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PhD Yearbook | 2021

DOCTORAL PROGRAM IN ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING

Chair:
Prof. Riccardo Barzaghi

The Doctorate in Environmental and Infrastructure Engineering has been operating since the academic year 2008/2009. The program introduces doctoral students to the world of research on key theoretical and technological elements associated with water, environment, hydraulic and transportation infrastructures, geology, as well as geomatics.

In this context, the program is grounded on environmental, civil, and industrial applications where water is the primary unifying element. The doctorate program is characterized by a strong inter- and multi- disciplinary structure and is organized according to the following key thematic areas.

1) *Hydraulic Engineering,* where major research themes include: fluid mechanics; fluid-structure interactions; hydraulic measurements; river hydraulics; sediment mechanics; hydraulic risk assessment and management; flow and transport processes in porous systems; hydraulic networks, hydro-energy; oil and gas development and applications.
2) *Hydrology, hydraulic structures, water resources and coastal engineering,* where the main research topics include: hydrology and water resources, with emphasis on the main physical processes of the hydrological cycle, water and energy budgets; hydrogeological hazard and mitigation strategies, including hydrological extremes, floods, droughts and precipitation, early warning operative systems, snow avalanching and flood risk; hydraulic networks engineering; and coastal engineering.
3) *Environmental technologies*, with focus on: water and wastewater treatment technologies (including disposal/reuse of wastewater, sludge management and disposal, anaerobic digestion processes; management and planning of environmental resources (including water quality modelling, knowledge-based decision support systems); solid wastes management (including Life Cycle Assessment of energy and resource recovery initiatives); phenomenology of the atmospheric environment and treatment of gaseous emissions; contaminated soils and their remediation.
4) *Transport infrastructures and geology*, with focus on: transport networks, including functional interactions with regional, national and international territory; sustainable development, in terms of dynamics of development and its relations with the infrastructure system; technological innovation, including methods and indicators for performance characterization of infrastructure construction and maintenance techniques; hydrogeological risk, landslide hazard; water resources identification and management, pollution problems.
5) *Geomatics*, with focus on: physical geodesy and satellite geodesy; positioning and navigation; surface surveying with optical or other sensors, such as SAR, LIDAR; digital photogrammetry and image analysis; remote sensing; geographic information systems; cultural heritage reconstruction and archiving.

The curriculum of PhD students has been tailored to the general and specific research questions associated with the multifaceted interactions between the water sphere and the key evolving anthropogenic activities responding to the needs of modern society.

Career perspectives include opportunities at Universities, Research Centers, public bodies and Authorities, as well as private companies / industry. Small and medium size enterprises (SMEs) which cannot afford the development of an in-house specific know-how program may also require such highly professional profiles to guarantee critical innovation and competitiveness.

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GNSS METEOROLOGY: THE ROLE OF TROPOSPHERIC DELAY ESTIMATES IN WEATHER FORECASTING STRATEGIES

Stefano Barindelli - Supervisor: Giovanna Venuti

The Global Navigation Satellite System (GNSS) main purpose is the positioning of an object with respect to an Earth fixed reference frame. Thanks to the system design, GNSS signals can be used also to sense atmospheric water vapor (Figure 1). This is of utmost importance for many meteorological and climate-related applications because it is one of the main ingredients of all the atmospheric processes, from cloud formation to energy flows balance. GNSS-based tropospheric water vapor monitoring is currently used for operational meteorology only in some countries like Japan, UK, and France. In these countries, time series of Zenith Total Delays (ZTD) or Precipitable Water Vapor (PWV), derived from GNSS observations, continuously collected by permanent regional networks of geodetic receivers, are routinely assimilated into mesoscale Numerical Weather Prediction (NWP) models.
This dissertation demonstrates the opportunity of using GNSS for meteorological applications, with the purpose of spreading this technology in all those countries, like Italy, where it is not already exploited.
GNSS water vapor products are first of all validated to assess the reliability of this source of information. In particular, a statistical comparison between GNSS ZTD and similar physical observations derived by other instruments has been performed.
For the comparison, conventional meteorological instruments like radiosondes, a radiometer, and also non-conventional ones like the Synthetic Aperture Radar (SAR) sensor have been considered. The results show good agreement between the different data sources, unlocking in some cases the possibility to realize a homogeneous water vapor dataset merging different sensing instruments and techniques.
GNSS tropospheric delays are then used to give a first characterization of rain events, highlighting the relation between ZTD time series from a GNSS receiver, rain, and other meteorological variables recorded by a co-located ground meteorological station. A preliminary analysis has been done and some conclusions obtained from selected case studies have been drawn.
One of the most important roles of meteorology is to provide forecasts of dangerous events like localized heavy rainfall. Due to the chaotic behavior of the atmospheric processes, this is a very difficult task in which water vapor plays a fundamental role. The availability of water vapor observations can bring improvements in the capability of forecasting intense rainfall events. In this regard, two different experiments are presented. The first deals with the assimilation of GNSS ZTD from a national network into a Numerical Weather Prediction model. Results show that the assimilation improves the forecast capability both in terms of intensity and localization of considered events. The second experiment deals with feeding black-box models with GNSS ZTDs to forecast convective rainfalls at a local scale. A neural network was built and trained with 10 years time series of meteorological data and GNSS ZTDs to predict the occurrence of intense convective events defined by means of a meteorological radar. Promising values of accuracy have been obtained, proving that the implementation of forecasting models based on black-box architectures could be a complementary solution to physically-based models.
We hope that the procedures, attempts, and discussions addressed in this thesis will contribute in the direction of an Italian operational use of GNSS ZTD estimates for meteorological forecasting purposes.

