A novel strategy to digitalize, integrate and analyse data for the characterisation of landslides in turbiditic deposits

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ABSTRACT

A phenomenological interpretation of the slope factors and lanslide mechanism represents the first stage for the assessment of landslide hazard at the slope scale. This requires processing, analysing and integrating a large set of multidisciplinary and heterogeneous data, obtained through diverse activities, among which: geological and geomorphological studies, geotechnical investigations and monitoring, topographic and structural damage surveys. The integration of such a variety of multisource data, to build up a sound conceptual model of the slope, can be particularly challenging, especially in geohydromechanical contexts characterised by a great spatial variability of soil properties and complex hydraulic boundary conditions, such as in the case of slopes composed of turbiditic formations. This paper presents a new methodological approach for the study of landslide hazard at the slope scale, based on the combined use of an open-source GIS platform and an in-house developed dashboard for the interactive visualisation and analysis of geotechnical laboratory data. The details of the GIS project and the potentiality of the data-analysis dashboard are described, highlighting the interoperability between the two digital tools. The proposed methodology is applied to a pilot site, the Pianello area in Bovino, in the souhteastern Apennines, a widely investigated hillslope composed of tectonised clayey turbidite, hosting a complex basin of slow-moving landslides.

Keywords: landslides; GIS; dashboard; phenomenological model

1. Introduction and background

The diagnosis of landslide processes at the slope scale requires the understanding of the landslide mechanism, which, in turn, entails the characterisation of the internal (predisposing) and external (triggering) factors (Terzaghi, 1950) that control the instability of the slope. A proper characterisation of the landslide mechanism is a prerequisite for the selection of the most adequate mitigation measures and, when the evaluation of the slope stability and its evolution is carried out on a quantitative basis, for their design. Cotecchia et al. (2014a) pointed out that a robust assessment of the landslide hazard at the slope scale should be consistently carried out using a stage-wise methodology (SWM) moving from a qualitative conceptual model of the landslide mechanism to detailed numerical analyses of the evolution of slope failure. The suggested methodology comprises three subsequent stages:

a. phenomenological interpretation;
b. simplified LEM stability analyses;
c. numerical modelling of the landslide evolution.

In particular, the characterisation of the slope factors entailed in stage a. requires the collection and analysis of large sets of heterogeneous and multidisciplinary data, spanning a variety of domains: geology (borehole corings, results of geomorphological, lithological, geo-structural, hydro-geological analyses); geophysics (data from geo-electrical and geo-seismic surveys); geotechnics (field and laboratory test data, inclinometer and piezometer monitoring); hydrology (monitoring of climatic variables, survey of vegetation, analysis of streams erosion). The integration of the aforementioned data can be particularly challenging, especially in geo-hydro-mechanical contexts characterised by extreme spatial variability at various scales, as in the case of slopes composed of so-called Structurally Complex Formations (Esu, 1977), of which turbidites represent a typical example. This paper presents a methodology for the integration of the diverse data in a digital platform consisting of opensource tools for data storage, analysis, and visualization, aimed at supporting the characterisation of landslides at the slope scale.

Widespread use of computerised relational databases and GIS software platforms (Batty, 1992), since the 1990s has significantly improved the ability to store, visualise and spatially correlate data, hence aiding in the design of geotechnical systems or in risk assessment activities. So far, GIS-based applications in geotechnics have been mainly employed for storing and displaying static information, such as borehole logs, results of field tests, etc. (Wan-Mohamad and Abdul-Ghani, 2011; Graettinger et al., 2019), also allowing for geo-spatial analysis of data and zoning (Khan et. al, 2021). For the execution of sensitive geotechnical engineering works, such as deep excavations in the urban environment, Rackwitz et al. (2013) demonstrated the coupled use of web-based GIS and an interactive dashboard for the visualization of monitoring data. The spatial analysis of borehole logs through GIS can be used effectively to build a 3D geo-lithological model (Hamman et al., 2017;

Balasubramaniam and Dodagoudar, 2018), which, as shown recently (Khan et al., 2023), can be endowed with spatially varying soil properties and rendered interactive through the combined use of GIS and BIM.

