Firestone guidelines for design of high altitude reservoirs with EPDM geomembrane

Construction of high altitude reservoirs is a delicate operation which is subject to many hazards and for which the consequences of poor design, construction or maintenance can have disastrous consequences for people and property located downstream.

This document sets out a series of points which must be studied in detail by project engineers in the design of high altitude reservoirs. This document does not purport to be exhaustive. The various points raised refer to very specific skills that must be studied by experts in the subject.

1. Site Selection:

The high altitude environment is extremely complex and fragile. Site selection therefore results from a detailed study of different factors:

- Topography.
- Availability of water supply.
- Existing facilities (villages, ski slopes, etc.).
- Altitude (implementation, thickness of ice crust on the pond, etc.).
- Environmental impacts (high ecological value, fragile environments).
- Hydrological study (watershed study).
- Seismic study.
- Geological and geotechnical study (slope slip, collapse, rock falls, water depth, differential settlement, cavitation collapse, karst topography, ground susceptible to water solubility (gypsum), etc.).
- Study of hazards specific to mountain areas (avalanches, torrential phenomena, etc.).
- Study of downstream basin in the event of breach (determining the safety level applied to the reservoir).

2. Embankment:

The classic design of high altitude mountain reservoirs is an excavation-embankment design.

- **Compacting:** In order to have a well compacted embankment with a uniform slope, it is strongly recommended to build the embankment by the excess fill method: a width greater than the project profile is compacted, then the poorly compacted faces are scraped.
- **Slope:** depends on the material used, the foundation quality, the height of the embankment, the position of the saturated zone. An accurate stability calculation must be made. The slopes recommended below are also a function of the presence of a covering over the membrane:
    - Covered geomembrane: upstream slope of 1:3 and downstream slope of 1:2-2.5
    - Non-covered geomembrane: upstream slope of 1:2.25-2.5 and downstream slope of 1:2-2.5
- **Berm:** use of a berm is not recommended for high altitude reservoirs (drainage discontinuity, difficulty of construction, damage from ice crust).
- **Crest:** the minimum crest width must be 4 m, with a slight slope towards the outside of the structure (1 %).
- **Downstream embankment:** necessary to protect against erosion (grassed topsoil) and freezing (draining materials).

- **Freeboard:** freeboard is the difference in level between the top of the crest and the highest water level. It is intended to prevent wind generated waves from overtopping the crest. The freeboard is specifically calculated for each project but in any case must always be more than 40 cm or the minimum value from the current legislation.
- **Drainage:** in order to protect the embankment from internal erosion mechanisms or downstream slope slippage in the event of leakage of the GSS (geomembrane sealing system) on the upstream embankment, it is essential to provide a water drainage system under the GSS and under embankments. The type of drainage envisaged will be adapted depending on the scale of the structure and construction of the embankment.

3. Excavation:

- **Slope:** the excavation must not destabilize the terrain slope. The slope will be determined by a stability study. It must never exceed 1:2.
- **Drainage:** in the case of natural water inflow upstream of the reservoir, it is essential to provide a water drainage system to ensure stability of the excavation slopes and avoid pressure under the membrane. This drainage system is separate from the GSS drainage system.
- **Ring road:** with a minimum width of 4 m, this shall be equipped with a culvert to collect upstream runoff.

4. Spillway:

All high altitude reservoirs must be equipped with a spillway to allow removal of excess water entering the basin (inflow flooding, heavy rains, etc.).

- **Type:** it is strongly recommended to build a free weir spillway whose discharge threshold is at the same height as the normal reservoir level. Use of "overflow" sluice openings are not recommended.
- **Hydrological dimensioning:** the dimension of the spillway must allow evacuation of excess water for flooding of the facility so that the reservoir level stays equal to or less than the high water level. A safety coefficient must be provided for (freezing over, snow accumulation, etc.).
- **Obstruction:** the spillway risks being obstructed by snow accumulation. This must be considered in its construction. It is recommended to build the spillway with gentle slopes and splayed walls to allow access by maintenance machines. In all cases accumulated snow and ice must be removed from the spillway at the end of winter.
- **Threshold:** a reinforced concrete threshold is recommended to resist hydrostatic and ice pressure. Its foundation must not be subject to freezing. Special attention must be given to the connection between the threshold and the geomembrane.
- **Sluice:** the sluice may be built of various materials (reinforced concrete, gabions, concrete permeated riprap, etc.). In all cases it is essential that the support resists erosion, especially at the exit downstream of the threshold. It is usually helpful to provide underside drainage to avoid erosion of the subsoil and uplift pressure.
- **Discharge:** may be built from the same materials as the sluice. Its design dissipates the energy of the water before discharge into the natural environment.

5. Drainage under embankments:

- **Emptying:** the discharge drain is an essential part of the structure's safety. It allows the reservoir water level to be rapidly and completely lowered. The discharge drain must be dimensioned so as to discharge half the contents within 8 days and completely empty the basin within 21 days. It is strongly recommended that discharge is by gravity.

