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GEOLAB – Science enhancing Europe's Critical Infrastructure

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ABSTRACT: Critical Infrastructure (CI) plays a fundamental role in supporting economic activity, enhancing quality of life, and safeguarding communities. However, infrastructure systems, whether they are roads, bridges, utilities, or communication networks, are increasingly being confronted with numerous challenges. These challenges compel CI owners and policymakers to adopt new strategies and solutions to reach desired levels of reliability. From ageing and climate-induced hazards to the necessity for sustainability and accessibility, infrastructure must evolve to meet societal needs while balancing economic, environmental, and technological pressures. GEOLAB emerged in 2021 from the European Large Geotechnical Institutes Platform (ELGIP) under the lead of Deltares to integrate top European research facilities into a one-stop-shop for performing excellent physical modelling research and innovation in the area of CI. The GEOLAB Research Infrastructure (RI) comprises 12 unique facilities in Europe for studying ground response and its interaction with structural components and the environment. It includes six Geo-Centrifuges of different sizes and capabilities, a Geo-Model Container, a Static Liquefaction Tank, a Geotechnical Test Pit, a Large-scale Triaxial Apparatus, a Railway Track Simulator and a set of five Field Test Sites. They represent the leading geotechnical experimental facilities available in Europe today. The GEOLAB RI realized 44 projects supporting research and innovation that address CI challenges. New technologies were implemented in these projects to increase the set-up and observation of the experiments. Beyond its overarching aim, GEOLAB's essential goal is to assess whether the experimental and numerical tools available will be able to address societal needs and demands of CI resilience in the future. The need of new or alternative methodologies, knowledge and development of the RI is explored. By doing so, GEOLAB evolved into an advanced community with an impact in critical areas such as sustainable development, digital transformation and scientific excellence.

KEYWORDS: research infrastructure; data; physical modelling; numerical modelling; critical infrastructure

1 INTRODUCTION

1.1 *Europe's Critical Infrastructure*

The landscape of new and existing Critical Infrastructure (CI) in Europe (e.g., water, energy, transport, communication and urban sector) is characterized by multifaceted challenges and increased levels of resilience are required. Climate change and the associated increasingly frequent extreme weather and geo-hazard events place additional pressures on CI. At the same time, most of the CI is reaching, or has already reached, its design life while still being in use, calling for rational retrofit measures. In addition, the societal developments of the past decades introduced significant changes in the way CI is being used, retrofitted and built, with particular emphasis on meeting long-term goals especially related to sustainability such as the energy transition, circularity of materials or environmental impact reduction. Finally, yet importantly, the shifting geo-political situation adds to the already complex landscape of CI in Europe.

A crucial aspect to building the resilience of CI networks is assessing the integrity and stability of the structure itself, particularly as experience has shown how structural failure can lead to major operational disruptions, with consequent economic losses and, sometimes even fatalities. This structural integrity depends to a great extent on the properties and behavior of the foundation ground, and on the interaction of the structure with the ground and other environmental elements (e.g., water during floods, or wind during storms).

In this context, strengthening CI resilience to meet present and future demands should therefore be at the forefront of societal goals, and to this end, excellent research and innovative solutions are needed. This is best achieved through interdisciplinary, cross-boundary research and by equipping expert teams with the most advanced suite of physical Research Infrastructure (RI) available.

1.2 *The GEOLAB Research Infrastructure*

The GEOLAB RI comprises 12 top experimental research facilities in Europe for studying ground response and the interaction of structural components with the ground and the environment. It includes six Geo-Centrifuges of different sizes and capabilities, a Geo-Model Container, a Static Liquefaction Tank, a Geotechnical Test Pit, a Large-Scale Triaxial Apparatus, a Railway Track Simulator and a set of six Field Test Sites.

Led by Deltares, the GEOLAB project started in February 2021, with the aim of integrating, coordinating and advancing these national facilities into a one-stop-shop for cutting edge physical modelling research and innovation.

Funded by an EU grant, the GEOLAB project is structured along three core components: Transnational Activities (TA); Joint Research Activities (JRA); and Networking Activities (NA). Through the TA component calls for proposals, aiming to enhance the resilience of CI, are organized and access to the GEOLAB RI is granted to user groups with stakeholders from academia, industry and policy makers. The JRA component of the project provides the framework for GEOLAB members to collaborate with the goal of advancing the capabilities of the RI beyond the current state-of-the-art. This will both enable ground-breaking experimental research, and improve data collection and storage protocols to facilitate the future re-use of experimental datasets produced by the GEOLAB members. The NA component includes knowledge transfer and training programs for Next Generation (NG) researchers who will deal with the challenges related to CI in the upcoming decades (Peters et al. 2022).

