



PERSPECTIVES

THE IMPORTANCE
OF GEOTECHNICAL
INSTRUMENTATION MONITORING
IN FORENSIC INVESTIGATION

Our perspectives feature the viewpoints of our subject matter experts on current topics and emerging trends.

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Introduction

A discussion about the importance of instrumentation in geotechnical engineering would be incomplete without referring to Professor R. Peck's landmark paper titled "Advantages and Limitations of the Observations Method in Applied Soil Mechanics". In effect, the observational method elevates instrumentation and monitoring from having a passive to active role in both design and construction, allowing for potential planned modifications to be enacted should performance deviate from the assumed baseline behavior.

This article explores the critical role of geotechnical instrumentation in forensic investigations, highlighting how it enhances the accuracy and reliability of failure analyses. Through selected case studies, we demonstrate how instrumentation data has been pivotal in uncovering the underlying causes of geotechnical failures and guiding remedial actions.

Background

Infrastructure projects have been constructed since ancient times, from the retaining walls of Acropolis of Athens, Greece, to the erosion control and flood defense of the Great Wall of China. Geotechnical engineering has played a vital role in the development of infrastructure. However, not all geostructures, from antiquity to modern times, managed to fulfil their purpose at the time, such as the collapse of the Colossus of Rhodes, the Malpasset Dam Failure, or the famous leaning Tower of Pisa.

Although geotechnical instrumentation monitoring began in the early 20th century, recent advancements in sensor technology, data acquisition systems, and data processing techniques have allowed for sophisticated, real-time monitoring capabilities.

Instrumentation has a significant role in forensic geotechnical engineering, as the scientific facts recorded by instruments during construction help guide the identification of the most likely hypotheses among several possible failure modes.

Forensic engineering is focused on identifying the root cause of failures and developing recommendations and mitigation measures to rectify or prevent them. In geotechnical engineering, such forensic investigation involves site investigation, data collection, developing failure hypotheses, and using geotechnical models and methods, such as back analysis.

Whilst geotechnical site investigation (e.g., borehole drilling, Cone Penetration Testing [CPT] and the like) may provide useful information in relation to the underlying factors leading to the failure, geotechnical monitoring data collected before, during, and following construction can provide the necessary information to determine the mode of failure and allow for the proper adjustment of the analysis model parameters to match observed behavior.

Failures in geotechnical engineering projects such as excessive deformations or even collapse of slopes, dams, shallow and deep foundations, deep excavations and retaining walls, and tunnel scan have serious consequences impacting the natural environment, anthropogenic structures, and population at risk. All these can have a financial impact. Understanding the root causes of these failures is essential for improving future designs and construction practices. This is where forensic geotechnical investigation plays a vital role. Among the various tools available to forensic engineers, geotechnical instrumentation monitoring stands out as a powerful method for collecting objective, real-time data about soil and structural behavior, and making informed decisions.

Instrumentation provides measurable insights into subsurface conditions, stress changes, pore water pressures, and deformation patterns during and after construction. These data are invaluable in reconstructing the sequence of events leading to failure, validating hypotheses, and distinguishing between competing explanations. Without such monitoring, forensic investigations often rely heavily on assumptions and retrospective analysis, which can be limited or inconclusive.

Stages & Procedures Involved in Constructing Infrastructure

In general, the various stages involved in an infrastructure project are presented in Figure 1 below:

However, for a project that experiences some form of failure—and subsequently requires forensic investigation to determine the cause

and recommend appropriate mitigation measures—procedures are as follows in Figure 2 below:

Although there is a clear distinction between the above stages and procedures to be followed, there are cases in which something may go wrong in either, as follows:

- » During the geotechnical investigation stage, potential issues that may arise and which could lead to subsequent failure are the lack of an adequate number of boreholes/CPTs, samples and the like, and errors in the lab test results.
- » Insufficient field investigations coupled with an incomplete desk study can lead to an incomplete understanding of the geological and hydrogeological model, with critical features that may affect the design and construction if not identified.
- » In the assessment of the geotechnical parameters, lack of experience and judgment may lead to improper and overestimated geotechnical parameters.
- » In the design stage, lack of experience, errors in modelling, or wrong interpretations of standards and specifications may lead to an insufficient or fragile design.