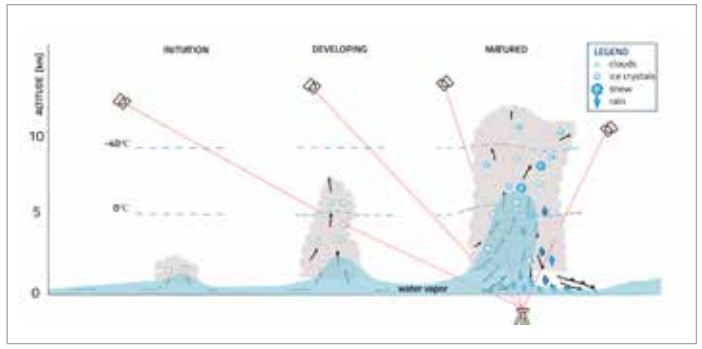

Fig. 1 - Schematic representation of GNSS water vapor sensing capabilities (original concept Shoji Y., Japan Meteorological Agency)

GRAVITY FIELD RECOVERY FROM GRADIOMETRIC MISSIONS BASED ON COLD ATOM TECHNOLOGY

Khulan Batsukh - Supervisor: Mirko Reguzzoni

This thesis focuses on the possible implementation of a new gradiometer exploiting ultra-cold atom interferometry for future gravity missions dedicated to high-resolution monitoring of the Earth mass variations on and below the Earth surface and describes the data simulation and analysis for two studies of such a new mission proposal.

Gravity is one of the four fundamental forces of nature. Even though gravity is the weakest force, it is the dominant one at astronomical scales and holds entire solar systems and galaxies. In particular, for the Earth, it influences many dynamic processes within its interior, on and above its surface.

The Earth gravity field is the result of mass redistribution and transport in the Earth system, which includes the solid Earth, oceans, atmosphere, ice, land as well as the biosphere. Mass redistribution and transport in any of the Earth subsystems cause gravity field variations.

In the first decade of the new millennium, three successful missions dedicated to the determination of the Earth gravity field, namely CHAMP (Challenging Mini-satellite Payload), GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity field and steady Ocean Circulation Explorer), were launched successfully for mapping the gravity field with unprecedented accuracy as well as in temporal and spatial resolution. The observations obtained from these gravity missions have found various applications in different branches of Earth science. Particularly, the idea of measuring localized functionals of the gravity potential along orbit using a single satellite with an onboard gravity gradiometer was proposed and successfully implemented in the concept of the GOCE mission. It was the first Earth Explorer mission of the European Space Agency (ESA) and delivered plenty of data to the scientific communities and the space agencies and brought ourunderstanding of the Earth gravity field to a new level.

In recent years, several research institutes have proposed the idea of exploiting a gravity gradiometer based on cold atom interferometers sensors for space applications, particularly for future gravity missions. Quantum sensors based on atom interferometry have evolved rapidly in the last few decades and have become one of the most sensitive and accurate inertial thanks to their excellent long-term stability and accuracy level combined with the possibility of easily implementing new measurement schemes. Currently, the cold atom interferometers for space applications is being developed and studied by a large community of about 50 groups worldwide both in the academic and in the industrial sectors. In this work, the performance of this new gradiometer is investigated in the scope of two studies of a future mission, the so-called MOCASS and CAI studies. The basic idea for both studies is a GOCE mission follow-on, launching a unique spacecraft with an onboard cold atom gradiometer capable of measuring some functionals of the Earth's gravitational potential. The main advantage of such a quantum gradiometer is that it presents a very low and spectrally almost white noise also at low frequency as opposed to classical accelerometers, which present a colored noise in the lower frequencies.

The first study project "MOCASS" (Mass Observation with Cold Atom Sensors in Space) was proposed and performed by a team of Italian universities under a contract by the Italian Space Agency in the framework of preparatory activities for future missions and payloads of Earth Observation. The research team consisted of Politecnico di Milano, University of Trieste and AtomSensors srl (Spin-off of the University of Florence). The goal of this study was to determine:

- the technological characteristics of an atom interferometer that delivers the gravity and gradient field at the satellite altitude;
- the estimation of the global signal characteristics as a result of the geodetic data analysis;
- the signal requirements from a geophysical point of view.

Overall, observables with a time span of 2 months were simulated for twenty different simulation scenarios, which differ from each other by the satellite altitude, the operation mode, and the gradiometer configuration.

The second study project "Cold Atom Inertial Sensors: Mission Application (CAI)" was performed by Thales Alenia Space Italia under ESA contract with the support of Marwan Technology, Politecnico di Milano and Technical University of Delft. The final goal was to identify the potential reference missions and understand the technological development needed for the cold atom interferometry to achieve better performance than the previous gravity missions.

