Automated monitoring of geotechnical works in urban environments

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July 2021

Abstract

In a geotechnical project, the characterization of the geotechnical parameters has an associated level of uncertainty as they are an estimate of real conditions. The more significant the uncertainties in the characterization of the geomaterial, the greater the associated risk. With the purpose of minimizing risk and consequently increase the level of safety in a geotechnical work, the Observational Method was developed by Peck. This methodology intends, through data collected by geotechnical monitoring, to adapt building methods and phasing to the real conditions found during the construction phase, providing optimization of time and work cost while at the same time maintaining a high level of safety. The method includes a preliminary investigation of existing conditions, the design of an execution project based on the most likely conditions, a monitoring and control plan with definition of acceptable limits for structural behavior and, if these limits are exceeded, corrective measures to be implemented.

Aiming to make the Observational Method known and its applicability to geotechnical works at the national level, the existing regulatory documents were analyzed, specifically the regulations referring to Lisbon municipality. A construction project with complex geotechnical characteristics was also analyzed, where an automated monitoring system to control uncertainties was implemented. With the data collected by the instrumentation and analysis, an optimized construction process was suggested and analyzed, promoting the reduction of costs and construction time.

Keywords: Automated monitoring, Observational Method, Instrumentation and observation plan, Complex geotechnical project, Construction in urban areas.

1. Introduction

In urban areas there is a significant pressure for space optimization. Because of this, buildings tend to be developed both in height and in depth, and in more complex geological and geotechnical conditions.

In construction works with an excavation and retaining walls, the choice of solutions and construction phasing is extremely dependent on the geological and geotechnical conditions (nature, spatial variability, and mechanical characteristics of the material), on the hydrogeological conditions (position and variations of the groundwater level), on the condition and sensitivity of neighboring structures and infrastructures and on technical and economic aspects. Given the large number of variables to control, it is difficult to ensure that the conditions defined in the project are the same as those found on site, and to this uncertainty it is associated an increased risk.

The occurrence of accidents in geotechnical works is usually caused by unexpected ground conditions, by the failure of anchoring systems, by the failure of shoring systems, or by the non-compliance with the designed construction sequence. Although there has been a downward trend in accidents in the construction sector over the years, they continue to exist, and when they occur almost always result in fatalities.

According to data for the European Union presented in Eurostat [1], the construction sector has a significant weight in fatal accidents compared to other sectors of activity, with 20.5% of all fatal accidents recorded in 2018.

In Portugal the tendency remains and, according to data from the Portuguese Authority for Working Conditions (ACT), the construction sector recorded 27% of fatal accidents in 2018, this being the sector with the highest weight when compared to all sectors [2].

Based on this data and acknowledging the impact of the construction sector on fatalities, it is imperative to increase safety on construction sites.

2. Observational Method

The need to pay attention to the possibility of geomaterial characteristics differing between the assumed design and the actual conditions encountered, and the importance of field observations for the designer to anticipate complications and change the design according to the new information was exposed by Therzaghi and Peck, in 1948 [3].

Having as goal the adaptation of the construction methods to the real conditions found on site, it was developed by Peck in 1969 the observational method (OM) [4]. The methodology gained importance over time with its introduction in procedures related to soil-structure interaction and with the increase of scientific publications on the subject leading to its introduction in 1995 in the EC7 for its application in geotechnical works [3].

The observational method is described as a tool for controlling the construction by a monitoring system and a design review method. It is possible, according to the OM, the introduction of pre-defined modifications in design phase for the application during the execution phase. For its application it is necessary to combine an adequate geotechnical prospection of the site to establish the initial conditions of the geomaterial, modelling based on available data and theoretical concepts, and establish contingency plans for the chosen solution based on scenarios [5].

In design the following scenarios are foreseen: the most likely scenario, usually the reference scenario, the favorable scenario, if conditions prove to be better than the reference scenario, and the unfavorable scenario, if the conditions are worse than in the reference scenario. For the various scenarios it is necessary to establish control parameters for evaluation of the actual scenario as the work progresses. These parameters are established from analyses and control measurements performed on site and should allow the assessment of which scenario the construction should proceed [6].

According to Nicholson at. Al. in CIRIA 185 the implementation of the OM should follow the structure illustrated in Figure 1 [3].

At a first level, the implementation must be developed in accordance with existing regulations, whether they are design regulations (EC), safety and health regulations, or others specific to each country or region and should allow compliance with the design requirements established by the Owner.

A second level of implementation of the OM encompasses the design, execution, verification, and modification phase.