2 CI-OWNER AND POLICYMAKER PERSPECTIVE

This chapter is based on Foresight Studies, performed as part of the GEOLAB project (Marin et al. 2024)

2.1 *Societal needs*

CI plays a fundamental role in supporting economic activity, enhancing quality of life, and safeguarding communities. Due to the numerous challenges faced by the CI, owners and policymakers are compelled to adopt new strategies and solutions to increase resilience levels. According to the outcome of GEOLAB's studies, addressing societal needs for infrastructure requires a comprehensive approach that considers accessibility, reliability, resilience, sustainability, affordability, and modernity of CI, as presented in Table 1.

Table 1. Societal needs and challenges CI-owners and policymakers.

Societal needs	Challenges of CI-owners and policymakers
Accessible infrastructure	Increasing the capacity of current infrastructure and building new ones.
Reliable infrastructure	Quantifying performance and capacity deterioration due to aging-induced and other effects.
Resilient infrastructure	Accounting for new hazard scenarios induced by climate change combined with aging-induced effects in design and verification processes.
Sustainable infrastructure	Using clean, environmentally friendly technologies, processes and materials without any compromise on safety and performance.
Affordable infrastructure	Managing scarce resources and energy.
Modern infrastructure	Increasing awareness levels concerning the latest research developments and translating them into practice.

CI-owners and policymakers must work together to overcome challenges such as those presented in Table 1 and build systems that serve the public effectively, while withstanding the pressures of aging, climate change, and resource scarcity. By prioritizing these needs, policymakers, CI-owners, developers, engineers and researchers contribute significantly to achieving the targets set by UN's 2030 Agenda for Sustainable Development (2015). In this way, the infrastructure is capable of supporting future generations while preserving the planet and ensuring equitable access to essential services.

Based on interaction with CI-owners and policymakers within the JRA component of GEOLAB, a set of specific CI development directions has been identified and is described in the following sections.

2.1.1 *Simplified design tools*

Promoting the use of design tools, based on simplified but realistic models that incorporate the latest research, ensures that engineers have practical and accessible resources to implement innovations efficiently. Tools, such as risk-oriented screening for large CI portfolios and guidelines for specific hazards, support pragmatic and risk-aware design strategies. A typical example of such tools, which will need development in the future, are macro-element based models. These tools are developed on the basis of solid theoretical fundamentals, using extensive experimental and numerical investigations, being able to incorporate complex interaction problems in a simplified manner. For their wide use in engineering practice, clear calibration guidelines and specifications of their limitations need to be provided.

2.1.2 *Novel Design Procedures*

Infrastructure in increasingly unavoidable areas of high-geotechnical complexity (e.g., soft soils, landslide-prone areas, offshore sites) benefits from novel design and construction methods. Such advanced techniques support reliable performance in challenging environments, enhancing safety and resilience against natural hazards. Moreover, such procedures can find their application also in retrofitting infrastructure with minimal impact on operations. Such concepts include adaptive, flexible designs and re-use of existing foundations to reduce disturbances, ensuring continuity of service of CI and lowering upgrade costs.

2.1.3 *Performance-Based and Multi-Hazard Design*

Consistent, performance-based design frameworks and multi-hazard guidelines enable infrastructure to meet resilience standards against multiple risks. By considering hazards in an integrated manner, these frameworks optimize design choices to ensure safety and continuity under various hazard scenarios. A design framework for CI foundations, considering flood and earthquake hazards in a combined manner, can be a good example for a future innovation that will be needed in performance-based design and multi-hazard analyses.

2.1.4 *Advanced In-Situ Inspection and Probing Tools*

To address gaps in parameters required in design, non-destructive in-situ inspection tools and probing systems are essential. Tools able to measure accurately the geometry of existing CI elements and compensate for missing geotechnical information are essential to ensure thorough understanding of existing conditions of aging infrastructure. In this context, self-driven probes for in-situ soil assessment can be mentioned as an innovation, which will continue to attract the attention of researchers in the coming decades. Such probes must be able to perform autonomous subsurface movement by creating their own reaction force while advancing (employing for example bio-inspired locomotion mechanisms), and to acquire meaningful in-situ soil parameters by means of specialized instrumentation.

