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Schwebstoff-Monitoring und Verschleiss an Peltonturbinen (Teil a)

Monitoring of suspended sediment and wear at Pelton turbines (Part a)

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Zusammenfassung

Bei Wasserkraftwerken, insbesondere bei Hoch- und Mitteldruckanlagen mit vergletscherten Einzugsgebieten, kann der Hydroabrasiv-Verschleiss an Turbinen infolge schwebstoffhaltigem Triebwasser erhebliche Unterhaltskosten und Ertragseinbussen verursachen sowie die Elektrizitätsproduktion infolge Wirkungsgradabnahme reduzieren. Quantitative Angaben über die Zusammenhänge zwischen Schwebstoffaufkommen, Turbinenabrasion und Wirkungsgradabnahme, die für eine wirtschaftliche Optimierung solcher Wasserkraftanlagen erforderlich sind, sind bisher nicht verfügbar.
Im hier beschriebenen Forschungsprojekt an einer bestehenden Hochdruck-Wasserkraftanlage im Wallis (KW Fieschertal), wurden die Konzentration und Partikelgrössenverteilung der Schwebstoffe im Triebwasser mittels verschiedener Messmethoden (in situ-Laserdiffraktometer, Trübungssonden und einer akustische Methode) kontinuierlich erfasst. Die Geometrieveränderungen und der Materialabtrag an Bechern der Peltonlaufräder sowie die Reduktion des Wirkungsgrads wurden durch mehrere Inspektionen bzw. Messungen dokumentiert.
In der Fortführung des Projekts werden diese mit der Schwebstoffführung des Triebwassers korreliert, um Berechnungsansätze zu überprüfen und zu erweitern. Dies dient als Grundlage für die wirtschaftliche Optimierung des Entwurfs, des Betriebs und des Unterhalts von Wasserkraftanlagen, die von Hydroabrasiv-Verschleiss betroffen sind, und trägt zur Steigerung der Effizienz der Wasserkraftnutzung bei.

Résumé

Aux aménagements hydro-électriques à haute ou moyenne chute, particulièrement dans des bassins versants avec des glaciers, l’usure des turbines, provoquée par des particules minérales dures contenues dans l’eau, peut engendrer des coûts de maintenance considérables et des pertes de production et de revenu dues à la réduction du rendement de la turbine. Pour l’optimisation économique de ces aménagements, des relations quantitatives entre la charge de particules, l'usure et l'efficacité de la turbine sont nécessaires, qui ne sont pas encore disponible.
Dans le projet de recherche décrit dans ce rapport, la concentration et la distribution des tailles des particules en suspension dans l’eau de turbinage ont été mesurées en continue à l’aménagement hydraulique de Fieschertal (Haut-Valais) avec plusieurs instruments (diffraction laser in situ, turbidimètres et une méthode acoustique). En parallèle, la géométrie actuelle des augets des roues Pelton, la perte du matériel et la réduction du rendement ont été relevées périodiquement.
Dans la suite du projet, ceux-ci seront mise en rapport avec la charge des particules afin de vérifier et adapter des modèles de calcul. Ces modèles serviront de base pour des optimisations économiques dans la conception, l’exploitation et la maintenance de tels aménagements et contribueront à la mise en valeur efficace du potentiel hydraulique.

Abstract

At high and medium head hydro-electric power plants (HPPs), particularly in glaciated catchment areas, hydro-abrasive erosion at turbines caused by hard mineral particles in the water may cause considerable maintenance cost as well as decreased revenues and production losses due to reduced turbine efficiency. For the economic optimization of such HPPs, quantitative relations between particle load, turbine wear and efficiency are required, which have not been available yet.
In the research project described in this report, the concentration and size distribution of particles in the water were continually measured at the Fieschertal HPP, located in the Swiss Alps in Canton of Valais, Switzerland, using various instruments, such as an in-situ laser diffractometer, turbidimeters and an acoustic method. In parallel, the evolution of the turbine buckets’ geometry, the material loss and the efficiency reduction were periodically measured.
In the continuation of the project, these measured quantities will be related to the particle load to verify or adapt existing calculation models. This serves as a basis for economic optimization of the design, operation and maintenance of such HPPs and contributes to the efficient use of the hydropower potential.

1 Ausgangslage

Bei Wasserkraftwerken, insbesondere an Hoch- und Mitteldruckanlagen in teilweise vergletscherten Einzugsgebieten (Abbildung 1), bei welchen gefasstes Wasser ohne Aufenthalt in einem Speichersee turbiniert wird, kann der Hydroabrasiv-Verschleiss an Turbinen (Abbildung 2) und Stahlwasserbauteilen infolge schwebstoffhaltigem Triebwasser erhebliche Betriebskosten und Ertragseinbussen verursachen (z. B. Gummer 2009, Felix & Boes 2011). Da bei Stauanlagen mit aktuellen Verlandungsproblemen auch die Möglichkeit des gezielten Turbinierens von schwebstoffhaltigem Wasser vermehrt geprüft wird und infolge des beobachteten Rückzugs von Gletschern und Permafrost im alpinen Raum mehr Sedimente anfallen, gewinnt die Thematik weiter an Aktualität.

Die Schwebstoffkonzentration und –partikelgrössenverteilung können zeitlich stark variieren. Eine Möglichkeit zur Optimierung des Kraftwerksbetriebs besteht in der vorübergehenden Ausserbetriebnahme von Kraftwerken in Phasen mit grossem Sedimentaufkommen im Triebwasser, wenn die Kosten infolge der Verschleissschäden, die in dieser Zeit entstehen würden, grösser sind als der Erlös aus der Elektrizitätsproduktion (Boes 2010, Boes *et al.* 2013). Eine Betriebsweise, welche auch das aktuelle Sedimentaufkommen berücksichtigt, bedingt ein kontinuierliches Echtzeit-Monitoring (Bishwakarma & Støle 2008) der Schwebstoffkonzentration und der Partikelgrössen im Triebwasser. Für Kraftwerksbetreiber, Planer und Turbinenhersteller stellt sich die Frage, welche Messsysteme zur Überwachung der im Zufluss und im Triebwasser enthaltenen Schwebstoffe je nach lokalen Bedingungen geeignet sind, angemessene Genauigkeit, hohe Zuverlässigkeit, ein gutes Preis-Leistungsverhältnis und geringen Betriebsaufwand aufweisen (z.B. Winkler *et al.* 2013).

Weiter benötigen Kraftwerksbetreiber und Ingenieure für wirtschaftliche Optimierungen, z.B. für die Planung des Laufradeinsatzes und der –revisionen, quantitative Angaben über die Zusammenhänge von Schwebstoffbelastung, Turbinenabrasion und Wirkungsgradabnahme. Solche Informationen sind bisher kaum vorhanden.

Zur Bearbeitung dieser Fragestellungen hat die Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich in Zusammenarbeit mit der Hochschule Luzern, Kompetenzzentrum für Fluidmechanik und Hydromaschinen, ein zweiteiliges Forschungsprojekt initiiert. Der vorliegende Schlussbericht bezieht sich auf den ersten Teil des Projekts, der von August 2011 bis Ende 2013 bearbeitet wurde.

Abbildung 1: Beispiel eines alpinen Einzugsgebiets mit teilweiser Vergletscherung und hoher Sedimentverfügbarkeit (Blick auf den Fieschergletscher, 2011, Bild: *VAW*).

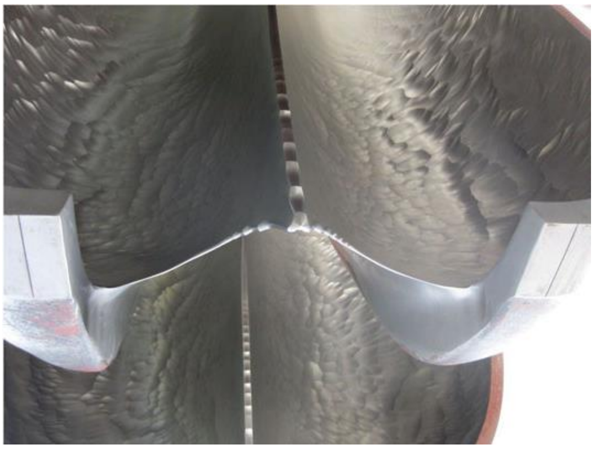

Abbildung 2: Beispiel von Abrasionsschäden an den Bechern eines Pelton-Laufrads (Ausstellungsobjekt bei der Wasserkraftanlage Emossion, VS, Bild: *VAW*, 2010).

2 Projektziele

Im ersten Teil des Forschungsprojekts (Teil a, 2011-2013) werden folgende Ziele verfolgt:

- Verbesserung des **Prozessverständnisses** (Schwebstoffaufkommen, Verschleissschäden),
- Evaluieren und untersuchen von **Messsystemen** (im Labor und am Prototypen) für das Echtzeit-Monitoring der Schwebstoffkonzentration und Partikelgrössenverteilung, mit Fokus auf die Anwendung in Wasserkraftanlagen.
- Kontinuierliche Messung der **Schwebstoffe** im Triebwasser einer bestehenden Hochdruck-wasserkraftanlage unter Berücksichtigung der Partikelgrössen,
- Periodische Messungen der **Abrasionsschäden** an Peltonturbinen sowie der **Wirkungsgrade**,
- Zusammenstellen eines möglichst vollständigen **Messdatensatzes**, welcher auch zur Kalibrierung von numerischen Modellen eingesetzt werden kann.

Im zweiten Teil des Projekts (Teil b, 2014-2015) sollen bestehende Berechnungsansätze zur Prognose des Hydroabrasiv-Verschleisses und der Wirkungsgradabnahme verifiziert und ggf. angepasst werden, als Grundlage für die wirtschaftliche Optimierung von Wasserkraftanlagen, die von starkem Hydroabrasiv-Verschleiss betroffen sind. Dadurch soll schliesslich auch die **Effizienz der Wasserkraftnutzung** gesteigert werden.

3 Vorgehen

Die Untersuchung wurde hauptsächlich an einer bestehenden Hochdruck-Wasserkraftanlage im Wallis durchgeführt. Als geeignete Anlage war das KW Fieschertal (Abb. 3), welches über keinen Speichersee verfügt und bei welchem seit Inbetriebnahme im Jahr 1975 starker Hydroabrasiv-Verschleiss beobachtet wurde, gewählt worden. Vorgängig zu den Messungen an der Prototypanlage, im ersten Semester 2012, wurden die Geräte für das Schwebstoffmonitoring im Labor der Hochschule Luzern in Horw unter kontrollierbaren und bekannten Bedingungen untersucht (Abb. 4).
Da die Partikelgrösse im Zusammenhang mit dem Turbinenverschleiss ein wesentlicher Parameter ist (z.B. Winkler *et al.* 2011), ist es erforderlich, die Schwebstoffkonzentration *und* die Partikelgrösse im Feld zu messen. Mit Trübungsmessgeräten und bisher erhältlichen akustischen Messsystemen ist die Partikelgrösse nicht kontinuierlich erfassbar. Seit wenigen Jahren sind tragbare Laserdiffraktometer erhältlich, mit denen die Partikelgrössenverteilung mit hoher zeitlicher Auflösung (z.B. jede Minute) vor Ort erfasst werden kann (Agrawal *et al.* 2011). Ein solches Messgerät wurde nach dem Wissen der Autoren erstmals in einer Wasserkraftanlage in der Schweiz installiert.

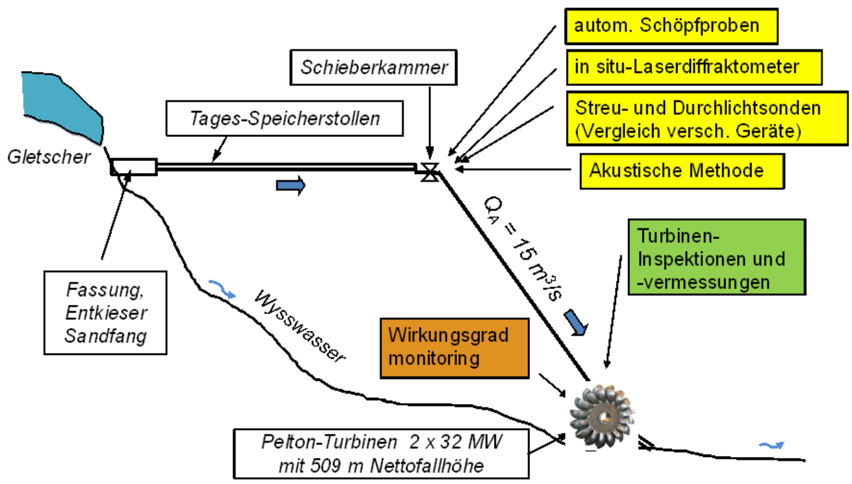

Abbildung 3: Schematisches Längsprofil der Kraftwerksanlage Fieschertal mit Darstellung der durchgeführten Messungen; nach Felix *et al.* (2012c)

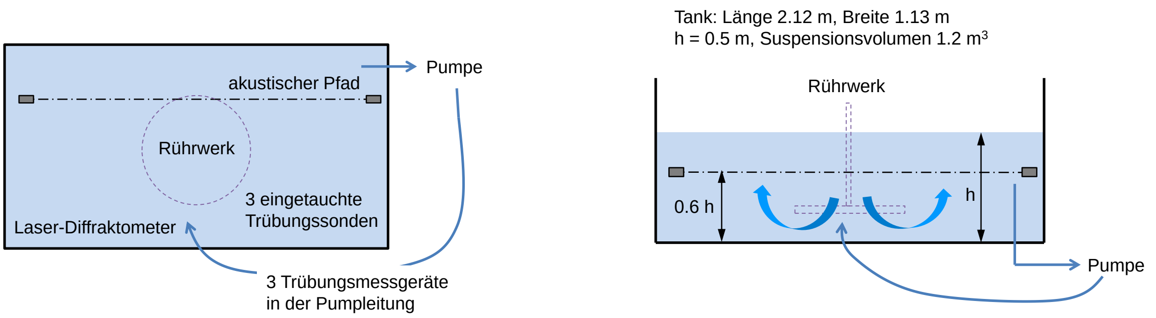

Abbildung 4: Mischtank mit optischen und akustischen Messgeräten für Schwebstoffmessungen im hydraulischen Labor, links im Grundriss und rechts im Vertikalschnitt; nach Felix *et al.* (2012b)

In diesem interdisziplinären Forschungsprojekt waren nebst der ETH Zürich und der Hochschule Luzern folgende Partner beteiligt:

- Gommerkraftwerke AG, Ernen, als Betreiberin des untersuchten Kraftwerks,
- BKW, Bern, Engineering für elektromechanische Ausrüstung und Leittechnik
- Andritz Hydro AG, Kriens, für beschichtete Peltonturbinen
- Rittmeyer AG, Baar, für Sedimentmonitoring mit akustischen Methoden sowie Sigrist Photometer, Ennetbürgen, und Endress+Hauser, Reinach, für Trübungsmessgeräte.
- swisselectric research, Bern

4 Ergebnisse

4.1 Schwebstoffmonitoring

4.1.1 Laboruntersuchungen

Aus den Labor-Messdaten verschiedener Trübungssonden und einer akustischen Methode (Costa *et al.* 2012) wurden Kalibrierkurven ermittelt (Felix *al.* 2012a, b). Weiter wurden die Messdaten des Laserdiffraktometers ausgewertet und mit Referenzmessungen verglichen (Abb. 5). Dabei zeigte sich ein bisher in der Literatur nicht quantitativ beschriebener Einfluss vor allem der Partikelform. Es zeigte sich, dass auch ein Laserdiffraktometer auf die am Einsatzort vorhandenen Partikel zu kalibrieren ist, um eine zufriedenstellende Messgenauigkeit zu erreichen (Felix *et al.* 2013c).

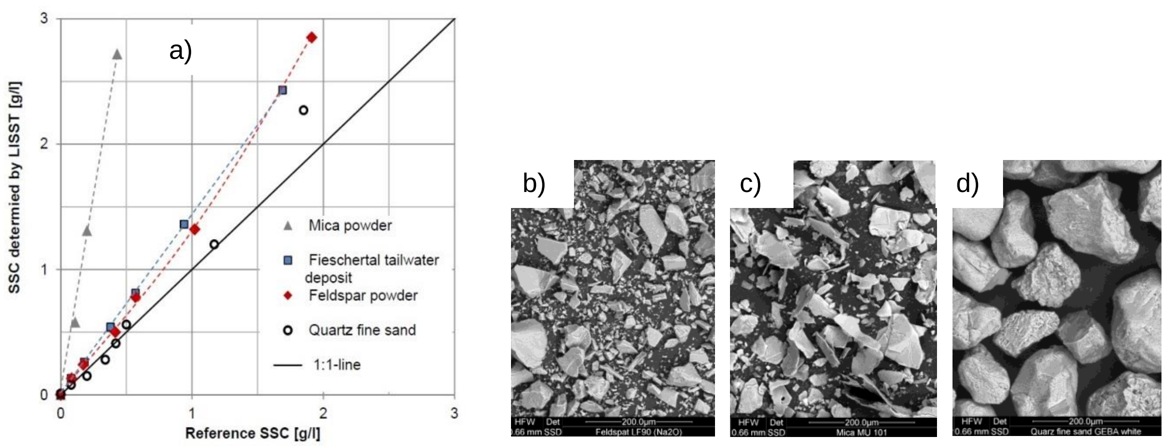

Abbildung 5: a) Schwebstoffkonzentrationen, welche mit dem Laserdiffraktometer gemessen wurden, im Vergleich zu Referenz-Konzentrationen, für die Partikelsorten b) Feldspatpulver, c) Glimmerpulver, d) Quarzfeinsand; aus Felix *et al.* (2013a)

4.1.2 Messungen an der Prototypanlage

Mit dem Laserdiffraktometer, den Trübungssonden, einer akustischen Methode und mit Laboranalyse von Wasserproben wurden seit Mitte 2012 kontinuierlich Daten zum Schwebstoffaufkommen im Triebwasser des KW Fieschertal erhoben (Felix *et al.* 2013b).
Abbildung 6 zeigt ein Beispiel von drei Tagen im August 2012. Die Linien im unteren Teil der Abbildung stellen die Schwebstoffkonzentrationen dar, welche mit den verschiedenen Messgeräten ermittelt wurden, nachdem diese basierend auf der Laboranalyse von Schöpfproben (schwarze Kreissymbole) für „normale Verhältnisse“, d.h. für relativ feine Partikel, kalibriert wurden. Die grüne Kurve mit Skala am rechten Rand des Diagramms zeigt den Median-Durchmesser der transportierten Partikel im Lauf der Zeit. Gemäss den Messungen werden zeitweise, in Phasen mit erhöhter Schwebstoffkonzentration, auch gröbere Partikel transportiert (Abbildungen 6 und 7). Das Laserdiffraktometer erlaubt im Gegensatz zu den andern Messmethoden auch die Messung der Partikelgrösse und ermöglicht, wie erwartet, eine genauere Messung der Schwebstoffkonzentration wenn die Partikelgrösse zeitlich variiert und kaum mit der Schwebstoffkonzentration korreliert.

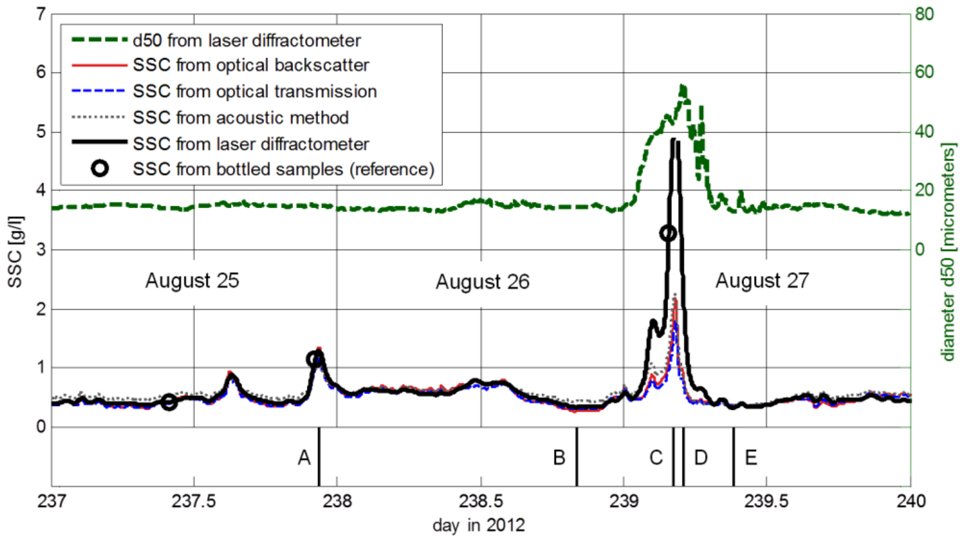

Abbildung 6: Ganglinien der Schwebstoffkonzentration (linke Achse) im Vergleich zu Schöpfproben (Kreissymbole) und der Median-Partikelgrösse (rechte Achse), gemessen im Triebwasser des KW Fieschertal; aus Abgottspon *et al.* (2013a)

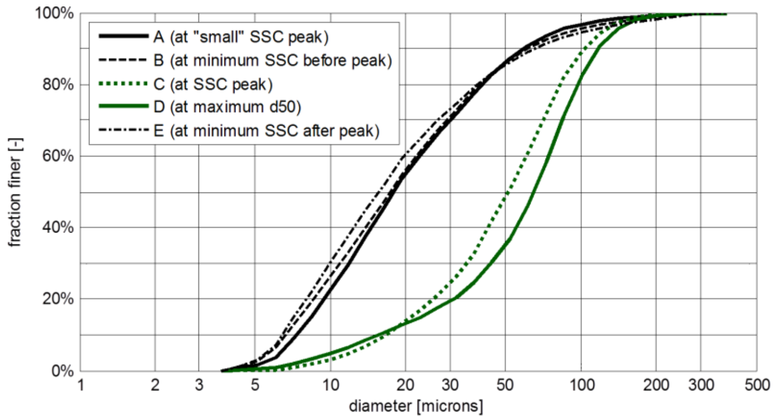

Abbildung 7: Ausgewählte Korngrössenverteilungen, die mit dem Laserdiffraktometer im Triebwasser des KW Fieschertal gemessen wurden, zu Zeitpunkten (A-E) gemäss Abbildung 6; aus Abgottspon *et al.* (2013a)

4.2 Monitoring der Turbinenabnutzung

Um den Verschleiss an Bechern der Peltonturbinen an der untersuchten Anlage zu quantifizieren, wurden und werden die Bechergeometrie und die Dicken der Beschichtung in ausgewählten Bechern vor und nach der Schwebstoffsaison gemessen. Durch Vergleich von Messungen, die zu verschiedenen Zeitpunkten durchgeführt wurden, werden die Geometrieänderung und der Materialverlust räumlich verteilt bestimmt.
Auf das Teilprojekt „Monitoring der Abnutzung an Bechern von Peltonturbinen mittels 3d-Digitalisierungen und Schichtdickenmessungen“ wird im entsprechenden Jahresbericht separat eingegangen.

4.3 Wirkungsgradmonitoring

Mithilfe so genannter „sliding needle“-Messungen (Abgottspon *et al.* 2013a) wurden Wirkungsgrad-Veränderungen an den Turbinen zu gewissen Zeitpunkten durch die Hochschule Luzern und GKW / BKW bestimmt (Abbildung 8). Nebst einer Wirkungsgradabnahme infolge Turbinenabnutzung konnte auch eine Wirkungsgradzunahme infolge der Unterhaltsarbeiten festgestellt werden, die normalerweise am Laufrad im Winter durchgeführt werden.
An einer der beiden Turbinen waren bis März 2013 keine „sliding needle“-Messungen möglich, da ein Düsenantrieb verklemmt war. Seit der Revision dieses Düsenantriebs ist vorgesehen, „sliding needle“-Messungen in monatlichem Rhythmus an beiden Maschinengruppen durchzuführen, sofern diese in Betrieb sind und die in der Volllastzeit entstehenden Produktionsverluste für den Kraftwerksbetreiber tragbar sind. So konnten im Jahr 2013 „sliding needle“-Messungen im März, April, Mai, Juni, August, September, Oktober und November durchgeführt werden.

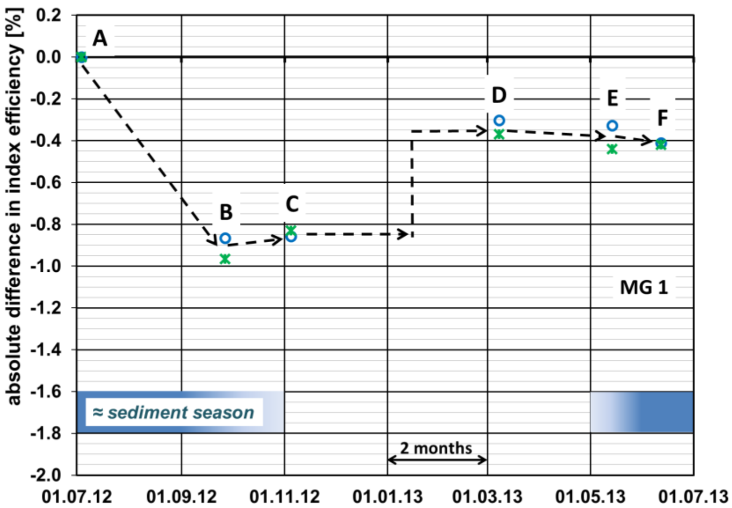

Abbildung 8: Wirkungsgradhistorie einer Turbine des KW Fieschertal (basierend auf zwei Arten der Durchflussbestimmung) aus Abgottspon *et al.* (2013b); wird fortgeführt

5 Diskussion und Schlussfolgerungen

Die Auswertung der Laborversuche zu Schwebstoffmessmethoden zeigte, dass damit wertvolle Informationen zum Verhalten und zur Kalibrierung der Messgeräte gewonnen werden konnten, die in der Literatur noch nicht beschrieben wurden (z.B. Kalibrierung des Laserdiffraktometers unter Berücksichtigung von nicht-kugelförmigen Partikeln) und für Schwebstoffmessungen mit angemessener Genauigkeit erforderlich sind.
Am 02./03.07.2012 kam es am KW Fieschertal zu einem bedeutenden Hochwasserereignis, welches im Obergoms als ein ca. 30-jährliches Ereignis eingestuft wurde. Dabei wurden im Triebwasser Schwebstoffkonzentrationen bis ca. 50 g/l gemessen. Die Phase mit stark erhöhtem Schwebstofftransport dauerte etwa einen Tag (Felix *et al.* 2012c). Da in der Folge ein Laufrad ausgetauscht werden musste, wurde nach dem Ereignis abgeschätzt, dass es wirtschaftlich vorteilhaft gewesen sein dürfte, den Turbinierbetrieb während dieses Ereignisses zu unterbrechen (Abb. 9).

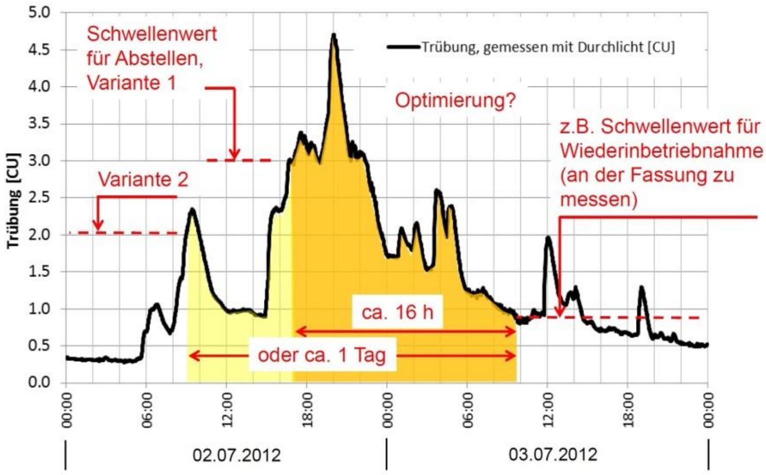

Abbildung 9: Verlauf der Trübung im Triebwasser des KW Fieschertal Anfang Juli 2012 und zwei fiktive Szenarien für das vorübergehende Unterbrechen des Turbinierbetriebs (Boes *et al.* 2013)

Im 2013 kam es in Fieschertal zu keinem grösseren Unwetter. Somit können das Schwebstoffaufkommen, die Abrasion an den Turbinen sowie deren Wirkungsgradabnahme in einer „normalen“ Schwebstoffsaison untersucht werden.

Da Schwebstofftransport-Prozesse relativ dynamisch sein können, sind zeitlich hoch aufgelöste Schwebstoffmessungen erforderlich (Felix *et al.* 2013b). Die Schwebstoffdynamik würde lediglich mit Laboranalysen von täglich entnommenen Schöpfproben nicht genügend erfasst. Der Einsatz von automatischen Wasserprobennehmern zur Kalibrierung der Geräte für die kontinuierlichen Schwebstoffmessungen bewährte sich. Im Gegensatz zu früheren Messungen mit Laserdiffraktometern an Wasserkraftanlagen (z.B. Agrawal *et al.* 2012) wurden in diesem Projekt die Laserdiffraktometer-Messungen mit Referenzmessungen verglichen. Die in diesem Projekt eingesetzte akustische Methode erlaubt ein mindestens qualitatives Schwebstoffmonitoring und ist für den Einsatz an Wasserkraftanlagen eine interessante Möglichkeit, da dafür vielerorts bestehende Einrichtungen akustischer Durchflussmessungen verwendet werden können.

Der Einsatz verschiedener Schwebstoff-Messgeräte ermöglicht einen Vergleich der Geräte bezüglich Einsatzgrenzen, Messgenauigkeit, Aufwand für Kalibrierung und Unterhalt etc., unter Bedingungen, wie sie bei einer stark von Hydroabrasiv-Verschleiss betroffenen Wasserkraftanlage vorherrschen.

Das Kraftwerk Fieschertal ist für das Erforschen der hier untersuchten Thematik sehr geeignet, da seit dessen Inbetriebnahme im Jahr 1975 ein relativ hohes Schwebstoffaufkommen und starker Hydroabrasiv-Verschleiss beobachtet werden.

6 Ausblick

Es ist vorgesehen, im zweiten Teil des Forschungsprojekts die kontinuierlichen Schwebstoffmessungen mit den verschiedenen Messmethoden im Jahr 2014 weiterzuführen. Bezüglich Turbinenabrasion und Wirkungsgradmonitoring ist geplant, in Zusammenarbeit mit den Projektpartnern weiterhin folgende Messungen periodisch durchzuführen:

- 3d-Digitalisieren von ausgewählten Bechern der Pelton-Laufräder (separates Teilprojekt)
- Schichtdickenmessungen an entsprechenden Bechern (separates Teilprojekt)
- Wirkungsgradmessungen („*sliding needle*“-Messungen)

Nebst der Fortführung der Datenerfassung sind Auswertungen der erhobenen Daten in allen drei Teilbereichen des Projekts und entsprechende Veröffentlichungen vorgesehen.

Aus der verbesserten Kenntnis der Einflussfaktoren des Hydroabrasiv-Verschleisses lassen sich Gegenmassnahmen und Strategien zur Verminderung von Abrasionsschäden ableiten und die Anlagenkonzeption bzw. der Anlagenbetrieb durch Betrachtung des Gesamtsystems, welches aus baulichen Anlagen und elektromechanischer Ausrüstung besteht, wirtschaftlich optimieren.

7 Referenzen

7.1 Aus dem Projekt hervorgegangene Publikationen

7.1.1 Konferenzbeiträge und Fachartikel

Abgottspon A., Staubli T., Felix D., Albayrak I., Boes R.M. (2013a): **Hydro-abrasive Erosion of Pelton buckets and Suspended Sediment Monitoring**. *Proc. Hydrovision International 2013*, Denver, USA

Boes R. M., Felix D., Albayrak I. (2013): **Schwebstoffmonitoring zum verschleissoptimierten Betrieb von Hochdruck-Wasserkraftanlagen**. *Wasser Energie Luft* 105(1): 35-42

Felix D., Albayrak I., Boes R.M., Abgottspon A., Deschwanden F., Gruber P. (2013b): **Measuring Suspended Sediment: Results of the first Year of the Case Study at HPP Fieschertal in the Swiss Alps**. *Proc. Hydro 2013 Conference*, Innsbruck, Austria: 18.03

Felix D., Albayrak I., Boes R.M (2013a): **Monitoring Suspended Sediment Concentration and Particle size using Optical and Acoustic Methods – Laboratory tests and Case study in the Swiss Alps**. *Advances in River Sediment Research*, Fukuoka S., Nakagawa H., Sumi T., Zhang H. (eds), ISBN 978-1-138-00062-9, Taylor & Francis Group, London: 1757-1766

Felix D., Albayrak I., Abgottspon A., Boes R.M., Gruber P. (2012c): **Suspended Sediment and Pelton Turbine Wear Monitoring: Experimental Investigation of various Optical and Acoustic Devices and Begin of the Prototype Study Fieschertal**. *Proc. Vienna Hydro 2012*, 17th International Seminar on Hydropower Plants, ISBN 978-3-9501937-8-7, Vienna, Austria: 483-494

Felix D., Albayrak I. & Boes R.M. (2012b): **Schwebstoffmonitoring und Verschleiss an Peltonturbinen am Fallbeispiel Fieschertal - Vorbereitende Laborversuche zu Partikelmessmethoden**. *Proc. Wasserbausymposium 2012*. ISBN 978-3-85125-230-9, Graz, Österreich: 117-124

Felix D., Albayrak I. & Boes R.M. (2012a): **Schwebstoff- und Verschleiss-Monitoring an Wasserkraft-Hochdruckanlagen: Laborversuche zu Partikelmessmethoden und Vorbereitung der Fallstudie Fieschertal**. 14. Treffen junger WissenschaftlerInnen an Wasserbauinstituten, *Berichte des Lehrstuhls und der Versuchsanstalt für Wasserbau und Wasserwirtschaft*, TU München, Nr. 125, ISBN 978-3-940476-23-4: 11-24

Felix D. & Boes R.M. (2011): **Turbinenabrasion durch Feinsedimente im Triebwasser**. *Newsletter des Energy Science Centers*, ETH Zurich, Oktober 2011: 6

7.1.2 Peer-Reviewed Journal Paper

Felix D., Albayrak I., Boes R.M. (2013c): **Laboratory Investigation on measuring Suspended Sediment by portable Laser Diffractometer (LISST) focusing on Particle Shape**. Geo-marine Letters 33(6): 485-498, doi 10.1007/s00367-013-0343-1

7.1.3 Dissertation

Das vorliegende Projekt ist Bestandteil der Dissertation von D. Felix, welche aus mehreren Teilprojekten besteht. Nach Abschluss der Dissertation, voraussichtlich ab 2016, wird die Dissertation in der ETH-Bibliothek sowie als VAW-Mitteilung in elektronischer Form frei zugänglich sein:

- http://e-collection.library.ethz.ch/search.php
- http://www.vaw.ethz.ch/publications/vaw_reports/2010-2019

7.2 Weitere Referenzen

Abgottspon A., Stern P., Staubli T., Felix D., Winkler K. (2013b): **Measuring Turbine Abrasion and Efficiency Decrease: First Results of the Case Study at HPP Fieschertal**. *Proc. Hydro 2013 Conference*, Innsbruck, Austria: 18.05

Agrawal Y., Mikkelsen O.A., Pottsmith H.C. (2011): **Sediment monitoring technology for turbine erosion and reservoir siltation applications**, *Proc. Hydro 2011 Conference,* Prague, Czech Republic: 29.09

Agrawal Y., Mikkelsen O.A., Pottsmith H.C. & Slade W. H. (2012): **Turbine abrasion: one year's experience in real-time sediment monitoring at Hidroagoyan HPP, Ecuador**. *Proc. Hydro 2012 Conference*, Bilbao, Spain: 14.08

Bishwakarma M. B. & Støle H. (2008): **Realtime sediment monitoring in hydropower plants**. *J. Hydr. Res*. 46(2): 282–288

Boes R. M. (2010): **Kontinuierliche Messung von Schwebstoffkonzentration und –korngrössenverteilung im Triebwasser und Quantifizierung der Hydroabrasion an einer Peltonturbine**. *Wasser Energie Luft*, 102(2): 101–107

Costa I., Storti G., Lüscher B., Gruber P. & Staubli Th. (2012). **Influence of solid particle parameters on the sound speed and attenuation of pulses in acoustic discharge measurements (ADM)**. *J. Hydrol. Eng.*, 17(10), 1084–1092

Gummer J. H. (2009): **Combating Silt Erosion in Hydraulic Turbines**. *Hydro Review Wordwide*, 17(1)

Winkler K., Dekumbis R., Rentschler M., Parkinson E., Garcin H. (2011): **Understanding hydro-abrasive erosion**, *Proc. Hydro 2011 Conference,* Prague, Czech Republic: 2.05

Winkler K., Rakusa F., Kuhn K. (2013): Hydro abrasive erosion: **Karcham Wangtoo as a case study for fully coated Francis runners and how to determine the particle load**. *Proc. Hydro 2013 Conference*, Innsbruck, Austria: 04b.07

ESC-NEWS

Newsletter des Energy Science Center der ETH Zürich | Oktober 2011

Wasserkraft: Höhere Effizienz unter veränderten Bedingungen

Die Wasserkraft ist die wichtigste Stütze der schweizerischen Elektrizitätswirtschaft, und ihre Bedeutung dürfte in den kommenden Jahrzehnten weiter zunehmen. Obwohl die Wasserkraft eine ausgereifte Technologie ist, stellt sie nach wie vor ein spannendes Forschungsgebiet dar. Auch an der ETH Zürich werden im Hinblick auf die künftige Stromproduktion eine breite Palette an Themen bearbeitet.

Energy Science Center

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Turbinenabrasion durch Feinsedimente im Triebwasser

David Felix und Robert Boes
Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), ETH Zürich, CH-8092 Zürich
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In natürlichen Fliessgewässern werden Laub, Treibholz, Kies, Sand und feine Gesteinspartikel mittransportiert (Abb. 1). Der Umgang mit solchen Feststoffen ist eine Herausforderung für Wasserbauingenieure und Betreiber von Wasserkraftanlagen.

In den Alpen sind die Wasserkraftanlagen in der Regel mit Rechen, Entkieser- und Entsandungsanlagen ausgerüstet. Bei Wasserkraftwerken, die Wasser aus vergletscherten Einzugsgebieten (sog. Gletschermilch) nutzen und keinen Speichersee aufweisen, kann im Triebwasser eine beträchtliche Konzentration von mineralischen Schwebstoffen vorhanden sein, durch welche die Turbinen abgenutzt werden. Bei einer Fallhöhe von beispielsweise 500 Meter schiesst der Wasserstrahl in einer Peltonturbine mit ca. 360 km/h aus der Düse in Richtung des Laufrads. Insbesondere durch die harten Gesteinspartikel werden die Turbinenbauteile «abgeschliffen». Man spricht dabei von Hydroabrasivverschleiss (Abb. 2).

Durch erhöhtes Sedimentaufkommen infolge des Klimawandels, durch die angestrebte Effizienzsteigerung in der Energieversorgung und angesichts der Anforderungen an einen nachhaltigen und insbesondere wirtschaftlichen Betrieb von Wasserkraftanlagen gewinnt das Thema an Bedeutung. Die VAW hat deshalb ein Forschungsprojekt initiiert, das von swisselectric research sowie dem Bundesamt für Energie (BfE) gefördert wird.

Bei der Untersuchung des Hydroabrasivverschleisses ist die hohe Variabilität des Schwebstoffaufkommens im Triebwasser über das Jahr eine Herausforderung, die eine fortlaufende Erfassung der Schwebstoffkonzentration und der Partikelgrössenverteilung erfordert. Bisher wurden die Partikelgrössen in der Regel nur mit einzelnen Schöpfproben, die im Labor ausgewertet wurden, bestimmt. Als Neuerung soll nun an einem Wasserkraftwerk im Oberwallis ein so genanntes in-situ Laserdiffraktometer zum Einsatz kommen, mit dem die Konzentration und die Korngrössenverteilung der Schwebstoffe kontinuierlich und in Echtzeit erfasst werden.

Durch die Untersuchung der Schwebstoffführung des Triebwassers sowie mit periodischen Inspektionen der Turbinen und einer Überwachung des Wirkungsgrads soll der Prozess des Hydroabrasivverschleisses besser verstanden und modelliert werden können. Dies dient der weiteren Optimierung der Anlagenkonzeption, der Anlagenbestandteile, der messtechnischen Ausrüstung und des Betriebs von Wasserkraftanlagen weltweit.

» **www.vaw.ethz.ch/people/as/felixda/projects/data/pelton_wear**

Abb. 1 Wysswasser (links im Bild) bei der Einmündung in den Rotten als Beispiel eines stark geschiebe- und schwebstoffführenden Bergflusses aus einem vergletscherten Einzugsgebiet in den Schweizer Alpen, August 2010 (Bild: VAW).

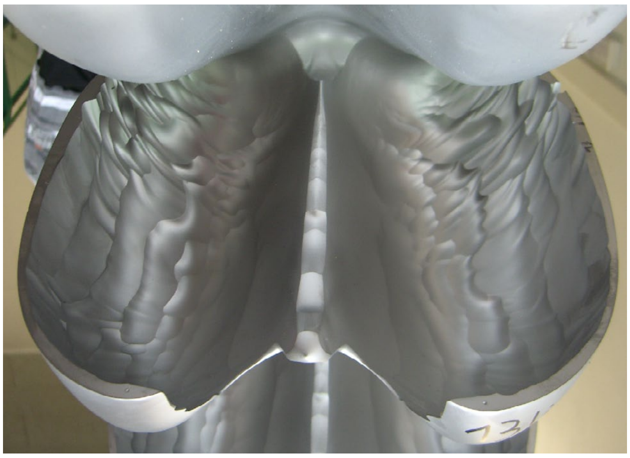

Abb. 2 Beispiel eines Pelton-Laufrads, das durch feine Gesteinspartikel im Triebwasser stark abgenutzt wurde. Es sind die Verbreiterung der Mittelschneide und Abrasion in den Bechern zu erkennen (Bild: TIWAG).

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Oktober 2011

Technische Universität München

14. Treffen junger WissenschaftlerInnen an Wasserbauinstituten

Beiträge zum JuWi-Treffen am 25. und 26. Juni 2012
an der Technischen Universität München

Technische Universität München

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Herausgegeben von Prof. Peter Rutschmann
Ordinarius für Wasserbau und Wasserwirtschaft, TU München

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Schwebstoff- und Verschleiss-Monitoring an Wasserkraft-Hochdruckanlagen: Laborversuche zu Partikelmessmethoden und Vorbereitung der Fallstudie Fieschertal

David Felix, Ismail Albayrak und Robert Boes

Zusammenfassung

Bei Wasserkraftwerken, insbesondere bei Hoch- und Mitteldruckanlagen, kann der Hydroabrasiv-Verschleiss an Turbinen und Stahlwasserbauteilen infolge schwebstoffhaltigen Triebwassers erhebliche Betriebskosten und Ertragseinbussen verursachen. Für einen wirtschaftlich optimierten Anlageentwurf und -betrieb besteht Bedarf an weiteren Bemessungsgrundlagen und an anwendungstauglichen Messverfahren.

Im Rahmen eines interdisziplinären Forschungsprojekts soll an einer bestehenden Hochdruck-Wasserkraftanlage (Kraftwerk Fieschertal, im Wallis, Schweiz), die über keinen Stausee verfügt, die Schwebstoffführung des Triebwassers (Konzentration und Partikelgrößenverteilung) mittels neuartiger Messtechnik kontinuierlich erfasst werden. Die Schädigung der Peltonturbine, d.h. der Materialabtrag an den Bechern und Düsennadeln, wird durch mehrere Inspektionen dokumentiert und mit der Einwirkung, d. h. der Schwebstoffführung des Triebwassers, korreliert, um Berechnungsansätze zur Prognose des Hydroabrasiv-Verschleisses und der Wirkungsgradabnahme zu überprüfen und zu erweitern.

Im Projekt werden verschiedene optische und akustische Messsysteme, die zur kontinuierlichen Überwachung des Schwebstoffaufkommens in Echtzeit eingesetzt werden können, untersucht und verglichen: *in-situ* Laserdiffraktometrie und Trübungs- bzw. Streulichtsonden sowie die Amplitudendämpfung von Ultraschallsignalen, wie sie bei akustischen Durchflussmessungen eingesetzt werden.

Der vorliegende Artikel beschreibt den ersten Teil eines mehrjährigen Forschungsprojekts, welches im August 2011 gestartet wurde. Zunächst werden die Problemstellung, das gewählte Vorgehen, die zu untersuchende Wasserkraftanlage und die gewählten Methoden zur Erfassung des Schwebstoffaufkommens beschrieben. Anschliessend wird auf die Versuche im hydraulischen Labor eingegangen, in welchen die Messeinrichtungen in einem Tank mit verschiedenen Wasser-Schwebstoff-Gemischen untersucht und kalibriert werden.

1 Einleitung

Sedimente an Wasserkraftanlagen und Verschleiss

Fliessgewässer können je nach Jahreszeit und Abfluss beträchtliche Mengen an Geschiebe und Schwebstoffen mit sich führen. Abb. 1 zeigt ein Beispiel eines stark geschiebe- und schwebstoffführenden Bergflusses. Für einen nachhaltigen Betrieb von Wasserkraftanlagen stellt der Umgang mit Feststoffen eine Herausforderung dar. Angesichts des im Alpenraum beobachteten Gletscherrückzugs gewinnt diese Thematik an Bedeutung, da zukünftig mehr (Fein-)Sedimente zu erwarten sind.

Abb. 1 Mündung des Wysswassers (von links im Bild) in die Rhone bei Fiesch (August 2010, Bild: VAW).

Bei Wasserkraftanlagen können die im Triebwasser enthaltenen mineralischen Partikel bei Fallhöhen von mehreren Hundert Metern und bei einem grossen Anteil harter kantiger Partikel (z.B. Quarz) zu beträchtlichen Abnutzungserscheinungen an den wasserführenden Bauteilen, besonders an den hydraulischen Maschinen (Turbinen und Pumpen) führen (z. B. Gummer 2009).

In Abb. 2 sind mineralische Partikel dargestellt, die welche in einem klassischen Sandfang nicht ausgeschieden werden und folglich mit dem Triebwasser die Turbine passieren und zu Hydroabrasiv-Verschliess führen. Abb. 3 zeigt ein Beispiel von Schäden an einem unbeschichteten Peltonlaufrad infolge Hydroabrasiv-Verschleiss.

Der Verschleiss an Turbinen kann erhebliche Betriebskosten (Revisionsarbeiten, Ersatzanschaffungen) und Ertragseinbussen (Minderproduktion infolge Wirkungsgradabnahme und Betriebsunterbruch während Revisionen) verursachen.

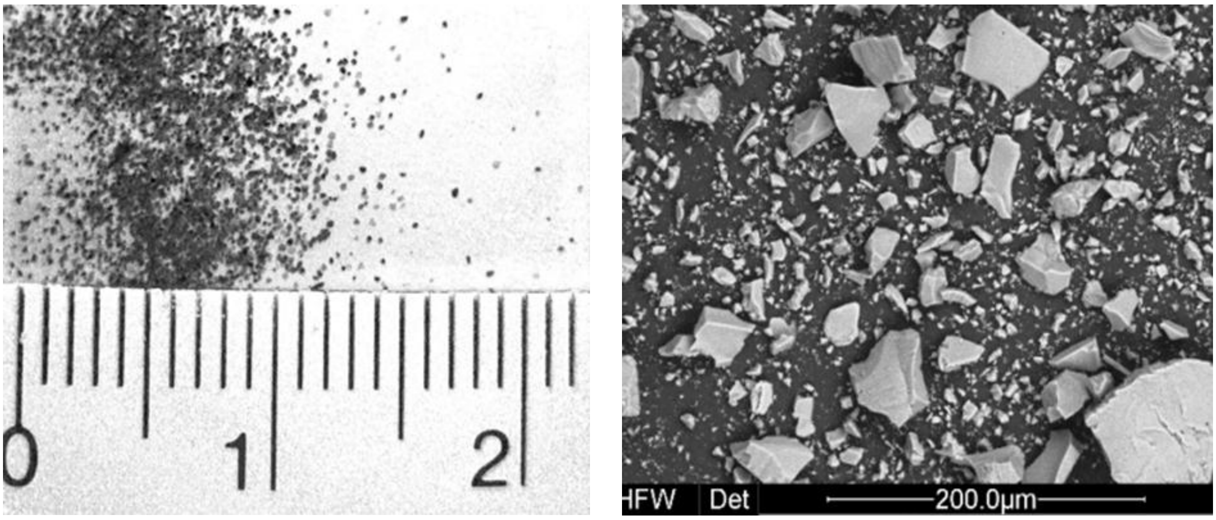

Abb. 2 Feinsand (links) sowie Quarzmehl unter dem Elektronenmikroskop (Bilder: VAW).