The design phase includes a risk assessment of the failure mechanisms associated with the structure or parts of the structure. This assessment aims to consider the probability of failure occurrence and the consequences that depend on it. Based on this weighting, the various failure mechanism scenarios are defined, and the characterization parameters are identified. The safety level is controlled for each scenario by calculating the ultimate limit states (fracture, collapse, loss of vertical equilibrium, occurrence of mechanism or rupture by fatigue phenomena) and/or by the serviceability limit state (deformations, vibrations, cracks or damage affecting serviceability) [6].

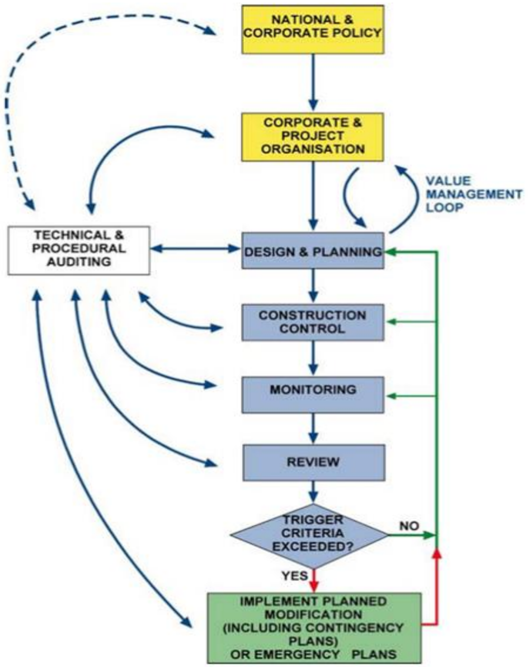

Figure 1 The Observational Method described by CIRIA 185 [3]

It is in the design phase that the quantities to be monitored and controlled are also defined for the established scenarios, as well as the appropriate instruments, where they will be installed and the frequency of readings to obtain the necessary information to support the decision. For this and to help control the quantities, a traffic light system is implemented to evaluate the behavior of the structures during the construction phase [7].

The traffic light system allows, through data collected by the instrumentation, to observe if the values collected are the expected ones, showing an acceptable behavior, or if the limits of acceptable behavior are exceeded. For the range of possible behaviors and established in design, action plans are pre-established. For example, if the behavior limits are exceeded, actions can be taken to reinforce the structure which should already be pre-established in design.

The traffic light system for active control of construction processes include two decision levels [5]:

- Alert level, indicating a change in the predicted values, in which corrections can be introduced in the project.
- Alarm level, indicating a change in the predicted values and requiring an immediate response with the introduction of an emergency plan.

Given that the traffic light system is established as a decision aid, a comparison is made between the values measured on site and the values defined in the project. The way in which the construction work is carried out depends on the behavior verified on site. Figure 2 shows the traffic light system used in a landfill slope stability improvement [3].

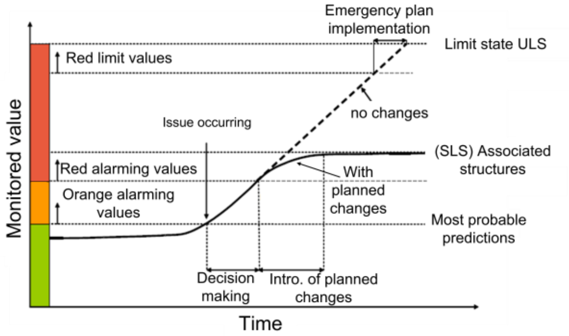

Figure 2 Observational method approach used in a landfill slope stability improvement [3].

In this example, three different zones with different action levels are defined.

Green zone - the measured values are below the first alert threshold, corresponding to the boundary between the green area and the orange area (most likely predicted values). The stability of the slope is ensured, and the works can proceed as stipulated.

Orange Zone - the values of the first alert threshold (predicted most likely values) are exceeded. Stricter monitoring control is needed, with increased frequency of readings to estimate the trend line and to aid decision-making. If necessary, reinforcement should be applied in critical areas.

Red Zone - the values of the second alert threshold, corresponding to the boundary between the orange zone and the red zone, are exceeded. The alternative plan stipulated in the design phase should be implemented, with immediate changes in the design, to avoid exceeding the values corresponding to the Serviceability limit state (SLS).