Chapter 1 includes the theoretical background of the Earth gravity field and the main principles of gravity field determination. The first section introduces the terms widely used in geodesy, while the next sections explain the measurement techniques.

Chapter 2 is dedicated to satellite geodesy, introducing different concepts for gravity field determination from space. Different satellite gravity missions will be described, which exploited different concepts and were launched for measuring and monitoring the Earth gravity field. Also, a summary of recent global gravity field models derived from these missions will be given to outline the actual knowledge of the Earth gravity field.

Chapter 3 describes the main idea of an innovative gradiometer exploiting ultra-cold atom technology. The proposed instrument concept will be presented, as well as further technological development required to achieve a better performance than the electrostatic gradiometer.

Chapter 4 explains the data analysis method exploited for this work, namely the space-wise approach. The simulated observables are the second derivatives of the gravitational potential at given points along the orbit in a given direction (e.g., the radial one). The unknowns are the spherical harmonic coefficients, retrieved by applying the space-wise approach.

Chapter 5 and Chapter 6 present the simulations and data analysis performed for MOCASS and CAI studies. Firstly, the mission proposal will be provided. Then numerical simulations set up according to the mission scenarios will be illustrated along with the mathematical model for data processing. Finally, the results will be explained and compared with those of the GOCE and GRACE missions, showing the applicability of the proposed concept and the improvement in modeling the static and time-variable gravity field, respectively.

	MOCASS	CAI	GOCE TIM
g at ground level (at degree ℓ = 200), [mGal]			
Static gravity field (2-month solution)	1.03	2.00	2.91 (R1)
Static gravity field (5-year solution)	0.19	0.38	0.52 (R5)
Trend error in Δg at ground level (at degree ℓ = 45), [μGal/month]			**GRACE (ITSG-Grace2014k)**
Time-variable gravity field (5-year mission with monthly solutions)	0.040	0.177	0.032

Tab. 1

UNDERSTANDING SEDIMENT PRODUCTION IN ALPINE BASINS TO IMPROVE INTEGRATED RISK SCENARIOS

Davide Brambilla - Supervisor: Laura Longoni

Hydrogeological risk in mountain basins has been studied since a long time, but still lacks an effective approach to simulate events. The need of developing resilience and mitigation measures in response to natural disasters remains crucial for the safety of citizens and infrastructure. Cities located at the downstream end of mountain catchments are exposed to specific flood risks, in which sediment transport plays a significant role. During the past few years, the natural calamities have increased in frequency, possibly related to climate change. Future smart cities must be ready to face natural hazards by implementing smart strategies.
The urgent need for a territorial policy that takes into account sediment transport has been discussed for decades. Several recent studies have demonstrated the significance of transported sediment (Figure 1).
The European Floods Directive (2007) recommends that flood risk maps based on calamitous scenarios should include information about “areas where floods with a high content of transported sediments and debris floods can occur”. Regarding the sediment discharge estimates, several models for sediment generation and transport have been proposed. Most of available models focus on specific aspects, preventing a complete understanding of the processes at basin scale. Even commonly used models employ approximate equation sets for surface water routing, which are generally not valid, especially in the strong transients associated with major flooding events. These are responsible for a large portion of the total liquid and solid runoff. In 2017 the need for an improved model arose and in Politecnico di Milano a research team has been started to conceive a new model, called SMART-SED, that won a grant by Fondazione Cariplo, funding this research.
The SMART-SED project aimed to develop a model able to simulate more realistically both long- and short-term scenarios focusing on the combined calculation of water and solid flows. The databases necessary for model calibration and validation are often extremely heterogeneous. This is the critical point from which this thesis stems and develops.
Generally, not many detailed field measurements of solid fluxes are available, but their evaluation is a key point to assess the ability to simulate the processes of any model.
Two different technologies have been outlined for sediment transport estimation – a static and a dynamic one. The static approach relies onto the monitoring of bathymetry of sedimentation basins along the river. As for the dynamic approach, the migration of single grains along the stream will be monitored by means of RFID (Radio Frequency IDentification) tags implanted in pebbles. Tracking the sediment samples will enable to understand the river/pebble features. The Lagrangian approach, based on RFID tracers, permitted to analyse the single displacement of more the 1,000 pebbles across 20 different events. The DB compiled with all the single displacements puts in relation tracers’ movements, geometrical features and event features. It was indeed possible to search, and find, a statistical model that describe single pebbles movements, in terms of magnitude and probability. Attempts to correlate movements and events and subsequently compute a total solid discharge have been performed but poor results have been showed. Further research led to encounter a phenomenon that has been just recently described in the literature, but never in real case, called ‘history effect’.
Events’ solid discharge is not an exclusive function of liquid discharge and flow features, but it is intrinsically connected to events occurred before and their effect on the gravel bed. Three key points are worth being reported.
Firstly, history effect means that any attempt to simulate a single event, and its related solid transport, cannot disregard previous ones and their distance in time. This finding directly reflects on the impossibility to conceive simulating models that just focus on a single event, isolated from the long-term evolution of the river.
The assumption that history effect is negligible is acceptable just for long-term simulation, where the effects are diluted in number of events.
Secondly, it is a remark about the stochastic nature of sediment transport. A stochastic approach has been attempted also to describe the RFID tracers’ data. After the ‘history effect’ existence become clear, it has to be noted that probability laws are not only site specific, but also not really describing the data from an event. An extraction from the found laws will just represent an average behaviour, valid for long-time simulation and not for a specific event.
Last conclusion drawn from the RFID tracers’ data is about the state of activity of the river. During low to medium intensity events, the morphology of the river influences the transport, tracers start from high flow areas (cascaded, steps) and stop in low velocity zones (pools). This behaviour creates a predictable evolution of the river with erosion and deposition areas concentrated in the thalweg. When a strong event occurs, the evolution scheme is disrupted and the whole river bed moves and evolves.
During the study, the tracers’ dimension has been accurately selected, but unfortunately physical constrains ended up in limiting the pebbles in the range 60-160 mm of nominal diameter. Thus, along with the described Lagrangian approach, an Eulerian approach was proposed. In the Eulerian approach, the survey is focused on a limited area, where all the sediments are relevant and tracked. The first immediate result of Eulerian approach is the measure of critical diameter. This value has been used to tune a hydraulic model of the reach. Accordance between measured and calculated value was good, demonstrating the possibility to use a simulation approach with confidence.
Second interesting conclusion is that critical diameter, in most case, fell in the RFID tracers’ diameter span. When this value is compared with granulometric curves of the surveyed areas it is evident how most of the material is in the classes with lower diameters than RFID tracers’ one (Figure 2). This means that the Lagrangian approach largely underestimates mean displacement length, or that the RFID tracers’ displacements are not well representing the mean velocity of the riverbed, but just the velocity of represented diameters.
All the data retrieved, the analysis performed created a good consciousness of the processes and their peculiarities. This knowledge improved the SMART-SED model.
The model binds together many different disciplines and expertise, in the ambitious attempt to overcome present state of art. Unfortunately, the integration of erosion data to model equations was not straight forward and further tests are required and currently challenging the development team. Nevertheless, many critical points have been tackled and solved to get to the first working version which includes all the features.

