Chair:
Prof. Fernando Sansò

DOCTORAL PROGRAM IN ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

The Doctorate in Environmental and Infrastructure Engineering has been formed in the academic year 2008/2009 as a result of an effort of the previous departmental doctorates to merge their subjects in a culturally unified vision, where the environment is the common background.
In this sense water, its physical behaviour in a natural and in a built context, is a primary constituent of the environment and it is therefore object of investigation of different groups of research looking at theoretical and numerical fluidynamic aspects, to the interaction water-solid earth, describing the flow of water in a natural catchment and projecting civil constructions to properly and sustainably exploit this fundamental resource.
Next to this item is the study of the geological setting in which water flows and with which it interacts, including the creation and possible mitigation of hydrological risks.
Indeed water is one of the basic vehicles through which pollution created by human activity is spread in nature and preserving its quality is one of the fundamental issues of environmental engineering. Not to be forgotten, the same problem has to be confronted with air and its quality, as well as with soil pollution due to solid pollutants, and solid waste management.
One activity which is then interacting with such problems, is that of transportation infrastructures, construction and management, including traffic risks and regulation.
Finally all the environmental problems treated are in fact seated on the surface of the earth or in its immediate surrounding, above and below. Such items as earth observation from different platforms, surveying and monitoring the earth surface by various sensors, are therefore just natural in the training of scientists for the environment.
All that is reflected in the structure of the doctorate which is organized over 5 research areas, namely: Hydraulic engineering, Hydrology, hydraulic structures, water resources and coastal engineering, Environmental technologies, Transport infrastructures, Geomatics.
Accordingly the PhD students first of all do follow a joint curriculum which is composed by a course supplied by the PhD School of Politecnico and deals with very general items, and then three specific courses tailored on the methods that have to be applied in all branches of our doctorate, namely "statistical analysis of environmental data", which comprise the arguments of "Monte Carlo Markov Chain" methods and "Risk assessment", and "numerical methods".

Then each specific area has its own courses and seminars:

Hydraulic engineering
- Fluid mechanics
- Underground waters
- Thermofluidynamics

Hydrology, hydraulic structures, water resources and coastal engineering
- Hydro geostatistics
- Urban hydrology
- Hydrology of mountainous areas

Environmental technologies
- Environmental chemistry and biology
- Environmental monitoring lab
- Models and control of environmental systems
- Reactors for the Environment

Transport infrastructures
- Transportations mathematical models
- Road construction materials
- Experimental and Lab methods
- Structural safety and risk management
- Geological risks
- Urban infrastructures hydrogeology

Geomatics
- Positioning
- Advanced GIS
- Photogrammetry and Image Analysis
- Physical and spatial geodesy
- Data analysis and human sciences

Not to be mentioned seminars, conferences, congresses, workshops at specialistic and international level are normal constituents of the curriculum of our PhD students.

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INVESTIGATION OF FLOW PATTERNS AND SEDIMENTATION IN RECTANGULAR SHALLOW RESERVOIRS

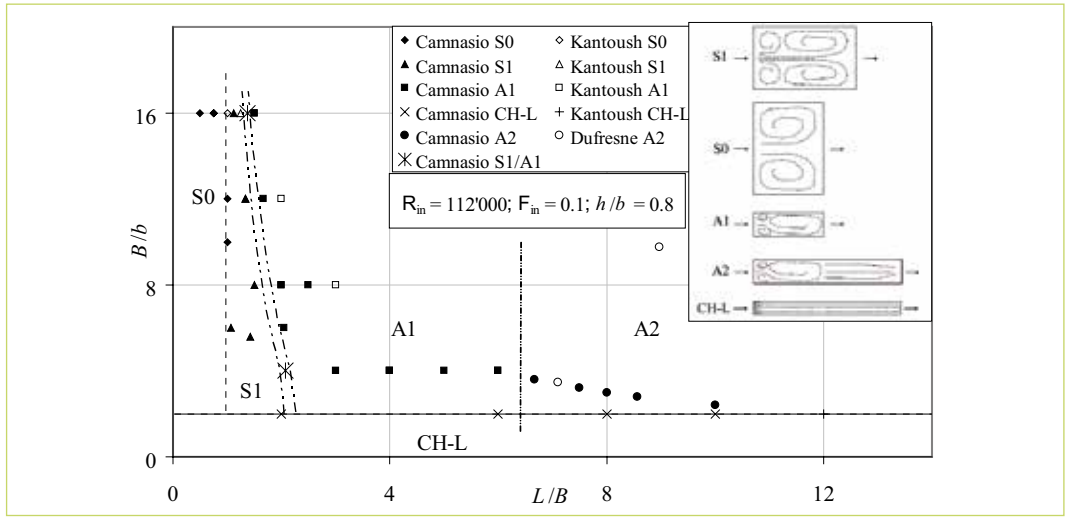
Erica Camnasio

This thesis deals with the classification of the different types of flow patterns that can develop in a rectangular shallow reservoir. After a bibliographic research, with the aim to get knowledge on the state of the art on the subject, the first part of the work has been an experimental activity carried out in the Laboratory of Hydraulic Construction at the Ecole Polytechnique Fédérale de Lausanne. From this research, a wide overview has been obtained on the types of flow patterns that can develop in different reservoir configurations depending on reservoir geometry, at fixed hydraulic conditions. In particular, two non-dimensional geometric parameters have been chosen to identify reservoir geometry, the expansion ratio and the length-to-width ratio. The different types of flow patterns as a function of reservoir geometry, found through the experiments, are represented in Figure 1.

The interest in the investigation of flow patterns types is generated by the strong influence that the fluid-dynamic of the reservoir exerts on the sedimentation processes inside the reservoir. The idea is that, if we better know the fluid-dynamics of the reservoir, then we could also manage in a more effective and efficient way the sediments deposits in the reservoir. So, as far as concerns sediments, experiments were also carried out in order to observe at laboratory scale the influence that the velocity field exerts on sediments deposition of suspended solids entering in the reservoir.
In particular, the influence of an asymmetric location of the inlet and outlet channel on the trapping efficiency of the reservoir has been studied and it has been shown that the presence of sediments in the flow is able in some case to modify the flow pattern.
Then, a numerical activity has been carried out in collaboration with Liège University, with the aim to have a numerical model able to reproduce the velocity fields experimentally found. The experimental data previously collected have been the basis to validate the numerical model WOLF2D, which revealed to be able to reproduce in a quite accurate way and in numerous reservoir configuration, the experimental results.

So, thanks to the validated numerical model, it has been possible to test new reservoir configurations, changing the boundary conditions of the problem. In particular not only the geometry of the reservoir could be easily modified, but also the hydraulic condition were varied, in order to extend the classification of the developing flow patterns not only as a function of reservoir geometry but also on the basis of the hydraulic conditions of the system, reaching a more complete view of the phenomenon.

The change of the hydraulic conditions opens a wide range of possible combinations of the non-dimensional hydraulic parameters of the system (mainly the Reynolds and Froude numbers), which could lead to different types of flow patterns and to a future flow patterns classification not only based on the geometry of the reservoir but also as a function of the hydraulics of the reservoir.
For the moment, the change of the inlet Froude number, that is to say the Froude number of the inlet channel, has shown the existence of a new type of flow pattern, not registered in the previous experiments object of this thesis: it is the meandering flow, whose characteristics have been partially investigated in this thesis by numerical simulations: in particular, the oscillation frequency of the meandering jet has been calculated, and a relationship has been found between the Froude number and the Strouhal number characteristic of the phenomenon. The aim is, in future, to collect quantitative experimental data in order to confirm the numerical model results, even if the existence of this type of flow pattern has been already assessed also from the experimental point of view.