So far, the vast majority of GIS applications for landslides concerns the wide-area assessment of landslide susceptibility or hazard, using semi-quantitative, statistics, or more recently, machine-learning based approaches (e.g. Dikau et al., 1996; Lee and Prdhan, 2006; Ayalew et al., 2004; Psomiadis et al., 2020; Conforti and Ietto, 2021). Instead, studies at scales large enough to carry out the analysis of landslide-induced damage and to implement risk-mitigation strategies are scarce (e.g. Petrucci et al. 2023).

For the assessment of landslide risk at the slope scale, this study presents a strategy to integrate multi-source heterogeneous data obtained from ground investigations, geotechnical monitoring, field surveys (also including structural damage), remote sensing, as well as the results of interpretative analyses of those data. The proposed methodology comprises the use of GIS for storing and visualising interactively georeferenced data, combined with a in-house developed dashboard for the analysis of geotechnical laboratory data. The integrated approach allows a significant speedup of the conceptual modelling, i.e. stage a. of the SWM for landslide hazard assessment. By including also the results of vulnerability studies, e.g. through surveys and classification of landslide-induced structural damage on buildings, the platform represents a valuable tool for landslide risk assessment and for the design of mitigation measures. Furthermore, by including duly processessed quantitative information, it grants the ability to perform further stability analyses (stage b. of the SWM) and to build up 3D numerical models of the slope (stage c.), thus allowing validation of the conceptual model and predictions of the slope evolution.

2. Description of digital tools

The digital tools employed in this study are an open-source GIS platform and an interactive dashboard. The GIS allows the development of interactive thematic maps, endowed with georeferenced information such as the results of ground investigations and field surveys, monitoring data, and interpretative models. The interactive dashboard, instead, serves as a data management platform, specifically devoted to the analysis of geotechnical laboratory and monitoring data. Combined use of the two tools allows to associate values of soil properties to specific zones in space, hence aiding in the development of a 3D geotechnical model of the hillslope. Fig. 1 shows a conceptual map of the proposed methodology: the GIS and the dashboard serve the integration of a variety of input data, and of models based on the interpretation of those data. Improvement of the interpretative models stems from integration performed through the proposed coupled digital tools, eventually leading to the conceptual model of the landslide.

2.1. GIS platform

The GIS software adopted for this study is the opensource Quantum-GIS (or QGIS; QGIS.org, 2024). In perspective, the approach described in this paper should be deployed as a web-GIS service, allowing access to the platform to end-users, including municipality administrations, governmental agencies, land planning institutions, civil protection, etc.

The QGIS maps include the following groups of layers, that can be switched on and off according to specific needs.

1) Input data layers:

- Topography: LiDAR surveys, Regional Technical Maps, orthophotos.
- Boreholes: location of existing boreholes, with the possibility to access all related data, including stratigraphy logs, geotechnical soil profiles, monitoring instruments, in-situ tests, undisturbed samples.
- Geophysical tests: traces of geoelectrical or geoseismic surveys. By clicking on the traces, the corresponding contour plots are shown.

