Sedimentation management in the Livigno reservoir

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Sedimentation caused by turbidity currents is a subject of major importance in Alpine reservoirs. Over the years, as the sediments accumulate, reservoirs lose their storage capacity. The sediments can also reach intakes and greatly accelerate abrasion of hydraulic machinery, decreasing efficiency and increasing maintenance costs. Other problems can be the blockage of bottom outlet structures or damage to gates that are not designed for sediment passage.

Turbidity currents are the flows driven by density differences caused by suspended fine solid material in an ambient fluid. They can occur in various forms, depending on the density of the current. Normally, they can be separated into two parts: the front or head, which has the pressure gradient caused by the density difference between the front and the ambient fluid ahead of it as the essential driving force; and, the body, with the gravitational force of the heavier fluid as the driving force. The flow in the front is unsteady, while for the body, it can be considered as being steady.

In turbidity currents, the quantity of the suspended sediment is not conserved and is free to exchange with the bed sediment by means of bed erosion and deposition. It can cause self-acceleration of the turbidity by entrainment of bed sediment. Fig. 1 shows a typical turbidity current.

1. Scope of the study

The aim of this study is to analyse and propose technical solutions to prevent the effects of sedimentation caused by turbidity currents in the Livigno reservoir on the Swiss-Italian border. For the current situation, the behaviour of the reservoir related to the sedimentation was analysed for: an annual flood event; the October 2000 flood event; the highest flood event ever measured in the catchment area (1960); and, the 100 year return period flood event. For the analysis of the performance of the proposed technical solutions, only the 2000 event was considered.

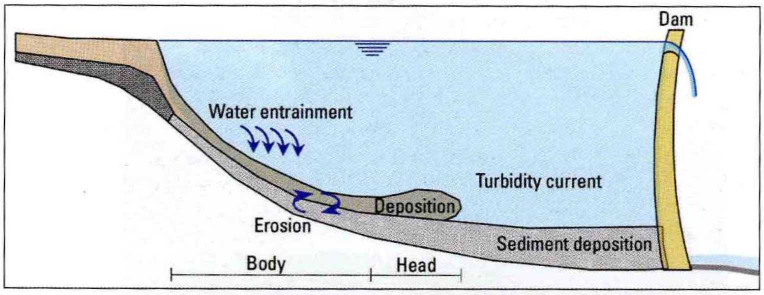


Fig. 1. Turbidity currents (according to De Cesare, 1998).

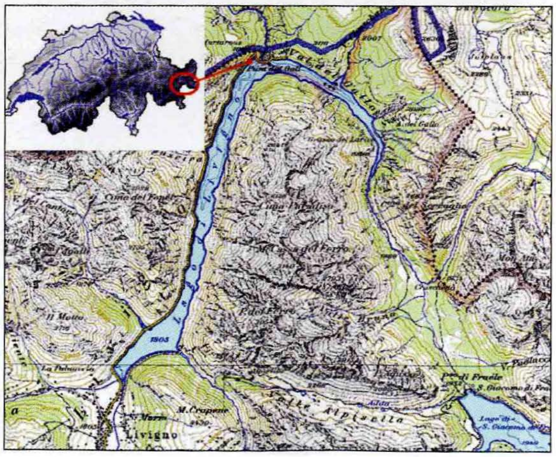


Fig. 2. Location on the Swiss-Italian border and map of the Livigno reservoir.

This paper aims to present the methodology of the study and provides details and discussion for the current situation of the reservoir and the performance of the proposed options. The calculations were carried out using CFX-4.4 [AEA Technology, 2001[1]], a 3D numerical flow solver which provides solutions for the standard equations of continuity, momentum and energy conservation on a non-staggered grid, by a finite volume approach. The program also offers several possibilities for its extension. In this study, the k-ε model was used to provide closure for turbulence. Routines were added to the program to take into account the settling character of the suspended sediments and the erosion-deposition at the bottom. These were done with help of FORTRAN routines developed at LCH-EPFL, Switzerland, by De Cesare [1998[2]] and De Cesare *et al.* [2001[3]], and extended by Oehy [2003[4]].