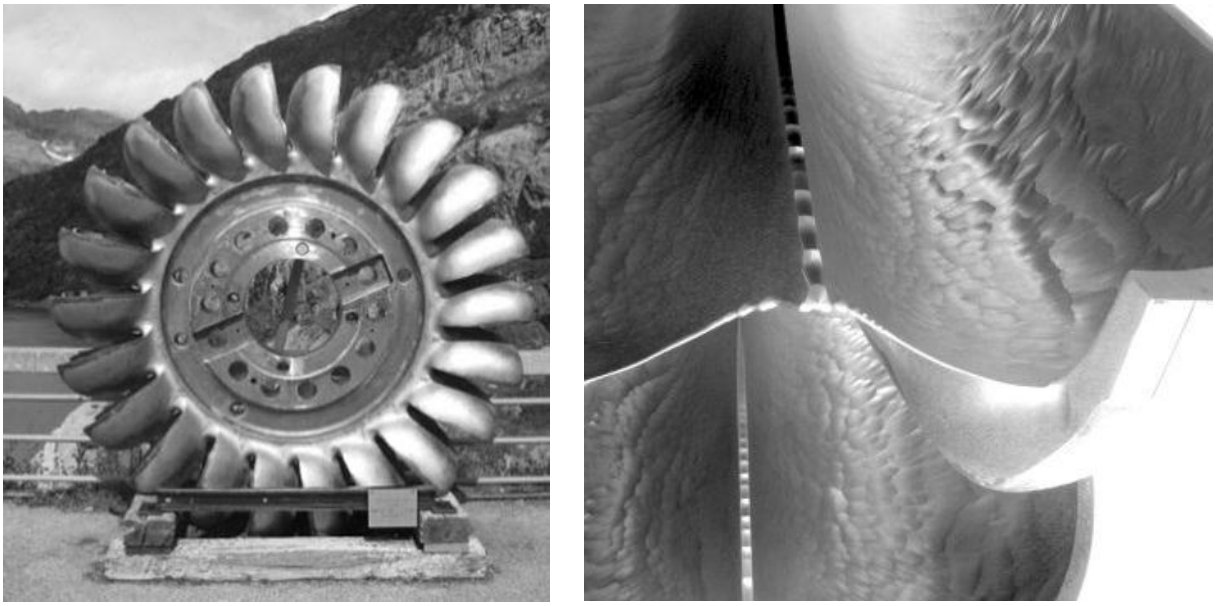
Abb. 3 Peltonturbine (links) und Schäden an den Bechern des Laufrads (Ausstellungsobjekt bei der Staumauer Emosson, Wallis, Schweiz; Bilder: VAW).

Bei Wasserspeichern können fortschreitende Sedimentablagerungen zu einer Reduktion des Nutzvolumens oder zur Beeinträchtigung der Betriebssicherheit führen. Massnahmen gegen die Speicherverlandung sind nicht Gegenstand dieses Artikels, es besteht jedoch eine Querverbindung: Heutzutage wird auch das gezielte Abführen von Feinsedimenten aus Stauseen über den Triebwasserweg (Jenzer Althaus 2011) vermehrt geprüft, wobei das Ausmass der je nach Fallhöhe, Partikelgrösse und Gesteinshärte zu erwartenden Hydroabrasiv-Verschleissschäden für die wirtschaftliche Abwägung von Interesse ist.

Gegenmaßnahmen

Bei Triebwassersystemen von Hoch- und Mitteldruckwasserkraftanlagen, welche keinen Stausee aufweisen (Laufkraftwerke), wird nach Möglichkeit grobes Geschiebe (in der Regel Steine und Kies) an der Fassung oder in Entkiesern abgewiesen, während Sand (über 0.3 bis 0.5 mm) in Entsandungsanlagen ausgeschieden und in das Gewässer zurück gespült wird. Aus wirtschaftlichen und praktischen Gründen ist eine vollständige Entfernung der im Triebwasser enthaltenen mineralischen Partikel jedoch nicht möglich.

Mit hartmetallischen, keramischen oder polymeren Beschichtungen von Turbinen kann die Einsatzzeit von Laufrädern in gewissem Masse verlängert werden. Von der Werkstofftechnologie her lässt sich allerdings der Abrasionswiderstand von Turbinen nicht beliebig steigern.

Da die Schwebstoffführung zeitlich meist sehr variabel ist, kann es wirtschaftlich sein - falls von den übergeordneten Bedingungen her möglich, das Turbinieren während kurzzeitig auftretenden Konzentrationsspitzen, beispielsweise nach einem Sommergewitter, vorübergehend für wenige Stunden einzustellen.

Forschungsbedarf und Zielsetzung

Bei zahlreichen bestehenden Hochdruck-Wasserkraftanlagen ist das Problem des Hydroabrasiv-Verschleisses qualitativ bekannt und es bestehen gewisse Berechnungsansätze zur Abschätzung des Materialabtrags (z.B. in DWA 2006). Da über die Schwebstoff-Führung des Triebwassers in der Regel jedoch kaum detaillierte Informationen zur Verfügung stehen, fällt es schwer, den Hydroabrasiv-Verschleiss zu prognostizieren und eine bezüglich Verschleiss optimierte Betriebs- und Unterhaltsweise zu finden. Weiter besteht Bedarf an Messsystemen, die für den Einsatz an Wasserkraftanlagen geeignet sind (z. B. Bishwakarma & Stole 2008).

Bei Neubauprojekten besteht auch ein Interesse an verbesserten Bemessungsgrundlagen für einen bezüglich Sedimentmanagement und Hydroabrasiv-Verschleiss wirtschaftlich optimierten Anlagenentwurf und -betrieb.

Das von der VAW der ETH Zürich initiierte und nachfolgend beschriebene Forschungsprojekt soll einen Beitrag zur Verbesserung der Kenntnisse betreffend des Schwebstoffaufkommens, der Schwebstoffmessung und des Hydroabrasiv-Verschleisses leisten.

2 Beschreibung des Forschungsprojekts

Methode und Projektbeteiligte

Der Schwerpunkt der Untersuchung liegt auf einer Prototypstudie an einer bestehenden Hochdruckwasserkraftanlage. Vorgängig werden im hydraulischen Labor Versuche zu optischen und akustischen Partikelmessmethoden durchgeführt.

Folgende Hochschul- und Industriepartner wirken an diesem interdisziplinären Forschungsprojekt mit:

- Hochschule Luzern, Kompetenzzentrum für Fluidmechanik und Hydromaschinen
- Kraftwerksbetreiber (Gommerkraftwerke AG)
- Engineering-Abteilung des Kraftwerksmiteigentümers (BKW FMB Energie AG, Bern)
- Turbinenhersteller (Andritz Hydro, Kriens/Luzern)
- Hersteller von akustischen Durchflussmessungen (Rittmeyer AG, CH-Baar)

- Trübungsmessgeräte Sigrist Photometer, CH-Ennetbürgen
- Laboranalysen von Schwebstoffproben: Institut für Geotechnik, ETH Zürich

Im Folgenden wird ein erster Teil des Forschungsprojekts, welches im August 2011 gestartet wurde und über mehrere Jahre laufen wird, beschrieben.

Beschreibung der Prototyp-Wasserkraftanlage

Als geeignete Wasserkraftanlage für dieses Forschungsprojekt konnte das Kraftwerk Fieschertal (im Kanton Wallis, Schweiz) identifiziert werden. Es handelt sich um eine Hochdruckwasserkraftanlage mit Fallrechenfassung, deren Einzugsgebiet stark vergletschert ist.

Nach der Fassung folgen ein unterirdischer Entkieser, ein Entsander und ein 2 km langer Freispiegelstollen (Abb. 4), der in Zeiten ohne Volllastbetrieb als Tagesspeicher eingesetzt wird. Vom Freispiegelstollen gelangt das Triebwasser durch eine erdverlegte Druckleitung zum Maschinenhaus beim Dorf Fieschertal, von wo das Triebwasser in den Vorfluter, das Wysswasser, zurückfliesst. Das Kraftwerk Fieschertal weist folgende technische Daten auf:

- Bruttofallhöhe 520 m
- Ausbauwassermenge 15 m^3/s
- Turbinen: 2 horizontalachsige, zweidüsige Pelton
- Nennleistung 2 x 32 MW = 64 MW

Es sind Laufräder mit Wolframkarbid-Beschichtung im Einsatz. Die mittlere Schwebstoffkonzentration am Kraftwerk Fieschertal wird bei weniger als 1 g/l erwartet. Es wurden aber schon Spitzen bis 90 g/l gemessen.

Untersuchungsprogramm

An der Kraftwerksanlage sind folgende Erhebungen vorgesehen:

- kontinuierliche Erfassung der Schwebstoffführung des Triebwassers bei der Fassung, beim Einlauf in die Druckleitung und in den Unterwasserkanälen der beiden Maschinen (Messmethoden und Messeinrichtungen gemäss folgendem Abschnitt)
- periodische Inspektion bzw. Vermessung der Laufräder und Düsen bzw. deren Beschichtungen an beiden Maschinen
- periodische Messung des Wirkungsgrads der beiden Maschinen (Index-Wirkungsgrad)

Die Messungen an der Kraftwerksanlage sind hauptsächlich in zwei Schwebstoffsaisons, d.h. in den Sommermonaten der Jahre 2012 und 2013, geplant.

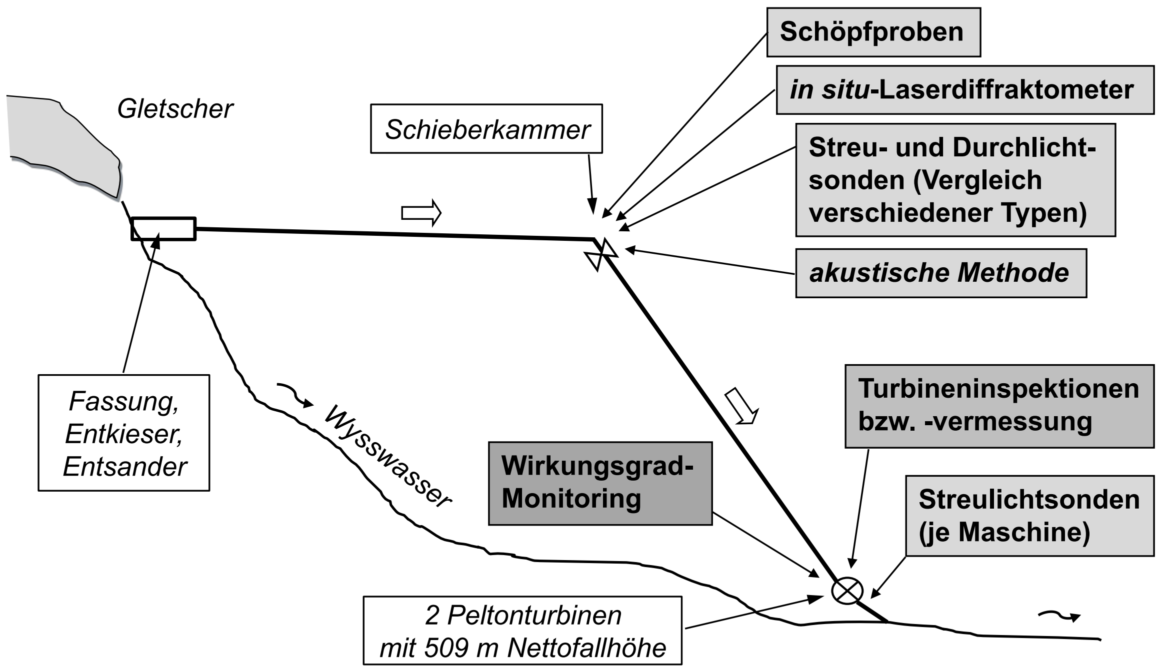

Abb. 4 Schematisches Längsprofil der Kraftwerksanlage Fieschertal mit Darstellung der vorgesehenen Untersuchungen

3 Schwebstoff-Monitoring

Streulicht- und Durchlichtsonden

Zur Überwachung von Flüssigkeiten bzw. Suspensionen in industriellen Prozessen, in der Trinkwasserversorgung, in der Abwassertechnik oder an einigen Abflussmessstationen an Fliessgewässern werden „Trübungssonden" eingesetzt. Bei diesen wird die Absorption und/oder die Streuung von Licht, typischerweise im nahen Infrarotbereich (NIR), nach dem Durchgang durch das Messmedium gemessen.

Beim Einsatz von Trübungssonden zur Bestimmung der Massenkonzentration von Feststoff-Partikeln in einer Flüssigkeit ist ein Zusammenhang (Kalibrierung) zwischen dem in optischen Einheiten gemessenen Wert (in der Regel mit der Einheit FNU) und der Massenkonzentration zu finden. Eine solche Kalibrierung kann im Labor für eine bestimmte Partikelart und für einen bestimmten Messbereich ermittelt werden.

Wenn nun aber, wie in der vorliegenden Anwendung, die Partikelzusammensetzung zeitlich veränderlich ist, kann die Umrechnung mit erheblichen Unsicherheiten behaftet sein. Einflussfaktoren für die Kalibrierung sind: Partikelgrösse, Partikelform und Partikelfarbe (und andere optische Eigenschaften).

In den Vorversuchen im hydraulischen Labor werden die in Tab. 1 aufgeführten Trübungsmessgeräte untersucht. Es ist vorgesehen, anschliessend eine Auswahl von Trübungssonden im zu untersuchenden Kraftwerk zu installieren.

Tab. 1 Untersuchte Trübungsmessgeräte

Messgerät	Hersteller	Einbauart
Solitax ts-line sc	Hach-Lange	eingetaucht
Turbimax W CUS41	Endress-Hauser	eingetaucht
TurbiScat (90° und 25°)	Sigrist Photometer	im Strang (unter Druck)
TF16-N mit Messzelle F20	Optek Danulat	im Strang (unter Druck)
AquaScat	Sigrist Photometer	im Strang (Freifall)

In-situ Laserdiffraktometrie und -transmissiometrie

Da die Grösse von mineralischen Partikeln für den Hydroabrasiv-Verschleiss eine entscheidende Grösse ist und zeitlich stark variieren kann, ist für den Einsatz an Wasserkraftanlagen ein Messgerät gefragt, welches nebst der Schwebstoffkonzentration auch die Partikelgrössenverteilung kontinuierlich erfassen kann.

Dies ist mit Geräten möglich, welche auf dem Messprinzip der Laserbeugung (Diffraktion) beruhen. Bis vor einigen Jahren wurden solche Geräte ausschliesslich im Labor eingesetzt. Nun sind tragbare Laserbeugungs-Geräte verfügbar, welche auch für Feldstudien eingesetzt werden können (Agrawal et al. 2011, Boes 2009). Von den derzeit angebotenen Geräten (Sequoia Scientific 2010), wurde das vielseitig einsetzbare Modell *LISST-100X*, Typ C, ausgewählt.

Ein Laserstrahl verläuft in der Längsachse des Geräts (Abb. 5): Der Laserstahl tritt aus der Optik im Messkopf (L) durch die zu untersuchende Suspension (Pfeil in Abbildung 5) in die Optik (R) im Hauptteil des Instruments, wo die Intensität des unter verschiedenen, kleinen Winkeln gestreuten Laserstrahls auf 32 ringförmigen Detektoren (D) aufgenommen wird. Weiter wird die Intensität des nicht gestreuten Laserstrahls, d.h. die Transmission registriert (P). Mittels einer mathematischen Umkehrung (Inversion) werden die Volumenkonzentrationen in 32 logarithmisch verteilten Partikelgrössenklassen berechnet. Mit einer anzunehmenden Sedimentdichte kann die totale Massenkonzentration berechnet werden. Das Messgerät bzw. die Software erlauben, jede Sekunde eine Partikelgrössenverteilung zu bestimmen.

Mit diesem Gerät können Partikelgrössen zwischen 2.5 und 500 Mikrometer erfasst werden, vorausgesetzt, dass die Suspension nicht zu trübe ist bzw. eine zu hohe Partikelkonzentration aufweist. Um den Bereich messbarer Konzentrationen zu vergrössern, wurde die optische Pfadlänge, d.h. die Strecke, auf welcher der Laserstrahl durch die Suspension geführt wird, mittels eines einsetzbaren Glaskörpers von standardmässig 50 mm auf 5 mm verkürzt.

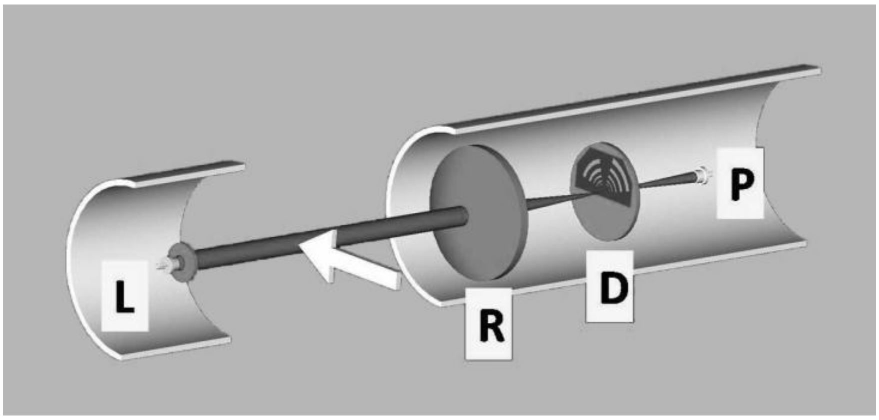

Abb. 5 Schematische Darstellung des Messprinzips des in-situ Laser-Diffraktometers (Sequoia 2010)

Akustische Messungen

Bei zahlreichen Wasserkraftanlagen wird der Durchfluss im Triebwassersystem laufend mittels Fliessgeschwindigkeitsmessungen berechnet, welche auf dem akustischen Laufzeitverfahren beruhen. Dabei wird beispielsweise zwischen baugleichen *Transducern*, die abwechslungsweise als Sender oder Empfänger dienen, ein Ultraschallpuls einmal in Fliessrichtung und einmal gegen die Fliessrichtung durch die Strömung gesendet, womit die Laufzeitdifferenz bestimmt wird. Diese wird in eine über den Pfad gemittelte Strömungsgeschwindigkeit umgerechnet.

Bei solchen akustischen Durchflussmessungen können mineralische Partikel im Wasser die Messung beeinflussen (Costa et al. 2010) oder bei hohen Konzentrationen unter Umständen verunmöglichen.

Es soll nun versucht werden, die zusätzliche Amplitudendämpfung des Ultraschallsignals infolge von mineralischen Partikeln für das Schwebstoff-Monitoring zu nutzen. Dabei ist eine Schwierigkeit, dass es verschiedene Kombinationen von Partikelgrössen und Konzentrationen gibt, welche die gleiche Dämpfung zur Folge haben. Wird ein bestimmter Partikeldurchmesser vorausgesetzt, kann eine Konzentration berechnet werden. Eine solche Annahme ist jedoch für die Anwendung im Bereich des Monitorings von Schwebstoffen ungeeignet, da Partikelgrössen *und* Konzentrationen überwacht werden sollen.

Akustische Methoden, welche mit mehreren Frequenzen arbeiten, haben das Potenzial, Informationen bezüglich Partikelgrössen zu liefern. Es wird nun geprüft, wie sich Ultraschallmessungen mit mehr als einer Frequenz im Zusammenhang mit bei Kraftwerken üblichen akustischen Durchflussmessungen realisieren lassen.

Wasserproben und Laboranalysen

Die Messgeräte sind durch Einzelproben, die im Labor bezüglich Schwebstoffkonzentration und Partikelgrössenverteilung untersucht werden, zu überprüfen.

Da bei der Prototyp-Untersuchung Schwebstoffproben bei hoher Schwebstoffführung besonders interessieren und keine dauernde Personalpräsenz bei der Fassung und in der Schieberkammer möglich ist, werden automatische Wasserprobenehmer installiert. Die Probennehmer werden so programmiert, dass in regelmässigen Intervallen und beim Überschreiten gewisser Trübungswerte Proben abgefüllt werden. So können auch während Phasen, in welchen das Schwebstoffaufkommen den Messbereich der Messgeräte überschreitet, Informationen über die Schwebstoffführung gewonnen werden.

Das Material von Schöpfproben wird für weitere Laboruntersuchungen verwendet: Bestimmung der mineralogischen Zusammensetzung (Gehalt an harten Mineralien mit Mohshärten ≥ 6, d.h. hier Quarz und Feldspat) und der Kornform.

4 Versuche im hydraulischen Labor

Zielsetzung

Vor dem Einsatz am zu untersuchenden Kraftwerk sollen die optischen und akustischen Messverfahren unter kontrollierten Bedingungen im hydraulischen Labor untersucht werden, um Kalibrierungen, Einsatzgrenzen und Messunsicherheit der Messgeräte in unterschiedlichen Suspensionen festzustellen. Gegenüber früheren Untersuchungen (z. B. Bittner 2008) soll hier auf den Einsatz eines in-situ Laserdiffraktometers *LISST-100X* in Verbindung mit Partikelsorten, die bezogen auf die Prototypstudie gewählt wurden, eingegangen werden.

Versuchseinrichtung und Methode

An der Hochschule Luzern, am Kompetenzzentrum für Fluidmechanik und Hydromaschinen in Horw, besteht eine Versuchseinrichtung, an welcher Versuche zu Partikelmessmethoden durchgeführt werden. In einem Tank mit Rührwerk (Abb. 6) werden unterschiedliche Partikelsorten mit Wasser gemischt. Der Tank hat eine Länge von 2.12 m und eine Breite von 1.13 m. Bei einer Füllhöhe von 0.5 m ergibt sich ein Volumen von 1.2 m^3.

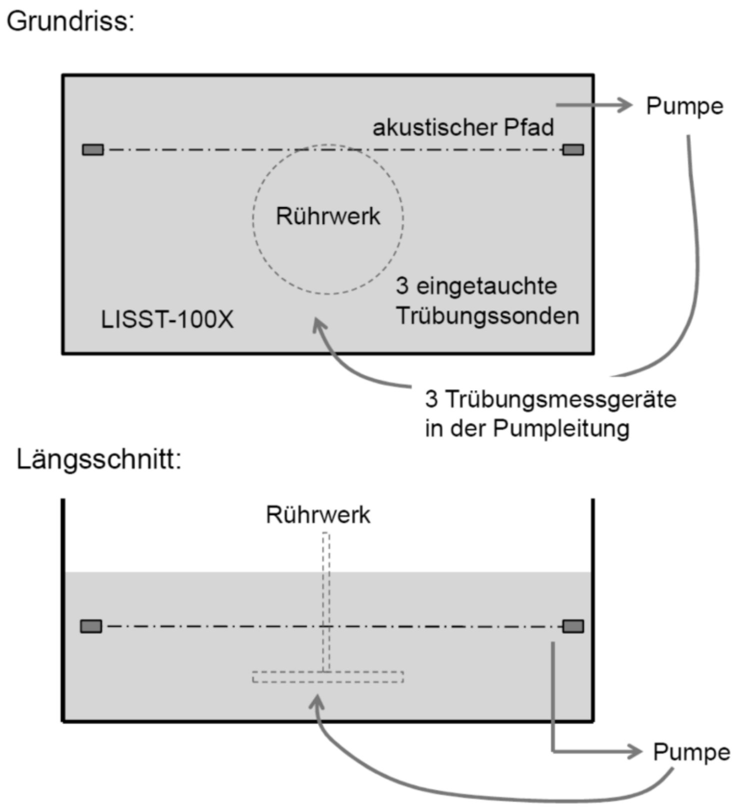

Abb. 6 Mischtank mit optischen und akustischen Messgeräten für Schwebstoffmessungen.

Ausgehend von einer „Nullmessung“ in Trinkwasser wird für jede Partikelsorte die Konzentration stufenweise gesteigert und mit allen am Mischtank installierten Geräten werden jeweils Messungen durchgeführt. Die Konzentration der Suspensionen wird nach Möglichkeit bis zum Erreichen der Messbereichsgrenzen der einzelnen Instrumente gesteigert.

Verwendete mineralische Partikel

Von früheren Untersuchungen am Kraftwerk Fieschertal ist bekannt, dass die dortigen Schwebstoffe zur Hauptsache aus Quarz, Feldspat und Glimmer bestehen, also den Hauptbestandteilen von Granitgestein.

Für die Schwebstoff-Messversuche im hydraulischen Labor wurden mineralische Partikel gesucht, welche mit den Schwebstoffpartikeln in der Natur vergleichbar und von industriellen Anwendungen her kommerziell erhältlich sind. Es wurden auch kugelförmige Partikel (Sandstrahlmittel aus Glas) in das Versuchsprogramm aufgenommen, da diese idealen Partikel oft den Messsystemen bzw. den Auswertungsalgorithmen zugrunde gelegt werden.

Aus dem Unterwasser der Turbinen des Kraftwerks Fieschertal, genauer gesagt aus dem Pumpensumpf des Turbinenkühlsystems, wurden während Revisionsarbeiten einige Eimer der abgelagerten Feinsedimente für die Laborversuche entnommen.

Von den im hydraulischen Labor verwendeten mineralischen Partikeln sind die Partikelgrössenverteilungen in Abb. 7 dargestellt. Diese wurden am Institut für Geotechnik der ETH Zürich mit dem stationären Laserdiffraktometer *Horiba* gemessen und als Referenz verwendet.

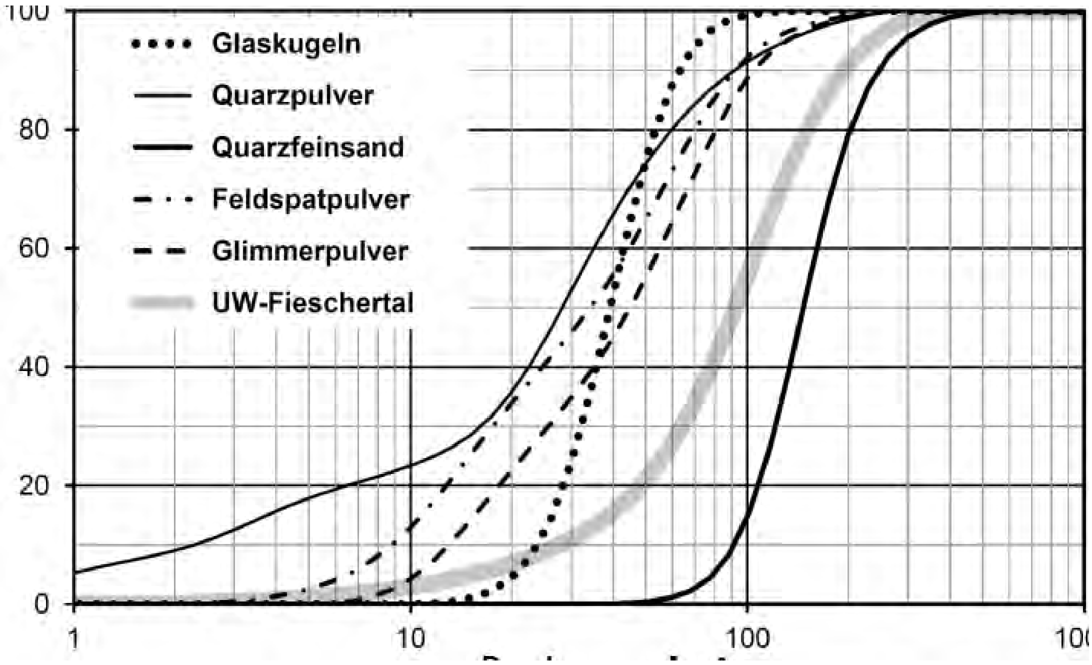

Abb. 7 Korngrössenverteilungen der untersuchten Partikel (mit Labor-Laserdiffraktometer gemessen)

Erste Versuchsresultate

Beispiele erster Resultate der Laborversuche sind in Abb. 8 und Abb. 9 dargestellt.

In Abb. 8 sind Partikelgrössenverteilungen von Quarzfeinsand, welche mit dem in-situ Laserdiffraktometer (*LISST-100X*) im Mischtank bei einer Schwebstoffkonzentration von 1 g/l gemessen und unter Annahme einer runden Kornform mithilfe der zughörigen Software berechnet wurden, in schwarz dargestellt. Aufgrund der turbulenten Verhältnisse im Mischtank mit Rührwerk variieren die gemessenen Kornverteilungen. Die dünnen Linien zeigen die Bandbreite von 100 Kornverteilungen, die mit einer Frequenz von 1 Hz gemessen wurden; die dicke schwarze Linie zeigt deren Mittelwert. Zum Vergleich ist die Referenzmessung (graue gestrichelte Linie) dargestellt. Der Mittelwert stimmt – vor allem im Bereich kleiner als etwa 120 µm – gut mit der Referenzmessung überein. Die Streuung ist bei kleineren Partikeln geringer.

In Abb. 9 ist eine erste Auswahl von in den Laborversuchen bestimmten Kalibrierkurven am Beispiel von Quarzfeinsand dargestellt. Die mit unterschiedlichen Geräten gemessenen Trübungswerte wurden in Funktion der Schwebstoffkonzentration aufgetragen, welche mit dem in-situ-Laserdiffraktometer (*LISST-100X)* gemessen wurde. Es wurde wieder mit einer Frequenz von 1 Hz gemessen und die Mittelwerte über jeweils 100 Werte gebildet. Die Schwebstoffkonzentrationen, welche mit dem LISST gemessen wurden, wurden mit Schöpfproben (Ofentrocknung) validiert. Der Zusammenhang zwischen Schwebstoffkonzentration und Trübung ist wie erwartet nahezu linear. Für die verschiedenen Sonden sind gerätespezifische Kalibrierkurven zu verwenden.

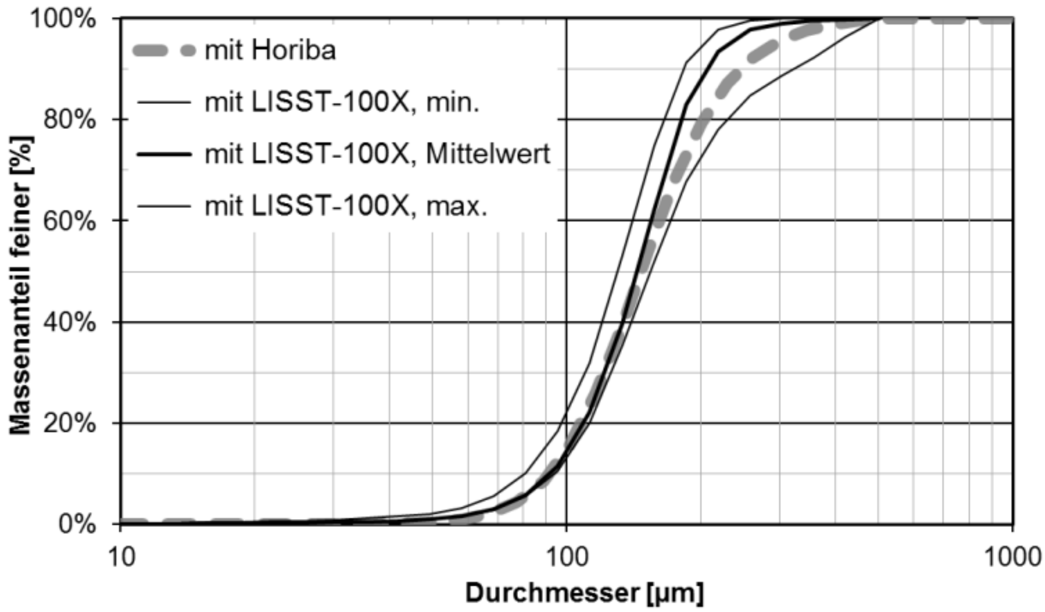

Abb. 8 Vergleich von gemessenen Partikelgrössenverteilungen (Beispiel Quarzfeinsand)

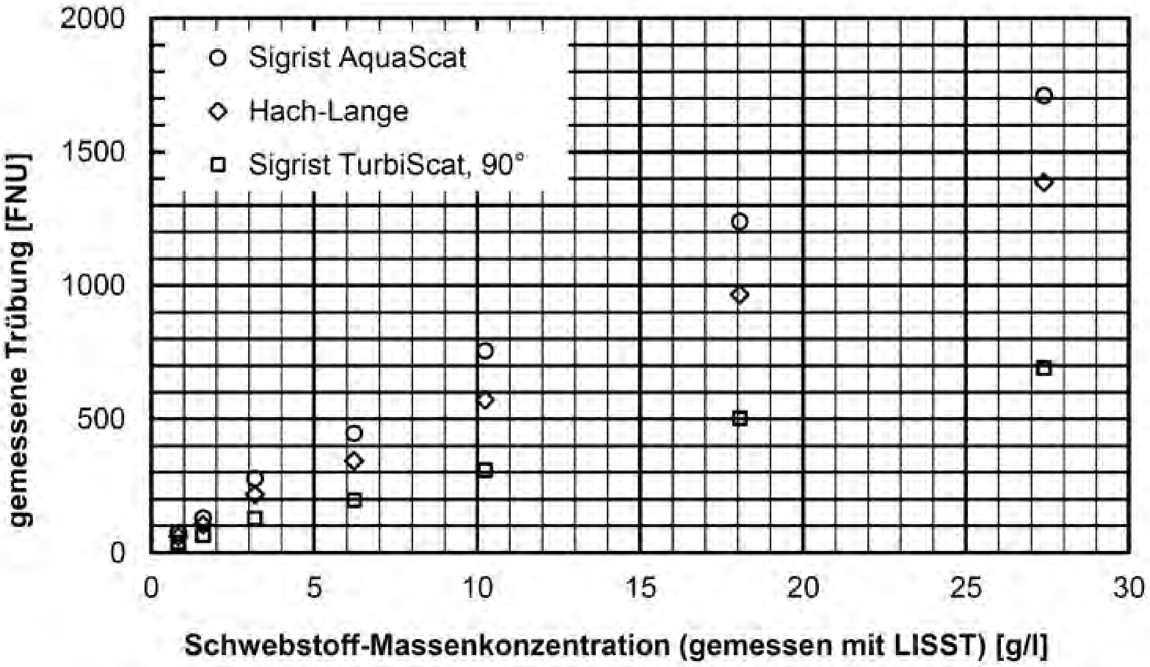

Abb. 9 Trübungswerte, welche mit drei Turbidimetern gemessen wurden, in Funktion der mittels in-situ-Laserdiffraktometer (LISST-100X) gemessenen Schwebstoffkonzentration, am Beispiel von Quarzfeinsand.

Schluss

Nach intensiven Vorbereitungen und ersten Versuchsreihen werden die Laborversuche mit den verschiedenen Partikelsorten weitergeführt und weiter ausgewertet. Für die Untersuchungen am Prototypen werden Messeinrichtungen installiert, so dass während der kommenden zwei Schwebstoffsaisons Felddaten erhoben werden können.

Basierend auf der Laboruntersuchung der Partikelmessgeräte und der Erfahrung beim Einsatz am Prototypen werden Empfehlungen bezüglich Messgeräten für Schwebstoff-Monitoring an Wasserkraftanlagen formuliert.

Ein möglichst vollständiger Datensatz über das Schwebstoffaufkommen, den Materialabtrag an den Turbinen und den zugehörigen Wirkungsgradverlust kann dazu genutzt werden, Berechnungsansätze zur Vorhersage des Turbinenverschleisses weiterzuentwickeln und zu verifizieren.

Dank

Das Forschungsprojekt wird durch swisselectric research, das Schweizer Bundesamt für Energie (BFE) und die Gommerkraftwerke sowie durch die eingangs genannten weiteren Projektpartner unterstützt. Die Autoren bedanken sich bei allen Projektpartnern für ihr Engagement.

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Literatur

[01] Agrawal Y., Mikkelsen O.A. & Pottsmith H.C. (2011). Sediment monitoring technology for turbine erosion and reservoir siltation applications. Proc. HYDRO 2011 Conference, Prague, Czech Republic.

[02] Bishwakarma M.B. & Støle H. (2008). Realtime sediment monitoring in hydropower plants. J. Hydr. Res. 46(2): 282–288.

[03] Bittner G. (2008). Vergleich von Trübungssonden bei der Schwebstoffmessung unter definierten Laborbedingungen. Diplomarbeit, Universität für Bodenkultur, Wien, Österreich.

[04] Boes R. (2009). Real-time monitoring of suspended sediment concentration and particle size distribution in the headwater way of a high-head hydropower plant. Proc. 33rd IAHR Congress, Vancouver, Canada: 4037–4044.

[05] Costa I., Storti G., Lüscher B., Gruber P. & Staubli Th. (2010). Influence of solid particle parameters on the sound speed and attenuation of pulses in acoustic discharge measurements (ADM), Switzerland. Journal of Hydrologic Engineering (accepted for publication).

[06] DWA (2006). Entlandung von Stauräumen. DWA-Themen, Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall, Hennef (Hrsg.), ISBN 978-3-937758-33-6.

[07] Gummer J. H. (2009). Combating Silt Erosion in Hydraulic Turbines. Hydro Review Wordwide, 17(1).

[08] Jenzer Althaus J. (2011). Sediment evacuation from reservoirs through intakes by jet induced flow. Dissertation Thesis, Communication Nr. 45 (A. Schleiss, ed.), LCH, EPF Lausanne.

[09] Sequoia Scientific (2010). Broschüren über das in-situ-Laser-diffraktometer LISST-100X, LISST-Hydro und LISST-Infinite, Sequoia Scientific, Inc., USA, http://www.sequoiasci.com.

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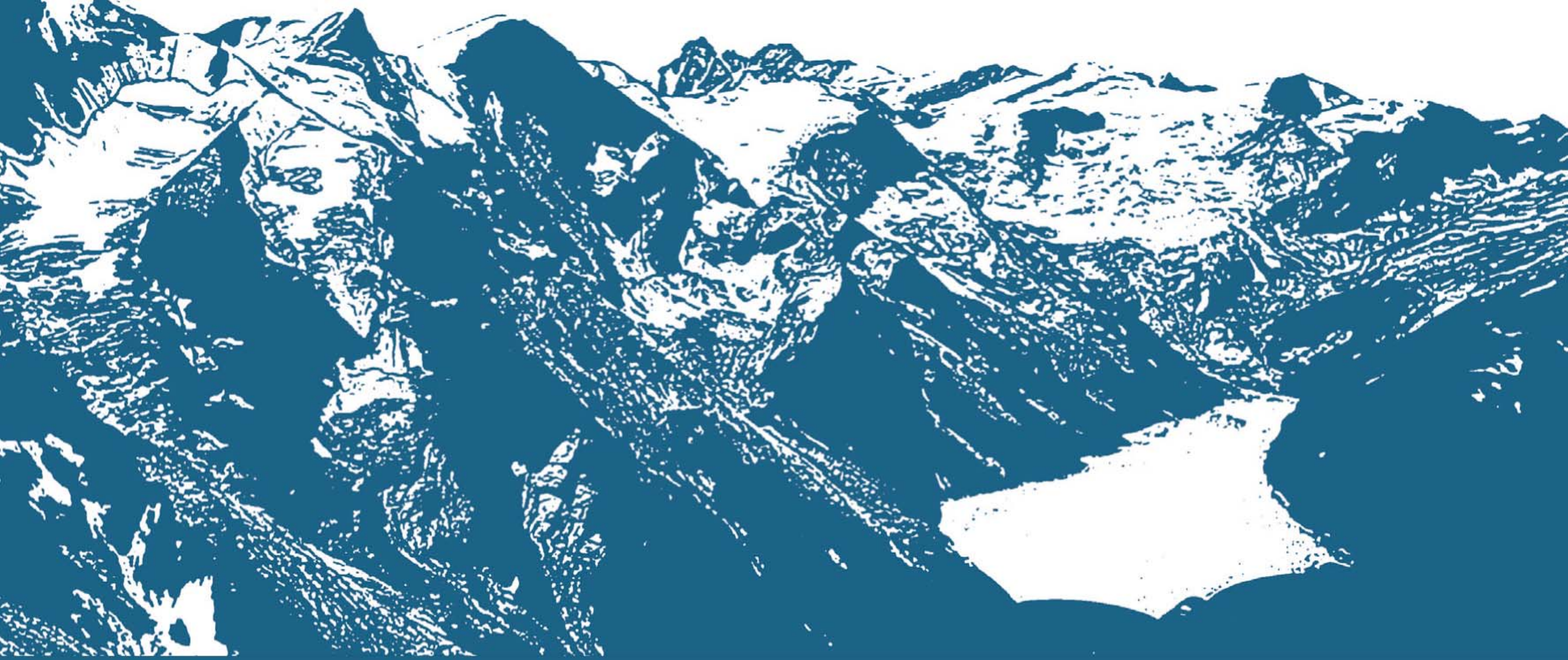

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Schwebstoffmonitoring und Verschleiß an Peltonturbinen am Fallbeispiel Fieschertal

Vorbereitende Laborversuche zu Partikelmessmethoden

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Kurzfassung

Bei Wasserkraftwerken, insbesondere bei Hoch- und Mitteldruckanlagen mit vergletscherten Einzugsgebieten und ohne Speicherseen, kann der Hydroabrasiv-Verschleiß an Turbinen und Stahlwasserbauteilen infolge schwebstoffhaltigen Triebwassers erhebliche Betriebskosten und Ertragseinbußen verursachen. Für einen wirtschaftlich optimierten Anlagenentwurf und -betrieb sollen die Bemessungsgrundlagen verbessert und anwendungstaugliche Messverfahren erprobt werden.

Im Rahmen eines interdisziplinären Forschungsprojekts soll am Kraftwerk Fieschertal im Wallis (Schweiz) die Schwebstoffführung des Triebwassers (Konzentration und Partikelgrößenverteilung) mittels neuartiger Messtechnik kontinuierlich erfasst werden. Die Schädigung der Peltonturbine, d.h. der Materialabtrag an den Bechern und Düsennadeln, und die Wirkungsgradabnahme werden am Prototypen mehrmals erhoben und mit der Einwirkung, d. h. der Schwebstoffführung des Triebwassers, korreliert, um Berechnungsansätze zu überprüfen und zu erweitern. Im Projekt werden optische und akustische Messsysteme zur Echtzeit-Überwachung des Schwebstoffaufkommens eingesetzt: in-situ Laserdiffraktometrie, verschiedene „Trübungssonden" sowie Ultraschallpulse.

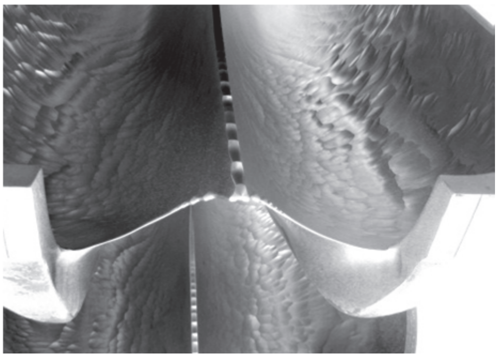
Vorgängig zur Messkampagne an der Prototypanlage wurden diese Messeinrichtungen im Labor in einem Tank mit verschiedenen Wasser-Schwebstoffgemischen untersucht. Erste Auswertungen bestätigen, dass instrumentenspezifische Kalibrierungen erforderlich sind und diese stark von der Partikelgröße und –form abhängen. Mittels in-situ Laserdiffraktometrie konnten Partikelgrößenverteilungen in einer Feldspatpulver-Suspension gemessen werden, die gut mit einer anerkannten Referenzmethode übereinstimmen. Es wird erwartet, dass die kontinuierliche Messung von Partikelgrößen „im Feld" zur besseren quantitativen Beschreibung des Hydroabrasiv-Verschleißes beiträgt.

Einleitung

Sedimente an Wasserkraftanlagen und Verschleiß

Bei Wasserkraftanlagen können die im Triebwasser enthaltenen mineralischen Partikel bei Fallhöhen von mehreren Hundert Metern und bei einem großen Anteil harter kantiger Partikel (z.B. Quarz und Feldspat) bekanntlich zu beträchtlichen Abnutzungserscheinungen an den wasserführenden Bauteilen, besonders an den hydraulischen Maschinen führen (z. B. [1]). Der Verschleiß an Turbinen kann erhebliche Betriebskosten und Ertragseinbußen verursachen.

Abbildung 1a zeigt ein Beispiel von Schäden an einem Peltonlaufrad infolge Hydroabrasiv-Verschleiß, welche durch feine mineralische Partikel (Abbildung 1b) im Triebwasser verursacht werden.

a) 

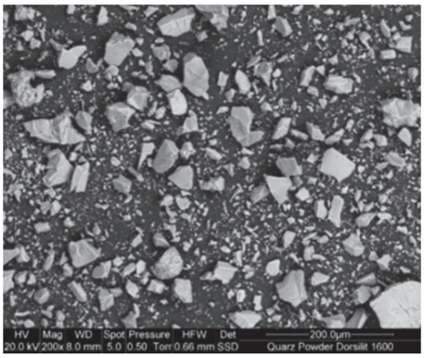
b) 

Abbildung 1: (a) Schäden an den Bechern eines unbeschichteten Pelton-Laufrades (Ausstellungsobjekt bei der Staumauer Emosson, Schweiz) und (b) feine Quarzpartikel, wie sie in sog. „Gletschermilch“ vorkommen, unter dem Elektronenmikroskop (Bilder: VAW).

Forschungsbedarf und Zielsetzung

Bei zahlreichen bestehenden Hochdruck-Wasserkraftanlagen ist das Problem des Hydroabrasiv-Verschleißes qualitativ bekannt und es bestehen gewisse Berechnungsansätze zur Abschätzung des Materialabtrags (z.B. [2]). Um Kenntnis über die vorhandene Schwebstoff-Führung des Triebwassers zu haben, besteht Bedarf an Messsystemen, die für den Einsatz an Wasserkraftanlagen geeignet sind [3].

Es besteht auch Interesse an verbesserten Bemessungsgrundlagen für einen bezüglich Sedimentmanagement und Hydroabrasiv-Verschleiß wirtschaftlich optimierten Anlagenentwurf und –betrieb, namentlich zur Bestimmung des Bemessungskorns für Entsandungsanlagen, für die Wahl von Turbinenbeschichtungen, die Auslegung von Pumpen, zur Prüfung der Option des gezielten Abführens von Feinsedimenten aus Stauseen über den Triebwasserweg oder zur Abschätzung eines Grenzwertes für vorübergehende Kraftwerksabschaltungen während kurzzeitig starkem Schwebstoffaufkommen.

Das von der VAW der ETH Zürich initiierte und nachfolgend beschriebene Forschungsprojekt soll einen Beitrag zur Verbesserung der Kenntnisse betreffend des Schwebstoffaufkommens, der Schwebstoffmessung und des Hydroabrasiv-Verschleißes leisten.

Im Folgenden wird ein erster Teil des mehrjährigen Forschungsprojekts, welches im August 2011 begonnen wurde, beschrieben.

Beschreibung des gesamten Forschungsprojekts

Methode und Projektbeteiligte

Der Schwerpunkt der Untersuchung liegt auf einer Prototypstudie an einer bestehenden Hochdruck-Wasserkraftanlage. Vorgängig werden im hydraulischen Labor Versuche zu optischen und akustischen Partikelmessmethoden durchgeführt. Folgende Hochschul- und Industriepartner wirken an diesem interdisziplinären Forschungsprojekt mit:

- Hochschule Luzern, Kompetenzzentrum für Fluidmechanik und Hydromaschinen
- Kraftwerksbetreiber (Gommerkraftwerke AG, Ernen, Schweiz)
- Engineering-Abteilung eines KW-Miteigentümers (BKW FMB Energie AG, Bern)
- Turbinenhersteller (Andritz Hydro, Kriens/Luzern)
- Hersteller von akustischen Durchflussmessungen (Rittmeyer AG, Baar, Schweiz)

Beschreibung der Prototyp-Wasserkraftanlage

Als geeignetes Fallbeispiel konnte das Wasserkraftwerk Fieschertal (Wallis, Schweiz) identifiziert werden. Es handelt sich um eine Hochdruckanlage mit Fallrechenfassung, deren

Einzugsgebiet stark vergletschert ist und bei welcher seit der Inbetriebnahme im Jahr 1976 starker Hydroabrasiv-Verschleiß beobachtet wurde.
Nach der Fassung folgen ein unterirdischer Entkieser, ein Entsander und ein 2 km langer Freispiegelstollen (Abbildung 2), der in Zeiten mit Teillastbetrieb als Tagesspeicher eingesetzt wird. Über eine Druckleitung gelangt das Triebwasser (Ausbauabfluss 15 m^3/s) auf zwei zweidüsige horizontalachsige Peltonturbinen mit einer Nennleistung von total 64 MW. Es sind Laufräder mit Wolframkarbid-Beschichtung im Einsatz. Die mittlere Schwebstoffkonzentration am Kraftwerk Fieschertal wird bei weniger als 1 g/l erwartet, es wurden aber schon Spitzen bis 90 g/l gemessen.

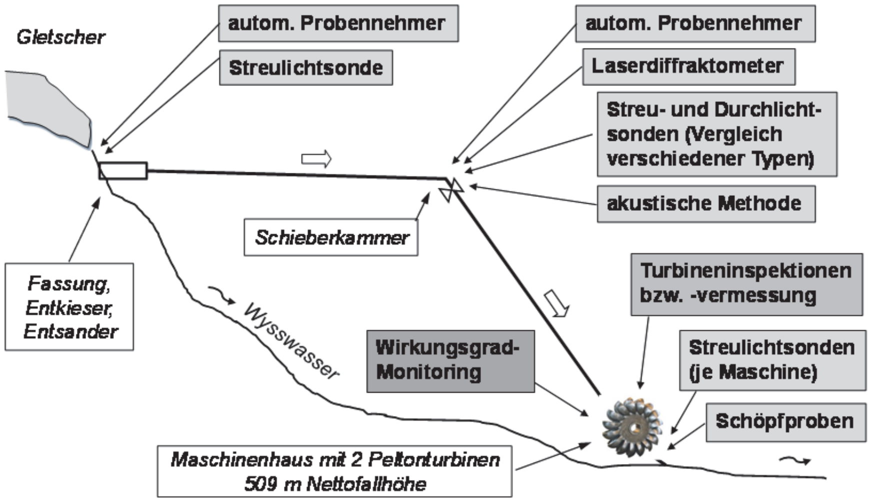


Abbildung 2: Schematisches Längsprofil der Kraftwerksanlage Fieschertal mit Darstellung der vorgesehenen Untersuchungen

Untersuchungsprogramm
An der Kraftwerksanlage sind folgende Erhebungen vorgesehen:

- kontinuierliche Erfassung der Schwebstoffführung des Triebwassers bei der Fassung, beim Einlauf in die Druckleitung und in den Unterwasserkanälen der beiden Maschinen (Messeinrichtungen gemäß folgender Beschreibung); Kalibrierung bzw. Überprüfung der Messeinrichtungen durch manuell oder automatisch zu entnehmende Schöpfproben mit Konzentrationsbestimmung und Laboruntersuchungen (Partikelgrößenverteilung; mineralogische Zusammensetzung und Kornform) ausgewählter Proben.
- periodische Inspektion bzw. Vermessung der Laufräder und Düsen bzw. deren Beschichtungen an beiden Turbinen
- periodische Messung des Wirkungsgrads der beiden Maschinen (Index-Wirkungsgrad)

Die Messungen an der Kraftwerksanlage sind hauptsächlich in zwei Schwebstoffsaisons, d.h. in den Sommermonaten der Jahre 2012 und 2013, geplant.

