MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING | URBAN PLANNING, DESIGN AND POLICY | AEROSPACE ENGINEERING | ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING | ARCHITECTURAL, URBAN AND INTERIOR DESIGN | BIOENGINEERING | DATA ANALYTICS AND DECISION SCIENCES | DESIGN | ELECTRICAL ENGINEERING | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | MANAGEMENT ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2024

DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Chair:
Prof. Stefano Mariani

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 process 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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ASYMPTOTIC HOMOGENIZATION OF METAMATERIALS AND METAPLATES: LINEAR AND NONLINEAR BEHAVIOUR

David Faraci - Supervisor: Prof. Claudia Comi

Metamaterials are artificial materials that have attracted a lot of interest thanks to their peculiar properties, which are provided by their designed microstructure rather than their constituent materials. They typically have periodic or almost-periodic heterogeneities, which can be voids or different materials, whose characteristic size is far below the global dimension of the macroscopic media. This aspect could represent a problem in finite element simulations of metamaterials, where the computational burden may be huge due to the fine mesh that would be required to discretize the microstructure. A possible solution is constituted by homogenization techniques, which are a family of methods that are able to characterize the macroscopic effective behaviour of metamaterials starting from their specific microstructure. The two-scale asymptotic homogenization method is a well-founded mathematical technique that in linear problems allows obtaining an explicit expression of the effective properties and, in some particular cases, closed-form analytical solution. The present work aims to exploit its potentialities in the linear analysis of metamaterials and to explore possible extensions to nonlinear problems, both for periodic solid media and periodic structural elements such as plates. In the first part of the work, asymptotic homogenization is employed for the static characterization of periodic solids in the linear regime. When sources of nonlinearity arise, we discuss how, in some cases, linear asymptotic homogenization can still be employed. Then, a computational micromorphic homogenization scheme is considered for the static characterization of hyperelastic materials in large displacements.

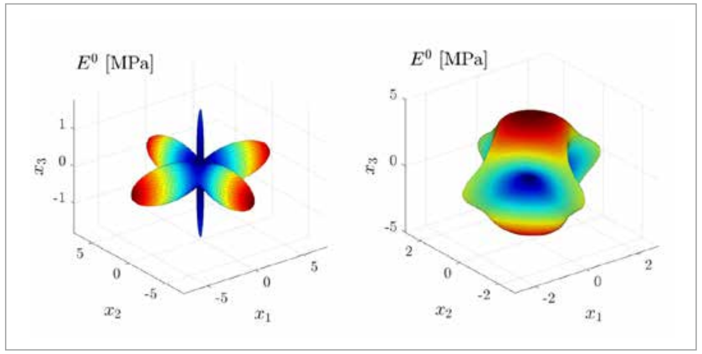

Fig. 1 - Spherical diagrams of the homogenized Young's modulus, as a function of the traction direction, for two different periodic metamaterials employed in impact protective devices.

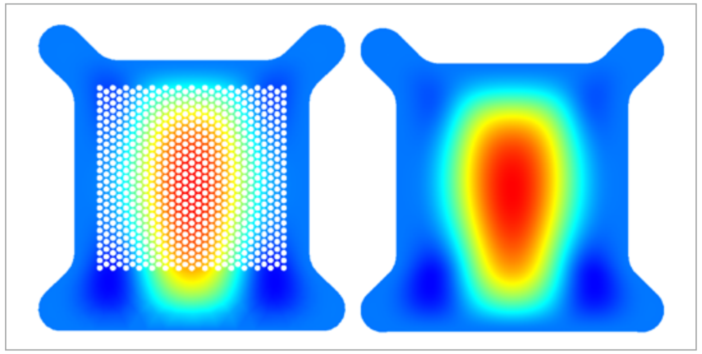

Fig. 2 - Comparison between the nonlinear response of a periodically perforated plate (left), subject to a transversal load and anchors-imposed displacements, and the corresponding homogenized one (right).

