Geomembranes mitigate environmental issues in tailings dams

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ABSTRACT

The increasing emphasis on environmental issues has crucial importance in mining projects, hence in tailings dams. Their water barrier needs a two-fold environmental assessment: the environmental impact caused by construction activities, and the environmental impact over time. Unfortunately, tailings dams' failures have great and long-lasting environmental consequences, and as mining sites become bigger and tailings dams higher, the risk of failures may increase. Furthermore, since these dams are mostly constructed over many years, design parameters/materials may change, the engineers may change, and since cost is a driving parameter, less attention may be given to quality control and monitoring. Geomembrane water barriers mitigate such impacts. Installation is performed with light equipment, with minimum impact on site organization and traffic and it can be tailored to follow the dam raising raise and not interfere with its construction, reducing construction times/constraints and minimizing costs. Their long-lasting watertightness provides higher safety in respect to stability and liquefaction and protects the groundwater and the downstream environment. Design, technical and economic advantages, and installation aspects will be discussed through the case history of the highest tailings dam in the world having a geomembrane as only water barrier, Las Bambas in Peru, now 173 m high.

1. Introduction

Tailings storage facilities are probably the largest man-made structures on earth. Different from water dams that are usually built to full height during one period of construction, tailings dams are constructed concurrent with operation of the dam, over a period sometimes lasting 20-30 years or even longer; some of the original design parameters may change during this period, requiring constant and frequent reviews, while possible less attention to Quality Control than in conventional dam construction may occur. Environmentally, at the end of operation, different from a water dam, a tailings dam will not be decommissioned, and shall store possibly toxic fluids and solids for up to hundreds of years.

While water dams are prestigious structures used to profitably store water for hydropower or water supply, and as such are considered an asset, tailings storage facilities store unwanted waste, and are seen as a cost (Roche, Thygesen &, Baker, 2017). Water dams are designed by specialist consultants, who supervise their construction, certify their correct completion and instrumentation, and supervise the first filling of the reservoir; in many countries these dams must be periodically supervised to check that they continue behaving satisfactorily. Modern tailings dams are often designed by competent consulting engineers, but because they are built over many years, and under conditions that may change with time, the supervision of their construction may become faulty.

Tailings dams pose much greater risks than water dams in terms of direct consequences and long-term environmental consequences. Direct impact on people, fauna, vegetation, habitats, human activities, infrastructures, heritage, is aggravated by higher environmental impact caused by the effluents, especially if they contain noxious/active remnant process chemicals: siltation of waterways, possible change in pH of water, chemical pollution of surface and groundwater, air pollution due to dust and gas, are the frequent additional outcomes of a tailings dam's failure. Environmental impact can continue over many years, affecting aquatic life, vegetation, groundwater, and the habitat in general. Public awareness of such impacts and risks has been increasing in the last decades; several bodies, agencies, and governments in several countries, are active to improve and spread knowledge, and to enforce regulations for increased safety of tailings storage facilities.

The most authoritative international body dealing with dams and with their safety is ICOLD, the International Commission on Large Dams. ICOLD has been active in issuing guidelines and recommendations for tailings dams since 1982. Ten theme bulletins have been published by ICOLD, addressing the various issues related to tailings dams: design, management, construction and operation, safety, monitoring, closure, and accidents and lessons learned. Recognizing the importance of environmental aspects and risks in tailings dams, the three bulletins published from 1996 onward (n. 106, 121 and 139) were prepared in cooperation and with input by UNEP, the United Nations Environment Program.

To control their own financial risk and reputation should a tailings dam fail, there is increasing pressure from finance houses for commitment to increased safety (ICOLD, 2011). Nevertheless, while water dams' failures are rare, major incidents in tailings dams continue, despite investments in improved practices. As the volume of waste from mines increases due to lower ore grades, with tailings dams becoming larger and higher, and as climate change brings about more intense and variable weather events, which can affect the water balance in the impoundment, tailings storage facilities face even more challenging scenarios.