1. Classification of the different types of flow patterns as a function of the length-to-width ratio L/B and of the expansion ratio B/b of the reservoir.

The numerical model WOLF2D has been also endowed with a suspended sediments transport module, by which the deposition process of suspended load can be modelled; the aim is to reproduce the sediments deposits thickness and the global trapping efficiency of the reservoirs configurations experimentally tested, in order to develop a suspended sediment transport model available to simulate other reservoir configurations, changing sediments characteristics or hydraulics parameters, and evaluating their influence on the sedimentation processes.

EARTH SURFACE DEFORMATION AND ELEVATION FIELDS FROM DIFFERENT OBSERVATION TECHNIQUES: VALIDATION AND FUSION PROBLEMS

Maddalena Gilardoni

The validation of novel Earth observations from satellite borne sensors is an actual and important issue for the scientific community. The exploitation of the large amount of data coming from space requires their accuracy assessment by comparison with well consolidated satellite or ground based techniques.
This is the case of the SAR products, different either for the kind of sensors used or for the mission characteristics or for the kind of data and data processing.
This thesis collects the results obtained in the framework of two different projects both funded by the Italian Space Agency in tackling the above problem. In the first case data come from the ENVISAT satellite mission, and the products under analysis are InSAR time series of deformations, in the second case data come from the COSMO-SkyMed satellite mission and the products are radargrammetry digital surface models, DSMs.
The focus of the work is on comparison strategies rather than on the validation results themselves. In order to make different observations of a same phenomenon comparable, they have to be transformed, very often predicted in space and time, thus introducing errors.
Of course it is possible to design validation campaigns in such a way to avoid as much as possible a subsequent data manipulation (for instance making reference observations in the same place and simultaneously with respect to those under evaluation) but very often already existent datasets are used and the way to compare them is to be defined.
A general formulation of the problem would be that of finding that transformation which minimize those errors. This approach was initially pursued by giving a stochastic interpretation to the observations and invoking as optimality principle that of minimizing the variance of prediction errors. The solution found however requires an observations behaviour that is not obeyed in the actual world unless some data pre-processing is applied.
Different ad hoc solutions were therefore adopted and a-posteriori compared. The question is still open, but some key elements have been pointed out.
This dissertation reflects in part the way we approached the problem: a general introduction is given on stochastic fields modelling as well as on collocation and kriging prediction techniques and a general optimal validation procedure is presented. Then the two real cases we dealt with within MORFEO and COSMO-SkyMed are presented, each in a different part of the manuscript.
After recalling the techniques used in the former case to monitor landslide deformations and in the latter to produce digital surface models, the data handling is described.
The strategies adopted are then introduced and compared by using a reference DSM as benchmark. Finally the results are reported both in terms of the evaluating strategies and in terms of validation results.

More precisely, within the ASI MORFEO project the main goal was to find a procedure to validate deformation time series obtained using two DInSAR algorithms (SBAS developed by the IREA of Naples and SPINUA developed by Politecnico of Bari). The validation was done making a local comparison of LOS deformation values and LOS deformation velocities between SBAS and SPINUA time series themselves and between an independent time series derived from GPS observations on the landslide of Ivancich (Assisi, central Italy). This study area was selected because already monitored by SAR and GPS from several years.
The comparison was performed at a local level since the deformation field irregularity make the spatial-temporal prediction error so high to compromise the result of the validation itself. More precisely, the deformation velocity of each GPS point was compared with the velocity of the three nearest SAR permanent scatterers and the cross-comparison between SBAS and SPINUA was done per areas of homogeneous deformation behaviour, testing the equality between the mean deformation velocities of the two datasets.

One of the limit of the comparison procedure is in the GPS dataset used as truth: it revealed to have a too poor accuracy for the validation purpose.
It would be necessary to: select GPS stations in areas with high density of permanent scatterers and recognized to be zones of homogeneous deformation behaviour (GPS permanent stations would be preferable), locate SAR corner reflectors near GPS stations to avoid additional interpolation errors, make more measurement campaigns and with measurement sessions longer than 24 hours in order to obtain very accurate coordinate estimate (few millimeters).
Regarding SPINUA and SBAS cross-comparison, statistical tests on mean velocities in areas with homogeneous behaviour show that the two algorithms, when applied to the same image dataset and after a planimetric bias correction see a statistically equal deformation movement.

To what concern height fields, namely the COSMO-SkyMed project, the purpose was to find a methodology to validate and merge together different DSMs of comparable accuracy; the work was performed on a test area located near the city of Como on ASTER and SRTM height models, used as test fields, in view to be applied to COSMO-SkyMed products initially not available to the project.

The validation was performed in two ways always on the grid of the DSM under analysis: an internal validation permits to identify and remove outliers on the base of their statistical behaviour with respect to their neighbours; both the model resulted to have a very low percentage of outliers (lower then 1%). After that, an external validation procedure was defined; it consists in a proper comparison with a higher precision DSM taken as reference, in this case it has been considered a LiDAR DSM.
The estimated accuracies of ASTER and SRTM agreed with those found in literature.
After that, different methodologies for merging different DSMs, with comparable accuracy and resolution, were tested.
In particular, a generalized collocation procedure to make predictions of the height field or of its linear functional from different functionals of the field itself was implemented.
This technique was applied to merge the point-wise ASTER DSM with 30m resolution and the average SRTM DSM with 90m resolution either to produce an average DSM on the SRTM grid or a point-wise DSM on the ASTER grid.
The final DSM is as or more accurate than the original one. However this strategy is strongly penalized by the empirical estimation of the covariance function as well as by data managing problems. One has always to select areas with a homogeneous behaviour, to be treated separately. This choice is quite arbitrary and heavy.
Merging strategies based on morphology dependent weighted average between height values referred to a same grid were finally adopted, as they prove to be more efficient than weighted average based on global constant weights.
Once the products of COSMO-SkyMed were made available within the project, the procedure to validate and merge different datasets were partially applied to create a DSM starting from sparse point coordinates, computed applying radargrammetry to ascending and descending COSMO-SkyMed stereo-pairs in two test areas near the city of Como (northern Italy).
The results showed that applying the radargrammetric approach to COSMO SkyMed Spotlight images is worthy; DSMs with an accuracy of about 7-8m with a resolution of 5m x 5m can be obtained. These DSMs could be used to improve and detail the SRTM DSM, freely available all over the world; to this aim the developed generalized collocation technique could represent a useful tool.