Versuche zu Partikelmessmethoden

Zielsetzung
Vor dem Einsatz am zu untersuchenden Kraftwerk sollen die optischen und akustischen Messverfahren unter kontrollierten Bedingungen im hydraulischen Labor untersucht werden, um Kalibrierungen, Einsatzgrenzen und Messunsicherheit der Messgeräte in unterschied-

lichen Suspensionen festzustellen. Gegenüber früheren Untersuchungen (z. B. [4]) soll hier auf den Einsatz eines in-situ Laserdiffraktometers LISST-100X in Verbindung mit Partikelsorten, die bezogen auf die Prototypstudie gewählt wurden, eingegangen werden.

Versuchseinrichtung und Methode

An der Hochschule Luzern, am Kompetenzzentrum für Fluidmechanik und Hydromaschinen in Horw, besteht eine Versuchseinrichtung, an welcher Versuche zu Partikelmessmethoden durchgeführt werden. In einem Tank mit Rührwerk (Abbildung 3) werden unterschiedliche Partikelsorten mit Wasser gemischt.

Ausgehend von einer „Nullmessung“ in Trinkwasser wird für jede Partikelsorte die Konzentration stufenweise gesteigert und mit allen am Mischtank installierten Geräten werden jeweils gleichzeitig Messungen durchgeführt. Die Messgeräte sind alle auf demselben Horizont bei 60% der Wassertiefe montiert (Abbildung 3, rechts).

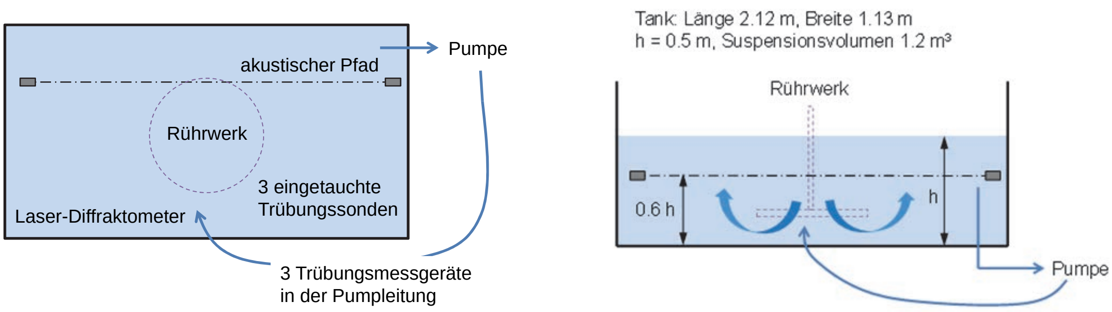


Abbildung 3: Mischtank mit optischen und akustischen Messgeräten für Schwebstoffmessungen im hydraulischen Labor, links im Grundriss und rechts im Vertikalschnitt

Streulicht- und Durchlichtsonden

Zur Überwachung von Suspensionen in der Prozessindustrie, der Wasserversorgung und der Abwassertechnik werden Streu- bzw. Durchlicht-Messgeräte, welche oft als „Trübungssonden“ bezeichnet werden, eingesetzt. Bei Streulichtsonden wird in der Regel die Einheit FNU (formazine nephtolometric unit) verwendet. Mittels einer Kalibrierung wird von dem in optischen Einheiten gemessenen Wert auf die Massenkonzentration der Feststoff-Partikel in der Flüssigkeit umgerechnet. In den Versuchen im hydraulischen Labor wurden die in Tabelle 1 aufgeführten Trübungsmessgeräte untersucht.

Tabelle 1: Untersuchte Trübungsmessgeräte

Messgerät	Hersteller	Einbauart
Solitax ts-line sc	Hach-Lange	eingetaucht
Turbimax W CUS41	Endress-Hauser	eingetaucht
TurbiScat (90° und 25°)	Sigrist Photometer	im Strang (unter Druck)
TF16-N mit Messzelle F20	Optek Danulat	im Strang (unter Druck)
AquaScat	Sigrist Photometer	im Strang (Freifall)

In-situ Laserdiffraktometrie und –transmissiometrie (LISST)

Da die Größe der mineralischen Partikeln für den Hydroabrasiv-Verschleiß ein entscheidender Parameter ist und zeitlich stark variieren kann, ist für den Einsatz an Wasserkraftanlagen ein Messgerät gefragt, welches nebst der Schwebstoffkonzentration auch die Partikelgrößenverteilung kontinuierlich in Echtzeit erfassen kann.

Dies ist mit Messgeräten möglich, welche auf der Beugung (Diffraktion) und Dämpfung

(Transmission) von Laserstrahlen beruhen. Seit einigen Jahren sind tragbare Laserbeugungs-Geräte verfügbar, welche auch für Feldstudien eingesetzt werden können ([5], [6]). Von den derzeit angebotenen Geräten [7], wurde das vielseitig einsetzbare Modell LISST-100X, Typ C, ausgewählt. Mittels einer mathematischen Umkehrung (Inversion) der gemessenen Laser-Intensitäten werden die Volumenkonzentrationen in 32 logarithmisch verteilten Partikelgrößenklassen berechnet. Mit einer anzunehmenden Sedimentdichte kann die totale Massenkonzentration berechnet werden.
Mit diesem Gerät können Partikelgrößen zwischen 2.5 und 500 Mikrometer erfasst werden, vorausgesetzt, dass die Suspension nicht zu trübe ist bzw. eine zu hohe Partikelkonzentration aufweist. Um den Bereich messbarer Konzentrationen zu vergrößern, wurde die optische Pfadlänge, d.h. die Strecke, auf welcher der Laserstrahl durch die Suspension geführt wird, mittels eines einsetzbaren Glaskörpers von standardmäßig 50 mm auf 5 mm verkürzt.

Akustische Messungen
Bei zahlreichen Wasserkraftanlagen werden Durchflüsse mit dem akustischen Laufzeitdifferenzverfahren gemessen. Dabei wird zwischen zwei schräg zur Fließrichtung an den Rohr- oder Kanalwänden angeordneten Transducern ein Ultraschallpuls in die eine Richtung und anschließend ein weiterer in entgegengesetzter Richtung durch die Strömung gesendet, womit die Laufzeitdifferenz und die Fließgeschwindigkeit bestimmt wird. Bei solchen akustischen Durchflussmessungen (ADM) können mineralische Partikel im Wasser die Messung beeinflussen [8] oder bei hohen Konzentrationen unter Umständen verunmöglichen.
Es wird nun untersucht, wie sich die Beeinflussung des Ultraschallsignals durch die suspendierten mineralischen Partikel für das Schwebstoff-Monitoring nutzen lässt.

Verwendete mineralische Partikel
Von früheren Untersuchungen am Kraftwerk Fieschertal ist bekannt, dass die dortigen Schwebstoffe zur Hauptsache aus Quarz, Feldspat und Glimmer bestehen, also den Hauptbestandteilen von Granitgestein. Für die Schwebstoff-Messversuche im hydraulischen Labor wurden zum einen mineralische Partikel ausgesucht, welche mit den Schwebstoffpartikeln in der Natur vergleichbar und von industriellen Anwendungen her kommerziell erhältlich sind. Aus dem Unterwasser der Turbinen des Kraftwerks Fieschertal, genauer gesagt aus dem Pumpensumpf des Turbinenkühlsystems, wurden zum anderen während Revisionsarbeiten einige Eimer der abgelagerten Feinsedimente für die Laborversuche entnommen.
Von den im hydraulischen Labor verwendeten mineralischen Partikeln sind die Partikelgrößenverteilungen in Abbildung 4 dargestellt. Diese wurden am Institut für Geotechnik der ETH Zürich mit dem stationären Laserdiffraktometer Horiba gemessen und als Referenz verwendet.

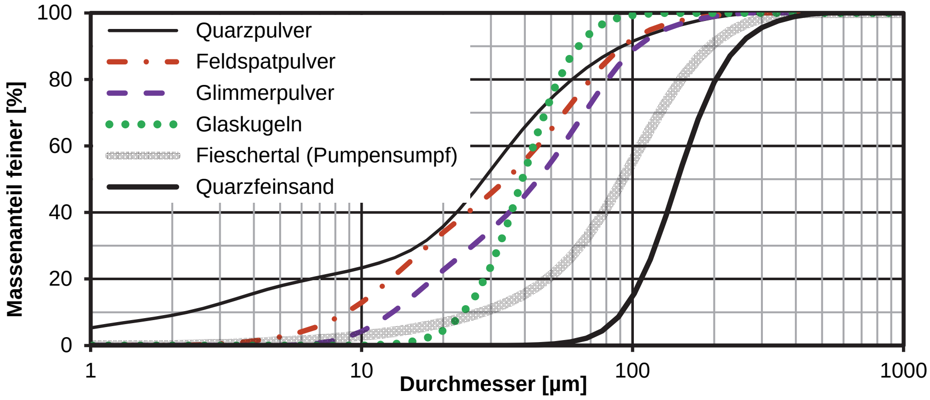


Abbildung 4: Korngrößenverteilungen der verwendeten Partikel

Erste Versuchsresultate und Diskussion

In den folgenden drei Abbildungen sind Resultate von ersten Auswertungen der Laborversuche bezüglich Partikelmessmethoden dargestellt.

Abbildung 5 zeigt Partikelgrößenverteilungen von Feldspatpulver, welche mit dem Laserdiffraktometer im Mischtank bei einer nominellen Schwebstoffkonzentration von 1 g/l gemessen und mithilfe der zugehörigen Software unter Annahme einer unregelmäßigen Partikelform berechnet wurden. Die gemessenen Partikelverteilungen variieren u.a. aufgrund der Turbulenz im Mischtank. Die gestrichelten schwarzen Linien zeigen die 5% bzw. 95%-Fraktilen von 100 Kornverteilungen, die mit einer Frequenz von 1 Hz gemessen wurden; die ausgezogene schwarze Linie zeigt den Median. Zum Vergleich ist die Referenzmessung (aus Abbildung 4) als graue Linie dargestellt. Die Messung der Partikelgrößenverteilung mit dem LISST-100X stimmt generell recht gut mit der Referenzmessung überein.

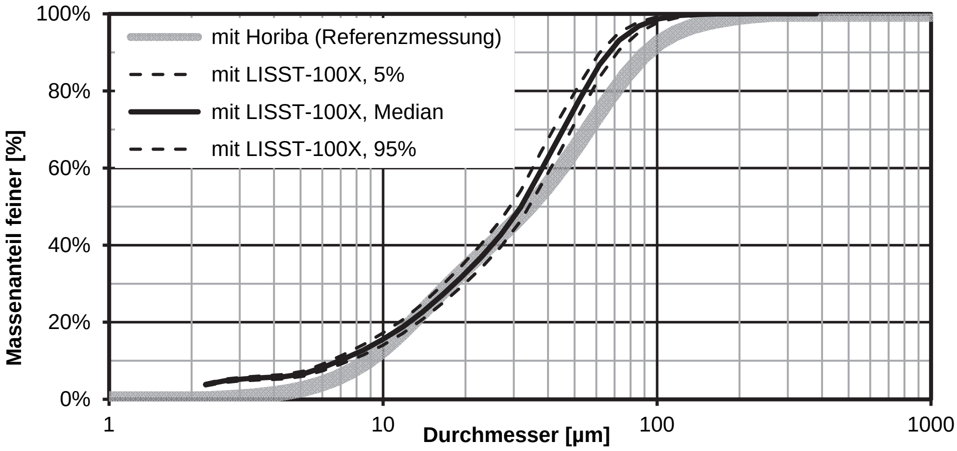


Abbildung 5: Vergleich von gemessenen Partikelgrößenverteilungen (Feldspatpulver)

Abbildung 6 zeigt ausgewählte Messresultate am Beispiel von Feldspatpulver in Funktion der Referenz-Schwebstoffkonzentration. Diese wurde mittels Schöpfproben, die aus dem Tank auf dem Horizont der Messgeräte entnommen und im Ofen getrocknet wurden, unter Berücksichtigung der im verwendeten Trinkwasser gelösten Mineralien ermittelt.

An der linken Ordinate ist die mit dem Laserdiffraktometer ermittelte Massenkonzentration der Schwebstoffe im Mischtank abzulesen. Dabei wurde pro Konzentrationsstufe die Volumenkonzentration über 100 Messwerte gemittelt und mit einer angenommenen Dichte von 2.65 g/l (wie Quarz) multipliziert. Die so mit der Werkskalibrierung ermittelten Schwebstoffkonzentrationen liegen bei dieser Partikelsorte ca. 20% bis 60% über den Referenzkonzentrationen.

An der rechten Ordinate sind die Messresultate von vier Streulichtsonden dargestellt. Es wurden jeweils die Mittelwerte über 500 Messungen, die im Sekundentakt aufgezeichnet wurden, gebildet. Der Zusammenhang zwischen Schwebstoffkonzentration und Trübung ist - wie in diesem Konzentrationsbereich erwartet - nahezu linear. Obwohl bei allen vier Geräten die Einheit FNU verwendet wird, weichen die Messwerte der unterschiedlichen Geräte bei gleichen Bedingungen bei dieser Partikelsorte im dargestellten Konzentrationsbereich um ca. 40% voneinander ab.

In Abbildung 7 sind wiederum Kalibriergeraden dargestellt, nun aber für Suspensionen mit verschiedenen Partikelsorten, am Beispiel der Trübungssonde Solitax ts-line sc (Hach-Lange). Für die Partikelsorten sind die Durchmesser bei 50% Massenanteil (d_{50}) gemäß Referenzmessung der Partikelgrößenverteilungen (Abbildung 4) angegeben. Wie aus der Literatur (z.B. [9]) bekannt, ist eine starke Abhängigkeit der Trübung vom Partikeldurchmesser zu erkennen. Die Lage der Geraden des Glimmerpulvers (plättchenförmige Partikel) und der

Glaskugeln zeigt weiter im Vergleich zu den gebrochenen Partikeln trotz ähnlichen d_{50} einen deutlichen Einfluss der Partikelform.

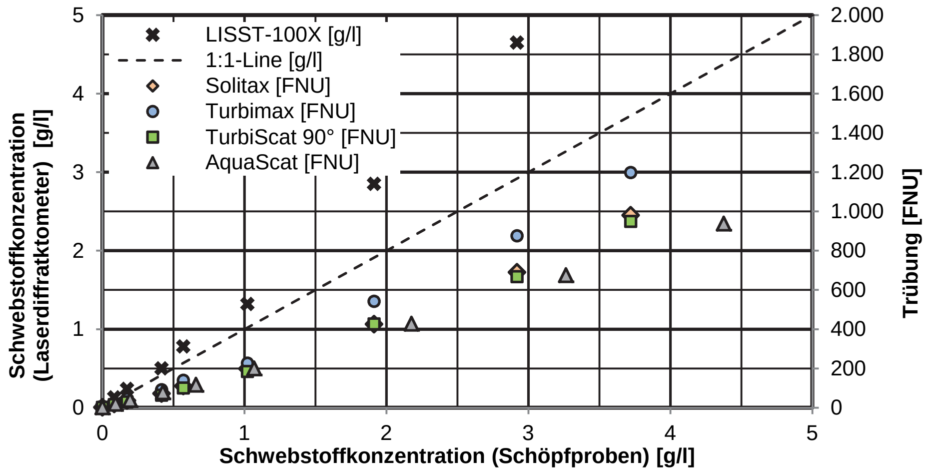


Abbildung 6: Messresultate des Laserdiffraktometers und ausgewählter Trübungssonden in Funktion der Referenz-Konzentrationsmessungen mittels Schöpfproben (Feldspatpulver)

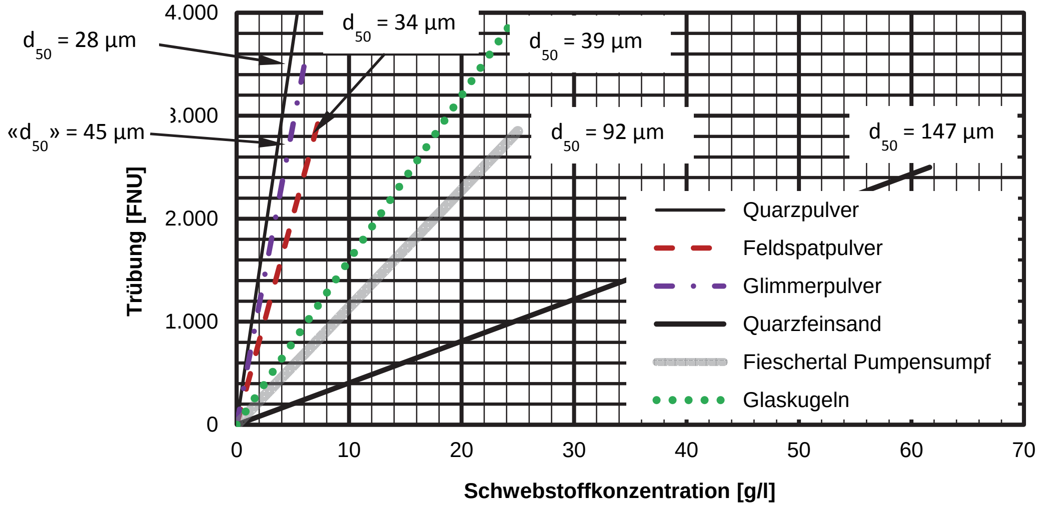


Abbildung 7: Trübungswerte, welche mit einer Trübungssonde (Hach-Lange Solitax ts-line sc) in Suspensionen mit sechs verschiedenen Partikelsorten gemessen wurden

Schlussfolgerungen und Ausblick

In Laborversuchen wurden verschiedene Partikelmessgeräte und -methoden an Suspensionen aus mineralischen Partikeln untersucht. Als Partikel kamen kommerziell erhältliche Gesteinspulver, Feinsand, Glaskugeln sowie ein Schluff-Feinsand-Gemisch aus einer alpinen Wasserkraftanlage zum Einsatz.

Die Kalibrierkurven von Trübungssonden können je nach Messgerät und Partikeleigenschaften, insbesondere der Partikelgröße, stark unterschiedlich sein. Für die Messgeräte sind Kalibrierkurven zu verwenden, die mit dem jeweiligen Messgerät und einer bestimmten Partikelsorte im interessierenden Messbereich durch Vergleich mit Schöpfproben ermittelt wurden. Für den Einsatz in der Praxis bringt dies einen gewissen Aufwand mit sich.

In Wasserkraftanlagen können sich die Größe und allenfalls die Form und Farbe der im Triebwasser mitgeführten Partikel im Lauf der Zeit ändern, was bei der Umrechnung von Trübungs- auf Konzentrationsganglinien eine beträchtliche Unsicherheit mit sich bringen

kann . Die Anwendung des in-situ Laserdiffraktometers für das Schwebstoffmonitoring an Wasserkraftanlagen wird weiter untersucht, da dies nebst der Konzentrationsmessung eine Messung der Partikelgrößen erlaubt.
Für die Untersuchungen am Prototypen werden Messeinrichtungen installiert, so dass während der kommenden zwei Schwebstoffsaisons Felddaten erhoben werden können. Basierend auf der Laboruntersuchung der Partikelmessgeräte und der Erfahrung beim Einsatz am Prototypen werden Empfehlungen bezüglich Messgeräten für das Schwebstoff-Monitoring an Wasserkraftanlagen formuliert.
Ein möglichst vollständiger Datensatz über das Schwebstoffaufkommen, den Materialabtrag an den Turbinen und den zugehörigen Wirkungsgradverlust kann dazu genutzt werden, Berechnungsansätze zur Vorhersage des Turbinenverschleißes weiterzuentwickeln und zu verifizieren.

Danksagung

Das Forschungsprojekt wird durch swisselectric research, das Schweizer Bundesamt für Energie (BFE) und die Gommerkraftwerke sowie durch die eingangs genannten weiteren Projektpartner unterstützt. Die Autoren bedanken sich bei allen Projektpartnern für ihr Engagement und besonders bei Prof. Dr. T. Staubli, Prof. Dr. P. Gruber, A. Abgottspon und M. Duss von der Hochschule Luzern, Kompetenzzentrum für Fluidmechanik und Hydromaschinen, für die Unterstützung bei der Durchführung der beschriebenen Laborversuche. Ein weiterer Dank geht an die Firma Sigrist Photometer, Ennetbürgen, welche ein Trübungsmessgerät für die Laboruntersuchungen zur Verfügung gestellt hat.

Quellenverzeichnis

[1] Gummer J. H. (2009). Combating Silt Erosion in Hydraulic Turbines. Hydro Review Wordwide, 17(1).
[2] DWA (2006). Entlandung von Stauräumen. DWA-Themen, Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef (Hrsg.), ISBN 978-3-937758-33-6.
[3] Bishwakarma M.B., Støle H. (2008). Realtime sediment monitoring in hydropower plants. J. Hydr. Res. 46(2): 282–288.
[4] Bittner G. (2008). Vergleich von Trübungssonden bei der Schwebstoffmessung unter definierten Laborbedingungen. Diplomarbeit, Universität für Bodenkultur, Wien, Österreich.
[5] Agrawal Y., Mikkelsen O.A., Pottsmith H.C. (2011). Sediment monitoring technology for turbine erosion and reservoir siltation applications. Proc. HYDRO 2011 Conference, Prague, Czech Republic.
[6] Boes R. (2009). Real-time monitoring of suspended sediment concentration and particle size distribution in the headwater way of a high-head hydropower plant. Proc. 33rd IAHR Congress, Vancouver, Canada: 4037–4044.
[7] Sequoia Scientific (2010). Broschüren über das in-situ-Laserdiffraktometer LISST-100X, LISST-Hydro und LISST-Infinite, Sequoia Scientific, Inc., USA, www.sequoiasci.com.
[8] Costa I., Storti G., Lüscher B., Gruber P., Staubli Th. (2010). Influence of solid particle parameters on the sound speed and attenuation of pulses in acoustic discharge measurements (ADM), Switzerland. Journal of Hydrologic Engineering (accepted for publication).
[9] Gippel, C. J. (1995). Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrological Processes 9: 83-97.

SUSPENDED SEDIMENT AND PELTON TURBINE WEAR MONITORING: EXPERIMENTAL INVESTIGATION OF VARIOUS OPTICAL AND ACOUSTIC DEVICES AND BEGIN OF THE CASE STUDY FIESCHERTAL

D. Felix, I. Albayrak, A. Abgottspon, R. Boes, P. Gruber

Abstract: Considerable hydro-abrasive wear may occur at turbines of hydroelectric power plants particularly at high-head run-of-river schemes in glaciated catchment areas.
In order to optimize the operation of such power plants, real-time information on suspended sediment is required. Optical and acoustic devices for suspended sediment monitoring were calibrated in the laboratory and installed at a case study site in the Swiss Alps, delivering first results. Furthermore, the 3D-geometry of the turbine buckets was digitalized with high accuracy to quantify changes in geometry and material loss.

1 Introduction

Hydro-abrasive wear at turbines and steel hydraulics parts due to suspended mineral particles in the water can lead to substantial maintenance costs and significant negative impacts on power generation and revenue at hydroelectric power plants (HPP), particularly at high-head run-of-river type plants in glaciated catchment areas with igneous rocks such as granite. For well-balanced plant design and operation there is still a need for improved design knowledge and adequate real-time measuring systems to monitor suspended sediment load at prototype conditions [1].
In order to advance in the understanding and addressing of this problem VAW of ETH Zurich initiated an interdisciplinary project in cooperation with Hochschule Luzern and supported by swisselectric research, the Swiss Federal Office of Energy, the power plant operator (Gommerkraftwerke) and co-owner (Bernische Kraftwerke) as well as industry partners (Andritz Hydro and Rittmeyer). This project focusses on the investigation of hydro-abrasive wear at the existing high-head HPP Fieschertal, in Upper Valais, Switzerland. Since the plant was built in 1976 severe hydro-abrasive wear at needles, nozzles and runners of the two 32 MW-Pelton units has been observed. Although coating of turbines and other hydraulics parts reduced the extent of the damages, sediment handling as well as optimized operation and maintenance of the HPP remain an important economic issue. Increased yield of fine sediment is expected in the Alps due to the glacier retreat.
In this project, suspended sediment in the turbine water is continuously monitored during two or three summer seasons using various measuring techniques. In parallel material loss on turbines and efficiency reduction are measured. Suspended sediment load, material loss on turbines and efficiency reduction shall be correlated in order to verify and improve forecasting of hydro-abrasive wear.

This paper focuses on suspended sediment monitoring (preliminary laboratory tests and first case study results) and the selected method for quantifying geometry changes at turbine runners.

2 Suspended sediment monitoring techniques

2.1 Overview

For the investigation of hyro-abrasive wear the following parameters are of interest:

- Suspended sediment (mass) concentration (SSC)
- Particles size distribution (PSD)
- Hardness (mineralogical composition) and shape of the mineral particles

Hardness and shape of the particles are assumed to be relatively constant and can be determined by laboratory analysis of a few periodically taken samples.
SSC and PSD however may vary considerably in time. Thus a continuous monitoring of these parameters is required. Various devices to monitor SSC are currently available or under development. The following optical and acoustic devices were selected for this study:

(a) Turbidimeters (attenuation and/or scattering of near infrared or laser light),
(b) Portable laser transmissiometry and diffraction (LD) and
(c) Acoustic transducers as used in acoustic discharge measurement (ADM) devices.

From literature (e.g. [2]) it is known that the particle size has a significant effect on hydro-abrasive wear. As to our knowledge the portable laser diffraction device is the only instrument that provides in-situ real-time particles size distributions in addition to information on SSC.

2.2 Turbidimeters

For monitoring of suspensions in industrial processes, water and wastewater plants optical probes - called “turbidimeters” - are used. The readings (displayed in optical units) delivered by such probes are converted to SSC using a calibration curve which has to be obtained by the user for the prevailing type of particles. The devices listed in Tab. 1 were tested in the lab prior to the installation at the case study site.

Product	Manufacturer	Measuring principle	Installation	Nom. range
Solitax ts-line sc	Hach-Lange	Combined scattering at 90° and 140°	submerged	0…4000 [FNU]
Turbimax W CUS41	Endress-Hauser	Scattering at 90° multiple channels	submerged	0…9999 [FNU]
TurbiScat	Sigrist Photometer	Scattering at 90° and 25°, in combination with transmission	in-line (pressure flow)	2 channels 0…4000 [FNU]
AquaScat	Sigrist Photometer	Scattering at 90°	in-line (free falling jet)	0…4000 [FNU]
TF16-N with flow cell F20	Optek Danulat	Transmission (0°)	in-line (pressure flow)	0...5 [CU]

Table 1. Tested optical probes

2.3 Portable laser transmissiometry and diffraction (LD)

Among the available portable laser diffraction devices a LISST-100X, Typ C (from Sequoia Scientific) was selected. This submersible instrument can also be used for investigations of suspended sediment in reservoirs and desilting facilities. A similar LD instrument is in use at a high-head HPP on a mountain stream in Austria [3]. The use of LD instruments at HPPs is discussed in [4]. By means of a mathematical inversion of the measured laser intensities the volume concentrations of 32 log-spaced particle size bins are calculated. The total mass concentration (SSC) can be calculated using an estimated sediment density. The nominal size range of measureable particles is 2.5 to 500 micrometers for the selected type of instrument. In order to extend the range of measurable SSC the optical path length was reduced from 50 mm to 5 mm by using a 90%-path reduction module.

2.4 Acoustic measurements at ADM-installations

In many HPPs worldwide discharges are measured using the acoustic transit time method (acoustic discharge measurement ADM). Ultrasonic pulses are subsequently sent through the flow on several paths, which are arranged oblique to the main flow direction. Between two identical transducers that are installed at the penstock or channel walls ultrasonic pulses are sent and received once forward and then backwards. From the difference in the measured “time of flight” between both directions the average flow velocity and discharge are calculated. Acoustic discharge measurement can be influenced or possibly disrupted in case of high SSCs [5]. On the other hand, the alteration of the received signals due to the presence of mineral particles can be used for (at least qualitative) suspended sediment monitoring.

3 Laboratory investigation on suspended sediment monitoring

3.1 Experimental set-up and methodology

Prior to the field study the devices for suspended sediment monitoring were tested in in the hydraulic laboratory of Hochschule Luzern, at an existing facility of the Competence Centre for Fluid Mechanics and Hydro Machines [6]. In a tank equipped with a stirrer (Fig. 1) various suspensions of water and mineral particles with SSC from 0.1 g/l up to 50 g/l (depending on the type of particles) were prepared. Starting from a zero measurement in drinking water the concentration was increased step-wise and measurements were done simultaneously with all devices involved. All devices were placed at the same level.

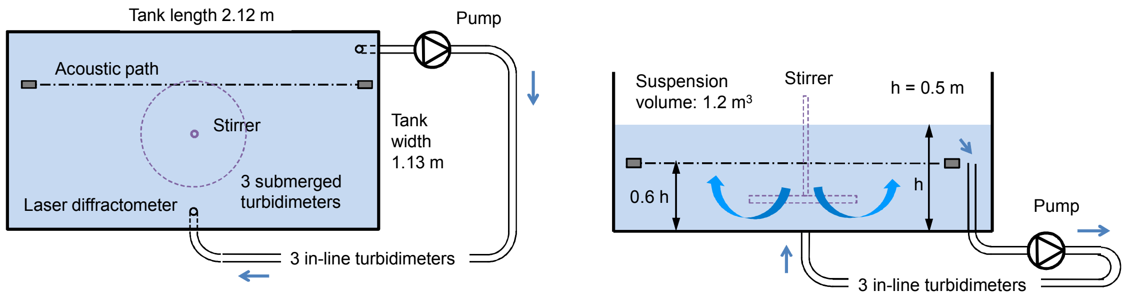


Fig. 1. Mixing tank in the hydraulic laboratory with optical and acoustic devices for measuring suspended sediment, left plan view and right vertical section.

3.2 Materials

According to previous investigations [6] the suspended sediment at the case study site consists of approximately 20 % quartz, 50 % feldspar and 30 % mica, i.e. the main components of granite rock. The mineral particles used in the laboratory tests were selected considering the similarity to natural conditions at the case study site. Most of the particles were bought from industrial applications. In addition, natural particles taken from the turbine's tailwater channel during revision works (deposit in the pump sump of the turbine cooling system) were included in the tests. Glass beads were used as a reference (spherical shape). Quartz and feldspar powder particles have angular shape (from grinding) while quartz fine sand and mica powder have rounded (natural sand) and flaky shape, respectively.

3.3 Results

First results of the measurements made with a turbidimeter, the LISST and the acoustic method are presented in this section.
The measured values (except for PSD) are plotted against the reference SSC, which was determined by samples taken from the tank at the instrument's elevation (three samples per concentration level). By weighing the samples before and after drying in the oven, the effectively prevailing SSC was determined, deducting the dissolved minerals from the residue. Reference measurements of PSD were obtained from the samples analysed by a non-portable laser diffractometer (Horiba) at the Geotechnical Institute of ETH Zurich.
Fig. 2 shows turbidity measured by the optical transmission probe (Optek) as a function of the reference SSC for four kinds of particles and d_{50}, which is the particle diameter of 50 % finer, according to the PSD reference measurement. The plotted values are averages of 500 measurements per concentration level, recorded at 1 Hz.

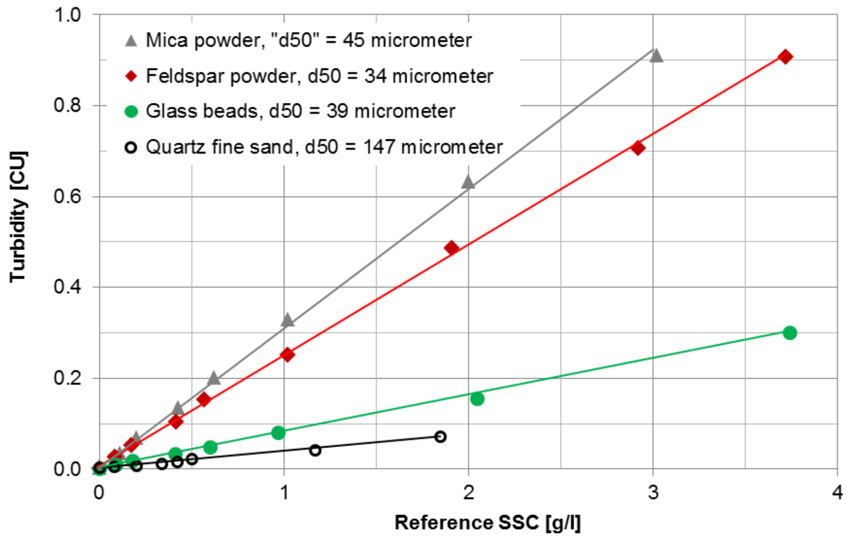


Fig. 2. Turbidity measured by optical transmission as a function of reference SSC

In the displayed range of SSC there is a linear relationship between turbidity and the reference SSC for each type of particle. However, turbidity is not only function of SCC but also of particle type with effects of particle size, shape and optical properties.
Fig. 3 shows the damping of the amplitude of the received ultrasonic pulses (forward scattering) normalized with the amplitude measured in drinking water (SSC = 0) as a function of the reference concentration for various kind of particles in the mixing tank. The amplitudes were measured at a distance of 1.73 m away from the sender and the sent pulses have a frequency of 1 MHz. The plotted values are averages over 60 values per concentration level, recorded at 1 Hz. The amplitude of the received signal decreases almost linearly as SSC increases. The damping depends on particle material, size and shape. Previous investigations [6] indicate that the calibration curves for the acoustic method vary less with particle size than those of turbidimeters.

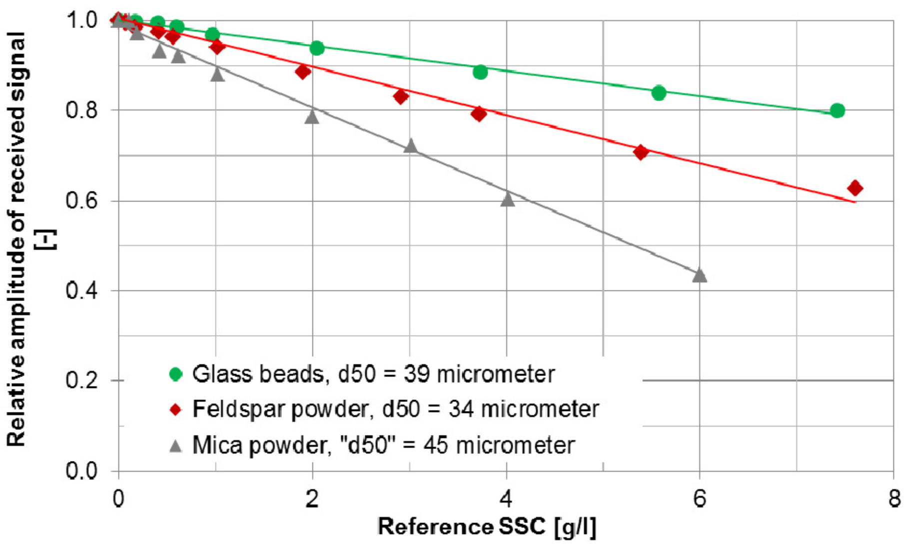


Fig. 3. Relative amplitude of received ultrasonic pulses as a function of reference SSC

Fig. 4 shows a comparison of the time-averaged PSDs measured by LISST at 1Hz for 100s at a nominal SSC of 1 g/l and the reference PSDs for feldspar and quartz fine sand. In LISST PSD calculations, particle shape was assumed to be “irregular”.
The PSDs measured by LISST match approximately with the reference PSDs, e.g. with respect to the range of d_{50} and the general shape of the PSD (narrow or wide distribution), for fine sand as well as coarse silt. The PSD of feldspar powder, whose left end touches the lower limit of measureable sizes, is biased by “fine out of range particles” [7]. The LISST underestimates the proportion of coarser particles within the PSDs; this is more pronounced for fine quartz sand. It should be noted that for the flaky shape of mica powder the definition of the particle diameter is not obvious and it was not possible to check the accuracy of the reference PSDs, since in contrast to SSC no primary measuring method is available. The deviations between LISST and the reference measurements will be further analyzed.
The relationship between the SSC measured by LISST and the reference SSC is presented in Fig. 5. Plotted values are again the time-averages of 100 measurements per concentration level at 1 Hz. For the conversion of volume concentration to mass concentration (SSC) a density of 2.65 kg/l (standard value for

quartz) was assumed for all materials, leading to an error of presumably less than 5%.
For fine quartz sand, which is the coarsest particle among the other particles, SSC measured by LISST correspond generally well to the expected SSCs (1:1-line). It should be noted that no custom calibration was applied. For feldspar powder, the LISST SSCs correspond to the reference SSCs at lower concentrations, but LISST increasingly overestimates SSCs at higher concentrations. This can be related to the effect of "fine out of range particles", which may bias the inversion and becomes more pronounced as the SSC approaches the upper measurement limit of the LISST. For the mica powder however, the LISST significantly overestimates the SSC (factor of 6), what can be attributed to the flaky shape of these particles producing over-proportional scattering.

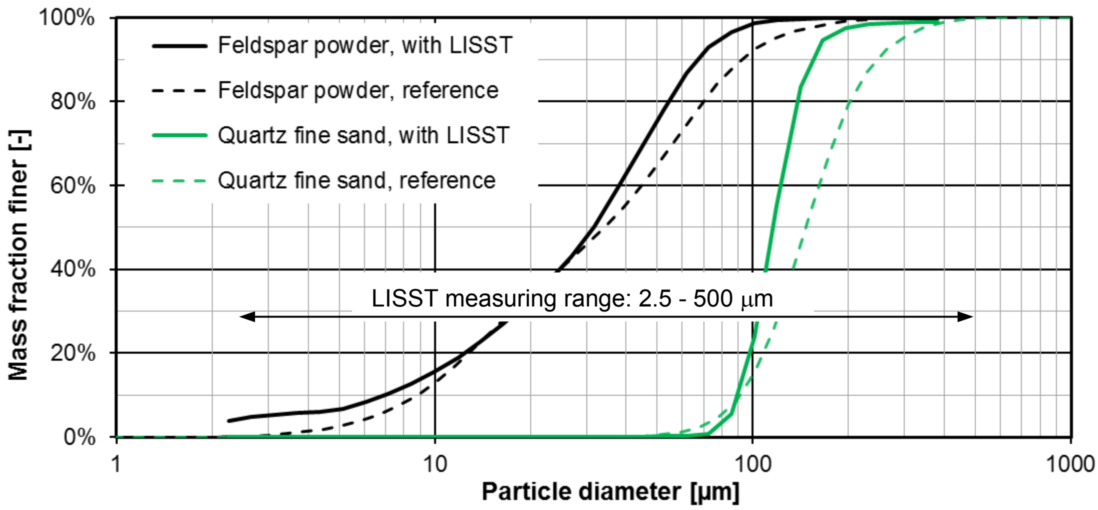


Fig. 4. PSDs measured in by portable laser diffraction (LISST) and by the reference method

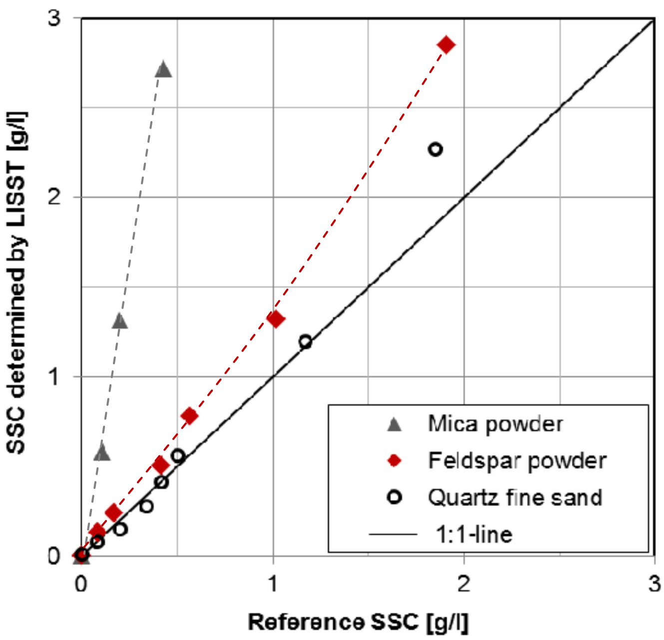


Fig. 4. SSCs determined by LISST as a function of reference SSC

4 Field investigations on suspended sediment and turbine wear

4.1 Installation of suspended sediment monitoring devices

After the tests were completed in the laboratory, the devices for real-time monitoring of suspended sediment were installed in the HPP of Fieschertal (see Fig. 6). Most devices were placed in the valve chamber at the top of the penstock and fed by a sampling pipe with sediment-laden water taken from the axis of the penstock. In addition, two turbidimeters were installed and turbined water is pumped up to them from each turbine unit's tailrace channel.
An automatic water sampler with 24 bottles in the valve chamber was installed to collect samples of the turbined sediment-laden water. SSC is determined from the water samples and used to calibrate the instruments with respect to the particles of the study site. The water sampler is triggered by a turbidimeter in order to take more samples during sediment peaks.

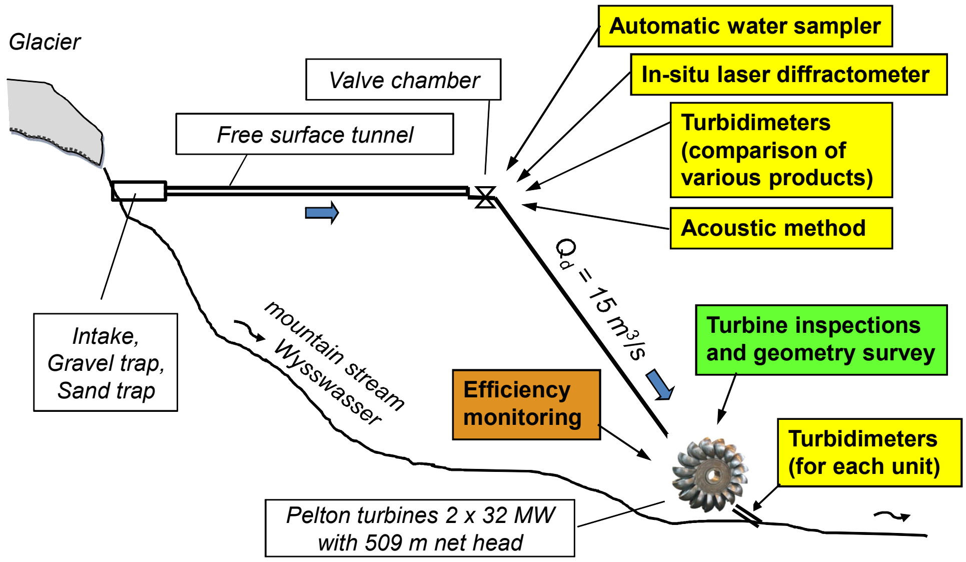


Fig. 5. Schematic longitudinal profile of the Fieschertal hydroelectric power plant showing the investigation program.

4.2 First results on suspended sediment monitoring

On July 2 and 3, 2012, a major thunderstorm occurred in Fieschertal, which produced a flood discharge with an estimated return period between 10 and 30 years. Fig. 7 shows the time series of turbidity measured by optical transmission (Optek) and the scaled relative amplitude of the received ultrasonic pulses at one path of the acoustic discharge measurement installation. The scaled relative amplitude of the received ultrasonic pulses is well in line with the turbidity time series, except for the highest peak that was only recorded by optical transmission. This means that the sampling pipe was not clogged during the event and that at least qualitative information on suspended sediment, measured directly in the power waterway, can be retrieved from ADM-systems existing in many HPPs. The results

are promising to develop a method to estimate real-time SCC using the amplitude of received acoustic signals available as an auxiliary parameter in ADM-systems.
Since the prevailing particles in Fieschertal consist of mostly feldspar and mica particles and the calibration curves of the optical transmission probe for powders of these materials are similar (Fig. 2), the calibration curve of feldspar powder was used to estimate the SSC. Based on the assumption, that the suspended sediment during the thunderstorm was similar to the feldspar and mica particles used in the laboratory, the turbidity peak of almost 5 CU (Fig.6) corresponds to approximately 20 g/l, what is relatively high. Water samples taken during the thunderstorm will be analysed to obtain more precise SSCs by weighing of dried samples.

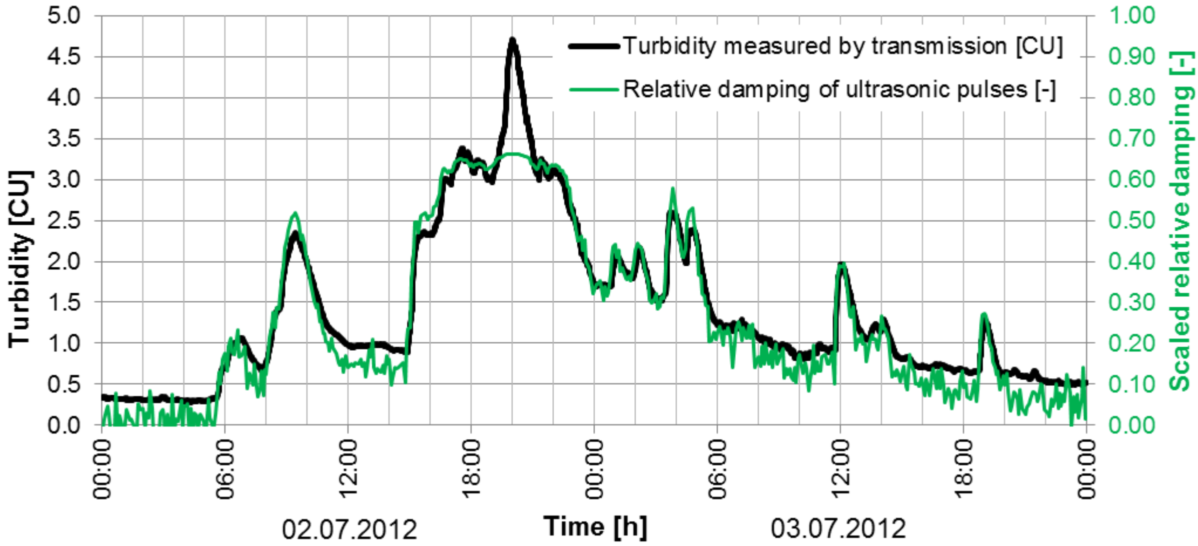


Fig. 6. Time series of measured turbidity (left vertical axis) and scaled relative amplitude of received ultrasonic pulses (right vertical axis) during the thunderstorm of July 2 and 3, 2012.

Besides sediment peaks due to weather phenomena, there are sediment peaks which depend on the power plant's operation and on the hydraulic conditions in the free surface tunnel, which serves as a daily storage reservoir. Low water levels in the free surface tunnel may cause re-suspension of settled particles and may thus lead to relatively high SSCs [6].

4.3 Turbine inspections and 3D-digitalization of bucket geometry

Besides monitoring of suspended sediment the turbines are inspected in the on-going project at least before and after the sediment season and occasionally during the sediment season, e.g. during flushing of the free surface tunnel. The local coating thicknesses in selected buckets are measured with a thickness meter based on magnetic induction.
Erosion damages on the turbine buckets are documented with photographs and their current geometries are measured with an optical scanner (Fig. 7). The working principle of the optical scanner is based triangulation and it has a resolution of five megapixels in a measurement volume of 480 x 400 x 250 mm. The 3D point distance is 190 µm and the accuracy of the system is within 25 µm. The optical measurements focus on the monitoring of the abrasion of the main splitter in selected buckets.

Fig. 7. Digitizing of Pelton buckets geometry in the power plant: Special camera mounted on a tripod below the buckets of the runner with stick-on reference points.

Fig. 8 shows the results of the geometric analysis. The mid-plane cut through the bucket in the axis of the main splitter is displayed with a solid black line. This cut is extracted from the point cloud of the 3D-digitization of bucket no. 1. The initial (theoretical) splitter profile is shown as a dotted black line. A serious abrasion of the main splitter can be observed from the difference of the two splitter contours.
The grey lines with the vertical axis on the right hand side show the abrasion (in mm) at the top of the main splitters of two digitized buckets. The abrasion processes on both splitters are comparable with respect to the affected parts of the splitters and the magnitude of the abrasion depth of approximately 8 mm.
Further scans after the sediment season will allow to obtain quantitative data on geometry changes and to relate the material loss to the suspended sediment load.
The second turbine inspection made in August 2012 after the thunderstorm described above revealed considerable wear on the runners of both turbines.