In the second part, we apply asymptotic homogenization to study the effective behaviour of periodic plates. The method is employed to characterize both the linear and nonlinear static regime of metaplates, as well as the dynamic behaviour of locally resonant plates. The homogenization procedure is applied throughout the work to several reference problems, which helps to emphasise the possible advantages of the method both in terms of accuracy and in terms of computational time.

DESIGN, MULTIPHYSICS MODELING AND EXPERIMENTAL CHARACTERIZATION OF A PIEZOELECTRIC MEMS LOUDSPEAKER FOR IN-EAR APPLICATIONS

Chiara Gazzola – Supervisor: Prof. Alberto Corigliano

Co- Supervisors: Prof. Valentina Zega, Prof. Pierrick Lotton

Micro-Electro-Mechanical-Systems (MEMS) represent one of the most promising technologies of the 21st century, being used in countless applications ranging from sensing (e.g. gyroscopes, accelerometers, magnetometers), to timing (e.g. resonators) and actuation (e.g. microactuators, micro-mirrors). Acoustic MEMS have seen a fast increase in interest over the last years, due to the exponentially increasing market demand for portable audio devices to become smaller and smaller. After the successful establishment of MEMS microphones as state-of-the-art solution for mobile applications, more and more attention is paid to the field of MEMS speakers, as they promise lower power consumption, smaller dimensions and cheaper mass production with respect to traditional microspeakers. The piezoelectric actuation principle, thanks to the relatively large driving force achievable at low voltages, has been recognized as the most promising implementation of loudspeakers at the microscale. Despite a significant number of new structures have been proposed in the recent years, MEMS Loudspeakers struggle to be competitive in terms of performances compared to the non-MEMS counterpart for free field applications. Whereas, some piezoelectric MEMS speakers for in-ear applications have been demonstrated to comply with the market requirements. For this configuration in fact, the pressure chamber effect due to the closed volume defined by the ear canal, allows the generation of high Sound Pressure Level (SPL) without excessive deflections of the mechanical diaphragm. Despite a significant number of promising proof-of-concepts, research work is still needed both at the design level, in order to obtain full-range microspeakers with good sound quality, and at the simulation level, to accurately capture the linear and nonlinear responses of this type of devices. In this work, the design, modeling and characterization of a high performance piezoelectric MEMS speaker for in-ear applications, based on a piston-like movement of the microspeaker central component, actuated through a set of folded springs, is proposed. The device features a Sound Pressure Level (SPL) greater than 110dB from 500Hz onwards for actuation voltages of 30Vpp and a compact footprint of 4.5x4.5mm2. Even if at a prototype stage, the proposed device represents a promising solution towards a new set of high performances piezo-MEMS speakers that do not require further additional closing membranes to minimize acoustic losses. On the simulation side, a small-signal lumped-parameters equivalent circuit for a fast and accurate modeling of piezo-MEMS speakers for arbitrarily complex geometries is proposed. Special attention is paid to the air-gaps modeling, by taking into account the acoustic shortcircuit between the speaker front and rear sides. The proposed equivalent circuit is then extended to the nonlinear regime with the inclusion of the piezoelectric hysteretical behaviour for the estimation of Total Harmonic Distortion (THD). The very good matching between the equivalent circuit predictions and experimental data demonstrates the ability of the proposed methods to accurately simulate the speaker performances, thus representing a fast tool for the design of this class of MEMS speakers.

ADVANCING SEISMIC RISK ASSESSMENT IN LARGE URBAN AREAS BY MEANS OF REGIONAL-SCALE 3D PHYSICS-BASED GROUND MOTION SIMULATIONS

Jiayue Lin - Supervisor: Prof. Chiara Smerzini

Seismic damage and loss scenarios in urbanized environments represent a key tool for Civil Protection to improve earthquake preparedness, to establish effective prevention policies for seismic risk mitigation and to support decision making in emergency planning and management. In estimating the seismic risk at urban scale, encompassing spatially distributed building portfolios or lifeline systems, key challenges exist in all components of the risk chain (hazard, vulnerability, exposure) but particularly in the hazard model. An accurate estimation of ground motion footprints and their associated uncertainty is crucial for understanding the potential extent of earthquake- induced economic and social losses, especially for cities located close to seismically active faults.