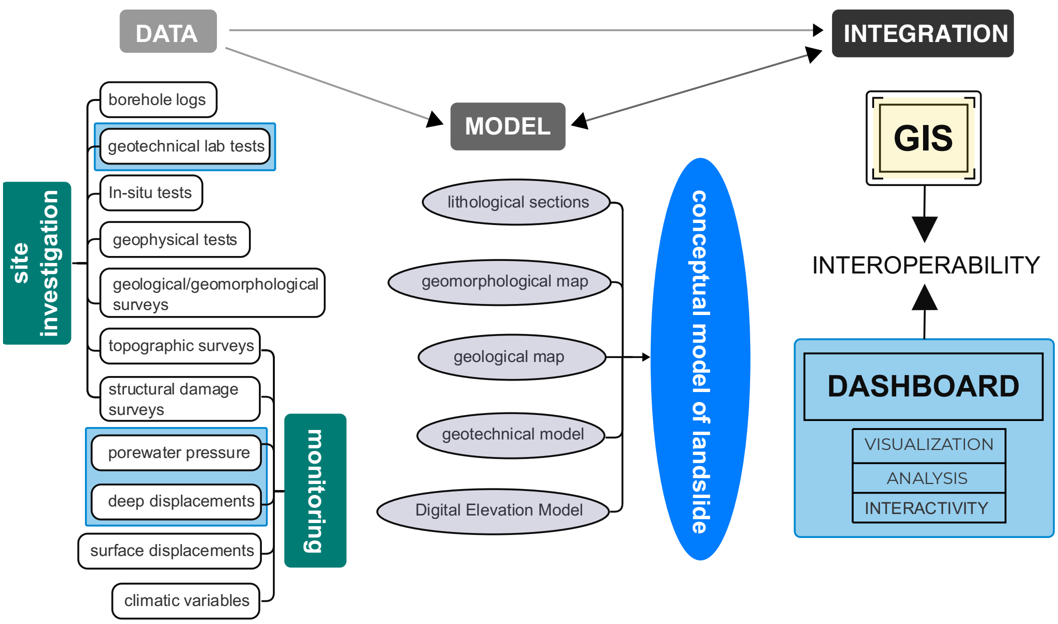

Figure 1. Conceptual map of the proposed methodology and digital tools

- Photographs of structural damage: containing the point of view and direction of pictures taken during field surveys of damage on buildings and infrastructures.
- InSAR data.

2) Interpretation layers:

- Geology: lithological units and geological structures such as faults and folds.
- Geomorphology: outlines of landslide bodies as well as other geomorphological features (scarps, fractures, etc.) obtained from multi-temporal analysis of aerial photos and from field walkovers.
- Cross-sections: can be shown by clicking on the corresponding traces on the map. They contain, among other information, soil stratigraphy, geotechnical parameters, slip surfaces and corresponding mobilised shear strength (if LEM analyses have been carried out), piezometric levels, etc.
- Geotechnical landslide damage map: for those buildings whose damage has been classified following the methodology devised in Palmisano et al. (2018). This layer shows the damage grade and symbols reflecting the. deformation mode of the building.
- Velocity vectors: obtained from time histories of horizontal displacement profiles with depth.

Other interpretative thematic layers, e.g. regional maps of landslide susceptivity, national geological map sheets, etc., can be added as Web Map Services.

2.2. Interactive dashboard

The dashboard for interactive data visualization and analysis has been developed entirely in Python, using the plotting library Bokeh (Bokeh Development Team, 2018) and pandas dataframes (Mc Kinney, 2010; The pandas development team, 2024) for data management. As such, it is open source and fully customisable. Just to mention an example of its functionalities, the dashboard allows grouping and filtering geotechnical data, e.g. based on campaign, lithological unit, depth. Fig. 2 presents an excerpt of a dashboard setup in which results of classification tests, as well as profiles of index properties with depth, are grouped by campaign of ground investigation and presented as scatter and bar plots side by side. All the plots are connected, in the sense that when some data points in one of the graphs are selected, the points corresponding to the same samples are selected automatically in all the other graphs. Other interactivity functionalities include, for instance, getting detailed information on borehole and sample by hovering the pointer on the data points, displaying a picture of the sample, showing a complete chart summarising the results of all laboratory tests carried out on the sample, performing statistical inference on subsets of datapoints. The dashboard is provided as a standalone HTML file—with embedded JavaScript code providing the interactivity functions—that can be opened in a web browser directly from the GIS project. As an option, the dashboard can be deployed as a server application. Interoperability between the GIS and the dashboard allows to select boreholes and samples in the GIS map so that the corresponding results are displayed in the dashboard, hence aiding in the zoning of the hillslope and building the 3D model.

3. Application to a prototype case: the Pianello hillslope in Bovino

The tools described in the previous sections were applied for the phenomenological interpretation of the landslide basin that affects the Pianello hillslope, in the small town of Bovino, which represents a prototype of slow landslide basins in structurally complex formations. The pilot site is located in the easternmost front of the Southern Apennines: the Daunia Apennines. In this territory, the slopes are mainly composed of clayey turbidites (Cotecchia et al., 2014b), characterised by high lithological and meso-structural heterogeneity.

Due to both the tectonic thrusts exerted during the Apennine orogeny and ancient landsliding, the geological formations encountered hereby are heavily sheared, exhibiting fissuring of the fine matrix and fracturing of rocky interlayers, that often float as disarranged inclusions in the clay (Lollino et al., 2010, Cotecchia et al., 2014c, Di Lernia et al., 2022). This adds up to the inherent weakness of the highly plastic clayey matrix, resulting in remarkably poor shear strength, that is one of the internal factors controlling the instability of the slope. Another important predisposing factor is represented by the very high piezometric levels measured even at great depths (Cotecchia et al., 2014c), implying a reduction of the available shear strength. As a result of the aforementioned internal factors, and possibly driven by seasonal rainfall (Cotecchia et al., 2016; Losacco et al., 2021), several slow-moving, medium depth to deep-seated landslides, affect the urban centres of the Daunia Apennines.