- **Intake:** it is preferable to provide several intakes in case of unavailability. Trash racks are to be provided to prevent obstructions (ice blocks).
- **Sluice gates:** the sluice gate system depends on the scale of the reservoir. For large scale structures, upstream sluice gates are to be provided in a dry and accessible valve house. It is essential that sluice gates are also accessible in winter. It is recommended to provide a sluice gate system that may be serviced when the reservoir is full.
- **Pipes:**
    - Pipes are to be in steel or cast iron.
    - Minimum diameter of 300 mm.
    - In order to prevent piping phenomena in case of leakage, the pipe shall be placed in a trench that will be filled with poured concrete.
    - Drainage shall be provided around the pipe for the downstream half of the dam body, to collect water under pressure coming from leakage of the pipe or failure of a connection between the pipe and the GSS.
    - Expansion/compensation joints are to be provided.
    - Special attention must be given to the connection between the pipe and the geomembrane. The connection will be made by mechanical anchoring of the geomembrane to a concrete block in which the pipe is embedded. The mechanical connection to the membrane shall follow the requirements described in the Firestone technical guide (Termination Bar + Water Block Seal + Lap Sealant HS). The concrete block shall be constructed so as to limit differential settlements and present a smooth surface in the area for connection with the geomembrane. It is essential that the concrete is of excellent quality and is applied in accordance with the rules of the art.
- **Inlet:** it is recommended that the inlet chamber be provided with bars (spaced about 1/3 the diameter of the pipe or sluice gates) and an orifice placed at such a height as to prevent obstruction.
- **Downstream discharge:** an energy dissipater shall be provided at the discharge outlet in order to prevent erosion of the downstream slope.

6. GSS:

- **Geometry of the structure:**
    - Favour simple shapes.
    - Use a bottom slope of at least 2%.
    - The change in angle between the bottom and the side slopes must be rounded (curvature of 0.5 m).
- **Support structure:**
    - **Subgrade:** good capacity, uniform, free of organic material or sharp objects.
    - **Granular bed:** protecting the membrane from puncture is essential to ensure sealing of the structure in the long term. It is strongly recommended to set down a granular bed at least 20 cm thick, having aggregate size of maximum 20 mm.
    - **Water drainage:** it is mandatory to place a water drainage network under the geomembrane that will allow any leakage of the GSS to be detected.
        - **Separate:** the GSS drainage system must be distinct and separate from the drainage network for natural water inflow and drainage of the embankment.
        - **Divided:** the drainage network shall be subdivided into several zones so that any leak can be localised (very important for covered membranes).
        - **Drainage through aggregates:** this bed may be made with sand or gravel (5/20). Its thickness depends on the transmissivity of the product's drainage. A minimum thickness of 10 cm is recommended. A filtering geotextile must be provided between the drainage layer and the neighbouring soil.

In some cases (subgrade of fine particle size), the granular bed may be replaced by the drainage aggregate bed.

- **Drainage by a drainage geocomposite:** the geocomposite shall be chosen depending on its cross-sectional flow rate (under load), its filtering geotextiles and its coefficient of friction (preferably self-stable on slopes).
- **Basin:** in the basin, the drainage system shall be complemented by collectors.
- **Berm:** if a berm absolutely must be used, a water collection/drainage system must be provided at the berm.

o **Gas drainage:** a gas drainage system under the membrane must be provided. The gas drainage system shall be well separated from the water drainage system.

o **Puncture resistant geotextile:** the type of geotextile shall be selected depending on the properties of the support soil (particle size, etc.), the type of geomembrane used and stresses anticipated in placing and operation. The minimum properties of the geotextile are given below, for reference only:

- type: nonwoven needled, 100% polypropylene
- ASQUAL Certified
- Basis weight (EN 965) 500-1000 g/m²
- Tensile elongation 50%
- Tensile strength (ISO 10319) min. 40 kN/m (with and across run direction)
- Puncture resistance (NF G 38019) min. 6 kN

The rolls of geotextile are to be sewn or thermo-bonded together after setting in place in such a way as to avoid any movement of the EPDM geomembrane while setting in place.

- **Geomembrane:** a geomembrane of 1.5 mm is preferably to be used, with 1.1 mm geomembrane minimum. The choice of the type of geomembrane will depend on the properties of the support, and the presence and type of covering. Design and installation of geomembrane must follow the requirements given in the Firestone Technical Manual. In areas where the membrane must be connected to a structure, it underlines the need for particularly careful compacting to avoid any differential settlement. Inside the basin, mechanical connection of the membrane with the details is to be favoured. Properties of Firestone EPDM geomembranes:

Properties	1.1 mm Geomembrane	1.5 mm Geomembrane
ASQUAL Certified	Yes	In process
Colour	Black	Black
Tensile strength (ISO R 527)	9 N/mm²	10 N/mm²
Water permeability (EN 14150)	< $4x10^{-6}$ m³/m² j	< $4x10^{-6}$ m³/m² j
Durability (EN 12224)	25 years	25 years
Static puncture (EN ISO 12236)	0.7 kN	0.9 kN

- **Double geomembrane:** use of a double geomembrane is recommended on sites where the subsoil presents risks of internal erosion or dissolution. In this case, any leakage of the GSS could have very serious consequences on the quality of the subgrade and the stability of the structure. Between the two geomembranes a geocomposite drainage system shall be connected to a leak detection system.
- **Covering:** at high altitude, the membrane risks being damaged by the ice crust on the surface of the basin, rock falls, floating objects, etc. In addition, as a general rule, high altitude basins are regularly emptied. The membrane then risks being put under tension from wind loads. For these reasons, it is strongly recommended to cover the entire surface of high altitude basins.