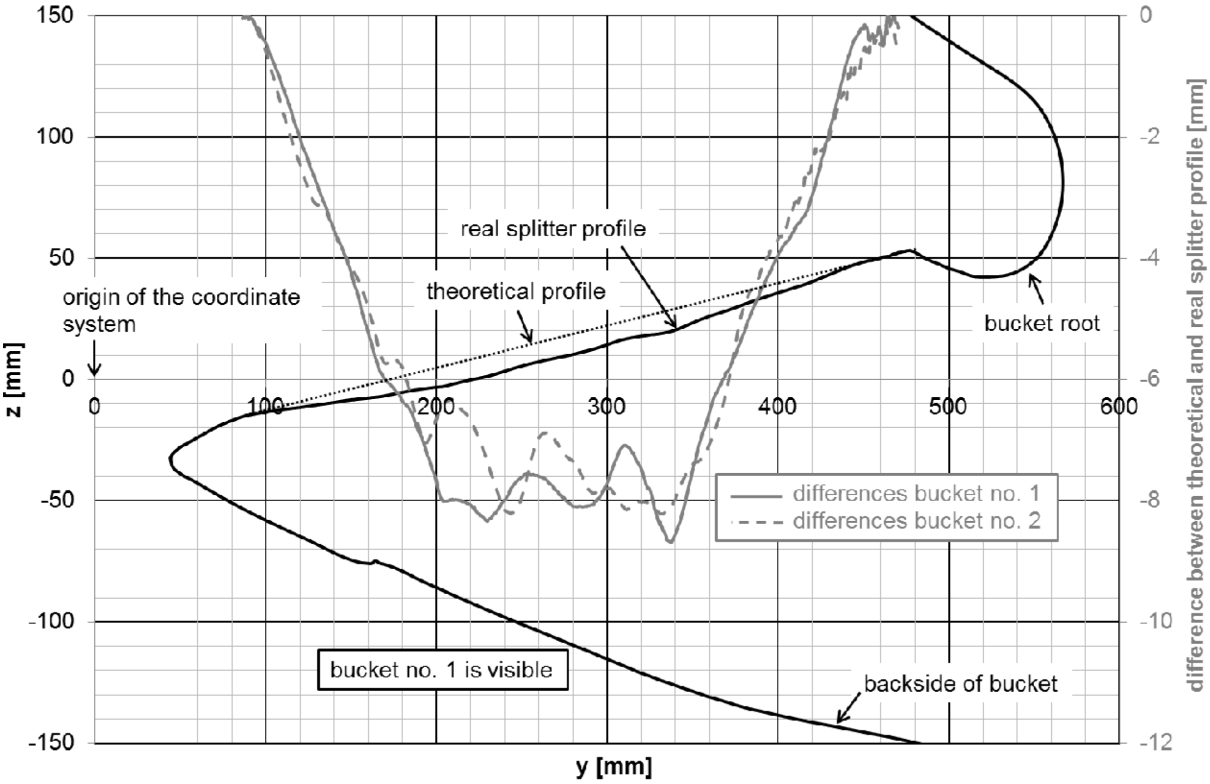


Fig. 8. Profile of main splitter (side view): Comparison of theoretical and real geometry

5 Conclusions

Regarding suspended sediment monitoring, various devices were investigated in the laboratory to assess the measuring range, measuring uncertainty and calibration parameters. Custom calibrations depending on the type of particles prevailing in the turbine water are required for turbidimeters and the acoustic method. As a drawback, temporal variation of the properties of the prevailing suspended sediment particles may lead to significant uncertainty when estimating SSC from turbidimeters or acoustic signals obtained from sensors used in ADMs.

First results show that LISST allows capturing PSDs and SSCs for particles in the range of silt to fine sand at concentrations up to a few g/l. Existence of particles smaller than the lower limit of the measurement range of the LISST may bias PSD and thus cause an overestimation of SSC. First results further indicate that coarser fractions within the PSDs are underestimated by the LISST. Concerning the particle shape effect, mica in suspended sediment may lead to a considerable overestimation of SSC. This is related to the fact that the flaky shape of mica differs greatly from the rounded or angular shape of the other investigated particles and from the currently assumed particle shape in the calculation model.

First evaluation of field data showed that during a major thunderstorm two devices (optical transmission probe and ADM) were able to record the time series on turbidity and amplitude, respectively. The good correlation between acoustic amplitude damping and optical transmission is promising to develop a real-time suspended sediment monitoring based on ADM devices. Devices for suspended sediment

monitoring based on optical methods are suitable at lower concentrations while the use of ADM signals is advantageous at higher concentrations.
Regarding monitoring of turbine wear, digitalization of the 3D-geometry of Pelton buckets by the means of an optical scanner offers the possibility to quantify geometry changes and thus material loss at turbine runners.

6 Outlook

The data from the laboratory measurements and the field will be further evaluated. The combination of acoustic and optical methods and the use of existing ADM-devices will be pursued. After the first sediment season the data from the turbine inspections and turbine efficiency measurements will be evaluated.
In view of the damages observed on the turbine runners after the thunderstorm, the option of temporary turbine shutdowns for some hours during extreme sediment peaks shall be further investigated towards the determination of economically balanced switch-off criteria based on SSC and possibly particle size.

Acknowledgements

The authors gratefully acknowledge the support by *Swisselectric Research,* the Swiss Federal Office of Energy and Gommerkraftwerke AG (the case study power plant operator) and further thank to all project partners mentioned in the text.

References

[1] Bishwakarma M.B. & Støle H. (2008). Realtime sediment monitoring in hydro-power plants. *J. Hydr. Res.* 46(2): 282–288.
[2] Gummer J. H. (2009). Combating Silt Erosion in Hydraulic Turbines. *Hydro Review Wordwide*, 17(1).
[3] Boes R. (2009). Real-time monitoring of SSC and PSD in the headwater way of a high-head hydropower plant. *Proc. 33rd IAHR Congress*, Vancouver, Canada: 4037–4044.
[4] Agrawal Y., Mikkelsen O.A. & Pottsmith H.C. (2011). Sediment monitoring technology for turbine erosion and reservoir siltation applications. *Proc. HYDRO 2011 Conference*, Prague, Czech Republic.
[5] Costa I., Storti G., Lüscher B., Gruber P. & Staubli Th. (2010). Influence of solid particle parameters on the sound speed and attenuation of pulses in acoustic discharge measurements (ADM). *Journal of Hydrologic Engineering* (accepted for publication in October 2012).
[6] Abgottspon A. (2011): Messung abrasiver Partikel in Wasserkraftanlagen. *Masterthesis* (unpublished), Hochschule Luzern, CC Fluid Mechanics and Hydro Machines, Lucerne, Switzerland
[7] Andrews S. W., Nover D. M., Reuter J. E. & Schladow S. G. (2011). Limitations of laser diffraction for measuring fine particles in oligotropic systems: Pitfalls and potential solutions. *Water Resour. Res., 47*

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Schwebstoffmonitoring zum verschleiss-optimierten Betrieb von Hochdruck-Wasserkraftanlagen

Robert M. Boes, David Felix, Ismail Albayrak

Zusammenfassung

Die Schädigung von Wasserkraftturbinen durch feinkörnige, harte mineralische Partikel im Wasser (Schwebstoffe) ist bei gewissen Hochdruck-Wasserkraftanlagen sowohl in der Schweiz als auch weltweit ein wirtschaftlich bedeutender Aspekt bei der Planung und im Betrieb. Durch die zunehmende Variabilität der Niederschläge und den Gletscherrückgang gewinnt diese Problematik an Bedeutung.

Für eine wirtschaftliche Optimierung ist es erforderlich, die Schwebstoffführung im Triebwasser, die Schädigung an den Turbinen (Hydroabrasivverschleiss) und die damit einhergehende Wirkungsgradabnahme zu quantifizieren. Als Grundlage für Verbesserungen des Betriebs und der Planung von Revisionsarbeiten ist eine Überwachung (Monitoring) der relevanten Parameter, möglichst in Echtzeit, wünschenswert.

Im vorliegenden Artikel werden Methoden des Schwebstoffmonitorings und die Notwendigkeit von Kalibrierungen der Messgeräte, vorzugsweise unter kontrollierten Laborbedingungen, aufgezeigt. Weiter werden Lösungsansätze zur Minderung der Hydroabrasion, insbesondere die Option eines wirtschaftlich auch bezüglich des aktuellen Verschleisses optimierten Anlagenmanagements, d.h. die Abschaltung von Turbinen während Schwebstoffkonzentrationsspitzen, diskutiert.

Résumé

Des dégâts aux turbines hydrauliques causés par des particules solides fines en suspension dans l'eau turbinée sont économiquement importants et doivent être pris en compte lors de la conception et l'exploitation de certains aménagements hydrauliques en Suisse et dans le monde. En raison de la variabilité croissante des précipitations et du recul des glaciers cette problématique ne cesse de prendre de l'ampleur.

Pour une optimisation économique il faut quantifier le transport solide en suspension dans l'eau turbinée, les dégâts aux turbines (l'usure par hydro-abrasion) ainsi que la réduction correspondante en rendement. Une surveillance des paramètres en jeu est désirable, si possible en temps réel, en tant que données de base pour l'exploitation et la planification des travaux de révision optimisées.

Le présent article décrit des méthodes actuelles pour la surveillance des solides en suspension et la nécessité d'étalonner les instruments, de préférence sous des conditions contrôlées en laboratoire. En plus, des approches pour diminuer l'hydro-abrasion, particulièrement l'option d'une exploitation économiquement optimisée entre autres par rapport à l'usure actuelle, c'est-à-dire l'arrêt des machines pendant des pointes de transport solide en suspension, sont discutées.

1. Einleitung

Der vorliegende Artikel bezieht sich auf einen am 8.11.2012 in Horw im Rahmen der Fachtagung Wasserkraft des Schweizerischen Wasserwirtschaftsverbands (SWV) gehaltenen Vortrag.

1.1 Hydroabrasion an Wasserkraftanlagen

Hydroabrasivverschleiss wird nach DIN 50320 (1979) definiert als Schaden an Oberflächen von Bau- und Anlagenteilen, der durch den Transport von Feststoffpartikeln in Flüssigkeiten auftritt. Verallgemeinert werden in diesem Zusammenhang oft die Begriffe der (Hydro-)Abrasion und der Erosion verwendet. Die Wasserkraft ist räumlich und zeitlich unterschiedlich stark von Hydroabrasivverschleiss betroffen. Bei Wasserkraftwerken an Gewässern mit hohem Feststoffgehalt, wie sie typischerweise im Gebirge dominant sind, tritt Hydroabrasion vor allem an Anlagen mit grossen Fallhöhen und ohne grösseren Kopfspeicher (Laufkraftwerke) auf, wo sich der Grossteil der als Schwebstoffe mittransportierten Feinanteile der Sedimente nicht in Speichern oder Entsandern absetzt und im Triebwasser mittransportiert wird. Zeitlich beschränkt sich der Verschleiss auf die sog. Schwebstoffsaison, also auf die Zeiten hohen Feststofftransportes während Schnee- und Gletscherschmelze bzw. während (oft nur kurz andauernden) Hochwassern, z.B. nach Gewitterereignissen. Peltonturbinen sind am meisten betroffen, da diese bei grossen Fallhöhen eingesetzt werden und die Beanspruchung der Turbinenbauteile infolge der hohen Strahlgeschwindigkeiten gross ist. Am meisten werden die Haupt- und Nebenschneiden der Peltonbecher beschädigt, an denen der eintretende Wasserstrahl aufgeteilt wird *(Bild 1)*. Die anfangs scharfen Mittelschneiden und Bechereintrittskanten werden im Lauf des Betriebs zunehmend breiter, was zu Sekundärströmungen führt, die Kavitationserosion zur Folge haben können. Bei unbeschichteten Laufrädern kommt es weiter zu flächigem Abtrag im Bechergrund. Die Auswirkungen werden schliesslich für den Betreiber anhand von Produktionsverlusten infolge Wirkungsgradabnahmen spürbar.

Die wesentlichen Faktoren für Hydroabrasionsschäden an Wasserturbinen (Sulzer Hydro 1996 in DWA 2006, Winkler et al. 2011) sind die

- Relativgeschwindigkeit u zwischen Strömung und Turbinenbauteil,
- in der Regel zeitlich sehr veränderliche Schwebstoffkonzentration C,
- zeitlich ebenfalls veränderliche Partikelgrösse,
- für ein gegebenes Einzugsgebiet eher

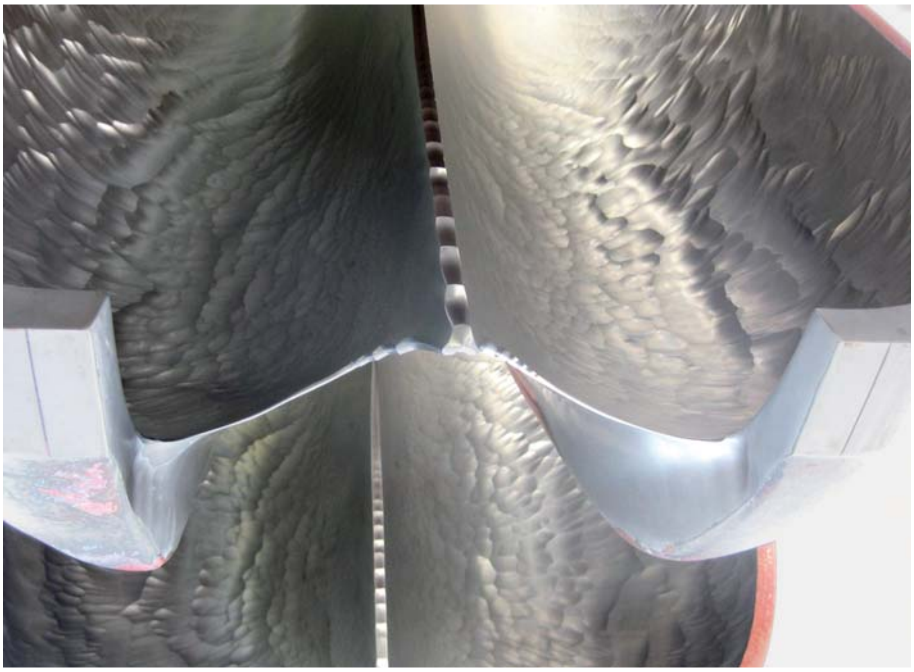

Bild 1. Becher eines unbeschichteten Pelton-Laufrads mit Verschleiss-Schäden (Ausstellungsobjekt bei der Staumauer Emosson, Foto: VAW).

konstante Partikelform (insbesondere kantige Partikel),

- Partikelhärte (vor allem Mohshärte grösser 6, d.h. Quarz- und Feldspatgehalt, da diese Minerale härter sind als das übliche Turbinengrundmaterial).

Um den Prozess des Hydroabrasivverschleisses besser zu verstehen, müssen die Schwebstoffeigenschaften im Triebwasser, der Materialverlust an den Turbinen und die Wirkungsgradreduktion quantifiziert werden. Solche Datensätze können zum Verifizieren und Weiterentwickeln von Prognosemodellen des Turbinenverschleisses (z.B. Nozaki 1990, Sulzer Hydro 1996 in DWA 2006) verwendet werden. Dazu wurde ein interdisziplinäres Forschungsprojekt von der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW) der ETH Zürich initiiert, im Rahmen dessen gemeinsam mit dem Kompetenzzentrum Fluidmechanik & Hydromaschinen der Hochschule Luzern sowie den Gommerkraftwerken (GKW), der BKW FMB Energie AG, Bern, und der Andritz Hydro AG, Kriens, u.a. Prototyp-Untersuchungen an einer bestehenden Kraftwerksanlage (KW Fieschertal, Wallis) durchgeführt werden. Die dabei verwendeten Messeinrichtungen für das Monitoring von Schwebstoffen wurden vorgängig im Labor in einem Mischtank mit verschiedenen Partikelsorten untersucht, bevor sie im Sommer 2012 an der Wasserkraftanlage Fieschertal im Wallis, einer stark von Hydroabrasivverschleiss betroffenen Hochdruckanlage mit stark vergletschertem Einzugsgebiet ohne Speichersee, basierend auf Vorarbeiten von Abgottspon (2011) eingebaut wurden. Die nachfolgend gezeigten ersten Resultate des laufenden Forschungsprojekts beziehen sich sowohl auf die Labor- als auch Prototypversuche (Felix et al. 2012a und b).

1.2 Lösungsansätze zur Minderung des Hydroabrasivverschleisses

Zur Verminderung des Hydroabrasivverschleisses gibt es verschiedene Ansätze, die entweder eine Verringerung der Beanspruchung oder eine Erhöhung des Widerstands bewirken:

a. Optimierung der Feststoffabscheidung (baulich) und des Turbinendesigns (elektromechanisch) (Verringerung der Einwirkungen),
b. Verbesserung der Turbinenmaterialien, z.B. mittels den heute üblichen rund 300 µm starken Wolframkarbid-Beschichtungen (Erhöhung des Widerstands),
c. Verschleissoptimierte Betriebsweise (Verringerung der Einwirkungen).

Die Schwebstoffbelastung (Konzentrationen und Partikelgrössen) kann bei Neuanlagen in einem gewissen Mass über die Absetzwirkung von Entsandern bzw. Kopfspeichern (Massnahmentyp a) beeinflusst werden (Ortmanns 2006). Solchen Anlagen zur Feststoffabscheidung sind aber wirtschaftliche, z.T. auch räumlich-topographische Grenzen gesetzt. Für bestehende Anlagen kann eine verbesserte Feststoffabscheidung in der Regel nur mit beträchtlichem bautechnischen Aufwand erreicht werden. Weitere Parameter wie Kornhärte, -form und Relativgeschwindigkeit zwischen Strömung und Laufrad spielen zwar, wie oben erwähnt, ebenfalls eine Rolle hinsichtlich Verschleiss, können aber praktisch nicht beeinflusst werden, da sie durch die Geologie des Einzugsgebiets bzw. die Fallhöhe (Lage von Fassungen und Maschinenhäusern) gegeben sind. Da der Massnahmentyp b trotz fallweise deutlicher Erhöhung der Turbinen-Standzeiten oft nicht allein das erhoffte Ergebnis bringt (und auch die Laufradrevisionen deutlich aufwändiger macht), soll der Fokus in diesem Beitrag auf einen verschleissoptimierten Anlagenbetrieb (Massnahmentyp c) gelegt werden. Als Voraussetzung dazu müssen die wichtigen Einflussgrössen des Hydroabrasivverschleisses, insbesondere die Partikelkonzentration und -grösse, in Echtzeit bekannt sein, was besondere Anforderungen an die Messtechnik stellt.

Ein kontinuierliches Schwebstoffmonitoring und vorübergehende Kraftwerksabstellungen aufgrund temporär hoher Stromgestehungskosten infolge starkem Hydroabrasivverschleiss sind bei Wasserkraftanlagen noch die Ausnahme. Temporäre Kraftwerksabschaltungen oder das vorübergehende Ausleiten von Fassungen werden bisher vor allem während starkem Geschiebetrieb, der den Betrieb der Wasserkraftanlage erschwert oder verunmöglicht, praktiziert (z.B. mit Geschiebe aufgefüllte oder überschüttete Fassungen).

2. Methoden des Schwebstoffmonitorings

Beim Schwebstoffmonitoring ist zunächst zwischen kontinuierlichen und diskontinuierlichen Messmethoden zu unterscheiden. Zu letzteren zählen klassische Schöpfproben, bei denen mit einem Schöpfgefäss von Hand ein Wasservolumen entnommen wird und entweder mittels Imhoff-Trichter oder im Nachgang im Labor mittels Filtrierung und/oder Ofentrocknung die Schwebstoffkonzentration und ggf. die Korngrössenverteilung bestimmt werden. Eine Weiterentwicklung sind automatische Probennahmegeräte, welche mittels einer Pumpe z.B. bis zu 24 Flaschen abfüllen *(Bild 2)*. Der Zeitpunkt der Entnahme kann durch einen Computer gesteuert werden, beispielsweise auch als Funktion der Trübung, die dann mit einem anderen Gerät in Echtzeit gemessen werden muss.

Kontinuierliche Schwebstoffmessungen sind im Wesentlichen auf optischem oder akustischem Weg durchführbar. Zu den optischen Geräten zählen die

Bild 2. Programmierbarer Wasserprobennehmer, im Bild mit abgehobenem Deckel, mit Pumpe und Vorrichtung zum Füllen von bis zu 24 Flaschen (Foto: VAW).

weithin eingesetzten Trübungssonden, sei es nach dem Streu- oder Durchlichtverfahren. Die Ausgabe der Messwerte erfolgt hierbei in Trübungseinheiten (z.B. FNU = Formazine Nephelometric Unit; CU = Concentration Unit). Bei konstanten und bekannten Partikeleigenschaften (insbesondere Grösse und Form) können die Messwerte von Trübungssonden in eine Schwebstoff-Massenkonzentrationen (z.B. [mg/l]) umgerechnet werden, bzw. diese Kalibrierung kann im zugehörigen Messumformer hinterlegt werden. In der Realität ist aber insbesondere die Partikelgrösse zeitlich oft sehr variabel, was ohne zusätzliche Informationen zu beträchtlichen Unsicherheiten bei der Bestimmung der Schwebstoffkonzentration führen kann. Anhand von Schöpfproben können die kontinuierlichen Messungen von Trübungssonden besser interpretiert werden.

Eine andere optische Messmethode, die Laserdiffraktometrie, ermöglicht neben der Konzentrationsmessung zusätzlich die Bestimmung von Partikelgrössen und deren Verteilung. Dabei wird ein Laserstrahl durch die Wasser-Sediment-Suspension gesendet und die an den Partikeln gestreute Strahlung auf verschiedenen Ringen detektiert. Über das gemessene Streuungsmuster lassen sich die Partikelgrössenverteilung und die Volumenkonzentration der Partikel bestimmen, welche das gemessene Streuungsmuster verursacht hätten (Agrawal et al. 2011). Das im KW Fieschertal – nach Wissen der Autoren erstmals an einer Schweizer Wasserkraftanlage – installierte in-situ Laserdiffraktometer (LISST-100X, Typ C) weist einen nominellen Korngrössenmessbereich von 2.5 bis 500 µm auf.

Bei Wasserkraftwerken wird der turbinierte Volumenstrom oft mit akustischer Durchflussmessung bestimmt. Dabei werden Ultraschallpulse diagonal durch die Druckleitung geschickt. Wenn das Wasser Schwebstoffe enthält, wird das Empfangssignal in Funktion der Schwebstoffkonzentration und der Partikelgrösse abgeschwächt. Da solche Einrichtungen für die akustische Durchflussmessung in vielen Kraftwerken vorhanden sind, ist – basierend auf der Amplitudendämpfung – zumindest ein qualitatives Schwebstoffmonitoring im Sinne von Warnungen für den Kraftwerksbetrieb denkbar. Diese Methode wird derzeit im Rahmen des Forschungsprojekts weiter untersucht.

3. Kalibrierung von Schwebstoffmessgeräten

Wie oben ausgeführt ist eine Kalibrierung von kontinuierlichen Schwebstoffmessgeräten unumgänglich, wenn eine der Realität nahe kommende Massenkonzentration C bestimmt werden soll. Die in der Regel gemessenen Trübungswerte müssen dazu zunächst in die Einheit einer Massenkonzentration umgerechnet werden, was besonders mit der Korngrösse und -form, aber auch mit den optischen Eigenschaften (z.B. Farbe) der Partikelminerale (Gippel 1995, Sutherland et al. 2000) variiert. Für die Laborversuche wurden mineralische Partikel *(Bild 3)*, die kommerziell erhältlich und mit den Partikeln in Fieschertal vergleichbar sind (Granitge-

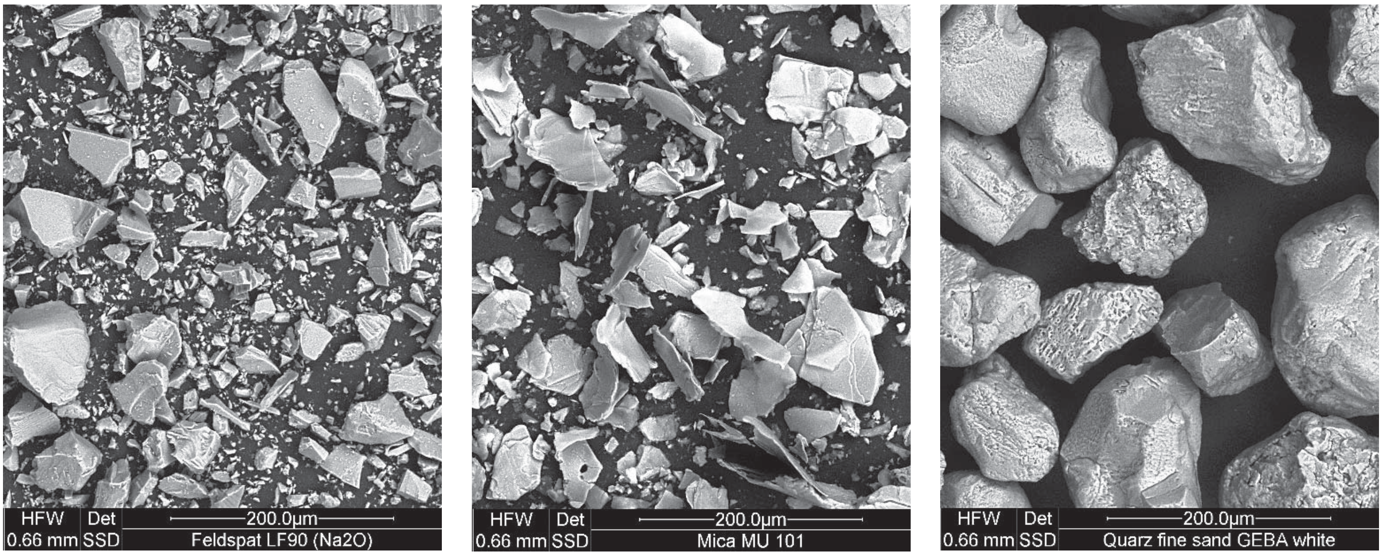

Bild 3. Mineralische Partikel, welche in den Laborversuchen betreffend Schwebstoffmessung verwendet wurden: Feldspatpulver (links, d_{50} = 34 µm), Glimmerpulver (Mitte, «d_{50}» = 45 µm) und Quarzfeinsand (rechts, d_{50} = 147 µm) (Bilder: VAW und IfB, ETH Zürich).

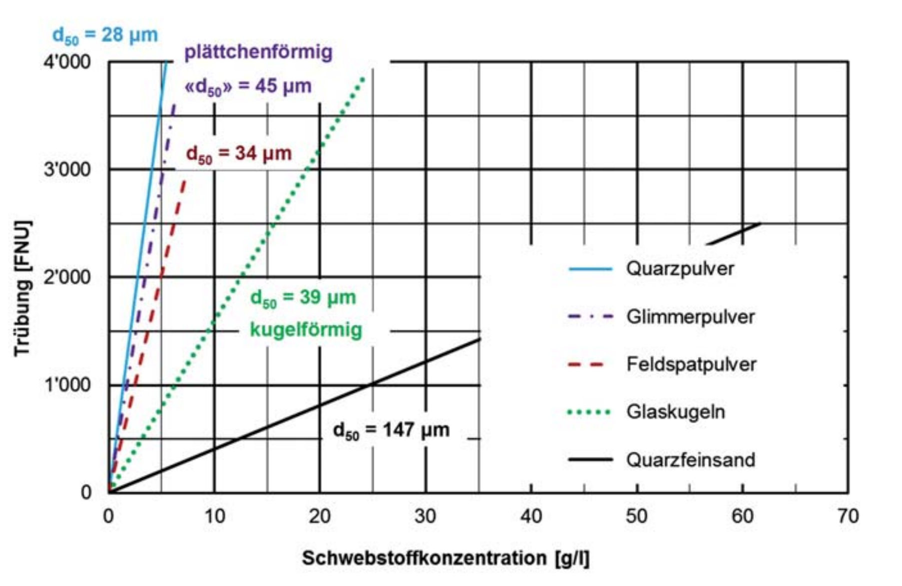

Bild 4. Trübungswerte, welche mit einer Trübungssonde (Hach-Lange Solitax ts-line sc) in Suspensionen mit verschiedenen Partikelsorten gemessen wurden (nach Felix et al. 2012a).

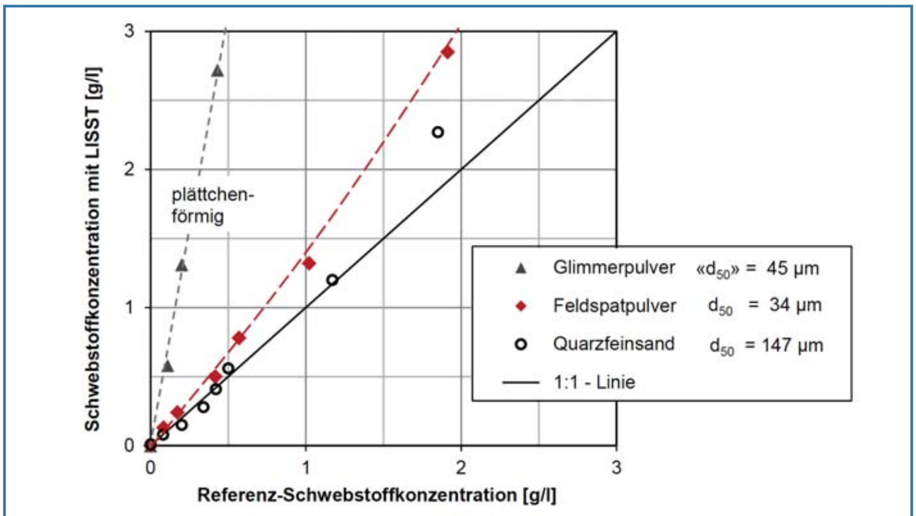

Bild 5. Mit einem tragbaren Laserdiffraktometer (Sequoia LISST-100X) bestimmte Schwebstoffkonzentrationen im Vergleich zur Referenz-Konzentration (nach Felix et al. 2012b).

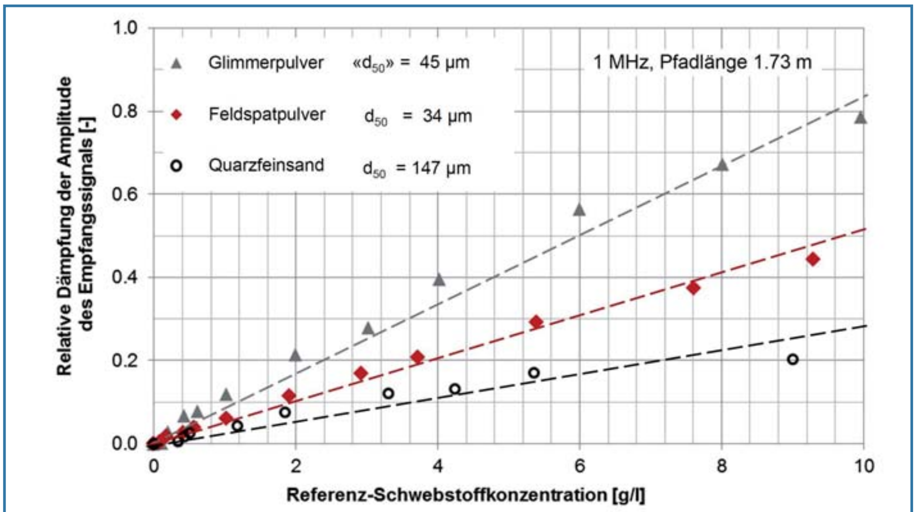

Bild 6. Relative Dämpfung von akustischen Ultraschallsignalen (akustische Durchflussmesseinrichtung, Rittmeyer) im Vergleich zur Referenz-Konzentration (nach Felix et al. 2012b).

biet mit Quarz, Feldspat und Glimmer), sowie Feinsedimente vom Unterwasserkanal des KW Fieschertal verwendet. Für Referenzzwecke kamen auch Glaskugeln zum Einsatz. Die bei *Bild 3* angegebenen Massen-Median-Korndurchmesser d_{50} stammen von Messungen mit einem nicht tragbaren Laserdiffraktometer am Institut für Geotechnik (IGT) der ETH Zürich, welche als Referenz verwendet wurden. *Bild 3* wurde mittels Rasterelektronenmikroskop am Institut für Baustoffe (IfB) der ETH Zürich aufgenommen. Weitere Angaben zu den durchgeführten Laborversuchen sind in Felix et al. (2012a und b) publiziert.

Bild 4 zeigt den deutlichen Einfluss der Korngrösse auf die Trübung. Die Korngrösse wird hier durch den Massen-Median-Durchmesser d_{50} ausgedrückt. Weiter sind in *Bild 4* Einflüsse der Partikelform zu erkennen, z.B. bei Vergleich der Linien für Glimmerpulver mit plättchenförmigen Partikeln und für Glaskugeln, die beide etwa denselben d_{50}-Wert aufweisen.

In *Bild 5* sind mit dem tragbaren Laserdiffraktometer gemessene Schwebstoffkonzentrationen im Vergleich zu den Referenz-Konzentrationen dargestellt. Letztere wurden durch Wägung von ofengetrockneten Schöpfproben, die auf der Höhe der Instrumente aus dem Mischtank bei den jeweiligen Konzentrationsstufen entnommen wurden, bestimmt. Beim Laserdiffraktometer ist die Bestimmung der Schwebstoffkonzentration theoretisch nicht von der Korngrösse abhängig. Dies wird durch die Punkte von Quarzfeinsand und Feldspatpulver, welche trotz unterschiedlichen Korndurchmessern in *Bild 5* relativ nahe beieinander liegen, bestätigt. Das Vorhandensein von feinen Partikeln, die kleiner sind als der Bereich der messbaren Partikel (< 2.5 µm), kann aber dazu führen, dass die Schwebstoffkonzentration überschätzt wird. Auch bei der Laserdiffraktometrie führt eine Kornform, welche stark von der in der Auswertungssoftware zugrunde gelegten abweicht, zu Fehlern bei der Bestimmung der Schwebstoffkonzentration. Die Streuung der Versuchsdaten, insbesondere bei gröberen Partikeln, kann den lokalen und zeitlichen Konzentrationsunterschieden in der turbulenten Suspension zugeschrieben werden. Es ist bemerkenswert, dass beim Laserdiffraktometer lediglich mit Verwendung der Werkkalibrierung, d.h. unter Annahme von unregelmässig geformten Partikeln mit einer Dichte von 2.65 t/m^3, die dargestellten Schwebstoffkonzentrationen resultierten, die mit Ausnahme des Glimmers relativ nahe an den erwarteten

Schwebstoffkonzentrationswerten liegen (1:1-Linie).

Auch die akustische Messmethode ist bei der Konzentrationsbestimmung nicht frei vom Effekt der genannten Partikeleigenschaften, was aus *Bild 6* hervorgeht, jedoch sind die Unterschiede zwischen den Kalibrierkurven geringer als bei Trübungssonden.

Bild 7 verdeutlicht, dass bei der Messung der Partikelgrössen mittels tragbarem Laserdiffraktometer die Breite der Korngrössenverteilung, d.h. die Stufung, gut erkannt wurde. Die Messwerte liegen sowohl für Feldspatpulver als auch für Quarzfeinsand in der richtigen Grössenordnung. Im Fall von Glimmerpulver mit der speziellen plattigen Partikelform gibt es eine systematische Abweichung von den Referenzmessungen, wobei zu bedenken ist, dass die Definition des «Durchmessers» eines plattigen Teilchens unklar ist. Zu den Referenzmessungen (durchgeführt mit nicht-tragbarem Laserdiffraktometer am IGT der ETH Zürich) ist zu bemerken, dass diese Proben zu Beginn der Versuchsreihen von den Behältern der Partikelsorten trocken entnommen wurden. Die Abweichungen zwischen den im Mischtank gemessenen Korngrössenverteilungen von den Referenzmessungen, insbesondere bei gröberen Fraktionen, sind vermutlich dem Phänomen zuzuschreiben, dass im Mischtank gröbere Partikel trotz Rührwerk tendenziell im unteren Bereich der Wassersäule, unterhalb des Messkopfs des Laserdiffraktometers, vorhanden waren (vertikales Konzentrationsprofil) oder nicht vollständig in Schwebe gehalten werden konnten.

4. Option temporärer Turbinenabschaltungen während Schwebstoffspitzen

Wie in Abschnitt 1 beschrieben, sind für den Hydroabrasivverschleiss von Turbinen insbesondere die Schwebstoffkonzentrationen (bzw. -frachten) und Partikelgrössen massgebend. Stark erhöhte Konzentrationen im Triebwasser kommen in der Regel bei grösseren Abflussereignissen vor, z.B. nach Starkregen wie Gewittern, und weisen meist eine kurze Dauer auf. Die in *Bild 8* und *Bild 9* zu erkennenden Konzentrationsspitzen am Kraftwerk Dorferbach in Tirol, Österreich, haben beispielsweise typische Dauern von wenigen Stunden, innerhalb derer eine vergleichbare Sedimentfracht über die Turbine abgeleitet wird wie bei Normalbetrieb während mehrerer Tage. Um diese Schweb-

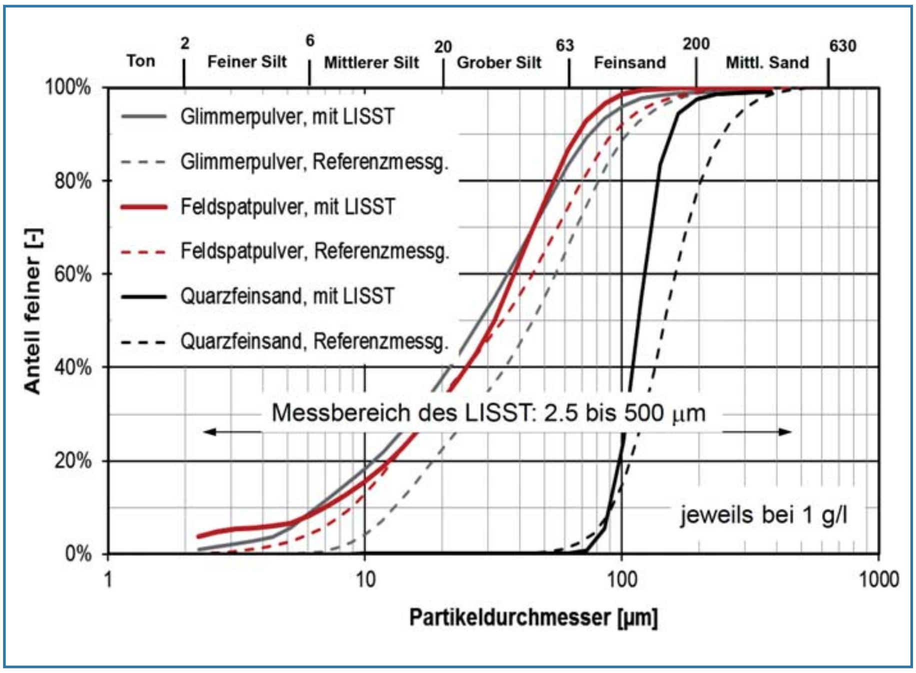

Bild 7. Mit tragbarem Laserdiffraktometer (Sequoia LISST-100X) ermittelte Korngrössenverteilung im Vergleich zu Referenz-Messungen (nach Felix et al. 2012b).

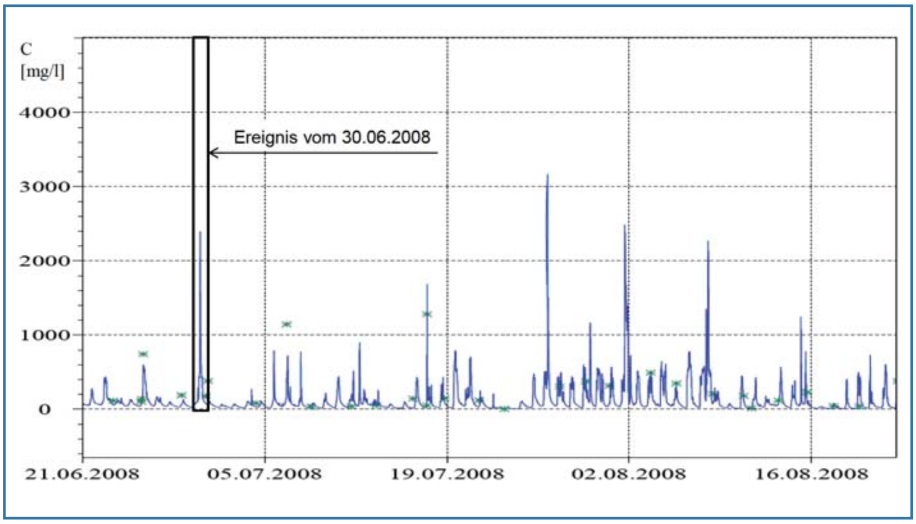

Bild 8. Verlauf der Schwebstoffkonzentration im Triebwasser des KW Dorferbach im Sommer 2008, (–) Daten der Trübungssonde nach Kalibrierung anhand von (*) Einzelproben (nach Boes 2010).

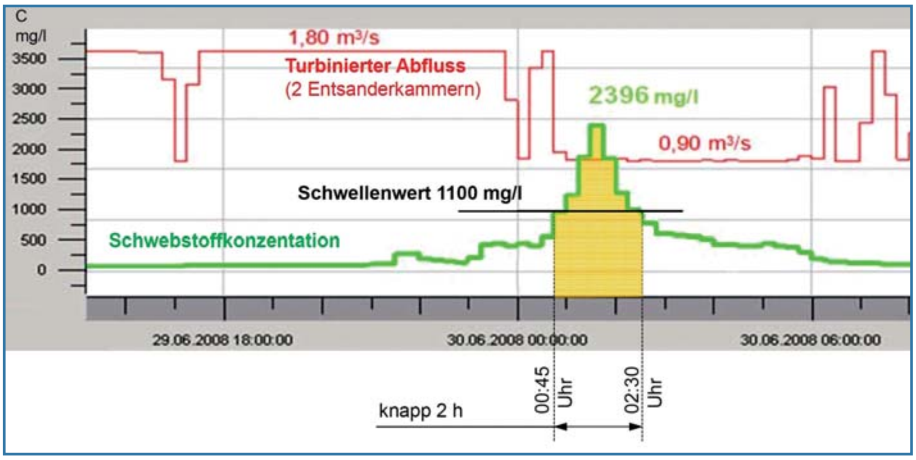

Bild 9. Verlauf der Schwebstoffkonzentration (linke Achse, gemessen mit kalibrierter Trübungssonde, Ausschnitt aus Bild 8) und des Turbinendurchflusses Ende Juni 2008 und Angabe des Schwellenwerts für die vorübergehende Ausserbetriebnahme des KW Dorferbach (Quelle: TIWAG).

ten die Hydroabrasionsschäden markant reduziert werden (Götsch 2012). In diesem Fall erlaubte das umfangreiche Schwebstoff- und Verschleiss-Monitoring eine anlagenspezifische Kalibrierung eines Verschleiss-Prognosemodells und eine rechnerische Abschätzung der Entwicklung der Mittelschneidenbreiten des Peltonlaufrads in Abhängigkeit der Schwebstoffkonzentration. Dabei wurde ein empirisch gefundener Zusammenhang zwischen der Schwebstoffkonzentration und dem mittleren Partikeldurchmesser verwendet (Boes 2010).

Vom Triebwasser des KW Fieschertal liegen erste Schwebstoffdaten vor. Ein seltenes Hochwasserereignis (ca. 30- bis 50-Jährlichkeit im Goms) führte Anfang Juli 2012 zu extremen Schwebstoffkonzentrationen von mindestens 68 g/l in der Spitze (auf Grundlage von Schöpfproben ermittelt), was zu erheblichen Schädigungen der beschichteten, schon eine zeitlang in Betrieb stehenden Turbinenlaufräder führte. In *Bild 10* und *Bild 11* ist der zeitliche Verlauf der mittels Durchlichtverfahren gemessenen Trübung dargestellt. Es ist deutlich zu sehen, dass die Trübung von den üblichen rund 0.2 bis 0.5 CU während des Ereignisses bis auf 4.7 CU anstieg, also um das rund 10-Fache *(Bild 10)*. *Bild 11* lässt zudem die gute Übereinstimmung der Trübungswerte mit der relativen Amplitudendämpfung der Ultraschallpulse erkennen. Dass die absolute Spitze mittels der akustischen Methode nicht aufgezeichnet werden konnte, hängt mit der vorhandenen Pfadlänge und der verwendeten Sendefrequenz zusammen. Von Mitte April 2012 bis unmittelbar nach diesem Hochwasser hat der Turbinenwirkungsgrad gemäss Indexwirkungsgradmessungen, die noch ausgewertet werden, relativ stark abgenommen. Es ist zu vermuten, dass ein Grossteil der Wirkungsgradabnahme in dieser Periode allein durch dieses Ereignis verursacht wurde.

Für den Fall derartiger Schwebstofftransportereignisse sollen hier exemplarisch zwei denkbare Varianten einer auch hinsichtlich aktuellem Turbinenverschleiss optimierten Betriebsweise des KW Fieschertal aufgezeigt werden. Die in *Bild 12* angenommenen Grenzwerte bezüglich Schwebstoffführung des Triebwassers beruhen vorerst auf der Beobachtung des Schwebstoffaufkommens in «normalen Sommerverhältnissen» und darauf aufgesetzten ereignisbedingten Schwebstofftransportspitzen. Im ersten fiktiven Szenario mit einem Trübungs-Schwellenwert von 3.0 CU für das Abstel-

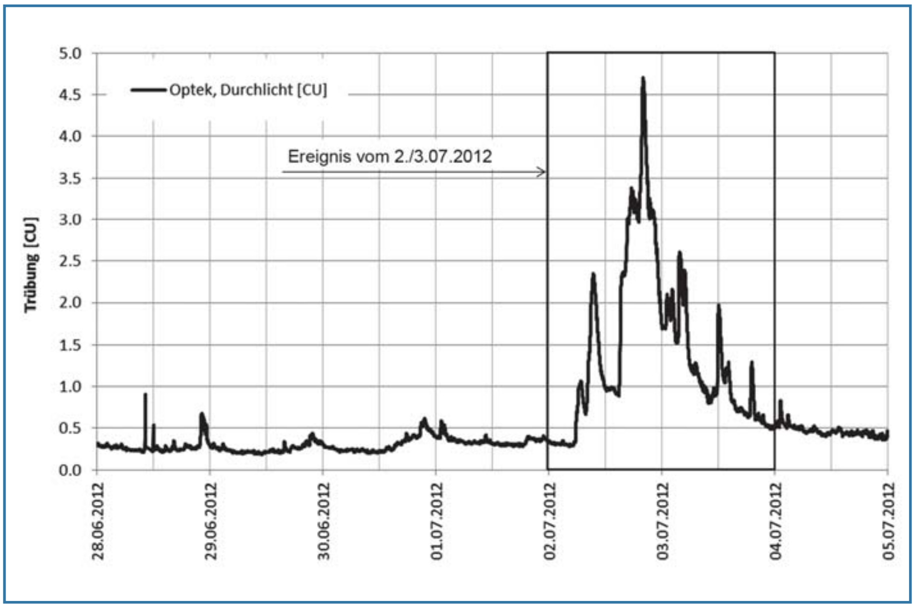

Bild 10. Verlauf der Trübung als Indikator für die Schwebstoffkonzentration im Triebwasser des KW Fieschertal Ende Juni/Anfang Juli 2012.

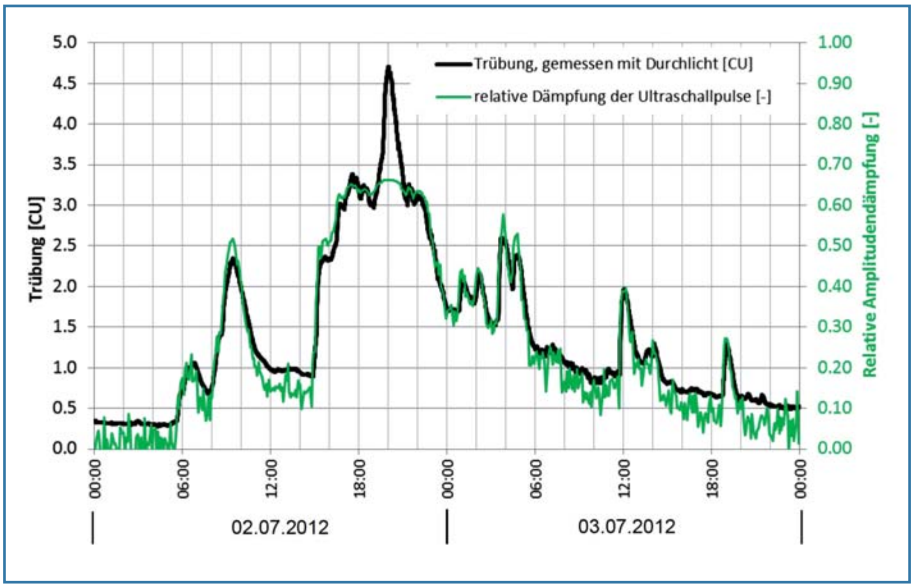

Bild 11. Verlauf der Trübung (linke Achse, Ausschnitt aus Bild 10) und der relativen Amplitudendämpfung von akustischen Ultraschallsignalen (rechte Achse) im Triebwasser des KW Fieschertal Anfang Juli 2012 (nach Felix et al. 2012b).

stoffbelastung zu reduzieren, liegt es daher nahe, eine von Hydroabrasion betroffene Wasserkraftanlage bei hoher Schwebstoffführung kurzzeitig ausser Betrieb zu nehmen, sofern dies von den übergeordneten Randbedingungen her möglich ist (Kraftwerkspark, Verbundnetz, Produktionsverpflichtungen, usw.). Dies bedingt jedoch einerseits ein verlässliches und kontinuierliches Schwebstoffmonitoring (Bishwakarma & Støle 2008), andererseits die Kenntnis von Grenzwerten bezüglich Konzentration und idealerweise auch der Korngrösse.

