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Méthodes d'observation et de prévision de l'alluvionnement des retenues des aménagements de pompage-turbinage

Sustainable sedimentation in pumped storage plants

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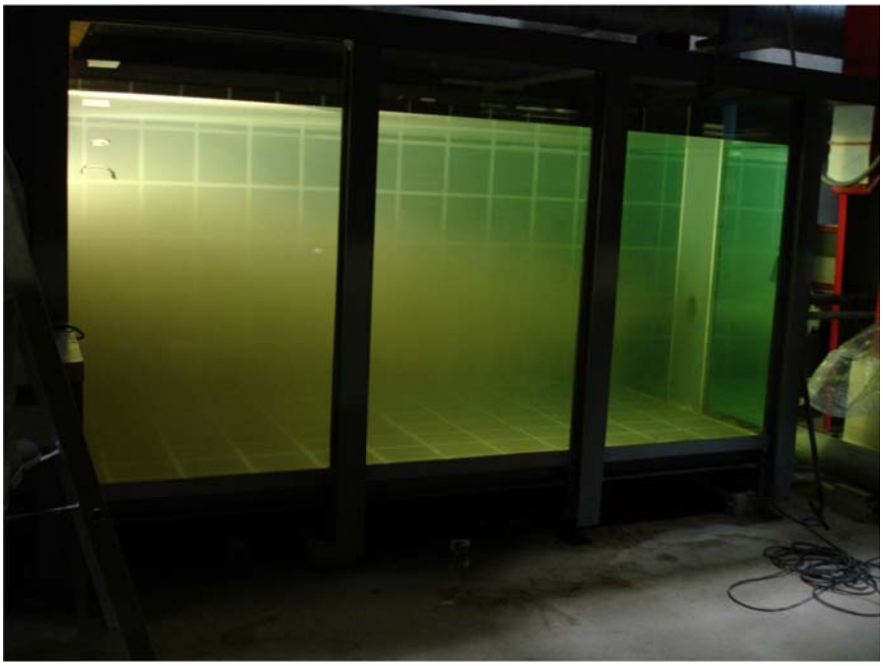
Rapport d'avancement 2010

Méthodes d'observation et de prévision de l'alluvionnement des retenues des aménagements de pompage-turbinage

(Sustainable sedimentation in pumped storage plants)



Lausanne, novembre 2010

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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Motivation et sommaire

Mots clés : *Sédimentation des réservoirs, aménagement de pompage-turbinage, turbulence, écoulements devant une prise, turbidité, ADCP, mesures sur prototype, modélisation physique, modélisation numérique, géométrie des prises d'eau*

La sédimentation des réservoirs conduit à des pertes de volume et affecte sérieusement la fiabilité, la durée de vie et l'exploitation des aménagements hydroélectriques. De plus, les dépôts sédimentaires devant les ouvrages essentiels des aménagements, à mentionner les prises d'eau et les vidanges de fond, mettent en péril la sécurité structurale. Comparés aux réservoirs crées par des barrages à l'échelle mondiale, qui se remplissent de sédiments à un taux d'environ 1% de leur volume utile par année, les réservoirs alpins suisses subissent d'un taux de sédimentation de 0.2% et sont donc plus durable du point de vue volume de stockage. Néanmoins, des courants de turbidité transportant des grandes quantités de sédiments en direction du barrage sous forme d'une avalanche sous-marine font, que les processus de sédimentation deviennent une menace non négligeable après 40 à 60 années d'exploitation.

Souvent, les bassins d'accumulation des aménagements hydroélectriques servent d'élément essentiel dans la protection contre les crues. Ils mettent à disposition un volume de stockage intermédiaire important, et donc permettent de laminer les crues et de protéger la population et les infrastructures situées à l'aval. En Suisse, le bassin versant du Rhône est un bel exemple d'une région composée de toute une série d'aménagements hydroélectriques qui, avec leurs réservoirs artificiels, font partie d'un système complexe de laminage de crues. Une perte de cette capacité de laminage par sédimentation aura des effets catastrophiques sur la vallée du Rhône lors des événements de crues.

D'autres domaines d'utilisation des réservoirs sont également concernés par les pertes de volume, notamment les fonctions de stockage d'eau pour l'approvisionnement en eau potable et pour l'irrigation. La sédimentation aggrave la future pénurie d'eau mondiale en réduisant la capacité des réservoirs déjà développés.

Contrairement à la sédimentation des bassins d'accumulation classiques, les processus de sédimentation dans les aménagements de pompage-turbinage sous l'influence des changements opérationnels répétés entre les modes de turbinage et de pompage sont relativement peu connu. Ce type d'aménagements hydroélectriques, se composant généralement d'un réservoir supérieur et inférieur afin de pomper et/ou turbiner l'eau entre ces derniers, gagnent d'importance à l'échelle suisse et mondiale afin de satisfaire la demande énergétique croissante.

Le projet de recherche présenté analyse l'influence des alternations modales de pompage-turbinage sur la concentration sédimentaire dans le système d'aménagement et sur les vitesses d'écoulement et la turbidité dans les réservoirs. Ainsi, il examinera des solutions pour garantir la sécurité des ouvrages d'évacuation et la durabilité à long terme des aménagements de pompage-turbinage.

Une réponse aux questions principales suivantes aimerait être trouvée: comment le processus de pompage-turbinage affecte-t-il la turbulence dans le réservoir ainsi que la sédimentation par des particules fines? Comment peut-on influencer la turbulence par les consignes d'exploitation ou la position de la prise d'eau afin de réduire le dépôt des sédiments fins?

Dans le cadre de cette thèse, les sujets suivants ont été traités pendant l'année passée:

- Une *étude de littérature* indiquait les paramètres d'intérêt primordial du problème et les pistes à conquérir.
- Des *bases théoriques* ont été établies afin de décrire les principaux processus physiques derrière les différents phénomènes en question.
- Les *mesures sur prototype* d'automne 2008 (vitesses devant une prise d'eau) ont été analysées et traitées pour décrire les conditions d'écoulement devant une prise d'eau en lac. Le puits blindé de l'aménagement Grimsel II a été équipé d'une sonde de turbidité permettant d'étudier la concentration en sédiments dans les conduites en charge d'un système de pompage-turbinage. En ce moment, les données sont enregistrées in situ et seront accessibles en ligne à partir de Janvier 2011.
- Le concept de la *modélisation physique à échelle réduite* a été développé, le modèle a été construit et son fonctionnement a été testé pendant des essais préliminaires purement hydrauliques. Actuellement, une évaluation de trois différents instruments de mesure est en cours, afin d'employer la technique la plus adaptée dans les essais systématiques. La modélisation physique servira de base pour étudier l'influence de la durée des séquences de pompage-turbinage, le débit et la position de l'ouvrage de restitution sur les processus de sédimentation.
- Une *modélisation numérique* des configurations d'essais préliminaires a été effectué. Grâce à la comparaison des résultats avec les essais hydrauliques, le modèle numérique pouvait être adapté et optimisé.
- La suite d'*analyse des mesures sur modèle et prototype* sera effectuée après le début des essais systématiques et la réception des premiers enregistrements de la sonde de turbidité.
- Basé sur l'analyse des résultats, un *modèle théorique et de nouvelles recommandations de conception* décrivant le comportement à long terme du transport sédimentaire et des dépôts dans les réservoirs exploités par des aménagements de pompage-turbinage seront développés. En particulier il est étudié comment l'exploitation et la position des ouvrages d'entrée et de sortie doivent être conçues pour obtenir un champ de turbulence favorable dans la retenue dans le but de réduire le processus de l'alluvionnement des sédiments en suspension.
- Une *publication scientifique* sera soumise à la fin de l'année 2010. Jusqu'à présent, le travail de recherche a été présenté lors de plusieurs conférences internationales et est décrit dans les proceedings correspondants. Le rendu du *rapport de thèse* est prévu pour fin 2011.

Le présent rapport décrit les objectifs de la thèse et résume brièvement les travaux effectués durant la période entre août 2009 et août 2010.

Motivation und Zusammenfassung

Stichwörter **:** *Verlandung von Stauseen, Pumpspeicheranlagen, Turbulenz, Strömungsfelder in Becken, Trübung, ADCP, Prototypmessungen, hydraulische Modellversuche, numerische Modellversuche, Geometrie von Ein- und Auslaufbauwerken*

Sedimentationsprozesse in Stauseen führen zu Kapazitätsverlusten und beeinflussen ernsthaft die Zuverlässigkeit und die Lebensdauer von Wasserkraftanlagen sowie die Kontinuität der Energieproduktion. Ablagerungen vor wichtigen Elementen wie Ein- und Auslaufbauwerken oder Grundablässen gefährden zudem die Sicherheit der Bauwerke. Während weltweit künstlich angelegte Staubecken jährlich rund 1% ihres nutzbaren Speichervolumens verlieren, weisen die Stauseen in den Schweizer Alpen eine niedrigere Verlandungsrate von 0.2% auf und sind folglich nachhaltiger im Bezug auf das verfügbare Speichervolumen. Trübeströme, die in Form einer Unterwasserlawine grosse Mengen von Sedimenten in Richtung Staumauer transportieren, führen jedoch dazu, dass die Ablagerungsvorgänge auch in Schweizer Stauseen nach 40 bis 60 Betriebsjahren Probleme bereiten.

Häufig spielen die Staubecken von Wasserkraftwerken zudem eine wesentliche Rolle im Hochwasserschutz eines Einzugsgebietes. Sie stellen ein grosses Zwischenspeichervolumen zur Verfügung und erlauben dadurch, Hochwasserspitzen zu brechen und die Bevölkerung und Infrastrukturen unterhalb der Anlage zu schützen. Das Rhonebecken bildet ein sehr gutes Beispiel für ein Einzugsgebiet in der Schweiz, welches durch eine Reihe von Wasserkraftwerken gekennzeichnet ist, die Teil eines komplexen Hochwasserschutzsystems sind. Ein Verlust dieser Speichermöglichkeit aufgrund von Stauseeverlandungen hätte bei Hochwasser katastrophale Auswirkungen auf das Rhonetal.

Weitere Anwendungsbereiche von Stauseen, beispielsweise die Speicherung von Wasser zur Trinkwasserversorgung oder zu Bewässerungszwecken, sind ebenfalls von Sedimentablagerungen betroffen. So verschärft der Kapazitätsverlust von bestehenden Speicheranlagen durch Sedimentation die zukünftige weltweite Wasserknappheit.

Im Gegensatz zur Sedimentation in herkömmlichen Kraftwerken sind langfristige Ablagerungsprozesse von Staubecken in Pumpspeicheranlagen unter Einfluss der stetig wechselnden Pump- und Turbiniersequenzen verhältnismässig unbekannt. Solche Kraftwerksanlagen, die im Allgemeinen aus einem oberen und einem unteren Reservoir bestehen, zwischen denen Wasser hin und her gepumpt wird, werden sowohl in der Schweiz wie auch weltweit stets wichtiger, um die steigende Energienachfrage zu befriedigen.

Das vorliegende Forschungsprojekt untersucht die Auswirkungen des abwechselnden Pumpspeicherbetriebs auf die Partikelkonzentrationen im System einer Anlage, sowie auf die Strömungsbedingungen und die Trübung in den Staubecken. Damit sollen Lösungen zu einem langfristigen und nachhaltigen Sedimentmanagement in Pumpspeicherkraftwerken gefunden werden.

Auf folgende Hauptfragen sollen Antworten gefunden werden: Wie beeinflusst der Pumpspeicherbetrieb die Turbulenz im Becken und die Ablagerung von Feinsedimenten? Wie kann die Turbulenz durch den Betrieb des Kraftwerkes und durch die Position der Ein- und Auslaufbauwerke beeinflusst werden, um das Absetzen feiner Sedimente zu reduzieren?

