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Mountain Reservoirs for Snowmaking: a Guideline for Design, Construction, Monitoring and Rehabilitation

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Abstract

Mountain reservoirs are hydraulic structures in ski resorts in the mountains, used to store water in general for snowmaking. There are more than one hundred of them in France, most of them less than 10 years of age. Despite their modest volumes (5,000 to 400,000 m³) and dam heights of between 5 and 20m, these structures do induce potentially high risks for people and property situated downstream from them. They are located at altitudes between 1,200 and 2,700m, and often face difficult topographical, geological and geotechnical conditions, mountain-specific hazards, a very limited period for construction in the year, considerable pressure from ice and intense cold, the difficulty of surveillance in winter, etc.

A survey conducted on about 70 of these mountain reservoirs provided considerable information, particularly on the behaviour and pathologies of these small dams at high altitudes. These reservoirs are generally entirely sealed by geomembranes (85% of cases). This feedback on experience served as a basis for writing a set of guidelines on studying, designing, constructing, monitoring and rehabilitating these mountain reservoirs [4]. This guideline has been supported by the French ministry of environment and it has been prepared by a working group lead by the Cemagref and with the contribution of EDF and ISL.

The article presents, through the guideline "Mountain reservoirs", a summary of the feedback on the behaviour and pathology of mountain reservoirs. It gives a general description of the guideline [4], and emphasis on the main key themes: environmental impacts, risks specific to the mountain, design of embankments and drainage system, monitoring and operation, and those aspects of the underlying layer, drainage and cover layer of the GSS that appear to be essential for the system to behave correctly.

Introduction

The French mountain dam fleet includes some 105 structures mainly constructed in the Alps or the Pyrenees. Mountain

reservoirs are settled within mountain entertainment resorts and are designed to store water mainly used for producing snowmaking.

Despite their low volumes, mountain reservoirs induce potentially high risks. Experience feedback shows that one out of two mountain reservoirs affects public safety since any break of the embankment part of the structure or any sudden expulsion of stored water would have significant adverse effects on downstream population and properties.

These are located up in mountains between 1,200 and 2,700m high. Such location entails difficult conditions at all stages: design, construction, operation and, where applicable, rehabilitation. The major difficulties include: geological and geotechnical conditions, mountain-specific hazards, technical devices that may prove fragile when applied to mountain reservoirs, a very limited window for construction during the year, considerable pressure from ice and intense cold, difficult monitoring conditions during winter time, etc.

From an ecological perspective, mountain sites often are very resourceful, while also fragile.

The experience feedback from mountain reservoirs currently in operation and from ongoing projects is somewhat lukewarm, showing a number of pathologies, incidents, even accidents, as well as design and construction faults. The rehabilitation of unsafe and unreliable mountain reservoirs is also among the major concerns of the site owners and their engineering and consulting agencies.

Following a first preliminary work [3], this paper outlines the "Mountain reservoirs" [4] recommendation guideline published in May 2009, which summarizes the experience feedback from their behaviors and pathologies. It describes all major recommendations related to environmental impacts, mountain-specific hazards, design of embankments and their drainage system, monitoring and operation.

Lukewarm experience feedback for mountain reservoirs

In order to draft this guideline, a number of documentary and on-site surveys have been performed in the mountain reservoirs located in the Alps and the Pyrenees. Various

investigations were performed in relation to the studied structures: structure project design study review (hydrologic engineering, mountain hazards, project management, environmental impact, flood wave), in-depth review focused on geological and geotechnical studies, detailed visit and in-depth assessment from time to time. A total of about 70 structures were reviewed, and thereby helped provide substantial experience feedback on mountain reservoir design, state, behavior, incidents, operation and monitoring. Below is outlined the technological experience feedback.

