Instrumentation guide for building excavations in urban areas

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Abstract

With regards to populational growth, the best areas for construction in urban areas have already been occupied. As a result, the only remaining spaces are those between pre-existing structures and sites with poor geotechnical characteristics, with building requalification being a sustainable alternative. However, when the construction work takes place in city centres there is an increased risk of accidents that may affect the neighbourhood infrastructures during the process. One way to minimise those accidents is increasing the construction safety; therefore, it is important and essential to implement an adequate monitoring plan to anticipate hazardous situations on the work site and/or in the surrounding area. The field monitoring must be implemented by the project designer, considering the intrinsic characteristics of each work, but this plan can sometimes be generic or non-existent. The aim of this paper is to present guidelines to planning an instrumentation program using geotechnical instrumentation, which will serve as a basis for futures works in urbanized areas. The main objective is to integrate several types of pre-existent methodologies and technologies to improve field instrumentation and monitoring of building construction sites in urban areas.

Key words: Geotechnical instrumentation, Construction monitoring, Urban excavation work

1. Introduction

With the populational growth in urban areas, the sites with better geotechnical conditions have already been occupied and with construction works between built edifications or their rehabilitation, there is a higher probability of occurring geotechnical or structural accidents.

Excavations in consolidated urban areas will expose the surrounding structures and infrastructures to risks, specially whenever they involve the execution of underground floors. The execution of these vertical excavations often requires a retaining wall design, which in soils usually includes the execution of diaphragm walls, whenever the groundwater level is located near or above the excavation bottom. In most other cases, a definitive Berlin-type wall or pile walls are used, and these walls may have multi-anchored levels.

One way to verify and monitor the potential adjustments in the surrounding structures and in the stress distribution during the construction works is with the implementation of a monitoring plan through the combinations of different types of instruments and equipment that will provide a record of the imposed changes and a timely prediction of eventual accidents. For that it is important to develop quality criteria for suitable monitoring, including the selection of the instruments as well as their performance or the construction site limitations. With site investigation, it’s possible to characterize the ground and predict their deformation and stability behaviour due to the induced conditions changes. However, any gaps in these studies or due to the natural heterogeneity of the ground can result in unpredictable situations. For an early detection of the potential instability or collapse, the Eurocode 7 (EN 1997-1:2004) recommends the implementation of field instrumentation.

One of the main problems with building excavations in city centres is sometimes the lack of monitoring plans or poor field instrumentation definition and if the excavation hasn’t been well executed and technically monitored there is an increasing probability of failures. Usually, the projects of deep excavations (> 7 – 10 m in depth) or higher buildings will certainly encompass a monitoring plan, but for more superficial excavations or rehabilitation projects this may not happen. The solution to this design gap in urban environments is the definition of general monitoring plan for immediate application, suitable for each building construction site. The aim of this paper is to propose some field instrumentation guidelines for those situations.

2. Field instrumentation

The first reports of geotechnical instrumentation as an assistance to visual inspections started between 1930s and 1940s, when the first mechanical and hydraulic devices appeared (Dunnicliff and Green, 1988), lately followed by electrical, pneumatic, vibration wire and, most recently, the optical fibre instruments/equipment.

the technological improvement allowed for a significant diversity of equipment/instruments in the market, but for monitoring it is necessary to analyse all those equipment's specifications to decide which of them are the most suitable for the various types of structures and infrastructures to evaluate. This way, an adequate monitoring is not only dependent on the right choice of equipment/instrument but also depends on the knowledge that the engineer has on the structures to maximize the quantities and the localizations for each of them (Segalini, Carri and Savi, 2017).

The main purpose inherent to field instrumentation in the context of this paper is promoting safety on site and in the surrounding area, which is achieved by comparing the deformations (both superficial and internal) estimated in the design phase with those that were verified during the construction phase (Oliveira, Brandt and Leão, 2016).

A second ambitious goal of instrumentation is optimizing the design project according to the conditions of the site and the results of geotechnical and structural observations.

In a general way, an adequate field instrumentation plan must consider:

- The aim and the properties to measure;
- The type of instruments to use (including the characteristics and the quantities considering the redundancy principle for critical values);
- The type of readings - manual, semi-automatic or automatised;
- The localization of the instruments;
- The reading frequency;
- The treatment and processing of the collected information;
- The monitoring alert and alarm criteria;
- The actions to implement if these levels are exceeded.

2.1 Instruments features

Geotechnical instrumentation by sampling involves monitoring of superficial and internal deformations, pore water pressures/groundwater level changes, displacement in existing cracks/fissures, vibrations and eventually stress variations.