Safety of a tailing storage facility largely depends on the safety of the tailings dam. Tailings dams can be constructed using mill tailings or mine waste, or earth or rock. Dams constructed with tailings have almost zero cohesion, are extremely sensitive to high levels of the phreatic surface, are highly susceptible to piping and surface erosion, and are susceptible to liquefaction during seismic events or change in loading. Seepage control is critical in these dams to maintain embankment stability in static and dynamic conditions. For tailings dams as well as for earthfill and rockfill dams, seepage control is critical also to decrease water losses, and to provide a barrier to the impounded tailings, thus maintaining water quality at the site. Overall, seepage control will increase the safety of the dam and decrease the risk of environmental pollution, especially in case of noxious effluents.

The most efficient way to control seepage is to provide an upstream water barrier to the dam. Since 1959 in water dams, and in more recent years in tailings dams, the use of synthetic thermoplastic geocomposites as watertight upstream facings is gaining increasing appreciation. Materials, design and installation techniques have developed in more than a half century, allowing constructing in stages large water dams and tailings dams.

The following chapter describes the design concepts of the upstream geomembrane sealing system for water and tailings dams that has been adopted in Las Bambas.

2. Las Bambas Tailings Dam

Las Bambas mine, located in the Andes of southern Peru, at elevation approaching 4000 m above sea level, is a joint venture project between MMG, a subsidiary of China's Guoxin International Investment, and CITIC Metal Co. Ltd. MMG owns 62.5% of the project and is in charge of operations at the mine, which spans the provinces of Cotabambas and Grau and is located 75 kilometers southwest of the city of Cusco. The open-pit quarry is one of the world's largest copper mines. For mine start-up purposes, the dam provided water storage for commissioning of the concentrator plant, and now it contains the tailings, bleed water released from the tailings, and water runoff from the catchment. Since there will always be water on top of the tailings, the dam had to be designed and constructed with the standards of a water retaining structure.

The dam is made with rock from mine quarrying, with no ore content, so it can be considered a reuse of waste rock. All materials are spread in layers and compacted.

The final design of the geomembrane system was made by ATC Williams. Based on the requirements for a high-water retaining dam, on the demanding environment conditions, on precedents, and on ICOLD experience, the design was modified, and the factor of safety improved as a consequence.

2.1. Geomembrane selection and watertightness

Especially in regions with high seismicity, the use of geomembranes can provide higher performance and safety, at competitive costs. The selection of the correct type of geomembrane however is crucial for performance. The requirements for a geomembrane system in embankment dams derive from the loads that it will have to sustain. The main loads exerted on the geomembrane are

- Those applied by the subgrade: puncture and burst over irregular subgrade under the water head, subsidence, displacements between deformable embankments and concrete structures
- Those applied by construction activities, generally in the category of puncture and burst
- Those applied by service conditions: environmental aggression, impact by floating debris, ice, boats etc., action of waves and wind, backpressure due to water table.

The characteristics required for a geomembrane to be installed in a tailings dam are therefore

- Low hydraulic conductivity (low osmotic permeability to water, i.e., watertightness)
- Good mechanical properties, tensile behavior in particular

- Endurance properties: UV resistance, oxidation resistance, thermal behavior
- Workability, welding (ease and reliability of welds), minimization of folds.

As far as watertightness is concerned, all modern synthetic geomembranes are essentially watertight. The permeability of the geomembranes used in the case histories presented by the paper is as low as 6.25·10-14 cm/s.

Appropriate tensile behavior is of essence. The flexibility and elongation capability of a polymeric geomembrane are illustrated by its tension-elongation curve. The tension-elongation curve allows determining the maximum tensile strength and corresponding maximum elongation (strain) of the material. In most typical situations in dams and reservoirs, maximum elongations induced in geomembranes are in the order of 50-60%. Geomembranes exhibiting a peak or plateau at elongations lower than 50-60% are prone to premature failure in case of local thickness reduction caused by a scratch (Giroud, 1984). Since it is well known that all geomembranes are scratched in the field during installation, and therefore local thickness reduction does occur, geomembranes should have a tensional behavior with tension increasing monotonically up to 50-60% elongation, while a peak or a plateau in the tension-elongation curve between zero and 50-60% elongation is unacceptable.