3. Applicability of the Observational Method in geotechnical works

Based on cases of geotechnical works already executed, Korff et al. established a SWOT matrix with the analysis of the applicability of the OM [8]. The following are identified as strengths (S):

- Incremental construction process.
- Short duration construction processes.
- Displacement control.
- Integrated responsibility between the parties.
- Organization culture based on risk and project flexibility.
- High soil heterogeneity and uncertainty about failure mechanisms.

Weaknesses (W) are identified as:

- Rupture mechanisms faster than the speed of implementation of corrective measures.
- Impossibility of measuring the rupture mechanism.
- Change of failure mechanism during construction.
- Cost of changes during construction higher than benefits gained.
- Communication between the parties.

Opportunities (O) are identified as:

- Presence of risks with low probability but unacceptable *a priori* due to high consequences.
- Ensuring that the construction process complies with safety criteria.

Threats (T) are identified as:

- Rapid variation of loads.
- Reluctance of regulators to approve OM based projects.
- Time constraints.

4. Instrumentation and observation plan

The instrumentation and observation plan is a fundamental part of an excavation and peripheral containment project (PECP) as it allows the proper applicability of construction methods and phases to be evaluated in the real conditions found on site, enabling an effective management of the geotechnical risk. The plan is a tool developed during the project phase and accompanies the entirety of the construction works. It allows control of the construction works and can be the basis for implementing design adaptations to improve safety on site. The plan includes [9]:

- Definition of project conditions, namely project typology, project layout, subsoil conditions, conditions of adjacent infrastructures and buildings, construction methods and phasing.
- Prediction of control mechanisms according to the project conditions, with the definition of the influence zones, failure mechanisms and evaluation of the risk associated to these mechanisms.
- Definition of what are the uncertainties and how to mitigate them.
- Definition of the control parameters.
- Prediction of the magnitude of variations.
- Action plans for adapting construction methods and phases to actual conditions.
- Acknowledgement of responsibilities and levels of access to the information obtained by the instrumentation.
- Selection of the instruments to enable the control of the parameters stipulated in the project.
- Selection of the location of the instruments.
- Definition of which factors could affect the readings.
- Creation of redundancy in the readings, so that in the event of a failure of an instrument,

safety and/or the progress of the work is not compromised.

5. Legislative framework

5.1. Contract Logistics

When the possibility of application of OM in geotechnical engineering is discussed, it is evidenced that the contract requirements should facilitate its application, or at least, not obstruct its use.

Geotechnical works have associated some uncertainty when it comes to the characterization of the geomaterial. It should be noted that it is not uncommon in a geotechnical project to assume approximate values for the characterization of the material and, in the construction phase, the real conditions of the geomaterial do not correspond faithfully to what was assumed by the designer.

To provide a better adaptation of the geotechnical project to the real conditions encountered and to provide greater safety through an adequate risk management, a revision of the Portuguese Public Contracts Code (CCP) was made, namely the objective modification of contracts (MOC), to open the possibility of adopting a project methodology based on scenarios: the reference scenario (most probable) and other alternative ones (less probable) [10].

For complex geotechnical works, defined as works in which the terrain performance, the executed constructions and the adjacent buildings and infrastructures may be significantly impaired by the unpredictability of the geotechnical site conditions, the parameters integrated in the CCP revision include:

- Geological geotechnical uncertainty.
- Risk management.
- Need for special technical assistance and monitoring.
- Application of the new public procurement directives.
- Carrying out projects for several scenarios.
- Application of the observational method.

To promote an adequate procurement model and given the importance of a good technical proposal in complex geotechnical works, it is advised to use a tender model where the contractors are limited by previous qualification and go through a two-stage evaluation. In the first phase of the tender the minimum criteria of eligibility are verified, namely the technical and financial capability of the contractors, and in the second phase the technical and economic merit of the proposal presented by the contractor is evaluated.

The following weighting of scores for the bidding phase is recommended [10]:

- Technical value of the proposal = 40 to 60%
- Price of the proposal = 40 to 60 %
- Deadline for the execution of the work = up to 10%

It should be explicitly stated that the project is intended to be developed for several different scenarios, and the following weighting is suggested for tender evaluation [10]:

- "Most likely" scenario = 75%
- “Pessimistic" scenario = 15%
- “Optimistic" scenario = 10%

Given the geotechnical geological risk associated with this type of geotechnical works, and to avoid conflicts between parties during the works, it is advisable to establish in the contract a correspondence between the typology of the risk and who has the best capacity to manage it. Thus, the owner should be responsible for the risk corresponding to the geological conditions being different from those initially foreseen and the contractor should be responsible for the risk associated with the effectiveness of the construction performance.

