

MECHANICAL ENGINEERING / PHYSICS /  
PRESERVATION OF THE ARCHITECTURAL  
HERITAGE / STRUCTURAL, SEISMIC AND  
GEOTECHNICAL ENGINEERING / URBAN  
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MATERIALS ENGINEERING / MATHEMATICAL  
MODELS AND METHODS IN ENGINEERING



Chair:  
**Prof. Umberto Perego**

## DOCTORAL PROGRAM IN STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING

### Objectives of the Doctoral Program

Structural, Seismic and Geotechnical Engineering (SSGE) encompasses disciplines and techniques allowing understanding, modeling and controlling the behavior of: (a) structural materials (concrete, steel, masonry, composites, bio-materials, materials for micro-systems and metamaterials), (b) structural systems (from civil and industrial structures and infrastructures to bio-mechanical systems and micro-systems) and (c) environment-structure interaction.

Deeply-rooted in the Civil Engineering, SSGE focuses on environmental actions, either external (such as earthquake, vibrations, irradiation, wind and fire) or ensuing from soil-structure interaction. The methods developed within the domain of SSGE apply to different scales and different physical processes and, as such, are of great importance also in other technical-scientific fields, whenever understanding and controlling structural and material behavior is necessary to guarantee design reliability and structural safety, as well as serviceability and durability. Many are the themes arising in connection to SSGE: from tall buildings and bridges to industrial bio-mechanical and micro-electromechanical systems; from off-shore structures and dams to the rehabilitation of historical buildings; from seismic design and structural dynamics to the behavior of geomaterials and new engineered metamaterials.

Within this framework, the main goal of our Graduate School is to promote the advancement of knowledge especially in the fields of: (a) innovation in structural materials and structures; (b) structural safety under highly-variable actions; (c) behavior of geomaterials and surface structures.

We pursue this goal by offering our PhD Candidates an advanced, research-oriented background, based on both the pivotal role of Structural Engineering and the multi-disciplinary nature of Seismic and Geotechnical Engineering.

### Contents of the Doctoral Program

Attainment of a PhD in Structural, Seismic and Geotechnical Engineering is conditional to: a minimum of three full-time years' study and research activities; the development of a PhD thesis; the achievement of the minimum credits required in terms of PhD courses.

Candidates are offered a variety of advanced courses on different topics, including mechanics of soils, materials and structures; computational and

experimental methods; structural dynamics and earthquake engineering.

The study plan includes courses and seminars given by scientists, experts and researchers active either at the Politecnico di Milano or in other Italian and foreign Universities, research institutions and high-tech companies. During their studies, PhD Candidates should develop their own original research work, consistent with the main disciplines dealt with in the Doctoral program, which will be reported in the PhD thesis.

The thesis should clearly state the goals of the research work, explaining the relation with the state-of-the-art, the used methods and the original results obtained.

The PhD research is developed under the guidance of a supervisor.

In order to widen and improve their research experience, PhD Candidates are strongly encouraged to spend a period abroad in one of the many Universities and research centers related to the Politecnico di Milano.

At the same time, the PhD School supports foreign scholars to give short courses and seminars in Milan, so that our PhD Candidates can constantly benefit from the opportunity to interact with the international scientific community.

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# GRADED ELASTIC METAMATERIALS FOR ENERGY HARVESTING

Jacopo Maria De Ponti - Supervisors: Alberto Corigliano, Francesco Braghin

Co-supervisor: Raffaele Ardito, Richard V. Craster

Interconnection between machines, devices and people is one of the key aspects of the contemporary society and its working paradigms, which are driving the so called *Fourth industrial revolution* or *Industry 4.0* (Hannover Fair, 2011). In this perspective, *Machine to Machine communication* (M2M) and *Internet of Things* (IoT) are able to provide increased automation, improved communication and self-monitoring, in different environments and industrial processes. A driving central force of innovation is represented by smart sensors and devices, which generate the data and allow further functionality from self-monitoring and self-configuration to condition monitoring of complex processes. This new generation of sensors has to be small, economically feasible and autonomous.

The reduced power requirements of recent small electronic components makes on-chip energy harvesting solutions a promising alternative to batteries or complex wiring. Amongst others, vibration-based energy harvesting schemes are particularly attractive due to the numerous and continuous sources of vibration present in the environment. However, due to the low amount of energy involved in common ambient vibrations, it is interesting to focus, or trap, waves from a larger region outside the device into a confined region in the near vicinity of the

sensor; once the wave is localised, by using electromagnetic, electrostatic, or piezoelectric effects, efficient conversion from elastic to electric energy can be achieved.