Empirical Ground Motion Models (GMMs) represent the reference tool of choice for earthquake ground motion predictions, but, in spite of their considerable evolution, they still suffer from the paucity of recordings, such as in the near-source region, for complex geological conditions and in spatially dense receivers configurations, which often prevents a well-constrained prediction of the ground motion and of its spatial variability in the variety of source-to-site conditions controlling the hazard at the site.

These limitations can be overcome by relying on 3D physics-based numerical simulations (PBS) which, in recent years, have emerged as one of the most promising tools for providing earthquake ground motions reflecting the specificity of the seismogenic fault, of the propagation path and of the local site conditions. In line with the research efforts promoting the development and application of such PBS, the main aim of this work is to explore and test an innovative approach for assessing seismic risk in large urban areas, where ground shaking scenarios are provided by 3D PBS in realistic geological and seismotectonic contexts. The high-performance spectral element code SPEED (https:// speed.mox.polimi.it/), developed at Politecnico di Milano, is used for the PBS. As a preparatory study for the application of seismic risk methodologies at spatial scale, this research has tackled the issues related to the modeling of the spatial correlation of earthquake ground motion intensity measures. For this purpose, a large set of broadband ground motions simulated by the SPEED code, and enriched in the high- frequency range with an Artificial Neural Network (ANN) technique, is used to assess the spatial correlation by means of state-of-the-art geostatistical techniques. Outcomes of this analysis:

validate successfully the numerical approach in predicting the spatial correlation in a broad frequency range, by comparison with results derived from recordings;
point out that spatial correlation of ground motion is region- and scenario-specific, as it is significantly affected by the local geology, magnitude, forward directivity effects, ground-motion directionality (fault normal versus fault parallel), and relative position from the causative fault. These features may make critical the use of isotropic and stationary models, especially in near-fault conditions, as typically assumed in empirically-based models.

As main application to carry out a comprehensive physics-based study, from the construction of the 3D numerical model up to damage and loss scenarios, the city of Thessaloniki (Northern Greece) has been selected owing to the high level of seismic risk and the availability of detailed exposure and vulnerability data.

After the setup, calibration and validation of the 3D numerical model, a set of 60 different fault rupture scenarios with moment magnitude in the range 6.5-7.0, originating from two major active faults in the surroundings of Thessaloniki (Gerakarou-Langadhas and Anthemountas fault systems), is simulated by SPEED. These simulations account for kinematic finite-fault source models and a 3D seismic velocity including the two main geological structures present in the area (Thessaloniki and Mygdonia basins). The ground shaking scenarios from these PBS are coupled with up-to-date exposure, fragility and vulnerability models for the residential building stock in Thessaloniki to generate seismic damage and loss scenarios using the OpenQuake platform (https:// platform.openquake.org/). After validation of the risk model on the damage observations available for the historical 1978 earthquake, the variability of damage and loss pre-dictions as a function of the fault rupture realizations is explored to gain insights into the potential impact of physical factors, such as the causative fault and magnitude, on seismic risk in Thessaloniki. As main conclusion, PBS-based results point out a higher seismic risk posed by the earth-quake scenarios rupturing the seismogenic sources located in the Mygdonia graben.

HOMOGENIZATION OF MICROSTRUCTURED MATERIALS VIA THERMODYNAMICS BASED ARTIFICIAL NEURAL NETWORKS AND DIMENSIONALITY REDUCTION TECHNIQUES