LIFE CYCLE ANALYSIS OF PREVENTIVE MAINTENANCE TREATMENTS ON ROAD PAVEMENTS: COSTS, PERFORMANCE, AND ENVIRONMENTAL IMPACTS

Filippo Giustozzi

The research aimed to investigate different techniques for maintaining pavement assets. Several maintenance treatments were presented and analyzed according to three main features: cost, performance or effectiveness of the treatment, environmental impact. In addition, the evaluation of maintenance techniques was extended over the service life of the pavement generating an assessment of different maintenance and rehabilitation (M&R) strategies. Several M&R strategies were therefore analyzed according to the three perspectives highlighted above. This comprehensive approach might consequently be useful for road authorities and municipalities in order to more accurately set a M&R plan, or strategy, over the long term. Budget allocation will result to be more efficient, pavement conditions over the service life of the pavement will preserve higher performance, and the environmental impacts related to road maintenance will be consistently reduced. Since uncertainty and variability are often associated to some of the parameters involved, several sensitivity analyses were therefore conducted to better understand results.
Beyond costs and performance assessment, evaluated through experimental pavement sections analysis in the United States, the research was particularly focused on the environmental impacts related to road maintenance and rehabilitation. Indeed, although a significant number of environmental protection measures concerning industrial products and processes have emerged over the past few years, similar procedures have only just started to appear in road construction and related practices. There is a need for understanding what a "sustainable pavement" would entail in terms of greenhouse gas emissions and energy consumption. Since environmental impact assessment of major projects is becoming mandatory in many countries, various studies are attempting to evaluate environmental impacts of different pavement materials, technologies, or processes over a road's life cycle. To support these efforts, there is a need to measure and describe different aspects of sustainability related to pavements.
Assessing the carbon footprint of a product or a project, that is, computing the total amount of pollutants involved and converting them into an equivalent quantity of carbon dioxide, is gaining interests throughout the community. "Low carbon", "green", "recycled", and "sustainable" items are often promoted by the media and reducing the amount of pollutants emitted in the atmosphere is becoming a common goal.
New environmental certification approaches have been developed during the last decade to certify companies, buildings and products. Moreover, road infrastructures are largely spread and account for a major part of land use. Huge amounts of materials, mainly non-renewable or high impact resources (virgin aggregates, bitumen, concrete, polymers, etc.), are consumed every year for construction, maintenance and rehabilitation activities on roads. Finding the way towards a low carbon road pavement over its life cycle represents a great opportunity to reduce greenhouse gasses emissions worldwide and ensure sustainability in infrastructure. Moreover, reducing material consumption through the implementation of recycling practices reflects another useful way to reach the goal previously stated.
Although computing impacts and emissions due to road activities is a step in the right direction, the environmental assessment cannot represent a stand-alone evaluation of a road project or material. It should always be linked together with the performance and the costs of the infrastructure over the life cycle. A potentially environment friendly strategy, in fact, may not be the best performing strategy and could therefore lead to continuous maintenance and rehabilitation interventions, therefore wasting funds and increasing user delays. Consequently, three aspects (cost, performance, and environment) were included in the present research in order to assist road authorities and municipalities in enhancing the management of their resources.

VALIDATION AND FUSION OF DIGITAL SURFACE MODELS

Sara Lucca

In the latest years, acquisition and manipulation techniques for Digital Surface and Terrain Models (DSMs and DTMs) are improving rapidly, allowing the production of data with high resolution and accuracy; on the other hand the development of new sensors allowed the survey of wide portion of the Earth surface, providing free products such as the SRTM DSM and the ASTER global DEM.
Once a dataset of ground point coordinates is available it is necessary to interpolate it to generate a continuous DEM surface; the point-wise dataset can be obtained from different data or surveying systems, such as cartography, photogrammetry, airborne LiDAR, SAR interferometry and radargrammetry.
Depending on the acquisition source the DEM may have different characteristics; in particular they can have various spatial resolutions and vertical precisions: for example DEMs from LiDAR or photogrammetric surveys are more dense and more accurate than DEM from SAR technologies or global DEMs.
The availability, on the same area, of different kind of models gives the possibility to combine different information to obtain more reliable models or to improve an existing one.
However, it is advisable, before attempting to merge different information, to validate the models, that is to assess their accuracy; this step is necessary to know how much a model is reliable, and afterwards the precision of the model can be used as a weight in the merging procedure.
This thesis addressed to all these topics, dealing with DEM creation and validation. All the models under analysis covered an area around Como (Italy); the availability of data created with different techniques and characterized by different resolutions and accuracies permitted to set up and test various fusion procedures.
To validate the DEMs in the area two procedures were carried on in sequence: at first, each model was internally validated and its outliers were removed, then they were compared to a model representing the ground truth to assess their accuracies. The ground truth was represented by a DSM obtained from a LiDAR survey; a raw LiDAR dataset, available in the area, was filtered with different software (TerraScan and GRASS GIS) to produce a high resolution DSM and DTM.
The internal validation step was carried on by using two algorithms developed for the GRASS GIS software (r.outledetect, r.outldetopt) in an adaptive approach; this step was useful to detect and remove possible outliers.
Furthermore, before attempting the fusion step, a two ways ANOVA (ANalysis Of VAriance) was performed on the models to evaluate dependencies on the slope gradient and aspect; in all the tests dependencies on the terrain morphologies were detected; their origin may be found in the survey geometry applied.
In conclusion, the validation and the ANOVA procedures revealed to be useful tools in the data analysis and can be easily applied to different digital models; moreover they provide useful information also for the subsequent fusion step (e.g. the accuracies of the ANOVA classes).
The validation step, in general, is necessary before attempting the data merging, mainly because knowing the accuracies of the models to be merged it is possible to choose the optimum fusion approach.
Once validated, that is, once the actual accuracies of the models are determined and proved to be within the nominal accuracy range, it is possible to merge the information provided by different models.
In the thesis two main fusion strategies were proposed: the former consisted in a weighted average fusion tested with different weights, assuming either the accuracy of the model to be homogeneous or different accuracies of the model according to the terrain morphology. Those accuracies were estimated in different areas, previously classified according to their slope gradient and aspect. The latter procedure was based on the stochastic collocation prediction method tested in areas with different morphologies.
The whole procedure was at first tuned on to the SRTM and ASTER DSMs; once established, it was applied to radargrammetric data to assess which strategy is the most advisable to generate a unique DSM from a couple of dataset, one from ascending orbits and the other from descending ones
Concerning the fusion step involving the SRTM and ASTER DSMs, two main methods were applied: a weighted average to improve the SRTM grid and a collocation approach to improve the ASTER one. The choice between the two different methods was driven by the different data characteristics of the two DSMs.
The former approach, consisting in the weighted average fusion on the SRTM grid generated models more accurate than the SRTM DSM; the latter one, based on the use of the stochastic collocation method to predict the final DSM on the ASTER grid, did not provide as good results as expected: the implemented algorithm is time consuming and the covariance model strongly depends on the region morphology and so does the collocation prediction.
The analysis was performed in six regions characterized by a specific morphology (hill, mountain and plain areas); the results pointed out that the application of this merging method is not worthy for all the dataset: in the mountain areas the SRTM accuracy is lower than the ASTER one, so the merged product is worse than the original one; in the hill areas the accuracies of the original DSMs are comparable, so the SRTM does not add significant information to the ASTER and the merged DSM has similar accuracy of the ASTER original model. The unique areas in which the fusion may represent an improvement with respect to the original ASTER DSM is the plain one: in correspondence with this morphology the SRTM DSM has a greater accuracy than the ASTER one, so it can provide additional information.
In conclusion the fusion on the ASTER grid is not advisable since improvements are possible only in areas where the SRTM accuracy is greater than the ASTER one.
Because of the results obtained in the SRTM-ASTER fusion approaches, on the radargrammetric data only the weighted average approach was tested.
Concerning the radargrammetric data, as already pointed out, two couples of COSMO Spotlight images in zero Doppler/slant range projection (two from ascending orbits and two from descending ones) were available in the area of Como under analysis; the data from the COSMO-SkyMed were too few to apply an interferometric analysis, but they were suitable for a radargrammetric one. The images were processed at La Sapienza University of Rome: the images were at first oriented and then the image matching step was applied to search for homologous points; in the end in two test region two datasets of points, that were then interpolated to generate the DSMs, were obtained.
In this case, the models had the same characteristics and there was the need to find the best method to merge data from ascending and descending orbits. Different approaches were tried, before and after the point-wise dataset interpolations. The best accuracies were obtained with the weighted average fusion of the interpolated models; since the use of the accuracies obtained from the LiDAR DSM comparison and the use of the ones from the ANOVA analysis provides similar results, the best choice is the former one, also because it is easier to implement than the ANOVA based one.
In case more accurate models (such as the LiDAR one) are not available, the best merging method consists in the fusion of the point-wise dataset and their interpolation: this approach mitigates the possible errors coming from the ascending or from the descending point dataset.
All in all, the obtained results confirm that the processing chain proposed in this thesis for the DSM validation and fusion can be successfully applied to different types of data, with the obvious recommendation of choosing the proper analysis method according to the specific data characteristics.