2.1.5 *Interdependent Infrastructure Models, Early Detection Mechanisms, Health Monitoring and Remote-Controlled Systems*

Models for spatially distributed interdependent infrastructure systems enhance understanding of complex CI interactions and vulnerabilities. Automated early detection and response mechanisms further ensure swift action, minimizing impact and protecting CI in the event of disruptions. These systems support ongoing evaluations of deterioration and event-induced damage, providing data that informs maintenance and repair decisions. Within this framework, innovations based on the Internet of Things (IoT) technology have the potential to optimize the current practice by reducing costs and generating fully scalable systems of health monitoring. The advantages of IoT and its scalability can significantly increase the general capabilities of medium to large-scale experimental investigations facilities, increasing their readiness level for a wider range of investigations.

2.1.6 *Digital Twins, AI, and Predictive Models*

Advanced technologies, including digital twins and AI-based models, provide critical insights into the current state and future performance of infrastructure. Informed by health monitoring data, these models enable accurate predictions of aging-induced deterioration and future demands, allowing stakeholders to make proactive maintenance decisions and optimize long-term performance. A good example for specific developments in this area, that will require research efforts in the future, is the creation of digital counterparts for large CI systems. By calibrating them using data collected from structural health monitoring systems, such digital twins can be used to evaluate realistically future behavior of the analyzed CI throughout its entire lifecycle (e.g. response of tailing dams or waste landfills).

2.1.7 *Sustainable Materials and Lifecycle Management*

The development of durable, sustainable materials is essential, particularly with a focus on long-term resilience and adaptability to evolving demands. Advanced material science, combined with lifecycle management, supports development of CI that is both environmentally friendly and durable, minimizing repair needs and extending useful life. Moreover, the wide range of meta-materials that are under current scrutiny of researchers across Europe can be added as a specific direction for future innovation.

2.1.8 *Knowledge Retention and Workforce Resilience:*

As the outcome of the NA activities has confirmed, ensuring continuity of expertise through mentorship and hands-on training of NG researchers and practicing engineers, and robust documentation of current knowledge is critical to sustaining innovation. In this context, workforce resilience is further to be supported by the GEOLAB community using innovative material management, adaptive resource use, and specialized training, helping to build skilled, resource-efficient teams capable of meeting future infrastructure demands.

2.2 *Agenda for future innovation*

The CI development directions described in the previous section provide the framework to formulate key actions to bridge the gap between research and practice and formulate an agenda for future innovations of the research community. The future innovation agenda summarized in Table 2 presents GEOLAB's contribution to realize these actions. Table 2

Table 2. Overview agenda for future GEOLAB innovation.

Key actions from CI development directions	Innovation agenda GEOLAB
Reinforce the development of simplified models.	Providing an experimental investigation platform for fundamental research problems, which are foundational for the development of simplified models. Catalyze the development of macro-element based models.
Quantify real-life impact of the novel design methods.	Facilitating the calibration of advanced models for the quantification of tangible benefits resulting from optimized design and construction methods. Develop standardized metrics for performance assessment, creating case studies, and engaging in outreach activities to showcase the real-world impact of relevant efforts.
Increase the awareness among CI stakeholders on the benefits of new design methods.	Organizing networking activities such as themed workshops, foresight studies, innovation workshops, advanced research workshops. Expand the GEOLAB community and strengthen relation to CI stakeholders (policymakers, owners, designers and users).
Feedback loops between research and practice.	Organizing training workshops for new generation researchers,

	internships and online instruction videos. Adopt the use of further technologies such as BIM, digital twins, advanced simulation software and AI-based models and include them in future outreach efforts.

Finally, yet importantly, effective policy support is crucial for the integration of new research into infrastructure standards and practices. The geotechnical research community in general, and GEOLAB members in particular, can increase their efforts aimed at policymakers to promote legislation that encourages or mandates the use of evidence-based design methods and innovative technologies. This can lead to the inclusion of research-backed methodologies in official guidelines, incentivizing their use and enabling researchers to directly influence regulatory standards that shape industry practices.

3 MAIN OUTCOME GEOLAB

In this section, a number of the highlights of the GEOLAB project are presented for each core project component.

