Scuola Superiore Meridionale

MERC PhD Project Proposal 2024/2025

Title of the research project:

AI-powered solutions for advancing natural hazard prediction

Keywords:

earthquakes, landslides, advanced geotechnical tools, digital twin, artificial intelligence

Supervisors:

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Project description

Object of the research and generalities

The 2030 Agenda (ONU, 2015) established the following target: shifting the paradigm from disaster management to risk mitigation. Thanks to significant efforts worldwide, global losses induced by natural phenomena (GCDL, 2025) in terms of human lives appear to be following a decreasing trend, despite rising economic losses. This contrasting trend may stem from cascading effects within interconnected systems, leading to various types of losses across economic, food, and health systems, as well as residential infrastructure and lifelines, over potentially prolonged periods beyond the initial occurrence of a natural event. Moreover, developing countries continue to experience human losses, likely due to the lack of proper ex-ante risk assessment for natural hazards, often disregarding the complex interactions between different types of hazards. In this context, improving the reliability of hazard estimation from natural phenomena for both ex-ante and ex-post applications appears to be a key factor in achieving, for instance, Goal 3 (Ensure healthy lives and promote well-being for all at all ages) and Goal 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation) of the 2030 Agenda.

It is important to note that ex-ante applications can be based on either local-scale approaches, which generally require site-specific data and time-consuming procedures to evaluate hazard, or large-scale approaches, which rely on so-called soft data to describe site conditions and perturbations, as well as empirical methods. Additionally, ex-post applications share the same limitations as large-scale approaches and require rapid procedures capable of providing near-real-time hazard estimates.

Focusing on slope response (whether influenced by climate or earthquake factors), this project proposal aims to improve risk assessment by enhancing hazard estimation over large areas. It is worth noting that hazard can be expressed through various engineering demand parameters, such as slope displacements induced by rainfall or earthquake, and the amplification of the reference hazard. The latter refers to the ideal condition of a horizontal ground surface and outcropping seismic bedrock. A number of monitored case studies will be analysed at the local-scale to establish *benchmarks for validating large-scale methods. In particular, large-scale approaches could be developed using AI tools. In summary, physical model can be used to validate numerical approaches, such as Finite Element, FE, simulations. For instance, earthquake induced displacements may be derived from real sites observations or physical model experiments. Digital twins of this case studies will be analysed using FE models, and the results will be compared with field data in order to calibrate and validate the numerical simulations. Traditionally, real sites are monitored at only a few locations, for example, approximately five points per square kilometre, whereas FE models can provide outputs for over 2,000 points within the same area. This allows for the generation of a vast amount of data, which can be used to train and validate an Artificial Intelligence, AI, model. Moreover, the FE simulations can be conducted as a part of a parametric study to further populate the database, enabling the development of AI tools that are more efficient and adaptable to diverse site conditions.*

The ultimate goal of the project is to propose different methodologies that can also be applied in developing countries, aligning with the "no one is left behind" (GAR, 2019) principle.

State of the arts

The use of digital twins is expanding across various research fields. In the context of natural hazard assessment (e.g., slope instability and earthquakes), a digital twin should incorporate topography, subsoil characteristics, and perturbations (e.g., rainfall or seismic activity). Additionally, it must solve equilibrium and consistency equations, considering constitutive laws and boundary conditions. This allows hazard prediction through numerical simulations, such as the Finite Element Method (FEM). For example, FEM can model slope displacements due to rainfall infiltration (Tawalo et al., 2025) or ground motion in complex subsoil conditions (Falcone et al., 2018).

Advances in hardware, software, and scientific methods now enable the creation of 3D geotechnical digital twins (Falcone et al., 2025) for small areas (<2 km^2, depth approximately 1 km). However, scaling up predictions while integrating local subsoil and topographic features remains a challenge. Large-area hazard assessments typically rely on empirical approaches using soft data. For instance, Ground Motion Prediction Equations estimate ground motion characteristics based on magnitude, epicentral distance, and average shear wave velocity in the upper 30 m of soil, ignoring topography and buried morphologies. Additionally, large areas approaches often focus on hazard susceptibility rather than parameters critical for risk estimation (d'Onofrio et al., 2024; Nowicki et al., 2018).