Figure 1 compares the tension-elongation curves of a 2.5 mm high density polyethylene (HDPE) geomembrane (in black) and of a geocomposite formed by a 2.5 mm geomembrane that is a special compound of polyvinylchloride (PVC) plasticized with high molecular weight branched plasticizers (in red). For the HDPE, the curve is limited to the range of admissible strains in the field, i.e., an allowable elongation up to the yield point in the HDPE, which occurs at about 12% elongation; beyond this point the behavior becomes plastic. The yield point is in fact a point of instability because once it is reached the geomembrane thins down locally and elongates like gum, presenting a plastic elongation under essentially constant tension up to the elongation at break value of 700%. Beyond the peak, the HDPE geomembrane ceases to function from a mechanical standpoint (Giroud, 1984). The presence of a yield point, even if the geomembrane has high elongation at failure, may be crucial in hydraulic applications. According to ICOLD, the International Commission on Large Dams (ICOLD, 2010), "*Mainly for HDPE, for a stress higher than the yield point, significant partially irreversible deformations (creep) occur after the stress has ceased.*" Therefore, HDPE geomembranes should be used only where the geomembrane elongation is well below the yield elongation, and with a substantial factor of safety. International literature (Seeger & Muller 1996, 2003, Peggs et al., 2005, and an article to be published by J. P. Giroud), indicate that to be on the safe side the allowable elongation of HDPE geomembranes should not exceed 3 to 5%, and that for elongations greater than 3% the "creep" phenomenon is important and cannot be neglected. In case of textured HDPE geomembranes, even lower percentages should possibly be considered.

On the contrary, PVC geocomposites have no yield. They are characterized by a monotonically increasing tension-elongation diagram that has two peaks: the first peak corresponds to the breaking of the backing geotextile and the second peak corresponds to the breaking of the geomembrane. Beyond the first peak, the material presents the characteristic behavior of the geomembrane until failure. Figure 1 shows the tension-elongation diagram of a geocomposite in its initial part up to break of the backing geotextile (first peak).

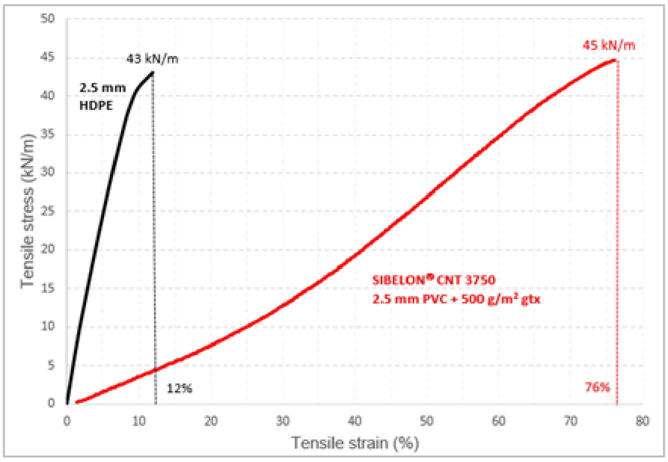

Figure 1. Tension-elongation curve of a 2.5 mm thick HDPE geomembrane (black) and of a PVC geocomposite (red).

It has sometimes been suggested to use low linear density polyethylene (LLDPE) geomembranes when large elongations are expected. However, the tension-elongation curve of LLDPE geomembranes is quite like the tension-elongation curve of HDPE geomembranes: it has a plateau that starts at about 30% strain rather than a peak at 15% strain for HDPE geomembranes. The co-energy concept (Giroud, 2005), which is a powerful tool to rank geomembranes according to their ability to withstand differential settlements, clearly demonstrates the lower factor of safety that is attained when using HDPE and LLDPE geomembranes.