5.2. Technical proposal

The geotechnical project should follow not only the technical regulations, as it is the case of the Eurocodes, but also the regional and municipal regulations and standards. In Lisbon, the Municipal Urbanization Regulation of Lisbon (RMUEL) is a normative element inserted in the Municipal Master Plan (PDM) of Lisbon where the rules applicable to urbanization and building in the municipality are established.

Regarding Excavation and Peripheral Containment Project, article 104º of RMUEL establishes the requirements to be considered[11]:

1) Geological geotechnical reconnaissance of the site, with indication of the studies carried out or to be carried out.
2) Hydrogeological reconnaissance, namely water level, depth, flows and permeability coefficients.
3) Neighborhood conditions, giving emphasis to structures in the subsoil.
4) Description of the construction methods and phases, to enable their monitoring by the municipal technical supervision team.
5) Dimensioning of the project elements, describing the solutions, indicating the characterization parameters adopted, the considerations taken in the dimensioning (safety coefficient, actions, mechanical characteristics).
6) Monitoring and Observation Plan, when it is intended to observe the behavior of structures, with the description of the type of instruments, their location and the definition of the admitted alert and alarm levels.
7) Complementary specifications of containment elements, such as anchors, struts, or nailing.
8) Proximity to underground structures of the Lisbon Metro. In this case, constraints are

defined by the Lisbon Metro entity for structures closer than 25 meters and the project must be approved by this entity [12].

Due to the recognition of the risks associated with excavation works, both for the workers involved in the execution and for those who interact with the environment surrounding the works, members of the Portuguese Order of Engineers with geotechnical specialization stress the importance, throughout the process of design/execution of a geotechnical project, of promoting actions to mitigate exposure to foreseeable risks by increasing the level of safety.

In the Recommendations Manual of the Portuguese Order of Engineers, the geotechnical risk management process, represented in Figure 3, is identified and should be implemented by those involved in both the preparation/planning and during the execution/supervision of the works.

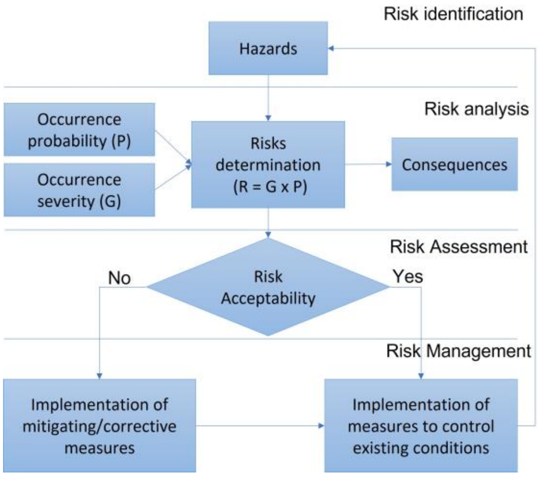

Figure 3 Risk management process [13].

To implement a risk management system in the design project and thus promote quality and safety on site, the importance of the documentation created is highlighted, including [13]:

- Geological and geotechnical study, carried out prior to the development of the project.
- Descriptive Memory of the work, of the constructive solutions and of the existing constraints.
- Calculation Note, including the description of the applied standards and regulations, definition of the applied assumptions, models, and calculation methodologies.
- Instrumentation and Observation Plan including the definition of the quantities to be observed, the devices to be installed, the frequency of readings, the definition of warning limits, recommendations for work monitoring and possible measures to be adopted.
- Drawings that identify and complement the documents previously identified.
- Complementary technical specifications.

If necessary, the following documents may also be included [13]:

- Damage Risk Analysis, fundamental in the case of major excavations with buildings in proximity.
- Risk Management Plan if the risks imply serious consequences.

6. Case Study – EXEO Site 1: Aura Edifice

The project under study is inserted in urban environment in the city of Lisbon, Portugal, and has an implantation area of 1922 m^2, with 12 elevated floors and 3 underground floors.

6.1. Site constraints

For the analysis of the geological and geotechnical conditions existing at the site, 9 mechanical boreholes made with rotation drilling and continuous sampling were executed for the macroscopic identification of the soils, and standard penetration tests (SPT) were performed. After establishing the characteristics of the soil and of the encountered materials, the designer defined the geological substrate in two geotechnical zones:

- Zone ZG1, consisting of alluvial formations, fill and other eventually displaced materials.
- Zone ZG2, this one being subdivided into 3 subzones:
    - ZG2A, made up of fine silty clayey sands and sandy silts
    - ZG2B, made up of silty clays, clayey silts, and sandy silts.
    - ZG2C, made up of Fossiliferous lumachelic/calcarenite levels

According to the information collected, the geomechanical parameters for each of these zones were established. These parameters, identified in Table 1 were used to model the finite element model to evaluate the behavior of the containment with respect to stresses and strains.