The rise of Artificial Intelligence (AI) in geotechnical engineering offers a potential breakthrough for large-scale hazard assessment, overcoming limitations of traditional tools designed for local applications (Baghbani et al., 2022). However, current AI models predominantly address ultimate limit states in slope stability (Gao & Ge, 2024) rather than serviceability limit states. As a result, they tend to provide safety factors rather than estimating displacements induced by triggering events such as rainfall or earthquakes. Furthermore, they often fail to integrate proxies for local site conditions (Meng et al., 2002; Monterrubio-Velasco et al., 2024).

Methods

This project aims to develop AI tools for estimating natural hazards, considering both ultimate and serviceability limit states. The key steps include:

- *Selection of physical benchmarks. Data will be gathered from existing case studies, including laboratory prototypes and monitored sites, to serve as benchmarks for subsequent numerical simulations. If necessary, additional laboratory tests will be conducted, or new monitored sites selected. Notably, real sites and prototypes typically provide limited monitoring points (fewer than 10 per km^2).*
- *Numerical simulations. Digital twins will be developed to simulate landslides and local seismic site response using Finite Element analyses. These models will first be validated against benchmark data. Unlike physical monitoring, numerical simulations can generate extensive*

datasets (over 2,000 monitored points per geotechnical twin), which will be used to train, validate, and test AI tools. Moreover, by performing parametric FE simulations, the database can be expanded, facilitating the creation of AI models with improved efficiency and adaptability across different geological settings.

- *AI Applications. With multiple case studies selected in the initial phase, data analysis will identify patterns and clusters to optimize model training. Key steps include determining: i) the optimal set of site parameters (predictors) for accurate hazard estimation and ii) the minimal set of predictors necessary for reliable predictions. AI applicability depends on data availability. For example, parameters such as V_{S30} (mean shear wave velocity in the upper 30 m), f_0 (fundamental frequency of soft soil layers), and H_{800} (soft soil thickness) are widely used to correlate ground shaking with subsoil conditions. However, only national-scale V_{S30} maps are generally available. Thus, two AI models must be developed for each hazard: one using the optimal predictor set and another relying solely on parameters available at a national scale.*

Relevance to the MERC PhD Program

Interdisciplinary Aspects

This project aligns closely with the MERC PhD program by integrating engineering, mathematical modeling, and computational science. It bridges multiple disciplines within engineering, focusing on landslides and earthquakes through both traditional and advanced computational tools. By combining physical models, numerical simulations, and AI-driven methodologies, the research fosters an interdisciplinary approach to hazard assessment.

Relevance in Application and Benefits

Soil mass movements and seismic events pose severe risks, leading to economic losses, infrastructure damage, and disruptions to communities. Slope failures and earthquake-induced damage impact structural and infrastructural serviceability, affecting populations and industries by causing service interruptions. These disruptions extend to emergency supply chains, which are critical for immediate response, such as providing medical care. In the long term, this research supports efficient restoration and repair strategies, contributing to societal resilience and economic sustainability through a deeper understanding of natural hazards.

Key references

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Joint supervision arrangements

The PhD thesis foresees inter-disciplinary parts, which concern above all the preliminary design of the research work and scientific comments on results. For these parts the student will be jointly supervised by the three supervisors during plenary meetings that will be held roughly every two months.
To develop the monothematic parts of the work, the student will be supervised in turn by one of the supervisors with whom meetings will be more frequent (weekly or bi-weekly).

Location and length of the study period abroad (min 12 months)

Foreign collaborating institutions are:
- ETH Zurich (Swiss), prof. Ioannis Anastasopoulos (email: ioannis.anastasopoulos@igt.baug.ethz.ch). The student is expected to travel abroad during the second year (6 months) of the PhD programme.
- Cerema Méditerranée (France), dr Julie Régnier (email: Julie.regnier@cerema.fr). The student is expected to travel abroad during the third year (6 months) of the PhD programme.

Any other useful information

Industrial partners will be involved in the project:
ANIA - Associazione Nazionale fra le Imprese Assicuratrici
Via di San Nicola da Tolentino, 72, Roma, IT

Leithà s.r.l (tech&data factory del Gruppo Unipol)
Via Stalingrado 37, Bologna, IT

Exprivia S.p.A
Via A. Olivetti 11, Molfetta, BARI, IT