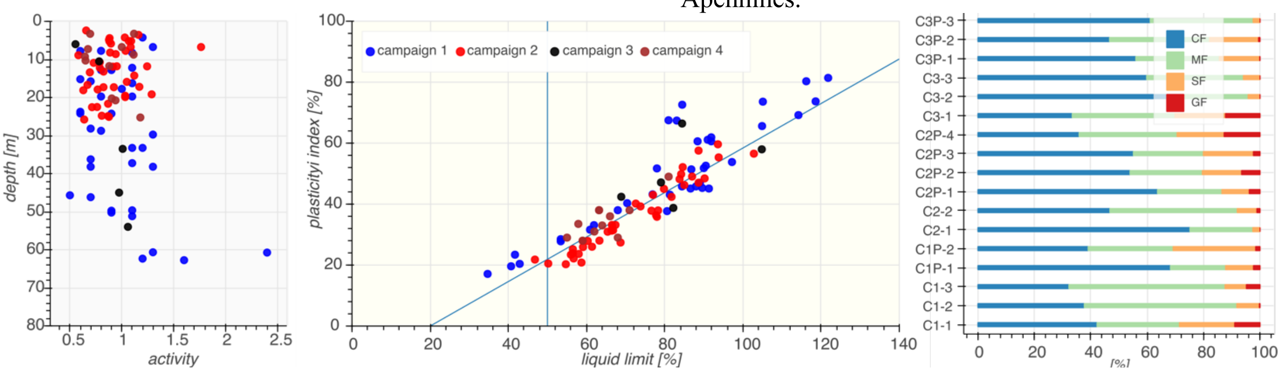

Figure 2. Dashboard setup showing activity profile with depth (left), Casagrande plasticity chart (centre), grain size distribution (right); scatter plot datapoints are grouped by ground investigation campaign