Fig. 1 - Intense sediment transport in mountain flash flood

A RISK-BASED APPROACH FOR CONTAMINANTS OF EMERGING CONCERN IN DRINKING WATER PRODUCTION AND DISTRIBUTION CHAIN

Beatrice Cantoni - Supervisor: Manuela Antonelli

The revision of the European drinking water (DW) Directive has introduced some contaminants of emerging concern (CECs) among the list of monitored parameters. Moreover, the EU Directive designs a general framework in which the conventional approach, based on controlling the exceedance of regulation limits, is enslaved to a wider approach based on human health risk minimization throughout the whole supply system (from source to tap). Quantification of the risk consists of understanding the level of exposure concentrations with respect to health-based guideline levels derived from toxicological studies. However, the use of a risk-based approach is not easy to be achieved for CECs due to several knowledge gaps. In particular, it is difficult to evaluate CECs exposure levels in DW, firstly because of their low concentrations compared to the LOQ (Limit of Quantification) of the analytical methods, which are in continuous refining; this results in monitoring databases characterized by high percentages of censored data, i.e. data below the LOQ. Moreover, uncertain estimation of CECs levels in DW is also due to a lack of consolidated knowledge about their fate throughout treatment processes in DW treatment plants (DWTPs) and in DW distribution networks (DWDNs). Finally, high uncertainty is related also to CECs toxicity that hinders the prioritization of CECs to be included in the regulations and also the limit to be proposed.

The goal of this PhD project is to contribute to fill the knowledge gaps in the field of risk assessment related to the spread of CECs in DW, providing effective tools to support water utilities in managing a reliable DW supply system and decision-makers in CECs regulation prioritization. Within this framework, lab-scale experiments have been combined with full-scale monitoring, development of predictive models and risk assessment procedures, and advanced statistical methods, to apportion the contribution of each element of the DW supply system in determining human health risk, in order to prioritize the interventions in view of an overall risk minimization.

Firstly, an advanced approach, based on Maximum Likelihood Estimation method for left-censored data (MLE_{LC}), was compared with the traditional methods used to handle censored data, that are their elimination or substitution with a value between 0 and LOQ. These methods have been applied on full-scale monitoring data of several micropollutants in samples collected throughout the whole DW supply system in a highly urbanized Italian area. Results demonstrated the benefits of MLE_{LC} method compared to the traditional ones, especially for high percentages of censored data, not only in terms of more accurate fit of concentration statistical distribution, but also in three data analysis applications, that are the estimation of concentrations time trend in source water, treatment removal efficiency and human health risk.