Im Rahmen der Doktorarbeit wurden dabei im vergangenen Jahr folgende Arbeiten durchgeführt:

- Eine *Literaturstudie* zeigte relevante Parameter auf und gab Forschungsanreize.
- Daneben wurden weiterhin *theoretische Grundlagen* erarbeitet, um die physikalischen Vorgänge der verschiedenen Phänomene zu beschreiben.
- Die Ende 2008 im Grimselsee getätigten *Messungen im Prototyp* (Geschwindigkeiten vor Ein- und Auslaufbauwerk) wurden ausgewertet, so dass die Strömungsbedingungen vor dem Bauwerk im See beschrieben werden konnten. Im Druckschacht des Kraftwerks Grimsel II wurde eine Trübesonde installiert, um die Partikelkonzentration in Abhängigkeit des Pumspeicherbetriebs zu analysieren. Die Daten werden derzeit vor Ort gespeichert, werden jedoch ab Januar 2011 online verfügbar sein und direkt zur Auswertung ans Institut gelangen.
- Die h*ydraulische Modellversuche* wurden konzipiert, die Versuchsanlage aufgebaut und deren Funktionstüchtigkeit in Vorversuchen mit Reinwasser überprüft. Zur Zeit werden drei verschiedene Messgeräte getestet, um in den systematischen Modellversuchen die bestmöglichen Resultate zu erhalten. Die Versuche sollen aufzeigen, wie die Dauer der Pumpspeichersequenzen, der Abfluss sowie die Position des Ein-/Auslaufs die Ablagerungsvorgänge im Becken beeinflussen.
- Im *numerischen Modell* wurden die Vorversuche gerechnet und durch einen Vergleich mit den Resultaten aus den hydraulischen Modellversuchen optimiert.
- Die weitere *Auswertung der Daten aus Labor- und Prototypmessungen* erfolgt nach Anlaufen der systematischen Modellversuchen und nach Erhalt der ersten Datensätze der Trübemessung im Kraftwerk Grimsel II.
- Basierend auf dieser Versuchsauswertung erfolgt die *Entwicklung eines theoretischen Modells und neuen Auslegungsregeln*, welche das langfristige Verhalten von Sedimenttransport und Ablagerungsprozessen unter wechselndem Pumpspeicherbetrieb beschreibt. Insbesondere wird der Frage nachgegangen, welcher Kraftwerksbetrieb und welche Position der Ein- und Auslaufbauwerke eine günstige Turbulenz im Stausee hervorrufen und damit das Absetzen der Feinsedimente verringern oder verhindern.
- Eine *Publikation* zur Veröffentlichung in einem wissenschaftlichen Journal wird Ende 2010 eingereicht. Bisher wurde die Forschungsarbeit anlässlich diverser internationaler Konferenzen präsentiert und in den jeweiligen Proceedings beschrieben. Das Einreichen der *Dissertation* ist auf Ende 2011 geplant.

Der vorliegende Bericht beschreibt die Ziele der Forschungsarbeit und fasst kurz den Projektfortschritt zwischen August 2009 und August 2010 zusammen.

Motivation and summary

Keywords : *Reservoir sedimentation, pumped storage hydropower plant, turbulence, flow fields in reservoirs, turbidity, ADCP, prototype measurements, physical modelling, numerical modelling, geometry of intake and outlet structures*

Sedimentation of dam reservoirs leads to storage loss and seriously affects the reliability and the lifetime of hydropower schemes. Deposits in front of essential elements, such as intake structures or outlet works, further endanger structural safety. Compared to dam reservoirs on a worldwide scale which present a storage loss of 1% per year, Swiss Alpine reservoirs silt up at a rate of only around 0.2% and therefore are more sustainable from the point of view of storage volume. Nevertheless, due to turbidity currents, transporting big amounts of sediments down to the dam like an underwater avalanche, the sedimentation process becomes a real threat after 40 to 60 years of operation.

In addition to hydropower production dam reservoirs are often an important element for flood protection strategies. They provide an intermediate storage and permit to reduce flood peaks and therefore to protect downstream population and infrastructures. In Switzerland, the Rhone River basin is a perfect example for a region characterized by a series of hydropower schemes along the main stream and its tributaries. With their artificial reservoirs, the power plants play an important role in a complex flood protection system. The loss of such storage due to sedimentation would result in catastrophic effects on the whole Rhone Valley in case of floods.

Other fields of exploitation of reservoirs, namely storage of drinking and irrigation water, are concerned by sedimentation processes which lead to reduced storage capacity. Sedimentation thus aggravates future worldwide water scarcity by reducing the storage from already developed supplies.

Compared to sedimentation in traditional hydropower schemes, long-term sedimentation issues of reservoirs in pumped storage plants under fast and repeated change of operations between generating and pumping modes are relatively unknown. Such projects, generally consisting of an upper and a lower reservoir in order to pump and/or turbine water between them, become more and more relevant on a worldwide scale to satisfy a continuously increasing energy demand.

The proposed PhD project investigates the influences of alternating pumping/generation modes on sediment concentrations throughout the whole scheme, and on flow fields and turbidity in the reservoirs. The main goal is to find solutions to guarantee long-term sustainability of pumped storage hydropower plants.

The following key questions are to be answered: how does the pumping and generating activity affect turbulence in the reservoir and sedimentation process by fine sediments? How could be influenced the turbulence by the operation mode of the plant and by the position of intakes and outlets in order to reduce settling down the fine sediments?

Thus, the following subtasks have been treated during the past year of the PhD project:

- A *literature study* pointed out the main parameters of interest of the problem.
- *Theoretical basis* were outlined with the main goal to describe the physical processes behind the different phenomena in question.
- *Prototype measurements* carried out in winter 2008 (velocity measurements in front of an intake/outlet structure) were analyzed in order to describe flow conditions in the reservoir next to the intake/outlet. The pressurized shaft of the Grimsel II plant has been equipped with a turbidity sensor which allows to study the sediment concentration as a function of pumping and generating operation. At the moment, data is acquired and stored in situ. By January 2011 it will be available online and can be accessed from the laboratory in Lausanne.
- The experimental setup for *physical scaled modelling* has been designed, the model has been built and its functionality has been approved during purely hydraulic preliminary tests. By now, three different measurement devices are tested and compared in order to employ the most effective technique in the systematic test runs. The hydraulic modelling is supposed to reveal how the duration of pumped storage sequences, discharge as well as the position of the intake/outlet affects settling processes by fine sediments in the reservoir.
- *Numerical modelling* was used during the preliminary tests and the comparison between calculations and results of the hydraulic modelling allowed adapting and optimizing the numerics.
- Further *analysis of model and prototype measurements* will take place after starting the systematic physical scaled modelling and after receiving data sets from the turbidity measurements at Grimsel II power plant.
- Based on the analysis of the test results the *theoretical model* and *new design guidelines* describing the long-term behaviour of sediment transport and deposition in a pumped storage hydropower scheme will be proposed. In particular, the question of how to design intake and outlet structures in order to obtain favorable turbulences in the reservoir in order to reduce settling down of the suspended sediments will be studied.
- One *scientific publication* will be submitted by the end of 2010. Until now, the research project has been presented in several international conferences and corresponding papers have been published in the conference proceedings. Submission of the *dissertation report* is planned by the end of 2011.

The present report resumes the main objectives of the PhD project and briefly describes the work accomplished during the period from August 2009 to August 2010.

1 RECALL

Pumped storage power generation has gained in importance since modern power plants are expected to operate at variable speed in a wide range of output power with improved efficiency, flexibility and safety. Such schemes allow storing and generating electricity to supply high peak demands by moving water back and forth between reservoirs at different elevations.

A project consortium called *HydroNet – Modern Methodologies for Design, Manufacturing and Operation of pumped storage power plants* aims to converge towards a consistent standardized methodology for design, manufacturing, operation, monitoring and control of pumped storage power plants in order to give new impulsions in the hydropower technology and maintain the strong position of Switzerland in peak hydropower production as well as in the exportation of high valued technology. *HydroNet* is funded by the *Competence Center Energy and Mobility* (CCEM) and *swiss electric research*.

As one of the partners of the *HydroNet* consortium, the *Laboratory of Hydraulic Constructions* (LCH) contributes with two PhD thesis in the civil engineering field. The present project consists in the description and the control of sedimentation issues in the reservoirs of pumped storage plants (Figure 1.1). Such storages are submitted to frequent exchanges of water during pumping and generating modes. The influence of alternating pumped storage activity and the geometry of the basin and the intake/outlet structures on the sedimentation processes are to be examined in prototype measurements, as well as in physical and numerical modelling.

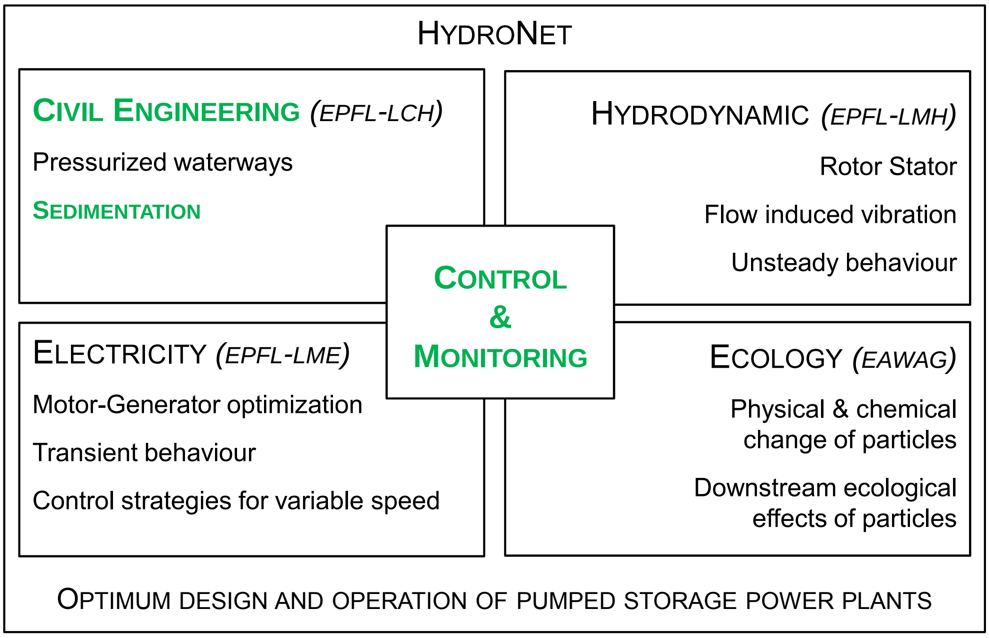


Figure 1.1 : *HydroNet* project consortium partners and main objectives

2 STATE OF THE ART AND CONTRIBUTION OF THE PHD PROJECT

2.1 State of the art

The state of the art in the field of reservoir sedimentation has been established based on a literature review during the first two years of the PhD project (refer to bibliography given in the report entitled ''Demande de subside'' submitted to OFEN by the end of 2008).

Sedimentation in hydropower plants leads to storage losses and to settling down of particles in front of intake/outlet structures and bottom outlets. Thus, it seriously affects sustainable operation of hydropower schemes and structural safety. Measures can be taken in the catchment area, in the reservoir or at the dam. A sustainable sediment strategy should also include the downstream reaches; therefore monitoring data should also include downstream impacts as well as sedimentation processes in the reservoir.

An integrated approach to sediment management that includes all feasible strategies is required to balance the sediment budget across reservoirs. The complete sediment problem and application of the range of sediment strategies as appropriate to the site has to be analyzed. The dam and other hydraulic structures have to be operated in a manner consistent with the preservation of sustainable long-term benefits.

At the present stage of the PhD thesis, the candidate focuses on literature concerning turbulence and jet phenomena, as well as sediment exchanges between two basins.

2.2 Contribution of PhD project

In contrary to traditional hydropower plants, the link between sedimentation problems and the more recent pumped storage hydropower projects remains poorly treated. Due to pumped storage operations suspended sediments are transferred from one reservoir of the system to the other. These sequences can create additional input of sediment and even artificial reservoirs with any natural sediment supply can fill up and suffer from storage losses. As the pumped storage activity is growing, flow conditions in the reservoir are alternating from one state to another during relatively short laps of time.

What are the effects of such changes between pumping and generating mode on the flow fields in reservoirs and consequently the behaviour of sediments? How toes the pumping/generating activity affect turbulence in the reservoir and sedimentation process by fine sediments? How can we use the turbulence introduced by the pumping and generating activity for hindering the suspended sediments to be settled?

