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Risk mitigation in deep excavations affected by Lava-Baked Paleosols

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Abstract

Deep excavations are traditionally designed based on ground conditions, geomorphological and hydrogeological framework, geometry and construction techniques. In this paper, the authors present a risk mitigation strategy to improve safety during construction of a typical deep excavation through retaining system in a geologically unconventional context.The project is located in the proximity of Catania, in the volcanic geological district of M. Etna and, specifically, in the synthem unit of “Supersintema Stratovulcano”. The local stratigraphy is characterized by a shallow basaltic layer 12-16m thick, mainly consisting of lava flows and pyroclastic fall deposits, overlying a variable (1.5-4.0m) layer of Paleosols altered by lava flows and a sub-stratum of Quaternary marine clay deposit. The unconventional order of this lithostratigraphy lies in the significative decrease of stiffness between the upper layer, characterized by competent geomechanical properties, and the underlying layers, which present average to weak geotechnical properties. The retaining structure consists of a multi-anchored micropile wall. The project excavation height is 21.0m, intersecting all three geotechnical units. The retaining system stiffness and deformative response is sensitive to the variability of Paleosols thickness and depth. The response of the retaining wall to the several excavations stages is modelled through a numerical 2D analysis. The study investigates how the thickness of Paleosols altered by lava flows influences the behavior of retaining walls. Multiple scenarios are analysed, accounting for the variability of the thickness of Lava-Baked Paleosols due to geomorphological conditions, eruption sequence and volcanic history.The results support the definition of a predictive model which consents identifying attention and alarm thresholds for specific excavation stages. The integration of sensitivity analyses into the design of the monitoring system enables the early identification of potential risks, associated with shallower layers of Lava-Baked Paleosols, allowing for mitigative measures to prevent critical conditions.

Keywords

Deep excavation, Risk mitigation, Monitoring, Paleosols, predictive modelling.

1 Introduction

1.1 The challenges of urbanization

Acceleration of urbanization requires even more often the use of underground space and associated with great uncertainty and geological complexity of the underground environment, this implies high challenging problem and intense risk perception (Zhang 2025). Deep excavations developed in volcanic terrains often present challenges associated with complex and unconventional lithostratigraphic arrangements. In the Catania region, the sequence of competent basalts overlying weaker Paleosols baked by lava flows results in a marked stiffness inversion. This singular stratigraphic configuration influences the mechanical behaviour of both the soil mass and the retaining structures, potentially increasing the vulnerability of the excavation.

1.2 The Ferrovia Circumetnea Misterbianco-Paternò Design & Build Contract

Within the urban areas of Catania and Misterbianco, South Italy and in the sub-metropolitan section up to Paternò, the line consists of a 11 km metropolitan railway connected to the greater Circumetnea Railway. The Misterbianco-Paternò lot, in particular, connects the city of Catania with the main towns on the southwestern side of the Etna foothills and allows transportation modal interchange (buses, private vehicles).The project is framed through a Design & Build contract type, awarded by the well-established Italian Contractor Consorzio Stabile SIS Inc SpA. The designers joint venture is formed by Lombardi Ingegneria Srl, Sipal SpA, F&M Ingegneria SpA. The overall Contractor and the Designers are working as a unique entity on behalf of Ferrovia Circumetnea (the Client). Ferrovia Circumetnea (FCE) is a public-sector infrastructure employer and contracting authority which constitutes the infrastructure manager of the metro line. FCE operates under the direction of the Italian Ministry of Infrastructure and Transport.

2 Case study: Belpasso Station

2.1 Description of the retaining structure

The project goal is the construction of an underground metropolitan station. The station extends 110.0 m in length and 33.0 m in width; foundation level is 21.0 m below ground surface. The temporary retaining structure is designed for the excavation and subsequent construction of the underground metropolitan station. The temporary works consist of sheet pile wall of small diameter (Ø250mm diameter micropiles) retained by 4 or 5 levels of ground anchors. The micropile walls are arranged around the excavation, micropiles are spaced by 0.40 m and connected by a 0.55 × 0.55 m reinforced-concrete capping beam. A multilevel anchored system is constituted by ground anchors (ie. tie-backs) connected by steel waling beams. The geometrical model of the retaining structure is reported inFig. 1.