Secondly, a new probabilistic procedure, that is a quantitative chemical risk assessment (QCRA), was developed to assess human health risk related to the occurrence of CECs in DW, including all the uncertainties related to both exposure and hazard assessments. The QCRA quantifies the risk in terms of benchmark quotient probabilistic distribution, from estimated CECs concentration in DW, simulating source water treatment by granular activated carbon (GAC). Sensitivity and uncertainty analyses were performed to identify main factors affecting risk estimation, highlighting future research needs and directions, to improve reliability of risk assessment. QCRA was applied to bisphenol A as an example CEC and various GAC management options. This demonstrated that QCRA is more effective than deterministic CRA, in evaluating the effect of each scenario in risk minimization for optimal prioritization.

Since QCRA outputs highlighted that modelling of GAC breakthrough curves has a relevant role in the accuracy of risk estimation, experimental work has been performed to more accurately model GAC performance towards CECs, namely perfluoroalkyl substances (PFAS) and pharmaceutical active compounds (PhACs). Four different commercial GACs were tested by batch tests, providing isotherms, and rapid small-scale column tests (RSSCT), to calibrate CECs breakthrough curves. These studies were performed on 8 PFAS and 8 PhACs in 3 water matrices. Finally, full-scale data collected through a monitoring campaign on PFAS were used for model validation. CECs removal was confirmed to rely on compounds hydrophobicity; GAC surface charge was demonstrated to have more influence than its porosity. Moreover, the interaction between CEC hydrophobicity and GAC porosity was found to have significant effect on performance. Finally, a correlation was found between the removal of UV absorbance at 254 nm and CECs removal, that was not dependent on the GAC nor the water matrix, but it was found to depend on the test scale.

Finally, potential recontamination events in the DWDN were studied focusing on BPA release from epoxy resins used to renovate pipelines. Lab migration tests were performed on three epoxy resins and designed with the Design of Experiments method to build a BPA release model as a function of water chlorine concentration and chemical stability. BPA release over time was well described by the combination of two first-order kinetic models, where the first describes the release of free BPA due to incomplete polymerization and the second describes BPA release due to resins' deterioration. The calibrated model was combined with the hydraulic model of a highly urbanized Italian area, through EPANET MSX, to simulate the current fate of BPA in the DWDN, identifying the most vulnerable areas; as a consequence, the combined model can be adopted to optimize monitoring and intervention plans to minimize the human health risk.

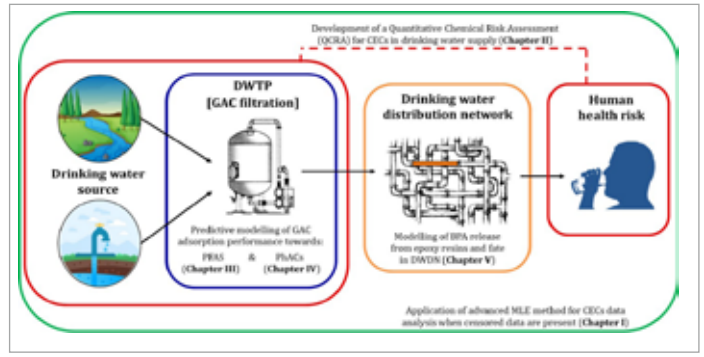

Fig. 1 - Schematic overview of the thesis chapters and their focus on each part of the drinking water supply system.

DEVELOPMENT OF THE ALBA MODEL: A COMPREHENSIVE MATHEMATICAL TOOL FOR RACEWAY SYSTEMS MANAGEMENT AND INTEGRATION IN WATER RESOURCE RECOVERY FACILITIES