Structure overview

- Type of dam: cut and fill structures
- Embankment and basin
- Total watertightness using a geomembrane
- Location altitude: 1,200 to 2,700m
- Reservoir volume: 5,000 to 400,000m³ (approx. mean 40,000m³)
- Maximum embankment height: 4 to 20m
- Upstream slope: 1/1.5 to 1/3
- Downstream slope: 1/1.5 to 1/3.5
- Flood gate: spillway with concrete rockfills, located on the embankment, most frequently without energy dissipator or very rustic
- Monitoring system: often limited to only one collection point for drainage flows
- Outlet device: pipe running through the embankment or located within the foundation

Experience feedback on geological, geotechnical and design aspects

The conducted surveys show that a large majority of embankments (90%) rely on a resistant (moraine or rock) and non compressible foundation. The geological typical section observed during the exploration of a mountain subsoil shows the following from top to bottom: (i) on the surface, a layer hardly longer than 2 meters, made of top soil, silts, peat, clay or talus; (ii) till clay and gravel moraines that may be close to the surface and thick enough to form the geotechnical substratum; (iii) the rock geological substratum (schists, sandstone, granite, quartzites, gneiss, limestone, marl and limestone...) that may be close to the surface, sometimes with a substantial weathered fringe. Such typical section underlines the geological specificity of mountain sites which are not naturally watertight: talus on slopes, moraines, fissured rock, karstic material, absence of clay at high altitudes, etc. The foundation hydrogeological analyses frequently (70%) indicate water inflows.

With regard to the geotechnical design of mountain reservoirs, embankment materials mainly (60%) comprise moraines and schists. At a lower level, embankments made of silt (15%) and rockfills (15%) are encountered. Rockfill embankments are built out of blasted and sometimes crushed excavated material mainly from quartzites, gneiss and limestones. Experience feedback shows that their

repositioning as embankment results in a material that is no longer a rock and shows significantly impaired drainage properties. Consequently, mountain reservoirs with draining embankment appeared to be rather marginal.

One embankment out of two has too steep a downstream slope considering the good engineering practices (slope over 1V/2H). A similar finding is produced as regards upstream slopes. This may lead to insufficient sliding security considering current design standards. As far as drainage is concerned, surveys have shown that 20% of dams do not have any embankment drainage device and, therefore, are vulnerable to any potential failure of the sealing device.

With regard to the performance of embankment works, the experience feedback from the construction site highlighted many challenging situations. The major challenges include: (i) excess water (very damp grounds and materials, difficult subsoil water inflow control, very low bearing capacity); (ii) difficult compaction (insufficient density, high level of deformability); (iii) challenges related to insufficient explorations (lack of materials, unsuitable materials for embankment, non bearing areas).

Therefore, mountain reservoir location sites, as well as their topographical and geological conditions, often imply general basin watertightness, mainly due to leak control within the foundations. Indeed, there are cases where basin underseepage may slip out of the thalweg and eventually link up with adjoining thalwegs. Consequently, it becomes necessary in practice to seal the whole surface of the basin. In addition, there are other reasons to pitch on artificial sealing for the basin and the embankment, including insufficient available watertight materials and, quite frequently, highly heterogeneous materials.

Experience feedback on geomembrane sealing system [2]

Most reservoirs feature an artificial sealing device using geomembranes and the "mountain reservoirs" guideline focuses on this technology.

There are four main families of synthetic geomembrane used on mountain reservoirs: EPDM, HPDE, f-PP and PVC-P. The latter accounts for nearly half of the geomembranes used, the other half being divided into the three remaining types in relatively equal shares.

Geomembranes are uncovered or covered only on the upper part of the slope in the very great majority (90%) of mountain reservoirs; they are entirely covered only in very few cases.

The quality of the geomembrane supporting layer varies widely from one structure to the other. We divided the aggressivity of the supports in four categories according to their level of coarseness: very irregular, irregular, regular and smooth. Half of the qualified reservoirs had an acceptable support: not very or not at all coarse. On the other hand, an equivalent number of reservoirs have an coarse (even very coarse) support which increases the risk of punctures.