Giovanni Piunno - Supervisor: Prof. Cristina Jommi

This thesis investigates the multiscale analysis of inelastic microstructured materials by introducing a homogenization technique that integrates machine learning tools with thermodynamic principles. The research utilizes dimensionality reduction techniques, neural networks, and dynamic system identification methods to develop a method for predicting the constitutive response of complex materials at the macroscopic scale. The methodology enables the unsupervised selection of features from microstructured material models to act as Internal State Variables (ISVs) at the macroscopic level.
Thermodynamics-based Artificial Neural Networks (TANNs) are employed to learn the macroscopic constitutive response in accordance with thermodynamics laws.
The work builds on the constitutive modelling framework introduced by Coleman and Gurtin in 1967, employing machine learning tools to define the system's state, energy potential, and evolution laws of ISVs within the constraints of thermodynamics. This approach is designed to minimize the reliance on extensive datasets, employing a loss function to facilitate the training process with limited data inputs and no energy data.
Dimensionality reduction techniques are used to identify macroscopic ISVs from microscopic internal coordinates, compressing complex data into a manageable set of variables. These ISVs, alongside macroscopic strain states, form a state space that correlates uniquely with the Helmholtz free energy density through a state function (Figure 1). The emphasis on computational efficiency and potential for further data compression are considered important for the applicability of these methods.
The use of Proper Orthogonal Decomposition (POD) for dimensionality reduction is highlighted for its computational efficiency, despite its potential limitations with highly nonlinear systems. This methodological choice underscores the emphasis on making advanced computational techniques accessible for practical use on standard computing platforms.
The study also examines the system's response to external excitations through evolution laws, which are derived from data using Dynamic Mode Decomposition with control (DMDc). This method has been modified in the work to improve the stability and accuracy of the time integration scheme.
A computational toolbox has been developed to support the analysis of continuous microsystems modelled as representative unit cells and volumes. This toolbox integrates with commercial software ABAQUS to generate periodic models, meshes, and assign periodic boundary conditions, facilitating the practical application of the developed methodologies.
The application of the proposed methodology is shown through various examples. At the material point level, the homogenization of both periodic heterogeneous unit cells and a random representative elementary volume is demonstrated (Figure 2). Furthermore, an application of the same methodology to a macroscopic system is reported. The application involves the homogenization of the behaviour of a 3D foundation system to an equivalent SDoF system (Figure 3).
The thesis also addresses the challenges related to the extrapolation capabilities of TANNs, the generalization ability of algorithms, and the collection of comprehensive training data. It suggests leveraging Physics-Informed Neural Networks (PINNs) to enhance generalization capabilities and addresses the need for further research into micro-mechanical aspects not covered in this study, such as the nonlocality of interactions at the microscale and multi-physics coupling in geomechanics.

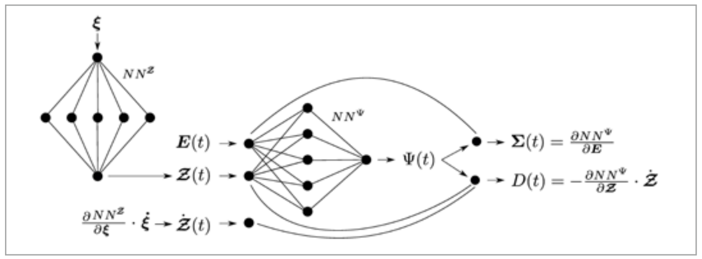

Fig. 1 - Thermodynamics-based Artificial Neural Network (TANN) architecture.

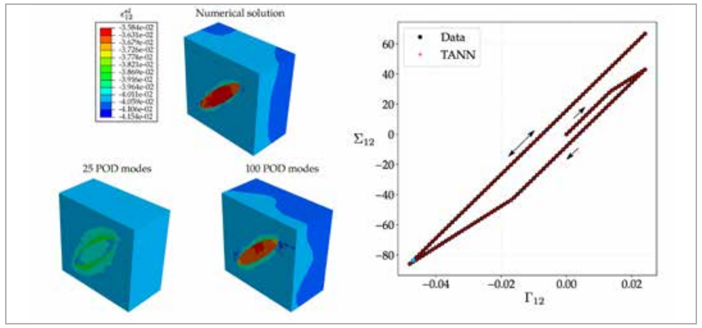

Fig. 2 - Application of TANN-based homogenization procedure to a periodic RUC. Top panel: comparison between simulated and predicted macroscopic response along a cyclic macroscopic path. Bottom panel: reconstruction of the elastic strain field as a function of the considered POD modes.