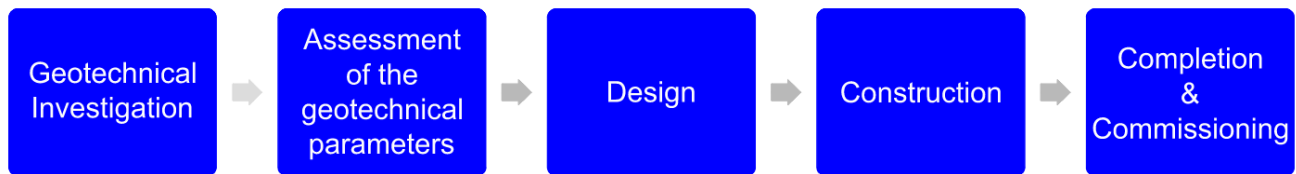


Figure 1 - Discrete stages for the construction of a project.

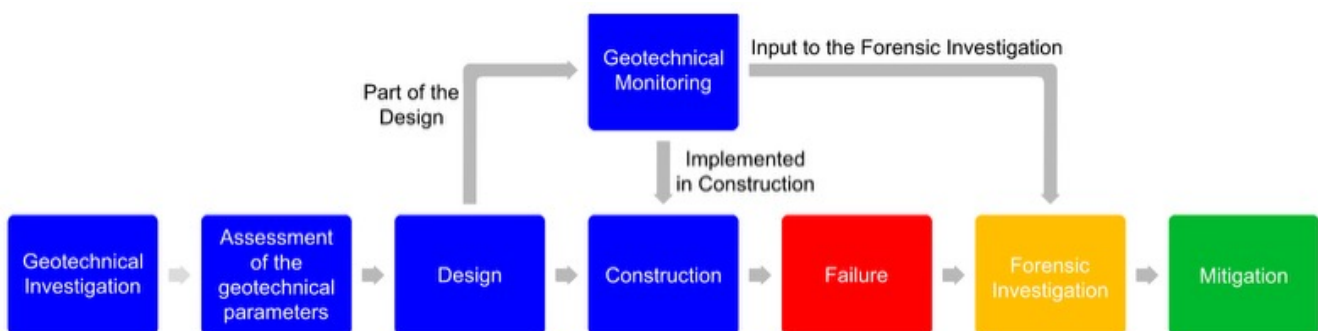


Figure 2 - Discrete stages for the construction of a project, and how geotechnical monitoring positively influences those that experience a failure.

On that basis, proper geotechnical instrumentation and monitoring are essential, in terms of the types and quantities of instruments used, to monitor performance and identify possible causes of failure.

Case Study 1: “Metro Project”

The station's headwall consisted of contiguous piles with three layers of prestressed anchors that provided lateral support, as illustrated below in Figure 3:



During the construction of the station (excavation and installation of lateral support), the structure and strength of the excavated material, as identified from face mapping of the exposed soils, was different from that which was anticipated from the borehole findings, as illustrated in the table below:

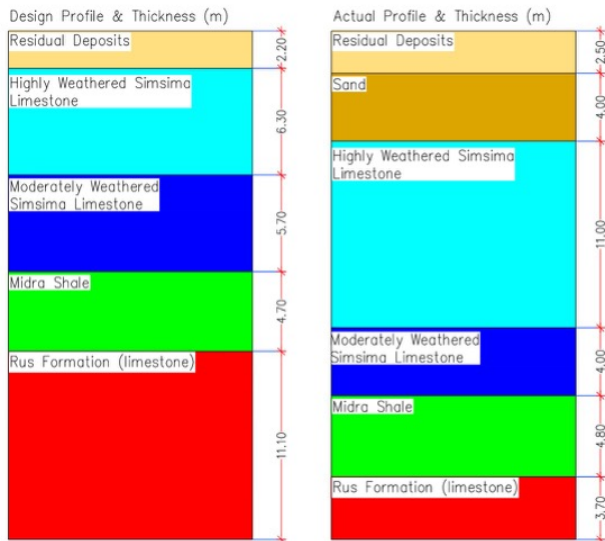


Figure 4 - Comparison between Design (Expected) and Actual geotechnical conditions on-site.