AIRBORNE REMOTE SENSING FOR LAND-USE AND MINERAL MAPPING OF LARGE AREA SURVEYS

Pieralberto Maianti

Among the many ways Earth Remote Sensing methodologies can be categorized, one of the most common distinguishes between airborne sensors and satellite-borne sensors. Their characteristics and use (Tab. 1) are so different and peculiar that, in some way, they almost can be considered complementary: the airborne sensors are generally used for selected hyperspectral analysis on limited areas (few km^2), while satellite sensors are recommended for synoptic vision of large area phenomena (hundreds of km^2). Data preprocessing operations for these two applications are quite simple and consolidated, and quickly provide images suitable for mapping and classification.
Remote Sensing applications like mineral mapping or land cover classification on large areas sometimes require that both spectral and spatial resolution be high, which is a condition that automatically excludes the use of satellite sensors. The only option is to design a hybrid methodology, like extending a hyperspectral airborne flight over a large area, but this choice entails new complex data management and processing issues that don't show up in the standard cases.
The first issue is related to the geometric distortions of airborne images, which effect is amplified when the ground strips are mosaicked. The second issue concerns long time acquisitions, which imply a strong variation in illumination and weather/atmosphere conditions.
The third issue is the presence in the images of Bidirectional Reflectance Distribution Function, an effect of the narrow field of view characterizing airborne sensors. The fourth issue is retrieving the synoptic view of a large area from a set of separated ground strips acquired at different time, flight altitudes and sun-surface-sensor geometry. The fifth and last issue regards storage and management of considerable amounts of data, which for hyperspectral images may reach tens of Gigabytes.
The available hyperspectral images were acquired with MIVIS, an airborne hyperspectral sensor, on two different areas and seasons: one dataset is characterized by anthropized/vegetated land cover and was acquired in a late summer morning, while the second consists in a large desert area flown during a winter morning. For both study areas some field data were available for atmospheric correction (in anthropized/vegetated dataset) and accuracy assessment (in desert dataset). The hyperspectral images, characterized by the aforementioned management and processing issues, were preprocessed in two ways: at first using standard procedures (radiometric calibration, georeference, spectral resampling and atmospheric correction), and then adding unconventional operations (mosaicking, geometric correction and BRDF correction). Afterwards, different classification algorithms (Spectral Angle Mapper, Binary Encoding, Spectral Information Divergence and Maximum Likelihood) were applied to map the territories and then evaluate a-posteriori which is the contribution brought by the standard and the unconventional operations.

The aim of the thesis is to evaluate if the preprocessing operations applied on standard airborne datasets are appropriate also for unconventional ones, or if further procedures have to be taken into account in order to obtain suitable images for land cover and mineralogical mapping. On the anthropized/vegetated dataset this contribution was evaluated through a subjective photo interpretation of the produced maps, while on desert dataset an accuracy analysis has been carried out to allow a comparison with a satellite's standard application on large area as well.
Two hyperspectral datasets were acquired using MIVIS sensor flights above two different environments; these data were then exploited to assess whether the standard airborne images' preprocessing is adequate or not to prepare suitable images for classification. Results on anthropized/vegetated and desert sites (Fig. 1; Fig. 2) proved that the standard preprocessing methodologies are inadequate for the management of unconventional datasets. If further operations are not taken into account, the classification results on large areas are unacceptable in terms of spatial/spectral coherence among runs and synoptic vision.

In order to compensate these problems, ad-hoc preprocessing procedures have been designed and applied to the single strips and the composed dataset:
- image mosaicking to retrieve the synoptic vision;
- further geometric correction to enhance the spatial coherence of the mosaic;
- spectral resampling to select the most significant spectral channels for classification;
- BRDF effect balancing.

If this type of preprocessing is applied, large areas Remote Sensing using an airborne hyperspectral sensor is possible.
Furthermore the classification map produced with an unconventional dataset is more accurate than one obtained using a standard large area monitoring method like Landsat-7 satellite image mapping.
In conclusion, the correct preprocessing of unconventional airborne datasets has to take into account two main problems derived from the use of airborne sensors which regard:
- georeference/geometric correction, as the proper number of GCPs are not always available and just a coarse correction has to be applied;
- atmospheric correction, because the required ancillary field data have high acquisition costs and often have to be retrieved from literature;

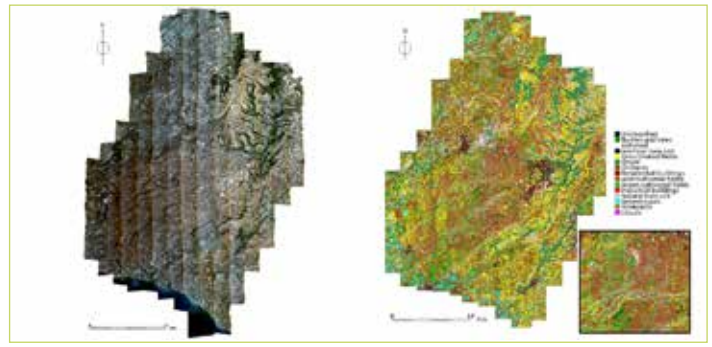
and four problems related to large areas surveys:
- solar illumination, extremely variable from the first to the last of acquired ground strips, induces problems in spectral classification;
- BRDF correction, which needs scan angle maps;
- spectral resampling, which requires a proper equilibrium between spectral characterization and space reduction;
- mosaicking, which entails heavy data managements issues.

If these issues are tackled with the proper preprocessing operations, the following advantages are obtained:
- georeference/geometric correction: proper spatial characterization of mapped surfaces, improvement of mosaic homogeneity and reduction of discontinuities between groundstrips;
- BRDF correction: balancing of groundstrips' illumination enhances classification accuracy;
- spectral resampling: rational data space reduction that keeps the required physical information;
- mosaicking: increase of processing speed and retrieved synoptic view.