Furthermore, how do parameters like discharge or duration of alternating pumping and generating mode affect the sedimentation processes in a reservoir? Can we predict sedimentation processes by controlling concentrations within the pipes relying two lakes? Are there conceptual solutions during the operation time of a pumped storage plant which allow to use the alternating pumping and generating activities in order to positively influence the reservoir sustainability? These are the key questions which are considered in the framework of this PhD thesis which will end to some practical applications, mainly:

- **Development of new theoretical model** based on the analysis of results of the physical scaled model and prototype measurements, describing the long-term behaviour of sediment transport and deposition in a pumped storage hydropower scheme.
- Relevant **monitoring methods** in order to predict sediment behaviour and concentrations throughout the whole scheme and for different hydraulic functions of the system.

The research plan of this project has been submitted to the Director of the ''Doctoral Program in Environment'' by November 2008. It was accepted by the dean of the doctoral school of the EPFL in January 2009.

3 RESULTS

3.1 Prototype measurements: Flow fields in front of Grimsel II intake/outlet

Prototype measurements and monitoring are an important part of the CCEM *HydroNet* project. In collaboration with the *Kraftwerke Oberhasli AG* (KWO) such data recording is carried out at Grimsel II pumped storage plant situated in the Central Alps of Switzerland (Figure 3.1). The underground powerhouse of this pumped storage scheme exploits water of the upper reservoir Lake Oberaar (2303 m a.s.l.) and the lower reservoir Lake Grimsel (1909 m a.s.l.).

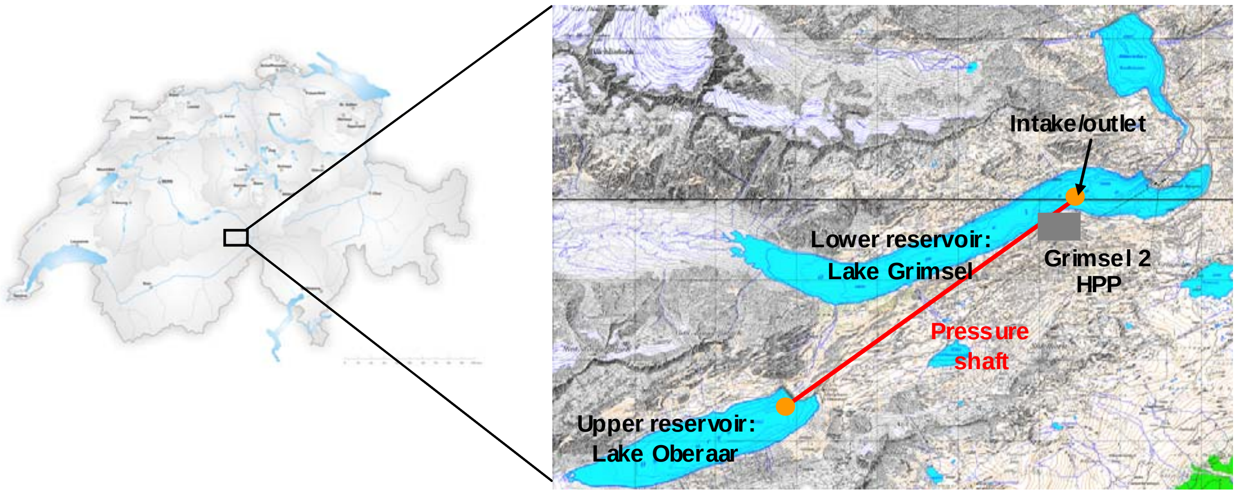


Figure 3.1 : Situation of the pumped storage scheme Grimsel II

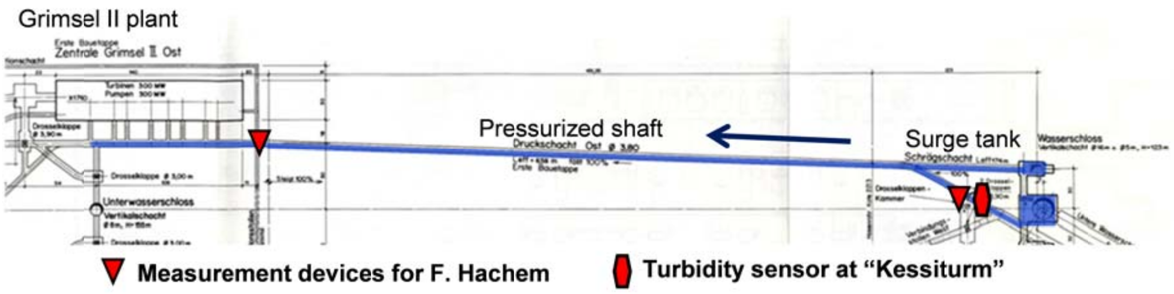
In September and November 2008, Acoustic Doppler Current Profiler devices (ADCP) had been implemented on the Lake Grimsel bottom in order to record flow velocities in front of the Grimsel II intake/outlet structure over a period of several weeks. Such measurements allow to observe eventual influences of the alternating pumping and generating modes between the upper and the lower reservoirs on the flow, as well as the influence of the geometry of the intake/outlet structure.

During the data acquisition periods, characteristic pumped storage cycles could be gathered, including short term (generating mode during the day, pumping at night) and midterm sequences (successive reservoir drawdown along the week, pumping activity during weekends). Time dependent flow fields observed during pumping and generating activity have then been presented graphically and compared to the expected main direction of the in- and out-flowing water (see publication in appendix 2: „Influence of pumped storage operation on flow conditions near intake/outlet structures: in situ measurement using ADCP").

A scientific paper describing the results of these prototype measurements and giving a comparison with results of a numerical model is in preparation.

3.2 Prototype measurements: Turbidity monitoring at Grimsel II power plant

Through several visits and discussions with the power producer KWO, a Zuellig Cosmos®-25 E sensor has been installed on a by-pass of the pressurized shaft at the shut-off valve “Kessiturm”, in the upper part of the pressurized shaft of the pumped storage hydropower plant of Grimsel II in Switzerland (Figure 3.2 and Figure 3.3). At this same location, pressure sensors, geophones and hydrophones sensors are installed (see “Rapport d’avancement 2010” submitted to OFEN by Fadi Hachem). Turbidity recording started on October 26th and the first version of the acquiring scheme is actually under testing process. Turbidity is registered every minute and can be downloaded from the industrial computer in situ. By the end of 2010, a fiber optic connection is planned to be installed by KWO in order to connect the acquisition system to the downstream measurement location of F. Hachem at the entrance of Grimsel II powerhouse. When this connection is established, the turbidity data can be retrieved on-line directly from the laboratory in Lausanne. At the moment, relevant discharge information available at the downstream acquisition system can already be controlled and downloaded by this way.



a) b) c)

Figure 3.2 : a) Measurement location for turbidity monitoring at shut-off valve “Kessiturm”, b) water extraction from the pressurized shaft, c) data acquisition system

Figure 3.3 : Zuellig turbidity measurement device

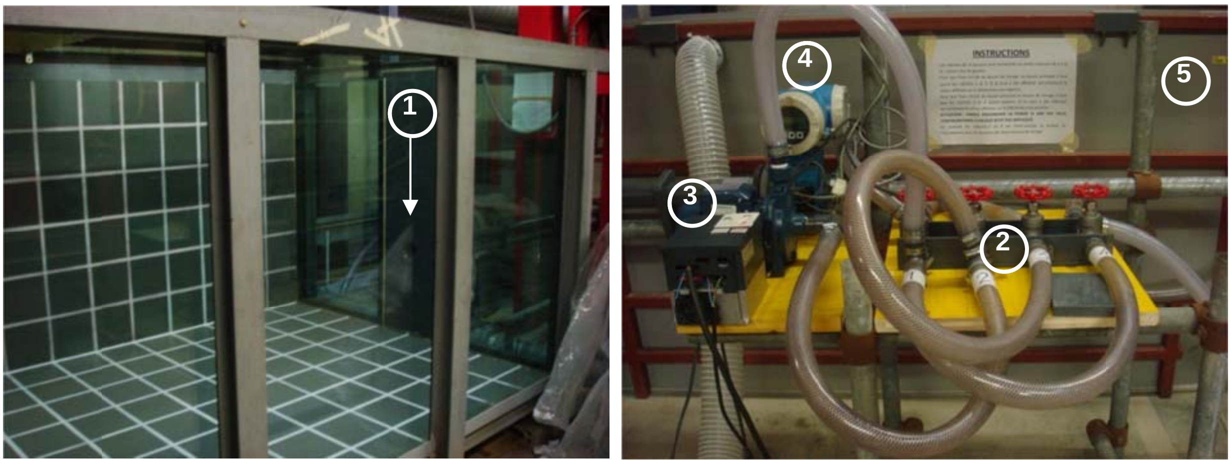
Thus, after a period of calibration and validation, the suspended load transported between the two reservoirs can be determined with the objective of observing influences of the pumped storage activity, water temperature and seasonal weather conditions.

3.3 Physical scaled model

Systematic tests on a physical scaled model are a key component of the present PhD thesis. These experiments will reveal how repeated changes of IN-OUT-sequences (corresponding to pumped storage activity in reality) affect turbulence in a reservoir. The influence of discharge, cycle duration, initial sediment concentration and intake/outlet position on flow velocities and settling down of fine sediments is investigated. During preliminary tests, a numerical model has been developed and results of the two models have been compared.

3.3.1 Experimental setup

In spring 2010, the design of the test rig has been developed. The experimental setup consists of a cuboidal main basin (Figure 3.4a) with a volume of 2.0 x 4.0 x 1.5 m^3 in which relevant measurements (flow velocities, turbidity and temperature) and filming are carried out. A smaller secondary 1.0 x 2.0 x 1.2 m^3 basin provides water and serves as mixing tank in which turbidity is recorded in order to study sediment exchange between the two basins.



a) b)

Figure 3.4 : a) Main basin of the physical scaled model, front wall with intake/outlet (1), b) reversible feeding circuit with flow diverter (2), pump (3) and flow meter (4). Secondary basin (5).

The two reservoirs are connected by a pump and a closed reversible conduit system (Figure 3.4b) allowing the simulation of the two exploitation directions defined as follows:

- *IN (Pumping)*: jet entering the main basin („outlet structure“)
- *OUT (Generating)*: water flowing out of the reservoir („intake structure“)

Flow is constant during the experiment and can be controlled by a flow meter. Model effects such as jet deflection at the outlet into the reservoir are reduced by the implementation of a rigid feeding pipe between the pump and the main basin and a trumped shaped intake/outlet structure.

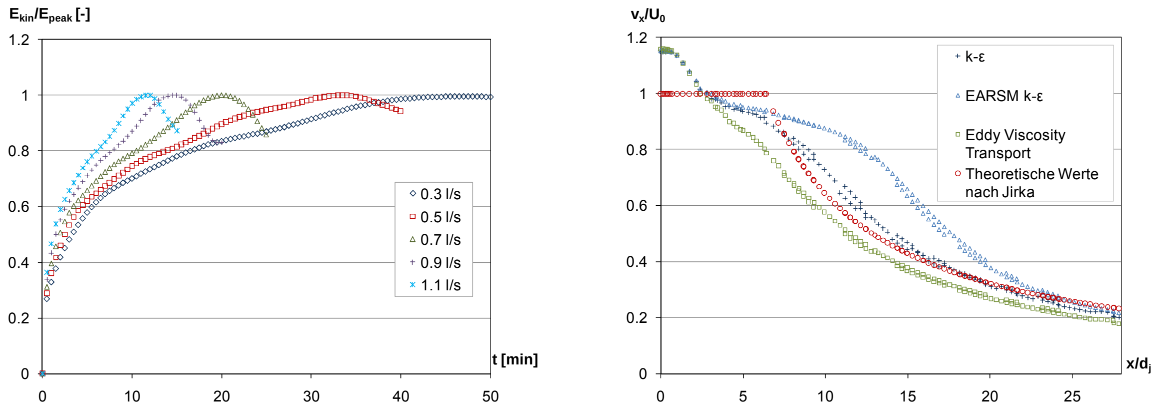
The fine sediments are represented by walnut shell powder in the physical model. Experiments in earlier PhD projects at LCH revealed satisfying characteristics and behaviour of this material for tests concerning reservoir sedimentation. At the beginning of each experimental run, the sediments are put in suspension by a bubble screen placed on the bottom of the basin.