2. Description of the hydraulic scheme

The Livigno reservoir, created by the Punt dal Gall dam, is mainly located on Italian territory, with the dam being half in Italy and half in the Canton of Grisons in Switzerland. The capacity of the reservoir is 164.6×10^6 m^3, with the maximum operational level at el. 1804.7. The minimum operational level is at el 1700. At present, the water level is never lower than el. 1740. The catchment area is 295 km^2. Fig. 6 gives an overview of the reservoir.

The construction of the Punt dal Gall arch dam was completed in 1968. The dam, 130 m high and with a crest length of 540 m, forms a lake with two 'arms'. The principal West arm of the reservoir, the object of this study, is approximately 9 km long and is formed by the Spöl river. The spillway is gated and has a capacity of 280 m^3/s.

The first main stage of energy production is at the Ova Spin power station in the Spöl Valley. With a capacity of 47 MW, the powerhouse uses water from Lake Livigno in winter and pumps water to the lake (50 MW) in summer. The Ova Spin power station, with the two units, is located like a bird's nest below the spillway chute of the dam, forming the compensation basin with a storage capacity of 6.2×10^6 m^3. The main inflow is water from the Inn river which is captured at the S-shape intake and directed through a free-flow tunnel over 15 km. The water from the Ova Spin compensation basin passes through the turbines at the

Pradella power station (280 MW), which represents 75 per cent of the gross energy produced. The water flows through a 23 km-long pressure tunnel between Ova Spin and Pradella and after the turbines, is collected in a compensation basin with a capacity of 260 000 m^3; the basin also receives water from the Inn river. The basin's contents are then further processed through another 14.3 km-long pressure tunnel to the Martina power station (74 MW).

The entire hydraulic scheme has an average annual energy production of some 1400 GWh. It is owned by Engadiner Kraftwerke AG (EKW), a shareholders' company, owned by EGL, ATEL, BKW, CKW, NOK, the Canton Grisons and the concessionary municipalities. A detailed description can be found on the website (www.engadin-strom.ch).

3. Basic data for the study

As mentioned, the Punt dal Gall dam forms a reservoir with two arms. The topographical data for the entire reservoir was taken from a map (1:2000) with elevation curves of 2 m each. This bathymetric map corresponds to the pre-impoundment topography of the submerged valley (1970). In the vicinity of the dam, a new bathymetry, obtained in November 2003 (1:500) was used. The longitudinal average slope along the invert of the West arm of the reservoir is about 1.2 per cent.

The hydrological basic data for this study are based on four representative flood events. The annual flood, the highest flood ever measured in 1960, the 100 year return period flood, (taken from the review of the initial basic hydrological study [Elektrowatt, 1992[5]], and the October 2000 flood event. These floods have a peak time of 8 h and a total time 48 h. The base flow was considered as 10 per cent of the peak discharge, except for the 2000 event, where this ratio was 8 per cent. An inflow hydrograph corresponding to a uniform spatial rainfall distribution was chosen. This hydrograph, suggested by Hager [1984[6]] on the basis of a detailed study of the floods in mountainous regions, has the form of an asymmetric bell, corresponding to a modified statistical distribution of Maxwell. Fig. 3 shows the hydrographs for this study.

The estimated return period for the October 2000 flood event is between 5 and 10 years, while the highest flood measured (1960) has a return period of between 30 and 40 years. Since there are no measurements for the concentration of the sediments in this reservoir and it is commonly accepted that during flood events in Alpine rivers a high concentration of suspended sediments can occur, a concentration peak of 15 g/l was adopted. According to De Cesare [1998[2]], who analysed concentration measurements in an Alpine river during one entire summer, this value can be exceeded. To estimate the influence of the concentration of turbidity currents in the Livigno reservoir, an exceptional value of 30 g/l was also simulated. The form and time evolution for the concentration is also based on the same distribution as for the inflow hydrograph. The peak time for the concentration was considered to be 85 per cent of the peak time according to the inflow hydrograph. The density of sediments was adopted as $\rho = 2650$ kg/m^3 and the average diameter of grains, d_{50}, was assumed to be 21 μm [Huwyler, 2003[7]].