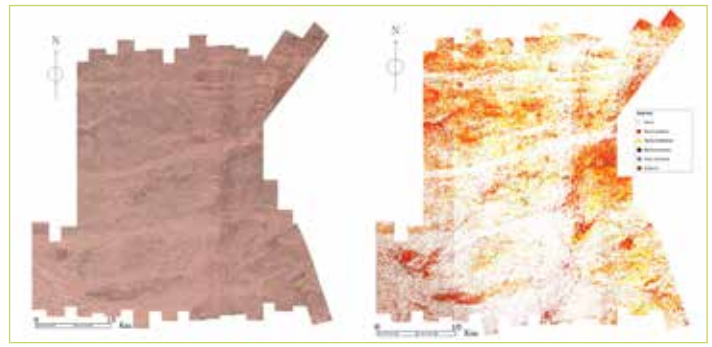
The suggested foreseen developments for this thesis are to apply mineral mapping and land cover classification on other types of environment, to automatize some preprocessing operations (geometric correction, BRDF balancing, mosaicking) and to use other datasets and hyperspectral airborne sensors.

	SATELLITE-BORNE	AIRBORNE
FIELD OF VIEW	synoptic	detailed
COST	low	high
ACQUISITION FREQUENCY	high	low
ACQUISITION PLANNING	fixed	customizable
SPECTRAL/SPATIAL RESOLUTION	conflictive	concurrent
MANAGEMENT COMPLEXITY	low	high

Table 1. Characteristics of satellite and airborne sensors' images.



1. Raw data and classification on anthropized/vegetated dataset.



2. Raw data and classification on desert dataset.

ENVIRONMENTAL COMPATIBILITY OF WASTEWATER TERTIARY REATMENTS TO CONTROL ORGANIC MICROPOLLUTANTS

Matteo Papa

Recent advances in environmental chemistry have brought increasing focus on the presence of anthropogenic substances in the environment: even though the concentrations of these compounds are in the range of µg/L or even ng/L (therefore called "*micropollutants*"), adverse effects on human health cannot be excluded. One such group of anthropogenic substances is represented by endocrine-disrupting chemicals (EDCs), exogenous agents that interfere with the synthesis, secretion, transport, binding, action or elimination of natural hormones in the body, responsible for the maintenance of homeostasis, reproduction and development. Beside the natural/steroidal estrogens, the organic compounds that have been shown to interact with estrogen receptors are the alkylphenols (poly-ethoxylates) AP(EOs), mainly nonylphenol (NP), and other phenolic compounds, mainly bisphenol A (BPA). Recent scientific literature reports data about their trace concentration in water, sediments and aquatic organisms, as well as removal efficiencies of different wastewater treatment schemes. Despite the availability of a huge amount of data, some doubts still persist due to the difficulty in evaluating synergistic effects of trace pollutants in complex matrices.

The application of conventional wastewater treatment does not provide complete elimination of all micropollutants and, consequently, residues of EDCs enter the aquatic ecosystem through WasteWater Treatment Plants (WWTPs) effluents, thus representing the major source of the wide presence of EDCs in water bodies. In order to prevent this kind of water pollution, an advanced treatment downstream the biological process effluent should be implemented.

Several technologies for further micropollutants removal have been investigated: in particular, the application of ozone proved to be a suitable technology for EDCs removal.

In this work, an integrated assessment procedure was used, based on chemical and biological analyses, in order to evaluate the performance of the tertiary chemical oxidation (with ozone). Nonylphenol (NP) and bisphenol A (BPA) were chosen as model EDCs, together with the parent compounds mono- and di-ethoxylated nonylphenol (NP1EO and NP2EO, respectively), and quantified by means of GC-MS). Water estrogenic activity was evaluated by applying the human breast cancer MCF-7 based reporter gene assay.

Experimental work was conducted at both pilot- (reactor volume = 1,500 L, flow-rate up to 6 m^3/h, treating the effluent of a municipal WWTP) and full-scale (a 140.000 p.e. WWTP equipped with a tertiary ozonation stage, treating both domestic and industrial wastewater) plants.

As pilot plant is concerned, influent trace pollutants concentrations were in the range 0.14-0.43 µg/L. Chemical oxidation was described by first order kinetics, rate constants being dependent on reagent dosage: for instance, a 80% removal could be achieved after 60 min at 12 mgO_3/L dosage.

In the full-scale plant, the WWTP effluent prior to chemical oxidation recorded average concentrations of 1.21 and 0.59 µg/L, respectively for NP and BPA, and the removal efficiency of ozonation basin (60 min. effective contact time and 11 mgO_3/L dosage) turned out to be only around 50%: the presence of a significant industrial input (with organic biorecalcitrant molecules) reduced the abatement of target EDCs, with respect to the previous case study.

Then, although chemical analyses successfully revealed the presence of EDCs, only biological assays could effectively measure the total estrogenic activity of a sample: in particular, MCF-7 bioassay was found to be appropriate to determine estrogenic activity in wastewater samples. In particular, in the case of pilot plant, biological analyses (processed with a simplified methodology) confirmed their beneficial effects on the reduction of estrogenicity of CAS effluent. However, unlike analytes, estrogenic activity abatement was not significantly affected by ozone dosage.

On the contrary, as a result for the full-scale plant, the bioassay outcomes (deeper processed with a dose-response pattern) displayed concentrations of estradiol equivalent in the order of ng/L and clarified that ozone is only partially able to reduce the estrogenic activity (less than 20% decrease); moreover, a comparison between measured (by means of *in vitro* bioassay) and predicted (through chemical analysis) estrogenic activity was executed: experimental data highlighted a discrepancy between measured and predicted estrogenicity; as a consequence, the effective estrogenic abatement achieved by means of ozonation was significantly lower than the one predicted based on EDCs concentration. This can be explained considering that: a) a mixture of compounds is responsible for the estrogenic activity, in addition to analyzed EDCs, b) synergistic and potentiating effects between EDCs can occur and c) active by-products can originate, as oxidation intermediates during ozonation.

Finally, the environmental compatibility of the treatment process was assessed, by means of an environmental appraisal framework. Indeed, the comparison of different scenarios (without and with ozonation treatment) highlighted the onset of a conflict (water *vs* atmospheric pollution): the increase of effluent quality, obtained via an energy-intensive treatment, is responsible for air quality decrease. This conflict can be solved only through the definition of an endpoint category: in particular, in this work the damage on human health was identified as final indicator. This approach, coupled with biological assays, made the comparison possible, displaying similar damage values for both the options, with a slight decrease for the scenario involving O_3 process. This analysis, anyway, confirmed that the optimal solution seems to be the control at the source of the pollution (green chemistry), rather than end-of-pipe, energy-intensive approaches.