This work contains current developments in this technology, by presenting innovative energy harvesting solutions based on the introduction of piezoelectric materials inside graded metamaterials made of arrays of resonators. Starting from the investigation of novel wave phenomena in inhomogeneous media and elastic metamaterials, advanced multiresonator designs for energy harvesting are proposed. The major contributions of this thesis are:

(1) study of wave propagation in elastic solids based on spatial heterogeneities. It is demonstrated that high vibration attenuation can be achieved in inhomogeneous structures independently on periodicity. Moreover, simple lumped models allow to characterise the behaviour of such structures, providing a rapid analytical tool for the definition of efficient designs;

(2) investigation of wave conversion phenomena in elastic half-spaces with graded arrays of resonators. Reversed mode conversion from surface Rayleigh to Shear (S) and Pressure (P) bulk waves is demonstrated leveraging on the Umklapp phenomenon. This mechanism allows

to manipulate surface waves, focusing the elastic energy in specific regions of space for a broadband input frequency spectrum;

(3) modeling, design, and experimental study of graded metamaterials based on the *rainbow effect*, i.e. the spatial signal separation depending on frequency, for energy harvesting purposes. Advanced multiresonator designs based on rainbow reflection (Figure 1,2), rainbow trapping and topological edge modes are investigated. Enhancement of the energy harvesting performances with respect to conventional solutions is demonstrated, for both the peak power production and the total transduced energy along time.

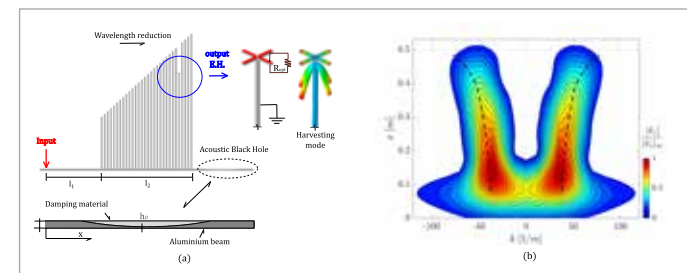


Fig. 1

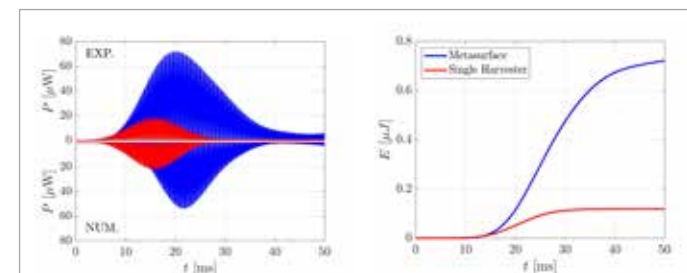


Fig. 2

## THEORETICAL MODELLING OF EMBANKMENTS BASED ON PILED FOUNDATIONS

**Viviana Mangraviti** - Supervisor: Claudio Di Prisco

Piled foundations are commonly employed to reduce settlements in artificial earth embankments on soft soil strata. To limit the number of piles and, consequently, construction costs, popular is the use of geosynthetic reinforcements laid at the embankment base. Due to the complex interaction phenomena occurring between (i) piles, (ii) foundation soil, (iii) embankment soil and (iv) geosynthetics, different aspects such as either time dependency or friction between piles and surrounding soil are

often ignored. Moreover, simplified displacement-based approaches to choose reinforcements, pile diameter and spacing are missing in the literature. In this thesis, a series of numerical analyses are performed and, by using an upscaling procedure based on both the concept of sub-structuring of the spatial domain and plane of equal settlements, a theoretical method capable of represent the mechanical behaviour of geo-reinforced piled embankments is introduced. The effect of: (i) friction between piles and soil; (ii)

consolidation occurring within the foundation soil and (iii) settlements at the pile base is considered. By sub-structuring the spatial domain, rheological models are provided to evaluate settlements at the top of the embankment. In particular, predictive tools allowing a rapid assessment of both (i) differential and average settlements at the top of the embankment and (ii) (when geosynthetics are present) the maximum tensile force acting within the basal reinforcement have been conceived.