4. Technical solutions

In this study, two types of technical measures were outlined, to try to stop the turbidity currents in the West arm of the reservoir and thus to decrease the problem of sedimentation and its detrimental consequences on the critical parts of the hydraulic scheme. The proposed technical measures follow the ideas of Oehy [2003[4]]; they have both been validated in the laboratory flume (Fig. 4). Their possible locations in the reservoir are shown in Fig. 5.

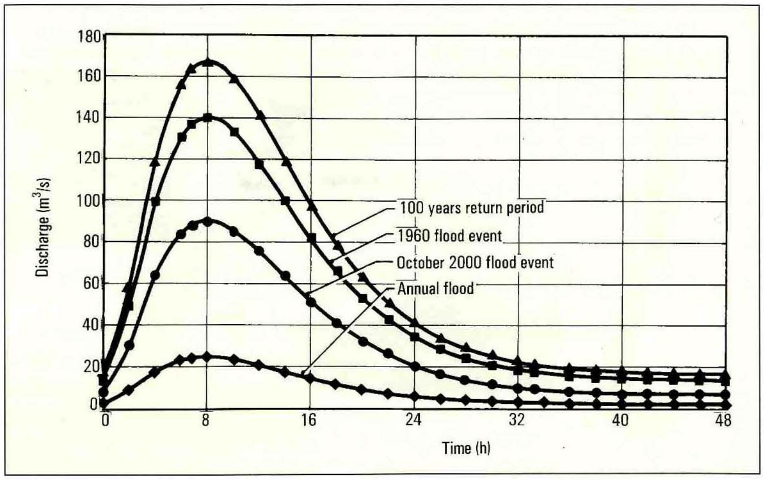


Fig. 3. Flood hydrographs used in the study.

4.1 Pervious rockfill dam

This alternative consists of an implantation of a pervious obstacle in the upstream part of the reservoir, almost 3 km downstream of the inlet of the Spöl river (Section 1). The obstacle would form a barrier to the sediments during the floods. At the maximum operation of the reservoir, at el. 1804.7, it will be submerged. The permeability of this dam should guarantee the emptying of the reservoir upstream during the lowering of the Livigno reservoir. It should also be resistant to overtopping during impounding. To estimate the volume of the construction material for this dam, its crest width was adopted as 2 m and the slope of the up- and downstream face as 2:1 (H:V). Thanks to its accessibility, this solution allows for the removal of deposited sediments upstream of the pervious dam.

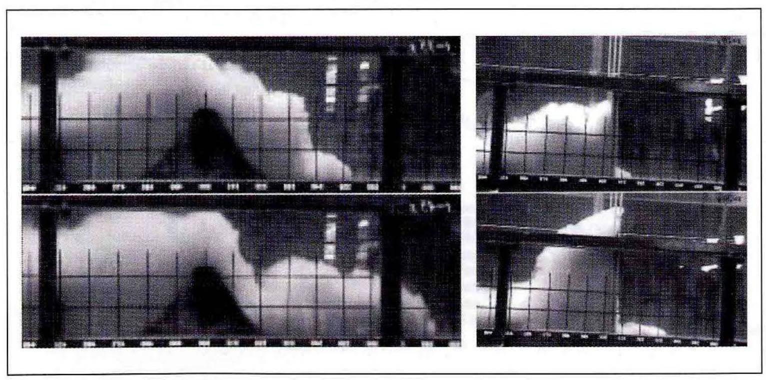


Fig. 4. Flow over an obstacle (left) and through a permeable screen (right) in the laboratory [Oehy, 2003[4]]. Flow is from left to right.

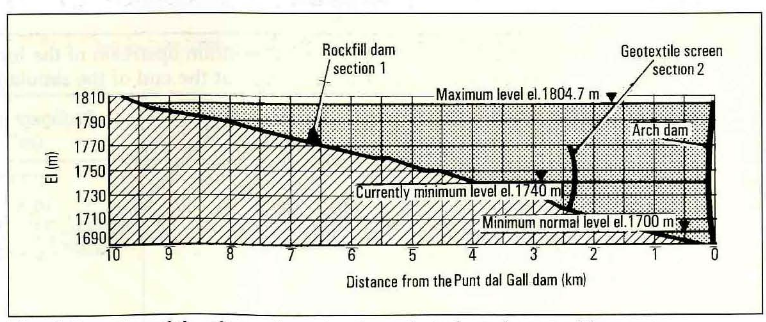


Fig. 5. Location of the alternatives, pervious obstacle and permeable screen.