Die Grenz- oder Schwellenwerte sind eine Frage der betriebswirtschaftlichen Optimierung (vor allem Verlust an produzierter Energie während Turbinenabschaltungen vs. Einsparungen bei Laufradrevisionen), zu deren Beantwortung der quantitative Zusammenhang zwischen den oben erwähnten Parametern und dem Hydroabrasivverschleiss an Turbinen bzw. dessen Auswirkungen (Wirkungsgradminderung) bekannt sein muss, was – wie einleitend erwähnt – noch Gegenstand der Forschung ist. Auf Grundlage von kontinuierlichen Schwebstoffdaten sowie von Verschleissmessdaten, die in einem zeitlich engen Raster während der Sedimentsaison 2008 erhoben wurden, wurde für das KW Dorferbach ein Konzentrationsgrenzwert von 1100 mg/l im Triebwasser festgelegt, bei dessen Überschreiten das Kraftwerk ausser Betrieb genommen wird (Boes 2010). Mit dieser Massnahme konn-

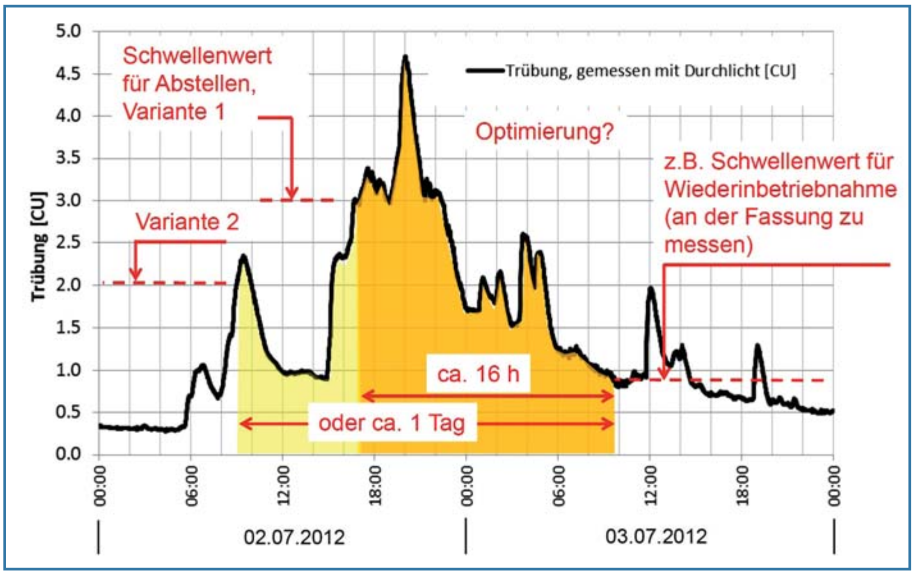

Bild 12. Verlauf der Trübung Anfang Juli 2012 (Ausschnitt aus Bild 10) und angenommene Schwellenwerte für die Ausser- und Wiederinbetriebnahme des KW Fieschertal in zwei fiktiven Szenarien.

len der beiden Maschinen, die nach dem Unterschreiten von 0.9 CU wieder in Betrieb genommen würden, würde die Anlage rund 16 h nicht produzieren. In einem zweiten Szenario würde die Anlage bereits b ei Überschreiten von 2.0 CU ausser Betrieb genommen, so dass die Turbinen mit weniger Schwebstoffen als bei Szenario 1 belastet würden. Mit demselben Grenzwert für die Wiederinbetriebnahme käme man auf einen Stillstand während rund eines Tages.

Die entsprechenden Produktionsausfälle würden sich bei einer Ausbauleistung des KW Fieschertal von 64 MW unter Ansatz eines Energiepreises von 60 CHF/MWh in den beiden oben genannten Szenarien auf gut 60 bzw. 90 kCHF belaufen. Obwohl dies zunächst hoch erscheinen mag, relativieren sich diese Werte bei einem Vergleich mit typischen Revisionskosten von mehreren 100 kCHF für derartige Pelton-Laufräder. Zudem verursacht ein Laufradwechsel, der infolge eines unvorhergesehenen Schwebstoffereignisses während der Volllastzeit erforderlich wird, bei einem Zeitbedarf von rund 16 h bei diesem Laufkraftwerk Produktionsausfallkosten von gut 30 kCHF. Laufradwechsel erfolgen normalerweise während der Niederwasserperiode, wenn eine Maschine ohne Produktionsausfall ausser Betrieb genommen werden kann.

Es sei darauf hingewiesen, dass die Schwebstoffe für eine solche Betriebsweise nicht nur im Triebwasser, sondern auch an der Wasserfassung gemessen werden müssen, um die Wiederinbetriebsetzung des Kraftwerks in Abhängigkeit des aktuellen Schwebstoffaufkommens im Gewässer zu ermöglichen, da ja nach dem Abstellen der Turbinen kein Wasser mehr im Triebwasserweg fliesst. Weiter sei erwähnt, dass die Wiederinbetriebnahme einer grösseren Kraftwerksanlage, die bei hoher Schwebstoffkonzentration ausser Betrieb genommen wurde, mit einigem Arbeitsaufwand verbunden sein kann (z.B. Entfernen von Ablagerungen in Hilfseinrichtungen). Der Aufwand für die Wiederinbetriebsetzung nach einer sedimentbedingten Abschaltung sollte aber gegenüber den vermiedenen Schäden in der Regel nicht ins Gewicht fallen.

5. Schlussfolgerungen und Ausblick

Es besteht ein zunehmender Bedarf an praxistauglichen Messeinrichtungen zur Echtzeit-Erfassung des Schwebstoffaufkommens (Konzentration und Korngrössenverteilung) nicht nur an Wasserkraftanlagen, sondern auch an Fliessgewässern und Seen. Die hier vorgestellten Schwebstoffmessmethoden lassen sich neben einer hinsichtlich dem aktuellen Turbinenverschleiss wirtschaftlich optimierten Betriebsweise von Hochdruck-Wasserkraftanlagen auch im Zusammenhang mit dem Sedimentmanagement an Stauanlagen und Seen sowie zur Untersuchung ökologischer Fragestellungen einsetzen. Die meisten der dabei zum Einsatz kommenden Messgeräte benötigen eine auf die am Einsatzort vorhandenen Schwebstoffe abgestimmte Kalibrierung, welche vorzugsweise vorgängig im Labor unter kontrollierten Bedingungen durchgeführt wird.

Die heutzutage auch für in-situ-Messungen verfügbare Methode der Laserdiffraktometrie ermöglicht es, die Schwebstoffkonzentration bei wechselnden Partikeleigenschaften genauer zu bestimmen und Informationen über die Korngrössen zu gewinnen, was für den Hydroabrasivverschleiss ein wichtiger Parameter ist. Weiter können akustische Durchflussmessungen, wie sie an zahlreichen Wasserkraftwerken vorhanden sind, durch geringfügige Anpassungen zumindest für ein qualitatives Schwebstoffmonitoring verwendet werden, was den Vorteil einer Messung direkt im Triebwasserweg mit sich bringt.

Die durchgeführten Laborversuche werden weiter ausgewertet und die Untersuchungen an der Kraftwerksanlage weitergeführt. Neben den Schwebstoffmessungen werden auch die Schädigung der Turbinen und die Wirkungsgradänderungen periodisch erfasst.

Ein verschleissoptimierter Betrieb von Wasserkraftanlagen erfordert eine langjährige Datengrundlage und eine anlagenspezifische Betrachtung des Gesamtsystems über den Lebenszyklus. Schlussendlich sollen die Forschungsergebnisse zur Effizienzsteigerung der Wasserkraft beitragen.

Verdankung

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Literatur

Abgottspon, A. (2011): Messung abrasiver Partikel in Wasserkraftanlagen. Masterarbeit (unveröffentlicht), CC Fluidmechanik & Hydromaschinen, Hochschule Luzern.

Agrawal, Y., Mikkelsen, O.A., Pottsmith, H.C. (2011). Sediment monitoring technology for turbine erosion and reservoir siltation applications. Proc. Hydro 2011 Conference, Aqua-Media Intl. Ltd., Prague, Czech Republic.

Bishwakarma, M.B., Støle, H. (2008). Realtime sediment monitoring in hydropower plants. J. Hydr. Res. 46 (2): 282–288.

Boes, R. (2010). Kontinuierliche Messung von Schwebstoffkonzentration und -korngrössenverteilung im Triebwasser und Quantifizierung

der Hydroabrasion an einer Peltonturbine. «Wasser Energie Luft» 102 (2): 101–107.
DIN 50320 (1979). Verschleiss; Begriffe, Systemanalyse von Verschleissvorgängen, Gliederung des Verschleissgebietes. Deutsches Institut für Normung, Beuth-Verlag, Berlin.
DWA (2006). Entlandung von Stauräumen. DWA-Themen, Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef (Hrsg.).
Felix, D., Albayrak, I., Boes, R.M. (2012a). Schwebstoffmonitoring und Verschleiss an Peltonturbinen am Fallbeispiel Fieschertal – Vorbereitende Laborversuche zu Partikelmessmethoden. Proc. Wasserbausymposium, TU Graz (G. Zenz, ed.), A15: 117–124.
Felix D., Albayrak I., Abgottspon A., Boes R., Gruber P. (2012b). Suspended Sediment and Pelton Turbine Wear Monitoring: Experimental Investigation of various Optical and Acoustic Devices and Beginning of the Case Study at HPP Fieschertal. Proc. 17th Intl. Seminar on Hydropower Plants (Viennahydro), ISBN 978-3-9501937-8-7. Wien, 483–494.
Gippel, C.J. (1995). Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrological Processes 9: 83–97.
Götsch, H. (2012). Private Kommunikation.
Nozaki, T. (1990). Estimation of repair cycle of turbine due to abrasion caused by suspended sand and determination of desilting basin capacity. Report Japan International Cooperation Agency, Tokyo.
Ortmanns, C. (2006). Entsander von Wasserkraftanlagen. Mitteilung 193, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (H.-E. Minor, ed.), ETH Zürich.
Sutherland, T.F., Lane, P.M., Amos, C.L., Downing, J. (2000). The calibration of optical backscatter sensors for suspended sediment of varying darkness levels. Marine Geology 162: 587–597.
Winkler, K., Dekumbis, R., Rentschler, M., Parkinson, E., Garcin, H. (2011). Understanding hydro-abrasive erosion, Proc. Hydro 2011 Conference, Aqua-Media Intl. Ltd., Prague, Czech Republic.

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HYDRO-ABRASIVE EROSION OF PELTON BUCKETS AND SUSPENDED SEDIMENT MONITORING

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ABSTRACT

Wear of turbine parts due to abrasive particles in the water of hydroelectric power plants (HPP) is of special importance for Pelton turbines where extreme redirection and deceleration of the flow occurs. In an on-going research project at HPP Fieschertal, Switzerland, wear on coated runner buckets is measured with a 3D optical scanner and a thickness gauge, turbine efficiency is periodically evaluated by “sliding needle” index tests and suspended sediment is monitored using various devices.

3D digitizations (measurements) of selected Pelton buckets allow quantifying material losses of the main splitter or of the cut-out section due to turbine operation during a sediment season. In the sediment season 2012 the splitter height decreased in the range of 3 to 5 mm, i.e. approximately 0.5 to 0.8 percent of the inner bucket width of 650 mm. The erosion on the splitter is influenced by the initial geometric condition of the splitter, the particle load and the operating hours.

The history of the index efficiency permits to identify relevant efficiency variations due to hydro-abrasive erosion or due to mechanical works on the turbine runner (e.g. grinding of the splitters). Measurements before and after mechanical works and during the sediment season (with no mechanical works) allow to separate both effects. For one runner the efficiency decrease was 0.9 percent for more than the half sediment season 2012.

Turbidimeters, an acoustic method and a laser diffractometer (LISST) were site-specifically calibrated based on automatically taken water samples. The measurements confirm that suspended sediment concentration (SSC) and particle size distribution (PSD) in turbine water may vary strongly in time. The LISST provides not only SSC but also PSD which is important in the context of hydro-abrasive erosion. All devices yielded similar SSC at low to moderate levels while the LISST measured SSC more accurately during periods of increased SSC with transport of coarser particles. Accepting a temporary bias, turbidimeters and the acoustic method can be used as pragmatic contributions to a real-time decision making system for the operation and maintenance of HPPs.

1. INTRODUCTION

The complications associated with wear due to abrasive particles in the water of hydropower plants (HPPs), so called hydro-abrasive wear or hydro-abrasive erosion, are not new, but the issue is increasingly emphasized because of the worldwide growing energy demand. Hydro-abrasive erosion has a detrimental effect on efficiency, leads to significant maintenance costs and may cause downtime of turbines with corresponding production losses.

To take adequate measures in design, operation and maintenance of HPPs, the knowledge on turbine wear needs to be improved and relevant parameters have to be quantified. The relevant parameters for hydro-abrasive erosion, such as suspended sediment concentration, size, hardness and shape of particles as well as relative velocity between the flow and turbine parts, turbine geometry and turbine material, have been identified (e.g. Gummer 2009, Winkler et al. 2011). But it is still not fully understood to which extent these parameters contribute to the dominant damages. Monitoring suspended sediment concentrations (SSC) and size distributions (PSD) throughout the year is still not common and the effect of hydro-abrasive erosion on efficiency is only qualitatively known.

In an interdisciplinary project initiated by VAW of ETH Zurich and Hochschule Luzern, the problem of hydro-abrasive erosion is investigated mainly by means of a case study at the existing HPP Fieschertal. The goal of the project is to contribute to a better understanding of interactions between suspended sediment load, turbine wear and efficiency as a basis for economic and environmental optimization (Fig. 1):

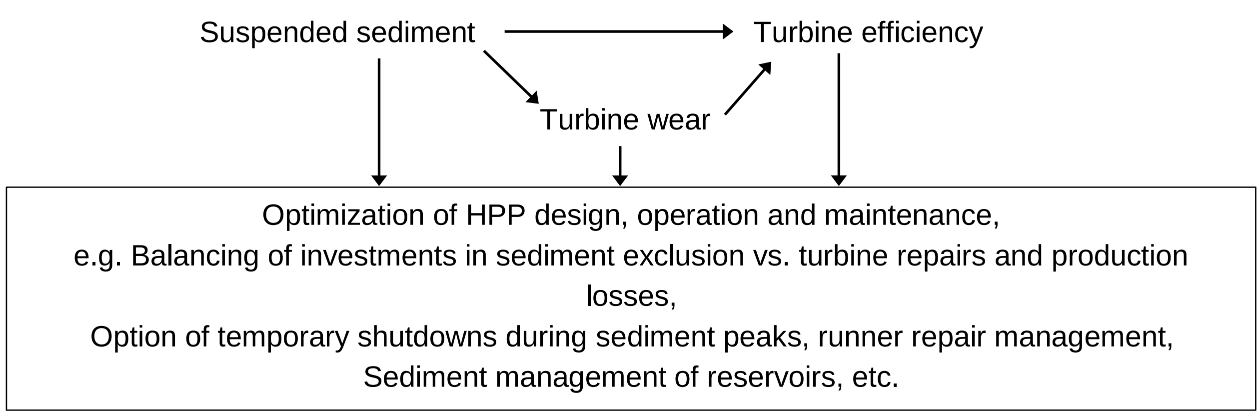

Fig. 1: Knowledge on turbine wear as a basis for optimization of HPPs

The HPP Fieschertal (Fig. 2) is a 509 m net head run-of-river type scheme located in the Canton of Valais in the Swiss Alps. Since the HPP was brought into service in 1976 severe hydro-abrasive erosion at needles, nozzles and runners of the two 32 MW Pelton units has been observed. Although coating of turbines and other hydraulics parts reduced the extent of the damages, sediment handling as well as optimized operation and maintenance of the HPP remain an important economic issue.

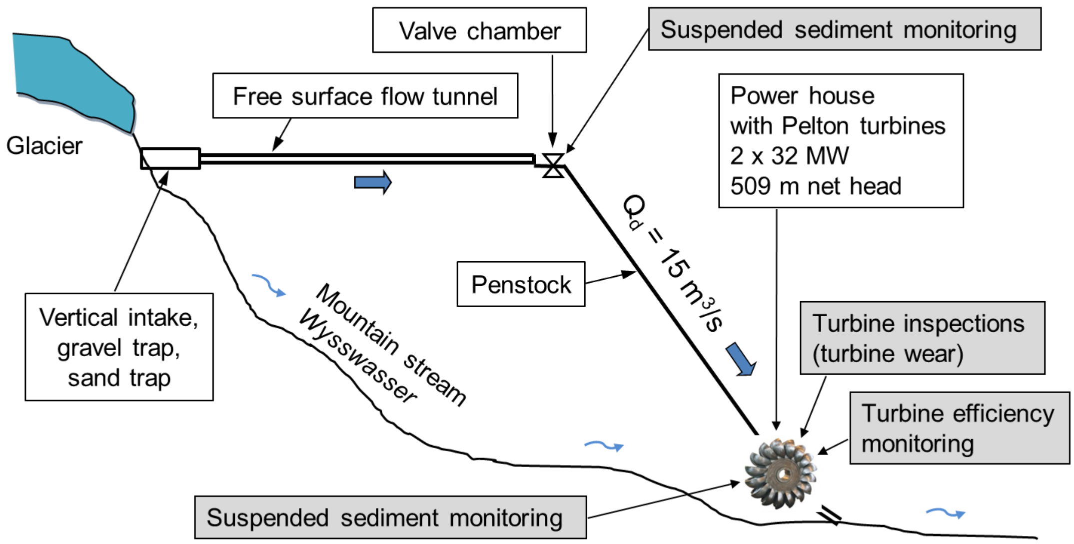

Fig. 2: Schematic overview of the HPP Fieschertal with the investigation program (grey).

This paper presents results from the on-going research project on turbine wear, efficiency and suspended sediment monitoring. Turbine inspections giving indications on turbine wear are documented with photographs, surface mapping using a 3D optical scanner and coating thickness measurements inside selected runner buckets before and after the sediment season. The evolution of turbine efficiency over time is measured by periodical efficiency index tests. Suspended sediment in the turbine water is monitored using various optical and acoustic devices, such as turbidimeters, a laser diffractometer and a method based on acoustic discharge measurement installation (see Felix et al. 2012). In the following sections, the measurement devices, the experimental procedure and the results are presented and discussed.

2. TURBINE WEAR MEASUREMENTS

2.1. 3D digitization

The geometries of selected buckets of Pelton runners were measured with a 3D optical scanning camera (Steinbichler Comet L3D) directly inside the turbine casing (Fig. 3). The working principle of the scanner is based on triangulation. It has a resolution of five megapixels in a measurement volume of 480 x 400 x 250 mm. The 3D point distance is 190 µm and the accuracy of the system is within 25 µm.

Since the surfaces of the buckets (stainless steel) are light reflecting a whitening spray has to be applied prior to the scanning. Furthermore, reference markers are used to improve the matching of point clouds and the measuring accuracy. One full day with a two-men team is required to digitize two buckets including calibration of the sensor before the digitizing.

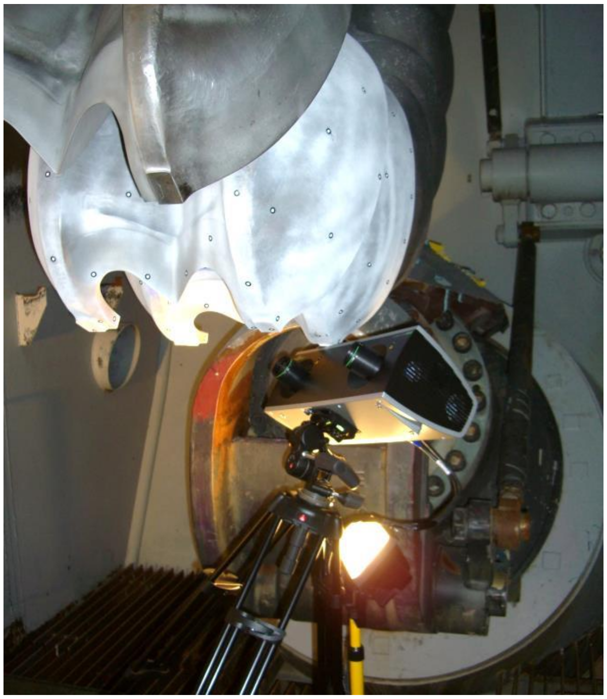

Fig. 3: 3D optical scanning camera used to digitize two selected buckets with reference points.

With regard to wear and efficiency of Pelton turbines the splitters and cut-outs of the buckets are of special importance. Brekke et al. (2002) formulated as a rule of thumb: When the thickness of the splitter has increased to 1 percent of the bucket width, the efficiency drops by 1 percent at full load. The maximum splitter width is practical to measure at turbine inspections. Boes (2009) related the evolution of splitter width with cumulated suspended sediment load.

In Figures 4 to 6, geometrical changes due to hydro-abrasive erosion at splitters and cut-outs, obtained from comparisons of digital geometric models taken before and after the sediment season, are shown.

At the beginning of the sediment season 2012 the runner installed in machine group 1 was fully reconditioned (welding, grinding and complete coating; with geometry close to planned geometry) whereas the runner in machine group 2 has been in use for several seasons after the last factory overhaul and was repaired on site (grinding and local re-coating).

The hydro-abrasive erosion at the splitter (analysed here as height differences along the splitter's longitudinal profile) for the bucket no. 1 of the runners of the machine group 1 and 2 is displayed in Fig. 4. During the sediment season 2012 the splitter height was reduced by about 3 mm after 3426 operating hours at machine group 1 and by 5 mm after 1430 operating hours at machine group 2. In summer 2012 a major flood event with SSC ranging up to approx. 50 g/l occurred when both turbines were running.

The erosion rates indicate that hydro-abrasive erosion does not mainly depend on operating hours but rather on suspended sediment transport events, e.g. during floods, and on the geometry of the splitters at the beginning of the sediment season (Fig. 5).

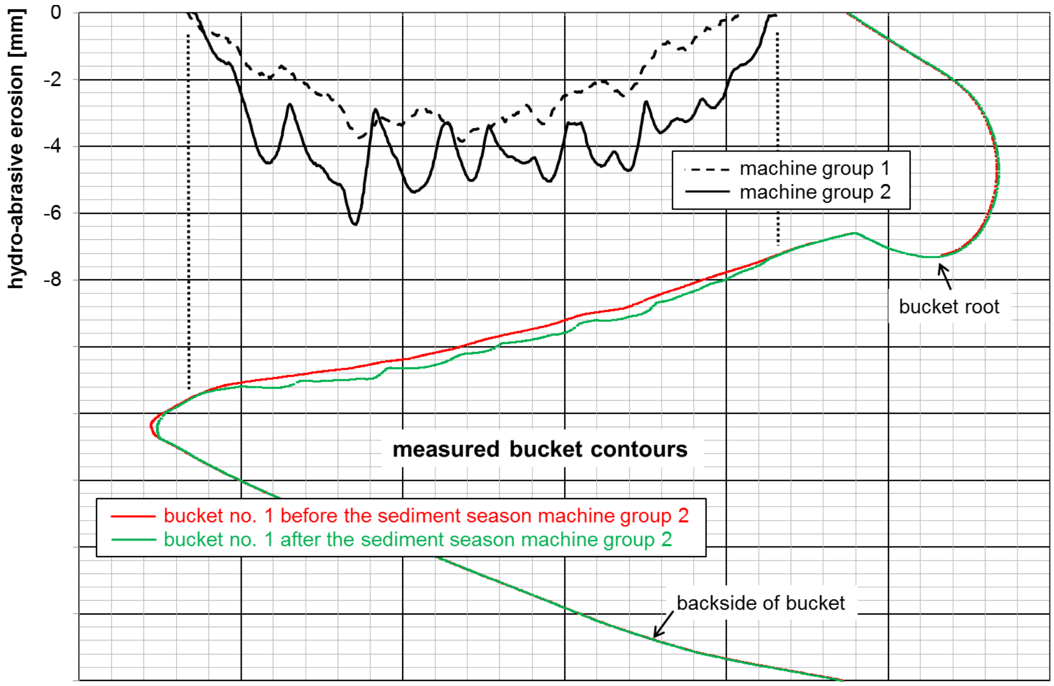

Fig. 4: Side view of the digitized main splitter: Comparison (black) between the splitter geometries of buckets no. 1 of the machine groups 1 and 2 before (red) and after (green) the sediment season.

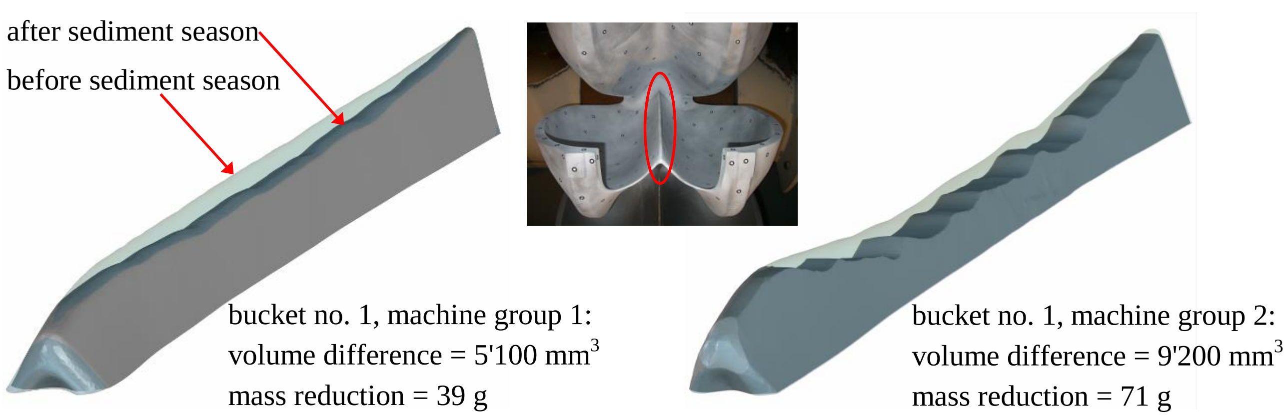

Fig. 5: 3D views of the digitized main splitters (red ellipse): Comparison between the splitter geometries before (transparent) and after the sediment season (grey) of buckets no. 1 of machine groups 1 and 2. The mass reduction is calculated with a density of 7.7 g/cm^3 for the base material.

Further damages occur at the cut-out section of the bucket. The digitized edges of the cut-outs of bucket no. 1 of machine group 1 before and after the sediment season are shown in the lower part of Fig. 6 (top view). The differences in geometry of the cut-outs before and after the sediment season are plotted in the upper part of Fig. 6 for both machine groups. The cut-outs were abraded by up to 9 mm towards the turbine axis at machine group 1 and by up to 6 mm at machine group 2. Interestingly, the erosion measured at the cut-outs exhibits an opposite behaviour compared to the erosion at the splitters.

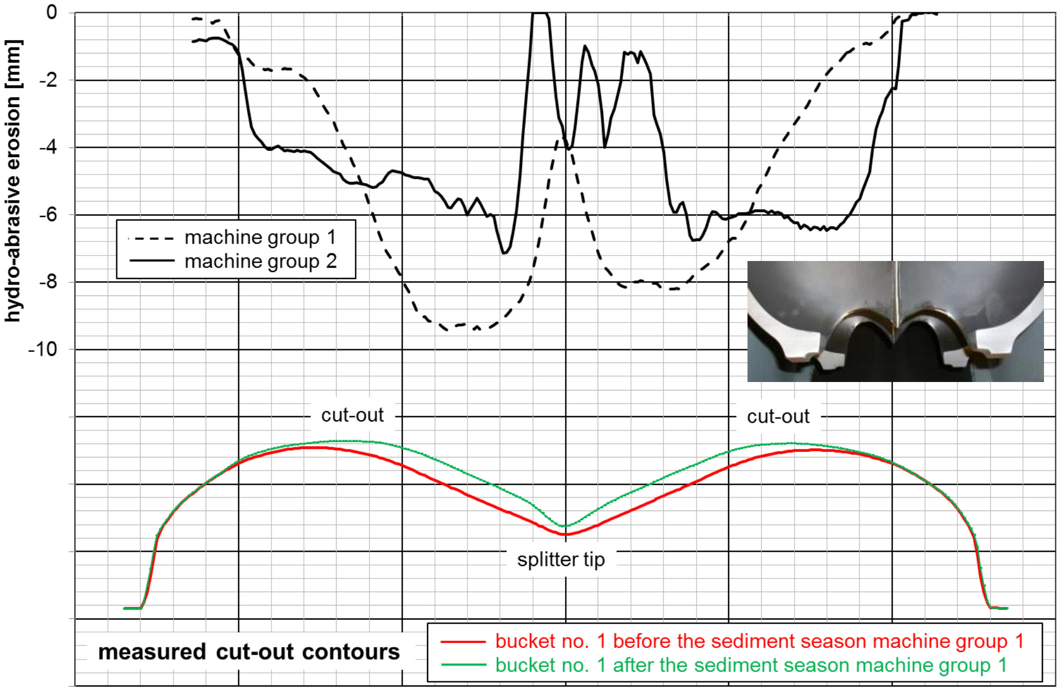

Fig. 6: Top view of the digitized cut-out (with the splitter tip in the centre): Comparison (black) of buckets no. 1 of machine groups 1 and 2 between the cut-out geometries before (red) and after (green) the sediment season.

2.2. Coating thickness measurements

To analyse turbine wear mechanisms and local damages in coated Pelton buckets as installed in the HPP Fieschertal, it is essential to quantify coating thicknesses. Since the coating material (approximate Mohs hardness 7.5) is much harder than the base material (approximate Mohs hardness 4.5) of the Pelton bucket, the erosion potential raises significantly when the coating material is removed locally. Reduced coating thicknesses can result from continuous silt and sand abrasion or from single grain or stone impacts, which may crack the coating surface.

In this on-going project the coating thickness distributions inside selected Pelton buckets before and after the sediment season are measured using a thickness gauge (Helmut Fischer Deltascope FMP30 with dual-tip probe) based on magnetic induction. First spatially distributed thickness measurements using a template that defines the measurement locations within the buckets were completed. An example of such a coating thickness distribution inside a bucket of the runner which has been fully reconditioned before the sediment season is shown in Fig. 7. The distribution was obtained from an interpolation between 153 measurement locations (black points in Fig. 7). At each location, ten repeated measurements were done to achieve a mean value with an expanded measurement uncertainty (at a confidence level of 95 percent) less than 3 percent (average over all measurement locations). As it can be seen from the colour bar, the coating thicknesses vary mainly between 200 and 400 µm with an approximate mean value of 300 µm.

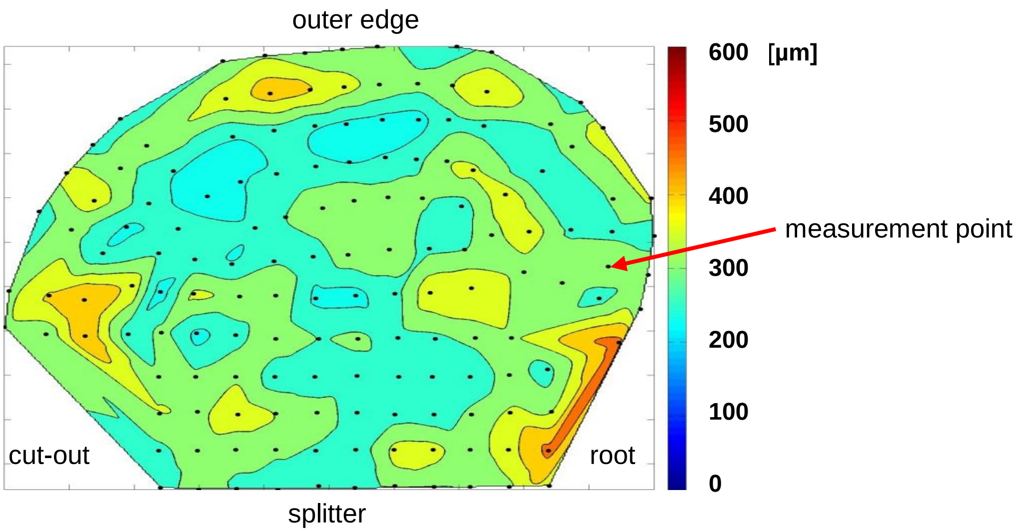

Fig. 7: Coating thickness distribution inside the left half of bucket no. 2 of machine group 1 after the sediment season.

3. EFFICIENCY MONITORING

Turbine wear leads to efficiency reduction. Only a few published data are available (e.g. Dahlhaug et al. 2010 or Bajracharya et al. 2008), describing quantitatively the efficiency decay in defined time intervals, correlated to different turbine damages. One main reason for this lack of published data is the effort associated with efficiency measurements with respect to direct costs and cost of eventual power losses during efficiency measurements.

With index efficiency measurements the efficiency changes between two tests can be determined, absolute efficiency data are not required. A periodical evaluation of the index efficiency allows thus to quantify the evolution in turbine efficiency. Classical index efficiency measurements encompass a series of measuring points (part load to full load) with constant operating conditions. Accordingly, such measurements are time-consuming. Almquist et al. (1995) introduced the so called "sliding gate method". In this method the guide vanes of a Kaplan turbine were continuously opened and closed while acquiring data for efficiency evaluation. This method can also be adapted to Pelton and Francis turbines, as discussed by Abgottspon and Staubli (2008). Necessary condition for good measurements is that they are performed under quasi-steady conditions. The closing and opening ramps must accordingly be slow enough to fulfil this condition. An example of such a "sliding needle" procedure in the HPP Fieschertal is shown in Fig. 8. The main advantages of this kind of index efficiency method are:

- feasible for Kaplan, Francis and Pelton turbines,
- reduced time required to perform efficiency tests, and
- continuous efficiency curves over the entire operating range, instead of discrete points.

A further advantage of such index tests is that in most cases the instrumentation of the HPP can be used or data can be extracted from the control system. To do so, an adequate data acquisition algorithm has to be implemented in the control system. At HPP Fieschertal three principal possibilities to calculate the index efficiency are available:

- acoustic discharge measurements at the upper and lower end of the pressure shaft,
- pressure difference measurements in a Venturi pipe section upstream of each machine group, and
- needle stroke measurements.

Redundantly performed measurements and evaluation allow cross-checks and contribute to an increase of the reliability of the evaluated differences in efficiency.

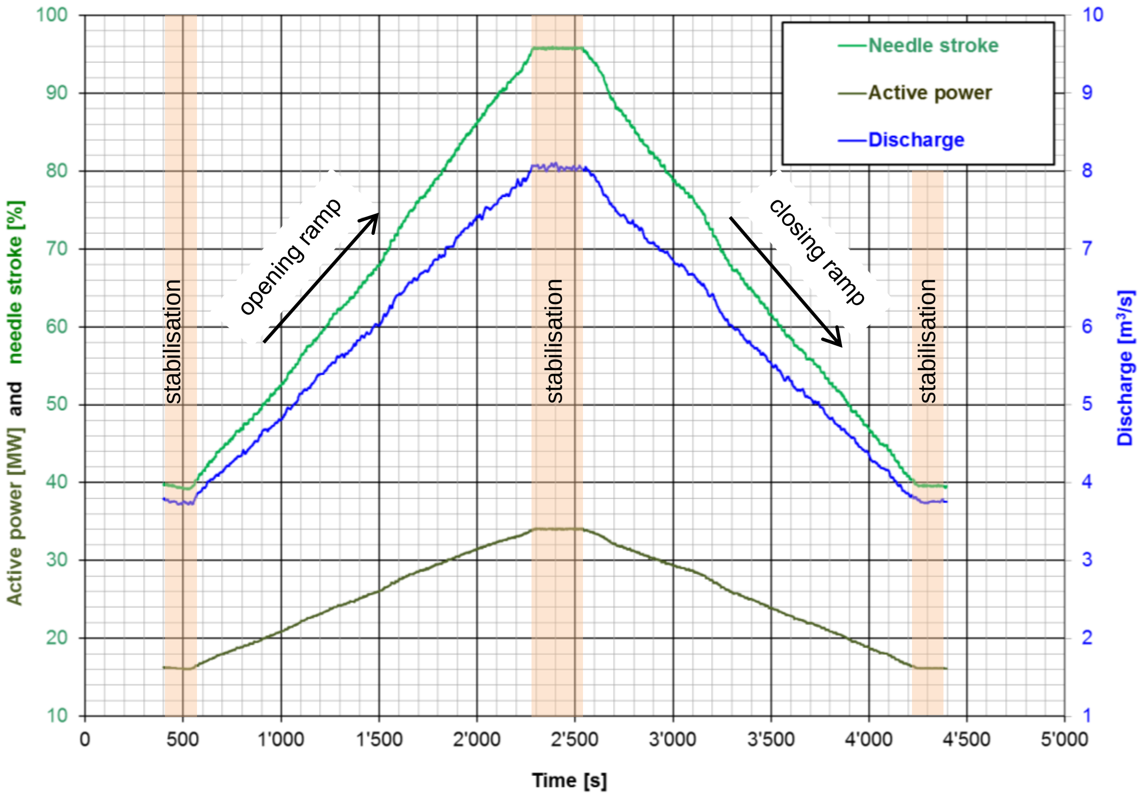

Fig. 8: Active power (dark green, lowest curve), needle stroke (green, highest curve) and discharge (blue, curve in the middle) variation during a sliding needle index efficiency measurement.

Fig. 9 shows the efficiency history of machine group 1, calculated twice (independently) based on the two available acoustic discharge measurements. The differences between the instruments indicate reproducibility within 0.2 percent.

Between the reference measurements of July 4, 2012 and the second measurements of Sept. 27, 2012 more than half of the sediment season passed. An index efficiency decrease of 0.9 percent is obtained. This decrease is attributed to hydro-abrasive erosion. On Nov. 5, 2012 none or only a minor rise in the index efficiency level is found compared to the previous measurement, i.e. the index efficiency level remained constant. This agrees with the suspended sediment load which is measured to be low during this period. In the period until the next measurement of March 8, 2013 very low suspended sediment concentrations were measured. The observed index efficiency level rise of up to 0.5 percent can be explained with maintenance works carried out at the main splitters of the Pelton buckets during winter.

In order to distinguish the effects of hydro-abrasive erosion or of maintenance works at relevant turbine parts on turbine efficiency, index tests are required as close as possible before and after such works.

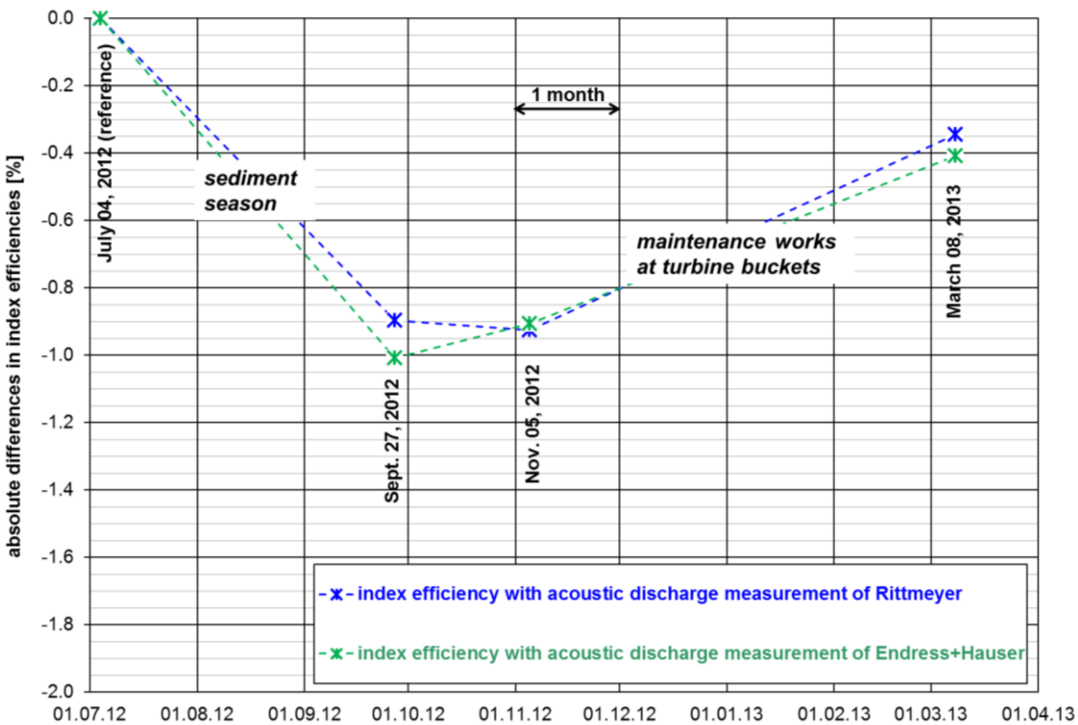

Fig. 9: History of the index efficiency for machine group 1: Absolute differences from weighted index efficiency levels with two different acoustic discharge measurement devices (blue: Rittmeyer crossed 4-path inside mount, green: Endress + Hauser 1-path clamp-on outside mount)

4. SUSPENDED SEDIMENT MONITORING

Among the available techniques for suspended sediment monitoring (SSM) turbidimeters are most popular, despite the fact that their calibration is strongly particle-size dependant and the calibration needs generally to be established by the user (Wren et al. 2000). Various kinds of turbidimeters (measuring optical transmission or scattering) have been used in the present study. An acoustic method for SSM based on installations for acoustic discharge measurement (ADM) is also applied (single frequency attenuation, see also Costa et al. 2012). Furthermore, a portable laser diffractometer (LISST) is used (Agrawal and Pottsmith 2000). The latter yields not only estimates of SSC, but also of PSD. Particle size is an important parameter in the context of turbine wear.

The devices for SSM used in this study are summarized in Table 1. In a first phase of the project, these devices were tested in the mixing tank in the hydraulic laboratory at Hochschule Luzern, Competence Centre for Fluid Mechanics and Hydro Machines. In summer 2012 they were installed at the study HPP (locations see Tab. 1 and Fig. 2). Most devices are installed in the valve chamber, at the inlet to the penstock. Further information on these devices, the laboratory tests as well as the installation at the study HPP and previous results are described by Felix et al. (2012) and Abgottspon (2011).

In addition to the devices for continuous real-time SSM, an automatic water sampler was installed in the valve chamber and the obtained samples are analysed in the laboratory as a reference for the other devices. Reference SSCs are determined by weighing of the solid residues (primary method). The sampler is programmed to take one sample every 2 days and is additionally triggered by the signal of a turbidimeter to increase the sampling rate during relatively high SSC.

Device type	Device model and manufacturer	Device output and measuring principle	Derived parameters	Installed in HPP Fieschertal at
Turbidimeter, submerged	*Turbimax W CUS41* Endress-Hauser	Turbidity [FNU] from backscatter	SSC	Intake (starting 2013)
	Solitax ts-line sc Hach-Lange	Turbidity [FNU] from backscatter	SSC	Tailrace channels of each unit
Turbidimeter, in-line	*TurbiScat (90°, 25°)* Sigrist Photometer	Turbidity [FNU] from backscatter	SSC	Valve chamber, at the inlet to the penstock
	TF16-N with F20 Optek Danulat	Turbidity [CU] from transmission	SSC	
Acoustic method	*Risonic Modular* Rittmeyer	Received amplitude [V] forward scattering	SSC	
Portable laser diffractometer	*LISST-100X, Type C* Sequoia Scientific	Volume concentrations in 32 size classes [ppm]	SSC and PSD	

Table 1: Devices used for continuous suspended sediment monitoring.

The time series of SSC in the turbine water obtained from the devices installed in the valve chamber are shown in Fig. 10 for the period from July 2012 to the end of the sediment transport season. The conversion (calibration) from original units of the devices (e.g. FNU) to SSC is based on the reference SSCs collected so far at the study site.

The time series of the in-line turbidimeter (optical backscatter and optical transmission) models used here show considerable drift. Their signals are increasingly biased by particles that accumulated on the optics in the flow-through cells and by bio-fouling. Flushing of the flow cells by increasing the discharge of the sampling line for some minutes was not sufficient to clean the optics. Only manual cleaning (at day 303) brought the signals back to the low level expected for the relatively clear water in late autumn. In the sediment season 2013 another turbidimeter model, measuring the turbidity at a free falling jet (*AquaScat* from Sigrist Photometer), will be installed at the sampling line in order to avoid signal drift and frequent manual cleaning. At the two turbidimeters installed at the tailrace channels no problem of signal drift occurred since those submerged turbidimeters are equipped with a wiper that keeps their optics clean.

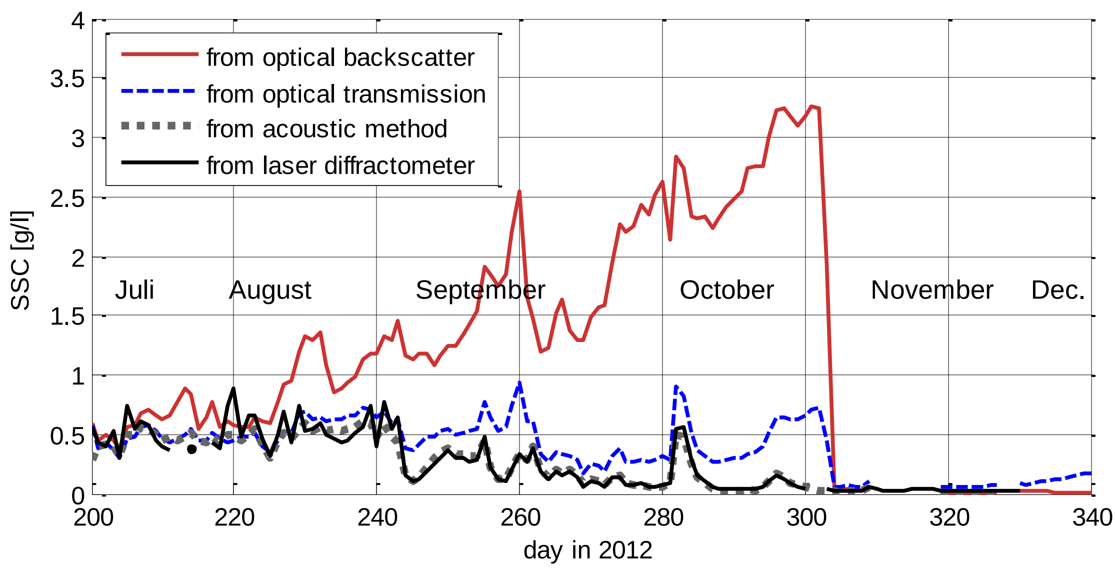

Fig. 10: Time series of daily averaged SSC in the turbine water, obtained from various devices installed in the valve chamber, from July, 19 (day 200) to December, 6 (day 340) in year 2012.

Figure 11 shows a close caption of Figure 10 as an example of suspended sediment transport during three summer days. In addition, three of the reference SSCs from laboratory analysis of bottled samples and the time series of the median size of the particles in the turbine water (d_{50}, i.e. the median diameter by mass) obtained from the LISST (right axis) are also shown in Fig. 11. Data were recorded every second for turbidimeters and the acoustic method and every minute for the LISST. The time series were smoothed by moving average over 20 minutes and implausible data were discarded. Trends and offsets visible in Fig. 10 were removed from the turbidimeter data.

During summer days SSC was approx. 0.5 g/l and the time series from all devices (turbidmeters, laser diffractometer and acoustics) show similar behaviour, except for a sediment transport peak in the early morning hours of day 239. During this event the LISST yields a higher SSC compared to the other continuous measuring methods. The LISST measurement is supported by the reference measurement taken during the rising limb of the SSC peak. From Figure 11 it can be seen that the median size of the particles in the turbine water is approximately 15 microns, except for the phase of increased sediment transport. During this phase, about three times coarser particles (d_{50} approximately 45 microns for some hours) were transported. The maximum of d_{50} occurred approximately one hour after the maximum in SSC.

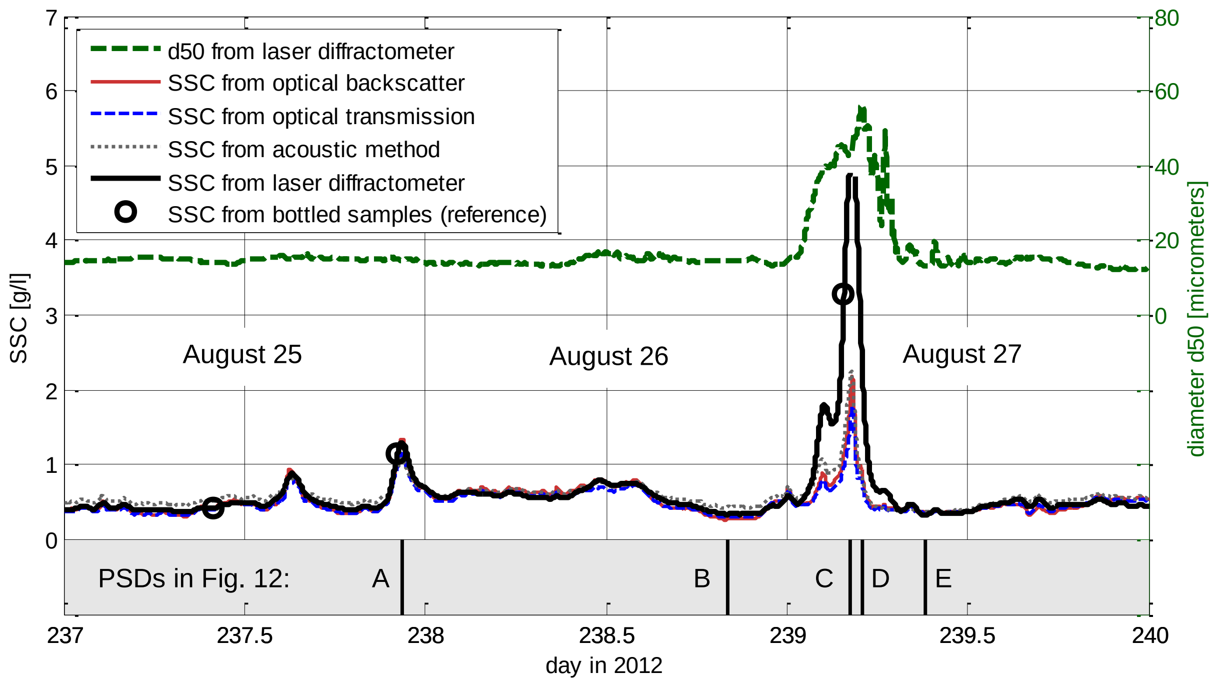

Fig. 11: Time series of SSC in the turbine water, from devices as in Figure 10, reference SSCs from bottled samples, and time series of d_{50} obtained from LISST; example of three summer days (August 25 to 27, 2012).

In Figure 12 selected PSDs obtained from the LISST are displayed. The times at which these PSDs were measured are indicated in Fig. 11 with capital letters. The PSDs measured before (B) and after (E) the SSC peak as well as during a minor SSC peak (A) are similar. The PSDs recorded at maximum SSC (C) and at maximum d_{50} (D) are considerably coarser.

The underestimation of SSC by the turbidimeters and the acoustic method (single frequency forward scattering) in times with transport of coarser particles is related to their physical operating principle. Coarser particles do not cause as much turbidity or scattering as finer ones (at same SSC). The calibration of those devices depends strongly on particle size, for which in practice a constant time-averaged value has to be adopted. As it can be seen from Figures 10 and 11, the deviation in SSC estimates of those devices with respect to SSC from the LISST and reference SSCs may be significant during phases of increased suspended sediment transport. In the rest of the time, however, those devices provide quite accurate SSC estimates.