From the above table, it is noted that the sand layer was not anticipated, whilst the thickness of the highly weathered limestone was underestimated.

The ground conditions, which differed from those that had been anticipated, caused a change in performance of the excavation, including a sudden increase in lateral displacements recorded at the inclinometer installed just behind the piles between the two tunnel soft eyes as the excavation advanced below the second anchor layer. The displacements evolved from 2.5mm up to 35mm during the works. At the same time, the anchor load gradually increased from 300kN to 500kN until the installation of the third anchor layer and continued at a decreased rate until the suspension of works.

Furthermore, the recorded settlements at the Mosque complex indicated a creep phenomenon (slow movement under a steady load over time, without significant change in stress), after the excavation advanced below the second anchor layer. The expected design and actual values for displacements and anchor loads are provided in the table below:

Table 1 - Expected design and actual values for displacements and anchor loads

Element	Design Value / Expected	Measured / Actual Value
Anchor level 1	400kN	520
Anchor level 2	460kN	400
Anchor level 3	400kN	460
Lateral Pile Displacement	10mm	35mm

Due to the increase of the displacements and the anchor loads that were beyond expectations, back analysis was completed in order to identify the actual geotechnical conditions of the area, forecast the response of the Mosque and the station's structure for the remaining portion of the works, and propose appropriate mitigation measures for the upcoming TBM breakthrough. The back analysis took into consideration the geotechnical profile from the face mapping, and the response of the structures (Mosque and station).

The back analysis calculation was performed in 16 stages, simulating in the first 14 of the as-completed stages, with the remaining two stages to be completed (circa 2.7m). The first 14 stages had been correlated with the available data from the site (excavation stages, depths, anchors installation sequence).

As per back analysis results, the actual geotechnical properties (e.g., strength and stiffness) of the geomaterials were much lower than those considered in the geotechnical assessment carried out prior to construction. By considering the updated and more refined

geotechnical parameters, the calculated displacements of the pile wall, as well as the loads of the anchors, were similar to the measured values as presented in the figures below, respectively.