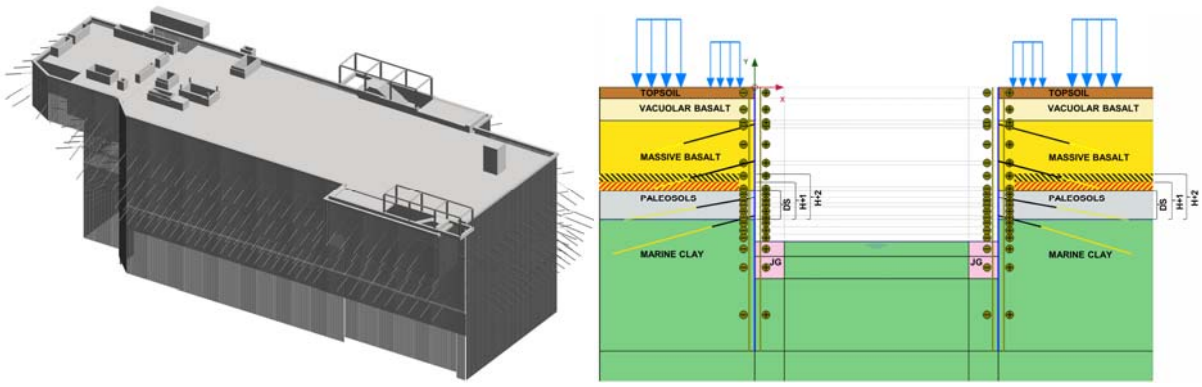


Fig. 1 Temporary retaining structure: Render 3D model (left) and numerical model (right).

Ground improvement is foreseen through wide-spread jet-grouting columns of variable thickness and height positioned along the internal perimeter, aiming to increase passive earth resistance. All tie-backs with rock-injected bulbs within basalt lava have a drilling diameter of 0.14 m and are composed of 4 steel strands. All tie-backs with bulbs injected into soil (clayey silt or marine clays) have a drilling diameter of 0.18 m and are composed of 4 or 5 steel strands. The horizontal centre distance and the length of the foundation bulb vary according to the stresses.

2.2 Geological and Geotechnical Framework

The project area is located on the edge of the south-eastern slopes of the Etna volcanic complex. The soils belong to the post-orogenic succession, in particular of a sedimentary nature, discontinuously covered by lava flows (Branca 2011). The lithostratigraphic succession reveals the presence of a substrate of Pleistocene marine sediments, represented by clays and marly clays (grey-blue clay formation, lower-middle Pleistocene) (S. Carbone 2010). These clays are overlain by volcanic lithotypes and alluvial deposits linked to the complex surface hydrography, dominated by more or less subparallel water streams that flowed into the coast, which has been greatly modified by successive lava flows, particularly that of 1669 (Lanzafame 2022).

A common feature of the volcanic products of the various Etna systems is the presence of horizons of materials locally known as "Rifusa", consisting of pyroclastic sediments and/or paleosols baked by the overlying lava flow. From a granulometric point of view, these horizons appear as a loosedeposit consisting of blocks and boulders in a predominantly gravelly-sandy matrix.

The excavation area extends approximatively 110 m by 33 m, no.9 investigative boreholes were carried out within the station footprint, revealing the presence of three main geotechnical units:

- Basaltic lava flows and pyroclastic deposits (12–16 m thick), representing the stiff and competent upper formation.
- Lava baked Paleosols (1.5–4.0 m thick), characterized by lower stiffness, strong heterogeneity, and high sensitivity to thickness variations.
- Quaternary marine clays, forming the foundation deposit.

The results of theground investigations demonstrate a marked vertical and lateral variability across the three geotechnical units. This heterogeneity reflects prolonged and recurrent depositional and erosional reworking driven by volcanic processes, which have progressively reshaped the original geomorphology. This process concludedwith the deposition of the superficial basaltic lava layer attributable to the most recent eruptive phases.