HDPE geomembranes can be subject to stress cracking as a result of their own weight and of sliding on the slopes. Stress cracking has been responsible for numerous failures of installations with HDPE geomembranes. The cause of stress cracking is related to the dimensional stability and creep characteristic of HDPE, and to the recombination of the molecular chains under a constant stress due to the high crystallinity of the polymer. Workability and seamability are also crucial for good behavior. An HDPE geomembrane, having higher coefficient of thermal expansion and stiffness, will be more difficult to place flat, especially in areas with considerable temperature excursions. Higher folds will form: calculations show that the height of the folds in an HDPE geomembrane is about 4 times larger than those in a geocomposite. The folds in the HDPE geomembrane can make proper seaming more difficult and time consuming and amplify the stresses due to the dynamic action of water and wind suction. The failure of HDPE geomembranes frequently occurs near the seams, due to the weakening of the polymer by excessive temperature or pressure during the execution of the seam, or in case of elongation of the waterproofing liner by wind suction or thermal expansion, when the geomembrane near the seam has an abrupt flexing that generates an excess of tension and reduction of thickness.

Concerning durability, PVC geocomposites formulated for use in large hydraulic structures have been tested by independent laboratories and proven by successful field installations in challenging conditions. Tests conducted on specimens extracted from geomembranes installed more than 30 years ago (the oldest installation dates back to 1976) in the Italian, French, Swiss and Austrian Alps at altitudes above 2000 m a.s.l. show that the residual mechanical properties are still excellent, with little degradation. Summarizing, unless high chemical resistance against particularly aggressive components requires using a PE geomembrane, an adequate PVC geocomposite will have the best performance as water barrier. The waterproofing geocomposite selected for Las Bambas is a 2.5 mm thick PVC geomembrane heat-bonded during fabrication to a nonwoven needle-punched 500 g/m^2 polypropylene geotextile.

2.2. Construction methodology and geometrical design

The geomembrane sealing system is based on the concept of placing a polymeric watertight liner on the upstream face of the embankment, with a drainage system behind; the liner is anchored to the face of the dam against wind uplift, and watertight sealed at the peripheries. In the state-of-the-art system the upstream liner is geocomposite a flexible watertight PVC geomembrane having >250% elongation, heat-bonded at fabrication to an anti-puncture geotextile, to form what is called a geocomposite. As the liner will be in contact with the tailings/supernatant pond/water, the geomembrane formulation is custom-made to resist the chemical aggression it will have to face over time.

The face anchorage of the geocomposite is provided by geocomposite anchor "wings" embedded in the finishing layer of the dam. An effective method to construct in short times and at reasonable cost a stable non-erodible finishing layer consists in extruding lean concrete curbs, superimposed and interlocking to avoid displacement caused by the compression exerted by possible deformations of the embankment. As discussed by ICOLD in a theme bulletin on geomembrane sealing systems for dams (ICOLD, 2011), the extruded curbs can provide a very effective and quick installation of a geomembrane sealing system when associated to the face anchorage system with "wings" of geomembrane. The curbs provide a free-draining full face layer under the geocomposite, and the geocomposite wings embedded in the curbs form vertical parallel anchorage bands on which the geocomposite liner is heat-seamed to provide permanent anchorage against uplift. The resulting technical advantages are a built-in face drainage system, which is crucial and recommended for tailings dams in particular, and a flexible anchorage system, which together with the tensile properties of the geocomposite allows constructing a completely flexible revetment, which will maintain watertightness under seismic loading, and as such has been used in many highly seismic areas in the world.