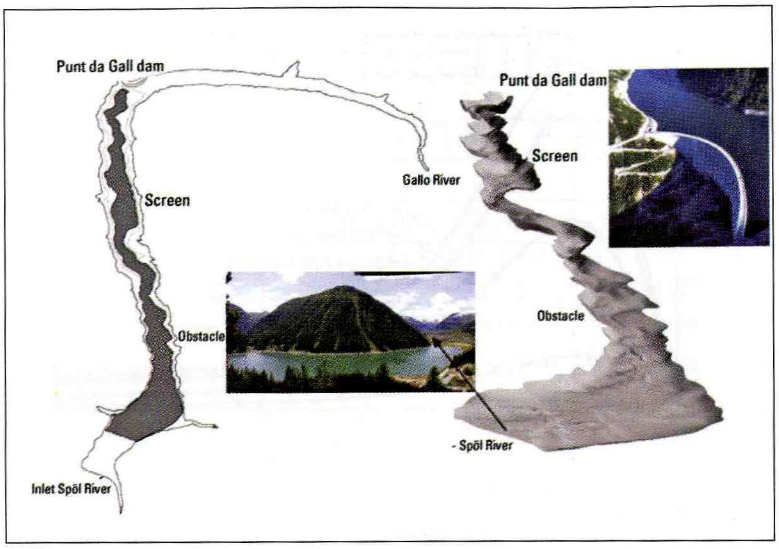


Fig. 6. Overview of the reservoir and computational domain for the study.

4.2 Permeable screen

Another solution is a geotextile screen inside the lake, approximately 2.5 km upstream of the Punt dal Gall dam (Section 2) to block the sediments brought by the turbidity currents.

After a first analysis of the deposition behaviour, this alternative proved not to be required.

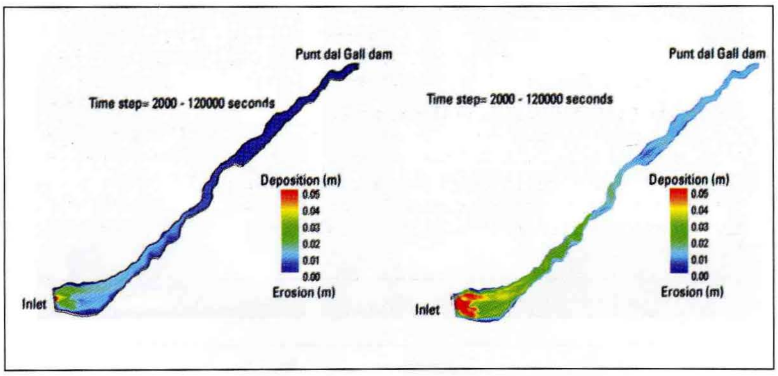
5. Validation using the 3D numerical model

5.1 Present situation

For the current situation of the reservoir, seven simulations were carried out: the 1960 and 2000 floods as well as the 100 year design flood were calculated with 15 and 30 g/l of maximum concentration, while the annual flood was only simulated with a sediment concentration of 15 g/l.

The computational domain for the calculations is shown in Fig. 6. The analysis was done after 33 h 20 min (120' 000 seconds) from the beginning of the flood. At this moment, the inflow concentration is practically 0 g/l and the inflow discharge has reached the base flow at the inlet. Fig. 7 shows the deposition of the sediments at the end of the simulation for the October 2000 flood event with 15 g/l of sediments and the 100 year design flood with 30 g/l, respectively.

Fig. 7. Sedimentation at the end of simulation for the October 2000 flood event with a maximum inflow concentration equal to 15 g/l (left) and the 100 year return period flood with a maximum inflow concentration of sediments 30 g/l (right).