3.3.2 Parameters

The following parameters will be varied from one test series to the other:

- *Discharge Q* : 0.3 to 1.1 l/s in five different steps
- *Initial sediment concentration* C_{init} : 0.3, 0.8 and 1.5 g/l
- *Position of intake/outlet* : 0.25, 0.50 and 0.75 m above the reservoir bottom

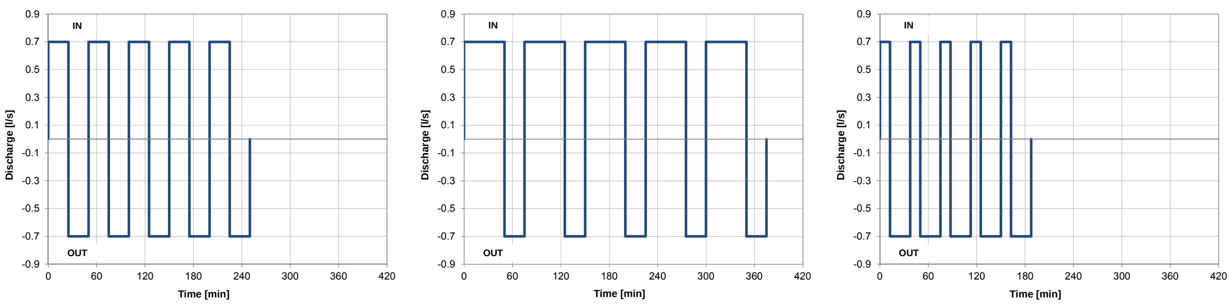
In order to define the specific *duration of the IN-OUT-sequences* a preliminary study has been carried out using numerical modelling (ANSYS software) and purely hydraulic tests on the physical model. A comparison between literature and the results of numerical simulations allowed to define the most adapted turbulence sediment settling model to be applied for the calculations (Figure 3.5b). The development of kinetic energy due to a jet entering the basin or water sucked out of the reservoir indicates the time necessary to reach stationary conditions in the latter. The time for which kinetic energy reaches its maximum is called T_P. Cycle durations of T_P = 10 to 40 minutes (model) have been found depending of discharge and operation mode (Figure 3.5a).



a) b)

Figure 3.5 : a) Development of E_{kin}/E_{peak} (IN-Cycle) as a function of time, b) axial velocity of the inflowing jet as a function of distance to outlet (U_0, d_i: jet velocity and diameter at outlet)

During experimental tests, repeated IN-OUT-Sequences are simulated as shown in Figure 3.6. Starting with the assumption that T_P is equal for the IN and for the OUT cycle, this parameter will then be varied to $T_{P,IN}$ / $T_{P,OUT}$ = 0.5 and 2.0, respectively, in order to take into account different duration of pumping and generating modes. Similarly, in order to investigate the influence of the time available for developing stable flow conditions in the basin additional tests with IN-OUT-sequences of 60%, 80% and 120% of T_P are carried out. Finally, some randomly generated IN-OUT-sequences will be simulated.



a) b) c)

Figure 3.6 : Example of IN-OUT-sequences applied in the physical scaled modelling, Q = 0.7 l/s
a) $T_{P,IN}$ / $T_{P,OUT}$ = 1.0, b) $T_{P,IN}$ / $T_{P,OUT}$ = 2.0, c) $T_{P,IN}$ / $T_{P,OUT}$ = 0.5

3.3.3 Measurement devices

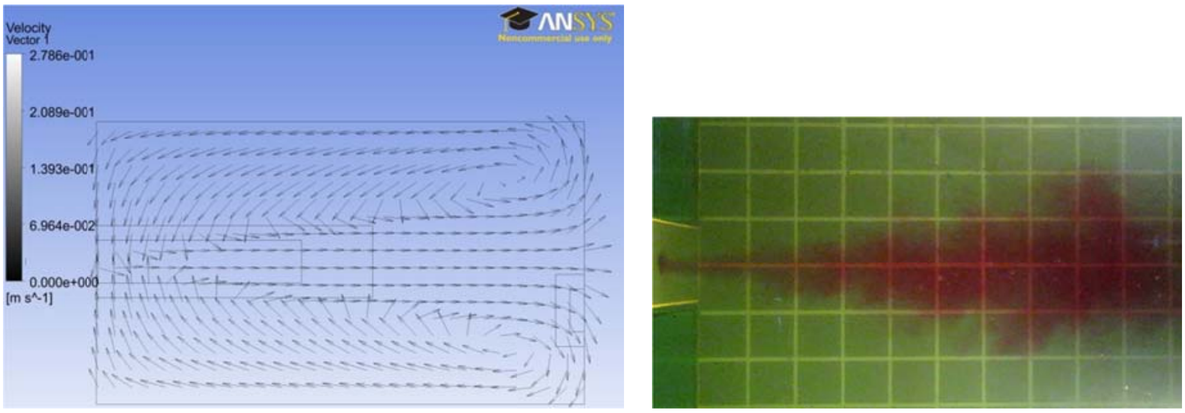
Ultrasonic Velocity Profilers (UVP) allow to measure velocity fields in the test basin and to describe the jet entering the reservoir, as well as the flow conditions in the reservoir. A supplementary study on the utility of three different UVP sensors is now carried out in the framework of a student project at LCH. The objective of this analysis is to find the most appropriate measurement device allowing to determine flow velocities in the entire basin with a minimum of time shift between each record.

During purely hydraulic tests, the inflowing jet has been visualized by color tracking and recorded by a zenithal camera in order to determine the UVP measuring grid necessary to capture the entire jet development.

Sediment concentration is measured in both the test reservoir and the mixing tank in order to determine which in- and out-flowing sequences lead to maximum sediment output.

3.3.4 Comparison of results of physical and numerical modelling

Purely hydraulic simulations reveal coherent results between the physical and numerical model. For the IN-cycle, the ANSYS calculations predict a stable jet entering straight into the basin for all discharges. This same phenomenon has been observed during the experiments on the physical model (Figure 3.7). The OUT-sequence is characterized by a uniform flow field directed towards the intake.



a) **b)**

Figure 3.7 : Jet entering into the main basin, Q = 0.5 l/s, t = T_P/4
a) Calculated flow field in the numerical model (at jet axis)
b) visualization in the physical scaled model (picture from above)

For tests with sediments, differences have been observed between the two models. When the jet entering into the basin is composed by a water-sediment-mixture it is slightly deflected towards the reservoir bottom. This phenomenon is amplified in the numerical model, which indicates that settling velocities are overestimated in the simulations. Therefore, the ANSYS model has to be adapted in order to be able to simulate test scenarios with sediments in an adequate manner.

4 OUTLOOK

4.1 Project timetable

The time schedule of the different project phases which are ongoing or which are to be accomplished during the next fifteen months can be given as follows:

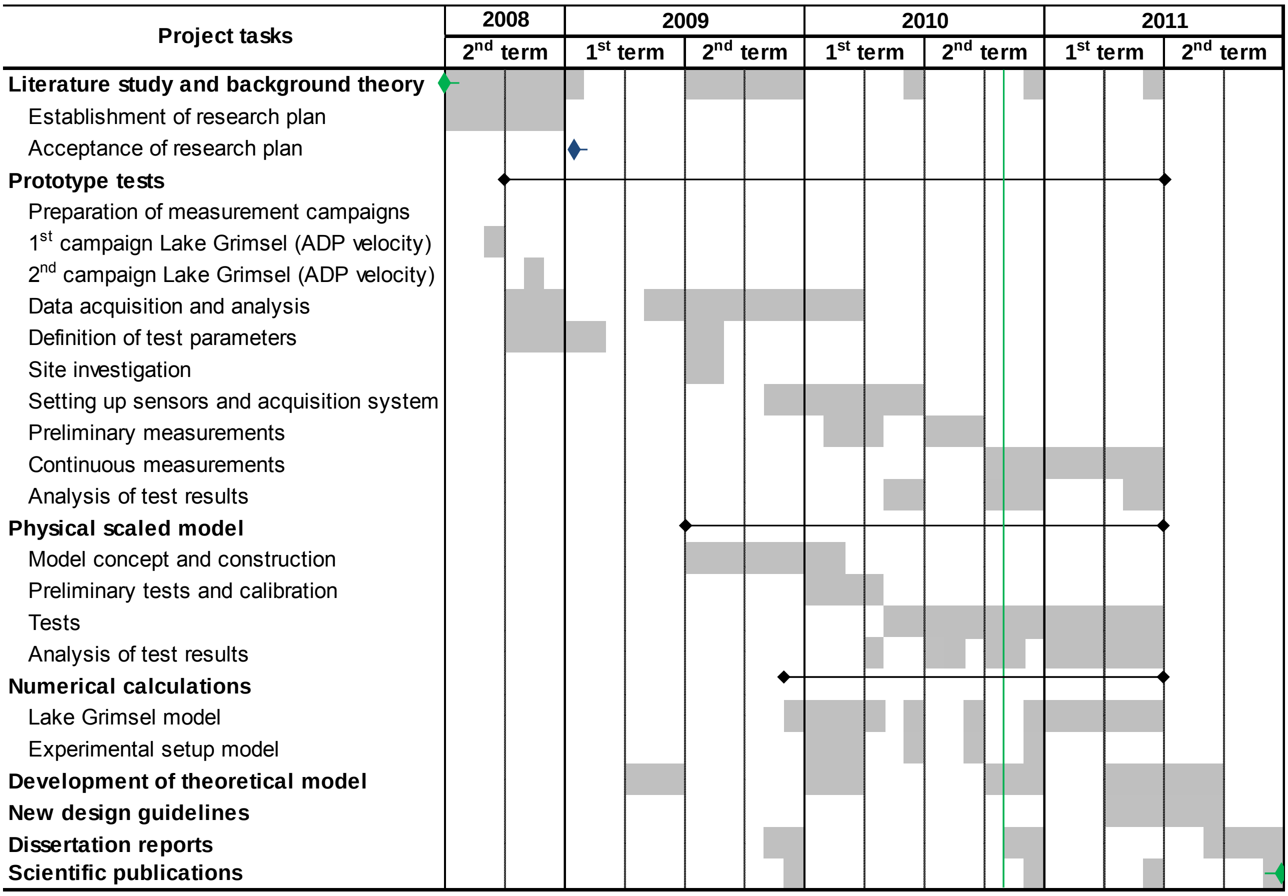


Figure 4.1 : PhD project schedule

4.2 Follow-up of the project

Beside the follow-up by the director of this research work, Prof. Anton Schleiss, the PhD thesis is closely supervised by the senior research associates, Dr Giovanni De Cesare, Dr Jean-Louis Boillat and Dr Michael Pfister. Accordingly, progress meetings are held regularly every six weeks, with the four afore mentioned people.

Every year, the progress state of the project is presented in the framework of an internal conference at LCH. The third presentation of the candidate has been given on the 30th of September 2010. An intermediate report has been submitted to the OFEN in August 2009 and an annual report has been handed in to the doctoral school in January 2010, a second will be prepared by the end of this year.

The multidisciplinary CCEM-consortium organizes periodical sessions (one or two per year), where information is shared, progress is discussed and common future work is defined. By now, five technical meetings have taken place.

5 PUBLICATIONS

Müller, M., Schleiss, A.J. (2009). *Monitoring und Vorhersage der Sedimentation in Pumpspeicherwerken*. 11. Treffen junger Wissenschafterinnen und Wissenschafter an Wasserbauinstituten, 26.-29. August 2009, Lausanne, Schweiz. Communication No 40 du Laboratoire de Constructions Hydrauliques, EPFL, S. 153-158, ISSN 1661-1179.

Müller, M., Schleiss, A.J. (2010). *Modellversuche zum Einfluss von Pumpspeichersequenzen auf Strömungsverhältnisse in einem quaderförmigen Becken.* 12. Treffen junger Wissenschafterinnen und Wissenschafter an Wasserbauinstituten, 11.-14. August 2010, Stuttgart, Deutschland. Mitteilungen Institut für Wasserbau, Universität Stuttgart, Heft 193, S. 72-78, Karolin Weber et al. (Hrsg.), ISBN 978-3-933761-97-2.