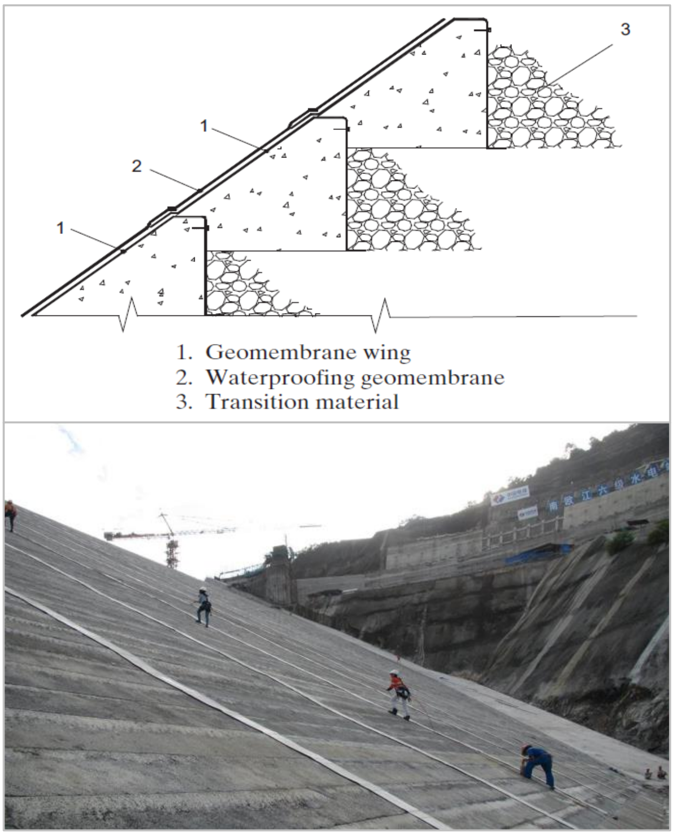

Figure 2. Face anchorage system with geomembrane anchor wings: at top, excerpt from ICOLD Bulletin 135, at bottom, the continuous anchorage bands formed the geomembrane "wings".

The above method allows designing dams with steeper faces, reducing the volume of fill, avoiding the construction of berms, increasing the volume of tailings storage, reducing the upstream surface area to be lined.

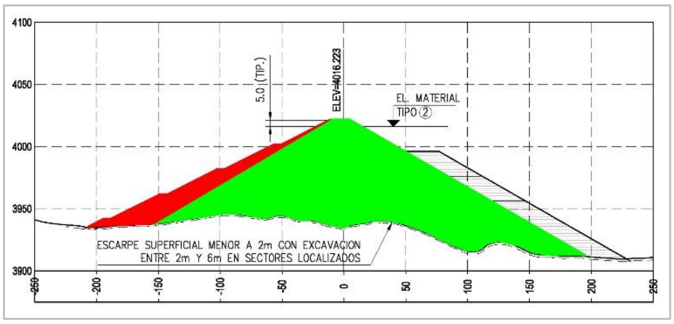

Figure 3. In green, the fill volume with a PVC geocomposite, in red the additional volume required by an HDPE geomembrane.

Figure 3 shows the concept, as applied in Las Bambas tailings dam: in red, the 1V:2H slope of original design with traditional high-density polyethylene (HDPE) geomembrane ballasted with 30 cm compacted earth, in green the reduced volume of fill with the adopted system: curbs + exposed PVC geocomposite

Figure 4, showing the plan view of the same dam of Figure 3, allows appreciating the advantage in terms of volumes and of resulting reduced construction time and costs. Figures 3 and 4 refer to the design used for the Las Bambas project.

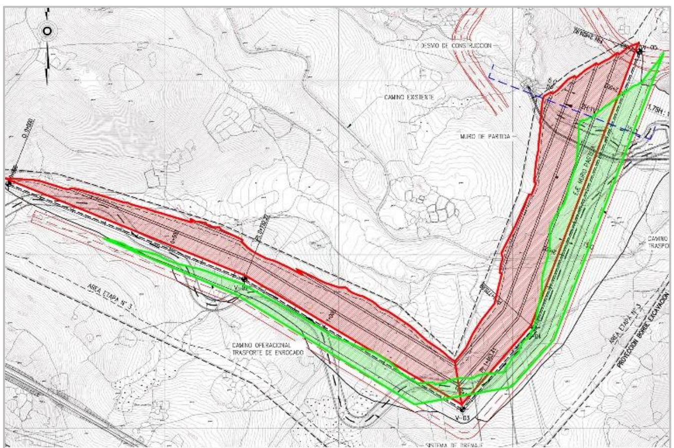

Figure 4. Plan view: PVC geocomposite (green), HDPE geomembrane (red).

Further significant advantage of the extruded curbs method is that it provides a high flexibility of construction: the waterproofing geocomposite can be installed after the embankment is completed, tested, finished and inspected, or it can be installed along with proceeding construction of the embankment. This makes it an asset for water dams, where it allows early impounding and provides early flood protection, and even more so for construction and operation of tailings dams, because the water barrier is constructed concurrent with construction of the dam, providing seepage control following the raising of the dam: theoretically, every time the construction of the curbs is risen of five to ten meters of height, the upstream face of the dam can be covered with the waterproofing geocomposite, and the dam can be filled up to that elevation.