Damage to the geomembrane is a very widespread pathology in mountain reservoirs: Lessons learned on geomembrane

pathology show numerous defects on half of the reservoirs, i.e.:

- 50% of the reservoirs are faced with geomembrane damage problems: 22% have tens, even hundreds of holes every year and/or major tears, 28% suffer from recurring perforations every winter;

- 50% of the reservoirs have never experienced any watertightness problem, or have only had a few perforations in their geomembrane (1 or 2 holes per year).

Surveys revealed that such damage to the geomembranes are mainly due to two factors: (i) the action of ice; (ii) the aggressive nature of the supporting layer. Experience feedback has shown that the presence of a berm with a rockfill cover layer on its upper part generally is an aggravating factor for the geomembrane damage: the ice forming around the berm and the cover layer above the berm remains attached to the rockfill; then, blocks of ice suddenly detach, sometimes dragging rocks along with them, and result in geomembrane perforations or tears on the lower part of the uncovered face and on the bottom of the reservoir when empty.

“Mountain reservoirs” guideline

The “Mountain reservoirs” guideline [4] is designed as an embedded manual for designing, constructing, monitoring and rehabilitating mountain reservoirs. It aims at determining good engineering practices, in the specific mountain environment, for designing small dams, most of them featuring a geomembrane sealing system.

This guideline first provides a quick summary of the experience feedback for mountain reservoirs (part I). Here are outlined frequent pathologies and faults observed on the existing reservoirs, with a view to subsequently suggest technical solutions to prevent those.

The second part deals with site assessment and key components thereof: environmental impacts of the future structure, hazards to which it may be exposed, flood wave and effects thereof downstream in the event of a dam break or stored water expulsion. This assessment is meant to provide site owners and their consulting agencies with data to help them make the appropriate decisions for setting up a mountain reservoir project.

Mountain reservoir design is covered in part III. Good engineering practices for small dams are then recalled and stated in the specific context of mountain hydraulic structures. The guideline addresses the fundamental aspects of mountain reservoir design, equipment and related structures. With regard to the foundation and embankment watertightness, the guideline focuses on designing mountain reservoirs sealed by a geomembrane sealing system, as preferred solution, and therefore on geosynthetic technology. It also emphasizes key geotechnical aspects for such structures.

Work performance and compliance check also require special

attention in mountain settings where construction windows during the year are reduced (part IV). The guideline describes the aspects in relation to the construction site management.

Monitoring, operation and maintenance of the structures in use are dealt with in part V. These are described in light of the new hydraulic structure safety regulation. Focus is cast on provisions specifically pertaining to mountain reservoirs and associated with their difficult operating conditions during winter.

A high number of mountain reservoirs suffer from pathologies and design or construction faults, thereby requiring their rehabilitation and leveling. Part VI puts forward a number of methodologies to produce a relevant diagnostic on existing reservoirs and discusses frequent pathologies or faults, in the form of case data sheets: illustrations, mechanisms at stake, potential consequences and proposed corrective actions for their rehabilitation.

Rich and fragile environments

Mountain environments are ecologically highly valuable, thanks to an outstanding wildlife and to damp areas with an important value as a natural heritage. They also typically consist in very fragile and slow mechanisms: any damage to the environment implies much longer recovery time than at lower altitudes and the natural reconstruction dynamics may last for several decades.

The study of environmental impacts is fundamental and must be dealt with in the early stages of the project. It should embrace a global perspective of the structure and provide an overview of the project and its various impacts on environment, especially on aquatic environments. The study should also list all sites where structure projects are restrained by specific environmental challenges (outstanding environments, regulatory provisions, etc.). To these ends, the "Mountain reservoirs" guideline recalls the environmental protection regulatory principles, provides data to assist in decision making and site prioritizing with regard to issues associated with the impacts, and puts forward a number of methods for performing impact reviews.