Müller, M., De Cesare G., Schleiss, A.J. (2010). *Influence of pumped storage operation on flow conditions near intake/outlet structures : in situ measurement using ADCP.* River Flow 2010, September 8-10, Braunschweig, Germany. River Flow 2010, Vol. 2, p. 1139-1146, Dittrich, Koll Aeberle & Geisenhaiener (eds), ISBN 978-3-939230-00-7.

6 APPENDICES

A.1 Artikel präsentiert beim 12. JUWI-Treffen, 11. – 14. August 2010, Stuttgart, Deutschland: „Modellversuche zum Einfluss von Pumpspeichersequenzen auf Strömungsverhältnisse in einem quaderförmigen Becken“

A.2 Conference paper presented at Riverflow 2010, September 8-10, Braunschweig, Germany: „Influence of pumped storage operation on flow conditions near intake/outlet structures: in situ measurement using ADCP”

A.1

Artikel präsentiert beim 12. JUWI-Treffen, 11. – 14. August 2010, Stuttgart, Deutschland:

„Modellversuche zum Einfluss von Pumpspeichersequenzen auf Strömungsverhältnisse in einem quaderförmigen Becken“

Modellversuche zum Einfluss von Pumpspeichersequenzen auf Strömungsverhältnisse in einem quaderförmigen Becken

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Kurzfassung

In systematischen hydraulischen Modellversuchen wird studiert, welchen Einfluss stetig wechselnde Pump- und Turbiniersequenzen auf die Turbulenz und die Ablagerung von Feinsedimenten in einem quaderförmigen Becken haben. Zudem wird untersucht, wie die Turbulenz durch Abfluss, Dauer der Pumpspeicherzyklen sowie Position der Ein- und Auslaufbauwerke beeinflusst werden kann, um das Absetzen von Feinsedimenten zu reduzieren.

Im Vorfeld der Laborversuche wurden erste Szenarien im numerischen Modell rein hydraulisch, dann mit Feinsedimenten simuliert. Der Vergleich der Resultate mit Beobachtungen im physikalischen Modell erlaubt, das Numerikmodell sowie die Versuchsanlage zu optimieren. Der vorliegende Beitrag beschreibt die Modellversuche, die Testanlage und die Resultate numerischer und hydraulischer Vorversuche.

Abstract

In systematic tests on a physical model, the influence of fast and repeated change of operations between generating and pumping modes on turbulence and sedimentation process by fine sediments in a rectangular cuboid is examined. It is studied how turbulence and settling down of fine sediments is affected by discharge, duration of pumped storage sequences and the intake/outlet location.

Prior to laboratory tests, several scenarios with and without sediments were simulated in a numerical model. A comparison between the results and observations on the physical model allows optimizing both numerical and experimental setup. The present paper describes the physical modeling concept, the test rig and presents results of the preliminary numerical and hydraulic tests.

1. Einleitung

Sedimentablagerungen in Speichern führen zu Stauvolumenverlusten und zur Bildung von Auflandungen vor Einlaufbauwerken oder Grundablässen. Sie gefährden damit die nachhaltige Nutzung von Wasserkraftanlagen sowie die Sicherheit der Bauwerke (Schleiss & Oehy 2002, Schleiss et al. 2010).

Eingebettet in das CCEM-Forschungsprojekt *HydroNet – a standardised methodology for pumped storage power plants* hat die vorliegende Forschungsarbeit zum Ziel, die Verlandungsproblematik spezifisch in Pumpspeicherkraftwerken zu untersuchen, um Lösungsansätze für die Überwachung und Vorhersage relevanter Sedimentationsphänomene in solchen Anlagen zu finden. Studiert wird insbesondere der Einfluss der im Betrieb stetig wechselnden Pump- und Turbinierzyklen auf die Turbulenz im Speicher und damit auf die Ablagerungsprozesse von Feinsedimenten.

Nach ersten Prototypmessungen auf der existierenden Kraftwerksanlage Grimsel II (Müller, 2009) werden nun in hydraulischen Modellversuchen Sedimentbilanzen, Strömungsbedingungen sowie Ablagerungsprozesse in einfachen Beckengeometrien untersucht. Im Vorfeld der systematischen Experimente wurden im Rahmen einer Masterarbeit am LCH erste Vorversuche durchgeführt, die zum Ziel hatten, ein numerisches Modell der Versuchsanlage zu erstellen und dessen Leistungsfähigkeit und Anwendungsgrenzen aufzuzeigen. In ersten Funktionstests auf der neu installierten Laboranlage wurden die Strömungsverhältnisse beobachtet und mit den Resultaten aus der Numerik verglichen.

2. Hydraulische Modellversuche

2.1 Grundkonzept

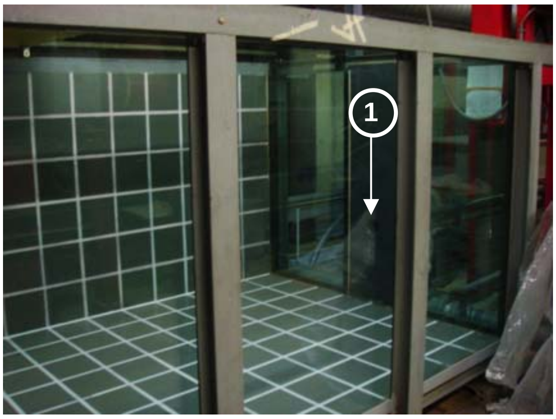
Die Laborversuche bilden die Grundlage des Forschungsprojekts. Testserien im hydraulischen Modell sollen Aufschluss darüber geben, wie wiederholte IN-OUT-Sequenzen (die in Realität den Pumpspeicherzyklen entsprechen) in Funktion des Abflusses, der Dauer, der initialen Sedimentkonzentration und der Position des Ein-/Auslaufbauwerks die Turbulenz in einem quaderförmigen Becken beeinflussen. In Abhängigkeit der oben genannten Parameter soll herausgefunden werden, welche Konfigurationen das Absetzen von Feinsedimenten zu reduzieren vermögen.

2.2 Beschrieb der Versuchsanlage

Das Hauptbecken der Anlage besteht aus einem quaderförmigen Stahlbehälter mit einer Grundfläche von 2.0 x 4.0 m^2 und einer Höhe von 1.5 m (Abb. 1a). Dieses kann als Oberbecken des Pumpspeicherwerks betrachtet werden. Die Front- und eine Seitenwand des Quaders bestehen aus Glas, um den Einblick in den Behälter und die Beobachtung der Strömungsbedingungen während der Experimente zu ermöglichen. Die restlichen Stahlwände wurden zur Auswertung des Bild- und Filmmaterials mit einem Raster von 25 x 25 cm versehen. Sämtliche Messungen (Strömungsgeschwindigkeiten, Temperatur Trübung) und Aufzeichnungen (Filme, Fotos) werden in diesem Becken vollzogen.

Ein kleineres Becken mit einem Volumen von 1.0 x 2.0 x 1.2 m^3 stellt die für die Versuche benötigte Wassermenge zur Verfügung. In diesem Behälter wird die

Trübung des Wassers gemessen, um den Sedimentaustausch zwischen den beiden Becken zu studieren.

a) 

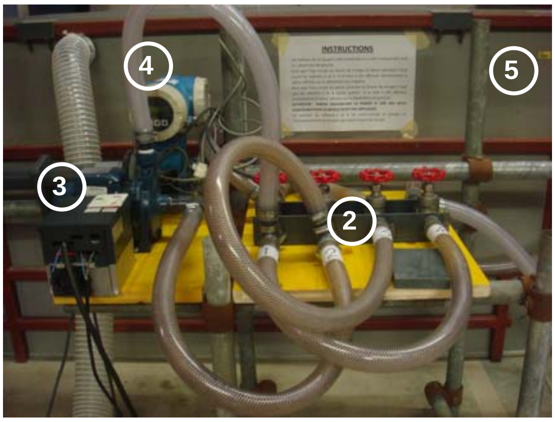
b) 

Abbildung 1: a) Hauptbecken der Anlage, Frontseite mit Ein-/Auslaufbauwerk (1)
b) Reversibler Speisungskreislauf mit Verteiler (2), regulierbarer Pumpe (3) und Durchflussmesser (4). Im Hintergrund: Sekundärbecken der Anlage (5)

Während der Versuchsvorbereitung werden die beiden Becken aus dem laboreigenen Wasserkreislauf gespiesen und danach von letzterem abgekoppelt. Die Testreihen werden dann in einem reversiblen, geschlossenen Wasserkreislauf (Abb. 1b) durchgeführt, wobei die beiden Betriebsrichtungen des Systems folgendermassen definiert sind:

- *IN (Pumpen)*: ins Becken eintretender Wasserstrahl („Auslaufbauwerk“)
- *OUT (Turbinieren)*: Wasserentnahme aus dem Becken („Einlaufbauwerk“)

Die zu- und abgeführte Wassermenge wird mithilfe eines Geschwindigkeitsregulators der Pumpe konstant gehalten und mit einem Durchflussmesser kontrolliert. Das Leitungssystem zwischen Durchflussmesser und Mischbecken besteht aus beweglichen Plastikrohren. Die Zuleitung ins Hauptbecken erfolgt über ein 1.0 m langes, starres PVC-Rohr von 4.8 cm Innendurchmesser, das auf der Frontseite des Quaders an ein aus strömungstechnischen Gründen trompetenförmiges Ein-/Auslaufbauwerk anschliesst (Abb. 2a und b).

a) 

b) 

c) 

Abbildung 2: a) Zeichnung und b) Foto des trompetenförmigen Ein-/Auslaufbauwerks
c) Im Modell als Feinsedimente verwendete gemahlene Baumnussschalen

2.3 Sedimente

Für die Sedimentversuche im hydraulischen Modell werden gemahlene Wallnussschalen gewählt (Abb. 2c). Diese sind nahezu kohäsionslos, leicht (spezifisches Trockengewicht ρ_s = 1480 kg/m^3) und homogen. Ihre geringe Dichte erlaubt ein ähnliches Verhältnis zwischen Strömungsgeschwindigkeiten im Behälter und Absetzgeschwindigkeit der Sedimente wie in natura herzustellen. Der mittlere Durchmesser des verwendeten Materials liegt bei d_m = 120 μm.

Die Sedimente können zu Versuchsbeginn in beiden Becken durch am Behälterboden zugeführte Druckluft aufgewirbelt werden, so dass eine homogene Wasser-Sediment-Mischung gewährleistet wird.

2.4 Parametervariationen

Die hin und her gepumpte Wassermenge variiert im Modell zwischen 0.3 und 1.1 l/s, wobei insgesamt fünf verschiedene Abflüsse getestet werden. Das Niveau des Ein-/Auslaufs kann auf drei Höhen, 0.25, 0.5, oder 0.75 m über dem Behälterboden, eingebaut werden. Drei unterschiedliche initiale Sedimentkonzentration von 0.3, 0.8 und 1.5 g/l in den Becken erlauben, den Einfluss des Feinstoffs zu evaluieren. Schlussendlich bleibt festzulegen, wie lange die jeweiligen IN-OUT-Sequenzen zu dauern haben. In den nachfolgend beschriebenen Vorversuchen wurde zu diesem Zweck die Zeit definiert, die benötigt wird, um ein stationäres Geschwindigkeitsfeld im Hauptbecken zu erreichen.

3. Resultate der Vorversuche

3.1 Numerische Simulationen

Die numerischen Simulationen wurden mit der ANSYS-Software durchgeführt, wobei das Modell das Hauptbecken mitsamt Ein-/Auslaufbauwerk und starrem Zuflussrohr abbildet. Die rein hydraulischen Simulationen dienten zur Definition der im Labor anzuwendenden Zyklendauer und zum Vergleich verschiedener Turbulenzmodelle.