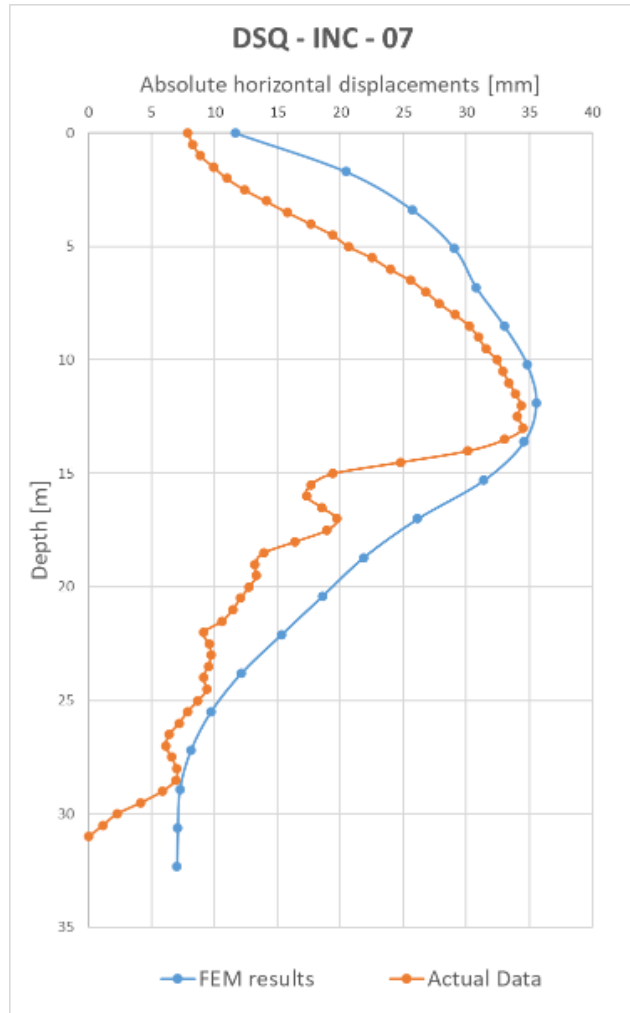


Figure 5 - Comparison between measured and calculated (forensic investigation) lateral displacements.

For the lateral displacement, the measured values increased with the depth down to 14m from the surface then decreased. This was a result of the existence of the sand layer and the thicker highly weathered limestone, contrary to the anticipated geology. The back analysis, which considered the actual ground conditions, resulted in displacements similar

to the actual, both in spatial development (development with depth) and magnitude.

Similarly, for the anchors loads, the measured and the calculated values are presented in the figures below.

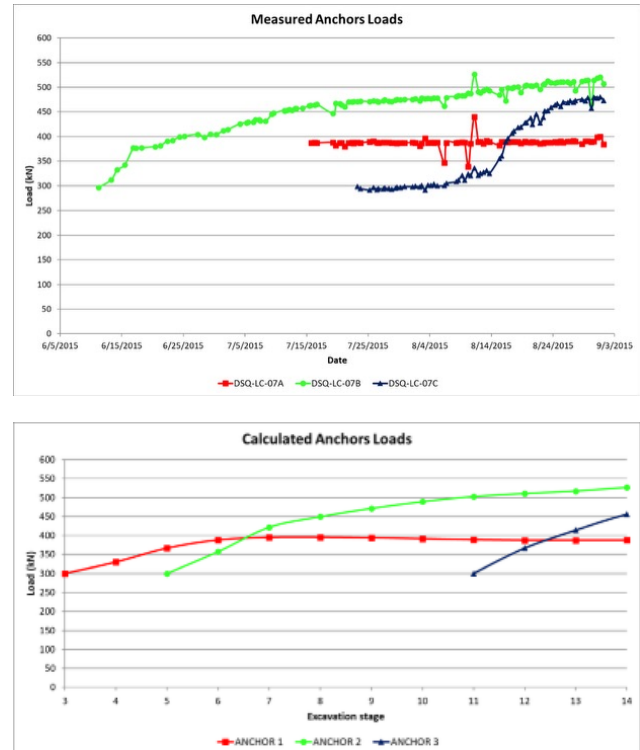


Figure 6 - Comparison between measured and calculated (forensic investigation) anchors loads.

Based on the back analysis that allowed calibration of the model to the field behavior as captured by the instrumentation data, further calculation stages were carried out in order to simulate the final excavation of the station, after the re-commencement of works. This allowed refined prediction of the retaining system, as illustrated in the following figures.

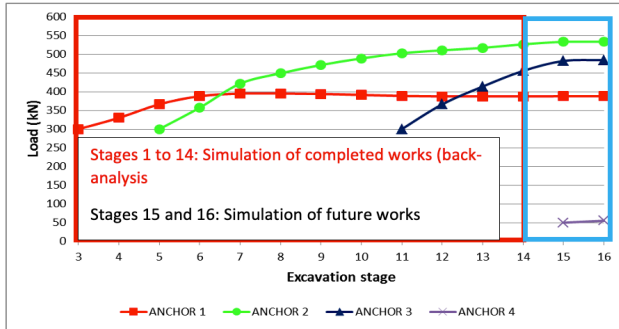


Figure 7 - Calculated anchors' loads for the remaining excavation stages.

The calculated anchor loads, including the fourth layer installed, following the back analysis (stages 1 to 14), predicted a small increase in load of the third anchor (Anchor 3 above) and a gradual stabilization of the system.

Using the refined model, a small increase in the lateral displacements had also been calculated, reaching a total value of about 54mm.

