installed underwater (zones 1, 3, and 5) the vertical anchorage lines will be at 7.4m spacing. The anchorage lines consist of a trapezoidal stainless steel profile fastened to the face of the dam with mechanical anchors, and by a flat stainless steel batten strip compressing the two adjacent and overlapping PVC geocomposite sheets on the trapezoidal profile, such as done at Lost Creek. Adequate gaskets will assure even compression all along the profiles, achieving a fastening line that is in itself watertight.

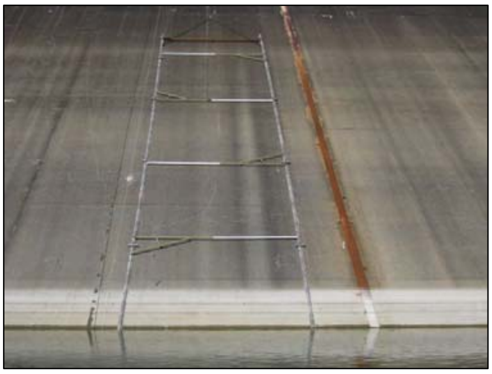
In the parts above water level (areas 2, 4, and 6) the vertical anchorage lines will be at 3.7m spacing. This spacing has been selected to ensure an easy and efficient transition between the dry and the underwater parts, which can be achieved either using the same spacing, or a sub-multiple of 7.4m. Based on the higher suction factor on the higher part of the slope, from the calculations, and on the higher possibility these areas will be exposed to wind, the 3.7m spacing has been deemed adequate. The anchorage lines consist of the tensioning system adopted in many projects worldwide and cited by ICOLD (ICOLD 2010).

Perimeter seals
The PVC geocomposite will be anchored at its peripheries by mechanical seals that will be watertight against water under pressure, and will involve compressing the geocomposite with 80mm x 8mm flat stainless steel batten strips. The perimeter seals installed in the dry will be bolted to the dam surface with chemical anchors at 150mm spacing. The perimeter seals installed underwater, due to the different requirements of the working environment, will be bolted to the dam surface with mechanical anchors at the same spacing. The selected configuration has had successful precedents in the field under a water head of 198m, and in the laboratory under a water head of 240m.

Schedule
The contract for installation was awarded to Carpi Tech in October 2008. Mobilisation of the equipment for the dry and underwater installations, and manufacturing and shipment of materials, were carried out from May to September 2009. Activities at site started in June 2009 and included construction of a camp and first aid post for 40 people, and improving the access roads.

Figures 9 and 10. At left equipment for removal of sediments, at right the structure for placing the waterproofing system, before assembling

The programme for the waterproofing works showed installation to be carried out first in the underwater part, and the divers' crew mobilized on November 1 2009. Divers started working in Zone 3, with water level at elevation 306m. Elevation 295m, originally established as the limit between dry and underwater installation, should be reached in June or July 2010. Divers will continue work as the water level varies depending on operational needs, and the extent of the underwater/dry installation will be adapted accordingly. By the end of 2009 work completed included cleaning the slabs, removal of sediments having a thickness of not greater than 300mm, and installation of 240m of vertical anchorage profiles.



Figures 11 and 12. The vertical anchorage profiles being lowered in to the water

CONCLUSIONS

Exposed PVC geomembrane systems have proven to be an effective long term measure to reduce leakage in CFRDs. They have also provided excellent behaviour when installed underwater. An equally successful result can reasonably be expected at Turimiquire CFRD.

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