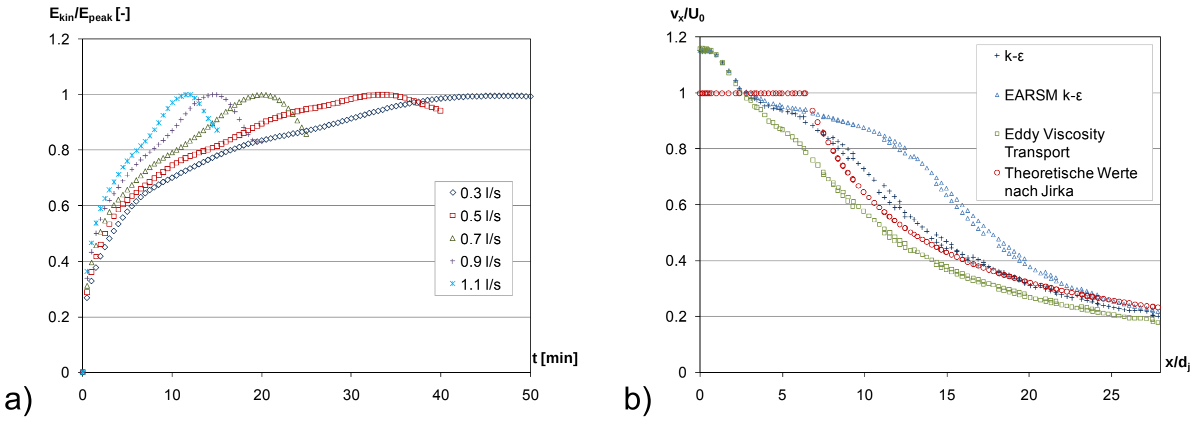


Abbildung 3: a) Zeitliche Entwicklung von E_{kin}/E_{peak} (IN-Zyklus)
b) Axialgeschwindigkeit des einströmenden Jets in Funktion der Distanz zum Einlauf
(U_0, d_j: Strahlgeschwindigkeit, resp. Strahldurchmesser am Austrittsquerschnitt)

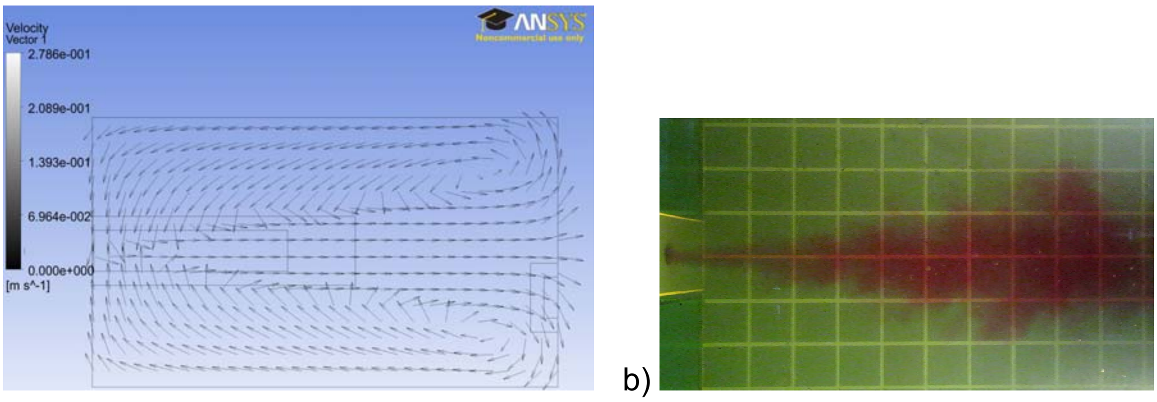
Als Indikatoren des benötigten Zeitschritts Δt im numerischen Modell und der Zyklendauer wurden die kinetische Energie E_{kin} sowie die turbulente kinetische Energie $E_{kin,turb}$ des Testvolumens verwendet. Ein Δt von 5 s ist erforderlich, um zuverlässige Resultate zu erhalten, wobei vor allem $E_{kin,turb}$ erst bei relativ kleinen Zeitschritten gegen einen konstanten Wert strebt. Die Abbildung 3a illustriert die zeitliche Entwicklung des adimensionierten Indikators E_{kin}/E_{peak} (*IN-Sequenz*) für verschieden Abflüsse. Die Versuchsdauer T_P bis zum Erreichen eines stationären Strömungsfeldes im Becken (E_{kin}/E_{peak} = 1) beträgt demnach 10 bis 40 Minuten.

Der Vergleich der Geschwindigkeitsprofile quer zur Strahlachse und der Entwicklung der Axialgeschwindigkeit v_x/U_0 des Strahls mit den von Jirka (2004) beschriebenen Werten zeigt, dass sich ein k-ε-Turbulenzmodell am besten eignet (Abb. 3b). Beide Strahleigenschaften werden sowohl für hohe, als auch für kleine Abflüsse zufriedenstellend abgebildet. Die erhöhte Axialgeschwindigkeit beim Eintritt ins Becken ($v_x/U_0 > 1$) ist durch eine nicht exakt symmetrische Verteilung der Eintrittsgeschwindigkeit des Strahls im Modell bedingt.

Schliesslich wurden zwei Abflusskonfigurationen mit Zugabe von Feinsedimenten getestet, wobei ein Wasser-Sediment-Gemisch in klares Wasser im Hauptbecken strömt. Die Absetzvorgänge basieren auf der Schiller-Naumann-Gleichung, die den Widerstandskoeffizienten in Abhängigkeit der Reynoldszahl beschreibt.

3.2 Vergleich der Resultate aus Numerik und physikalischem Modell

Die Versuchszenarien ohne Feststoffzugabe zeigen kohärente Resultate zwischen den beiden Modellen. Für den IN-Zyklus sagt die Numerik einen stabilen, geradlinig ins Becken eintretenden Wasserstrahl voraus, der im physikalischen Modell ebenso beobachtet werden kann (Abb 4). Die Wasserentnahme aus dem Hauptbecken verursacht in beiden Modellen ein sehr lokales potentielles Geschwindigkeitsfeld in unmittelbarer Nähe des Einlaufbauwerks, wobei das restliche Wasservolumen quasi stagniert. Die Strömungen können in der Versuchsanlage mit Farbstoff, oder mit sich in Strömungsrichtung orientierenden Nylonfäden nachgewiesen werden.



a) b)

Abbildung 4: Ins Hauptbecken eintretender Wasserstrahl, Q = 0.5 l/s, t = T_P/4
a) Berechnetes Geschwindigkeitsfeld im numerischen Modell (Höhe Strahlachse)
b) Visualisierung durch Farblösungzugabe im hydraulischen Modell (Zenithalfoto)

Beim Eintritt des sedimentbeladenen Strahls in klares, ruhendes Wasser tritt ein deutlicher Unterschied auf zwischen simuliertem und im physikalischen Modell beobachtetem Strömungsbild. Im Gegensatz zur Numerik zeigt der Wasserstrahl im Labor eine geringere Tendenz des Absenkens in Richtung Beckenboden, was auf eine zu hohe Absetzgeschwindigkeit im numerischen Modell hinweist.

3.3 Schlussfolgerungen und Ausblick

Die Vorversuche haben gezeigt, dass die Numerik die Strömungsverhältnisse in klarem Wasser ausreichend genau abbildet. Trotzdem sind Langzeitsimulationen nötig, um zu zeigen, dass der stationäre Zustand im numerischen Modell effektiv erreicht wird. Die gerechneten Geschwindigkeitsfelder werden im hydraulischen Modell durch UVP-Messungen (Ultrasonic Velocity Profiler) überprüft und das ANSYS-Modell allenfalls überarbeitet.

Da Sedimentversuche in der vorgestellten Forschungsarbeit von zentraler Rolle sind, muss die Funktionsweise des numerischen Modells für diese Szenarien optimiert werden. In zukünftigen Experimenten wird dabei auch das Hauptbecken eine initiale Feststoffkonzentration aufweisen, damit studiert werden kann, für welche IN-OUT-Sequenzen und für welche Parameterkonfiguration ein maximaler Sedimentaustrag aus dem Becken erreicht werden kann.

Verdankung

Das vorliegende Forschungsprojekt wird vom *Competence Center Energy and Mobility* (CCEM), *swiss electric research* und *swiss energy – hydropower research* (Bundesamt für Energie) finanziert. Die Autoren danken allen Partnern für ihr Engagement.

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A.2

Conference paper presented at Riverflow 2010, September 8-10, Braunschweig, Germany:

„Influence of pumped storage operation on flow conditions near intake/outlet structures: in situ measurement using ADCP“

Influence of pumped storage operation on flow conditions near intake/outlet structures: in situ measurement using ADCP

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ABSTRACT: In the framework of a research project studying the influences of pumping/turbine modes on turbulence, flow fields and suspended sediments in reservoirs, prototype measurements are carried out at the Grimsel II pumped storage plant (Switzerland). In situ recordings comprise flow and velocity patterns in the lower reservoir. For the measurement of flow velocities, Acoustic Doppler Current Profiler (ADCP) devices have been fixed on the reservoir bottom in front of the intake/outlet structure. The temporal evolution of three-dimensional velocity profiles in front of the intake is compared to the operation data provided by the hydropower producer. Flow fields corresponding to the expected main direction of the in- and out-flowing jet are observed during both pumping and generating activity. Periods, where their orientation and the expected main direction of the jet do not correspond clearly are studied in more detail, splitting up data series in characteristic sequences and applying frequency analysis. Such signal processing reveals the correlation between the velocity profiles in front of the intake/outlet and the change between pumping and turbine mode.

Keywords: Pumped storage hydropower plant, reservoir sedimentation, turbulence, flow and velocity patterns in reservoirs, Acoustic Doppler Current Profilers

1 INTRODUCTION

Modern power plants are expected to operate at variable speed in a wide range of output power with improved efficiency, flexibility and safety. Therefore, the pumped storage power generation has gained in importance since it allows storing and generating electricity to supply high peak demands by moving water back and forth between reservoirs at different elevations.

In the context of a project consortium called *HydroNet – Modern Methodologies for Design, Manufacturing and Operation of pumped storage power plants* aiming to converge towards a consistent standardized methodology for design, manufacturing, operation, monitoring and control of pumped storage power plants, a research project consists in the description and the control of sedimentation issues in the reservoirs of such hydropower schemes.

Reservoir sedimentation and the main measurements against reservoir sedimentation are well described (Morris et al., 2008, Nicklow, 2000, De Cesare et al., 2005, Morris, 1996, Oehy, 2002). However, the direct link between sedimentation problems and the more recent pumped storage hydropower projects remains poorly treated. Due to pumped storage operations suspended sediments are transferred from one reservoir of the system to the other. As the pumped storage activity is growing, flow conditions in the reservoir are alternating from one state to another during relatively short laps of time.

What are the effects of such changes between pumping and generating mode on the turbulence in the reservoirs and consequently the sedimentation process by fine sediments? How do discharge and duration of pumped storage operations affect the sedimentation processes in a reservoir? Are there conceptual solutions during the operation time of a pumped storage plant which allow using the alternating pumping and generating activities to positively influence the reservoir sustainability?

These are some of the questions which are to be examined in physical and numerical modeling in the framework of the Ph.D. thesis. As the *HydroNet* project focuses on prototype monitoring and control, fundamental research is completed with in situ measurements.

Such prototype data collection was carried out in autumn 2008 on the occasion of two field campaigns. With the objective of investigating flow conditions near an intake/outlet structure of a pumped storage plant, Acoustic Doppler Profilers were placed on the reservoir bottom, recording flow velocities over a period of three weeks. After data extraction, three-dimensional velocity profiles are established, their temporal evolution is compared to the pumped storage operation data provided by the power producer, and correlation between the flow fields in front of the intake/outlet structure and the pumped storage activity is studied.

The present paper covers the main characteristics of the study site and the measuring device and discusses the results of these first in situ recordings.

2 METHODS AND ANALYSIS

2.1 *Prototype characteristics*

In collaboration with the Swiss power producer *Kraftwerke Oberhasli AG (KWO)* prototype data recording and monitoring is carried out at the Grimsel II pumped storage plant, situated in the Central Alps of Switzerland downstream of the two glaciers of Ober- and Unteraar and upstream of Lake Brienz (Figure 1).