The water regulation prescribes that the impact document should take into account all structures subject to registration and authorization, as well as all elements related to the structure that contribute to the impacts on water. Therefore, it appears necessary to analyze not only the impact of building a mountain reservoir and its related structures, but also the impact of implementing networks for feeding or emptying the reservoir, the access channels to the construction site and the potential quality and quantity-related impacts on waters and environments in relation to the sampling conditions and the quality of waters used for producing snowmaking.

Impacts should more specifically be assessed with regard to the following aspects:

- mountain damp areas: the survey conducted as part of this guideline indicates that about one third of the mountain reservoirs have been set up on damp areas. The works

directly carried out on the damp area shall permanently destroy the affected sections and the works performed near the same damp area, even though they are not in direct contact with it, might also have an important impact (alteration of hydrological conditions, filler inflows, etc.);

- the presence of protected species: potential animal and plant species must be detected long before the beginning of the project in order to avoid any complication. Indeed, the survey conducted as part of this guideline shows that this is a frequent issue;

- torrents and surface flows: the most acute impacts are associated with samplings performed during the winter low flow season when large samplings may induce the freezing of small outlets and limit the survival abilities of the fish fauna (pollution dilution, compensation water);

- underground waters: stored water may be polluted due to samplings performed in surface waters receiving sewerage waste, animal excreta or physico-chemical pollutions associated with anthropogenic activities. The overall highly permeable mountain grounds and the incremental runoff during ice melting make aquifers vulnerable and may then be a potential threat for drinking water abstraction [1].

Lastly, climate change must be incorporated in the study of environmental impacts; more specifically, it is necessary to assess the site climate-related potential.

Mountain-specific hazards and potentially high risks

In addition to traditional hazards encountered in lowland areas (flood, earthquake), mountain reservoirs may be exposed to mountain-specific hazards: avalanches, rapid flows and geological hazards – slope slip-offs, cavings, falling blocks). The strength of most of these hazards is very difficult to quantify during unusual to exceptional return periods, which makes it even more difficult to design reservoir protection structures when necessary.

Despite their low volumes, mountain reservoirs induce potentially high risks. Experience feedback shows that one out of two mountain reservoirs affects public safety since any break of the embankment part of the structure or any sudden expulsion of stored water would have significant adverse effects on downstream population and properties. There are several reasons to such a situation: (i) their towering position above highly touristic facilities or ski resort residential areas; (ii) steep slopes and hillside geological conditions that would lead to rapid flows in the event of a release of substantial flows; (iii) short distance between the reservoir and downstream challenges, and extremely reduced time interval for the arrival of a break wave.

The safety level expected from a mountain reservoir varies according to the risks it bears upon downstream areas. Mountain reservoirs that affect public safety must be highly reliable, in line with the requirements for a civil engineering work which, in the event of a break, would have substantial impacts on populations. In order to reach this goal, project preliminary studies should include the investigation and

assessment of any potential reservoir locations: (i) to review mountain-specific natural hazards and (ii) to analyze the impacts on downstream areas in the event of a defaulting structure.

The “mountain reservoirs” guideline suggests answers to the questions related to site assessment, hazard analysis and flood wave review. The general rules differentiate the following:

- *small structures without downstream challenges*. For these structures, at least a protection against 1/100 to 1/500 a year frequency project scenarios is targeted. For more exceptional frequencies, the Owner, upon his Engineer's advice, may agree that the structure might suffer from potentially serious damage that would require repair work.