1. View of the ozonation pilot plant: generator (left) and reactor (right).

ANALYTICAL PROBABILISTIC MODELING OF STORAGE BASINS FOR STORMWATER MANAGEMENT

Anita Raimondi

Storage basins have proven to be effective facilities for flood control; they are used to reduce peak flow rates in the downstream conveyance system and to limit spills of uncontrolled runoff into receiving waters.
In addition detention removes sediments, improving water quality.
Storage basins can be on – line or off – line to the urban drainage system; stormwater can be collected directly from the drainage surfaces (as happens for small catchments like roofs, car parks ...) or diverted into the facility from the main conveyance system by a weir.
Stored waters can then be discharged into receivers, conveyed to treatment plants, infiltrated or reused. It depends on the capacity of the downstream conveyance system and on the characteristics of the soil.
In the traditional urban drainage systems, storage basins were mainly used for the downstream control of runoffs by mean of large, localized facilities as concrete basins and open ponds. On the contrary, in the more modern concept of **Sustainable Urban Drainage System (SUDS)**, stormwater control is localized at the source itself of the runoff. This configuration has a lot of advantages respect to traditional one and allows a more efficient utilization of the downstream urban drainage system.
Examples of source control are percolation and infiltration basins, swales and ditches, permeable surfaces, rainwater tanks...
Many authors have proposed different approaches for modelling and sizing storage basins that can be grouped into three main families: "design storm" methods, continuous simulations and analytical probabilistic approaches.
Traditional **"design storm" methods** are user – friendly and easy to apply but have, as known, some important limitations: they wrongly assume that all rainfall variables in input to the storage and those in output have the same return time, that is meaningless because each rainfall characteristic (volume, intensity, duration) and runoff characteristic (volume, duration, peak rate) generally has its own frequency. In addition, "design storm" methods consider a single event at a time that is the storage completely empty at the beginning of the runoff, neglecting dry weather processes that highly influence the modelling of storage basins.
On the contrary, **continuous simulations**, developed since the fifties, take into account the filling – emptying processes of the storage, considering the possibility of pre – filling between consecutive rainfall events. However these methods, in some cases, are time – consuming and expensive; moreover, a common limitation to their use is the lack of long – continuous series of rainfall data.
As alternative to disadvantages of both "design storm" methods and "continuous simulations", **analytical probabilistic approaches** have been developed. They enable to compute the statistics of the variables in output from the system starting from the statistics of the meteorological variables in input, yielding often to closed – form solutions.
Anyway, in literature, applications of analytical probabilistic approaches to model storage basins neglect or include the possibility of pre –filling from prior storms only as an initial condition of storage, not considering its dynamics in the design.
This work first proposes an analytical probabilistic approach to estimate the **probability of pre – filling and its entity respect to storage capacity**.
Since water carryover from previous storms can be relevant, especially for some management rules and for low outflow rates, a new procedure that considers the probability of pre – filling in the design of storage basins has been developed.
Three different types of common – used storage basins have been modelled: stormwater detention storages, infiltration basins and rainwater tanks.
Stormwater detention storages belong to traditional facilities for downstream runoff control. Infiltration basins and rainwater tanks instead represent an example of local control of runoffs at their source. The first take advantage of the infiltration capacity of the underlying soil; the second reuse stormwater reducing supply demand to water distribution system. They have similar functions but in their design different targets have to be met.
In modelling **stormwater detention storages** the goal is to limit spills; two different management rules for the control of outflows have been considered and the possibility of pre – filling from the previous rainfall event has been taken into account. Starting from analytical conditions that determine an insufficiency of the facility, expressions to compute the Probability Distribution Functions (PDFs) of the failure risk have been proposed. They use as input the PDFs of the rainfall variables that more influence the storage process (rainfall depth, duration, interevent time).
A similar procedure has been applied for the design of **infiltration basins**; in this case the possibility of by – passing the so called "first flush volume" has been also considered, depending on the type of drainage surface and on the characteristics of the soil underlying the basin. The emptying of infiltration basins is a slow process that often lasts some days. As consequence, respect to stormwater detention basins, infiltration basins have higher probability of pre – filling from prior rainfall events. Their modelling depends also on the size of the infiltration area, or better on the ratio between infiltration area and drainage area.
Finally, in the modelling of **rainwater tanks** the interest is to guarantee the stored volume satisfies the need of water for reuse. In this work only the reuse for irrigation during dry periods has been considered. To meet this water demand, it is important that rainwater tanks retain a water carryover from the prior event.
For all types of considered storage basins, expressions for their design have been derived; all these new formulas take also into account the so called InterEvent Time Definition (IETD) for the identification of independent rainfall events and the Initial Abstraction (IA) for hydrological losses.
For their validation the series of rainfall events recorded at the meteorological station of Milano – Monviso, during the period 1991 – 2005 has been used.
Results from the application of the proposed analytical probabilistic approach have been compared with those obtained from the continuous simulation of the observed data.
In addition, to control the effects that the simplifying assumptions of independent rainfall variables – exponentially distributed have on results, a rainfall series whose variables are perfectly independent and exponentially distributed has been generated by a Monte Carlo method.
Comparison of results obtained from the new formulas with those obtained from the continuous simulation of the observed and synthetic series has confirmed the correctness of the proposed analytical probabilistic approach. Its application to different types of storage basins has underlined potentials and limits of the derived expressions.

ADVANCED BIOLOGICAL PROCESSES FOR NITROGEN REMOVAL FROM AGRICULTURAL DIGESTATE

Davide Scaglione

Anaerobic digestion is more and more applied with the double purpose of effectively treating livestock waste-water and as a mean to produce renewable energy as biogas. The liquid fraction of the digested material is rich in ammonium nitrogen; however, its disposal on agricultural soil is often not possible as intensive-breeding farms do not have enough arable land available to comply with the stringent limits on allowed nitrogen loads for land application of manure and other animal wastes. These limits derive from the enforcement of the European directive on nitrates (91/676/CEE) and other recent national and regional regulations, aiming at protecting groundwater from nitrate pollution.
This has stimulated the search for cost-effective nitrogen removal techniques. This thesis is part of a bigger project ("BRAIN", founded by the Italian Ministry of Forestry and Agriculture) that has the general aim of exploring the feasibility of advanced biological processes to reduce nitrogen from agricultural digestate. The main challenges in treating these type of wastewaters with innovative biological nitrogen removal processes concern the wide variability in the characteristics of agricultural digestate, due to (i) the seasonality of the digested matrixes, (ii) the variable operating conditions of the digesters and (iii) the occasional or permanent occurrence of inhibitors such as recalcitrant organics (antibiotics, humic and fulvic acids) or heavy metals.
The BRAIN project considers two biological processes to treat the liquid fraction of agricultural digestate:

- the nitritation-denitritation process (here called "DENO2") and
- the fully autotrophic nitrogen removal process.

The DENO2 process is based on the fact that nitrite is an intermediate compound in both nitrification and denitrification steps, and therefore both nitrate production and reduction can be bypassed. In the fully autotrophic nitrogen removal process, partial nitritation is followed by anaerobic ammonium oxidation via the anammox process, resulting in the production of dinitrogen gas. This thesis deals with the DENO2 process and with the anammox process.
A pilot-scale SBR (800L) has been operated according to the nitritation-denitritation mode. It is located at a piggery farm (20000 pigs) in Lombardy, treated the supernatant from a full scale digester, fed on thickened piggery manure, poultry manure and agro-wastes (maize, wheat). High influent variability in terms of C/N ratio was registered depending on seasonal variation in the piggery waste production, variation in the co-substrates fed to the digester in addition to the piggery wastewater (maize, wheat, poultry manure) and variable anaerobic digestion efficiency. The initial inoculum was already rich in AOB and a stable nitritation efficiency has been maintained: in fact, the NO_2/NOx ratio at the end of the aeration phase remained always around 80-90% at temperature of both 25°C and 30°C, SRT up to 30 d and oxygen concentration of 0.75-1 mgO_2 L^{-1}. Operation at high SRT (20-25d) allowed to maintain nitrogen removal efficiency in the range 60% to 95%, in spite of the high influent COD/N variability (from 1.3 to 5). When COD/N ratio in the influent was higher than 3, the nitrification process in the reactor was less efficient, mainly because of oxygen limitation, which was due to concurrent heterotrophic activity and the thick flocculent biomass matrix. Respirometric tests and microbiological analyses confirmed the hypothesis on oxygen limitation, which was probably due to diffusion through the thick flocculent biomass matrix. Free ammonia and free nitrous acid inhibitions on nitritation activity were assessed: IC50 values were found to be 148±5 $mgNH_3$-N L^{-1} and 0.16±0.02 $mgHNO_2$-N L^{-1}, respectively. During the experimentation, free ammonia affected AOB activity more than free nitrous acid. However, under stable operation, the overall FA and FNA inhibition was calculated to be averagely 8±4% and always lower than 20%. Relevant N_2O emissions, accounting for 14-20% of the N treated, have been detected in preliminary tests.
In this thesis three different lab-scale studies on the anammox process are included, namely:
- anammox enrichment from conventional sludge samples;
- tests to assess the applicability of anammox to treat the liquid fraction of agro-waste digestate;
- nitrite inhibition and recovery of anammox biomass.