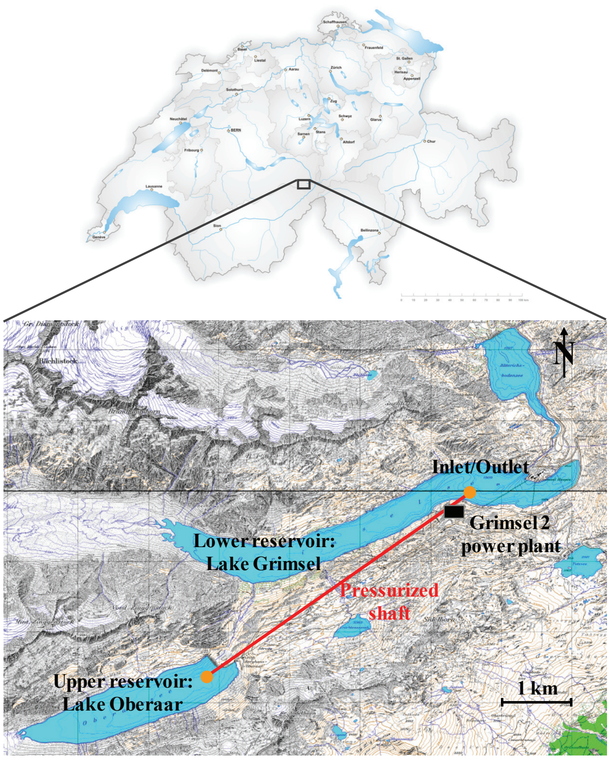

Figure 1. Location map and situation of the pumped storage scheme Grimsel II, Switzerland

The underground powerhouse of this pumped storage plant exploits water of the upper reservoir Lake Oberaar (2303 m a.s.l.) and the lower reservoir Lake Grimsel (1909 m a.s.l.), where the present study of flow conditions near intake and outlet structure has been carried out. Lake Grimsel, impounded by the Spittellamm arch dam and the Seeuferegg gravity dam, is characterized by a surface of 2.72 km^2, a gross storage volume of 95 × 10^6 m^3 and a maximum depth of 100 m.

The major driving forces for sediment movement in narrow and rather steep alpine reservoirs such as Lake Grimsel are turbidity currents (Fan & Morris, 1992, De Cesare et al., 2001, Schleiss & Oehy, 2002). This mechanism, mainly occurring during flood events and transporting large amounts of suspended sediments to the deepest zones of the reservoir near the dam, has been investigated and applied to the lower reservoir of Grimsel II power plant by Oehy (2002).

The Lake Grimsel intake/outlet is characterized by a shape similar to a morning glory spillway embedded in a recess of the lake topography with its foundation platform situated at a level of 1942 m a.s.l. The lateral open cylinder has an effective height of 6.25 m and a diameter of 21.70 m and is equipped with ten guiding walls which are supposed to distribute the out-flowing discharge equally on the ten side openings of the tulip (Figure 2).

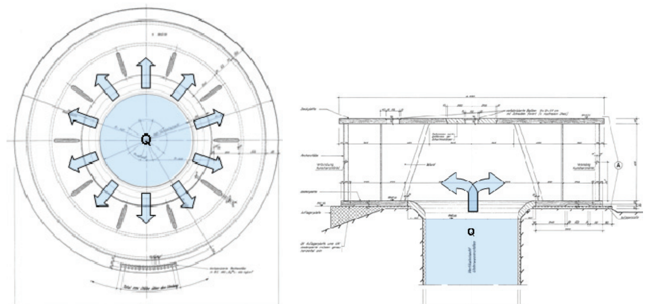

Figure 2. Grimsel II intake/outlet structure in Lake Grimsel; schematic plan view (left) and cross section (right)

The connection to the Grimsel II powerhouse is assured by a pressure conduit of 7.50 m in diameter which, during generating activity, ejects discharges up to 100 m^3/s through the cylinder and into Lake Grimsel. During pumping mode, a maximum discharge of 80 m^3/s is ingested by the intake structure and led to the four pumped storage units of Grimsel II.

2.2 *Data collection*

2.2.1 *Acoustic Doppler Current Profilers*

3D flow velocity data was collected by using three 300 kHz Acoustic Doppler Current Profilers (ADCPs). The three Teledyne RDI units were frame-mounted and placed on the bottom of the Grimsel reservoir. In early autumn 2008, the ADCP data were recorded for 5 days from September 15th to 20th. In November 2008, sampling went on for two more weeks from November 6th to 20th.

The RDI profilers covered the whole water column and operated with 85 1-meter size bins and recorded mean currents every 5 minutes. The mooring of the device on the bottom and the blind zone of the instrument place the first bin at about 5.0 m above the lake bottom. Since acoustic backscattering at the free surface strongly disturbs current data for the bins near the surface, the last bins were omitted. Consequently, current profiles from 5.0 m up to 80 m above the lake bottom (depending on the reservoir level) were recorded. Horizontal velocity resolution is better than 0.12 m/s in this configuration.

2.2.2 *Profiler position*

The location of the ADCP near the intake/outlet structure takes into account implementation criteria for the RDI units. Minimal distance of 25 m from the intake/outlet structure and 5 m below the horizontal intake axis limits interference between the emitted beam and the concrete civil engineering works. Sidelobe interference between the instruments can be limited by respecting a distance of 50 m between two profilers.

Furthermore, the alignment of the three ADCPs is based on the intake/outlet geometry. It is assumed that at the ten outlet sectors shown in Figure 2 the main direction of the out-flowing jet corresponds to the axis of these sectors. Hence, measurement axes are orientated in this same direction as the axes of intake/outlet sectors.

However, Lake Grimsel bathymetry is the main parameter governing the implementation position of the measuring devices. To the West, the structure is surrounded by relatively steep rock slopes and to the East, in the direction of Spittellamm dam, the reservoir bottom is flat and situated almost 10 m below the intake level (Figure 3).

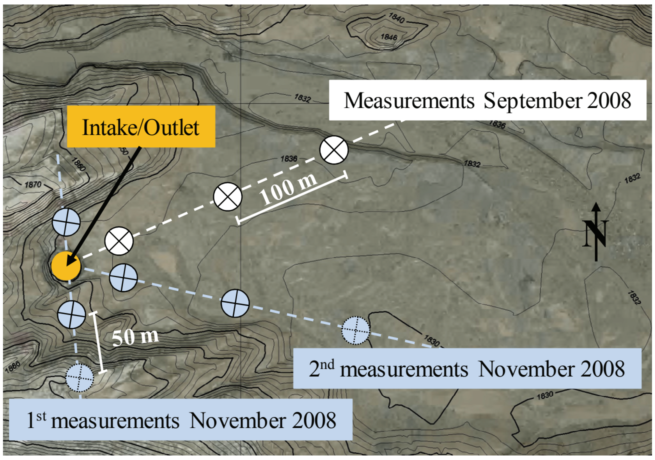

Figure 3. Lake Grimsel bathymetry and positions of the Acoustic Doppler Current Profilers for the three measurement campaigns

This NE-ESE sector of the plain suits best for the velocity sampling since it guarantees a stable position of the frame-mounted ADCP and limits the risk of losing important velocity data within the blind zone of the instrument.

The September 2008 measurement axis is thus orientated in ENE direction and situated in the flat part of the reservoir bottom. Concurrently, this alignment corresponds to the principal geographical orientation of Lake Grimsel. According to the results of this sampling period, two additional measurement axes have been determined, the first one almost exactly in N-S, the other one in ESE-direction. Apart from revealing influences of reservoir bathymetry and pumped storage operation on flow conditions near the intake/outlet, this measurement configuration could allow detecting eventual internal longitudinal or transversal movement of the entire lake (internal seiches). Such large scale dynamics have been investigated by Stevens & Lawrence (1997) for several reservoirs in Canada, as well as by Bouffard (2008) and Lemmin (2005) for Lake Geneva and could also occur in Lake Grimsel. Whether these oscillations are affected by the pumped storage operation remains to be studied.

The correct position of the ADCPs was determined by GPS from a small vessel and controlled measuring the water depth at the lowering point by manual echo sounder. When the profiler reaches the reservoir bottom, a system of a two plane articulation allows orientating the measuring device in an exact upward-looking position. The two angles related to vertical and horizontal positions are recorded by the instrument, in order to know at what moment the measuring device stabilizes. Constant values of these two angular parameters indicate the beginning of a reliable recording period.

2.3 *Data analysis*

During the entire measuring periods, KWO provided relevant data related to the Grimsel II plant, namely pumped storage discharge and the level of Lake Grimsel. Comparing the reservoir level to the pressure measurement given by the ADCPs, a second control of depth at the lowering point was possible and correct positioning of the instruments could be confirmed.

Water temperature is measured and registered by the ADCP and provides additional information about the conditions on the lake bottom near the intake/outlet structure and about the temperature difference between the two reservoirs. Generally, in winter, the reservoirs are covered by ice and inversely stratified, with increasing temperature from 0 °C at the surface to 2.5 °C at the bottom. In summer, both reservoirs are ice-free and thermally normally stratified, with surface temperatures reaching 10 °C. In the upper reservoir, the thermocline is located at 15 m depth and bottom temperature is about 4 °C. In Lake Grimsel, no well defined thermocline is measured and bottom temperature reaches some 5 °C (Bonalumi, 2009). These observations are confirmed by the ADCP recordings which do not reveal temperature differences due to pumped storage operation at the intake/outlet depth.

For the reliable recording period, each RDI unit provides North and East velocity components of the flow on every meter of the water column. In a first step, data points with either velocity values smaller than the measurement error or no reasonable record (indicated by the ADCP setting the velocity to a very high specific value) are set to zero. This process leads to gaps in the velocity time series at correspondent water depths and to abrupt unreasonable changes between reliable velocity value and zero within the given time step of 5 minutes. Therefore, the velocity has been averaged over five time steps at every position, allowing smoothing the series without losing information about the dynamics of the movements in the Lake.

During the first field campaign in September 2008, reliable data is available for a period of three and a half weekdays, from September 16th to 19th (midday). As shown in figure 4a, this measuring term is characterized by three main generating sequences, with only marginal pumping activity at night.

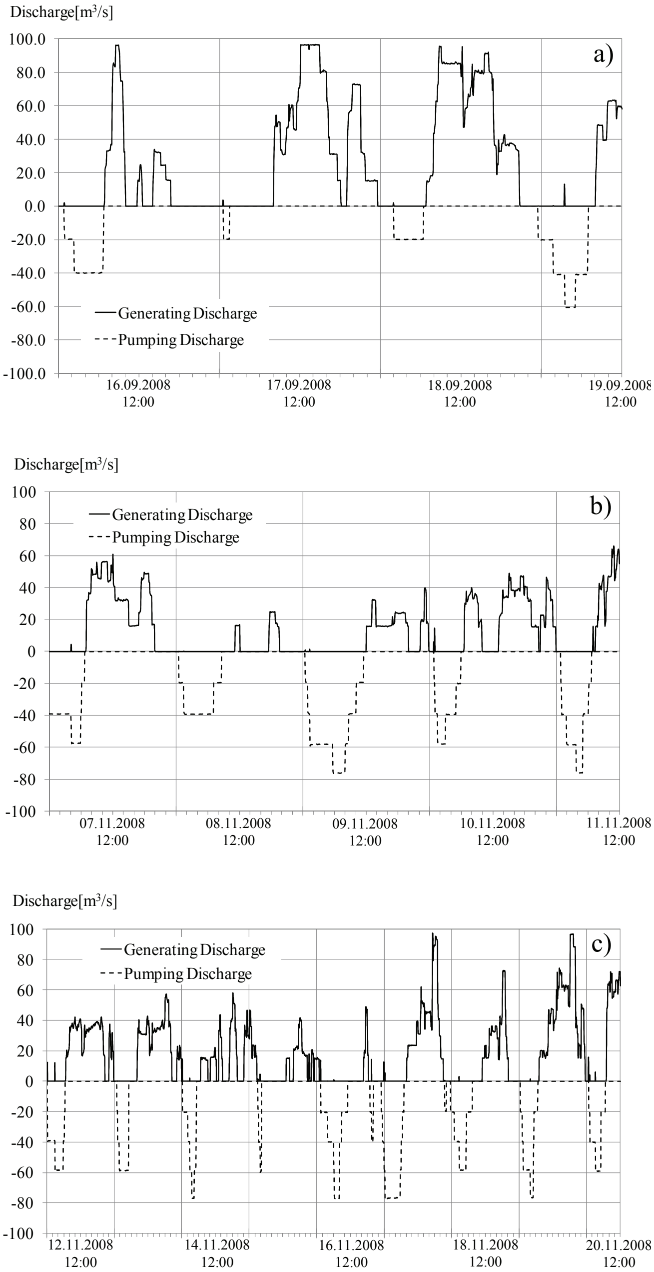

Figure 4. Pumped storage operation data of Grimsel II plant during the velocity sampling periods in a) September 2008, b) and c) November 2008

When extracting data from the RDI units after the second measurement campaign, one instrument turned out to have suffered from a short circuit probably when lowered onto the reservoir bottom. Consequently, results from only two ADCPs are available for the period in November 2008. This time, the instruments remained in the lake during 15 days, resulting in velocity profiles for periods of six (1st measurement axis) and eight days (2nd measurement axis, Figure 3). As shown in Figures 4b and 4c, data has been gathered not only for weekly pumped storage operation with main generating sequences interrupted by short terms of pumping activity, but also during weekends when water is pumped back into the upper reservoir during several hours of the day.