At boundaries, the geocomposite is typically anchored by a continuous mechanical or insert-type seal impeding water infiltration behind the liner. Perimeter seals are watertight against water in pressure at submersible boundaries, and against rains, snowmelt and waves at crest.

Details on various design aspects such as characteristics and selection of the type of geomembrane, dimensioning of the anchorage system, and features of the perimeter seals, are out of the focus of this paper and widely covered in international literature (e.g. Noske et al., 2014).

2.3. Installation at Las Bambas

The dam is constructed in several stages with the downstream raising approach. Stage 1 from elevation 3932 to elevation 4020 (divided in intermediate substages), Stage 2 from elevation 4020 to elevation 4050, Stage 3 from elevation 4050 to elevation 4080, Stage 4 from elevation 4080 to elevation 4105, and Stage 5 from elevation 4105 to elevation 4130. A further stage is expected up to elevation 4150, and probably further stages for a final height of about 230 m.

Stages 1,2,3, and 4 have been completed, with the geocomposite being installed over the substages as soon as they had been raised; the dam now is about 173 m high and 3,150 m long at crest, corresponding to the end of stage 4 at elevation 4105. Materials for Stage 5 are under production and installation is envisaged to start by November 2022.

Figure 5. Las Bambas. Geocomposite installation at Stage 1 (height 88 m).

Figure 6. Las Bambas. Geocomposite installation at Stage 2 (height 118 m).

Figure 7. Las Bambas. Geocomposite installation at Stage 3 (height 148 m).

Figure 8. Las Bambas. Geocomposite installation at Stage 4 (height 173 m), current situation.

2.4. Technical advantages of the system

The tensile properties of the geocomposite and of its face anchorage system by geocomposite wings construct a completely flexible watertight facing, matched by a peripheral seal allowing accommodating differential movements at interfaces embankment/concrete. The geocomposite system will adapt to settlements in the dam and to differential displacements between the dam body and the plinth that should occur after impoundment. The good behavior of the system under seismic loading is an additional important asset for the safety of the tailings dam and of the environment.

Current practice indicates that geomembranes are a feasible alternative to concrete slabs in rockfill dams exceeding 100 m, and it can be expected that geomembranes facings will be used as only waterproofing barriers in super-high rockfill dams. As they are always available in the needed quality and quantity, they are an asset also when there is shortage of low permeability materials (clay) for an impervious core.

2.5. Enviromental advantages

Durability of the components of the waterproofing system, hence of the geomembrane, is one aspect of sustainability. Past field experience, laboratory testing and analytical methods concur to estimate a service life exceeding a hundred years for geocomposites exposed to the environment. In tailings dams, the geocomposite will eventually be covered by the tailings, and according to scientific studies on buried geomembranes the durability is estimated in many centuries. The groundwater and the downstream environment will thus profit of a long-term protection.

The small volume and weight of the components of the waterproofing system and of the equipment needed for installation are an additional environmental asset: they make transport and site organization easier, quicker and less cumbersome, resulting in lower carbon footprint, and minimized environmental impact.

Construction of a geomembrane facing consists of simple repetitive tasks that can be easily and quickly executed, practically in all weather conditions. Any construction schedule can thus be met, achieving waterproofing at a much faster pace than what would be required by a concrete facing or a clay barrier, and in a wider range of climatic conditions.

3. CONCLUSIONS

The use of PVC geocomposites as only waterproofing barrier in tailings and rockfill dams has shown to be a technically effective solution, allowing steepening the slopes, reducing the volume of fill, shortening the construction time and lowering the overall costs. A PVC geocomposite increases the safety of the project also from an environmental standpoint and makes feasible projects that would not otherwise be feasible at acceptable financial or environmental costs.

Particularly at Las Bambas, the upstream water barrier is capable of providing higher structural safety to the dam, enhancing environmental safety by avoiding/minimizing contact between the impounded tailings and the groundwater.

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