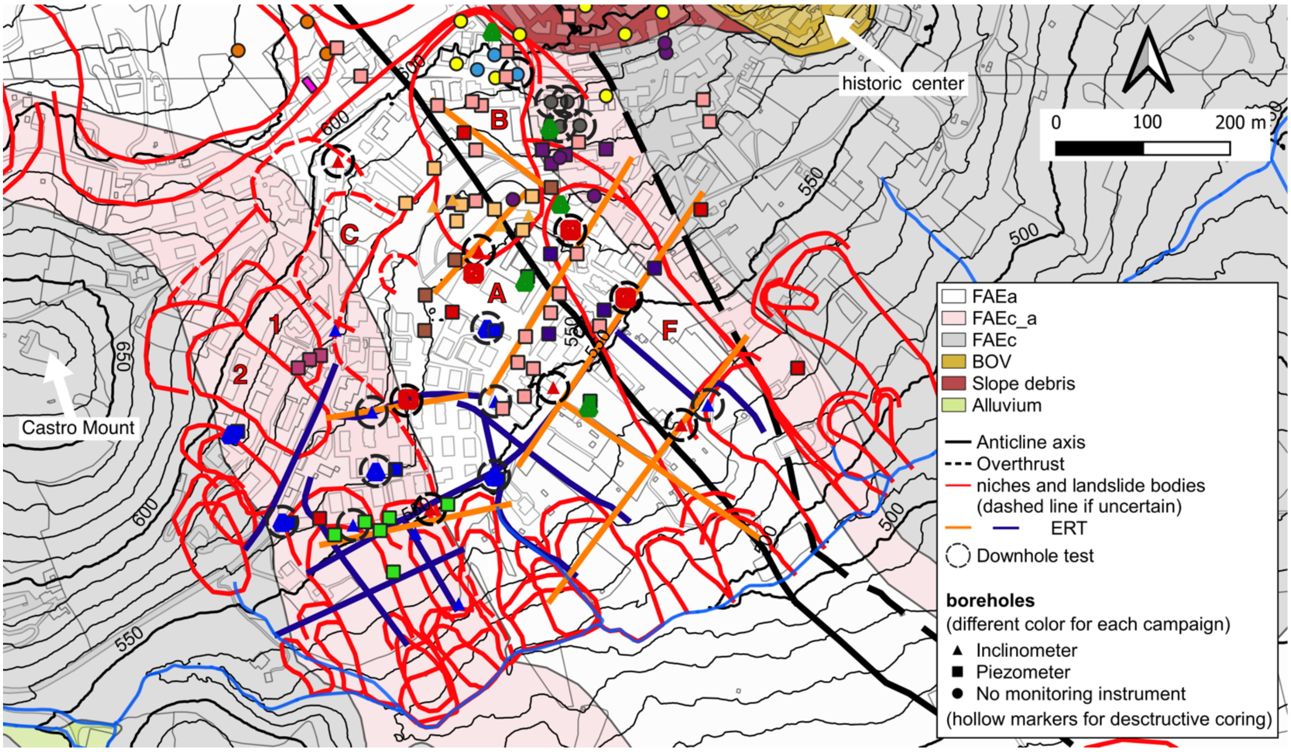

Figure 3. GIS map of the Pianello hillslope showing topography, location of boreholes, monitoring instruments and downhole tests, traces of ERT surveys, geological structures, main lithological units, landslide bodies and scarps

As for many other municipalities of Daunia (Zezza et al., 1994), the historic centre of Bovino rises on a stable rocky outcrop (the Bovino Synhtem; BOV). On the contrary, the more recent urban expansion, that started in the 1970s, occurred on an outcrop of the most clayey member of the Faeto Flysch (FAE) and hence is the most affected by the landslide activity. Thus, even though the landslide activity in Bovino is “extremely slow” to “very slow” (Cruden and Varnes, 1997), due to sudden accelerations, or simply to cumulated slow displacements over a timespan of tens of years, buildings and infrastructures suffer recurrent structural damage.

Fig. 3, obtained from the QGIS project, shows a geological-geomorphological map of the Pianello area. As seen in the figure, the Pianello hillslope stretches in the SE direction from the top of the morphological saddle between the Castro Mount and the historical centre down to the Biletra river. The area is crossed by an overthrust, approximately aligned NW-SE, that involves the FAE, and caused the development of an anticline. The FAE is characterized by an alternation of clay strata and rocky interlayers. It is possible to identify a mainly calcareous member, FAE_C, and a predominantly clayey member, FAE_A (Di Nocera & Torre, 1987), separated by a transition unit, $FAE_{C\text{-}A}$. The FAE_A occupies the core of the anticline and emerged after the erosion of the above FAE_C, which was, in turn, lifted, and is found at the flanks of the hillslope.

Fig. 3 highlights the landslide bodies identified on the Pianello hillslope, the most relevant of which are: the main body A, with maximum depth of at least 60 m, head at the ridge between the Castro Mount and the historical centre, and toe at the Biletra river; a secondary, shallower body B, with toe on the western part of the head of body A; the secondary bodies 1 and 2 with toes at the east of the head of body A; a secondary, elongated body F, occupying the eastern portion of body A. An unstable area, C, has been recognised from scarps and detachment niches. Several secondary superficial bodies are found in the accumulation zone of body A, the majority of which have their foot corresponding to the Biletra.

Due to recurrent damage to buildings and infrastructures, several surveys and monitoring campaigns have been carried out since the 1980s, in order to characterize the active landslide mechanisms and to design appropriate mitigation measures, as well as for research purposes. Fig. 3 also shows the location of the boreholes and the traces of the ERT surveys executed during the campaigns of ground investigations carried out on the Pianello hillslope. These campaigns yielded a large set of multidisciplinary and heterogeneous data, inherently difficult to manage and to integrate. Therefore, the described site represents an ideal protype for testing the proposed methodology employing digital tools.

The implementation of the QGIS project made the data easily explorable. As displayed in Fig. 4, it is possible to query data from any active layers on the map, (e.g., in the figure: location of boreholes equipped with piezometers of inclinometers, traces of ERT, buildings footprint), and the corresponding embedded content pops-up (in the figure: time-histories of porewater pressure and profiles of horizontal displacements at depth, electric resistitvity contours, photos of damage on buildings). Other noteworthy embedded data that can be displayed with a simple click—not shown in Fig. 4—include summary sheets of laboratory results for each tested undisturbed sample, results of downhole and Lefranc tests, geotechnical sections representative of the landslide processes in 2D.