# SEISMIC RESPONSE AND STRENGTHENING OF FLAT SLAB BUILDING

**Teresa Netti - Supervisor: Dario Coronelli**

With the aim of clarifying flat slab design rules and to dedicating a specific design code, several experimental studies have been carried out and a specific section of this dissertation examines the state of the art for these tests. Many tests regard the isolated slab column connections, fewer the single flat slab floor and even fewer that of a complete building. The main reason for this lack of tests on real scale building is the limitation imposed by the dimensions, in fact it is frequently impossible to build and to test a whole building inside a laboratory. The related costs are another important factor, limiting this type of research.

The SlabSTRESS project was developed to satisfy this need and this dissertation studies the behaviour of a real scale flat-slab building. This dissertation is focuses mainly on the behaviour of a real scale flat-slab building with the aim to correlate the overall behaviour to the response of single connections, considering location within the floor, the longitudinal reinforcement layout and presence otherwise of transversal reinforcement for punching shear. The SlabSTRESS experimental campaign was performed at the ELSA Reaction Wall in the European Commission's Joint Research Centre (JRC) in Ispra (VA, Italy) during the transnational access activities of the SERA project.

The real-scale mock-up consisted of a reinforced concrete building with two ordinary thick slabs, supported by twelve columns on each floor one of which provided with transverse reinforcement.

The building was designed considering the flat slabs as secondary members, with seismic resistant walls as primary ductile elements. The structure was designed to bear gravity loads and able to reach a lateral relative inter storey drift compatible with moderate-high seismic lateral actions. This design procedure was inspired by the method used in the North American codes for the seismic design of flat slabs.

The primary seismic walls were not actually built in the structure but were virtual elements, simulated by the sub-structuring allowed by the pseudo-dynamic method used in the host lab.

A specific design was made for the RC columns, with a structural steel stub in the middle of these members. These last were required for measuring internal forces and bending moment in each slab-column connection. The first phase of the test programme simulated two levels of seismic activity: the service limit state (SLS) and the ultimate limit state (ULS). The seismic loading was applied using the pseudo-dynamic technique with linear sub-structuring. The pseudodynamic (PsD) testing method

is a hybrid technique based on an equation of motion formulated for a discrete number of degrees of freedoms (DoFs), integrated in time using appropriate numerical schemes. The seismic response of large-size specimens can be obtained by the combination of the experimental restoring forces with the analytical inertia and seismic-equivalent forces. The method is based on an equation that combines a numerical model for the inertial and external forces with an experimental model for the restoring forces.

Successively, during the second phase two cyclic tests were carried out to test the floors for a combination of gravity and lateral cyclic loading of increasing amplitude, up to near-failure conditions. Prior to the second cyclic test some of the damaged connections were strengthened and then were tested again.

Both the global and the local measurements were acquired. Each column on both floors was provided with a system designed ad hoc that allowed to measure the internal forces and bending moment. A large number of sensors were used in this experimental campaign, 80 inclinometers, 48 extensometers and 192 strain-gauges, which permitted to collect a series of data. All the sensors had been previously calibrated to ensure the precision of the measurement system. A new controller and data acquisition system, called

ElsaREC, was developed by the team of the ELSA laboratory and here used for the first time, allowing a systematic calibration procedure for all the sensors adopted in the experimentation for the first time at ELSA.

Given the complexity of the analysed structure, a simplifying procedure was required to break down the structure into parts, allowing a more precise analysis of all the connections involved. Using the main statics and kinematics parameters, two simplified models were chosen to represent the structure from a global and a local point of view. Two kinematics parameters, one displacement for each floor and two static parameters, one force for each floor described the global system. These parameters were acquired by the load cells applied to the actuators, while displacement transducers applied on two reference frames near the structure recorded the corresponding displacements.

The local system to capture the behaviour of each slab-column connection was more complex. The slab and the column rotations represented the local kinematic parameters that were recorded using the inclinometers, and the slab cracks opening was recorded using the displacement transducers.

Local kinematic measurements were acquired in the surrounding area of the slab on eight out of the twelve

columns. The three typologies of connection (internal, edge and corner) were analysed with four, three and two instrumented sides respectively. Each side of slab-column connection was equipped with an inclinometer to measure slab rotation along the East-West direction and a set of displacement transducers to measure crack opening through an increase of the slab thickness.

Using the acquired slab rotation data and the column of each slab-column connection, it was possible to derive the relative rotation of the slab with respect to the column.