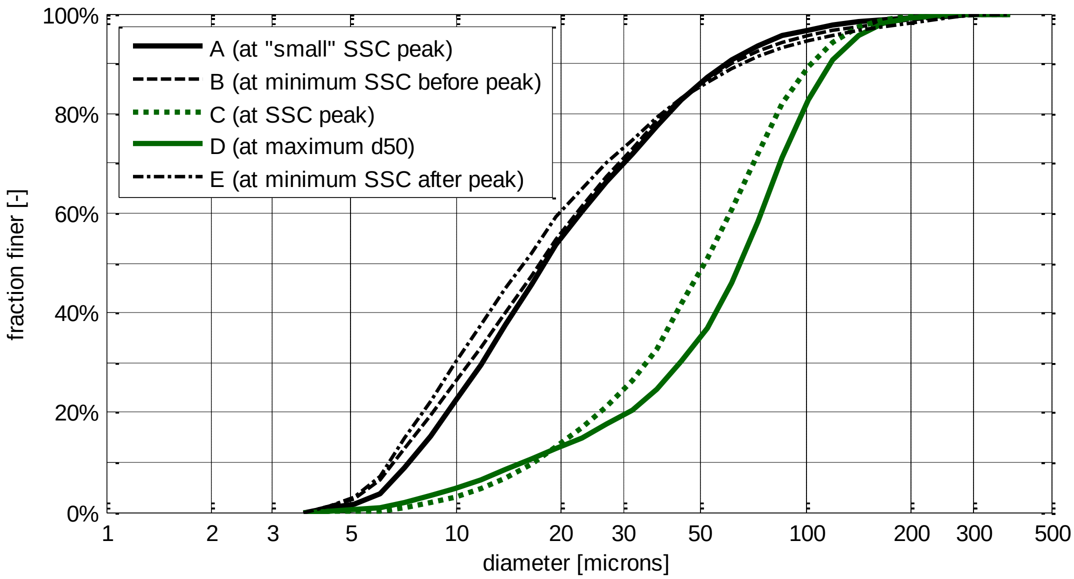

Fig. 12: Selected PSDs obtained from LISST, measured in the turbine water at times indicated in Fig. 11.

5. CONCLUSIONS

First analyses of the hydro-abrasive erosion rates for both machine groups in the HPP Fieschertal, Switzerland, showed that single events such as heavy rains lead to major material loss at Pelton buckets. Therefore, temporary shutdowns of the HPP would help to prevent excessive hydro-abrasive erosion during such events. To do so, a reliable method for continuous real-time measurement of suspended sediment load is needed.

Using several devices for SSM based on different physical principles allows for a cross-comparison of their measuring capabilities under field conditions and leads to higher reliability. The combination of devices for continuous SSM with an automatic water sampler allows calibrating the devices based on the site-specific conditions, e.g. with respect to typically prevailing particle sizes and mineralogical composition (particle shape, optical properties). The calibration of the devices will be improved based on the increasing data set of reference SSC from the study site.

Since frequent manual cleaning of measuring devices is not practical, turbidimeters with an automatic cleaning system (wiper or pressurized air) or turbidimeters with optics not in contact with the sediment-laden flow (free falling jet type) are recommended, even in cold and relatively nutrient-poor water of mountain streams. The acoustic method based on ADM installations existing in many HPPs offers the advantage of monitoring suspended sediment directly in the penstock. Among the devices used here, LISST offers new possibilities for SSM, since it provides not only information on SSC, but also on PSD. In environments with variable particle sizes LISST measures SSC more accurately than devices with a fixed calibration depending on particle size. For a better understanding of hydro-abrasive erosion, measuring PSD is important since coarser particles have higher abrasion potential (for a given SSC) and are therefore particularly harmful to turbines. Devices with particle size-dependant calibration may be used as pragmatic contributions to a real-time decision making system for the operation and maintenance of HPPs, especially for smaller schemes.

In summer 2012 SSC of approximately 0.5 g/l with d_{50} of normally 15 microns was observed in the turbine water of HPP Fieschertal. The measurements confirmed that SSC and PSD may vary strongly within short time, e.g. due to precipitation events, to SSC of up to approximately 50 g/l and d_{50} of e.g. 45 microns.

Wear at coated Pelton runner buckets was measured with a 3D optical scanner and a thickness gauge. Digital models of selected Pelton buckets allowed quantifying material losses at the main splitter and at the cut-outs due to turbine operation over a sediment season. The analysis showed that the splitter height decreased 3 to 5 mm during the sediment season 2012, this corresponds to approximately 0.5 to 0.8 percent of the inner bucket width of 650 mm. The hydro-abrasive erosion at the splitter is influenced by the splitter geometry at the beginning of the sediment season, particle load and the operating hours. Local coating thicknesses in the bucket of a Pelton runner were measured with a thickness gauge based on magnetic induction.

Turbine efficiency was periodically evaluated by “sliding needle” index measurements. The history of the index efficiency permits to identify relevant efficiency variations due to hydro-abrasive erosion. For one of the investigated turbines the efficiency decrease was 0.9 percent for half of the sediment season 2012. In order to distinguish the effects of hydro-abrasive erosion and the effects of maintenance works at relevant turbine parts (e.g. grinding of the splitter) on turbine efficiency, index tests should be performed before and after such works. Redundantly performed index measurements and evaluation allows cross-checking and increasing the reliability of the evaluated differences in efficiency.

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REFERENCES

Abgottspon A. (2011). Messung abrasiver Partikel in Wasserkraftanlagen. *Master Thesis* (unpublished, in German), Hochschule Luzern, CC Fluid Mechanics and Hydro Machines, Lucerne, Switzerland.

Abgottspon A., Staubli T. (2008). Index Tests of a Francis Unit using the Sliding Gate Method. *Proc.* 7th Intl. conference on Hydraulic Efficiency Measurements, IGHEM, Milan, Italy.

Agrawal Y.C., Pottsmith H.C. (2000): Instruments for particles size and settling velocity observations in sediment transport, *Mar. Geol.* 168:89-114.

Almquist C. W., March P. A., Pearson H. S., Fransen H. W., Whitehead B. H. (1995). The Sliding Gate Method for Hydroturbine Efficiency Testing. *Proc.* WaterPower '95, American Society of Civil Engineers, New York, 793-801.

Bajracharya T. R., Acharya B., Joshi C. B., Saini R. P., Dahlhaug O. G. (2008). Sand erosion of Pelton turbine nozzles and buckets: A case study of Chilime hydropower plant. *Wear* 264(3-4):177-184.

Boes R. (2009). Real-time monitoring of SSC and PSD in the headwater way of a high-head hydropower plant. *Proc.* 33rd IAHR Concress, Vancouver, Canada, 4037-4044.

Brekke H., Wu Y. L., Cai B. Y. (2002). Design of hydraulic machinery working in sand laden water, in *Abrasive Erosion & Corrosion of Hydraulic Machinery*, Book series on Hydraulic machinery, Vol. 2, edited by Duan C. G. and Karelin V. Y., ISBN 1-86094-335-7, Imperial College Press, London, 155-233.

Costa L.I., Storti G., Lüscher B., Gruber P., Staubli T. (2012): Influence of solid particle parameters on the sound speed and attenuation of pulses in ADM, *J. of Hydrologic Eng.*, 17(10):1084-1092.

Dahlhaug O. G., Skåre P. E., Mossing V., Gutierrez A. (2010). Erosion resistant coatings for Francis runners and guidevanes, *Intl. J. on Hydropower & Dams*, 17(2):109-112.

Felix D., Albayrak I., Abgottspon A., Boes R., Gruber P. (2012). Suspended Sediment and Pelton Turbine Wear Monitoring: Experimental Investigation of various Optical and Acoustic Devices and Beginning of the Case Study at HPP Fieschertal. *Proc.* 17th Intl. Seminar on Hydropower Plants (*Viennahydro*), Vienna, 483-494.

Gummer J. H. (2009): Combating Silt Erosion in Hydraulic Turbines. *Hydro Review Worldwide*, 17(1).

Winkler K., Dekumbis R., Rentschler M., Parkinson E. & Garcin H. (2011): Understanding hydro-abrasive erosion, *Proc.* Hydro 2011, Aqua-Media International Ltd., Prague, Czech Republic.

Wren D., Barkdoll B., Kuhnle R., & Derrow R. (2000): Field Techniques for Suspended Sediment Measurement. *J. of Hydraulic Eng.*, 126(2):97-104.

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Monitoring of suspended sediment—laboratory tests and case study in the Swiss Alps

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ABSTRACT: There is an increasing demand for continuous real-time monitoring of Suspended Sediment Concentration (SSC) and Particle Size Distribution (PSD), e.g. for sustainable operation of hydraulic schemes. Most optical and acoustic devices need to be calibrated with respect to the properties of the suspended particles. Prior to a field study in the Swiss Alps, various turbidimeters, a portable laser diffractometer (LISST) and an ultrasonic system were tested in suspensions made of various mineral particles in a mixing tank. Significant influences of particle size and shape on the SSC estimation were observed and quantified. The data from the devices that have subsequently been installed in the headwater of a hydropower plant confirm temporal variation of PSD and allow cross-comparing the measuring capabilities of the devices under field conditions. LISST has the advantage to provide not only SSC but also PSD, and SSC data is less or not affected by varying size of suspended particles.

1 INTRODUCTION

Sediment transport in rivers and waterways is an important issue when planning and operating hydraulic schemes. Particularly, hydro-abrasive wear at turbines due to hard suspended mineral particles in the water or reservoir siltation may cause substantial maintenance costs and significant negative impact on power generation and revenue at Hydroelectric Power Plants (HPP). For optimized design and operation of hydraulic structures as well as for environmental concerns, there is an increasing need for real-time monitoring of Suspended Sediment Concentration (SSC) and Particle Size Distribution (PSD) in rivers, lakes and seas.

Such data can be used for a better design of desilting facilities or sand traps at hydraulic schemes, conveying or removing sediments from reservoirs by evacuating suspended sediment through outlets of dams or power waterways (e.g. Jenzer Althaus 2011), and for estimates of hydro-abrasive wear at turbines (e.g. Winkler et al. 2011). Real-time data on SSC and PSD from streams at intakes and/or waterways of HPPs can be used as a basis for economically optimized operation in which actual wear of hydraulic turbines is considered with the option of temporary switch-offs of HPPs during suspended sediment peaks.

Thus, the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of the Swiss Federal Institute of Technology, ETH Zurich, initiated an interdisciplinary research project in collaboration with Hochschule Lucerne, supported by swisselectric research, the Swiss Federal Office of Energy, a HPP operator (Gommerkraftwerke) and co-owner (Bernische Kraftwerke) as well as industry partners (Andritz Hydro and Rittmeyer). As an initial part of this project various devices for Suspended Sediment Monitoring (SSM) were investigated in the first half of 2012. As a second and main part of this project, these devices were installed in the existing HPP Fieschertal located at a tributary of the upper Rhone River in the Swiss Alps for continuous real-time in-situ SSM.

This paper presents selected results of the laboratory investigation and exemplary field data from a suspended sediment transport event that occurred at the study HPP in late summer 2012. The presented event may occur several times a year and gives thus an impression of the measuring capabilities of the devices during the sediment season.

Information on parts of this laboratory investigation as well as a preliminary analysis of suspended sediment data during a major flood event in July 2012 are given by Felix et al. (2012). In the following section, an overview of measuring techniques for SSC and PSD is given. Thereafter, the experimental setup and methodology, and the results and discussion for the laboratory and field investigations are presented, followed by conclusions and outlook.

2 MEASURING TECHNIQUES

2.1 *Suspended sediment concentration (SSC)*

Suspended Sediment Concentration (SSC, in g/l) of mineral particles can be determined by laboratory analysis of bottle samples (discontinuous) or using mainly acoustic or optical instruments (continuous). Bottle sampling can be made manually or automatically and is a direct, widely used and reliable technique. However, it has many disadvantages such as time consuming laboratory analysis of the samples, effort of transporting bottles from the study sites to the laboratory, being flow intrusive, having a poor temporal resolution and giving results not in real-time (Wren et al. 2000).

As an optical technique, turbidimeters are popular and widely used for SSM at rivers and lakes (e.g. Spraefico et al. 2005, Habersack et al. 2008). These devices measure either the scattering (at one or several angles, then they are also called optical backscatter probes) or the absorption (transmission) of near infrared or laser light. Output values are given in optical units (e.g. Formazine Nephelometric Unit, FNU) and have to be converted to SSC. Therefore, a custom calibration based on the particle properties (particle size, shape, colour or composition) is required (e.g. Gippel 1995). A main disadvantage of turbidimeters is the problem of the dependency on particle size and shape.

Recently, portable laser diffractometers (Laser in-situ Scattering and Transmissiometry, LISST) have become available for in-situ SSM (e.g. Boes 2009, Agrawal et al. 2011, Agrawal et al. 2012). SSC estimates made by LISST have the advantage of being not or less dependent from particle size since particle size is considered in the design of the instrument and its software. The use of in-situ laser diffractometers for SSM at rivers and lakes is not yet widespread, because it is relatively expensive and its SSC measuring range (without dilution) is limited.

Acoustic methods are another approach to monitor SSC. Among many possibilities (backscatter as used in ADCP etc.) the method of measuring the attenuation of ultrasonic pulses sent through the sediment-laden water in tunnels, penstocks or channels is of particular interest for HPP operators since installations for Acoustic Discharge Measurement (ADM) existing at many HPPs can be upgraded to be used for SSM. This method of single frequency acoustic forward scattering (e.g. investigated by Costa et al. 2012) can be calibrated for constant particle properties. In order to determine SSC at variable particle sizes the use of multi-frequency-acoustics is required. Such methods are currently under development (e.g. Skripalle et al. 2012).

Lastly, the SSC of sediment-laden flow can be determined by measuring its density with a precise, temperature compensated Coriolis mass flow meter (Biswakarma & Støle 2008) if SSC is above approximately 0.5 g/l. This mass-based method has the advantage of being not sensitive to particle properties.

2.2 *Particle size distribution (PSD)*

Besides SSC, PSD of mineral particles in the water is an important parameter for sediment dynamics (transport, deposition and re-suspension) and hydro-abrasive wear of turbines.

The primary method to obtain PSDs is by sieve analysis of collected particles. Especially for smaller fractions, laser diffraction has been used in laboratories for decades. However, as mentioned above, analysing collected sediment in the laboratory has many disadvantages. Therefore, portable laser diffractometers are recently used as a practical real-time monitoring system of both SSC and PSD in field studies.

3 EXPERIMENTAL SET-UP AND METHODOLOGY

3.1 *Laboratory investigation*

3.1.1 *Experimental set-up*

Prior to the field study the devices for SSM were tested in the hydraulic laboratory of Hochschule Lucerne at the facility of the Competence Centre for Fluid Mechanics and Hydro Machines. Experiments were carried out in an existing mixing tank (Abgottspon 2011) equipped with a stirrer (Fig. 1). All devices were placed in the tank at

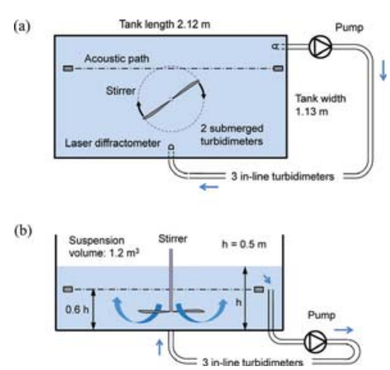

Figure 1. Mixing tank in the hydraulic laboratory with optical and acoustic devices for measuring suspended sediment, (a) plan view and (b) vertical section (Felix et al. 2012).

the same level in order to reduce effects of possible vertical SSC gradients.

3.1.2 *Tested devices*

The devices used for SSM are listed in Table 1. Two different submersible turbidimeters with wipers were installed in the tank. Two in-line type turbidimeters were installed in the pump line connected to the tank. Another turbidimeter, which measures scattering of light at a free falling jet, was mounted above the tank and fed from the pump line, letting the water fall back into the tank.

Among the available portable laser diffraction devices a *LISST-100X*, Type C with a nominal particle size measuring range from 2.5 to 500 microns (10^{-6} m) was selected. These size limits apply to spherical particles; for random shaped particles the size range is 2 to 380 microns. In contrast to a stream-side type model, this submersible instrument can be used for investigations of SSM in reservoirs (down to 300 m water depth) and desilting facilities, too. In order to extend the range of measurable concentrations the optical path length was reduced from 50 mm to 5 mm by insertion of a 90%-path reduction module (glass cylinder).

As far as acoustics are concerned, ultrasonic transducers operating at 1 MHz at a path length of 1.73 m were used in the experiments (Fig. 1a & b). The signal sent by the emitter, i.e. by one of the ultrasonic transducers, is attenuated (damped) when travelling through the water or the suspension to the receiver. The attenuation due to the existence of suspended particles in the water (excess attenuation) is examined. The difference between the received signal's amplitudes in clear water A_c and in the suspension A_s gives the amplitude of attenuation due to suspended sediments A_a (Equation 1). The relative attenuation A_r due to suspended sediment is obtained by normalizing A_a with A_c (clear water). Thus $A_r = 0$ in clear water, increasing with SSC (up to 1).

$$A_a = A_c - A_s \quad (1)$$

$$A_r = A_a/A_c \quad (2)$$

3.1.3 *Tested mineral particles*

The previous studies at HPP Fieschertal show that the mineral particles prevailing in the turbined water are mainly quartz, feldspar and mica, i.e. the components of Granite rock, and the size of the mineral particles in normal summer conditions (with glacier melt) was estimated to be $d_{50} = 20$ to 40 microns (d_{50} stands for the diameter of graded particles of which 50% by mass is finer). During flood events bigger particles up to 0.3 or 0.5 mm corresponding to the design grain size of sand traps of HPPs may be transported in the turbine water.

In the mixing tank experiments feldspar powder, mica powder, fine quartz sand and natural sediment of the study HPP were used. The latter was taken from deposits in the tailrace channel whereas the other three types of particles were bought from commercial applications. It should be noted that the natural sediment taken from the tailrace channel is coarser than the sediment normally found in the turbine water since these particles settled while finer ones were transported downstream.

The size distributions of the particles used in the experiments are shown in Figure 2. These results were obtained from the measurements performed by a non-portable laser diffraction instrument (*Horiba*) in the geotechnical laboratory of ETH Zürich. Note that particle samples for the sieve analysis were taken from the boxes in which

Table 1. Tested devices for suspended sediment monitoring.

Type	Model	Manufacturer
T (submerged)	*Solitax ts-line sc*	Hach-Lange
T (submerged)	*Turbimax W CUS41*	Endress-Hauser
T (in-line)	*TurbiScat (90°, 25°)*	Sigrist Photometer
T (in-line)	*TF16-N with F20*	Optek Danulat
T (free fall)	*AquaScat*	Sigrist Photometer
LD	*LISST-100X, Type C*	Sequoia Scientific
ADM	*Risonic Modular*	Rittmeyer

Legend: T = Turbidimeter, LD = Laser diffractometer and ADM = acoustic system as used in acoustic discharge measurement.

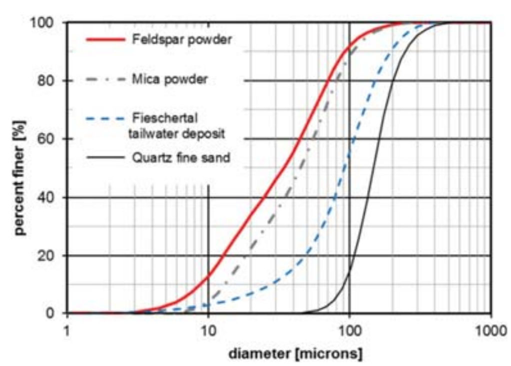

Figure 2. PSDs of selected mineral particles used in the laboratory tests of suspended sediment measuring devices.

the particles were kept prior to the mixing tank experiments. The grading of the natural particles collected from the tailrace channel may not be homogeneous throughout the whole lot.

Based on the images from a scanning electron microscope (Fig. 3) feldspar powder, mica powder and fine quartz sand particles have angular (from grinding), flaky (corresponding to the mechanical properties of mica) and rounded (natural sand) shapes, respectively. The natural sediment from the study site is expected to be composed of particles of these shapes. The size information on the mica particles have to be interpreted with precaution since it is not clear how laser diffraction determines the diameter of flaky particles.

Furthermore, fine glass spheres and quartz powder were used in the experiments. Glass spheres were included in the test program to allow a later comparison with theoretical models of attenuation and scattering of light or sound, in which particles are assumed to be spherical.

3.1.4 *Methodology*

Firstly, a zero measurement of all devices was done in still drinking water. Then the SSC was step-wise increased and the measurements at each step were simultaneously done with all devices until the SSC-measuring range of most devices was exceeded. SSC was increased up to 50 g/l for coarser particles (fine sand).

For the turbidimeters and the acoustic system 500 data points were recorded at a frequency of 1 Hz at each nominal SSC level. For LISST, 100 values were recorded at the frequency of about 2 Hz at each nominal SSC level. Finally, the data obtained from each device were time-averaged for each SSC-level.

Reference SSCs were determined by weighing of suspension samples before and after drying in an oven. The weight of minerals that were dissolved in the drinking water before drying of the sample was deducted from the residue. Three samples per nominal SSC-level were taken from the tank at the same vertical position as the instruments were placed.

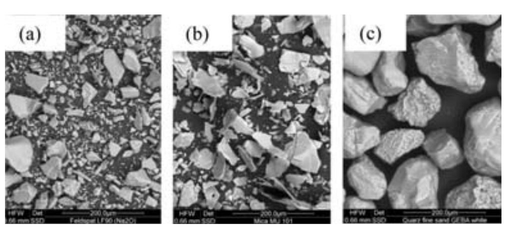

Figure 3. Selected mineral particles used for laboratory tests, (a) feldspar powder, (b) mica powder and (c) quartz fine sand.

For feldspar and mica powders the reference SSCs agreed well with nominal SSCs that were calculated from the amount of water and particles added to the tank. With coarser particles, such as fine quartz sand and the particles from the tailrace channel of the study site, however, SSCs determined in the tank at the level of the instruments were lower than nominal SSCs. This can be attributed to settling of coarser fractions due to insufficient mixing.

The LISST records the intensity of scattered laser light at 32 ring detectors and the attenuation in the axis of the laser beam. From these values the volume concentrations in 32 log-spaced size classes can be calculated, using the corresponding software (inversion algorithm) from the instrument manufacturer. The inversion mode assuming "irregular shaped" particles (Agrawal et al. 2008) was used for the calculation of the results presented here (no spherical particles). The total volume concentration of suspended sediment results from summing up the volume concentrations of all 32 size bins.

For the conversion of volume concentration to mass concentration (SSC) a density of 2.65 kg/l (standard value for quartz) was assumed for all materials, leading to an error of presumably less than 10%.

3.2 *Field investigation*

3.2.1 *Installations at the study HPP*

After the laboratory tests were completed in June 2012 two turbidimeters and the LISST have been installed at the waterway of the high-head HPP Fieschertal (Fig. 4), a run-of-river type HPP located in the Canton of Valais, in the Alps of Switzerland.

Water used in the HPP comes from a mountain stream emerging from a glacier, which is on retreat. This glacier leaves an abundance of easily erodible sediments of all sizes in the lower part of the barely vegetated catchment area.

At this HPP, there is no storage lake in which fine particles could settle. In the free surface flow tunnel, partial settling and also re-suspension of

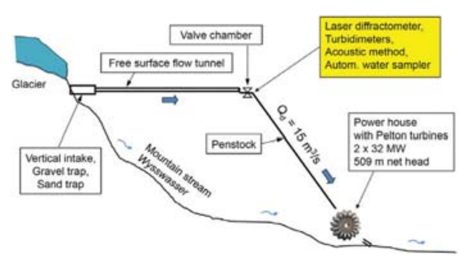

Figure 4. Schematic longitudinal profile of Fieschertal HPP at which suspended sediment is monitored.

particles occur according to the operation conditions (in- and outflowing discharge, water level). Since the commissioning of the HPP in 1976 relatively high SSC have been observed in the turbine water during the summer season.

In the valve chamber, two turbidimeters (*TF16-N* and *TurbiScat*) as well as the LISST are fed through a pipe (DN 40 mm) with sediment-laden water taken from the axis of the penstock (Abgottspon 2011). The measuring end of the LISST device is inserted laterally into a bucket with an overflow and a flushing outlet. An automatic water sampler (*Isco 3700*) with 24 bottles was installed with a suction line from the LISST bucket.

As far as the acoustic method is concerned, no modification of the existing ADM installation was required. The ADM is a four path arrangement on two horizontal layers in the penstock, with 1 MHz and path lengths of 2.27 m. At the controller of the ADM the amplitudes of the received signals at the four paths were defined as additional output signals.

The output signals of all instruments were connected to a data acquisition board running with an industrial computer which can work under tough field conditions.

3.2.2 *Methodology*

Data from the turbidimeters and the acoustic method were recorded at 1 Hz; LISST-measurements were performed and saved every minute. The time series in Figures 9, 10 and 12 were obtained by plotting one-minute values, smoothed with moving average.

The automatic water sampler was set to take water samples every two days and more frequently in case of increased SSC. The water sampler is controlled by a custom-made software that is triggered by a turbidimeter. Sampling rules depend on several turbidity levels, which can be adjusted depending on the season.

4 RESULTS AND DISCUSSION

4.1 *Laboratory investigation*

4.1.1 *Turbidimeters*

The calibration curves of a submersible and an in-line optical backscatter probe obtained from the laboratory measurements are presented in Figures 5 & 6, respectively. The values of d_{50} for the four types of particles indicated in the legends of Figures 5 and 6 were obtained from the reference laser diffraction measurements (Fig. 2).

The relationships between reference SSC and turbidity can be approximated with linear functions for both turbidimeters (Figs. 5 & 6). As known from literature, turbidity is not only a

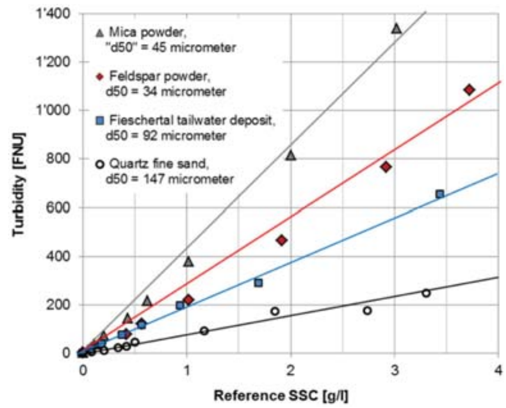

Figure 5. Turbidity measured with a submerged optical backscatter probe (*Solitax ts-line sc*) as a function of reference SSC.

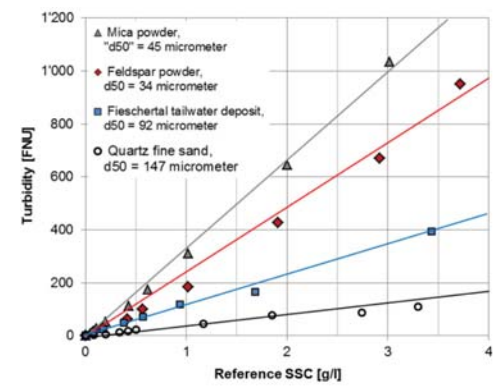

Figure 6. Turbidity measured with an in-line optical backscatter probe (*TurbiScat, 90°*) as a function of reference SSC.

function of SSC but also of particle size, shape and optical properties.

The calibration curves of both devices are qualitatively similar. The *Solitax ts-line sc* yields higher values than the 90° channel of the *TurbiScat* although both devices measure turbidity in the same physical unit (FNU). This means that for accurate SSC estimates not only particle-specific but also instrument-specific calibrations are required.

4.1.2 *Acoustic system*

Figure 7 shows the relationship between the relative attenuation A_r due to suspended sediment and the reference SSC for each type of particles. Up to about 6 g/l the relationships can be approximated with linear functions. At higher SSC a non-linear fitting is required.

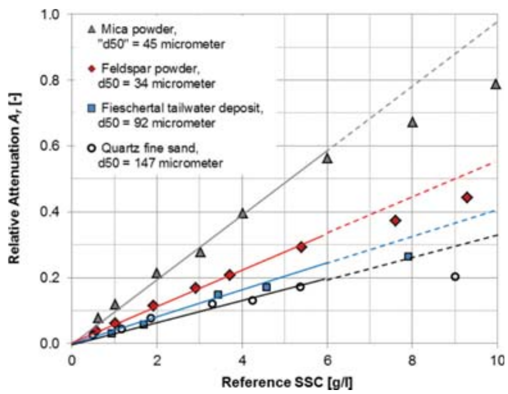

Figure 7. Relative attenuation A_r of ultrasonic pulses due to suspended sediment particles as a function of reference SSC.

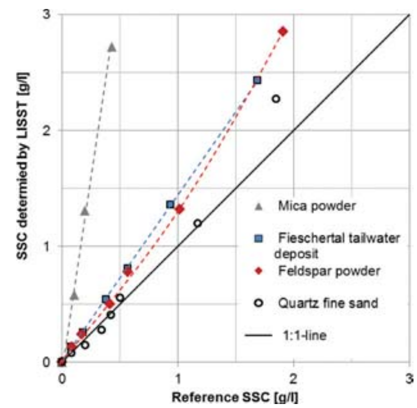

Figure 8. SSCs determined by LISST as a function of reference SSCs.

Comparable to optical backscatter, the damping due to the particles is not only a function of SSC, but also of particle size and shape. The curves of the four types of particles in Figure 7 are in the same sequence as those of turbidity (Figs. 5 & 6).

Compared to Figures 5 & 6, the range between the curves of the finest to the coarsest type of particles is smaller in Figure 7. This is a sign for a less pronounced effect of particle properties in the acoustic method compared to optical backscatter (turbidimeters), indicating a reduction in possible errors in SSC estimates when using a fixed calibration in case of variable particle properties.

The acoustic method with the frequency and path length used here is not well adapted to measure SSCs below 0.5 g/l, but allows measuring up to higher SSCs in comparison to the turbidimeters.

4.1.3 *Laser diffraction*

The relationships between SSCs measured by LISST and the reference SSCs are shown in Figure 8 for the four types of particles.

The measured data for fine quartz sand are generally in good agreement with the 1:1-line. It should be noted that no custom calibration was applied and the SSC in the tank was subject to possibly imperfect mixing.

For feldspar powder, the LISST increasingly overestimates SSC as SSC increases, mainly due to relatively high contributions in the lowest size classes. This effect becomes more pronounced as the SSC approaches the upper measurement limit of the LISST. Possible reasons for overestimation at lower size bins can be multiple scattering, strongly non-spherical particle shape or refractive index (Agrawal & Pottsmith 2000, Agrawal et al. 2008, Andrews et al. 2011).

For the mica powder LISST SCCs are about 6 times higher than reference SSCs. This can be attributed to the flaky shape of these particles that produces over-proportional scattering compared to particles with a more compact shape at given SSC.

For the natural sediment particles from Fieschertal, which are coarser than the feldspar and the mica powders, the LISST overestimates SSC by about 40%. It is assumed that this approximately constant deviation can be attributed to particle shape as the Fieschertal sediments contain mica and angular particles.

Furthermore, PSDs can be calculated from the volume concentrations in the 32 size classes. PSD data from LISST experiments are currently being evaluated. When comparing LISST PSDs measured in the tank to reference PSDs (from non-portable laser diffraction) the effect of possibly imperfect mixing in the tank and uncertainty in true PSDs of non-spherical particles have to be taken into account.

4.2 *Field investigation*

4.2.1 *Laser diffraction*

Figure 9 shows—as an example—the time series of SSC measured by LISST during two weeks in late summer 2012. Time is indicated in days from the beginning of the year 2012. As in the data analysis of the laboratory experiments, the "random shaped" inversion mode was used and a density of 2.65 kg/l as for quartz was assumed. No corrections for effects of particle shape or for overestimations at lower size bins (possibly due to fine out-of-size-range particles, as e.g. described by Andrews et al. 2011) were applied yet. The bold dots in Figure 9 indicate the reference SSCs obtained from

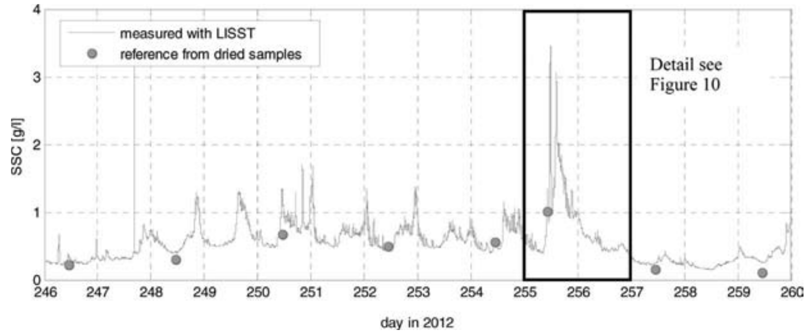

Figure 9. SSC obtained from LISST-measurements in comparison to laboratory results of water samples (September 3 to 17, 2012).

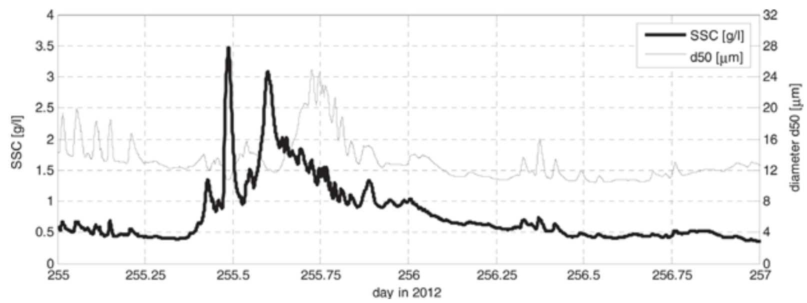

Figure 10. SSC and diameter d_{50} from LISST during a minor suspended sediment transport event (September 12 and 13, 2012). A, B, C and D indicate times at which selected PSDs are plotted in Figure 11.

laboratory analysis of the bottle samples taken by the automatic sampler.

The LISST SSCs lie in reasonable agreement with the reference SSCs in most cases displayed in Figure 9. The LISST SSC tends to be higher than the reference SSC. This can be attributed to the shape effect or overestimations at lower size bins. Deviations between the LISST and the reference SSCs will be further analyzed. Typical daily patterns of SSC (from glacier melt), SSC peaks induced by precipitation events and periods of relatively low SSC are seen in Figure 9.

Figure 10 shows a detail of two selected days of the SSC time series from Figure 9, corresponding to September 12 and 13, 2012. During approximately one day, the SSC rose from 0.5 to 3.5 g/l and fell back to the initial level. The thin line in Figure 10 shows the time-series of the d_{50} of the particles measured by LISST (right axis).

The d_{50} increased from about 12 to 24 microns and fell back to the initial level. Interestingly, the peak in d_{50} occurred some six hours after the SSC peak. A physical reason for this could be that finer particles are transported before coarser ones. Before and after the period of increased SSC, however, peaks of SSC and d_{50} occurred simultaneously (in the time range of Fig. 10). The sediment dynamics in the free surface tunnel including in- and outflowing discharge and water level will be further analysed.

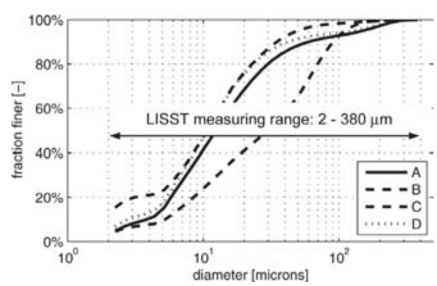

Figure 11. Selected PSDs obtained from LISST, at times specified in Figure 10.

In the rising limb of the SSC curve the d_{50} curve dips during SSC peaks. This can be partly real and partly an effect of overestimation at lower size bins (see curve B in Fig. 11). The cross-correlation between d_{50} and SSC will be further analysed.

Figure 11 shows four selected PSDs measured by LISST; (A) and (D) before and after the SSC peak, (B) at the SSC peak and (C) at the d_{50} peak. Whereas curves A, B and D are comparable, curve C indicates a considerably coarser particle distribution (in the range below 100 microns). Overestimation at lower size bins can lead to PSDs which do not depart from zero at the lower end of the size measuring range (especially curve B). Corrections to reduce overestimation of concentrations at lower size bins in LISST measurements will have to be further studied.

4.2.2 *Turbidimeters*

Figure 12a shows the time series of turbidity measured by *TurbiScat* at 90° in comparison to SSC measured by LISST (as in Fig. 10). This in-line turbidimeter (without wiper) was affected by bio-fouling and deposition of particles on the window of the flow-through cell even though the water temperature did never exceed 2°C. The raw data recorded at this device show a general temporal increase (trend) of turbidity from the installation in early summer (correct measurement with clean window) to the beginning of the winter season (increasingly biased measurement). This trend, however, is not continuous since manual flushing of the sampling pipe was done occasionally, leading to offsets in the recordings. The turbidity time series shown in Figure 12a was de-trended (by 40 FNU per day). The unknown offset in the turbidity time series could not be removed. With the selected scaling of the turbidity axis in Figure 12a a relative comparison with the LISST SSC is however possible.

The turbidity time series matches reasonably with that of LISST SSC until September 12 at 6 p.m. (day 255.75). Then, the turbidimeter data deviate from the LISST data as the first do not fall back completely to the level before the sediment transport peak. This remaining offset is attributed to the deposition of particles and bio-fouling on the window in the flow-through cell of the in-line turbidimeter.

4.2.3 *Acoustic system*

Figure 12b shows the time-series of the relative attenuation A_r from the acoustic method again in comparison to SSC measured by LISST (as in Fig. 10). A_r can be used to derive an SSC-estimate. With an appropriate scaling A_r is generally well in line with the LISST data. Peaks measured by the acoustic method are less pronounced compared to the LISST measurement. LISST SSC peaks may be overestimated due to overestimation at lower size bins.

In Figure 12b, during some hours around September 12, 6 p.m. (day 255.75), the offset between the two curves is slightly different compared to the rest of the time. This is attributed

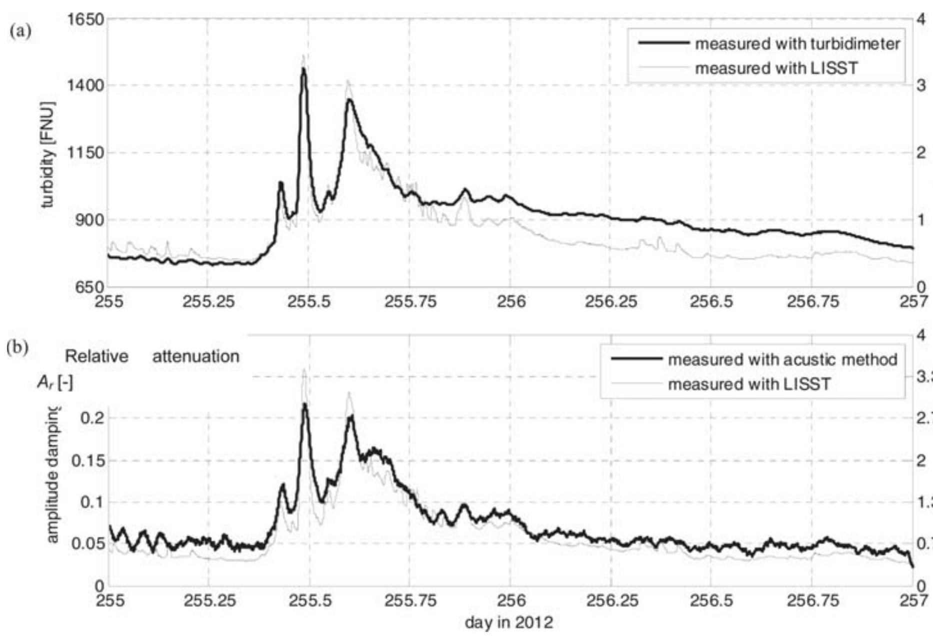

Figure 12. Measurements of (a) in-line turbidimeter (*TurbiScat, 90°)* and (b) relative attenuation A_r obtained from acoustic method, both in comparison to SSC measured by LISST (right axes), from September 12 to 13, 2012.

to effects of varying particle size (compare d_{50} in Fig. 10) and can be observed accordingly for the turbidimeter in Figure 12a.

The good temporal correlation between A_r and LISST data also indicates that the sampling pipe was not clogged and the sediment-laden water measured at the end of the sampling pipe differs not much from the water in the penstock.

The field data on acoustics (Fig. 12b) cannot directly be compared to the laboratory data (Fig. 7), since the path lengths are different. The attenuation of ultrasonic pulses due to the particles shall be normalized considering the length of the acoustic path.

5 CONCLUSIONS

The calibration and measuring range of various optical and acoustic devices for SSM were assessed in the laboratory using different types of mineral particles in a range of concentrations and selected results were presented in the first part of this paper.

It was found that turbidimeters have to be calibrated for each device and each type of particles. This requires quite an effort. Such fixed calibrations may lead to considerable uncertainties in SSC measurements if the particle properties vary in time. The acoustic method seems to be less sensitive to particle size and shape.

The LISST allows measuring SSC and PSD of particles in the range of medium silt to fine sand. SSCs obtained from LISST showed generally good agreement with reference SSCs if the particle shape does not differ considerably from the rounded or slightly angular particle shape assumed in the current inversion procedure. The existence of mica with a flaky shape or strongly angular particles may lead to a considerable overestimation of SSC.

The operating range of the used *LISST-100X* with the strongest available 90% path reduction module is limited to a few g/l of the used mineral powders with d_{50} in the range of coarse silt. Another model of in-situ laser diffractometers with automatic dilution (*LISST-Infinite*) would allow measuring up to 90 g/l according to the supplier's specifications.

In the second part of this paper the installation of the devices for SSM at the study HPP in the Swiss Alps was described and examples of the field data on SSM were given. The presented data from late summer 2012 cover "normal" suspended sediment transport conditions with glacier melt and an example of a suspended sediment transport event.

In the presented period the LISST provides reasonable estimates of SSC when compared to reference SSCs obtained from bottle samples. SSM based on laboratory analysis of occasionally taken bottle samples would not be sufficient to capture the SSC dynamics in this environment. In the example data, coarser particles were observed in conjunction to an SSC peak. A time shift between the peaks in SSC and d_{50} was observed. In the present research project information on PSD is important as it is a decisive parameter for turbine wear. LISST offers the great advantage to collect information on PSD with high temporal resolution directly at the study site.

For turbidimeters, models with a wiper or no window in contact to the sediment-laden water are advisable to use, even in cold and nutrient-poor water, in order to avoid effects of bio-fouling and deposition of particles in the instrument optics. Frequent manual cleaning (with opening of the flow cell) is not practical and flushing with temporarily increased discharge is not sufficient. With the relatively moderate variation in average particle size during the presented suspended sediment event of small extent, a turbidimeter with a fixed custom calibration is able to provide reasonable estimates of SSC. With stronger variations of particle size, however, larger errors in SSC estimates have to be expected according to the laboratory investigations.

Using ADM systems for SSM is an interesting option for operators of hydraulic schemes at which relatively high SSC occur. No requirement for additional hardware and sampling pipes and the direct measurement of path-averaged values in the waterway are practical advantages of SSM monitoring based on ADM installations. However, with the current state of research, a site-specific calibration for time-averaged particle properties is required in order to convert the measured values in g/l (as for turbidimeters). For qualitative warnings of high SSC events to operators of hydraulic schemes no conversion to g/l is required. Since this acoustic method is not suitable to measure SSC below approx. 0.5 g/l a combination with an optical device can be advantageous.

6 OUTLOOK

The measurements at the study HPP will be continued and the installations will be extended (e.g. turbidimeter and automatic water sampler at the intake) and modified based on the first year's experiences.

The data from the laboratory measurements and the field including a major flood event with measured SSC in the range of 50 g/l in July 2012 will be further evaluated. The laboratory analysis of on-going water sample collection will be used for the interpretation and calibration of the recorded data in order to estimate the sediment flux in the penstock and the abrasion potential (considering particle size and particle hardness based on mineralogical composition).

In view of the damages observed on the turbine runners after a major flood event the option of temporary turbine shutdowns for some hours during significant sediment peaks will be further investigated towards the determination of economically balanced switch-off criteria based on SSC and possibly PSD.

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REFERENCES

Abgottspon, A. 2011. Messung abrasiver Partikel in Wasserkraftanlagen. *Master thesis* (unpublished, in German), Hochschule Luzern, CC Fluid Mechanics and Hydro Machines, Lucerne, Switzerland.

Agrawal, Y.C. & Pottsmith, H.C. 2000. Instruments for particle size and settling velocity observations in sediment transport, *Mar. Geol.* 168: 89–114.

Agrawal, Y.C., Whitmire, A., Mikkelsen, O.A. & Pottsmith H.C. 2008. Light scattering by random shaped particles and consequences on measuring suspended sediments by laser diffraction, *Journal of Geophysical Research* 113.

Agrawal Y., Mikkelsen, O.A. & Pottsmith, H.C. 2011. Sediment monitoring technology for turbine erosion and reservoir siltation applications. *Proc. Hydro 2011 Conference*, Aqua-Media Intl. Ltd., Prague, Czech Republic.

Agrawal, Y., Mikkelsen, O.A., Pottsmith, H.C. & Slade, W.H. 2012. Turbine abrasion: one year's experience in real-time sediment monitoring at Hidroagoyan HPP, Ecuador. *Proc. Hydro 2012 Conference*, Aqua-Media Intl. Ltd., Bilbao, Spain.

Andrews, S.W., Nover D.M., Reuter J.E. & Schladow S.G. 2011. Limitations of laser diffraction for measuring fine particles in oligotropic systems: Pitfalls and potential solutions. *Water Resources Research*, 47.

Bishwakarma, M.B. & Støle, H. 2008. Realtime sediment monitoring in hydro-power plants. *Journal of Hydraulic Research* 46(2): 282–288.

Boes, R. 2009. Real-time monitoring of SSC and PSD in the headwater way of a high-head hydropower plant. *Proc. 33rd IAHR Congress*, Vancouver, Canada: 4037–4044.

Costa, I., Storti, G., Lüscher, B., Gruber, P. & Staubli, T. 2012. Influence of solid particle parameters on the sound speed and attenuation of pulses in acoustic discharge measurements (ADM). *Journal of Hydrological Engineering,* 17(10): 1084–1092.

Felix, D., Albayrak, I., Abgottspon, A., Boes, R. & Gruber, P. 2012. Suspended Sediment and Pelton Turbine Wear Monitoring: Experimental Investigation of various Optical and Acoustic Devices and Beginning of the Case Study at HPP Fieschertal. *Proc. 17th International Seminar on Hydropower Plants*. Vienna: 483–494.

Gippel, C.J. 1995. Potential of turbidity monitoring for measuring the transport of suspended solids in streams. *Hydrological Processes* 9: 83–97.

Habersack, H., Haimann, M., Kerschbaumsteiner, W. & Lalk, P. 2008. Schwebstoffe im Fliessgewässer, *Leitfaden zur Erfassung des Schwebstofftransportes*. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft BLFUW (Hrsg.), Wien, Österreich (in German).

Jenzer Althaus, J. 2011. Sediment evacuation from reservoirs through intakes by jet induced flow. *Dissertation Thesis*, Communication Nr. 45 (A. Schleiss, ed.), LCH, EPF Lausanne, Switzerland.

Skripalle, J., Hies, T., Liu, Y. & Nguyen, H.H. 2012. Application of multi-frequency acoustics to estimate concentration of suspended sediments from Jurong Lake, Singapore. *Proc. 17th International Seminar on Hydropower Plants*. Vienna: 725–736.

Spraefico, M., Lehmann, C., Jakob, A. & Grasso, A. 2005. Feststoffbeobachtung in der Schweiz—Ein Tätigkeitsgebiet der Landeshydrologie. *Berichte des BWG*, Serie Wasser Nr. 8, Bern (in German).

Winkler, K., Dekumbis, R., Rentschler, M., Parkinson, E. & Garcin, H. 2011. Understanding hydro-abrasive erosion, *Proc. Hydro 2011 Conference*, Aqua-Media Intl. Ltd., Prague, Czech Republic.

Wren, D., Barkdoll, B., Kuhnle, R., & Derrow, R. 2000. Field Techniques for Suspended-Sediment Measurement. *Journal of Hydraulic Engineering*, 126(2): 97–104.

Measuring suspended sediment: results of the first year of the case study at Fieschertal in the Swiss Alps

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Rivers and waterways may transport large quantities of suspended sediment that can cause severe damages to turbines of hydropower plants (HPP) and lead to reservoir sedimentation. To mitigate these negative effects, continuous and real-time suspended sediment monitoring (SSM) is required. In a research study at the HPP Fieschertal, a high-head scheme in the Swiss Alps with a strongly glaciated catchment area and without storage lake, suspended sediment mass concentration (SSC) and particle size distribution (PSD) are measured since summer 2012 using a portable laser diffractometer (LD). PSD is an important parameter for hydro-abrasive erosion and sediment transport or deposition. For comparison, also devices based in simpler measurement principles, such as turbidimeters and an acoustic method based on existing installations for acoustic discharge measurement (ADM) are employed to obtain SSC estimates.
Based on the data recorded at the study HPP, prior laboratory tests of the devices and site-specific time-invariant SSC-calibrations obtained from laboratory analysis of automatically taken bottle samples, time series of SSC and PSD in the turbine water were calculated. The calibration factor for SSC from LD accounts for strongly non-spherical shape of the particles. The results show that not only SSC but also PSD may vary considerably in time. In an example period of ten summer days, with SSC ranging between 0.2 and approx. 10 g/l, the median particle size d_{50} increased occasionally from 12 to approx. 100 μm. Although the transport of coarser particles was observed to be mostly associated with increased SSC, there is a wide scatter in the correlation between SSC and PSD due to a different temporal behavior of SSC and PSD. SSC and PSD depend on meteorological and hydrological processes and also on the operation of the free-surface-flow storage tunnel of HPP Fieschertal.
The turbidimeters, and to a smaller extent also the acoustic method, underestimate SSC if particles are greater than assumed in the time-averaged calibration. At HPPs with existing ADM installation, no additional hardware is required to get estimates of SSC in the penstock by means of the acoustic method. The accuracy of SSC estimates from the acoustic method and turbidimeters decreases as the variability in PSD increases and the PSD variations are not well correlated with SSC. In such environments, LD is recommended for SSM, since actual particle sizes are considered in SSC-estimates and information on PSD with high temporal resolution is provided. Further acoustic systems to measure SSC together with PSD are under development.
The measurements of suspended sediment at HPP Fieschertal will be continued and SSC and PSD data will be further evaluated. The particle load passing the turbines in time intervals between turbine inspections or efficiency measurements will be calculated in order to find correlations between particle load, turbine wear and efficiency which contribute to optimized design and operation of HPPs.
This paper focuses on measurements of suspended sediment, whereas the corresponding paper by Abgottspon et al. (2013b) treats measurements of wear at Pelton buckets and turbine efficiency changes at the same HPP.