- *medium to large structures with downstream challenges*. For these structures, an expert study is required to establish the nature and characteristics of the incidents that might affect the reservoir and/or the structures, as well as their frequency and impacts as considered in a scenarios-based approach. The idea here is to keep only those location sites with a very low hazard level. This principle is divided into two rules:

- 1/ Reservoirs are located on sites with extremely low annual chances to be affected by a potentially harmful event; to establish an order of magnitude: an 1/1 000 to 1/10 000 probability range is targeted;

- 2/ Although the extremely low level of such annual probability may not be entirely ascertained, a location on the relevant site can still be accepted as long as the following double requirement is observed:

- 2.1/ The probability that the site will be affected by a potentially harmful gravity incident is, in any event, below 1/100;

- 2.2/ The goal to protect the reservoir (affection probability between 1/1 000 and 1/10 000) is reached through the implementation of structures and other possible protection measures (avalanche barriers, for instance, coupled or not coupled with a freeboard to ensure the run-up security or temporary protective actions). It is commonly recognized that such protective structures need to be sized up by an expert, electing relevant safety margins and factors taking into account all the uncertainties associated with the partial knowledge on the events involved and interferences such as flow channels blocked by floating debris leading to occasional overflows.

Cut and fill design

Mountain reservoirs are traditionally designed as cut and fill reservoirs. Once he knows the desired water volume for the reservoir, the designer drafts the structure, usually made of excavated material collected from the basin and embankments built out of this excavated material (Figure 1).

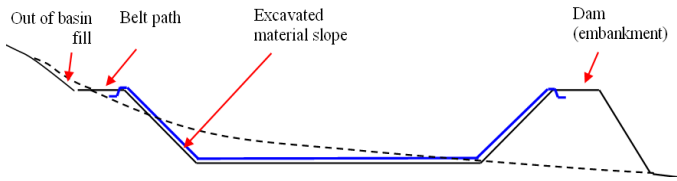


Figure 1: Principle of a cut and fill structure, for an overall geomembrane sealing of the basin

Mountain reservoir embankments are built using the residual embankment method: a width larger than the project profile is compacted before planing both poorly compacted faces.

The embankment upstream slopes must be sized up according to the GSS and its potential coverage. In the event of a covered GSS, this typically leads to selecting the upstream slope. In addition, both slopes also need to be sized up according to the embankment material characteristics, to the foundation quality, to the height and to the position of the saturated area.

This sizing operation is performed as part of the stability analysis. A number of indicative values for the slopes may be provided here (Table 1) for use only during the preliminary studies to determine a pre-sizing. Such values shall then be confirmed at the design stage based on laboratory testing and stability computations.

TABLE 1: INDICATIVE VALUES FOR THE MAXIMUM SLOPES OF AN EARTH DAM MADE OF COARSE MATERIALS ON NON COMPRESSIBLE FOUNDATION

height	type of dam	upstream	downstream
< 5m	covered geomembrane	1/3	1/2
	uncovered geomembrane	1/2.25	1/2
5 to 10m	covered geomembrane	1/3	1/2
	uncovered geomembrane	1/2,5	1/2
10 to 15m	covered geomembrane	1/3	1/2.25
	uncovered geomembrane	1/2.5	1/2.25

It is specifically observed that the recommended slopes are at most equal to 1/2. Earth slopes with a 2/3 slope are unstable on the long run or show a limit-state stability.

Some designers plan to place a berm on the upstream slope to help setting up cover materials on the upper part of the geomembrane. This has many drawbacks associated with blocked ice layers, the potential dragging of rocks and the difficult conditions for maintaining an ongoing drainage.

Therefore, it is not recommended to install a berm. However, landscape considerations may induce covering the upper part using rockfill, provided that it comes just below the normal water level and up to the top.

Embankment drainage

Mountain reservoir drainage is vital for the safety of such artificially watertight structures. The drainage device for a mountain reservoir should enable: i) GSS stability and ii) the embankment stability.

For the first goal, please refer to [2]. With regard to the second goal, the embankment must feature a drainage device that helps drawing out any flow induced by relatively substantial damage on the upstream slope geomembrane so as to protect the embankment from the internal erosion or sliding mechanisms of the downstream slope. Design recommendations for embankment drainage are as follows, and vary according to the structure size.