3.1 *Transnational Access*

3.1.1 *TA project realization*

The coordination of access to the GEOLAB RI was organized through a common Access Policy. Under this procedure, a User Selection Panel (USP) was established, consisting of independent experts and representatives of the experimental facilities. Three calls for proposals were organized as part of the TA inviting user groups to propose projects to be implemented free of charge in the GEOLAB RI. The USP reviewed and selected the proposals based on a set of pre-defined feasibility and quality criteria. With this procedure, a transparent, fair and impartial selection of the best proposals was ensured.

In total, 44 TA projects were realized since the start of the GEOLAB project. An example TA project is shown in the next section.

3.1.2 *PEBSTER: modelling and performance assessment of Piled Embankments with Basal STEel Reinforcement*

In cases of soft surface soils, the traditional approach to building roads and railways can cause large deformations. For safety reasons, the traffic speed may then need to be reduced. Furthermore, this leads to higher repair and maintenance costs.

In such conditions, a geosynthetic basal-reinforced pile-supported embankment is a widely adopted solution. Steel mesh reinforcement, however, can be appealing for its high axial stiffness, which reduces the deformations at the embankment base, minimizes pile bending moments, ultimately enhancing the embankment stability. Applying welded steel mesh reinforcement allows for application in higher embankments, for example in abutments of viaducts or bridges (Schneider et al. 2024).

The goal of PEBSTER was to investigate the performance of such a pile-supported, using a welded steel mesh as basal reinforcement. Model tests at two scales were conducted:

- Small-scale model tests at Deltares (see Figure 1)
  Model size: in plan 1.1 m x 1.1 m, depth 1.2 m
- Large-scale model test at TU Darmstadt (see Figure 2)
  Model size: in plan 5 m x 5 m, depth 5.5 m


Figure 1. Building the small scale model prior to testing, including four piles with a diameter of 0.1 m (2022, Deltares Geo Model Hall facility)

The objectives of the research, the test set-up and the final research program were discussed intensively with the user group led by Keller, a large specialized geotechnical contractor. The collaboration with an industrial partner like Keller ensures that the innovation will be implemented in practice and that the research project is enriched by practical experience, thereby enhancing its relevance and applicability.

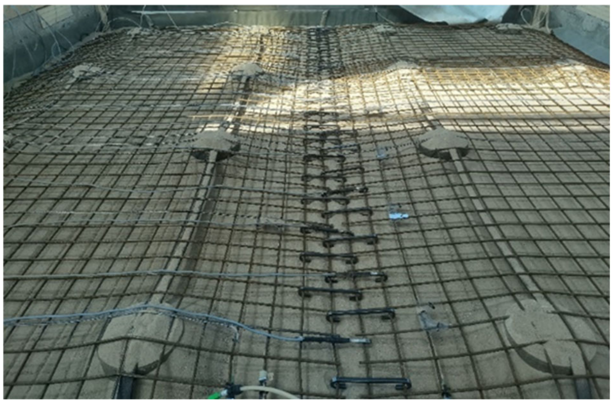
Figure 2. The large-scale test set-up showing the deformed steel mesh during excavation after test performance. Some of the 16 piles with a diameter of 225 mm and instrumentation are visible (2023, TU Darmstadt Geotechnical Test Pit facility)

The company SHM System, a Polish Small and Medium-sized Enterprise (SME), was also part of the user group that initiated the project with support of the GEOLAB expertise and funding. SHM System provided the Distributed Fibre Optic Sensing (DFOS) technology for measurements in both the small-scale and large-scale model tests. This technology played a key role in delivering a detailed and innovative 3D perspective on the strains and deformations of the reinforcement and soil at various levels in the fill. It also provided important experience and lessons for future application of the technology, such as how to determine effectively 3D deformation from multiple strain measurements (Van Eekelen et al. 2024).

The PEBSTER project was selected to showcase the way GEOLAB works. Many other examples could be given. Key added values are:

- The close interaction with industry providing the solution leading to practical results.
- The positive impact of the research on the resilience of CI, in this case roads and railways, reducing failure and congestion risks and maintenance costs.

- The SME participation in the experimental investigations and consequent improvement of their DFOS 3D data interpretation protocols, all leading to a strengthened business position.