Project Conclusions

During the construction of the Souq Waqif Metro Station in Doha, unexpected ground

conditions—specifically an unanticipated sand layer and underestimated thickness of highly weathered limestone—led to excessive lateral displacements and increased anchor loads at the east headwall near the historic Al Qubaib Mosque. A detailed back analysis was carried out to recalibrate the geotechnical model using the instrumentation monitoring data, which resulted in significantly lower material strength and stiffness than initially assessed. This refined model accurately predicted structural behavior and allowed for mitigation measures for the remaining excavation and TBM breakthrough, ensuring stability and protection of nearby heritage structures.

Case Study 2: “Tunnel Portal”

Tunnel T26 is a twin-bore motorway tunnel, part of the underground complex of the EKPPT Motorway Panagopoula Tunnels, and is in the northwestern part of Peloponnesus, Greece, with a general direction from east to west. The north tunnel bore has a length of circa 3.2 km, and the south tunnel is about 4.0 km long.

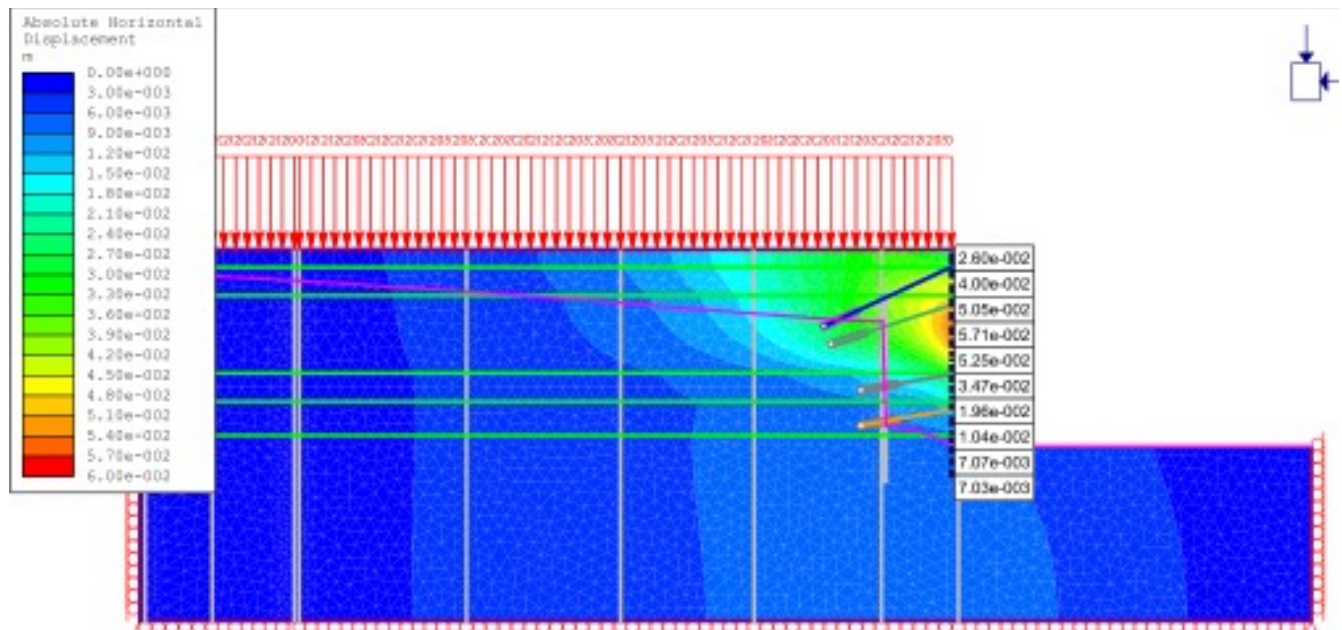


Figure 8 - Calculated lateral displacements for the remaining excavation stages.