The static parameters are two for each slab-column connection: shear and bending moment; making four static quantities for each column. These parameters were acquired using load cells located at the centre of each column on each floor, appositely designed for this experimental campaign.

The recorded signals were then processed in order to characterise both the global behaviour and the local behaviour of slab-column connections. All the global analyses were performed using the inter-storey drift ratio as main coordinates to represent the behaviour of the structure. At local level the inter-storey drift ratio was correlated to local measures, columns and slabs rotations. Finally reported is the procedure followed to obtain the conversion factors that allow

to convert the inter-storey drift ratio to the column-slab rotation in function of the slab-column connections typology. The final aim of the developed methodology is to compare SlabSTRESS results with the experimental results obtained in the past, mainly on single slab-column connections, together with the simplifications of those numerical analyses in which the inter-storey drift is known but the corresponding rotation is unknown.

The comparison between the SlabSTRESS experimental results and the literature data was done firstly considering similar experiments on entire building or on single flat-slab floors and then considering experiments on single slab-column connection. The SlabSTRESS results are compared, evidencing their innovative aspects.

# MICROSTRUCTURE-BASED MODELLING OF THE VOLUMETRIC CHEMO-HYDRO-MECHANICAL BEHAVIOUR OF CLAYS

**Giulia Scelsi** - Supervisor: **Gabriele Della Vecchia**

**Co-supervisor: Guido Musso**

Pore fluid salinity has relevant effects on the hydro-mechanical behaviour of clays and its appropriate modelling is essential in many applications in the field of environmental geotechnics.

Starting from microstructural observations, this research project aims at modelling the volumetric chemo-hydro-mechanical behaviour of clayey materials.

The framework makes a clear distinction between non-active clays, for which salinity changes mostly affect the mutual orientation between single particles or between clusters of a limited number of particles, and active clays, for which salinity changes also impact on the volume of aggregates made of a larger number of particles.

For saturated non-active clays, a simple chemo-mechanical model is formulated in the context of elasto-plasticity with generalized hardening. The model stems from physical evidences of the processes

triggered by osmotic changes, and specifically on the influence that the osmotic suction has on the normal compression line of the soil.

The modelling framework is extended to partially saturated non-active clays in saline environments. The extension is based on the observation that both increases in matric and osmotic suction are related to the transition from a closed to an open microfabric. The equivalence introduced between matric suction and osmotic suction, based on the anticipated effects on material microfabric, enables the reproduction of the joint effects of degree of saturation and salinity changes on non-active clays.

As for active clays, the modelling framework is extended to account for aggregate evolution due to changes in pore fluid salinity and the consequent interaction between the micro and macro-structure. The effect of pore water salinity on retention properties of compacted active clays

is reproduced adopting a double porosity framework.

The role of the deforming aggregates is also accounted for in the elasto-plastic modelling of saturated active clays. The framework for describing their chemo-mechanical response stems from the model of non-active clays. Additional elements were introduced in order to incorporate explicitly the effects of chemical changes at the aggregate level and to consider the irreversibility of salinization and desalinization processes.

Both chemo-mechanical models for non-active and active clays are used with success to simulate chemo-mechanical oedometer tests on reconstituted, compacted, and natural materials. The water retention model is also validated against experimental data from the literature, showing good predictive capabilities.

# CHARACTERIZATION AND MONITORING OF AN UNSTABLE ROCK FACE BY MICROSEISMIC METHODS

Zhiyong Zhang - Supervisor: Luigi Zanzi

Unstable rock slopes are likely to cause rockfalls, threatening human lives and properties, industrial activities, and transportation infrastructures in mountain areas. There is an increasing demand to forecast and mitigate the potential damage of rockfalls by developing a reliable early warning system. Since passive seismic techniques can acquire information about the propagation of fractures within the rock mass, microseismic monitoring has been increasingly used in rockfall studies during the last two decades. In this thesis, a mountain slope that is facing Lecco city in northern Italy was selected as the research target. The mountain slope is a 300 m-high steep limestone rock face. This area has been historically prone to rockfalls and is still dangerous due to the occurrence of rockfalls. A microseismic monitoring network was installed and has been operating since 2013 as a field research laboratory to study the microseismic monitoring technique in the perspective of developing rockfall early warning systems. Locating microseismic events is a basic step of this technique to obtain the location of developing cracks as possible precursors of rockfalls. However, it is still a challenging task due to the heterogeneity of fractured rock slopes and the weakness of acoustic emissions generated from the release of stress. The main purpose of this