3 Instrumentation and monitoring

Geotechnical and structural monitoring systems are fundamental to risk mitigation in deep excavations projects. An effective monitoring strategy ensures that the excavation proceeds within safe limits and that emerging anomalies are identified before they evolve into critical conditions(Ruggeri 2024).An effective monitoring system relies on cutting-edge instrumentation to acquire data from multiple technologies, enabling comparison and interpretation of the measured responses. A multi-instrumentation approach allows a combined assessment of displacement-based and force-based monitoring strategies. For an efficient interpretation of recorded data, it is good practice to establish predefined threshold levels, typically defined as attention and alarm threshold levels (T.S. Chua 2006). Threshold values, reading frequency and corresponding actions are defined for each monitoring technique. The Attention level is set as a fraction of the design-predicted values. Exceeding this limit requires an increase in the measurement frequency, with the objective of determining and monitoring the rate at which the phenomenon is evolving. The Alarm level is set as a threshold occurring at the most critical deformation or stress condition detected at a given excavation stage. Once the alarm threshold is reached, it becomes necessary to evaluate the implementation of appropriate countermeasures, which aim to bring the actual behaviour back within the ranges anticipated in the design.

4 Methodology

4.1 Risk mitigation strategy

The risk mitigation strategy for the realization of the project is based on the following steps:

1) Sensitivity analysis through numerical modelling: focus on Lava-baked Paleosols thickness. Proceeding through a parametric approach enables identifying the most critical scenarios.
2) Design the monitoring system and define limit thresholds based on numerical modelling outputs.
3) Install and monitor a multi-instrumentation monitoring system, which combines displacement-based and force-based measurements.

This strategy allows foreseeing the response of the monitoring system to unexpected ground conditions, increasing the Contractor and Design team's confidence on the monitoring system.This predictive model-based derisking strategy shall help defining the soil-structural response based on the observed monitoring data and according to varying ground conditions (ie. Lava-baked Paleosols thickness). Besides, this shall determine which sensors are to be detected as the more sensitive to soil-structural behaviour and may be representative of an early-warning (ie. Attention level achieving).This risk mitigation strategy allows anticipating the response of the monitoring system to unexpected ground conditions, improving the prediction of soil-structural behaviour. The achieved results through FEM sensitivity analyses predicttypical soil-structural responses and clarify how monitoring datasets shall be interpreted asindicators of adverse behaviour.

4.2 Monitoring system

The monitoring system that controls retaining wall behaviour during excavation is based on three technologies: *topographic monitoring* with optical targets on multiple levels on the retaining wall, *inclinometers* installed behind the retaining wall and *toroidal load cells* installed on ground anchor heads. Monitoring during excavation shall be driven by daily readings. A zero reading shall be taken prior to works initiation to define baseline noise.

4.3 Numerical modelling

A two-dimensional Plaxis (Bentley Systems) finite element model is developed to simulate the staged excavation of the 21.0 m deep cut and the sequential activation of micropiles and anchors. The numerical model configuration is reported in Fig. 1. The model reproduces the stratigraphic conditions and the construction sequence adopted on site. The basaltic rock has been modelled with Mohr-Coulomb constitutive model, while Topsoil, Lava-baked Paleosols and Marine clay are modelled with Hardening Soil constitutive model (Material Models Manual 2D); geotechnical parameters are reported in Table 1.

Table 1. Geotechnical parameters adopted in the numerical analyses.

Material	γ_{DRY}	**c'**	**φ'**	E_{50}^{ref}	E_{ur}^{ref}
[-]	[kN/m^3]	[kPa]	[°]	[kPa]	[kPa]
Topsoil	18.0	5	30	10000	30000
Vacuolar basalt	24.0	107	35	1100000	-
Massive basalt	27.0	268	35	1100000	-
Paleosols	18.5	11	36	85000	255000
Marine clay	19.0	20	25	225000	675000

The influence of Paleosols thickness was investigated through three configurations: the design stratigraphy called "Design scenario" corresponding to the actual approved Final design, a scenario called "H+1" where Paleosols thicknessis increased by 1.0 m , and a scenario called "H+2" in which Paleosols thickness is increased by 2.0 m (see Fig. 1). These thickness increments of Paleosols stratum correspond to a decrease of the thickness of the overlying Basalt layer. These variations represent plausible geological conditions arising from local geomorphology and volcanic depositional history. For each scenario, the evolution of wall displacements, forces redistribution along the sheet pile wall and anchor loads were analysed at the main excavation stages, showing the sensitivity of the retaining system to Paleosols upperbound interface level.