Zone	NSPT	ϕ' [°]	C_u [KPa]	E' [MPa]	E_u [MPa]
ZG1	1-17	30	-	10	-
	0-8				
ZG2A	10-41	33	-	50	-
ZG2B	24-60	-	200	-	100
ZG2C	>60	38	-	150	-

Table 1 Geomechanical parameters of the geotechnical zones defined for Site 1.

As water was detected in all boreholes, 5 piezometers were installed in boreholes to analyze the hydrological conditions of the site. Varying water levels were detected between 1,25m and 7,20m. The permeability of the intersected strata was also assessed. The results are shown in Table 2.

	Permeability
Fill deposits	High to moderate - favors percolation (water inflow may be expected in the excavations intersecting these deposits)
Alluvial formations	Low to moderate (the horizon between the layer of fill deposits and alluvial deposits acts as a free aquifer)
Miocene formations	In general, it presents moderate to low permeability, providing favorable conditions for the percolation of water with moderate to insignificant flows

Table 2 Permeability conditions of the intersecting strata.

Besides the geological geotechnical and hydrogeological constraints, the constraints related to the surrounding structures were also analyzed, and in the site under study the deformation control was important due to the proximity of the Lisbon Metro structures, located 17m east, and the fuel deposits, located 11m north.

6.2. Constructive solutions and phasing

The choice of construction methods and phases is intrinsically dependent on the control of displacements to preserve the integrity of the adjacent structures, on the existing constraints, and on the design requirements. As such, a peripheral containment solution was chosen with the use of diaphragm walls and mat foundation, to act as a barrier to water ingress and to minimize wall deformations. The retaining solution was complemented in the provisional phase with a metallic strut solution at level 0, and a mixed solution of slab bands and metallic struts at levels -1 and -2, to accommodate the soil impulses and overloads.

The combination of 3 different elevations along the entire floor 0 area with a variable ground level up to 2,0 m made a slab band solution unfeasible on floor 0 or would imply a very complex analysis due to compression stresses in the discontinuity region. On floors -1 and -2 this variable elevation did not exist and allowed the execution of a mixed solution, promoting a cost reduction since the slab bands are an integral part of the final structure.

6.2.1. Diaphragm walls solution

The diaphragm wall solution is widely used in urban environments because it is a slender solution, increases the usable area inside the excavation and it is part of the final structure performing foundation functions [14]. It is a so-called "flexible" support structure because, in service, it suffers deformation by bending [15]. It is a solution that does not produce significant noise or vibrations, minimizes decompression and deformation of the soil, allows high depths to be reached and guarantees watertightness against the passage of water from the soil to the interior [16].

This solution consists of reinforced concrete walls built completely from the surface, without the need to excavate the front or the back of the wall, up to the desired depth. The construction method begins with excavation by panels, the hole produced is stabilized with bentonite slurry, then the reinforcement is placed and later the panel is filled with concrete using a trémie [16].

6.2.2. Metallic struts solution

The excavation process causes a variation in the actions to which the diaphragm wall is subjected to due to the unbalance of impulses between opposite sides of the wall. To prevent the decompression of the soil on the back of the walls, temporary metallic struts were applied.

The metallic strut has the function of supporting and directing the tensions of the soil to be contained, the self-weight and the loads resulting from the operation of the equipment at the borders of the excavated area, and also has the function of controlling the deformations of the structure [15]. These elements resist well to compression, since they present high stiffness [14]. At Figure 4 shows the metallic struts used in the construction site under analysis.

Figure 4 Metallic struts applied in site.

6.2.3. Slab bands solution

Slab bands are a construction system that are intended to sustain the deformation of containment structures and ground pressures. They are defined as horizontal beams that form a rigid support frame and present a free central space [14].

In this solution, the load mobilization occurs during the excavation phase, allowing the transmission of impulses exerted by the soil to the buried floors [15]. This system ensures less decompression of the soil, increasing the level of safety, and it is an integral element of the final phase of the work.

In Figure 5 is illustrated a view of the structural floor plan in level -2.