Francesca Casagli - Supervisor: Elena Ficara

The use of microalgae for wastewater treatment was first studied in the 50s and more recently revisited, in view of a more sustainable and circular approach to bioremediation. When applied to wastewater treatment, these microscopic photosynthetic organisms contribute to reduce the energy demand by supplying the oxygen through photosynthesis. Moreover, microalgae assimilate inorganic nitrogen and phosphorus and thus participate in the treatment process. Compared to classical activated sludge processes, algae will also recycle the carbon dioxide produced by bacteria, reducing the greenhouse gas emissions. Moreover, some algal species can contain high amounts of lipids, protein or other compounds that become elemental bricks for green chemistry, becoming then new players to recycle nitrogen and phosphorus using the solar energy and providing useful products such as biofuel, bioplastics, or bio-fertilizer. However, several challenges must still be addressed to benefit from the key advantages of integrating microalgae in Water Resource Recovery Facilities (WRRFs). Facing seasonal fluctuations of light and temperature is particularly difficult, especially to keep an effective algal activity at low temperatures and light during autumn and winter. Moreover, promises of the microalgae-based technology have rarely been quantified, mainly because most of the underlying processes are not easily measurable (e.g.: the balance between oxygen production by photosynthesis, consumption by bacterial and algal respiration, and the oxygen exchange with the atmosphere, was never fully assessed). On top of this, estimating the benefits and costs based on non-optimised pilots run over a yearlong period is challenging and requires expensive field testing and data collection. All these open questions can be effectively addressed with the support of numerical simulations. Mathematical models can indeed be used to quantify the mass and energy fluxes. They are powerful tools for understanding and predicting bioprocesses, especially for decoding the complex nonlinear interactions among microorganisms. In addition, an accurate model is a very powerful tool to identify the most efficient operating modes, and then run an environmental or economic analysis from design to operation. Modelling has demonstrated its power in many fields of biotechnology, and especially in wastewater treatment, where the ASMs and ADM1 models are currently used at industrial scale. Up to now, only models describing bacteria-based systems for wastewater treatment were more extensively studied and were indeed validated on longer time scales. So far, the challenge for algae- bacteria based treatment for wastewaters, is that currently few models have been developed for simulating such interactions in outdoor systems, but no comprehensive models have been validated over a yearly period and applied to different case studies.
This Ph.D. thesis proposes a new model, named ALBA (ALgae-BActeria), describing the ecosystem evolution in outdoor raceways for wastewater treatment. In this work a global model was developed, integrating the main chemical, physical and biological processes taking place in outdoor systems of algae-bacteria consortia treating different type of wastewaters. The model was calibrated and validated, both on nychthemeral and seasonal datasets, to assess the predictive capability of the model. For this purpose, fifteen months of an original field-testing campaign on an outdoor demonstrative raceway pond treating municipal wastewater (56 m^2, located in Narbonne area) were used for supporting model advanced experiments along the four seasons (i.e.: sensitivity analysis under periodic regime, calibration, validation and uncertainty analysis). In addition, the ALBA model was validated with the same set of parameters on another case study, along six-months of monitoring campaign, including the start-up phase, with a different type of influent and different environmental conditions, i.e. a pilot scale raceway (3.8 m^2, located in Milan area), processing agricultural digestate from a piggery farm.
The last chapters of this work, describes how the model was used for investigating the Carbon, Nitrogen and Oxygen fluxes partitioning from the influent to effluent and also the possible optimization strategies keeping the system efficient along the seasons, focusing mostly on algal biomass productivity, nutrient removal rates, biomass fractionation and considering environmental impacts due to the atmospheric emissions (CO_2, NH_3). Several scenarios were analysed, under different light, temperature and pH conditions, unravelling the effect of key parameters, such as the volumetric liquid/gas mass transfer coefficient (k_La), the hydraulic retention time (HRT) and the pH control set-point, showing that finding a working mode balancing conventional efficiency parameters and atmospheric emissions is indeed challenging. Unexpectedly, simulations revealed the key role of alkalinity as process parameter to control for avoiding very low levels of inorganic carbon in the system, despite an active pH regulation, that in principle was expected to guarantee for not limiting conditions of CO_2 for algae and nitrifiers growth.

EXPERIMENTAL STUDY ON THE MONITORING OF SHALLOW LANDSLIDES IN NON-COHESIVE SOILS WITH A NOVEL OPTICAL FIBRE SENSOR

Vladislav Ivanov - Supervisor: Laura Longoni

The optical fibre technology has become indispensable, currently supporting a great deal of the world's internet connection, television, and telephone network. Optical fibre cables are designed to carry high quality data over long distances at unprecedented velocity. Apart from their dominant role in telecommunications, optical fibre cables have been successfully used as sensing devices due to the sensitivity of the propagating light signal to disturbances such as strain and temperature change. Hence, coupling an optical fibre cable with strain- and/or temperature change-inducing phenomena permits the process to be observed and, in some cases, quantified by the differences recorded between a forward propagating signal and its reflected counterpart.

Optical fibre sensing has opened a new chapter in the field of geohazard monitoring. Embedding a simple optical fibre cable into the ground or coupling it to a structure allows for monitoring of strain and/or temperature change with an unprecedented accuracy, frequency of observation, and spatial coverage. Current commercially available sensing technologies are able to provide strain measurements in the order of microstrain with a spatial resolution in the order of meters across tens of kilometres of range. That allows for an abundance of sensors to be distributed across a potentially hazardous area and/or a corresponding supporting structure. Even so, by far, the majority of the monitored phenomena are slow moving geohazards, while swiftly developing ones are somewhat underrepresented in the scientific literature on this topic. Shallow landslides – notorious for the lack of precursory signals that indicate the onset of instability – are seldom monitored per se, while alarming scenarios and early warning is typically based on rainfall intensity-duration thresholds.

The development of optical fibre sensing technology allowed for the revival of coherent interferometric optical fibre sensors which feature a simple but efficient sensing principle and therefore emerge as a viable alternative to commercially available optical fibre sensors. Interferometric optical fibre sensing is the least experimented with in the context of geohazard monitoring. On the other hand, the simplicity of the sensing approach allows for an interrogator to be assembled at a fraction of the cost of what is typically available on the market. The proposed sensing solution offers the possibility of a real-time monitoring of dynamic strain, pressure, and vibrations with a broadband spectral analysis, limited only by the adopted analog-to-digital converter and digital signal processing acquisition bandwidths (up to MSamples/s).
Laboratory scale experiments are often carried out to test the applicability of optical fibre sensors for geohazard monitoring. The correspondence of the obtained results in the context of a full-size phenomenon however remains a mystery as the timescale of the process would certainly differ between the two realms and this is seldom accounted for in such studies.

In this thesis, the author proposes the application of a novel optical fibre sensor for the detection of instability caused by intense rainfall in a shallow granular slope. The application is tested in a laboratory environment, while the results are interpreted in the context of a real phenomenon through dimensional analysis.