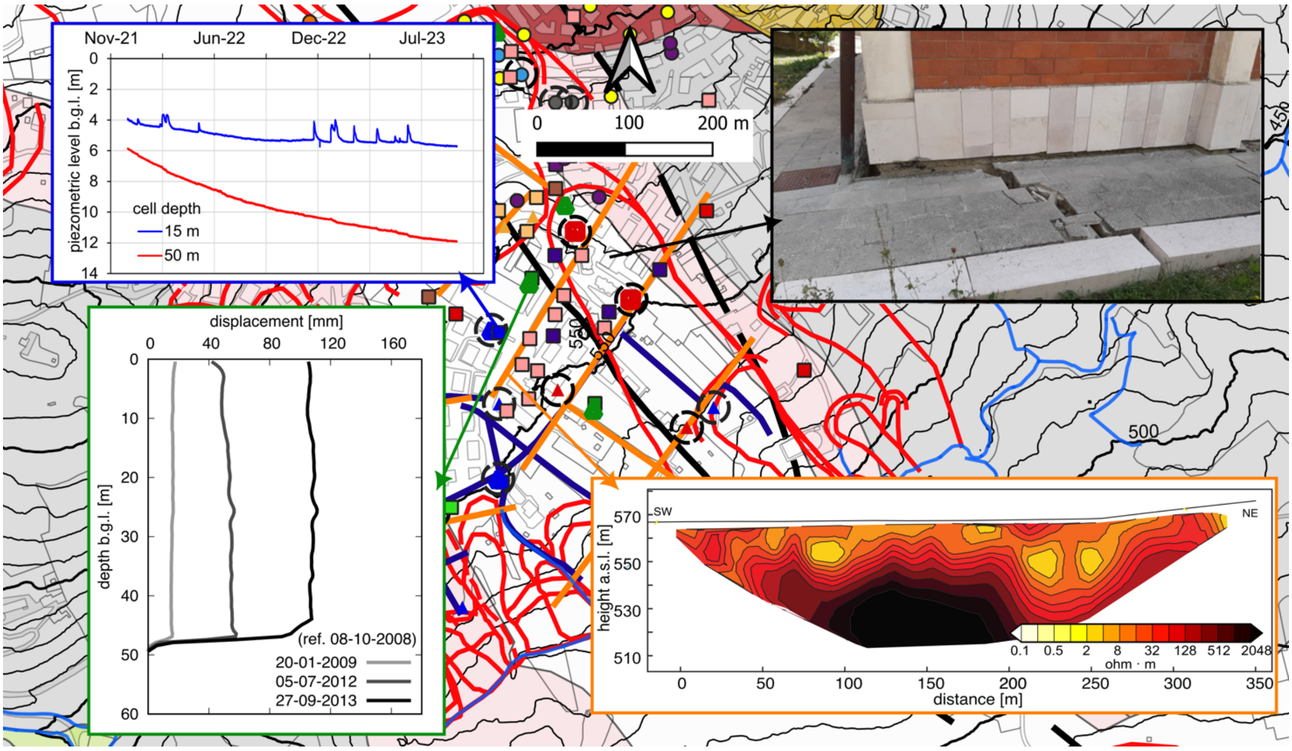

Figure 4. Interactivity of the GIS, showing embedded data as pop-ups on the base map; from top left, clockwise: electric piezometers readings in time, detail of damaged building, ERT contours, inclinometer profiles in time (legend of underlying map in Fig. 3)

The development of the dashboard for data analysis has been crucial to allow interactive visualisation, clustering, comparison and mathematical elaboration of geotechnical laboratory data, e.g. index and physical properties, results of oedometric, direct shear, and triaxial tests. A similar dashboard for monitoring data is currently under development. The interoperability between the QGIS project and the dashboard was fundamental to correlate geomechanical data in space, providing the quantitative information needed to build 2D sections and a 3D geotechnical model of the hillslope, to complement the phenomenological interpretation and to serve as an input for numerical analyses. Fig. 5 provides an example of such interoperability. Borehole C7 is instrumented with an inclinometer, installed during the most recent campaign of ground investigation. By querying the borehole location in the QGIS map, it is possible to show the lithological column, the depth of collected undisturbed samples and the installed monitoring instrument. By clicking on any of the undisturbed samples, the dashboard can be accessed to show, for instance, an interactive plot of the q-p' stress path obtained from isotropically consolidated undrained triaxial tests performed on that sample. The stress-paths of all other samples are also shown in the same graph, as dimmed curves, for further analysis and comparison. It is worth underlining that the laboratory test results may also be examined in their original format as tables or static plots, by performing a query in the QGIS project.