Before the commencement of the underground excavation at the West Portal of the North Branch, a stiff pile system consisting of reinforced piles connected with a pile cap and supported with fully grouted rockbolts had been constructed. A concrete cover reinforced structure formed in three discrete levels (steps) had been constructed above the pile cap, due to the limited and insufficient side-cover overburden at the first forepoling umbrella, as illustrated below.

The geotechnical conditions in the area of the portal consisted of:

- » Scree materials (Sc). They originate from the weathering process of limestones and they consist of particles of great variety in size, from a few millimeters fine to grains and boulder sized rocks.
- » Lm: Cretaceous limestones (Lm). Thin to medium bedded limestones of grey to grey-white color. The thickness of the limestones ranges between 20cm to 40cm. Locally thin interlayers of cherts and schist are also presented.

- » T-Lm: Transition limestones (T-Lm). Alternations of grey-yellow thin bedded limestones and grey-green siltstones and shale. The thickness of the limestones and siltstones ranges between 10cm to 30cm. Locally thin interlayers and nodules of cherts are also presented.
- » F-T(Lm) Fractured Transition limestones. This geotechnical unit is excavated mostly by heavy mechanical means.
- » Lm with Cl: A thin layer of fragmented limestone in a clayey matrix.

After the completion of the aforementioned piling system and during the tunnel top heading excavation, excessive displacements were measured at the ground surface above the tunnel (in the order of 100mm) and at the tunnel's support shell (in the order of 50 mm). This exceeded design expectations. For that reason, additional geotechnical investigations were carried out to gain a better understanding of the geology in the area between the slope and the tunnel.