The objectives of this thesis are therefore the following:

- To verify the ability of the proposed sensors to detect instability precursors in shallow landslides under two different configurations – as a strain and a vibration sensor.
- To infer the laboratory scale results to a full-scale counterpart.
- To illustrate the potential added value of optical fibre sensors when used as a stand-alone monitoring tools and in a combination with rainfall thresholds for the improved definition of early warning systems.

The original contributions of this this work include:

- The use of an innovative optical fibre sensor in the face of coherent interferometric sensing
- Its application to the monitoring of a complex and often poorly understood phenomenon in terms of instability precursors.
- A method for the interpretation of laboratory scale results with reference to a full-scale phenomenon.
- A method for the potential creation of improved rainfall intensity duration thresholds featuring quantitative data from the proposed optical fibre sensors.

The major outcomes of this work can be summarized in the following paragraphs:

Sensor development
The proposed sensors proved to be a viable alternative to commonly used technologies such as the distributed BOTDA/R and OFDR devices in terms of bandwidth and sampling frequency. This allows for the monitoring of both slow-moving and swiftly developing instabilities such as the rainfall-induced landslides. One of the main advantages of the proposed sensing system is its simplicity and limited cost of the interrogating device, which renders it a strong competitor to currently available similar technology.

Contribution to optical fibre sensing based monitoring
Providing a first application of the proposed sensor for geohazard monitoring adds to the research development in this field, where typically sensing installations are based on well-established sensing devices. Experimenting with new technologies promotes the variability, redundancy and efficiency of landslide monitoring tools and generates an echo in the scientific community. The experimental results presented in chapters 3 and 4 demonstrated the potential of the technology to be used as a monitoring tool in two different modes – both as strain and vibration sensors.

Data interpretation
The measurements data obtained from the optical fibre sensors does, to say the least, reflect the development of destabilization and runout phases under both experimental modes.
For what is more, following the data processing techniques, precursory windows were identified in all of the experiments, ranging from 2 to 8 minutes prior to failure for events of duration 15-31 minutes. The length of the precursory windows was found to be a function of the event duration – the shorter the event, the shorter the precursory window and vice versa.

Contribution to landslide monitoring
In order to extend this result to a large scale, an upscaling procedure was proposed based on the conceptual framework of dimensional analysis. This created a bridge between the laboratory and real scale phenomena. It further allowed a broader significance to be attributed to the experimental results, especially in terms of the duration of precursory windows. More specifically, the results of this analysis indicate that a precursory window could potentially range between some tens of minutes to more than an hour for a landslide of a realistic rainfall intensity and soil layer thickness. Finally, the tentative integration between the upscaled experimental results, the optical fibre sensing measurements, and the definition of rainfall intensity-duration thresholds illustrated the potential creation of early warning systems based on quantitative displacement/vibration data.

ON THE DEVELOPMENT OF A GENERAL UNDIFFERENCED UNCOMBINED ADJUSTMENT FOR GNSS OBSERVATIONS

Giulio Tagliaferro – Supervisor: Fernando Sansò

The thesis describes the development of a general processing strategy for GNSS observations and the corresponding software implementation. The strategy was developed during a doctorate program conducted at Geomatics Research & Development (GReD) s.r.l, a company spin-off of the geodetic school of Politecnico di Milano.
The processing strategy has been developed for the purpose of GReD applications, geodetic monitoring of displacement and estimate of tropospheric parameters, but has a general setup in basis to serve most purposes of the use of (Global Navigation Satellite System) GNSS networks of receivers. The whole strategy has been developed with a focus on flexibility, meaning that should be able to process all available GNSS signals with a general as possible parametrization. The strategy has been implemented in the framework of the goGPS project, an open source MATLAB based GNSS processing software, with an important evolution in term of proprietary software of GReD.
The strategy builds upon decades of research in the field referenced in the bibliography. Besides specific implementation aspects, original parts are however presents. The first one is more theoretical and consists of a general way to solve integer least squares rank deficient problems.
In the document a general strategy is presented to derive constraints that generate integer estimates for any rank deficient mixed real and integer least squares problem. The presented strategy is based on the Hermite Normal Form, it's usage for the derivation of a lattice basis for the integer null space and for the finding of a suitable set of constraints is discussed . Specific cases for GNSS estimation are presented, tsuch cases covers most integer rank deficient problem that can be found in GNSS estimation problem. The second original part is more applied and consists on the use of numerical methods to solve rank deficiencies in systems of GNSS observation equation. Popular numerical rank revealing algorithm are applied to GNSS estimation cases. The case of both rank deficiencies for real value parameters and rank deficiencies for integer value parameters are presented. Their performance are validates against state of the art GNSS software or official (International GNSS Service) IGS products. The presented examples contains adjustments of multi GNSS observations coming from both local and global networks. In such validation, data coming from both geodetic grade and low-cost receivers are presented, showing the flexibility of the software in terms of input data quality.
The document is organized as follows, after a few words on the notation used the necessary mathematical foundations are presented. They concern with least squares estimation theory and the presentation is split in two chapters. The first one describes the theory and the corresponding problems the second regards the methods to solve such problems. Both chapters describe the cases of real and integer parameters for both full rank and rank deficient systems. The Least squares theory previously presented is then applied to specific meaningful estimation cases For each problems specific behavior of the system are highlighted. Particular attention is given to typical cases of mixed integer real rank deficiencies and to the derivation of constraints leading to integer estimates. Finally a chapter is dedicated to the specific software implementation and to the presentation of two cases studies.