3.2 *Joint Research Activities*

3.2.1 *Standardized data sharing*

A key success factor for GEOLAB is the development of an approach that allows for sharing and re-using of experimental data obtained from TA projects. In the first step, common standards were developed for the archiving of data from all TA project activities. Efficient re-use of data demanded an enhancement of meta-data requirements, improving the findability of datasets and allowing researchers to judge the suitability and quality of the data, and to download and use it, without having to interact directly with the authors. The development of this approach was guided by the FAIR principles of Findable, Accessible, Interoperable and Re-usable data (Žlender et al. 2022).

In the second step, several data management platforms were assessed taking into account the EU legislation on Protection of Personal Data (POPD) and General Data Protection Regulation (GDPR). Based on the assessment, Zenodo was selected as a repository for the GEOLAB datasets (Peters et al. 2022).

The Zenodo repository is a discipline agnostic database operated by CERN. For each submission, a persistent Digital Object Identifier (DOI) is generated, allowing datasets as well as publications to be readily cited. The user groups performing the experiments as part of the GEOLAB project had the obligation to store the dataset package from their experiment(s) in the Zenodo repository. A dedicated GEOLAB community was established in the Zenodo repository.

3.2.2 *Innovation of the GEOLAB RI*

The GEOLAB consortium has engaged itself in different areas of innovation and cooperation with SMEs. Successful innovations initiated in GEOLAB contributed to the business development of these SMEs and therefore to the wider availability of advanced engineering tools. This leads to optimizations in CI design and management (e.g., cost savings, risk reduction, improved resilience). Some examples of success stories are:

- For research in the field of mud flow landslides, a set-up was needed to simulate the mud material during flight of the geo-centrifuge. This set-up consisted of a container with mud material, which is placed on top of the slope and opened during flight to study the flow slide and impact on barriers present. A challenge in this regard is the fact that under increased g-forces particle segregation will happen in the container influencing behavior of the flow slide. To avoid this, a container with in-flight mixing capabilities was developed in collaboration with an SME.
- In the field of pile foundations, an innovative system had been designed to install displacement piles and load them laterally while the centrifuge is in-flight condition in order to quantify the impact of the pile group installation effects on the performance of laterally loaded groups. After exchanges with several suppliers, miniature earth pressure cells could be selected and installed at the surface of the pile shafts to monitor the stress development during the horizontal pile deflection.
- In cold regions, the shallow layers of soil are periodically subjected to freezing-thawing cycles and associated frost-heaving phenomena, increasing the risk of uplift failure mechanisms of pile foundations. A Vortex freezing system was developed for use in-flight, to study experimentally in the geotechnical centrifuge such mechanisms. Centrifuge tests reproducing freezing and thawing cycles of cold climates on several different configurations of foundations were enabled by the newly developed system.
- Several innovations in field investigation methods provided by SME have been applied in the Norwegian Geo-Test Sites. For instance, advanced non-intrusive geophysical techniques have been employed, aiming to protect critical infrastructures against quick clay hazards (Le et al. 2024). An innovative in-situ ground investigation tool (i.e. Medusa DMT/SDMT) for soil characterization has been tested (Monaco et al. 2024). The tool contributes significantly to more effective and accurate characterization of ground conditions prior to or during construction. This reduces risk and the costs associated with building new infrastructure.

3.2.3 *Material properties database*

Physical modelling is usually coupled with numerical modelling for better understanding and analysis of the phenomena being examined. In general, however, use and re-use of experimental data for numerical studies is often hampered because information on the properties of the materials used is incomplete, insufficient, scattered or not readily available. Details on how these material properties are acquired (e.g., test type, standards, conditions) are also usually lacking, consequently making it difficult for users to verify the accuracy of information. Moreover, data related to material constitutive models, which are required to perform realistic simulations, are usually absent. Thus, in the GEOLAB project a comprehensive unified material properties database was developed for the typical soils and constitutive models used in the GEOLAB facilities that address the above problems (Beroya-Eitner et al. 2024).

3.2.4 *Benchmark test*

The benchmark test is an exercise conducted at multiple geotechnical experimental facilities within the GEOLAB RI. The aim is to compare two prototype large-scale pile tests with several small-scale centrifuge tests replicating the large-scale conditions. The piles were subjected to various lateral load combinations, including monotonic loading until failure and cyclic loading at different load amplitudes. The outcomes are open-access data, which significantly contributed to understanding reproducibility and scale effects in geotechnical physical modelling. The exercise has shown strategies for enhancing consistency and provided a valuable database for validating numerical models (Liaudat et al. 2024).