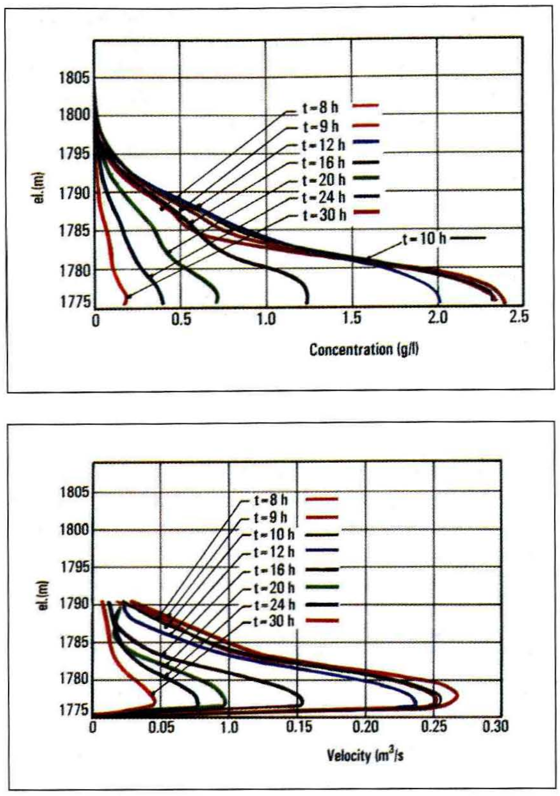


Fig. 8. Time evolution of the current in the cross section of the obstacle, concentration (above) and velocity (below).

The simulated turbidity currents caused by the floods can be considered to be sub-critical and non-conservative (the deposition is greater than the erosion) in all cases. In fact, there is no erosion in this reservoir as a result of turbidity currents. As shown in Table 1, approximately 60 per cent of the total deposited sediments occur in the first 3 km of the reservoir for all studied events, except for the annual flood, where 74 per cent is deposited within this reach. For all simulations, the quantity of sediments deposited on the hydraulic structures is not relevant. This can be explained by the weak slope of the inlet bottom (1.2 per cent) and the width of the inlet trumpet, which both decrease the velocity of currents and facilitate the deposition. The length of the reservoir is another factor reducing sedimentation close to the hydraulic outlet structures and the Punt dal Gall dam. The current loses its forces while flowing downstream as a result of water entrainment.

Table 1: Ratio between the deposition upstream of the local of implementation of alternatives and the total deposition in full West arm of the reservoir at the end of the simulations

Flood event	Concentration (g/l)	Sediment inflow (m^3)	Deposition upstream of Section 1	Deposition upstream of Section 2
Annual	15	4'730	74%	98%
	15	16'877	63%	94%
Octber 2000	30	33'375	60%	92%
	15	26'485	60%	92%
1960	30	52'971	58%	91%
	15	31'593	59%	91%
100 Years	30	63'187	58%	90%

The maximum depth of sediment deposition varies from 3 cm for the annual flood with a maximum inflow concentration of 15 g/l and 10 cm for the 100 year flood with a maximum inflow concentration of 30 g/l.

The volume deposited upstream of each location for the alternatives studied was compared with the total volume deposited at the end of the calculations in the entire West arm of the reservoir. Table 1 shows the behaviour of the deposition in the reservoir for the simulated scenarios.

According to this analysis of the present situation, the alternative of installing a geotextile screen is not a feasible option for this reservoir, since more than 90 per cent of the sediments settle upstream of its proposed location.

The evolution of the current at the Section 1 for the October 2000 flood event and maximum inflow concentration of 15 g/l is shown in Fig. 8. The peak of the current in this section occurs after 9 h of flood and with a maximum concentration of sediments equal to 2.4 g/l and a velocity of 0.25 m/s.

5.2 Pervious obstacle

For the simulation of a pervious dam in the reservoir, three heights were considered. The obstacles with 4, 8 and 12 m height were simulated based on the October 2000 flood event with the maximum concentration of sediments of 15 g/l. Table 2 shows the ratio of sedimentation for the various heights of obstacle studied, as well as the volume of material needed to construct the obstacles.

The performance of an obstacle against turbidity currents starts to be significant for the obstacles higher than 8 m. In this case, the sedimentation upstream of the obstacle increases from 63 per cent to 76 per cent for the 8 m-high obstacle and from 63 per cent to 87 per cent for the 12 m-high obstacle.

Fig. 9 shows the situation at the end of the simulation for the obstacles with 8 and 12 m heights.