COPPER TAILINGS AS SUPPLEMENTARY CEMENTITIOUS MATERIAL: ACTIVATION, LEACHING AND ENVIRONMENTAL BEHAVIOUR

Felipe Andres Vargas Munoz - Advisors: Lucia Rigamonti, Mauricio López

The impact of the cement industry on the generation of greenhouse gases (5-8% of the total worldwide) makes mandatory the search for more environmentally compatible alternatives, without affecting the advantages that allow for its wide use in the construction industry. Moreover, waste generation from copper industry, at increasing rates due to the progressively lower grade of minerals, reaching 200 tons of tailings per ton of produced copper, makes mandatory the search for new ways of using such a waste and offers an opportunity for mining industry to be environmentally compatible as well. This is especially critical in countries where copper industry is relevant and a high impact activity such as Chile. This research project associated these challenges by using tailings from the copper industry as a supplementary cementitious material (SCM) capable of replacing an important part of the cement. The use of wastes and/or by-products in the concrete and cement industry is a trend that will rise in the future from actual levels of use, due to necessity of reduction of impacts of cement and construction industry. In the case of copper tailings, increasing levels of production and the increasing need of construction materials to achieve these production levels, including concrete, is relevant to propose the use of alternatives materials for most of the stages of production of a mining site.

To achieve this, the use of mechanical and thermal treatments was studied to improve the cementitious capacity of the tailings, also analysing the capacity of the cementitious matrix to entrap copper and reduce leaching, and finally assessing and evaluating the environmental performance of concrete mixtures with treated tailings.

Copper tailings activation, through grinding and calcination, was studied comparing cementitious mixtures without tailings, with un-treated tailings, and treated tailings, the latter chosen among cases that showed the highest activation potential. Compressive strength results showed that in mixtures at 20% replacement levels, at optimum treatment levels (different for each tailing), an average increase of 34% was observed. At 40% replacement levels, 40% increases on mechanical performance were observed as average. Measurements on pozzolanic activity tested through calorimetry showed an increase between 50% and 130%, that was related with a loss of mass at certain ranges of temperature. Leaching of heavy metals from cementitious samples containing tailings was analysed, studying specifically the mechanism of entrapment of copper phases within the cementitious matrix. The water-to-binder ratio was found to be statistically significant in affecting copper leaching from the cementitious matrix, while the other two factors under investigation (concentration of calcium hydroxide and sodium hydroxide) were found to be not statistically significant, and migration of copper phases during the hydration process towards cementitious products such as calcium silicates hydrates (CSH) was observed. SEM- EDS mapping reveals a higher copper concentration in the calcium silicate hydrates (C-S-H) compared to other hydrated phases, after 7 days of hydration. This suggests that copper migration is controlled by the physical fate of hydration products. Cu K-edge XANES results show that for the case of the LS1 tailing, dissolution of copper sulfate and precipitation of cupric hydroxide results from hydration of the cementitious matrix. Notably, copper sulfide and oxide phases remain mostly invariant from the tailing to the cementitious matrix. Association of copper associated with aluminosilicate phases was not detected. Leaching concentrations were also measured for other metals, observing that when tailings are incorporated into the cementitious matrix, leaching levels are negligible. Finally, with the previous information and results, a methodology was developed to measure the environmental impact of the use of tailings as SCM, using life cycle analysis (LCA) to determine the possible benefit of the use of these materials. As a result, it was determined that the benefits of the use of treated tailings vary depending on their cementitious capacity as SCM, and, at a higher level of mechanical performance, environmental indicators show better results compared to mixtures without tailings. The use of treated tailings as replacement of cement in concrete mixtures can be a promissory way to reduce the use of cement and reduce the impact of the deposit of tailings. Nevertheless, studies need to be carried out to analyse and determine what would be the best use and replacement level of those tailings to improve mechanical and environmental performance. Nevertheless, it is not evident whether a tailing will produce an environmental benefit by its use as replacement of cement or not. Calculations on the effect of the treatment of tailings and the performance of the mixtures are relevant. Also, the performances are not linear, so it is not simple to translate mechanical performance into environmental performance for this type of material. The new proposed methodology allows an accurate comparison of cementitious mixtures with SCM, allowing a proper environmental study of these and other residues.

This research proposed and studied the use of copper tailings as supplementary cementitious material. Results showed that it is possible to use copper tailings as SCM, in a safely way, limiting leaching of heavy metals from cementitious materials, increasing the capacity of the tailings with some treatments from a cementitious point of view and with environmental benefits from their use. Nevertheless, limitations due to heterogeneity of tailings and production systems rise as a major obstacle to generalize conclusions on the use of any specific tailing.