4. Concluding remarks

For the prototype case of the Pianello hillslope in Bovino, combining the digital tools with the classic desk study made it easier to access and explore the large available database, speeding up the creation of a phenomenological model of the landslide processes. In the future, the current GIS project will be enriched by adding the ability to run LEM stability analyses on representative cross-sections, hence moving to the first quantitative stage (stage b.) of the SWM for landslide hazard assessment.

By including information along the *z*-coordinate (lithological profiles, displacements, porewater pressures, etc), and easing the construction of 2D geomechanical sections of the slope, the devised GIS project marks a step forward towards a full 3D model of the subsoil.

In particular, the combined use of the GIS and the dashbord allows to describe the spatial distribution of the mechanical properties of the soils, hence aiding in the creation of a 3D geotechnical model of the slope, which is the prerequisite to run detailed numerical analyses (stage c. of the SWM).

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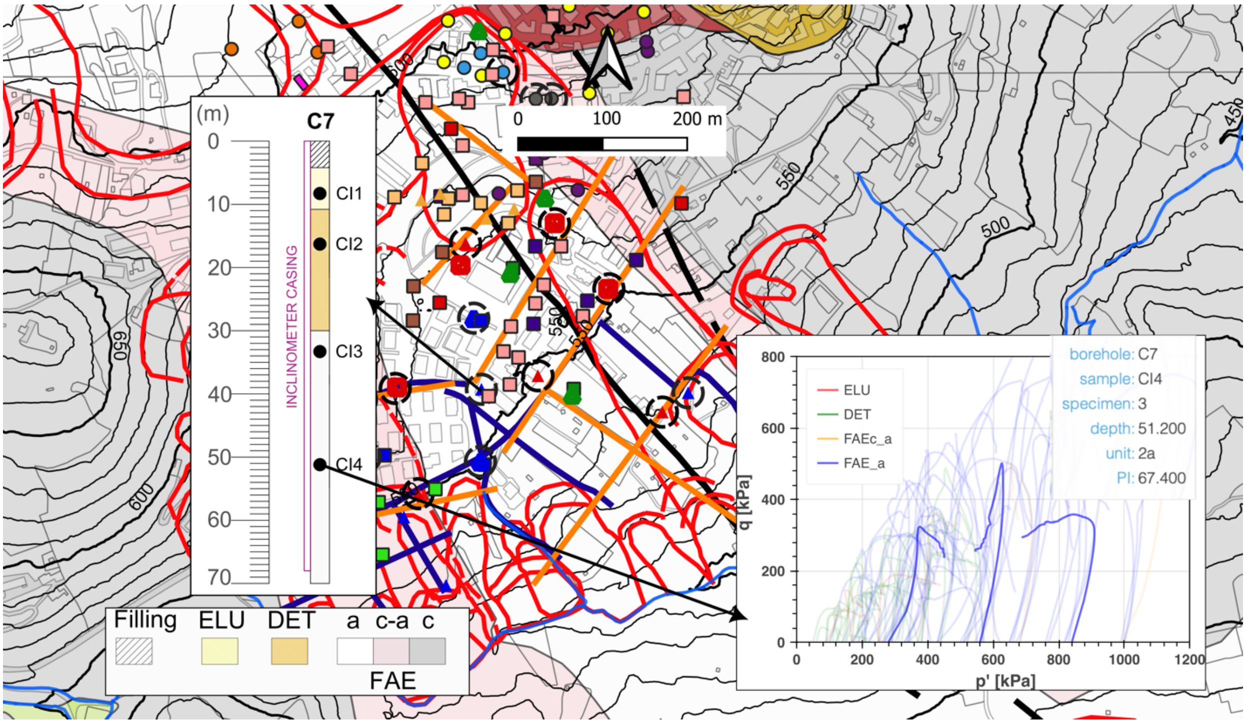

Figure 5. Example of GIS – dashboard interoperability: from borehole to stress paths of CIU triaxial tests on picked sample (legend of underlying map in Fig. 3)

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