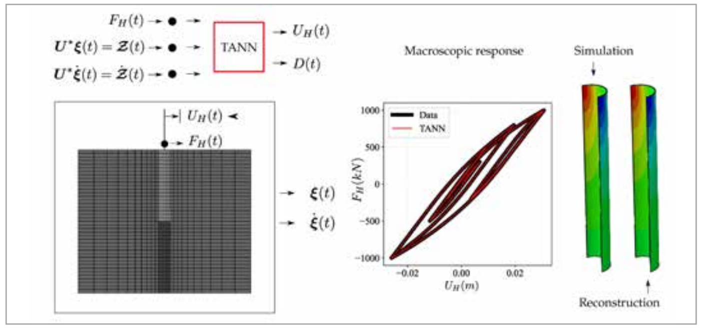

Fig. 3 - Application of the TANN-based homogenization procedure to a macroscopic model of a monopile in a saturated clay layer: prediction of the macroscopic response and reconstruction of the local strain fields.

A NUMERICAL APPROACH TO INVESTIGATE THE ROLE OF PARTIAL SATURATION IN THE VIBRATION INDUCED BY UNDERGROUND RAILWAY TRAFFIC

Nicola Pontani - Supervisor: Prof. Cristina Jommi

Co- Supervisor: Prof. Luca Martinelli

In crowded urban areas around the world, the theme of transportation of people is rightly held in high regard. Even though the efficiency of the transportation net is crucial, the quality of life of people can be deeply affected by the presence of this traffic. As a matter of fact, vehicles involved in urban transportation always produce noise and vibration associated with their passage. Among them, subways have been a solution extensively exploited to save urban spaces and reduce surface traffic (the cities of London, Paris or New York can be recalled just among the most famous examples in the world). Ground-borne vibration generated by the passage of underground trains may also change over time for several reasons, such as the increasing weight and speed of trains or ageing of the infrastructure components, as well as because of a variation in the dynamic response of the soil surrounding the tunnel. Among the possible causes of changes in the soil dynamic response, its hydrologic state has been seldom investigated. Water exchanges with the atmosphere produce a continuous variation in the conditions of partial saturation of soil layers above phreatic aquifers, resulting in modifications in the soil-tunnel interaction behaviour. Stress waves induced by the passage of underground trains are unavoidably affected by the occurrence of such changes, especially in the presence of rather shallow tunnels. The growing attention to quality of life in urban areas, together with the increasing concerns about extreme climatic events, put in evidence the relevance of a topic which has not been thoroughly investigated yet. Starting from the analysis of the case study of the M1 line in Milano (two of the geometries considered in the work are reproduced in Fig. 1), a complete framework has been developed to take care of variations of conditions of partial saturation in train-induced vibration problems. The fulfilment of this scope comes together with some questions which are believed to be answered thanks to this work. How much the saturation profile above the water table is expected to vary for a given stratigraphic profile? Consequently, what are the corresponding variations in the dynamic response of the soil? Is it possible to find evidence of these changes? Are they capable of affecting the induced vibration? How much are they overestimated assuming the shallow portion of soil completely dry? Is it possible to identify a "worst" situation related to climate stress changes? Thanks to the non-invasive in-situ testing campaigns conducted by Metropolitana Milanese along the M1 line in Milano in two different years, evidence of the temporal variation of the dynamic response of soils has been identified. The reason for this discrepancy was found to be related to the different hydraulic state of the soil in the two moments. As a first step, this information was exploited as an input to a plane strain finite element model to numerically predict possible changes in the vibration induced by the running of a train at varying dynamic behaviour of the soil (as an example, the accelerations predicted during the train passage are reported in Fig. 2). Then, a comprehensive numerical approach has been proposed to address issues related to traffic-induced vibration in unsaturated soils, which can be exploited for a broad range of circumstances. In the process, special care has been devoted to the identification of the hydraulic behaviour of the soil layers starting from the knowledge of basic geotechnical properties for which databases are available. These have been used in a simple numerical model able to predict soil-atmosphere water exchanges at the surface according to the hydrological cycle, using meteorological data as input to obtain upper and lower bounds for the profiles of degree of saturation. Two-dimensional plane-strain numerical models have been set up to assess the response of the system and test the effect of changes in the soil dynamic response due to variable saturation on train-induced ground-borne vibration. In reproducing the passage of the convoy in the 2D models, the frequencies of relevance in terms of human perception to vibration have been reproduced and a comparison between predictions and measured vibration has been provided to validate the approach.