5 Results

The numerical modelling results aim to identify potential early-warning indicators that support the excavation staging and predict the deformations of the retaining wall. The underlying working hypothesis is that Paleosols layer thickness variations constitute the primary geotechnical uncertainty. The correct interpretation of monitored data and the suggested predicting model aim to ensure the safe and successful execution of the civil works.

5.1 Forecasting of the topographic monitoring

The results of the predictive analysis simulating the topographic monitoring are reported in Fig. 2, where the numerical analysis provides the forecasted displacement for two optical targets located at -5.0m and -10.0m from ground level during the excavation stages. The maximum displacement difference between the Design scenario and H+2 scenarios at the second anchor level during excavation stage no. 3is equal to 3.7 mm.

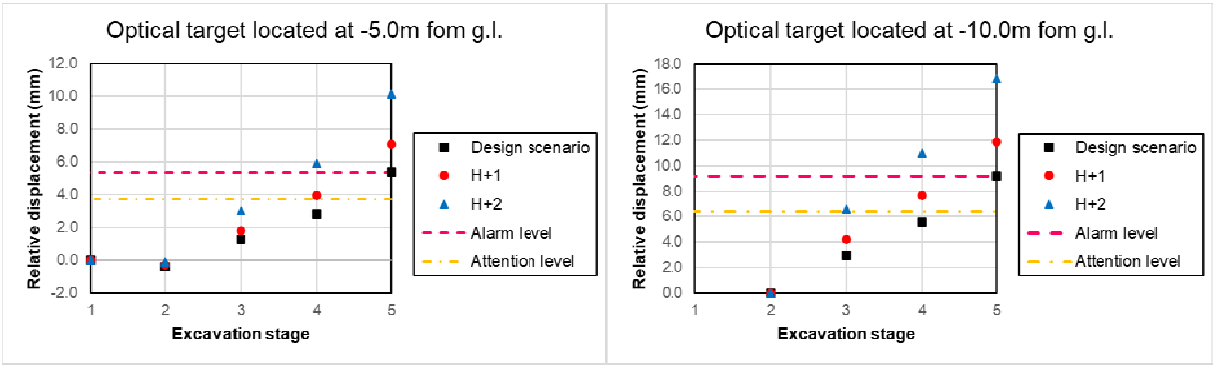


Fig. 2 Forecasting of the topographic monitoring measurements for each excavation stage.

5.2 Forecasting of the inclinometer measurements

The results of the predictive analysis simulating the inclinometer monitoring are reported in Fig. 3, where the numerical analysis provides the detailed displacement profile during the excavation stages no. 2, 3 , 4 and 5. The maximum horizontal deformation occurs in excavation stage no. 5 ranging between 13 and 20mm depending on the ground scenario.