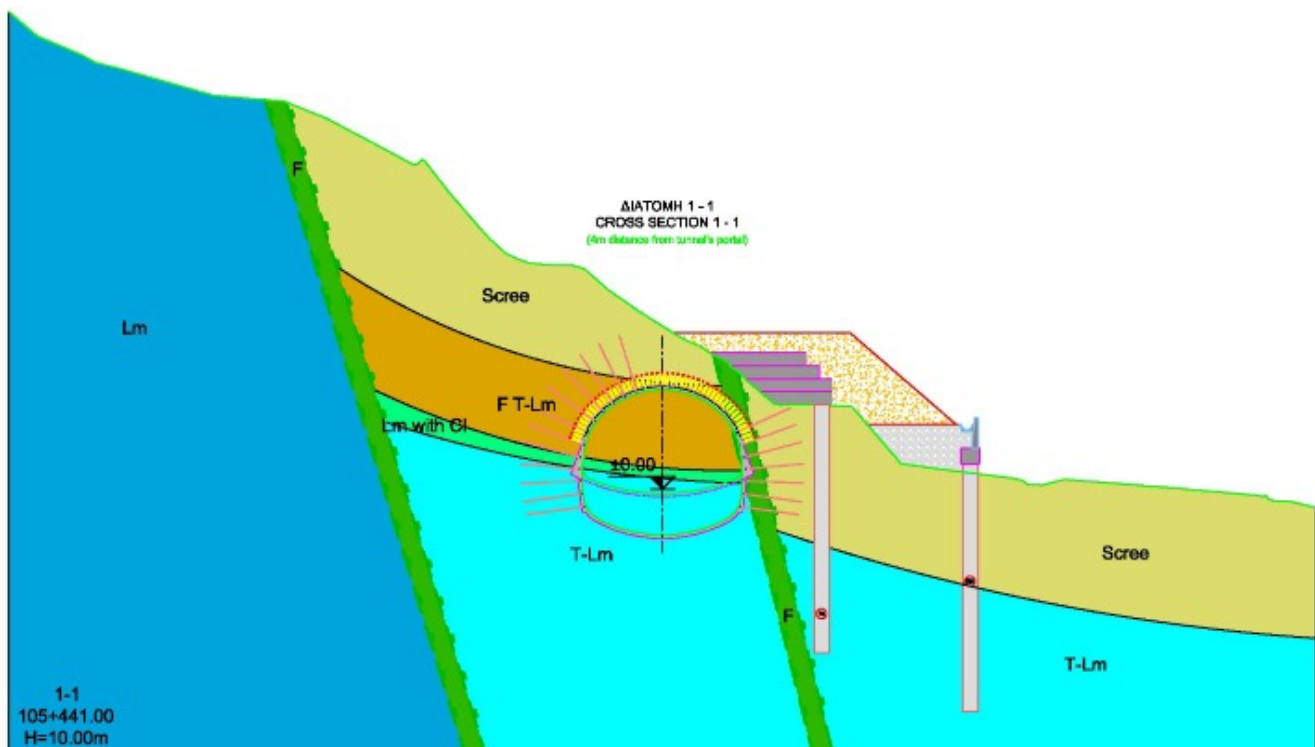


Figure 9 - Tunnel and slope support system, including the geotechnical model.

From the borehole results and the tunnel face mapping logs, the existence of a thin clayey layer was identified. This layer represented a weak, less permeable feature within the tunnelling zone of influence.

Added to the above-mentioned ground surface tunnel shell movements, the ground conditions, which differed from those that had been anticipated, caused a sudden increase in the lateral displacements recorded at the inclinometer installed at the piles as tunnelling progressed. The displacements evolved from 2mm up to 37mm during the works. At the same time, the surface 3D targets displayed horizontal movements approaching 120 mm. These movements and displacements were 17mm for the tunnel and 90mm for the slope, greater than those expected based upon the pre-construction modelling.

The excessive displacements caused significant design and construction concerns. An approximate three-month delay was experienced to further investigate the condition, then stabilize the slope and provide a safe working environment for the tunneling works.

The findings were forensically investigated through back analysis, and the design was updated to forecast the response of the slope and tunnel works following the recommencement of the tunnel excavation, and to propose adequate mitigation measures, including the construction of a toe-reinforced concrete retaining wall and a reinforced embankment.

The back analysis considered the updated geotechnical profile from the additional geotechnical investigation, the tunnel face mapping, and the structures' (pile wall and tunnel) responses.

The weak properties of the thin clayey layer were detrimental to the system's stability. By considering the new layer in the back analysis, the calculated displacements of the pile wall

and the tunnel convergence were similar to the measured, as illustrated below.

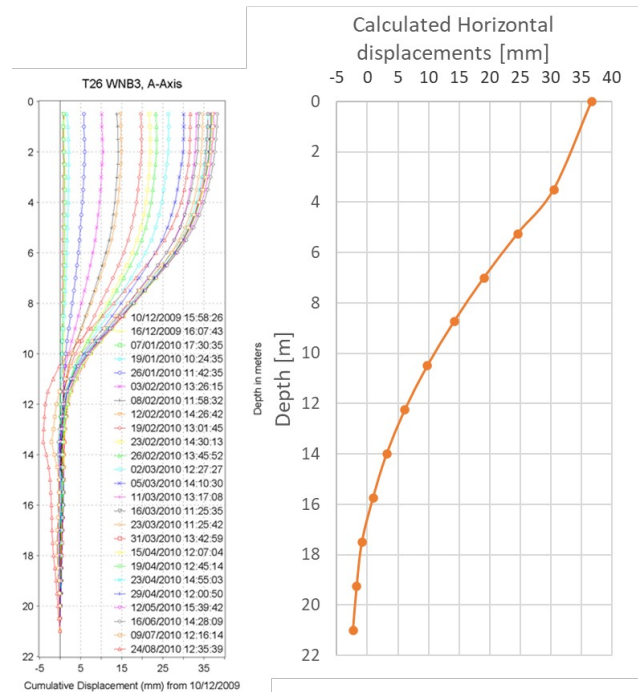


Figure 10 - Comparison between measured (left) and calculated (right - forensic investigation) lateral displacements of the slope.

The accuracy and validity of the updated geological model are reflected in the figure above, with the maximum displacement at the ground surface being about 37 mm, and the displacement profile with depth being similar.

Table 2 - Comparison between measured and calculated (forensic investigation) surface displacements at the tunnel axis.