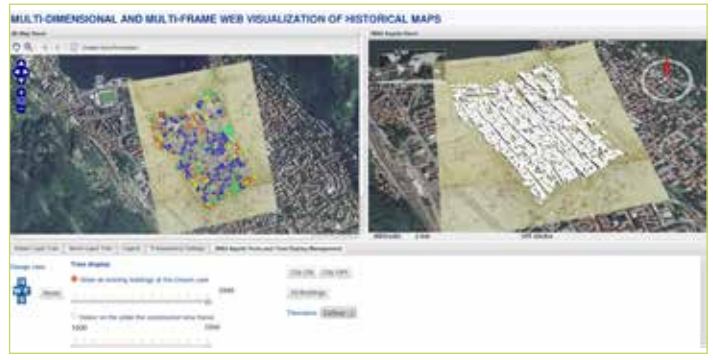
Although anammox microorganisms are widely diffused in both natural and man-made environments, these microorganisms grow very slowly, and the availability of a suitable biomass inoculum is important both for research and applicative purposes. Enrichment from environmental sludge samples is a way to fulfill this need. A simple fed-batch method was applied to enrich six sludge samples collected from Italian wastewater treatment plants treating municipal, yeast-production or swine effluents. All samples were found to be adequate for anammox microorganism enrichment. The length of the lag-phase before such anaerobic ammonium oxidation was observed was around 100 days for most samples, thus similar to that measured in previous attempts. Three of the enriched samples were subsequently mixed and used to inoculate a SBR reactor fed with mineral medium. A 10 fold increase in the nitrogen removal rate was achieved in 80 days, reaching 0.22 gN $L^{-1}d^{-1}$. In the following experimental phase, an highly enriched granular biomass taken from a full scale reactor was used. The stability of the anammox process when treating agricultural digestate after solid/liquid separation and aerobic pre-treatment at different dilution levels was evaluated in a lab-scale SBR. The study was conducted at stable influent nitrogen concentrations comparable to those expected in a full-scale plant. The nitrogen loading rate applied was maintained around 0.6 kg N $m^{-3}d^{-1}$ during the whole experimentation. No pretreatment was applied and the fraction of real wastewater in the influent was gradually increased up to 100% (v/v). Anammox process was stable and could efficiently remove the applied nitrogen load when the percentage of real wastewater in the feed was lower than 70%. The maximum nitrogen removal capacity in the reactor increased 4 times in around 60 days reaching 5.1 kg N $m^{-3}d^{-1}$ despite the fraction of real wastewater blended in the SBR was increased from 10% to 70%. Later on, anammox activity dropped. The causes are still unclear. The most probable reasons may be: the presence of one or more compounds that are already present in the real waste water (e.g. antibiotics, humic/fulvic acids) or one or more compounds which may have been produced in the reactor by hydrolysis of slowly degradable organic compounds. Nevertheless, the anammox process appears to be applicable to this real wastewater after a moderate dilution of 0.5:1, without any further pretreatment. This result need to be confirmed by a future long term experimentation under stable conditions.
Finally the nitrite inhibition effect on anammox biomass was evaluated. Anammox granules from two SBRs fed on very different wastewaters (synthetic medium and landfill leachate) shared many similarities in terms of microbial population and kinetics, resulting in similar response to increasing concentrations of nitrite (100, 200, 300, 500 mgN-NO_2^- L^{-1}). Anammox granules from both reactors were proven to be quite tolerant to moderate to high nitrite concentrations, as long as the exposure time was limited to 3-4 hours with less than 40% activity loss at 500 $mgNO_2^-$-N L^{-1}. However, after prolonged exposure (24 h), the activity loss was substantial (IC50 around 170 $mgNO_2^-$-N L^{-1}). After washing the granules with nitrite-free medium, anammox activity recovered substantially from both SBRs, reaching 60-80% of the initial maximum specific activity. This confirms that major activity losses in anammox reactors can be avoided by a timely identification of process operational conditions causing nitrite build-up in the reactor.

MULTI-DIMENSIONAL AND MULTI-FRAME WEB VISUALIZATION OF HISTORICAL MAPS

Luana Valentini

In the last years, Internet GIS tools have been developing and becoming widespread to allow a more efficient distribution and use of geographic information. An example, investigated in this thesis, is the visualization into a WebGIS of early maps digitized by historical archives, to make this information more user friendly and directly comparable with the reality. In fact, once those maps are georeferenced, they can be overlapped to current cartography to analyse urban evolution in time.
Besides the artistic aspect, maps describe with great accuracy the status of the territory and therefore they are a valuable tool for scholars and professionals working on the represented area (e.g. for urban planning and restoration projects).
In addition to the traditional 2D display of geographical data, nowadays the so-called virtual globes, like Google Earth, are increasingly used in order to extend the perception of the area of interest and give a more realistic representation of reality. These tools are becoming familiar also to non expert users for geographical data browsing. The potential of a 3D system is manifold: complete and more realistic representation of geographic data, greater expressive power, better contextualisation and intuitive navigation.

This leads to the need of revising the way data are presented into WebGISs, which will be no longer two-dimensional only.
In this thesis work a new solution for managing historical and current information, as well as 2D and 3D representation, is presented. This is done exploiting the potentiality of free and open source software, that gives the possibility of extending and modifying the software code according to the particular needs of the problem under study. A multi-frame WebGIS has been realized (see Figure 1), in which a 3D panel, synchronized with the 2D one, helps users in data visualization and understanding, considering also the time domain.
This WebGIS has been specifically applied for the display of various map series made available by the State Archive of Como. These maps are superimposed on the current orthophoto of the city, which is served as a Web Map Service (WMS) by the National Geoportal. In this way users can appreciate the evolution along time of Como walled city.
As mentioned before, this solution can manage the time dimension too. In fact, assigning to building geometries two dates (i.e. 'date of construction' and 'date of demolition'), it makes possible to dynamically view how buildings changed in time, both in shape and height, simply acting on a graphical interface.
At the server-side MapServer has been used. It is an open source platform for publishing spatial data and interactive mapping applications on the Web and serves maps as WMSs.
At the client side, the 2D map panel has been realized using the OpenLayers Web-client and the support of GeoExt, Ext JS libraries. It displays all the historical maps, a recent orthophoto and the current city cartography, representing buildings according to the construction period, the parishes of XVIII century and buildings under conservation programme.
A widget allows users to dynamically change map transparency, so that differences among the different epochs are visually detectable.
The 3D frame is obtained through NASA World Wind, a particular virtual globe which is customizable in content area (texture), elevation (digital elevation model) and in which 2D/3D objects can be placed and themed using colours and/or variable geometry, according to specific attributes associated with the objects themselves.
Having the possibility of improving software code, *ad hoc* functionalities have been developed. A specific data model has been designed to