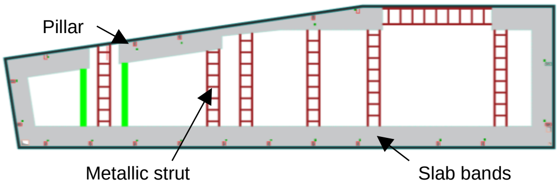

Figure 5 Structural Floor Plan View of Floor -2.

6.2.4. Mat foundation solution

The mat foundation solution considers the concreting of the entire foundation area, preventing the penetration of water into the interior of the structure from the underside. The main requirement in its design was the minimization of differential settlements of the structure, being the serviceability limit states the most conditioning. With this objective, a solution with direct foundations with varying thicknesses along the building's implantation area was preconized. In Figure 6 is illustrated the preparation of the mal foundation solution.

Figure 6 Preparation of the mat foundation solution.

6.2.5. Construction phasing

The construction work begins with the execution of the diaphragm walls. When these are complete around the perimeter of the site and joined by the crowning beam, excavation work begins inside.

The excavation is carried out to the first-floor level, formwork and reinforcement work begins on the slab band and when these have sufficient resistance, metal shoring is applied. When this process is complete, the same work begins for the second-floor level.

When the final depth is reached, work starts on the superstructure, including the foundations, vertical elements (columns and beams) and horizontal elements (slabs), also by floor, from the bottom of the excavation to the top.

To avoid an incorrect deactivation of the vertical shoring, the definitive horizontal elements are executed on a phased manner. In a first phase, the areas between the metal props are executed and, when these already have resistant capacity, the floor props are removed and then the sections previously occupied by the metal props are executed.

6.3. Instrumentation and Observation Plan for Site 1

Due to the characteristics of Site 1, the entire excavation process and the application and removal of shoring is the most critical process and the one that requires the greatest level of attention, especially when the final depth of the excavation is reached.

The instrumentation for monitoring the construction processes was installed in 4 distinct zones, each zone along one side of the site, as identified in Figure 7.

In each zone an in-place inclinometer was installed on an inclinometer rail with the purpose of measuring the horizontal displacements of the soil, and a pair of vibrating rope piezometers at different depths with the purpose of measuring water pressure variations. Both with readings were obtained remotely and hourly.

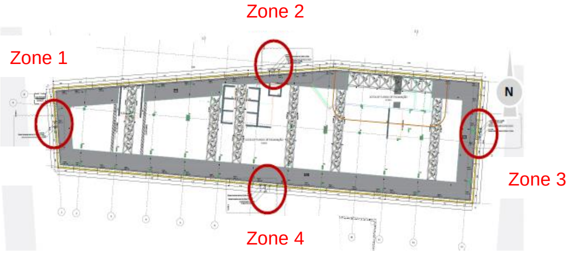

Figure 7 Identification of the instrumented zones.

The selection of these instruments was motivated by the most important quantities to monitor, namely the need to control the displacements, because any significant displacement of the diaphragm walls could jeopardize the safety inside the site, and the monitoring of the interstitial pressure variations, to be able to predict an overload in the diaphragm structures that could create instabilities and insecurity.

The in-place inclinometer used includes sensors installed in series, reducing the number of connecting cables, and allows self-referencing, so it is not necessary to associate a depth with a particular sensor. They are water-resistant, allow remote, continuous, and real-time readings with high accuracy, allowing the detection of both progressive and sudden movements.

The installed vibrating string piezometers are fast response instruments and allows to obtain immediate information of the existing pressures remotely and automated.

Both instruments allow programming and issue automatic alerts if the limits set by the designer are exceeded. In Figure 8 are illustrated the instruments used.

Figure 8 On the left, the vibrating wire piezometer [17]. *On the right, an in-place inclinometer sensor* [18].

The alarm criteria established are indicated in Table 3.

Instruments	Alarm criteria		
	Green	Yellow	Red
Absolute displacement			
Vibrating wire piezometer (kPa)	10	20	30
In-place inclinometer (mm)	12	20	60
Incremental displacement, T_i-T_{i-1}			
Vibrating wire piezometer (kPa/day)	1	2	3
In-place inclinometer (mm/day)	1,2	2,0	6,0

Table 3 Alarm criteria establish for Site 1.

In case the limit values set in Table 3 are exceeded, the designer has stipulated the control procedures described in Table 4.

Alarm criteria exceeded	Procedure
Yellow alarm	Instrumentation retrofit and implementation of more sensors/instruments
Red alarm	Stopping the work and studying alternative solutions; Emergency landfill of the unstable zone

Table 4 Interventional procedure stipulated in case of exceedance of established alert criteria.