1 Introduction

In the design and operation of hydropower plants (HPPs) handling of sediment transported in river water is a major challenge. Siltation of reservoirs and hydro-abrasive erosion at turbines can be economically important issues. In order to improve the understanding of the processes related to hydro-abrasive erosion and to contribute to an appropriate design and operation of HPPs, suspended sediment mass concentration (SSC) and particle size distribution (PSD) have to be measured continuously and in real-time at intakes and/or waterways of HPPs in combination with regular turbine inspections and monitoring of turbine efficiency decrease.
The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich in cooperation with Hochschule Luzern (HSLU) initiated an interdisciplinary research project to investigate the problem of hydro-abrasive erosion on turbines mainly by means of a case study at the existing HPP Fieschertal. It is a high-head scheme located at a

tributary of the upper Rhone River, in the Canton of Valais, in the Swiss Alps. Since the first operation in 1976 severe hydro-abrasive erosion at needles, nozzles and runners of the two 32 MW-Pelton units has been observed. Although coating of turbines parts reduced the extent of annual on-site revision works and increases the time between factory overhauls, sediment handling as well as optimized operation and maintenance of the HPP have remained important economic issues. In the past decades an increased yield of fine sediment has been observed due to glacier retreat and increased variation in precipitation. One operational option studied in this project is to systematically switch-off turbines during suspended sediment peaks if the costs caused by turbine wear exceed the benefits from power sales.

In a first part of this research project various devices for SSM as described in section 2 were tested in a mixing tank in the hydraulic laboratory of HSLU using suspensions made of mineral particles. This allowed establishing calibration curves for various types of particles and to investigate effects of particles size and shape (Felix et al. 2012). Particle size is a relevant parameter for turbine wear since the hydro-abrasive erosion potential is higher for coarser grains at given SSC (e.g. Winkler et al. 2011). In a second part of this on-going project, these devices were installed in the case study HPP (Fig. 1) for continuous SSM. In parallel periodical turbine inspections are made and turbine efficiency is monitored.

In this paper, methods and selected results of suspended sediment measurements of the year 2012 at this HPP are presented. Project components related to SSM are highlighted in Figure 1. The corresponding paper by Abgottspon et al. (2013b) describes methods to quantify wear at buckets of Pelton turbines and efficiency changes, and first results from the same case study HPP. Further results of this study were presented by Abgottspon et al. (2013a).

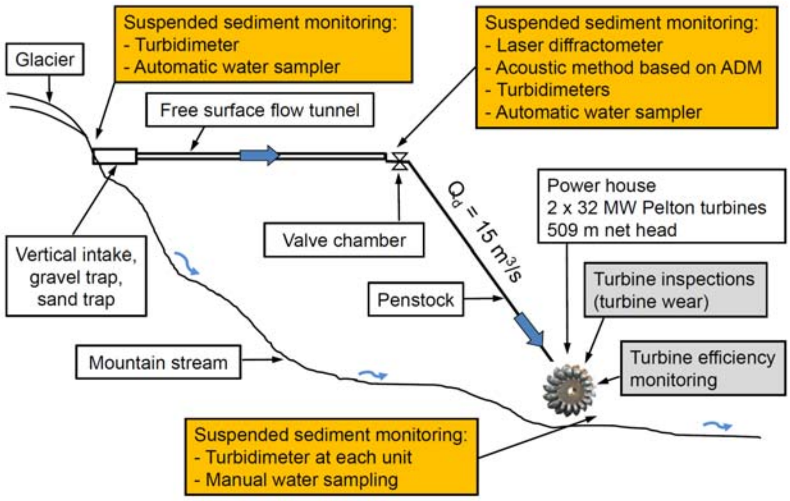

Fig. 1: Schematic longitudinal profile of the Case Study HPP Fieschertal

2 Devices used for suspended sediment monitoring

As particle size is an important parameter for turbine wear, a portable laser diffractometer (LD), which provides not only information on SSC but also on PSD was employed (item 6 in Table 1). For the use in HPPs specific models of LD devices were developed (Agrawal et al. 2012). In this project a multi-purpose model, as used in marine science and limnology, was used. In order to extend the range of measurable SSC the optical path length of the LD was reduced from 50 mm to 5 mm by insertion of a glass cylinder (90 percent path reduction module). The used LD has a nominal particle size measuring range from 2 to 380 µm in the calculation mode for so called 'random shaped' particles, which are according to Agrawal et al. (2008) particles with an irregular surface and no preferred axes (no elongated or platy particles). The working principle of LD is based on the inversion of a scattering pattern, which, in the portable LD device used here, is measured at small angles (up to approx. 10 degrees, Agrawal et al. 2008). Similar LD devices are used for SSM at a few HPPs so far (Boes 2009, Agrawal et al. 2012).

For comparison and in view of the acquisition costs, also devices for SSC estimates based on simpler measurement principles, such as tubidimeters and an acoustic system, were included in the study. Two models of submerged turbidimeter probes as mainly used in waste water treatment plants (items 1 and 2 in Table 1), two in-line turbidimeters measuring in flow-cells on a pipe as mainly used in the process industry (items 3 and 4 in Table 1) and one turbidimeter measuring at a free falling jet are employed (item 5 in Table 1). Turbidimeters measure either the back-scattering of light from suspended particles (e.g. at 90 degrees) or the attenuation of light through the suspension (optical transmission). Turbidimeter data are usually converted to SSC with a linear and time-invariant calibration curve. Turbidimeters are inexpensive and widely used. The major drawback thereby is that their calibration depends strongly on particle properties, mainly particle size (e.g. Gippel 1995, Wren et al. 2000).

The acoustic method for SSM used in this project (item 7 in Table 1) is based on existing acoustic discharge measurement (ADM) installations. ADM is widely used at waterways of HPPs. In ADM, ultrasonic pulses are sent from one transducer through the water and are received by a transducer at the other end of the path (Fig. 2). For the basic task of an ADM, i.e. the calculation of discharge based on flow velocity, differences in transit time of acoustic pulses travelling in and counter flow direction are measured. For SSM, one possibility is to use the additional attenuation of the received signals caused by suspended sediment particles. The correlation of attenuation of forward scattered ultrasonic signals and SSC has been investigated in recent laboratory tests at HSLU using transducers that are similar to those in ADM installations (Costa et al. 2012, Felix et al. 2012). At HPP Fieschertal a 4 path arrangement (2 crossed path of 2.27 m length in two horizontal layers) operated at 1 MHz is available at the top of the penstock. In the software of the ADM controller the amplitudes of the received signals at the four paths were defined as additional output parameters and no additional hardware had to be installed for SSM.

Table 1: Devices used for continuous suspended sediment monitoring (SSM)

Device type		Item No.	Device model and manufacturer	Device output and measuring principle	Derived parameters	Installed at
Turbidimeter, submerged, with wipers		1)	*Turbimax W CUS41* Endress-Hauser	Turbidity [FNU] from backscatter	SSC	Intake
		2)	*Solitax ts-line sc* Hach-Lange	Turbidity [FNU] from backscatter	SSC	Tailrace channels
Turbi-dimeter, in-line	Pressure flow (in flow-cells without wipers)	3)	*TurbiScat (90°, 25°)* Sigrist Photometer	Turbidity [FNU] from backscatter	SSC	Valve chamber, at the inlet to the penstock
		4)	*TF16-N with F20* Optek Danulat	Turbidity [CU] from transmission	SSC	
	Free falling jet	5)	*AquaScat* Sigrist Photometer	Turbidity [FNU] from backscatter	SSC	
Portable laser diffractometer (LD)		6)	*LISST-100X, Type C* Sequoia Scientific	Volume concentrations in 32 size classes [ppm]	SSC and PSD	
Acoustic method (based on existing ADM installation)		7)	*Risonic Modular* Rittmeyer	Received amplitude [V] forward scattering	SSC	

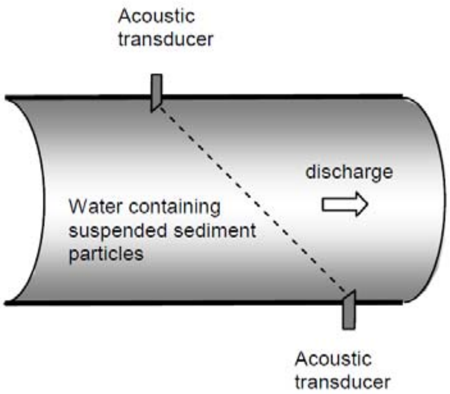

Fig. 2: Schematic of penstock with an acoustic path of an ADM installation, which can also be used for estimating suspended sediment concentration

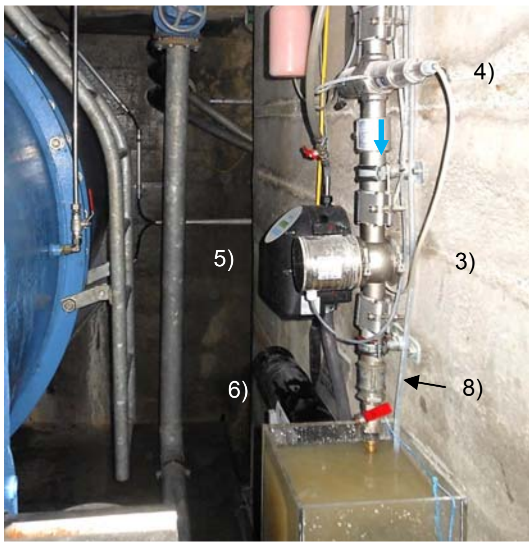

Fig. 3: Optical devices for continuous suspended sediment monitoring installed in the valve chamber of HPP Fieschertal; numbers 3 - 6 refer to items in Table 1

The devices for SSM were installed at the study HPP in summer 2012 (locations see Tab. 1 and Fig. 1), except items 1 and 5, which were added in 2013. Most of the devices are placed in the valve chamber at the top of the penstock (Fig. 3). The turbidimeters are installed at a sampling pipe fed from the penstock, which leads to a bucket with overfall and bottom outlet. The measuring head of the LD is inserted laterally into the bucket and the optical path of the LD is arranged below the end of the pipe. Further information on the devices, the laboratory tests as well as the installation at the study HPP and previous results are described by Felix et al. (2012) and Abgottspon (2011).

3 Method

The LD was programmed to take a measurement every minute whereas the signals of the other devices were recorded every second. The devices and the sampling pipes were checked and flushed regularly.

In addition to the devices for continuous SSM, automatic water samplers are operated in the valve chamber and at the intake, respectively. They are programmed to take samples every three days. In addition to that, the samplers are triggered by signals of turbidimeters at the respective sampler locations in order to increase sampling frequency in case of increased turbidity. The samplers contain each 24 one-litre bottles. The bottles are filled by means of a peristaltic pump. The transparent suction hose of the sampler in the valve chamber can be seen on Figure 3 (item 8). From each bottle sample the SSC (g/l) was determined in the laboratory by weighing before and after drying in an oven, deducting dissolved minerals.

From selected samples the quantitative mineralogical composition was determined using x-ray diffraction (XRD). The samples contain mainly quartz, feldspar and mica, i.e. the main components of granite rock. The solid density of selected samples of mineral particles was determined by means of a gas pycnometer and was found to be close to the density of quartz (2.65 g/cm^3).

The volume concentrations obtained from LD in the three smallest size classes (approx. 2-3 μm, not relevant for turbine wear) were discarded, since these contributions were considered to be overestimated with the prevailing particle mix (compare Andrews et al. 2011, Felix et al. 2013). Since the particle mix at the study site contains angular (not yet rounded by fluvial transport) and flaky (mica) particles, which differ considerably from the particle shape assumed in the LD inversion software (Agrawal et al. 2008), SSC obtained from LD was calibrated based on bottle samples using a constant factor.

The time series from turbidimeters and the acoustic method were also converted to SSC based on time-averaged calibrations from bottle samples. The calibration curves obtained from field data were compared to those from laboratory tests and were found to be within a plausible range.

4 Results and discussion

4.1 Time series of suspended sediment concentration and particle size

From the time series of SSC and median particle size d_{50} in the turbine water of HPP Fieschertal obtained from LD, an extract of ten days during the sediment season is presented in Figure 4. The median particle size d_{50} stands for the diameter of graded particles of which 50 percent by mass are smaller. Whereas the average SSC during this period was 0.5 g/l, periods of increased SSC ranging up to several g/l for some hours occurred (Fig. 4b). Strong SSC increases occur within less than a few hours, decreases however are generally slower; similarly to typical flood hydrographs. Calibrated SSC is in overall good agreement with reference SSCs (circular markers in Fig. 4b).

The median particle size d_{50} had a base level of 12 μm and rose occasionally up to approx. 100 μm (Fig 4a). Periods of increased SSC are mostly associated with the occurrence of coarser particles. The time series of SSC and d_{50} are, however, not synchronous and time shifts among peaks in SSC and d_{50} were observed.

Figure 5 shows a detail with one selected period of increased SSC (suspended sediment transport event), as indicated by the shaded areas in Figure 4. SSC obtained from LD rose from 0.2 g/l to several g/l and fell back to 0.4 g/l (Fig. 5b). The SSC-estimate from LD is supported by one bottle sample. With the particle sizes in this event, LD measurements were possible until approx. 10 g/l and resumed when SSC was falling below approx. 7 g/l.

In Figure 5a, d_{16} and d_{84}, i.e. the sizes of particles of which 16 or 84 percent by mass are smaller, are plotted in addition to d_{50}. The diameters d_{16} and d_{84} are often used in geotechnical and river engineering to characterize the "width", i.e. the so called spreading, of a PSD. d_{84} of up to approx. 200 μm was measured, this is smaller than the classical design grain size for sand traps of 250 to 300 μm. Whereas SSC decayed rather continually after the peak, d_{50} remained at an elevated level until SSC fell back to the base level.

In addition to LD, SSC estimates from the other SSM devices in the valve chamber are displayed in Figure 5b. The turbidimeter signals were de-trended in order to compensate signal drift caused by accumulating contamination of the optical windows in the flow-cells. It turned out that the flow in the flow-cells is not strong enough for self-cleaning and that occasional flushing of the sampling pipe without manual cleaning of the windows in the flow-cells was insufficient to prevent signal drift (Abgottspon et al. 2013a).

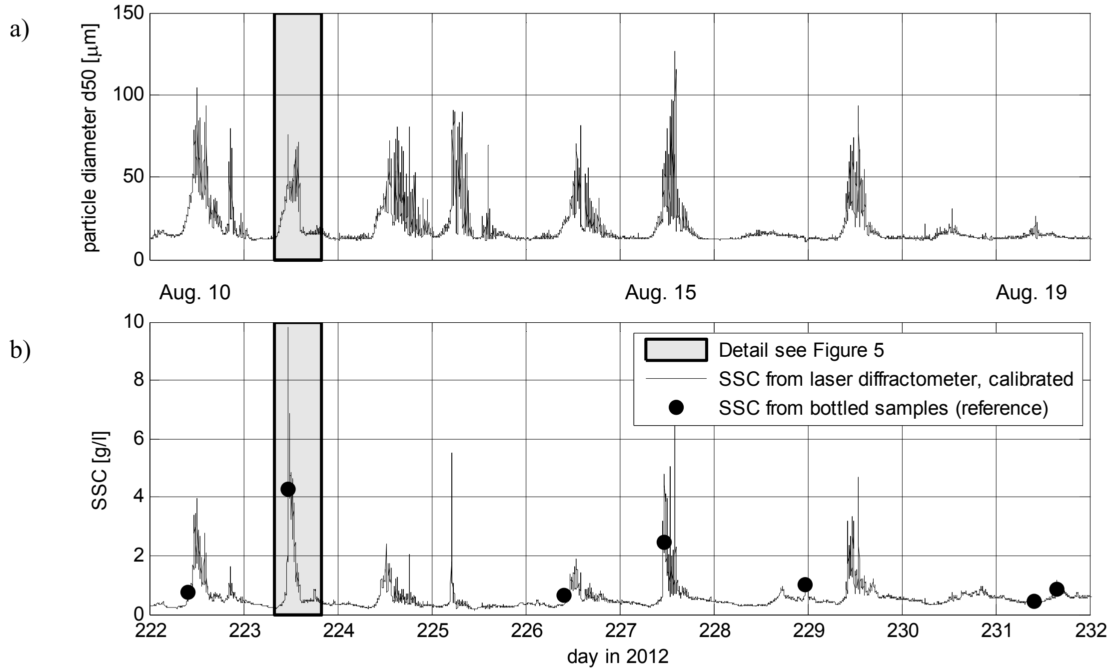

Fig. 4: Time series of (a) d_{50} and (b) SSC in the turbine water obtained from LD after calibration to reference SSCs from bottled samples (circular markers); example of ten days in summer (from August 10 to August 19, 2012)

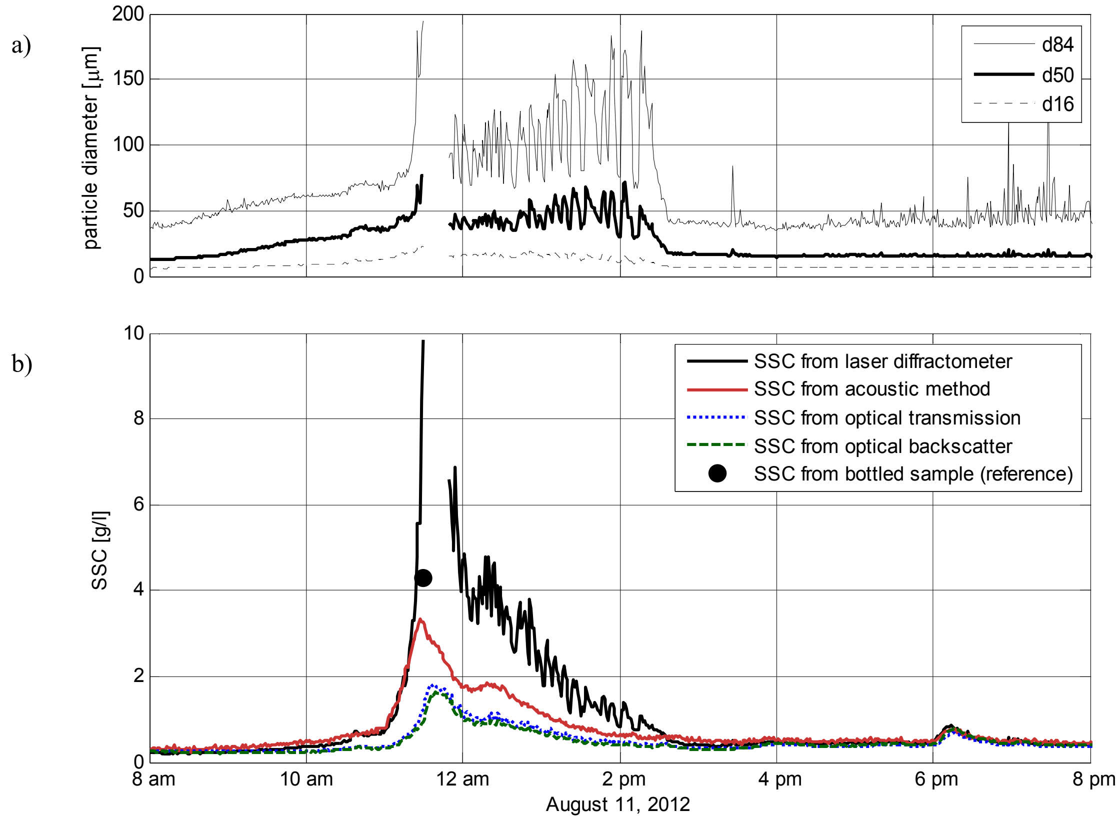

Fig. 5: Detail of half a day out of the time series in Figure 4, additionally including SSC-estimates from the other devices installed in the valve chamber and particle sizes d_{16} and d_{84} (from LD)

Before and after the period of increased SSC all devices yielded similar SSC estimates. During the period of increased SSC, however, the acoustic method and the turbidimeters underestimated SSC, because their calibration is based on the usually prevailing relatively fine particles ($d_{50} \approx 15$ μm) and these devices do not recognize the variation in particle size in contrast to LD. At given SSC, turbidity and attenuation are smaller with coarser particles. The acoustic method is less sensitive to changes in particle size than the used turbidimeters, what was also observed in laboratory experiments (Abgottspon 2011, Felix et al. 2012).

4.2 Correlation of suspended sediment concentration and particle size

As observed from Figures 4 and 5, coarser particles tend to be associated with higher SSC. Figure 6 shows an example of pairs of SSC and d_{50} values obtained from LD during ten summer days from August 10 to 19, 2012 (as in Fig. 4). A positive correlation with a wide scatter can be seen. In that period, SSC above approx. 1.5 g/l were associated with $d_{50} \geq 30$ μm. SSC and d_{50} may be quite independent variables, depending on sediment availability and the processes which govern suspended sediment transport in a specific system.

SSC and PSD depend generally on meteorological and hydrological factors, such as glacier melt, precipitation in form of rain or snow, extent of snow cover in the catchment area, changes of flow paths in the glacier, etc. In the present case, SSC and PSD depend also on the operation of the turbines and the free-surface-flow storage tunnel (Fig. 1) upstream of the measurement location; as observed earlier by the HPP operator and described by Abgottspon (2011). Depending on the turbine discharge and the water level in the storage tunnel, sediment particles settle or are re-suspended, according to the prevailing turbulence and bottom shear stress. If the river flow exceeds the design discharge of the HPP, turbines are run at full load with filled storage tunnel, whereas in other periods the water level and the discharge in the storage tunnel fluctuate due to intermittent part-load operation of the turbines.

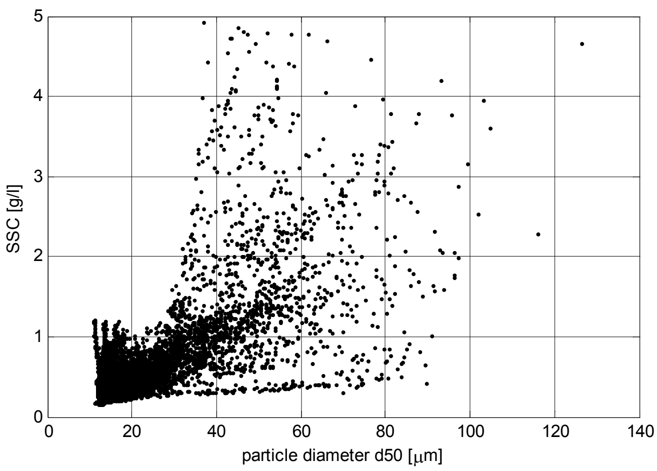

Fig. 6: Correlation of concentration (SSC) and median diameter (d_{50}) of suspended sediment in the turbine water of HPP Fieschertal, example from August 10 to 19, 2012, obtained from LD (SSC calibrated with bottle samples)

5 Conclusions and recommendations

Selected results of concentration and PSD of suspended sediment measured in summer 2012 in the power waterway of HPP Fieschertal, which has a strongly glaciated catchment area and no storage lake, were presented. This gives information on site-specific SSC and PSD ranges of an example period of 10 days in the sediment season (without rare events) and allows also a cross-comparison of the measuring capabilities of the instruments used for SSC-estimates.

The measurements confirm that not only SSC but also PSD can vary considerably in time. In periods of increased SSC coarser particles were transported compared to the conditions before and after such events (positive correlation of PSD and SSC). However, it was observed that peaks of SSC and PSD do not occur simultaneously and that after a SSC-peak particle size did not decrease as quickly as SSC. This different temporal behaviour of SSC and d_{50} contributes to a wide scatter in the correlation of SSC and PSD.

In dynamic sediment environments, where SSC and PSD are quite independent variables, the use of portable LD is recommended. With LD, actually prevailing particle size is considered in SSC measurements and PSDs with high temporal resolution can be obtained, what was previously not affordable with laboratory PSD analysis of bottled samples. The portable LD device is suitable for SSM in the power waterway of HPPs since particles greater than the upper limit of the size measuring range are usually excluded by sand traps. An option to extend the limited range of

measureable SSC is to perform LD measurements on suspension samples that are diluted with clear water at a known mixing ratio (Agrawal et al. 2012).
SSC estimates from methods that are based on simpler measurement principles, such as turbidimeters and the described acoustic system, are biased in periods in which the size of the transported particles differs from that assumed in the calibration. Such methods can be used with good accuracy for SSC estimates in situations where (i) particle size is almost constant over time or (ii) a strong correlation of SSC and PSD exists and is known. In the latter case, a calibration curve which accounts for changes in PSD with increasing SSC has to be used. Correlations between SSC and PSD can be investigated using portable LD for some period at a certain measurement location. If turbidimeters and the described acoustic system are used in situations with no clear correlation of SSC and PSD, temporarily biased SSC estimates and less accuracy have to be accepted.
If turbidimeters are used, it is highly recommended to select models which have an automatic cleaning system (wiper or pressurized air) or measure turbidity at a free falling jet, in order to prevent signal drift and the need of frequent manual cleaning, even in cold waters of mountain streams, were little bio-fouling may be expected. In contrast to the acoustic method, turbidimeters are suitable for measuring low SSCs (e.g. < 0.2 g/l).
The acoustic system described here showed less sensitivity to variations of particle size than the investigated turbidimeters. Since the measurements are performed directly in the penstock, no sampling pipe is required that could be clogged or lead to non-representative sampling. Measurements are averaged over the path length and several paths over the cross-section of the penstock can be considered. Using the existing installation at the study HPP measurements up to several 10 g/l were possible. No maintenance (cleaning of the sensors) is required. If no information on actually prevailing PSD is required, this method lends itself particularly for HPPs with an existing ADM installation, since in these cases no additional hardware is required for SSM. The obtainable accuracy in SSC estimates depends on the temporal variability of PSD or its correlation with SSC at a given site.

6 Outlook

The measurements of suspended sediment at HPP Fieschertal will be continued. SSC and PSD will be further evaluated seasonally and event-based. The correlation of SSC and PSD time series will be further investigated and duration curves will be produced.
SSC and PSD time series based on LD will be used to calculate the so called 'particle load' that was passing the turbines in time intervals between turbine inspections or efficiency measurements. According to IEC Standard 62364 (2013), particle load is defined as the integral of the product of SSC and weighting factors for particle size, shape and hardness over time.
Regarding SSM using acoustics, methods and systems that allow estimating both SSC and PSD are being investigated and various attempts have been made (e.g. Thorne et al. 2007, Moore 2011, Skripalle et al. 2012). The joint determination of SSC and PSD is physically not possible using one frequency. Therefore, multi-frequency approaches are investigated. With forward scattering (as described above), the use of multiple frequencies is limited due to the small frequency sensitivity of the damping in the particle size and concentration range of interest. If however backscattered signals are used a stronger frequency dependency can be observed, which can be exploited for estimating particle size and SSC simultaneously, although one has to deal with much lower signal levels. The low signal-to-noise ratio of the backscattered signals poses a big challenge for estimating PSD and SSC from the recorded signals (inversion of the backscattering process). HSLU in collaboration with ETH Zurich is currently analysing various analytical models predicting backscattered signals. Having once identified the best suited model for the application range, the ill-posed inversion problem in a noisy environment will be tackled. It is planned to verify the applicability and accuracy of such an approach by experimental investigations at HSLU.
Besides SSM, measurements of turbine wear and efficiency (see Abgottspon et al. 2013b) will be continued. Data on suspended sediment, turbine wear and turbine efficiency will be evaluated to find correlations which contribute to the development of respective prediction formulas and to determine economically balanced criteria for temporary turbine switch-offs during suspended sediment peaks.

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References

1. **Abgottspon A.** 2011. Messung abrasiver Partikel in Wasserkraftanlagen. *Master thesis* (unpublished, in German), Hochschule Luzern, CC Fluid Mechanics and Hydro Machines, Lucerne, Switzerland.
2. **Abgottspon A., Staubli T., Felix D., Albayrak I., Boes R.M.** (2013a). Hydro-abrasive Erosion of Pelton buckets and Suspended Sediment Monitoring. *Proc. Hydrovision International* 2013, Denver, USA.
3. **Abgottspon A., Stern P., Staubli T., Felix D., Winkler K.** (2013b). Measuring Turbine Abrasion and Efficiency Decrease: first Results of the Case Study at HPP Fieschertal. *Proc. Hydro 2013 Conference*, Innsbruck, Austria.
4. **Agrawal, Y.C., Whitmire, A., Mikkelsen, O.A. & Pottsmith H.C.** 2008. Light scattering by random shaped particles and consequences on measuring suspended sediments by laser diffraction, *Journal of Geophysical Research* 113, C04023.
5. **Agrawal Y., Mikkelsen O.A., Pottsmith H.C. & Slade W.H.** 2012. Turbine abrasion: one year's experience in real-time sediment monitoring at Hidroagoyan HPP, Ecuador. *Proc. Hydro 2012 Conference*, Aqua-Media Intl. Ltd., Bilbao, Spain.
6. **Andrews S.W., Nover D.M., Reuter J.E. & Schladow S.G.** 2011. Limitations of laser diffraction for measuring fine particles in oligotropic systems: Pitfalls and potential solutions. *Water Resources Research*, 47, W05523.
7. **Boes R.M.** 2009. Real-time monitoring of SSC and PSD in the headwater way of a high-head hydropower plant. *Proc. 33rd IAHR Congress*, Vancouver, Canada: 4037–4044.
8. **Costa I., Storti G., Lüscher B., Gruber P. & Staubli T.** 2012. Influence of solid particle parameters on the sound speed and attenuation of pulses in acoustic discharge measurements (ADM). *Journal of Hydrological Eng.*, 17(10): 1084–1092.
9. **Felix D., Albayrak I., Abgottspon A., Boes R.M & Gruber P.** 2012. Suspended Sediment and Pelton Turbine Wear Monitoring: Experimental Investigation of various Optical and Acoustic Devices and Beginning of the Case Study at HPP Fieschertal. *Proc. 17th International Seminar on Hydropower Plants*. Vienna: 483-494.
10. **Felix D., Albayrak I., Boes R.M.** 2013. Laboratory Investigation on measuring Suspended Sediment by portable Laser Diffractometer (LISST) focussing on Particle Shape. *Geo-marine Letters*: accepted.
11. **Gippel C.J.** 1995. Potential of turbidity monitoring for measuring the transport of suspended solids in streams. *Hydrological Processes 9*: 83–97.
12. **IEC 62364**. 2013. Hydraulic machines - Guide for dealing with hydro-abrasive erosion in Kaplan, Francis and Pelton turbines, Edition 1.0 (June 2013), *International Electrotechnical Commission*, Geneva, Switzerland.
13. **Moore S.A.** 2011. Monitoring flow and fluxes of suspended sediment in rivers using side-looking acoustic Doppler current profilers. *Dissertation*, Université de Grenoble, France.
14. **Skripalle J., Hies T., Liu Y. & Nguyen H.H.** 2012. Application of multi-frequency acoustics to estimate concentration of suspended sediments from Jurong Lake, Singapore. *Proc. 17th International Seminar on Hydropower Plants*. Vienna: 725-736.
15. **Thorne P.D., Agrawal Y.C., Cacchione D.A.** 2007. A Comparison of Near-Bed Acoustic Backscatter and Laser Diffraction Measurements of Suspended Sediments, *IEEE Journal of Oceanic Eng.*, 32(1): 225-235.
16. **Winkler K., Dekumbis R., Rentschler M., Parkinson E. & Garcin H.** 2011. Understanding hydro-abrasive erosion, *Proc. Hydro 2011 Conference*, Aqua-Media Intl. Ltd., Prague, Czech Republic.
17. **Wren D., Barkdoll B., Kuhnle R., & Derrow R.** 2000. Field Techniques for Suspended-Sediment Measurement. *Journal of Hydraulic Eng.*, 126(2): 97–104.

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ORIGINAL

Laboratory investigation on measuring suspended sediment by portable laser diffractometer (LISST) focusing on particle shape

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Abstract This paper deals with a laboratory investigation on measuring suspended sediment volume and mass concentration (SSC) and particle size distribution (PSD) by a portable submersible laser diffractometer (*LISST-100X*) focusing on effects of particle shape and inversion modes on the results. Experiments were carried out in a mixing tank using suspensions of glass beads, fine quartz sand, feldspar and mica powder particles of spherical, rounded, angular and flaky shapes respectively, at various SSCs. SSCs and PSDs measured by LISST were compared to SSCs from gravimetric analysis and to PSDs obtained from image analysis of dry particles and from a non-portable laser diffractometer. Experiments using spherical and rounded particles showed that LISST with the corresponding inversion modes, i.e. spherical and 'random shaped', provides PSD and SSC values similar to reference methods. For angular and flaky particles, however, SSCs were found to be overestimated by factors of 1.5 and 8 respectively. Measurements in a mixture of 70% feldspar and 30% mica powders showed that the SSC overestimation factor for mixed particle-type suspensions can be predicted as the weighted sum of the SSC factors of the components and their mixing ratio. For known highly non-spherical particle types, LISST SSCs can be corrected by a gravimetrically determined or predicted overestimation factor. Moreover, correction of overestimated contributions of lower size bins, the range of measureable SSC and time averaging of LISST measurements are addressed. Further investigations are necessary to assess effects of non-spherical particles and mixtures of various particle types on LISST SSC and PSD estimates.

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Introduction

Monitoring of suspended sediment mass concentration (SSC) and particle size distribution (PSD) is important for improved understanding and management of sediment-related processes in natural aquatic systems such as rivers, lakes, estuaries and seas, and at hydraulic schemes for hydropower, irrigation or flood protection. An overview of methods for measuring suspended sediment is given by Wren et al. (2000). Pumped or manual bottle sampling is a discontinuous technique with poor temporal resolution. Samples have to be transported to a laboratory, where SSC is determined by weighing of oven-dried residues (gravimetric analysis) and PSD by sieving, hydrometer or pipette analysis (Konert and Vandenberghe 1997), image analysis or laser diffraction (LD). Such sampling is costly, not practical and insufficient to capture the dynamic processes of sediment mobilization, transport, deposition and re-suspension in field conditions. Hence, practical systems for continuous measurements, preferably in real time, are required.

Among the techniques employed for such measurements, turbidimeters are the most common with the drawback of a particle size-dependent calibration leading to significant errors in SSC estimates in environments where PSD considerably varies in time and is not well correlated with SSC. Similarly, acoustic systems using one frequency are also affected by particle size. Multi-frequency acoustic devices to determine SSC and PSD are under development (e.g. Thorne et al. 2007; Skripalle et al. 2012). Since 1995, portable and submersible LD devices, from which both SSC and PSD estimates can be obtained, are available for field studies (known as 'laser in-situ scattering and transmissiometry', LISST). Such devices are mainly used in marine research (e.g. Bowers and Braithwaite 2012; Fettweis et al. 2012). Since a few years, their use has been extended to suspended sediment measurements in the context of turbine wear (e.g. Boes 2009, Agrawal et al. 2012) and reservoir sedimentation (e.g. Haun et al. 2013). LISST has the advantages of yielding particle volume concentration (PVC), which is converted to SSC using particle density, theoretically without effect of particle size, and PSDs with high temporal resolution (approx. 1 Hz).

LD has been used for decades and is widely accepted in industry and research for particle size analysis in laboratories. In the technique of LD, measured data on scattering and transmission are inverted to obtain PSD and PVC by an algorithm (kernel matrix), which is usually based on the assumption that particles have spherical shape (Mie solution to Maxwell equations). More recently, an additional inversion mode for so-called random shaped particles was developed by Agrawal et al. (2008) and added to the LISST software for data analysis. Agrawal et al. (2008) stated that the term ‘random’ refers to particles with no preferred axes, and clarified that elongated and platy particles were not considered. Although the latter particle types exist in natural environments, no specific inversion mode is available yet to the knowledge of the present authors. The literature review given in Agrawal et al. (2008) indicates a lack of experimental investigations on effects of highly non-spherical particle shapes on PSD and especially on SSC estimates from LD.

In the study reported here, effects of particle shape, inversion modes and mixture of particle types on LISST SSC and PSD estimates and on the SSC-measuring range are addressed by an experimental investigation using a *LISST-100X*. A series of experiments with suspensions made of water and four types of mineral particles varying in shape (glass beads, fine quartz sand, feldspar and mica powder) was carried out in a mixing tank. This laboratory investigation was an initial part of a research project on suspended sediment monitoring in the context of hydro-abrasive wear at turbines in hydropower plants (Felix et al. 2012, 2013) initiated by the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of the Swiss Federal Institute of Technology, ETH Zurich in collaboration with Hochschule Luzern, Competence Centre for Fluid Mechanics and Hydro Machines.

Materials and methods

Mineral particles

The mineral particles used in this laboratory investigation were selected with reference to a case study site in the Swiss Alps, where suspended sediment consists of mainly quartz, feldspar and mica particles, i.e. the main components of granite rock. In the upper reaches of mountain streams, especially from glaciated catchment areas, suspended mineral particles have typically angular shape, as opposed to downstream sites where particles tend to be more rounded due to fluvial transport. The basic particle shape depends on mineral properties, such as the characteristic layer structure of mica that generates platy particles.

This paper covers investigations using four types of particles listed in Table 1 and shown in Fig. 1. The particles were purchased from commercial applications. Glass beads were chosen as a reference due to their ideal shape. Since the water at the study site comes from a highly glaciated catchment area and has a temperature of less than 5 °C throughout the year, no organic particles were studied. The density of the selected particle types was measured using a gas expansion pycnometer. Particle shapes are seen from Fig. 1. All four types of particles have whitish color.

Definitions of particle sizes and shape

When considering non-spherical particles, the parameterization of particle size and shape in three-dimensional space is not evident. An approach described by Nichols (2009) is adopted here. A particle is characterized firstly by the three dimensions of an enveloping cuboid and secondly by the degree of rounding of its primary shape. The longest, the intermediate and the shortest diameter of a particle are denoted by a, b and c respectively, where c is measured perpendicular to the longest diameter and b is measured perpendicular to a and c. The aspect ratios b/a and c/b (ranging between 0 and 1) indicate the basic particle shape, which can be cubic (equant), platy (discoid, flaky), blade- or rod-like. The volume-equivalent sphere diameter d_{es} serves as a simple and comparable parameter for the size of non-spherical particles.

Additionally, the Sauter mean diameter (SMD), defined as 6 times the volume divided by the surface area of an ensemble of particles, is used when the specific area of graded, especially non-spherical particles is relevant. For non-graded spheres SMD corresponds to the sphere diameter.

Instrumentation and experimental setup

A portable submersible LD device, a *LISST-100X*, Type C (from Sequoia Scientific, Inc., Bellevue, WA) was used. Its optical path length was reduced from 50 mm to 5 mm by insertion of a 90% path-reduction module (glass cylinder) to extend the range of measurable SSC. The principles of LD, the construction of LISST instruments, and the mathematical approach used in the data treatment and analysis are described in Agrawal and Pottsmith (2000). In the present study the two inversion modes available with LISST are referred to as IMS for spherical and IMR for ‘random shaped’ particles. The nominal range of measurable particle sizes of this device is 2.5 to 500 μm for IMS, and 1.9 to 381 μm for IMR (Sequoia

Table 1 Properties of mineral particles

Particle type (material and grading)	Shape (qualitative)	Description	Density (g/cm^3)
Glass beads	Spherical, smooth		2.423
Quartz fine sand	Irregular, rounded	Natural, washed (no fines)	2.658
Feldspar powder (Na-plagioclase)	Elongated, angular	Milled	2.648
Mica powder (muscovite)	Flaky, not rounded	Milled, typical mica structure	2.856

2011). LISST yields PVCs in 32 log-spaced size bins. Cumulative PSD is calculated from the contribution of each size bin. SSC is obtained by multiplying the sum of the PVCs with the particle density, which has to be either known a priori or measured by another device.

Measurements were carried out on suspensions prepared in a mixing tank shown in Fig. 2 as used previously by, for example, Abgottspon (2011) and Costa et al. (2012). The tank (2.12 m long and 1.13 m wide) is equipped with a central stirrer running at about 300 revolutions per minute, resulting in highly turbulent flow conditions to prevent particles from settling. This relatively big tank allowed accommodating a set of instruments. The LISST was mounted horizontally at 60% of the water depth above the tank invert, with the laser beam approx. 0.2 m off the wall. A pump line, connected to the tank for simultaneous testing of in-line turbidimeters, contributed to mixing in the tank.

Experimental procedure

Five series of measurements were carried out at increasing SSCs. While in four series single types of particles as listed in Table 1 were used, 70% feldspar and 30% mica powders were mixed for the last series (mixing ratio according to mass). From many possibilities of mixed particle-type experiments, a mixture of feldspar and mica was chosen with regard to the study site, where mainly angular particles (quartz and feldspar) and up to 30% by mass of platy particles (mica) are expected (Abgottspon 2011).

Suspensions were prepared with clear drinking water and mineral particles (no dispersant agent added). As a preparation of each series, the tank was filled to a water depth of h=0.5 m (Fig. 2), corresponding to a volume of 1.2 m^3. In each series, SSC was increased stepwise until the SSC-measuring range of the LISST was exceeded. SSC was increased to the next level by adding a portion of particles with weights calculated to

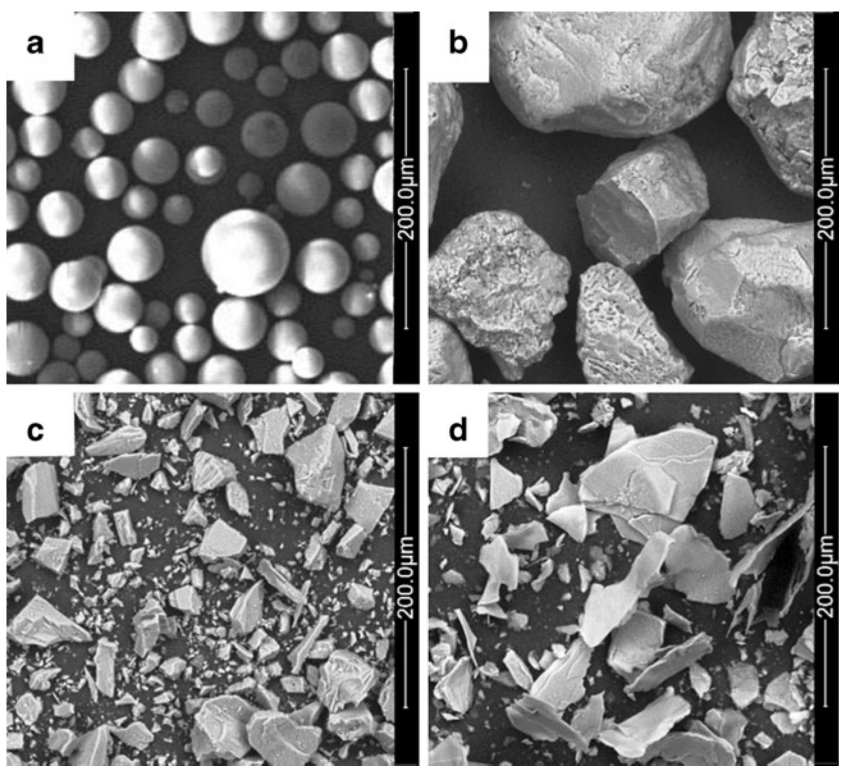

Fig. 1 Particles used in the experiments: **a** glass beads, **b** quartz fine sand, **c** feldspar powder and **d** mica powder (SEM images **a** courtesy of Hochschule Luzern, **b**–**d** ETH Zurich)

reach the next nominal SSC level. Nominal SSC is the total weight of added particles divided by the volume of suspension in the tank. At the beginning of each test series, the so-called background scatter in the water (with no added particles) was recorded by LISST. This allows also checking whether the path reduction module has been installed properly (no air between the receiving window and the module).

At each nominal SSC, after a mixing time of at least 10 minutes, a LISST measurement consisting of 100 single measurements was performed in real-time mode using the LISST SOP (v5) software. The measuring frequency in this mode was between 0.4 and 0.6 Hz, corresponding to a measuring duration of approx. 3 to 4 minutes at each nominal concentration level. From the raw data of each single measurement, PVCs were processed with both IMS and IMR using the recorded background scatter of the respective test series. SSCs were calculated from the PVCs using the densities listed in Table 1.

SSC reference measurements

In order to have a reference for LISST SSCs, two suspension samples per nominal SSC in each test series were taken from the tank at the level of the LISST's laser beam. SSCs of these samples were calculated based on the weight of the samples before and after evaporating the water in an oven (primary method for SSC). The sample volume was normally 0.1 l, and was increased to 0.5 l at low SSCs to achieve sufficient precision in weighing of residues for all samples. Since dried residues contained not only particles but also minerals that had been dissolved in the drinking water, the dissolved solids concentration was deducted from the total mass concentration. The concentration of dissolved solids in the drinking water was measured at the beginning of each series and was found to be approx. 0.15 g/l. SSCs from the bottle samples were averaged for each nominal concentration level. In the following, these are referred to as 'reference SSCs'.

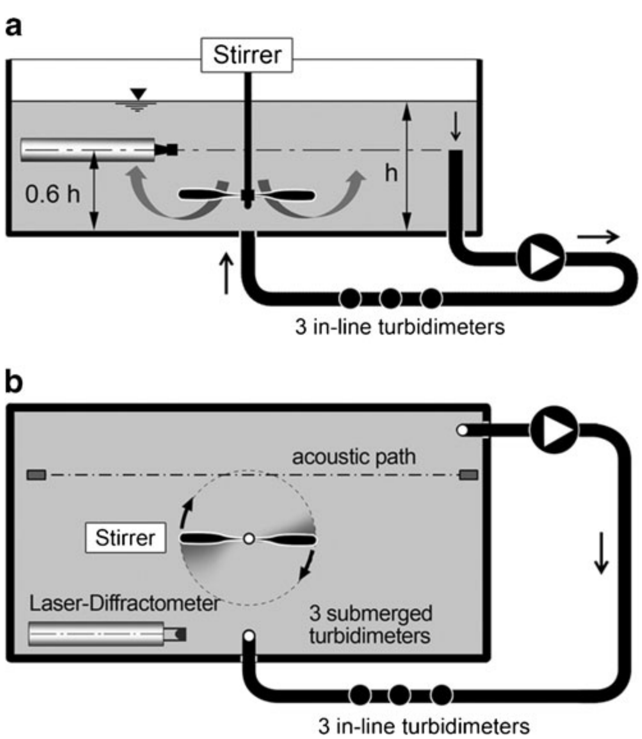

Fig. 2 Mixing tank with LISST device: **a** vertical section and **b** plan view (modified from Felix et al. 2012)

PSD reference measurements

For comparison with LISST PSD estimates, PSDs for each particle type were obtained from both the analyses of scanning electron microscope (SEM) images and a non-portable LD device. The samples for the reference PSD measurements were taken from the dry particle material prior to the LISST measurements.

Image analysis

Information on PSD and particle shape of the four particle types was obtained from geometric measurements on microscope images shown with scaling bars in Fig. 1. The two dimensions of particles visible in the plane of the image, i.e. usually a and b, were measured for each particle type for approx. 100 selected particles. For mica, with some upright-standing flakes visible in the image (Fig. 1d), the flake thickness c was measured and correlated with a. The correlation between c and a was used to estimate the flake thickness when it was not visible in the image. For the other particle types, c was estimated from the image assuming a typical shape. For mica and feldspar powders containing particles with a<5 μm, which could not be individually counted, the fraction of finer particles was estimated (<10%). From the listed a, b and c values, the volume and surface area of each particle were calculated assuming spheres, ellipsoids or cuboids, depending on the particle type. The sorted volume values were used to obtain distributions of the particle sizes a, b, c and d_{es} according to the mass fraction, similar to classical sieve curves. The total volume and surface area of the measured particles served to estimate SMD. In this study, image analysis is used as primary method for particle size and shape.

Non-portable laser diffractometer

Additional PSD measurements were performed with a *LA-950* from *Horiba*, which was available for this study at the Geotechnical Institute of ETH Zurich. This device is a non-portable laboratory LD with a nominal size-measuring range of 0.01 μm to 3 mm. In addition to forward scattering at small angles, it measures and evaluates side- and backward scattering as well, which allows assessing particle sizes below the wavelength (sub-micron range). Calculation of PSDs is based on the assumption of spherical particles. The PSDs were measured in suspensions of adequate concentrations in a small stirring chamber (SSC was not measured).

Results

Particle size and shape based on image analysis

The particle sizes obtained from image analysis are summarized in Table 2 using the definitions given above. To describe sizes of graded particles, a subscript serves to denote the percentage of finer particles (by mass). In addition, the aspect ratios b/a and c/b, which give quantitative information on the basic particle shapes, are presented in Table 3. Qualitative information on the degree of rounding is found in Table 1. Feldspar and mica powders include more elongated particles compared to quartz fine sand (low b/a values at 90% fractile). Whereas the particle shapes of glass beads, quartz fine sand and feldspar powder are approx. independent of particle size (self-similarity), the shape of mica particles varies strongly with size. Since the flake thickness c of mica is almost constant at about 2 μm, the aspect ratio c/b decreases with increasing particle size (b and a).

Effects of particle shapes and LISST inversion modes on SSC estimates

SSCs obtained using IMS and IMR are shown as a function of reference SSCs in Fig. 3 for each particle type. Each point represents one LISST measurement at a nominal SSC, i.e. the time average of 100 single measurements. The effect of inversion mode is quite small with all four investigated particle types. For glass beads, SSC obtained by IMS was found to be generally closer to reference SSC than by IMR, as expected for this particle shape. For the highly non-spherical particles (feldspar and mica), IMR yields slightly smaller SSC estimates than IMS, closer to reference SSCs.