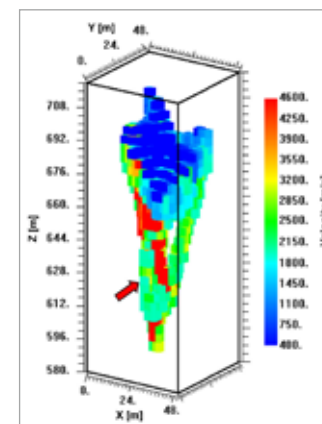
thesis is to address the issues related to event localization for microseismic monitoring strategy applied to the unstable rock face. The most original contributions of the thesis include the analysis of the localization accuracy extended to the whole monitored rock mass, the microseismic event classification based on hypocenter location and the design of expanded networks to improve location accuracy and microseismic event classification. To construct the three-dimensional (3D) velocity model required for reliable hypocenter localization, a seismic tomographic survey was performed on the mountain surface above the rock face. Source test measurements were conducted to select a suitable source capable of triggering all geophones. Hammer emerged among the other tested

options as the preferred source because it performed like the seismic gun in terms of signal energy and spectral content while demonstrating superiority in terms of portability and flexibility in the harsh environment of the study site. Seismic traveltimes inversion showed high heterogeneity of the rock mass with significant contrasts in velocity distribution. Low velocities were found at the shallow depth on top of the rock cliff and intermediate velocities were observed in the most critical area of the rock face corresponding to a partially detached pillar. Two sensitivity tests were implemented to evaluate the resolution and stability of the inversion. After obtaining the 3D velocity model from the inversion, the global grid search location method was selected for event localization and the misfit



**Fig. 1 - The study site in the southern part of Mount San Martino. (a) Front view of Mount San Martino from Lecco city. The yellow rectangle indicates the monitored area where the monitoring network was deployed. (b) Rock face with the positions of the five geophones and the acquisition board of the microseismic monitoring system. The red arrow indicates the partially detached pillar below geophone 4. (c) Photogrammetric model of the monitored area with the orientations of the five geophones.**

function was defined based on the Equal Differential Time (EDT) method. Seismic shots with known positions were located to estimate the location accuracy on the upper part of the rock mass. The hypocenter misfits were around 15 m with the 5 geophones of the microseismic network and the error was significantly decreased compared to the results produced by a constant velocity model. Besides, the analysis of location accuracy was extended to the whole volume of the rock mass by using synthetic traveltimes affected by random errors. Although three geophones of the seismic network are installed near the critical area where the partially



**Fig. 2 - Velocity model obtained from 3D tomographic inversion using a 2x2x4 m grid. Colored blocks indicate the velocity field in the rock mass where at least one ray travels. The red arrow indicates the partially detached pillar on top of which geophone 4 is installed.**

detached rock pillar was located, accuracy in this area is not better than the accuracy on the upper part of the rock face probably due to the high heterogeneity of rock mass and the higher velocities in this area. The classification procedure for microseismic events was explored by the hypocenter location of a subset of microseismic events with high data quality, which is one of the novelties of this research work. The microseismic events were preliminarily classified into two subclasses: suspected rockfall events with multiple signals in the recordings and suspected fracture events with a single signal in the recordings. The location results for the suspected rockfall events almost met our expectations. Most of the signals in rockfall events were located on or near the rock face thus confirming the initial classification. For the suspected fracture events, only a few (4 out of 20) events were located inside the rock mass at such a distance from the rock face that they cannot be confused with rockfalls. Further improvements in location accuracy are necessary to distinguish suspected fracture events that were located close to the rock face from rockfalls. On the other hand, the hypocenter location helped to identify events generated outside the monitored area and rockfalls that were located on the rock surface at the summit of the rock face. This feasibility study shows

that the hypocenter location is a promising method to improve the final classification of microseismic events. Another original contribution of the thesis is to suggest a procedure for designing an expanded network in order to improve the localization accuracy in the most critical part of the rock mass. Additional geophones were progressively added to the existing network, selecting their positions with special care to improve the azimuth coverage and source-receiver distance coverage. Three progressively expanded networks with 9, 13 and 15 geophones were studied to explore the improvement in location accuracy and it was observed that the location error was reduced from 12-24 m (5 geophones) to 4-6 m (15 geophones). The relatively low location errors in the critical part with 15 geophones would help to improve the classification of microseismic events. The method can be used in future network expansion.