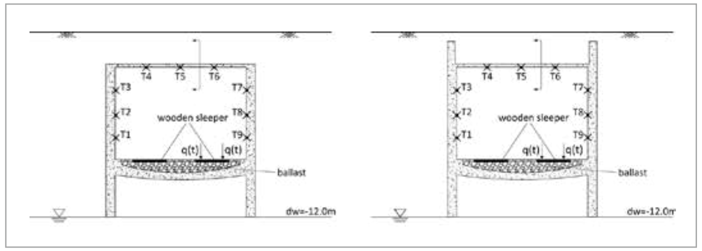

Fig. 1 - Geometry of the tunnel implemented in the FE models.

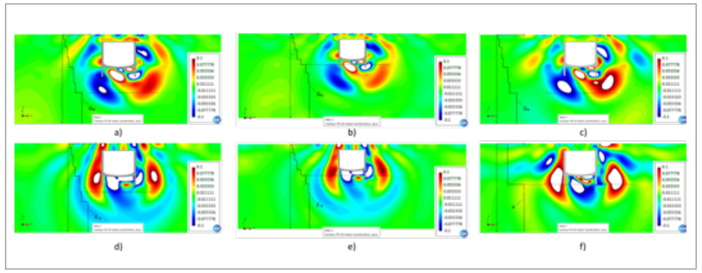

Fig. 2 - Maps of the horizontal (a), b) and c)) and vertical (e), f) and f)) acceleration retrieved at t = 1.0 s from the beginning of the train passage for different soil dynamic response.

THE EVOLUTION OF SELF-HEALING PERFORMANCE OF ULTRA HIGH PERFORMANCE CONCRETE UNDER HARSH CONDITIONS: EXPERIMENTAL INVESTIGATIONS AND MACHINE LEARNING MODELING DEVELOPMENT

Bin Xi - Supervisor: Prof. Liberato Ferrara

Ultra High-Performance Concrete (UHPC) has garnered significant attention in previous research and applications due to its outstanding mechanical properties and durability. Given the inevitability of concrete cracking, extending the service life of UHPC structures and reducing maintenance costs have become possible by equipping UHPC with self-healing capabilities. However, current research has rarely considered the impact of UHPC exposure to complex conditions, particularly UHPC exposure to hash environments under simultaneously applied mechanical loading, on its self-healing ability.

Therefore, this thesis commences with an extensive literature review covering the design and various properties of UHPC. Subsequently, it delves into the investigation of UHPC's self-healing properties under both mechanical and environmental loading conditions. The study compares the long-term development of self-healing capacity in pre-cracked UHPC samples exposed to tap water, saltwater, and geothermal water and under contemporary sustained loading. Furthermore, it explores UHPC's ability to sustain its self-healing performance when subjected to cracking/healing cycles and aggressive conditions. A series of tests, including Ultrasonic Pulse Velocity Testing (UPV), image processing techniques, and double-edge wedge splitting tests, have been employed to assess the progression of UHPC's self-healing properties. Additionally, Scanning Electron Microscopy (SEM) with Energy Dispersive Spectrometry (EDS) analyses have been carried out to examine the impact of different exposure environments on self-healing products. Finally, the study compares the predictive performance of self-healing models for UHPC developed using traditional machine learning techniques integrated with two metaheuristic algorithms. The most suitable models for predicting UHPC's self-healing capacity are proposed by using various evolution metrics.

Through extensive experimentation and model development, this study aims to contribute to the promotion of UHPC material usage, especially for structures exposed to extremely aggressive conditions, by demonstrating its superior performance overall the structure life-cycle, incorporating into the design of UHPC durability the development of its self-healing performance.