Surface displacements at the tunnel axis [mm]	Measured	Calculated
Horizontal	37	40
Vertical	108	119

Based on the back analysis and model calibration to the field instrumentation data, further calculation stages were considered to simulate the remaining works for the tunnel excavation to predict the behavior of the retaining system and the tunnel shell.

With the model, the calculated displacements were calibrated to the measured values. Through these calibration efforts, the overall stability conditions in the area were re-examined by considering the future tunnel's bench excavation. Based on the "c, ϕ Reduction Method" (Gradually Decreasing of the Geotechnical Parameters including cohesion, friction angle, and elastic modulus), the horizontal and vertical calculated, future displacements, for different factors of safety (1.1 to 1.4). This method involves a gradual reduction of the shear strength parameters of the soil mass, until the model reaches the critical failure state. The reduction factor at this point is the factor of safety, as illustrated below:

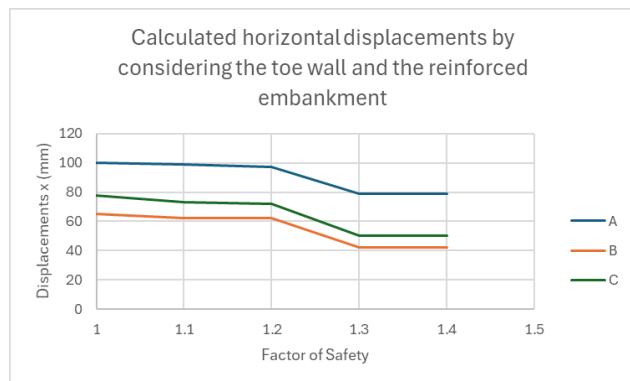


Figure 11 - Calculated horizontal displacements by considering the toe wall and the reinforced embankment.

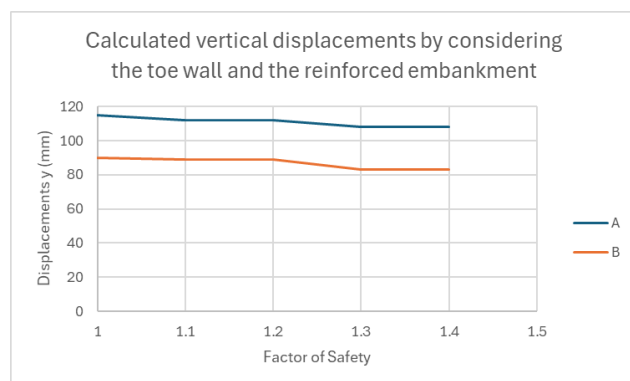


Figure 12 - Calculated vertical displacements by considering the toe wall and the reinforced embankment.

From the calculations, it was verified that the adopted mitigation measures (toe wall and reinforced embankment) increased the factor of safety of the system slope-tunnel to 1.4, producing slightly higher displacement than that measured before the mitigation measures.

Project Conclusions

The tunnel excavation at the Panagopoula Tunnels faced significant challenges due to unexpected geotechnical conditions, particularly the presence of a weak clayey layer that led to excessive displacements and compromised stability. A detailed back analysis incorporating updated geological and instrumentation monitoring data, enabled accurate modeling of the system's behavior and informed the design of effective mitigation measures, including a toe-reinforced wall and embankment. These interventions successfully increased the factor of safety to 1.4, ensuring structural integrity and allowing safe continuation of the tunneling works.

Conclusion

The presented case studies highlight that geotechnical instrumentation and monitoring is crucial for the safety and success of infrastructure projects. By providing real-time data on soil and structure behavior, these tools allow for accurate forensic analysis, defining the root cause, updating analysis models, and determining the proper mitigation measures. The examples outlined above have roots in the aforementioned observational method, which elevates the importance of instrumentation and monitoring during the design and construction, having in place a robust risk management plan that can be enacted should performance deviate from expectations. Such data can enable efficient implementation of rectification to avoid failure, or in the event of a failure, accelerate

supplemental investigations, assessment of the root cause and implementation of mitigation measures

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