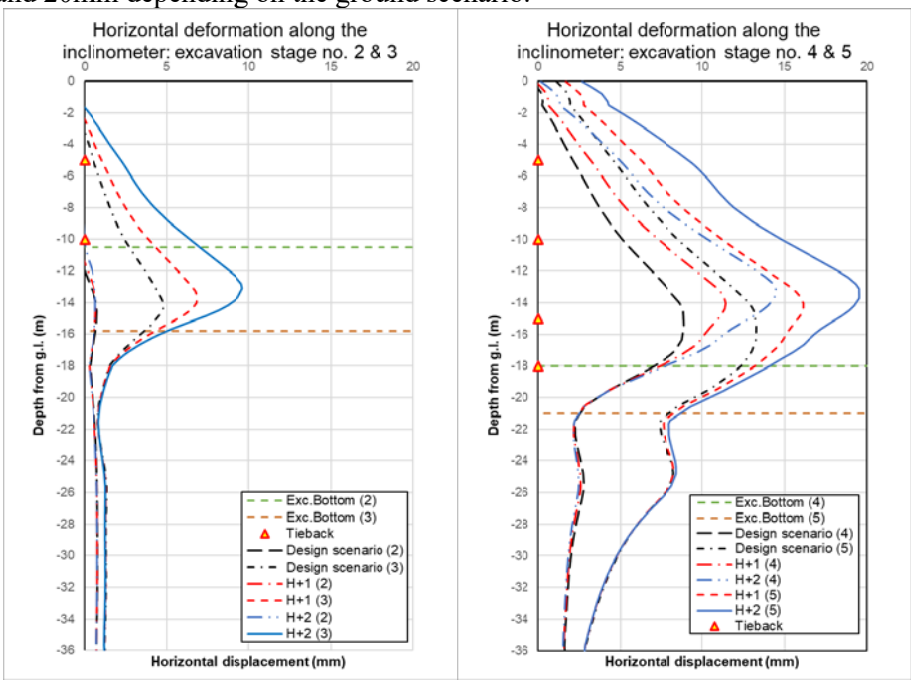


Fig. 3 Forecasting of the inclinometer measurements for each excavation stage. In the legend the excavation stages are noted in brackets.

5.3 Forecasting of the load cell measurements

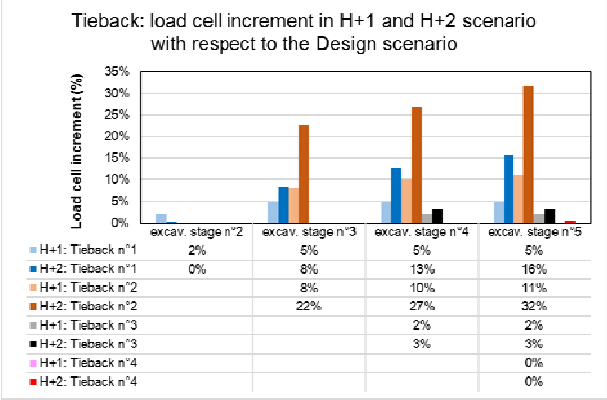


Fig. 4 Increment forecasting of the load cell measurements for each excavation stage with respect to scenario H+1 and H+2.

The results of the predictive analysis simulating the toroidal load cell monitoring are post-processed to detect the load cell increment for the scenarios H+1 and H+2, as reported in Fig. 4. Relevant load cell increments are observed from excavation stage no. 3 onward. For the displacements increments forecasted at the second anchor level on excavation no. 3,the predictive analysis indicates a load

increase of +8% under the H+1 scenario and +22% under the H+2 scenario, both relative to the Design scenario.These results keep growing up to excavation stage no. 5, with a maximum increase in load cell pressure of 11% in H+1 scenario and 32% in H+2 scenario, respectively.

6 Considerations

Main considerations from the predictive analysis, detailed in the previous chapter, are summarised herein:

- *Topographic monitoring*: given the instrument precision (2 mm + 2 ppm), the forecasted displacements are not enough consistent to clearly identify an early warning signal, thus limiting the reliability of topographic measurements for identifying stratigraphic anomalies.
- *Inclinometer monitoring*: the results show a clear representation of the soil–structure interaction, however, the forecasted differences in deformations between the Design scenario, H+1, and H+2 scenarios remain too small in absolute magnitude to offer a reliable indication of Paleosols thickness variations.
- *Load cells monitoring*: the forecasts exhibit a markedly high sensitivity to stratigraphic variations, providing a clear and early indication of unfavourable stratigraphic conditions. In detail, an early warning signal is observed at the second anchor level on excavation no. 3.

7 Conclusions

The study highlights how an appropriate monitoring strategy can support the detection of stratigraphic anomalies, such as variations in the thickness of the Lava-Baked Paleosols, which in turn modify the mechanical response of the retaining system.

Displacement-based monitoring methods lack the sensitivity required to identify stratigraphic variations during early excavation stages. Their response is limited, and the induced horizontal displacement patterns remain too small to be clearly detectedin the monitoring outcomes.
Force-based monitoring through load cells mounted on ground anchors exhibits a clear signal of soil-structural response variations due to stratigraphic changes manifesting at initial excavation stages. Anchor loads respond directly to local reductions in stiffness, providing an effective early-warning indicator for anomalous subsurface conditions.

In this geologically unconventional context, the prediction of expected monitoring trends based on plausible stratigraphic variability represents a valuable support tool. Such sensitivity is crucial for timely risk-mitigation decisions. The anticipation of the system mechanical response enhances the interpretation of monitoring anomalies and improves the capability to detect and mitigate risks before critical conditions develop.

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