FRACTURE INSTABILITY IN HEATED CONCRETE: A REASSESSMENT OF THE FUNDAMENTAL MECHANISMS BEHIND EXPLOSIVE SPALLING

Ramin Yarmohammadian - Supervisor: Prof. Roberto Felicetti

Concrete spalling, the detachment of fragments from heated surfaces during a fire, is a complex phenomenon influenced by thermal, mechanical, and hygral factors. Existing literature suggests two main mechanisms—pore pressure and thermal stress—yet fails to fully explain the explosive nature of concrete failure. The combination of pore pressure and thermal stress is likely the reason for concrete failure.
A "two-stage mechanism" is introduced to clarify spalling intricacies, involving incipient crack formation and unstable crack propagation. Stable cover delamination, observed in post-fire assessments, is considered a distinct first stage, impacting material continuity but not reinforcing bars' protection.
The study addresses the fracture behaviour of concrete, a key parameter in both spalling stages, using an innovative frameless test rig. Then, each stage of concrete spalling is analysed in more detail.
The first stage, incipient crack formation, involves the synergistic interaction of external loads inducing high compressive stress and hydrostatic tension from pore pressure. This stage sets the foundation for the second stage and is influenced by various parameters, including cracks in restrained or loaded sections, mesoscale heterogeneity, element shape, weak planes and strain incompatibility of rebars, and cracking fostered by pore pressure. The crack onset stage is discussed by comparing different concrete samples by means of FEM modelling, considering the shape of the structure as a significant factor in the triggering force.
The second stage, unstable crack propagation, leads to the rapid opening of cracks and the high-speed projection of particles. The study identifies thermal energy accumulated by the heated concrete as a potential driving force. The conversion of thermal energy into mechanical work requires flash vaporization of water from a thin concrete layer with sufficient pore saturation. The experimental test adds new insights into the fundamental mechanisms behind explosive spalling. The crack instability stage is addressed, highlighting the role of moisture in inducing acceleration leading to a novel small-scale screening test setup. The value of net pressure inferred by measuring the relative acceleration between the spalled parts shows values which are close to saturated pressure corresponding to the spalling temperature in the crack. The ability of this setup to categorize spalling sensitivity in different concrete mixes is validated against standard fire tests.
The proposed two-stage mechanism offers a consistent interpretation of spalling phenomena, addressing the stability of ensuing cracks and providing a foundation for future research directions. His PhD thesis also emphasizes the significant obstacle posed by spalling in the widespread utilisation of concrete, affecting both normal-grade and high-performance varieties. Despite the superior mechanical and durability performance of high-performance concrete, its susceptibility to spalling presents challenges for structural design.
In conclusion, his PhD dissertation outlines a comprehensive and systematic approach to understanding concrete spalling, offering new insights for both academic and practical applications.

NUMERICAL INVESTIGATION OF IMPACTS ON/OF GRANULAR MASSES

Matteo Zerbi - Supervisor: Prof. Claudio Di Prisco

Impacts are dynamic interactions between two colliding bodies, characterized by an impulsive nature. In the literature, by interpreting energetically the phenomenon, a distinction is made between dissipative and non-dissipative impacts. This thesis is devoted to the study of the former category. In particular, the author analyses impacts in which dissipation mainly takes place within one of the two bodies, assumed to be constituted by a granular material.

Indeed, impacts involving granular masses are very common in the engineering practice. They include natural events such as landslides, where rock boulders or debris flows collide with structures/infrastructures, as well as human-induced activities such as the installation of foundation structures like pile driving and offshore foundation construction. Furthermore, dynamic compaction for soil improvement and applications in military and aerospace sectors also provide examples of the wide spectrum of impacts on/of granular materials.
Despite the different applications, these very different processes can be schematized in two different impact configurations:

- impacts of blocks on still granular strata (in this case, the impacting object is assumed to be rigid whereas the granular cushion to dissipate most of the kinetic energy of the block) (Figure 1a);
- dynamic interactions of flowing granular masses with rigid obstacles (in this case, the impacting mass dissipates most of its initial kinetic energy) (Figure 1b).