1. WebGIS interface.

2. Selection of buildings built up between 1675 and 2000 in the 2D view.

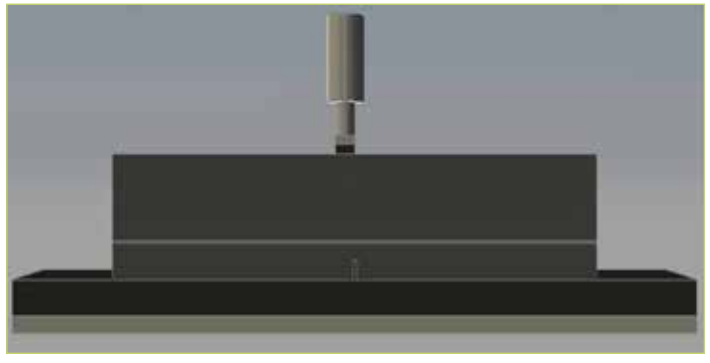
3. Selection of buildings built up between 1675 and 2000 in the 3D view

enable the time support at the server side. In particular, 3D buildings are displayed using their mean height stored in the attribute table of the shapefile, directly read by the NASA World Wind Java Applet. Buildings can be thematized by colour or height according to the construction period and turned on/off by the users.
JavaScript graphical user interfaces make data visualization intuitive also for non-expert users. Thanks to sliders, in fact, it is possible to dynamically display buildings on the globe according to different criteria (see Figure 2 and 3). A synchronization between OpenLayers and World Wind has been implemented in order to maintain a constant alignment of the content represented by the two viewers. Once map layers are turned on for the 2D panel, they are automatically visible also on the globe. The location can be synchronized, too: enabling the synchronization, bounding box extent coordinates are read, transformed from projected to geographic and sent to the NASA World Wind frame in order to visualize the same portion of the globe.

EVALUATION OF THE EFFECTS OF GEOSYNTHETIC EMBEDDED IN ASPHALT PAVEMENTS

Stefania Vismara

Reflective cracking is a challenging topic in road engineering, representing one of the major distresses of asphalt overlays. This phenomenon is commonly defined as the propagation of cracks from the movement of the underlying pavement or base course into and through the new overlay as a result of load-induced and temperature-induced stresses. Three mechanisms start the crack reflection: fatigue due to thermal action (which produces expansion and contraction movements in the old layer), fatigue due to thermal shrinkage (because of the thermal gradient variation throughout the pavement) and fatigue caused by the action of traffic. Further mechanisms are related to differential consolidation and ground contraction. Traffic loads help to spread over cracks. Loads produce high tension and deformation levels in the new layer, just above the existing crack. This discontinuity reduces the bending stiffness strength of the rehabilitated section and creates an area of stress concentration, having a consequent strong influence on durability and functional life of the wearing course.



1. Non-conventional fatigue test set-up.

Asphalt overlay is the most common way to recover damaged pavements and is extensively used to improve flexible pavements. This approach is designed to protect the existing surface against water intrusion, reduce roughness, restore skid resistance, increase structural capacity and improve the overall ride quality to the travelling public. However, cracking has occurred in nearly all types of asphalt overlays due to mechanical and environmental loadings.

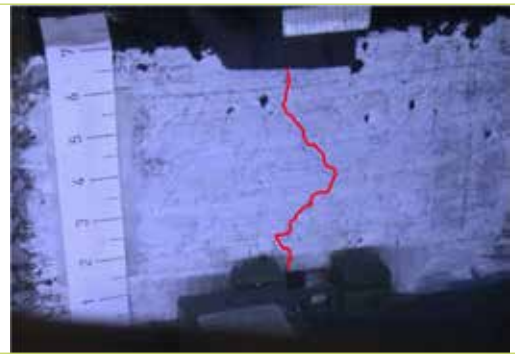
Many different treatments have been studied over the years to prevent reflection cracking. Some treatments have shown significant delays in the appearance, reduction and severity of reflective cracks. Since 1990s reinforcement by means of paving fabrics has represented a method to reduce reflective cracking in asphaltic pavements becoming an important alternative for pavement rehabilitation. Some of the newer and more successful products are geosynthetics, used as reinforcement or separation in subgrades, base and subgrade reinforcements in asphalt overlays. They act as a blocking layer to attenuate and retard the reflective cracking through the new asphalt overlay, as well as providing waterproofing barrier to control water flow through layers below. The literature shows positive results for reflective cracking, regarding asphalt-impregnated geosynthetics. Non-woven geotextiles are the most withstanding materials to rehabilitate damaged pavement structures due to their good adsorption. This type of anti-reflective cracking system is believed to be a solution that improves the pavement performance. They represent effective techniques to control reflective cracking in damaged pavements.

In recent years a significant amount of efforts have been done in laboratory as well as in field, in the context of characterization of behaviour of geocomposites embedded in asphalt pavements.

The present research is the result of collaboration between Politecnico di Milano and Delft University of Technology. It has been undertaken within the study of two types of geosynthetic embedded in asphalt overlays that are made up of polypropylene non-woven and fiberglass grid with high tensile strength. To gain this aim double-layer systems were prepared and tested in the laboratory to evaluate the response to both monotonic and cyclic loadings to failure.

An exhaustive experimental program was conducted. Mechanical performance of the composite systems, as prepared in the laboratory, was investigated by means of different laboratory tests, such as indirect tensile strength test and traditional shear tests. A decrease of shear and tensile strength values were observed when the geosynthetic was included in the system.

2. Crack path in unreinforced double-layered system.



3. Crack path in reinforced double-layered system.

Despite the outcomes, the geosynthetics provided benefit to the response of asphalt pavement to monotonic loadings to failure; in fact the corresponding positive effect was the prevention of layers to separation and the consequent ability to be reloaded. The slippage was avoided by the adhesion guaranteed between the reinforcement and the asphalt layers and the two halves of the specimen were prevented from separation.

Further investigations focused on the response of reinforced systems to cyclic loading. A non-conventional fatigue test was performed in order to study the crack propagation in reinforced systems and simulate the real operating conditions of a pavement. The overlay tester consists of an asphalt overlay glued to a rubber plate resting on a fixed steel plate. The set-up is reported in Figure 1. The beams were mechanically notched in the middle lower part to simulate the effect of a crack in the existing pavement. Simulated-repeated loading, axisymmetric and haversine, was applied to the specimens and crack opening displacements were measured around the notch and immediately above and below the interlayer.

The characteristic fracture process was monitored recording the tests, highlighting the different crack paths, as reported in Figure 2 and Figure 3. Without the geosynthetic the crack developed under the loading continued to penetrate the entire layer and quickly reached the top of the overlay. With the inclusion of the reinforcement crack developed from the bottom of the overlay, then cracking energy was trapped by geogrid. Moreover, the horizontal movements were significantly reduced immediately above and below the geosynthetic. It suggests the ability of the geosynthetic to strengthen the pavement and delay the crack propagation. Findings have clearly shown the contribution of the composite embedded in the samples to enhance the asphalt pavement performances.