For quartz fine sand and glass beads, LISST SSCs are in good agreement with reference SSCs (generally close to 1:1 lines). For feldspar powder, however, LISST overestimates SSC by a factor of 1.53 and for mica by a factor of about 8. Note that for quartz fine sand LISST measurements were possible beyond the range plotted in Fig. 3b. The SSC-measuring range of the LISST is treated below in the section ‘Upper limit of measureable SSC’.

Effects of particle shapes and LISST inversion modes on PSD estimates

Figure 4 shows the PSDs obtained from LISST using IMS and IMR, as well as PSDs obtained from the non-portable LD and information on particle sizes from image analysis (Table 2) for the four particle types. LISST PSDs are the results of the measurements taken at a nominal SSC of 1 g/l, i.e. the averages of 100 single measurements each. Selected results from LISST measurements shown in Fig. 4 and the so-called spreading, $\sigma=(d_{84}/d_{16})^{0.5}$, which describes the ‘width’ of a PSD, are given in Table 4 for each particle type.

As expected for glass beads, the PSD obtained from LISST with IMS (broken line in Fig. 4a) matches well with the PSD from non-portable LD (grey line), and the median particle size d_{50} from LISST with IMS (40 μm, Table 4) corresponds well to the value obtained from image analysis (39 μm, Table 2). Using IMR instead of IMS produces smaller sizes at the coarse fractions within the PSD.

For quartz fine sand, PSDs from LISST IMS and non-portable LD are similar again, and using IMR instead of IMS has a similar effect as observed with glass beads. The intermediate and the equivalent sphere diameter at 50% by mass obtained from image analysis ($b_{50} \approx d_{es,50}$ = 130 μm, Table 2) are within the d_{50} values from LISST IMR and IMS (116 and 141 μm respectively, Table 4).

For feldspar powder, the PSD obtained with LISST IMS is well in line with that from non-portable LD, except for finer particles, where LISST shows more fine particles towards the lower end of its size-measuring range. With IMR the deviation at fine particles is less pronounced. Although

Table 2 Particle sizes obtained from image analysis

Particle type	Particle size (μm)												
	Longest diam.			Intermediate diam.			Shortest diam.			Equiv. sphere diam.			Sauter
	a_{10}	a_{50}	a_{90}	b_{10}	b_{50}	b_{90}	c_{10}	c_{50}	c_{90}	$d_{es,10}$	$d_{es,50}$	$d_{es,90}$	SMD
Glass beads	24	39	~55	≈a			≈a			≈a			37
Quartz fine sand	130	200	~270	80	130	~190	~45	~70	~140	87	130	~190	110
Feldspar powder	10	40	~80	6	23	~45	~4	~11	~20	7	25	~50	13
Mica powder	16	55	~90	9	24	~48	1	2	3	7	15	~25	4

Table 3 Quantification of basic particle shapes based on image analysis

Particle type	Aspect ratios (-)					
	b/a			c/b		
% finer by no. of particles	10	50	90	10	50	90
Glass beads	~1					
Quartz fine sand	0.82	0.63	0.50	No data available		
Feldspar powder	0.86	0.60	0.31	No data available		
Mica powder	0.80	0.60	0.33	0.21	0.11	0.06

the measurement with non-portable LD indicates that the feldspar powder contains no particles smaller than the lower limit of the size-measuring range of the LISST (approx. 2 μm), the LISST PSDs using both IMS and IMR do not set in at 0% at the lower limit of the size-measuring range. This means that, in the LISST measurements of feldspar powder, a considerable proportion of PVC is detected in the lowest size bin. Similar to glass beads and fine quartz sand, IMR yields smaller sizes in the coarse fractions within the PSD compared to those obtained with IMS or non-portable LD. The d_{50} values of the feldspar particles (with angular and elongated shapes) obtained from LISST IMR and IMS (32 and 34 μm respectively, Table 4) are greater than the corresponding intermediate and equivalent sphere diameters obtained from image analysis (b_{50}≈23 μm, $d_{es,50}$=25 μm, Table 2).

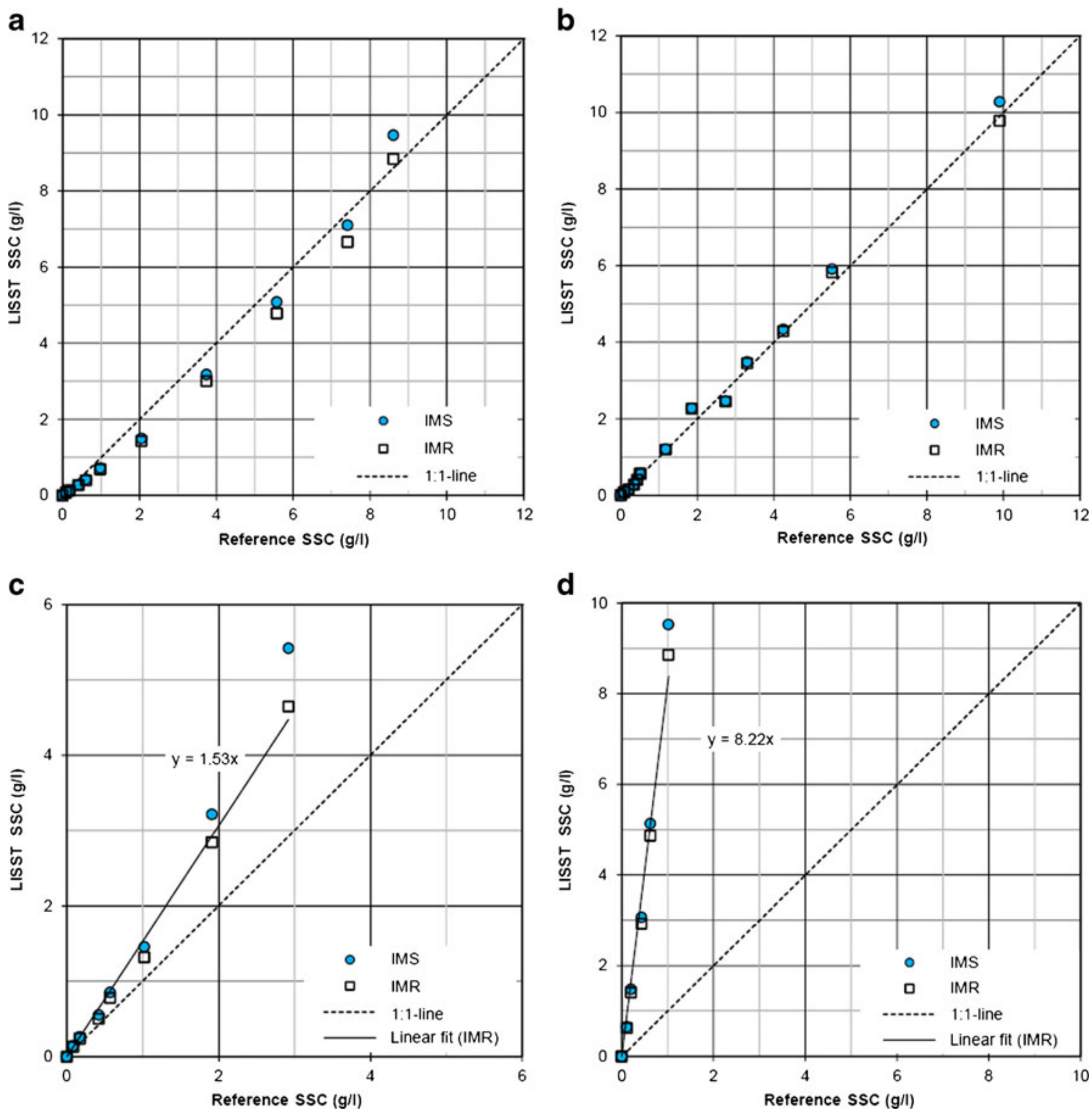

Fig. 3 SSCs obtained from LISST using both inversion modes compared to reference SSCs: **a** glass beads, **b** quartz fine sand, **c** feldspar powder and **d** mica powder

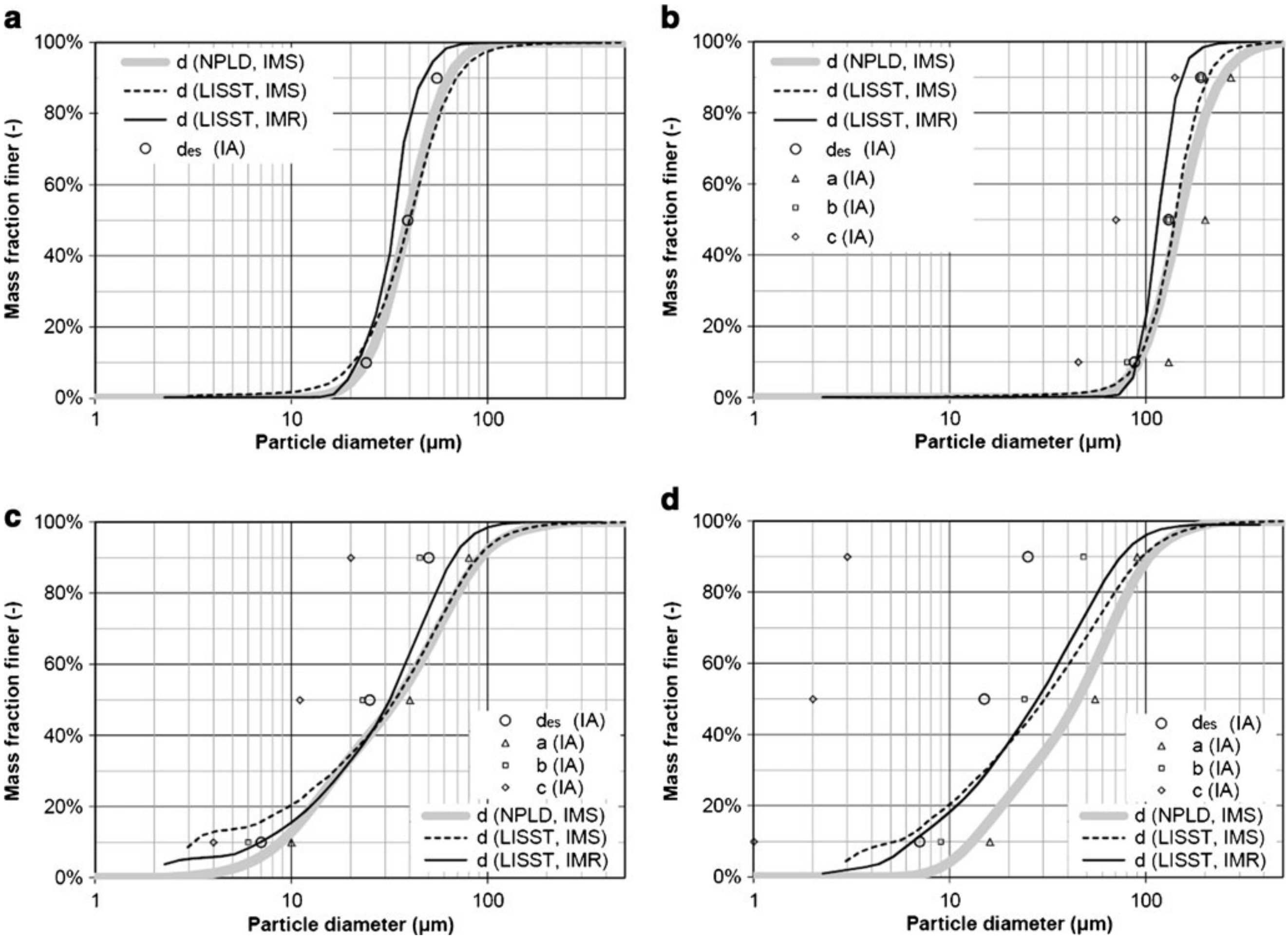

Fig. 4 PSDs obtained from LISST (using both inversion modes, at nominal SSC=1 g/l) and from the non-portable LD device (NPLD) in comparison to particle sizes from image analysis (IA): **a** glass beads, **b** quartz fine sand, **c** feldspar powder and **d** mica powder

For mica powder, LISST yields with both inversion modes smaller particle sizes than the non-portable LD. The particle size d_{50} with IMR (28 µm) is slightly greater than the intermediate diameter of the mica flakes (b_{50}≈24 µm) and considerably greater than the equivalent sphere diameter ($d_{es,50}$=15 µm), which were obtained from image analysis. IMR yields less fine and coarse particles within PSDs compared to IMS, i.e. the spreading of the PSD obtained by IMR is smaller, which is qualitatively similar to the results for feldspar powder.

Table 4 Particle sizes and spreading obtained from LISST (at nominal SSC=1 g/l)

Particle type	Particle size (µm)						Spreading σ of PSDs (-)	
	IMS			IMR				
	d_{10}	d_{50}	d_{90}	d_{10}	d_{50}	d_{90}	IMS	IMR
Glass beads	20	40	69	22	33	47	1.59	1.33
Quartz fine sand	89	141	208	89	116	154	1.37	1.22
Feldspar powder	3	34	89	7	32	67	3.23	2.40
Mica powder	5	30	95	6	28	75	3.15	2.65

Effects of SSC on LISST PSD estimates

Ideally, PSD should not depend on SSC for a given particle type. However, in the experiments shifts in PSDs were observed with increasing SSC, especially with SSC approaching the upper limit of the SSC-measuring range of LISST. The PSDs using IMR for a range of SSC are shown in Fig. 5 for the four particle types. For glass beads and quartz fine sand, the PSDs up to a few g/l are quite constant with increasing SSC and slightly deviate to finer sizes at higher SSCs such as 10 or 20 g/l. The proportion of fine particles within the measured PSDs of mica and feldspar powders increases with increasing SSC. For feldspar powder the proportion of PVC obtained in the lowest size bin increases at higher SSC (growing offset at the fine end of PSDs in Fig. 5c). This effect is also visible in Fig. 6 in which the contributions of the size bins to total PVC are shown. Similarly, SSC overestimation slightly increasing with SSC is seen at the individual

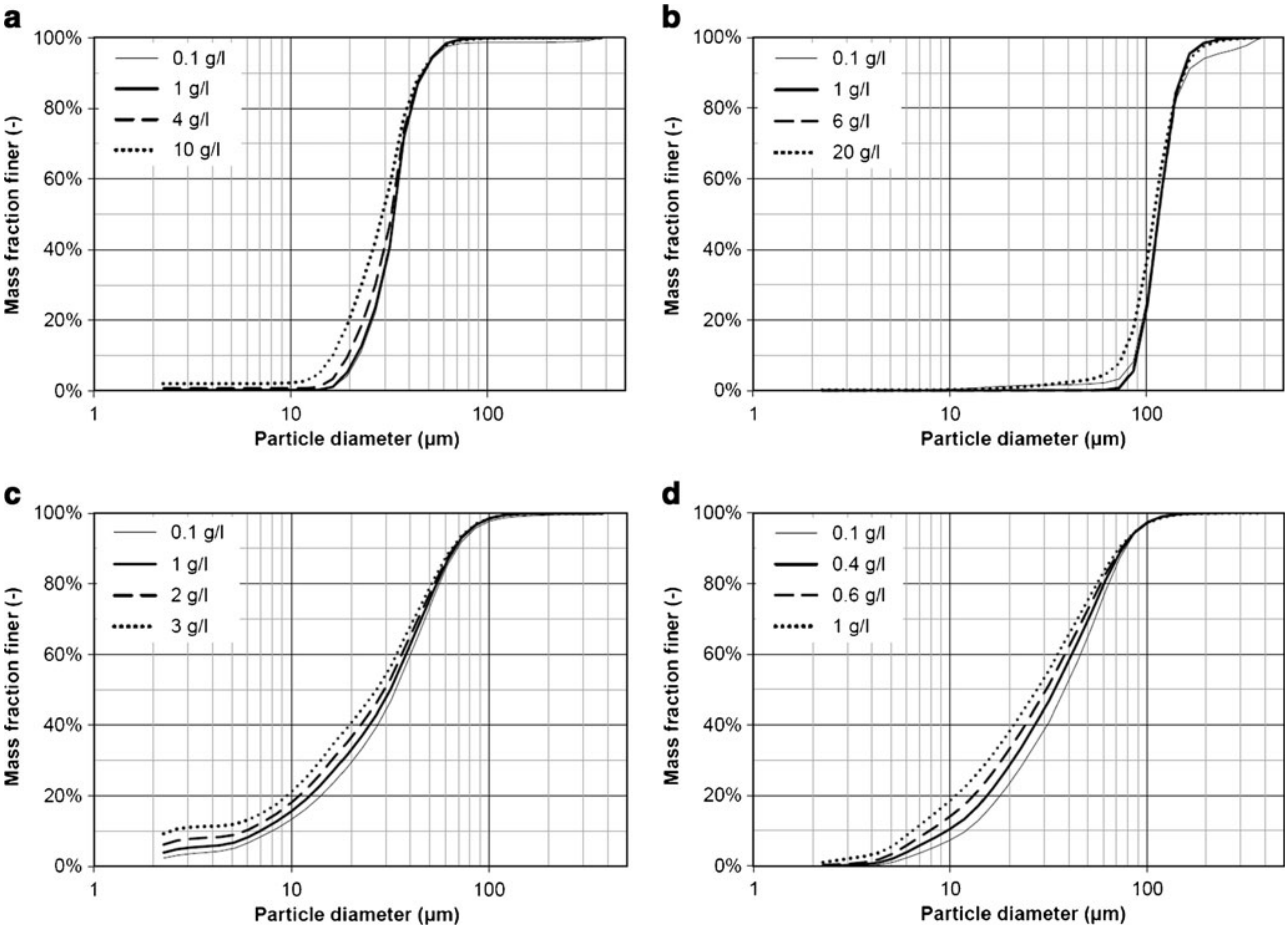

Fig. 5 PSDs obtained from LISST using IMR at increasing SSCs: **a** glass beads, **b** quartz fine sand, **c** feldspar powder and **d** mica powder

IMR points in Fig. 3c. On the contrary, for mica powder there are no offsets at the fine end of the measured PSDs.

Mixed particle-type effects on SSC and PSD

Figure 7 shows IMR SSCs of feldspar and mica suspensions (as in Fig. 3c and d) and of a suspension made of 70% feldspar and 30% mica as a function of reference SSC with linear fits (calibration curves) and equations (SSC overestimation factors). LISST overestimates SSC of this mixture by a factor of

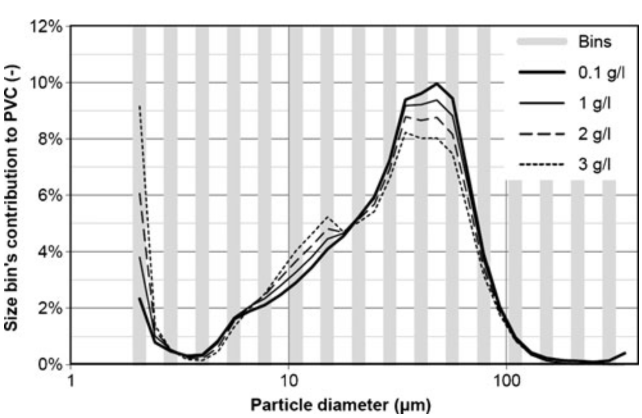

Fig. 6 Contribution of each of the 32 size bins to total PVC measured in feldspar powder suspension at increasing SSC using IMR

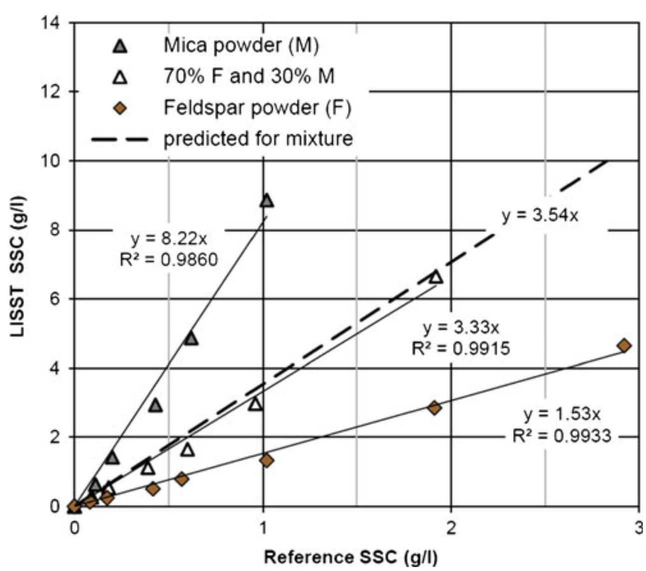

Fig. 7 LISST SSCs of feldspar and mica powders and a 7:3 mixture of these components as a function of reference SSC using IMR, in comparison to the predicted curve for the mixture

3.33. Assuming that the SSC overestimation factor for a mixed particle-type suspension can be calculated as the weighted sum of the SSC overestimation factors of the components and their mass fractions, the predicted calibration curve for the mixture was plotted, too. The slope of this curve, i.e. the predicted overestimation factor, is 70% × 1.53 + 30% × 8.22 = 3.54, which is in a good agreement with the experimentally determined value of 3.33, justifying the assumption of linear superposition.

Figure 8 shows the PSDs for the mixture and its two components individually (Fig. 4c and d). Again, the curves are the averages of 100 single measurements taken at a nominal SSC of 1 g/l, processed with IMR. By coincidence, the LISST PSDs of the feldspar and mica particles are similar even though their particle sizes and shapes are different according to image analysis. For the mixture, no considerable shift in PSD was observed.

Upper limit of measureable SSC

The nominal range of SSC that can be measured with LISST according to the instrument manufacturer (Sequoia 2008) is plotted in Fig. 9 (shaded area) as a function of SMD. The upper limit of the nominal SSC-measuring range scales linearly with SMD and is based on the recommended value of optical transmission $\tau \geq 0.3$ and a particle density of 2.65 g/cm^3 (Sequoia 2008). Below this limit, measurements may still be possible, but reportedly with less accuracy due to multiple scattering.

With τ decreasing below 0.3, some or eventually all of the single measurements performed at one nominal SSC result in zero values for PVCs when the data are processed using the LISST software. In other words, data in some or all rows of the raw data file may be non-invertible as SSC reaches or exceeds the upper limit of measurable SSC. In the present study, the ratio k of the number of invertible to the total number of single measurements at each nominal SCC was calculated. The highest reference SSC with k=1 and the reference SSC of the next higher nominal SSC level (with k<1) are plotted in Fig. 9 for each particle type, as a function of SMD obtained from image analysis (Table 2). The values of k and τ are also indicated in the figure. The latter were obtained from LISST and averaged over the invertible measurements. The inversion of all single measurements (k=1) at each nominal SSC was possible down to τ values between 0.12 and 0.27. As the SSC was increased stepwise in the experiments, the highest SSCs with k=1 are not exactly known; nevertheless, it is known that the upper limit of the SSC-measuring range lies between each pair of points (with τ<0.3). Note that the information shown in Fig. 9 refers to a *LISST-100X* with a 90% path reduction module inserted (without path reduction module, the upper limit of measurable SSC would be 10 times lower).

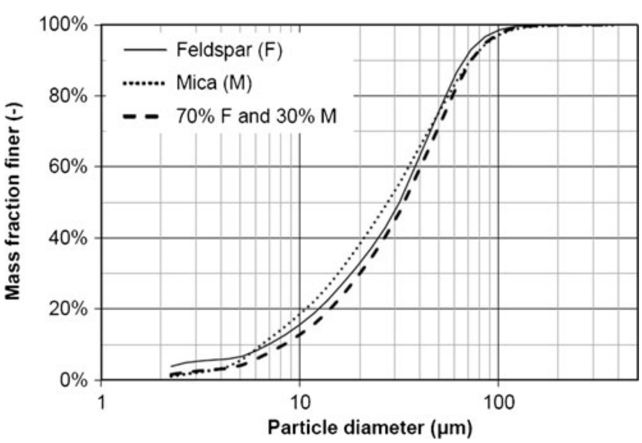

Fig. 8 LISST PSDs of feldspar and mica powders, and a 7:3 mixture of these components (using IMR at nominal SSC=1 g/l)

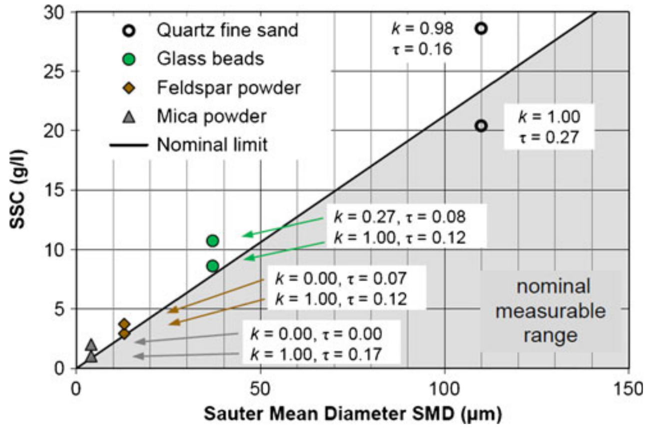

Fig. 9 SSC range that can be measured by LISST as a function of SMD: experimental results (with rate of invertible measurements k and optical transmission τ) in comparison to nominal range (*shaded area*)

Fluctuations of SSC and PSD

SSC and PSD data obtained from measurements at each nominal SSC level exhibit temporal variations (fluctuations). Figure 10 shows two examples of SSC time series (extract of 2 minutes) measured in suspensions of quartz fine sand or

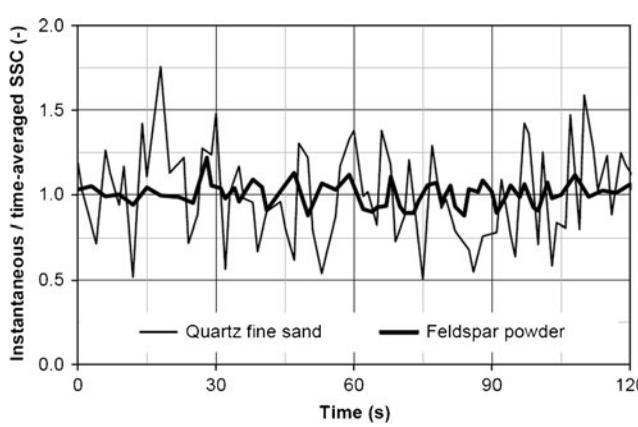

Fig. 10 Normalized time series of LISST SSC for feldspar powder and quartz fine sand at nominal SSC=1 g/l

feldspar powder, both at nominal SSC=1 g/l using IMR. The instantaneous SSC values of each series are normalized by their time averages. SSC fluctuations for quartz fine sand are greater than for feldspar powder.

Table 5 summarizes the coefficients of variation (CV) of LISST SSCs, i.e. the standard deviation of 100 single measurements divided by their time average, for the four particle types with increasing SSCs. The CV is a measure of relative deviations of instantaneous SSC from its mean value and allows a comparison across measurements at various SSCs. It was found that the CVs of quartz fine sand are about 3 to 6 times higher than those of the other particle types. Moreover, for quartz fine sand the CV decreases with increasing SSC while for the other particle types less dependence on SSC was observed.

Characteristic ranges of PSDs obtained from LISST again using IMR for quartz fine sand or feldspar powder at nominal SSC=1 g/l are shown in Fig. 11. For both particle types the time-averaged PSD (thick lines) are plotted together with the 5% and 95% fractiles (thinner lines). The fractile values were obtained by taking the 5th and the 95th value out of 100 sorted values in the respective size classes. Absolute PSD fluctuations (in μm) are greater with coarser particles. The relative fluctuation of, for example, d_{50} is similar for both particle types.

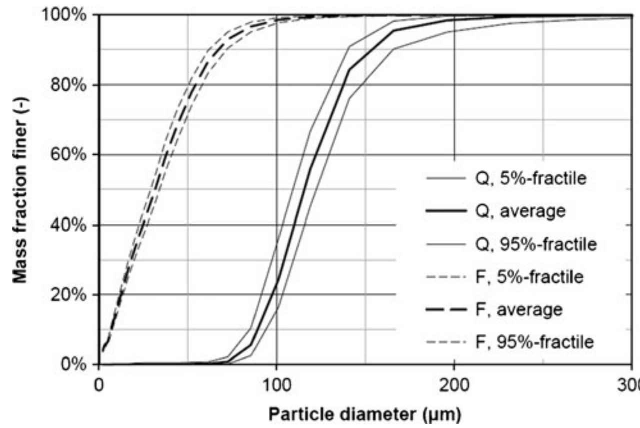

Fig. 11 Fluctuations of LISST PSDs for feldspar powder (F) and quartz fine sand (Q) at nominal SSC=1 g/l

Discussion

Accuracy and experimental errors

For the relatively fine particles (feldspar and mica powders, as well as glass beads), the determined reference SSCs were not more than 10% below nominal SSCs, indicating a satisfactory mixing in the tank. For coarser particles (quartz fine sand), however, SSCs of individual bottle samples fluctuated considerably and average reference SSCs per concentration level were generally some 40% below nominal SSCs due to incomplete mixing. Besides incomplete mixing, deviations between reference and nominal SSCs can be attributed partly to instantaneous local SSC variations and partly to imperfections when taking or treating the samples. The SSC data points in Fig. 3 indicate that the experimental setup and procedure allowed getting systematic results, although the SSC data show some scatter around the average for each particle type. An independent second measurement performed with quartz fine sand at reference SSC of 0.5 g/l showed a good reproducibility (5% deviation among repeated reference SSC measurements and less than 1% deviation among repeated time-averaged LISST SSCs).

Table 5 Coefficients of variation (CVs) of LISST SSCs

Nominal SSC (g/l)	Quartz fine sand (-)	Glass beads (-)	Feldspar powder (-)	Mica powder (-)
0.1	0.45	0.15	0.10	0.07
0.2	0.35	0.07	0.08	0.07
0.4	0.30	0.06	0.07	0.06
1	0.27	0.06	0.08	0.07
2	0.30	0.05	0.07	-
4	0.28	0.06	-	-
10	0.26	0.07	-	-

Reference PSDs were not determined from the samples taken from the mixing tank but from the dry material prior to the experiments, which potentially lead to non-representative sampling. With respect to image analysis, coarser fractions within PSDs are subject to uncertainty depending on the selected investigation area and due to the small number of coarser particles. PSDs from non-portable LD are, as LISST, subject to effects of particle shape and should thus not be considered as results of a primary method for the non-spherical particle types but rather as an additional independent measurement from an LD device with a wider size-measuring range. For future laboratory investigations, analyses of a high number of microscope images based on automatic object detection and/or using certified particles are recommended to increase the accuracy of reference PSDs.

The effect of incomplete mixing in the tank is not relevant with regard to SSC since the SSC prevailing in the tank at the instrument's level was taken as reference. With regard to PSDs, however, incomplete mixing occurring especially at high SSC and with coarser particles may cause deviations from reference PSDs because the samples were not directly taken from the tank in which coarser particles may settle or preferentially stay below the instrument's level (vertical SSC gradient). Effects of potential flocculation were neglected, since it was assumed that the particle densities correspond to the solid densities of the minerals.

Particle shape and inversion mode

The biases on LISST measurements due to particle shape are discussed first with respect to SSC and secondly with respect to PSD. It was found that non-spherical particles cause stronger biases on SSC than on PSD.

For glass beads and quartz fine sand with spherical and rounded shapes, and with d_{50} in the size range of coarse silt to fine sand, the LISST yields SSC estimates with reasonable accuracy (Fig. 3a, b). Note that this is based on the factory calibration (instrument-specific volume conversion constant). With respect to SSC, the selection of inversion mode plays a minor role for these particle shapes. However, the measurements in suspensions of feldspar and mica powders showed that LISST considerably overestimates SSCs (Fig. 3c, d). The elongated and partly very angular or flaky shapes of these particles (Fig. 1c, d) differ considerably from those of the natural sediment grains depicted in Agrawal et al. (2008) and used in the development of IMR. Using IMR instead of IMS only slightly reduces the overestimation of SSCs for strongly non-spherical particles (Fig. 3c, d).

The considerable SSC overestimation measured with mica and feldspar powders can be explained by the deviation between the particle sizes d obtained from LISST and the equivalent sphere diameters d_{es} from image analysis. For mica, the ratio of the median diameters obtained by the two methods is $d_{50}/d_{es,50} = 28/15 = 1.87$ (using IMR). A factor of 1.87 in particle diameter causes a change in volume and thus SSC of $1.87^3 = 6.5$. Considering the ratio of particle diameters obtained by the two methods not only for the median diameters but also for the whole PSD, an SSC overestimation of 9.6 was calculated (based on diameter ratios in steps of 10% by weight). For feldspar powder an SSC overestimation of 1.8 was calculated with the same procedure. The measured SSC overestimations by a factor of 8 for mica and by a factor of 1.53 for feldspar powders are thus not surprising and are mainly attributed to non-spherical particle shapes. Further investigations on this aspect are recommended, considering also the light scattering of angular particles.

LISST measurements in glass beads suspension, for which IMS is applicable by definition, yield PSD similar to those obtained from image analysis and non-portable LD (Fig. 4a) as expected. For quartz fine sand, at which IMR is applicable, IMR yields particle sizes that are comparable to intermediate (b-axis) and volume-equivalent sphere diameters from image analysis (Fig. 4b). From the LISST PSDs using both inversion modes and the analysis of only one microscope image, it cannot be concluded whether IMR is an improvement over IMS with respect to PSD for this particle type. For feldspar and mica powder, i.e. highly non-spherical particles, the use of IMR reduces the spreading of PSDs and the overestimation at small particle sizes, which is discussed in the next section.

Overestimation at small particle sizes

In feldspar powder suspension, especially at SSC approaching the upper limit of measureable SSC, the LISST yielded relatively high PVCs at the lower end of its size-measuring range, i.e. in the lower size bins (Figs. 5c and 6). Previous studies (Agrawal and Pottsmith 2000; Agrawal et al. 2008; Andrews et al. 2011) report that LISST may overestimate PVCs mainly in lower size bins contributing to the overestimation of SSC. This can be due to one or several of the following reasons: (1) presence of fine out-of-range particles, (2) multiple scattering at low optical transmission, (3) effects of refractive index and (4) effects of particle shape.

With respect to *out-of-range particles*, i.e. particles smaller or larger than the nominal sizes measurable with a given LD model, Agrawal and Pottsmith (2000) describe that such particles may affect LISST results since part of the scattering they cause is recorded at the most inner or most outer rings ('leakage' of out-of-range particles into the measuring range). The size-measuring range of a LD device is related to the range of angles at which scattering can be recorded. Andrews et al. (2011) describe that fine out-of-range particles have a stronger effect on LISST measurements than coarse out-of-range particles. As mentioned in the Results section above, there were no out-of-range particles based on the PSDs from the non-portable LD device with a measuring range down to 0.01 μm (grey lines in Fig. 4). The relatively high PVCs at lower size bins obtained by LISST in feldspar powder suspension are thus unrealistic and are not explained by fine out-of-range particles.

With respect to *multiple scattering*, Agrawal and Pottsmith (2000) reported that PSD may be biased to small sizes at optical transmission $\tau<0.3$ (high turbidity). In the present study, in feldspar powder suspension at nominal SSCs of 0.1, 1, 2 and 3 g/l (see Fig. 5c), the corresponding optical transmissions τ were 0.93, 0.50, 0.24 and 0.12 respectively. Multiple scattering may thus be an issue at higher SSCs. However, since unrealistically high PVCs in lower size bins were also obtained at $\tau>0.3$, these cannot be attributed to solely multiple scattering.

As far as the *refractive index* is concerned, Andrews et al. (2011) reported a reduction of unrealistically high PVCs in lower size bins as a result of an alternative inversion procedure with a different refractive index. The refractive indices of glass, quartz and feldspar in water are quite similar; for mica it may vary according to the orientation of the particle. As the optical properties of the particles were not measured and custom inversion procedures were not treated in this study, effects of refractive indices cannot be addressed in detail but are considered to be unimportant except for mica. Since the highest overestimation of PVCs at small particle sizes was observed for feldspar powder, it is concluded that this effect is not to be explained by refractive index.

With respect to *particle shape*, Agrawal et al. (2008) showed that relatively high PVCs obtained in lower size bins can be associated with particle shape. By developing IMR, unrealistic contributions of lower size bins were reduced in comparison to IMS. Based on the measurements in this study, however, it is concluded that a non-negligible overestimation at lower size bins remains with feldspar powder suspension when using IMR. It appears that this effect is mainly associated with very angular particle shape and, possibly, to a smaller extent with multiple scattering.

Omitting contributions of three lowest size bins

Since PVCs measured in the lower size bins in feldspar powder suspension are not realistic, a simple correction method was applied to the data. Expecting a unimodal PSD in Fig. 6, it was decided to discard the PVCs of the three lowest size bins (1.9 to 3.1 μm) in the calculation of SSC and PSD. In other words, the 'raising tail' at the fine end of the non-cumulative size distribution (Fig. 6) is omitted. Figure 12 shows the effect of this correction on LISST SSCs for feldspar powder. These are reduced, but do not reach reference SSCs. With the correction the SSC overestimation depends less on SSC (better linear fit in Fig. 12 compared to Fig. 7) and is reduced from 1.53 to 1.38. When the three lowest size bins are omitted, the corresponding PSDs in Fig. 13 are almost not affected by increasing SSC, in contrast to those before the correction shown in Fig. 5c. Further experiments including angular particles are recommended to investigate the causes of unrealistically high PVCs at lower size

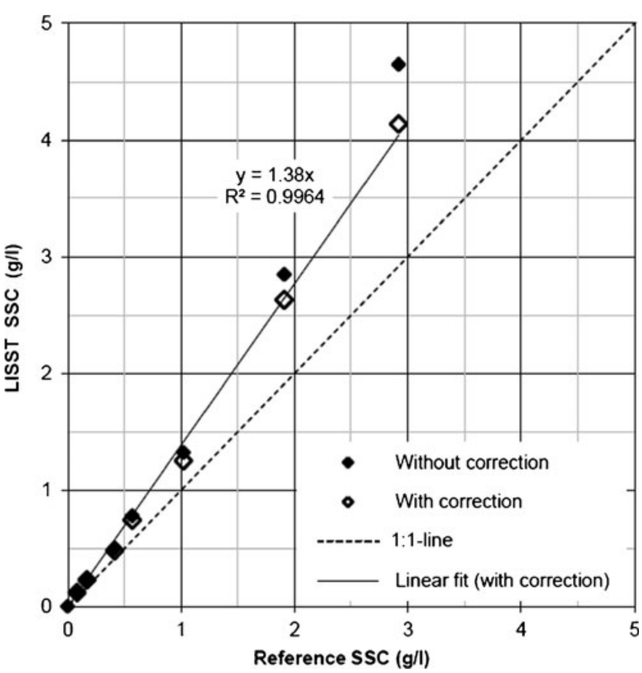

Fig. 12 Effect on LISST SSC estimate if contributions of three lowest size bins are omitted (feldspar powder)

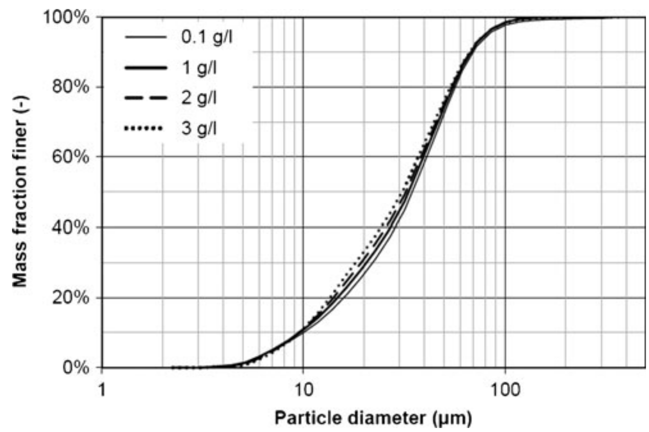

Fig. 13 LISST PSDs at increasing SSC without contributions of three lowest size bins (feldspar powder)

bins and PSD variations due to increasing SSC in order to find and validate correction methods with higher accuracy.

Particle shape-dependent SSC correction factors

LISST raw data are recorded on detector rings in a plane and are related to the average projected area of particles. For the calculation of PVC, information on the ratio of average projected area to particle volume is required. Such information comes from the selection of the inversion mode (according to particle shape) and the device-specific volume conversion constant—e.g. for mica flakes the ratio of average projected area to particle volume differs strongly from that of spheres.

The experiments showed that LISST IMR does not provide PVCs and SSCs with good accuracy for highly non-spherical particles. SCCs can be corrected using the overestimation factor, i.e. the slope of the calibration curve for a known particle type. For a known suspension made with particles of different shapes and known overestimation factors for the involved particle types, SSC can be corrected by the weighed sum of these factors and the mass fraction of the components, as found in one example (see Results section, 'Mixed particle-type effects on SSC and PSD'). Further investigations are suggested to support the generalization of this approach. The prediction of the overestimation factor in the example is improved when unrealistic contributions of the three lowest size bins, which occurred with feldspar powder, are omitted (cf. above; Fig. 12): then, the predicted overestimation factor is 70% × 1.38 + 30% × 8.22 = 3.43, which is closer to the experimentally determined slope (3.33) than before.

The magnitudes of the correction factors found in this study for feldspar or mica powders should not be taken as fixed values since there are many different types and sub-types of minerals and particle shapes differing from those investigated in this study. In field studies, flaky or very angular particles usually make up just a fraction of the particle mix and therefore it is suggested to determine a time-averaged SSC correction factor specifically for such a particle mixture prevailing at a measuring location. This can be done by a comparison of LISST and reference SSCs obtained from laboratory analysis of manually or automatically taken bottled samples at corresponding times. In addition, microscope images of the particles prevailing at the study site may be useful to characterize the geometrical properties of the particles.

Range of measureable SSC

The SSC-measuring range of the LISST determined in this study is in good agreement with the nominal range given by the manufacturer as a function of SMD (Sequoia 2008), although optical transmissions slightly below τ=0.3 were measured at the nominal upper limit of the SSC-measuring range. For many LISST applications the upper limit of measurable SSC is important. In order to estimate it realistically, SMD has to be used for graded particles rather than d_{50}, as recommended by Sequoia (2008). This is particularly important for elongated and platy particles, for which SMD is usually considerably smaller than d_{50}. If higher SSCs are to be measured, a further reduction of the optical path length can be considered, or an in-line LISST device with a mixing chamber in which pumped samples are diluted with clear water at a known mixing ratio (Agrawal et al. 2011). The lower limit of measurable SSC (detection limit), however, was not relevant in the context of this study.

Time averaging

As seen from Table 5, the CV values of LISST SSCs for glass beads, feldspar or mica powders are considerably smaller than those for fine quartz sand. This difference in the CVs can be attributed (1) to the interaction between the particles and the turbulent flow and (2) to the measurement method. Particle size has an influence on the particle behavior in the flow field because smaller particles (powder) mostly follow the local flow like a passive tracer, whereas larger particles (fine sand) show different behavior resulting in a less homogenous distribution. With respect to the measurement method, it has to be considered that the number of particles in the relatively small measurement volume (thickness of the laser beam over an optical path length of 5 mm) decreases strongly with increasing particle size: at identical SSC the number of fine sand particles (e.g. 150 μm) is about 1,000 times lower than the number of silt particles (e.g. 15 μm), leading to phenomena well known in the statistical description of small populations. Therefore, time averaging of repeated single LISST measurements is particularly important for coarser particles, especially at low concentrations. The measuring frequency and the period over which measurements are averaged have to be selected in accordance to the time scale of the process, the PSD and SSC of the expected particles, as well as the desired accuracy.

Conclusions

The results convincingly demonstrate that the LISST yields reasonable PSD estimates in the range of coarse silt to fine sand. With respect to SSC, the factory calibration of the instrument was found to be satisfactory for spherical and rounded particles using IMS and IMR respectively. However, when IMR is used with very angular, elongated or flaky particles, PSDs are biased, for feldspar mainly at lower size bins, and SSCs are considerably overestimated. For highly non-spherical particles, SSC estimates can be corrected by the overestimation factor of a given particle type. For suspensions containing various particle types, the SSC estimate can be corrected by the weighted sum of the overestimation factors of the components and their mass fractions. If these are not known, then gravimetrical analyses of samples with a specific particle mix are required for calibration of SSC. In addition to applying factors on SSC, SSC and PSD can be corrected by omitting overestimated contributions of lower size bins if applicable.

With an optical path length of 5 mm, SSCs can be measured up to a few g/l in a suspension of angular silt particles and up to approx. 25 g/l for rounded fine sand. Measurement accuracy can be improved by time averaging over a higher number of individually inverted single measurements, especially for coarser particles at low SSC.

The intermediate diameter b was found to be similar to d_{es} for all particle types except for mica, which has a flake thickness that is an order of magnitude smaller than the length or width of the particles. Further investigations are necessary to assess effects of non-spherical particles and mixtures of various types of particles on LISST SSC and PSD estimates.

Prior to field deployments, testing and calibrating of measuring devices under controlled laboratory conditions with respect to the specific application are important and strongly recommended. Compared to other available instruments for continuous real-time in-situ suspended sediment monitoring, LISST offers the great advantage of providing not only SCC but also PSD data at high temporal resolution, and the provided SSC estimates are not, or less, affected by particle size changing in time.

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References

Abgottspon A (2011) Messung abrasiver Partikel in Wasserkraftanlagen. MSc Thesis, Hochschule Luzern, Switzerland

Agrawal YC, Pottsmith HC (2000) Instruments for particle size and settling velocity observations in sediment transport. Mar Geol 168: 89–114. doi:10.1016/S0025-3227(00)00044-X

Agrawal YC, Whitmire A, Mikkelsen OA, Pottsmith HC (2008) Light scattering by random shaped particles and consequences on measuring suspended sediments by laser diffraction. J Geophys Res 113, C04023. doi:10.1029/2007JC004403

Agrawal YC, Mikkelsen OA, Pottsmith HC (2011) Sediment monitoring technology for turbine erosion and reservoir siltation applications. In: Proc Hydro 2011 Conf, Aqua-Media Int Ltd, Prague, Czech Republic

Agrawal YC, Mikkelsen OA, Pottsmith HC, Slade WH (2012) Turbine abrasion: one year's experience in real-time sediment monitoring at Hidroagoyan HPP, Ecuador. In: Proc Hydro 2012 Conf, Aqua-Media Int Ltd, Bilbao, Spain

Andrews SW, Nover DM, Reuter JE, Schladow SG (2011) Limitations of laser diffraction for measuring fine particles in oligotropic systems: pitfalls and potential solutions. Water Resour Res 47, W05523. doi: 10.1029/2010WR009837

Boes RM (2009) Real-time monitoring of suspended sediment concentration and particle size distribution in the headwater way of a high-head hydropower plant. In: Proc 33rd IAHR Congr, Vancouver, Canada, pp 4037–4044

Bowers DG, Braithwaite KM (2012) Evidence that satellites sense the cross-sectional area of suspended particles in shelf seas and estuaries better than their mass. Geo-Mar Lett 32(2):165–171. doi:10.1007/s00367-011-0259-6

Costa LI, Storti G, Lüscher B, Gruber P, Staubli T (2012) Influence of solid particle parameters on the sound speed and attenuation of pulses in ADM. J Hydrol Eng 17(10):1084–1092. doi:10.1061/(ASCE)HE.1943-5584.0000555

Felix D, Albayrak I, Abgottspon A, Boes RM, Gruber P (2012) Suspended sediment and Pelton turbine wear monitoring: experimental investigation of various optical and acoustic devices and beginning of the case study at HPP Fieschertal. In: Proc 17th Int Seminar Hydropower Plants, Vienna, Austria, pp 483–494

Felix D, Albayrak I, Boes RM (2013) Monitoring of suspended sediment - laboratory tests and case study in the Swiss Alps. In: Fukuoka S, Nakagawa H, Sumi T, Zhang H (eds) Advances in river sediment research. Taylor & Francis Group, London, pp 1757–1766

Fettweis M, Baeye M, Lee BJ, Chen P, Yu JCS (2012) Hydro-meteorological influences and multimodal suspended particle size distributions in the Belgian nearshore area (southern North Sea). Geo-Mar Lett 32(2):123–137. doi:10.1007/s00367-011-0266-7

Haun S, Kjærås H, Løvfall S, Olsen NRB (2013) Three-dimensional measurements and numerical modelling of suspended sediments in a hydropower reservoir. J Hydrol 479:180–188. doi:10.1016/j.jhydrol.2012.11.060

Konert M, Vandenberghe J (1997) Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. Sedimentology 44:523–535. doi:10.1046/j.1365-3091.1997.d01-38.x

Nichols G (2009) Sedimentology and stratigraphy, 2nd edn. Wiley-Blackwell, Chichester

Sequoia (2008) LISST concentration limits. Article dated 29 August 2008, accessed 27 September 2013. Sequoia Scientific, Inc, Bellevue, WA, http://www.sequoiasci.com/article/lisst-concentration-limits/

Sequoia (2011) LISST bin sizes for inversions based on randomly shaped grains. Article dated 18 March 2011, accessed 27 September 2013. Sequoia Scientific, Inc, Bellevue, WA, http://www.sequoiasci.com/article/lisst-bin-sizes-for-inversions-based-on-randomly-shaped-grains/

Skripalle J, Hies T, Liu Y, Nguyen HH (2012) Application of multi-frequency acoustics to estimate concentration of suspended sediments from Jurong Lake, Singapore. In: Proc 17th Int Seminar Hydropower Plants, Vienna, Austria, pp 725–736

Thorne PD, Agrawal YC, Cacchione DA (2007) A comparison of near-bed acoustic backscatter and laser diffraction measurements of suspended sediments. IEEE J Oceanic Eng 32(1):225–235. doi:10.1109/JOE.2007.890978

Wren D, Barkdoll B, Kuhnle R, Derrow R (2000) Field techniques for suspended-sediment measurement. J Hydraul Eng 126(2):97–104. doi:10.1061/(ASCE)0733-9429(2000)126:2(97)