The site was divided into 3 zones, with different work progressions, represented in Figure 9. In the work phasing, construction zone A was the most advanced and construction zone C the least advanced.

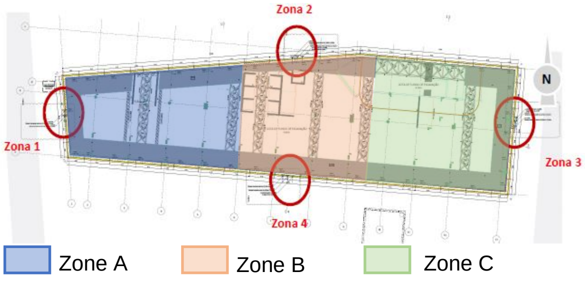

Figure 9 Identification of the construction zones.

From the analysis of the data obtained from the inclinometers it was concluded that the installation depth was insufficient for the calibration of the readings. Despite the installation depth of these instruments being approximately twice the bottom of the excavation, a marked deviation was verified between the readings of the first and second sensor in the 4 installed inclinometers.

When the excavation for the last floor (floor -3) of Zone A was in progress, a distortion on the order of 20 mm was observed. Although the observed movement exceeded the green alarm criteria and coincided with the most critical zone of the excavation, the movement occurred to the outside of the excavation. Since this is an unexpected movement, it was considered that it was a defect of the sensors installed in the abrupt change zone, at 11.0 m depth, not being a concern for the stability of the structure. In Figure 10 it is shown the observations of the piezometer in Zone 1.

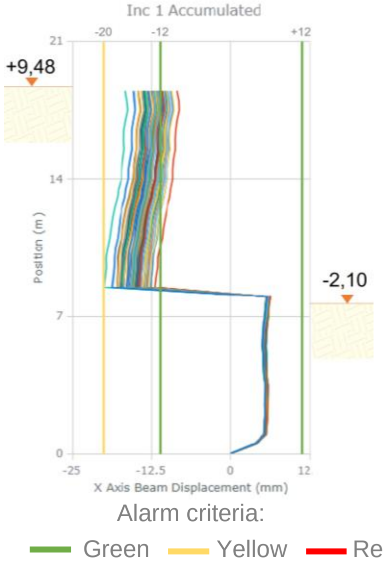

Figure 10 Cumulative reading for displacements with the inclinometer in Zone 1 for 25/12/2020.

When the excavation reached the last level (floor -3) of zone B, the values recorded by inclinometer 2 did not show alarm signals, and the green alert criterion was not exceeded, as illustrated in Figure 11. At the same time, inclinometer 4 presented a significant displacement between the first and the second sensor that influenced the reading of the accumulated displacement for the following sensors and, therefore, the green and yellow alert criteria were exceeded, as illustrated in Figure 12.

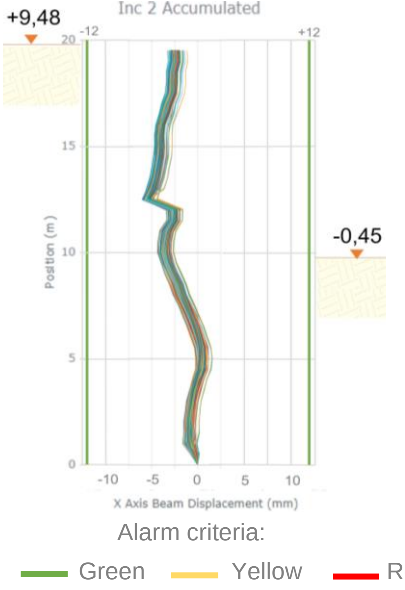

Figure 11 Cumulative Reading for displacements with the inclinometer in Zone 2 for 30/01/2021.

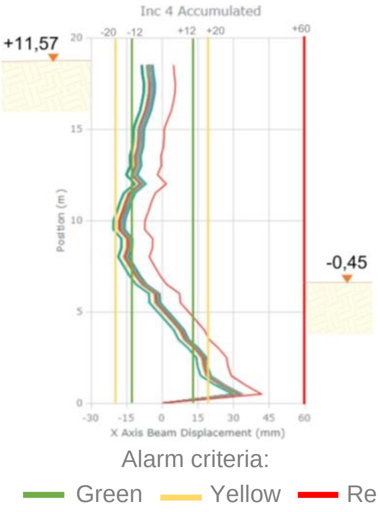

Figure 12 Cumulative reading for displacements with the inclinometer in Zone 4 for 31/01/2021

When excavation and construction work was underway for the last level of floor -3 in Zone C, the area closest to the Lisbon Metro structures, the readings from inclinometer 3 showed no signs of alarm as indicated by the record in Figure 13, not jeopardizing the stability of either the Site 1 structure or the adjacent structures.