Dissipative impacts are characterised by large displacements, large strain rate values (due to the high impulsiveness), damage processes, wave propagation and the occurrence of regime transitions (from solid to fluid and viceversa). The study of the mechanical response of granular media under large strain rates is particularly interesting, since, according to effective confining pressure, strain rate and void ratio, they may behave like either solids or fluids. For example, during impacts of flowslides against sheltering structures, the materials, due to their agitation, initially behave like a fluid. During the impact, the materials progressively dissipate their kinetic energy and experience a reconsolidation, permanent force chains develop and most of the fluctuating energy is transformed into elastic energy.

These very different behaviour depends on the way in which the granular material stores energy: when the system is particularly agitated, soil grains interact mostly throughout instantaneous inelastic collisions and energy is mainly stored as kinetic fluctuating energy and the overall behaviour resemble that of a compressible fluid. On the other side, under quasi-static conditions, granular materials store energy mainly as elastic through long-lasting frictional contacts (the "force chains"). When this latter mechanism of storing energy prevails, the macroscopic behaviour resembles that of a solid.

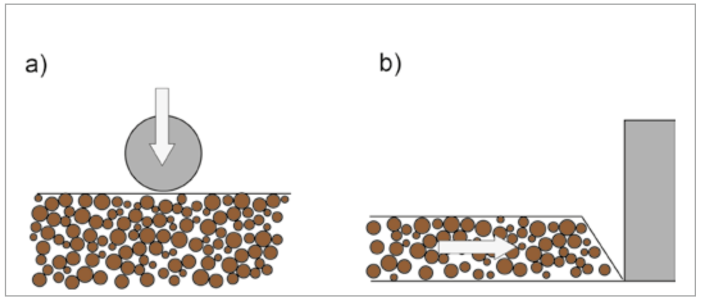

Fig. 1 - Impact configurations considered: a) impacts of blocks on still granular strata and b) impacts of flowing granular masses with rigid obstacles

Under saturated conditions, the dynamics of grain-grain interaction are altered by the presence of water, resulting in additional dissipations arising from grain-water contacts. Specifically, the interaction between grains is dampened by the presence of the liquid phase, leading to an increase in energy dissipation within the granular phase as particle movements become constrained by the liquid.

Despite the huge academic and industrial interest on impacts, due to their intrinsic complexity, they have not been completely understood, since: (i) field measurements are rare and (ii) the results obtained by performing small-scale experimental tests (eventually performed in centrifuge apparatus) very often provide partial information.

In recent years, robust numerical codes, able to deal with large displacements and based on both discontinuum (Discrete Element Method) and continuum mechanics (Material Point Method, Particle Finite Element Method, Smoothed Particle Hydrodynamics, ecc.), have allowed the numerical simulation of impacts, opening new frontiers on the study of these processes.
In this thesis, both the two impact configurations are analysed with special emphasis on landslides and dynamic compaction applications.

The two configurations have been studied employing both Discrete Element Method (based on discontinuum-mechanics) and a Material Point Method code (based on continuum-mechanics) in which a recently formulated multi-phase and multi-regime model is implemented.

To this aim, such a constitutive model, conceived for ideal monodisperse spherical materials, has been further developed by the author to extend its applicability to real polydisperse materials and to account particle damaging for. In addition, the assumptions introduced in the extension of the multi-regime model to saturated conditions are discussed, taking advantage from DEM-LBM tests performed at REV scale.

The impact of spherical boulder on still dry granular strata has been investigated considering both DEM and MPM. The comparison with available large-scale experimental test results and empirical correlations has allowed to assess the reliability of the obtained numerical results. These latter have then been used to highlight the propagation of the stress wave, the occurrence of regime transitions and particle damaging processes and the failure mechanism in the soil, under the penetrating block.
The impact of flowing granular masses against rigid obstacles has been instead investigated by using only MPM, considering both dry and saturated granular masses. The MPM analyses results have allowed to discuss the importance of constitutive and numerical assumptions to obtain reliable predictions of impact force and mass deformation. Under dry conditions, the numerical results have been critically compared with those already obtained by using DEM. In particular, the capability of the model to reproduce the dependence of compression and rarefaction wave velocities on material porosity and Froude number is shown. In the saturated case, the role of front inclination is emphasized and the evolution with time of the force transmitted to the obstacle by water and grains is discussed and compared with what obtained in case of dry masses.