For medium to large structures with downstream challenges, the geomembrane must be entirely covered. Therefore, temporary and confined damage to the geomembrane is anticipated and the designer should ensure that leak flows associated with such failures can be drained by the structure. Mountain reservoirs are usually made of semi-permeable materials and the designer should then provide for a specific embankment drainage system. Two types of design may be considered:

- a thick granular drain placed on the lower face of the geomembrane and connected to the downstream slope through a drainage blanket or a collector network (Figure 2a); such granular drain, also used as a drain for the GSS, should be sized up so as to collect leaks induced by a confined failure of the geomembrane;
- a traditional vertical drain placed within the embankment body and connected to a drainage blanket or a collector network (Figure 2b). In such a configuration, there are two drains: a geosynthetic (or granular) GSS drain underneath the geomembrane and a vertical granular drain inside the embankment.

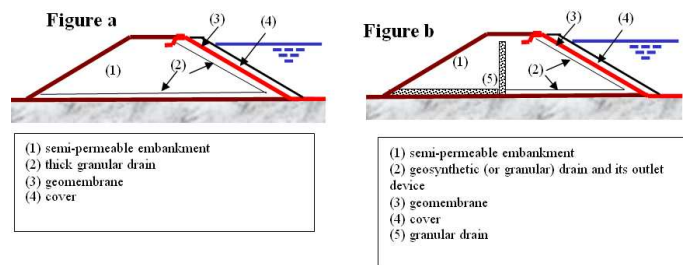


Figure 2 (a and b): Principles for large mountain reservoir drainage system.

As regards small mountain reservoirs without high challenges,

it can be recognized that the embankment drain may be the same as the GSS drain. Such drainage device is designed to collect any leaks associated with a failure in the geomembrane:

(i) if the reservoir is designed with an uncovered geomembrane, the drainage device should enable embankment protection against leaks induced by the complete obliteration of the geomembrane on one of the embankment profiles (top to bottom tearing on the relevant profile). Otherwise, the structure sizing and stability design should take into account such complete obliteration of the geomembrane on one of the embankment profiles and the drainage device capacity, to define the embankment saturation conditions;

(ii) if the reservoir is designed with a covered geomembrane, the drainage device should enable the embankment protection against leaks induced by temporary and confined damage to the geomembrane.

Conclusion

The mountain is a separate and highly specific type of land which implies close and complex interweavings between an outstanding environment and human activities. Mountain settings always require a considerable amount of energy as well as adaptation and innovation abilities, but also special regulations and implementation rules. Mountain reservoirs are fully suited to such a complex reality and this recommendation guideline meets this requirement.

The “Mountain reservoir” guideline was drafted, over two years, by a multidisciplinary team comprising several research and development engineers from the Cemagref, belonging to various research department, and EDF and ISL engineering agency experts. The different fields and areas of expertise involved in this group work are ecology, hydrology, mountain-specific natural risks, geology, geotechnics and civil engineering.

This guideline was also drafted with the help of many external experts from governmental administration services, specialized agencies or freelance experts. Experts in all the aspects of this industry worked in close cooperation: dam engineering thanks to the help of the Comité Français des Barrages et Réservoirs (French Committee on Large Dams) as steering committee, mountain dam engineering through the contribution of ABEST agency and in-depth technical expertise of the Syndicat National des Téléphériques de France. In this respect, we were anxious to include all specialized professionals in the different stages of the project in order to ensure an optimum reach for this guideline.

This guideline was developed with the financial support of the environment Ministry (Department for ecology and land use planning), of the Délégation Interministérielle à l'Aménagement et à la Compétitivité des Territoires (Interministerial delegation for land planning and

competitiveness) and of the Conseil Régional Provence-Alpes-Côte d'Azur.

Mainly designed for owners and operators as well as engineering agencies involved in the various aspects of mountain reservoirs, this recommendation guideline sets mountain reservoirs back in the mountain context, taking into consideration all implications in terms of impacts with regard to site selection, construction, monitoring or detection of issues in the structures already in operation that might result in substantial risks, and to the impact on a very fragile and sensitive environment in this type of area and as part of the risk prevention policy.

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