3.3 *Networking Activities*

From the start of the project a clear communication strategy was implemented with a focus on the following main stakeholders: CI-owners & policymakers, industry including SME and Academia among which the owners of the RI facilities. Dedicated workshops (nine during the entire project) were organized at the yearly GEOLAB event with the aim increasing outreach and discussing topics of research and innovation.

3.3.1 *Training the Next Generation researchers*

Many of our actions were specifically targeted at educating and training the NG researchers so they can acquire the ability to better assess the added value of physical modelling and use the physical modelling tools in combination with data and numerical modelling for science and engineering. Developing the skills of these future research leaders ensures our impact on future research and innovation. Through the six universities in GEOLAB and the other universities in the user community, we have access to an extensive academic network and international societies for reaching these NG researchers. The interest in our training workshops, webinars and internships opportunities have been overwhelming. In total 97 NG researchers have participated in the three 2-day training workshops in Madrid, Zürich and Oslo. Next to that, 15 NG researchers joined GEOLAB organizations which hosted a 2-week internship at their RI facilities.

3.3.2 *GEOLAB Knowledge Platform*

GEOLAB developed a branded website as a tool for use by the consortium participants and as a portal to help disseminate our activities and knowledge to other stakeholders and potential collaborators. The GEOLAB website was also used to provide access to the Knowledge Platform, to promote news and results and contain social media tools that facilitated participation in our online activities.

At the moment the Knowledge Platform contains all project deliverables. The most important key deliverables are:

- D06.03 Science and Innovation Agenda. Roadmap of Future Developments of the Research Infrastructure.
- D08.01 Inventory of facilities, technical specifications and experiment portfolio
- D08.03 GEOLAB User Manual – How to use the RI facilities
- D09.01 GEOLAB Experimental challenges and technology readiness
- D09.02 Physical modelling of the impact of climate change, extreme events and aging on CI
- D09.03 New materials, new sensing and new manufacturing methods
- D09.04 Remote sensing, geophysics and imaging technology for monitoring and characterization of geo-structures and geo-materials
- D09.05 3D High Density Spatial Measurements

Next to that, we have video recordings and presentations of workshops, webinars and the NG training.

3.3.3 *ECPMG2024 in Delft*

Hosted by Deltares and TU Delft, the 5th European Conference on Physical Modelling in Geotechnics (ECPMG2024) took place in the city of Delft, the Netherlands, from 2nd to 4th October 2024. ECPMG2024 was organized by the Technical Committee on Physical Modelling (TC104) of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) in cooperation with the GEOLAB project.

The conference was an excellent opportunity to showcase the outcome of the GEOLAB project. A total of 17 papers on work performed in GEOLAB were published. All papers are available in open access at the online library of the ISSMGE.

4 CONCLUSION

4.1 *Future development GEOLAB RI*

One of the technical innovations awaiting development is centrifuge-mounted wave and flood generator. Such an experimental tool is extremely relevant for investigations with combination of hazards such as flooding and earthquake. The ability to model at small scale all aspects of the problem (i.e. both hydro-mechanical and geotechnical processes for this specific hazard combination) in a realistic manner, including stress similitude with the prototype, is essential.

A further technical innovation still to be developed for the framework of multi-hazard analyses in relation to climate change effects are the climate chambers, at either large scale for prototype investigations or reduced scale for tests in the geotechnical centrifuge.

Next to that, there is continuous workflow of innovation to optimize building of physical models (e.g. impact and vibro hammer) and parts for the measurements systems (e.g. sensors). Cross cutting technologies, such as MEMS, robotics, 3D printing, high speed cameras and fibre optics sensing offer opportunities for these innovations.

4.2 *Beyond the GEOLAB project*

The GEOLAB initiative emerged from the European Large Geotechnical Institutes Platform (ELGIP). Many of the GEOLAB partners are also members of ELGIP. The outcome of GEOLAB will be transferred to ELGIP with the following actions:

- The GEOLAB website and Knowledge Platform will be migrated to the ELGIP website and remain managed and accessible.
- The social media accounts will be handed over to the ELGIP secretary.
- The GEOLAB partners and other interested ELGIP members will continue collaboration as a working group under the umbrella of ELGIP.

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