- It is strongly advised not to protect only a part of the slope. Not covering a basin may be justified at where it is at low altitude (<1800 m), protected from the prevailing winds, of small size and with a support structure of sand. Geomembranes of non-covered basins must be weighted to prevent uplift of the geomembrane by wind action (minimal water layer, sandbags, concrete slabs, etc.).
    - **Different types of coverings:**
        - Riprap / layer of sand or gravel / geotextile.
        - Gabion bed / geotextile.
        - Onsite poured concrete slab / geotextile. The geotextile must have sufficient transmissivity to permit drainage under the slab and prevent uplifting pressure.
        - Interlocking concrete / geotextile
    - **Stability:** it is essential to ensure stability of the covering on the slope. This is the reason why a 1:3 slope is recommended on covered slopes. Coverings of poured concrete may have a somewhat steeper slope. In stability calculations, it is necessary to take into account situations of sustainable operations (weight of materials, ice, snow, etc.), transient situations (weight of machinery and excess material during construction, rapid emptying, etc.) and accidental situations (seismic, blocked drain, etc.).
    - **Basin:** considering the low slope of the basin and the lower stresses, the covering may be less robust in this area.
    - **Structure of a riprap covering:** a riprap covering must be sized so as to resist wind driven waves and ice:
        - **Thickness:** between 0.3 and 0.8 m.
        - **Block diameter:** Maximum diameter < covering thickness (0.3 – 0.8 m), minimum diameter > 0.1 m. It is considered that the median diameter of the blocks must be greater than the thickness of the ice (between 0.2 and 0.5 m).
        - **Typical structure:**
            - Geomembrane.
            - Geotextile between 600 and 1200 g/m².
            - 0.2-0.3 m bed of sand or gravel
            - Blocks.
        - **Stability:** the effect of the slope is overriding for the stability of the riprap. It is very important to respect the 1:3 slope. If necessary, an abutment at the toe of the slope and/or geosynthetic reinforcement at the top of the slope shall be provided.
        - **Permeability:** permeability of the covering structure must be sufficient to avoid developing hydraulic pressure at its base.
        - **Test plate:** in order to select the puncture resistant geotextile and to check the stability of riprap on the slope, it is strongly recommended to use an on site test plate.
    - **Setting in place:** it is often during setting in place of the covering bed that the membrane is subjected to the most significant stresses. It is therefore essential to take all possible precautions when applying the covering over the geomembrane. Movement of machinery on the membrane should be prohibited unless absolutely necessary and with the use of special measures.

- **Anchor trench:** anchor trenches must be sized as described in the Firestone Technical Manual.

    - Non-covered membrane: the trench is used for intermediate and final anchoring.
    - Covered membrane: the covering will serve as final anchoring. The trench is used for intermediate membrane anchoring during setting in place and while waiting for the covering.
- **Inflow zone:** if the membrane is not covered, it is advisable to provide a reinforced area if the basin inflow is directly onto the membrane.

7. Bubbling system:

Installation of a bubbling system (high pressure air injection) at the bottom of the reservoir is strongly recommended to reduce the thickness of ice on the reservoir surface.

- Network of 10 bar HDPE tubes spaced every 6 m.
- Nozzles of 0.6 m diameter every 2 m.
- Pressure of 5 to 6 bars and flow rare equal to 5 % of the reservoir volume (m^3/h).
- Weighted and placed 10 cm from the bottom.
- Independent ring diffusers.

8. Monitoring device:

The drainage network located under the GSS shall be equipped with a flow measurement system that can evaluate the quality of the GSS and its drainage system. The measurement system must be accessible throughout the year. It is strongly recommended to compartmentalise the drainage system so as to be able to localize the area that is leaking. This is especially important for systems where the membrane is covered (not possible to see membrane condition).

It is also recommended to set up a water level measurement system.

9. Maintenance, control and safety of facility:

During design, it is necessary to take overall account of maintenance activities (snow removal, vegetation control, repair of the GSS, etc.), and of surveillance and safety needs (installation of a perimeter fence, ladders for workers, rodents, etc.).

These guidelines have been drawn from the book "Retenues d'altitude" [High Altitude Reservoirs], published by Éditions Quae, Savoir-faire collection. Authors: Laurent Peyras, Patrice Mériaux, coordinators.