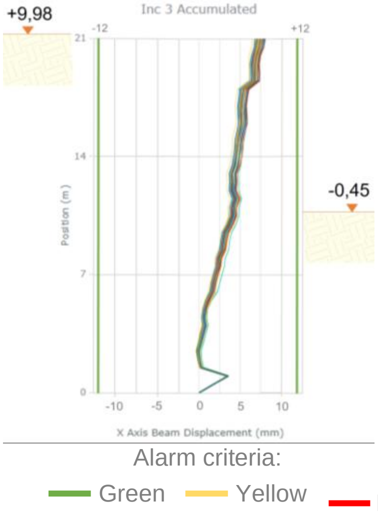

Figure 13 Cumulative reading for displacements with the inclinometer in Zone 3 for 14/02/2021

The installed piezometers maintained constant values throughout the construction process, showing no signs of alarm. The readings obtained prove that it probably would not have been necessary to build the mat foundation solution recommended for this project.

6.4. Possibilities for optimization measures

Despite not having been studied in the design nor implemented optimization measures on site, the stability observed in the readings and the compliance with the established behavior limits allowed this to be considered.

A first hypothesis considered to not execute the metal shoring of the intermediate level, level -1, as identified in Figure 14.

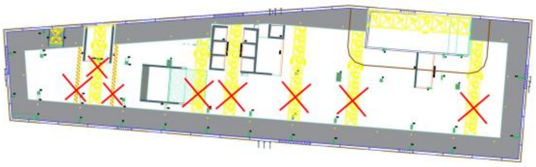

Figure 14 Floor plant -1, with the identification of the eliminated metal shoring considered.

This would optimize direct costs, such as material, transportation, assembly, disassembly, reduce the difficulty of the excavation process due to the increased space provided, and indirect costs, with a 1,5 month reduction in time, which is associated with a reduction in the cost of the construction site. The reduction in these costs is identified in Table 5.

	Cost reduction
Direct Costs	- 260 000,00 €
Indirect costs	- 180 000,00 €
Total	**- 440 000,00 €**

Table 5 Total cost reduction associated with not performing level -1 shoring.

Another solution that was possible to consider is the replacement of the mat foundation by a solution with footings and foundation beams, given the stable information from the piezometers and given that the pumped flow was reduced.

In the estimation shown in Table 6 a floor load of $12kN/m^2$ was considered, since it is an office building, and an admissible soil tension of $600kN/m^2$. It was also considered a cost of $100€/m^3$ of concrete and 1,3€/kg of steel.

	Original solution	**Optimized Solution**	**Cost difference**
Steel	207 368€	198 145€	- 9 223€
Concrete	188 548€	127 716€	- 60 832€
Total	395 916€	325 861€	- 70 055€

Table 6 Cost difference between the original solution and the optimized solution.

7. Final Considerations

Besides the possibility of optimizing deadlines and costs, the increase of on-site safety and the prevention of incidents is of extreme importance and was ensured in the construction site analyzed. Automated monitoring has a significant weight in the validation of geotechnical uncertainties and, consequently, in site safety, mainly due to the fast response time, the reliability of the readings and the alerts issued automatically.

It should be highlighted that, although optimization measures can be implemented during the construction process that were not previously evaluated during the design phase, this should not be common practice. A change in construction methods and phasing would require study by the designer to verify compliance with design, quality, safety, and compatibility with the design of other specialties, and its implementation would require approval by regulatory agencies. The time spent in this process could imply a suspension in the works invalidating the possible advantages with the optimization proposal.

The project under study is a prime candidate for the implementation of the observational method because, in addition to having displacement control as a design constraint, it is also part of an urbanization with other sites with similar characteristics and constraints, providing that the information collected in this one can be used in the following sites. In addition, and as the Lisbon Metro structures are in the immediate surrounding area, the method makes it possible to ensure with documented evidence that the construction process complied with the established safety criteria.

Even though the conditions have been created in Portugal, both at the design level and at the contract model level, for the adaptation of the construction project to the actual conditions found, the implementation of the observational method and the active management of geotechnical risk by this methodology depends on the acceptability by the Owner and by the regulatory authorities.

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