The proposed obstacles are above the water level of the Livigno reservoir during the period of approximately end of January to mid-July.

6. Conclusions and recommendations

This paper presents the analyses of technical measures against sedimentation caused by the turbidity currents in the Livigno reservoir, owned by Engadiner Kraftewerk EKW. At first, two types of alternatives are outlined. A pervious rockfill dam placed some 3 km downstream of the main tributary mouth in the West arm of the reservoir, and a geotextile screen placed approximately 2.5 km upstream of the Punt dal Gall dam. The following flood events were considered in this study: the annual flood, the October 2000 flood with a return period of between 5 and 10 years, the highest ever measured flood of 1960 (30-40 years return period) and the 100 year flood with 15 g/l, and 30 g/l inflow sediment concentration.

Based on a 3D numerical simulation using CFX-4.4, it could be concluded that the present situation of the reservoir does not present a major sedimentation problem in the vicinity of the dam. Approximately 60 per cent of the sediment deposits during a flood occur in the first 3 km of the reservoir, which acts as a natural desilting basin, and about 90 per cent settle upstream of a proposed geotextile screen for all analysed events. Thus, a geotextile screen is not required. The maximum thickness of the deposits is less than 10 cm, even for the 100 year flood with a 30 g/l maximum inflow concentration.

Table 2 : Ratio between the deposition upstream, the implementation of alternatives and the total epostion in the full west arm of the resevoir at the end of the simulation for the different obstacles heights

Alternative	Volume of the rockfill dam (m^{3})	Deposition upstream of the cross section 1	Deposition upstream of the cross section 2
Present situation		60%	92%
Obstacle 4 m	1700	69%	95%
Obstacle 8 m	12 300	76%	97%
Obstacle 12 m	34 600	87%	99%

To improve the present behaviour of the reservoir with regard to sedimentation, an obstacle with three different heights was studied. The results of the flow simulations show that with a 8 m-high barrier, the volume of sediment deposits in the first 3 km of the reservoir increases to 76 per cent and with a 12 m height, the efficiency of this obstacle reaches 87 per cent. The maximum deposition attains some 5 cm upstream the obstacle for a single event. Because of the accessibility of the upstream area of the obstacle, removal of the sediment deposits can be organized if necessary over the years. A topographical survey before and after the implementation of the obstacle makes it possible to monitor its efficiency, and this is even simplified as a result of the annual lowering of the water level in the reservoir.

The proposed technical measures could form part of the sustainable sediment management process for the Livigno reservoir. ◊

Acknowledgements

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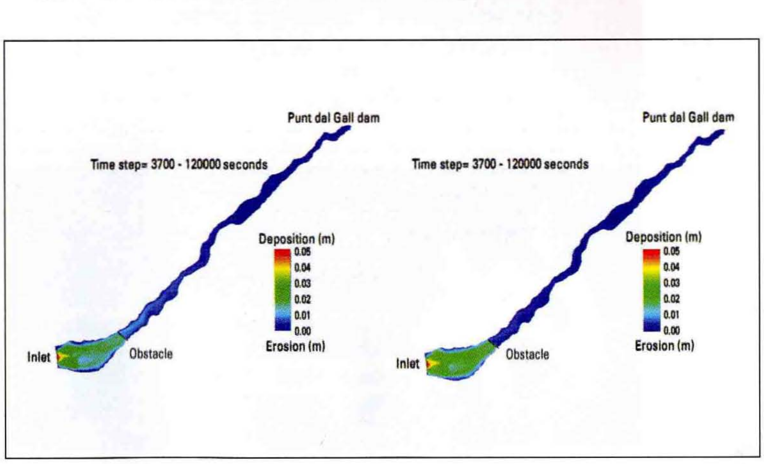

Fig. 9. Sedimentation considering obstacles with 8 m (left) and 12 m height (right) for the October 2000 flood event and maximum concentration of sediments 15g/l.

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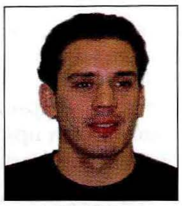

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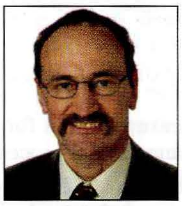

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