Consequently, the two campaigns allowed recording flow velocities related to short term sequences, with generating mode during the day, and pumping activity at night, as well as midterm sequences consisting of successive upper reservoir drawdown along the week and pumping activity during weekends.

3 RESULTS AND DISCUSSION

3.1 *3D velocity fields in front of intake and outlet*

After data extraction and treatment, time dependent, three-dimensional velocity profiles are generated in the reservoir with the objective to obtain information about flow conditions in front of the intake/outlet structure. The visualization by a movie allows comparing the temporal evolution of the velocity profiles to the pumped storage operation data provided by the power producer in order to detect whether the orientation of the flow field could be linked to the expected main direction of the in- or out-flowing water masses.

Characteristic velocity profiles, averaged over five time steps, observed while the power plant operates in generating mode are shown in Figures 5a to 5c, for the three different measurement axes. In the plain to the East of the outlet, the velocity vectors are leading away from the outlet in a radial direction, which corresponds to the expected orientation of the jet (5a and 5c). In contrast, the velocity profiles recorded to the North and South of the outlet do not point away from the structure but are directed eastwards again towards the flat reservoir bottom (5b). This redirection of the out-flowing jet is probably due to the lake topography with its steep slopes to the West of the outlet which do not allow a uniform circular flow distribution around the structure.

Apart from the orientation of velocity vectors, some general properties of the profiles can be pointed out which are observed for either measurement axes. Each profile can be divided in four zones on the water column.

From the reservoir bottom up to the top of the intake/outlet structure only small or even no velocities have been registered. Thus, the bottom layer of the lake seems not to be influenced by the pumped storage activity due to its position on a small platform situated about 10 m above the reservoir bottom.

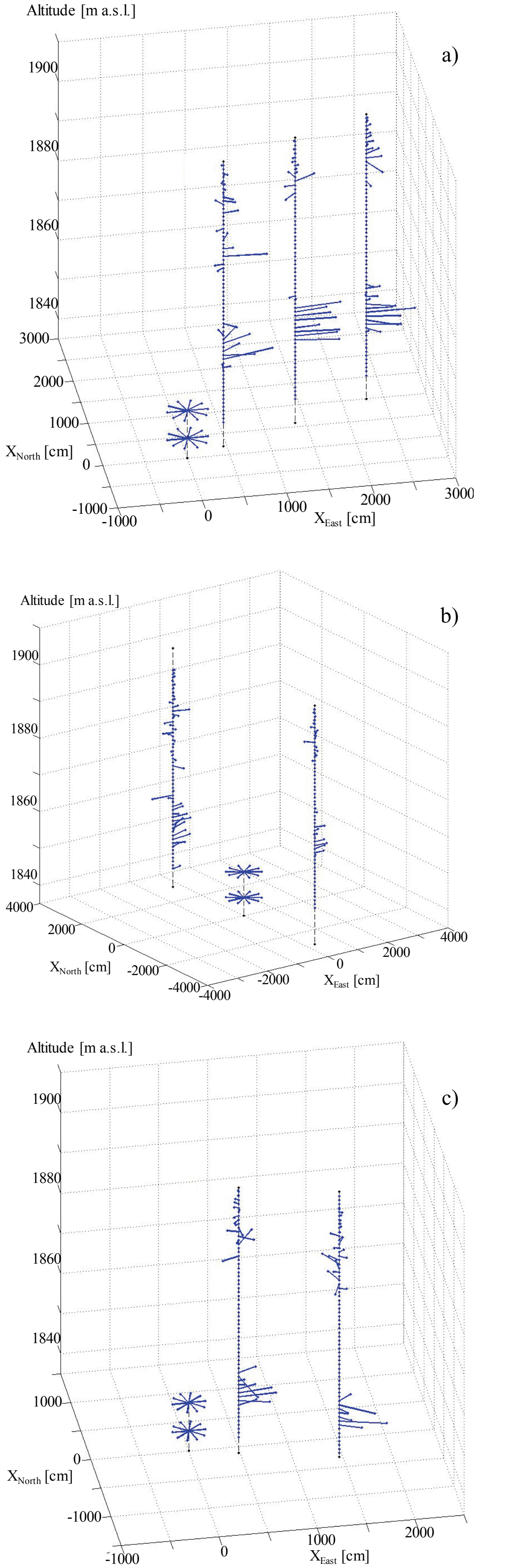

Figure 5. Velocity profiles during generating mode (out-flowing jet) in front of the Grimsel II intake/outlet structure; a) September 2008, b) 1st measurements in November 2008, c) 2nd measurements in November 2008

The main velocity field induced by the generating activity of Grimsel II plant has a height of 5 to 10 m and is not situated on the level of the horizontal axis of the outlet, but slightly above. When being ejected from the pressure conduit into the cylinder, the jet has an important vertical velocity component which could lead to this vertical shift of the velocity profile.

In the central part of the lake, as for the bottom layer, no velocities were recorded by the instruments. Apparently, no horizontal movement is occurring in this zone of the reservoir.

The water masses close to the lake surface present small velocities often pointing in opposite direction of the velocity vectors in the jet zone, indicating a circulation of the lake. Nevertheless, as surface velocities are strongly affected by wind, it cannot be assumed that only the leaving the outlet jet is provoking a big circulation cell in the entire lake.

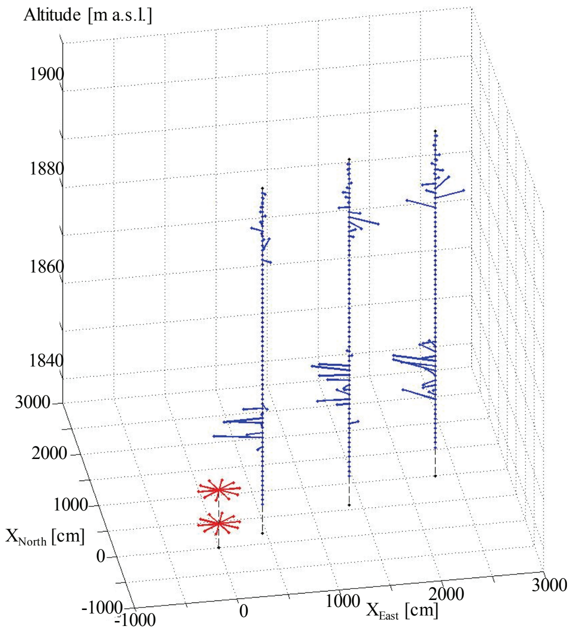

Figure 6. Velocity profiles during pumping mode (inflowing discharge) in front of the Grimsel II intake/outlet structure; September 2008 measurement axis

Figure 6 shows the flow field in front of the intake measured during a pumping sequence in September 2008. The velocity vectors are this time directed towards the intake structure, again orientated quite precisely in the axis of one of the ten intake sectors. Except for the orientation, the profile characteristics are similar to what has been observed in generating mode. The main field covers between 5 and 10 m of the water column and is situated slightly above the level of the intake. Again, neither the zone close to the reservoir bottom nor the central layer present measurable velocities, they remain stable and are not affected by the pumping activity. Surface velocities cannot be linked to the direction of inflowing discharge, they seem presenting mainly random directions or the same orientation as during generating mode.

3.2 *Statistical signal processing*

Flow fields corresponding to the expected main direction of the in- and out-flowing jet are observed during both pumping and generating activity. However, there are periods where the orientation of the velocity vectors and the expected main direction of the jet do not correspond clearly. Especially right after changes from one operation mode to the other, velocity profiles keep their initial orientation during a certain time before redirecting according to pumping or generating mode. Furthermore, water masses are in movement even though there is no pumped storage activity. At first view, no preferential orientation of the flow direction can be observed in these periods.

In order to determine whether the recorded velocities are directly correlated to the pumped storage activity, power spectra of the data series and the discharge data have been compared. This approach, based on the Fast Fourier Transform (FFT) method, is often used in signal processing and allows finding the main frequencies of a data series (Lyons 2004).

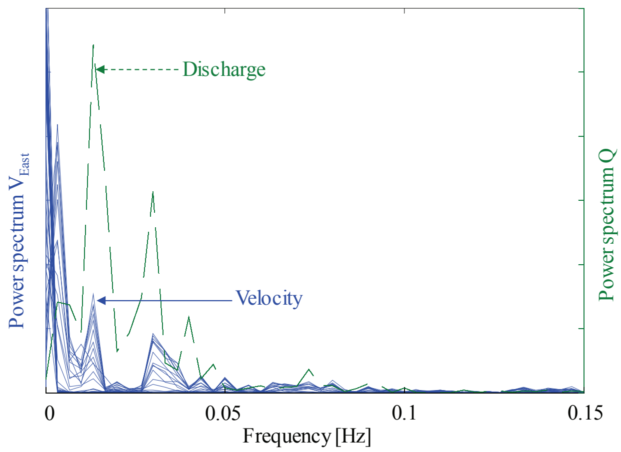

Figure 7. Power spectra of East velocity component and discharge data, 1st measurement November 2008, profiler 1 (to the north of the intake/outlet, Figure 3)

Figure 7 reveals that the main frequencies of the two signals (peaks) are close to each other and therefore foreshadow a direct link between the recorded velocities and the pumped storage discharge.

In order to get better information about correlation between velocity and discharge, raw ADCP data is used for the establishment of power spectra. Velocity has thus been split into its two components (North and East) and signal processing reveals that East velocity shows equal main frequency as discharge data while North velocity cannot be linked to the pumped storage activity.

3.3 *Outlook*

The processes induced by pumped storage activity in Lake Grimsel are to be studied in more detail in order to confirm the observations presented in this paper and to understand the ongoing flow phenomena more in detail.

Especially the influence of bathymetrical conditions have to be analyzed since the Grimsel II intake/outlet structure is embedded in a very complex topography which influences directly on the flow conditions and the redirection of the outflowing jet. The importance of such topographical effects on flow distribution near intake/outlet structures has been revealed by earlier field investigations using ADCP, for example in the reservoirs of the Okumino hydropower plant (Goto & Tsuchiyama, 1998). A numerical model of Lake Grimsel will therefore be set up containing the Grimsel II intake/outlet structure, but also all other hydraulic works which are supposed to interact with the flow fields in the lake. ANSYS CFX 12, a CFD package including a solver based on finite volume method and pre- and post processing tools, will then be used for the calculation of flow fields.

Surface velocity profiles will be compared to wind data provided by KWO and the Swiss Federal Office of Meteorology and Climatology in order to evaluate the origin of circulation cells in Lake Grimsel and eventually link them to the pumped storage operations.

Additional signal processing is carried out in order to detect or reject correlations between the flow velocities and the in- and out-flowing jet.

Further research includes physical modeling of the influence of turbulence induced by pumped storage activity on the suspended sediments in a simple reservoir geometry.

4 ACKNOWLEDGEMENTS

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