The measuring devices must be reliable and simple, although robust, have the required range and resolution. The devices used should have a high accuracy to make readings as close to reality as possible and they could be manual, semi-automatic or automatic. As the technology advances, the equipment becomes more precise and accurate, as they allow for automatic registrations of data without the intervention of an operator in the reading process, thus decreasing the potential for acquisition errors. The use of automatic collection of data from all the equipment/instruments in the field also implies that all the readings are made simultaneously and in real-time. However, it must be considered that automatic systems:

- are usually more expensive than the manual or semi-automatic, and they may consist in a higher burden on the construction budget, especially in small projects; and

- the visual inspections are still necessary to extend the sampled measures to the entire construction site and surroundings.

2.2 Devices usually used for monitoring excavations in urban areas

The monitoring consists in the measuring, storing and analysis of the changes that are induced on the site. It encompasses the following properties (Duncan and Jeanne Brooks-Gunn, 2006):

- The movements, which includes deformations, settlements, and displacements of the ground or in the neighbourhood structures;
- The loads applied to the structures and/or retaining walls;
- The pore water pressures.

Automatic systems provide real time monitoring as data is collected and transferred during all the phases of work allowing a time prediction off possible accidents.

One way to overcome the limitations of automatic systems as mentioned before, it is to implement them with higher frequency of readings, for an immediate alert of any change, and to complement the monitoring plan with manual systems to allow for the confirmation of the results obtained, ensuring the necessary redundancy of measures.

Table 1 resumes the most common instruments used in a building project monitoring plan.

<table>
<tr><th colspan="2">Measurement</th><th>Type of readings</th><th>Instruments, equipment & devices</th></tr>
<tr><td rowspan="3">Deformations</td><td rowspan="2">Superficial</td><td>Manual</td><td>Total station
Topographic targets
Mechanical tiltmeter
Optical and mechanic crack meter</td></tr>
<tr><td>Automatic</td><td>Digital tiltmeter
Vibrant wire tiltmeter
Wireless tiltmeter
Electric crack meter</td></tr>
<tr><td>Internal</td><td>Manual</td><td>Inclinometer</td></tr>
<tr><td rowspan="4">Pressure/stress Variation</td><td rowspan="2">Water pressure</td><td>Manual</td><td>Stand pipe piezometer
Pneumatic piezometer</td></tr>
<tr><td>Automatic</td><td>Pneumatic piezometer
Vibrant wire piezometer</td></tr>
<tr><td rowspan="2">Load</td><td>Manual</td><td>Mechanical
Hydraulic</td></tr>
<tr><td>Automatic</td><td>Vibrant wire</td></tr>
<tr><td colspan="2">Vibration</td><td>Automatic</td><td>Accelerometer</td></tr>
</table>

Table 1 – Most common types of devices that may be used in excavation works in urban areas

3. Proposed basic field instrumentation

Considering the possibility of the building projects in consolidated urban centres with a superficial excavation (< 7-10 m in depth) with lack of or insufficient monitoring plan, the proposed field instrumentation will consider the implementation to sites with old buildings in the surrounding area, typical of an old city centre, with soft rocks, soils, fills, and sub horizontal geological structures (e.g., gently dipping). The excavation may, or may not, intersect the groundwater level and there will be multi-anchored walls. The monitoring time to be considered must be larger than 6 months.

The proposed solution falls on the implementation of a combination between automatic and manual standardized instrumentation, reliable and simple to adapt to any type of excavation project and it will be supplemented by periodic visual inspections.

In most of the superficial excavations in urban areas, manual measuring equipment is used, so the readings will be taken when the operator goes to the site, which implies that it doesn't exist data recordings for a certain period. During the gaps between these readings, there may occur significant variations of parameters that will be registered after the occurrence, with time delay.

It is still commonly used only one type of instrument for monitoring a single property, losing the principle of redundancy. The redundancy of systems allows a rigorous analysis and a greater confidence in the results assessed. In this scenario, it is essential to implement a larger system, with a tighter reading frequency, which in the construction phase shouldn't exceed weekly intervals, and with a greater number of observation points with manual readings.

Table 2 present the suggested instruments, their accuracy and range.

Measurement		**Type of readings**	**Instrumentation**	**Accuracy**	**Range**
Deformations	Superficial	Manual	Superficial markets Topographic targets Total station Crack meter	0,5°; (0,8/0,5) +1ppm 0,2 %	Variable 15 – 50 mm
		Automatic	Tiltmeter	± 0,01 %	± 30°
	Internal	Manual	Inclinometer	± 0,01 %	± 30°
Variation	Water pressure	Manual	Stand pipe Piezometer for low permeability and pneumatic piezometer for heigh permeability	0,5 mm	Variable
	Load	Manual	Load cells	± 0,5 %	150 %
Vibration		Automatic	Accelerometers	0,01g	0,5 – 250 Hz

Table 2 - Field instruments suggested for the proposed monitoring plan

3.1 Localization of the devices

Figure 1 presents a possible scheme for the location of the proposal field instruments (Table 2). They were placed close to each other to create monitoring profiles along the excavation walls, enabling the compilation of all recorded information for possible analysis and reporting.

The crack meters aren't represented in the Figure 1, because they are used only in certain situations, whenever cracks are observed.

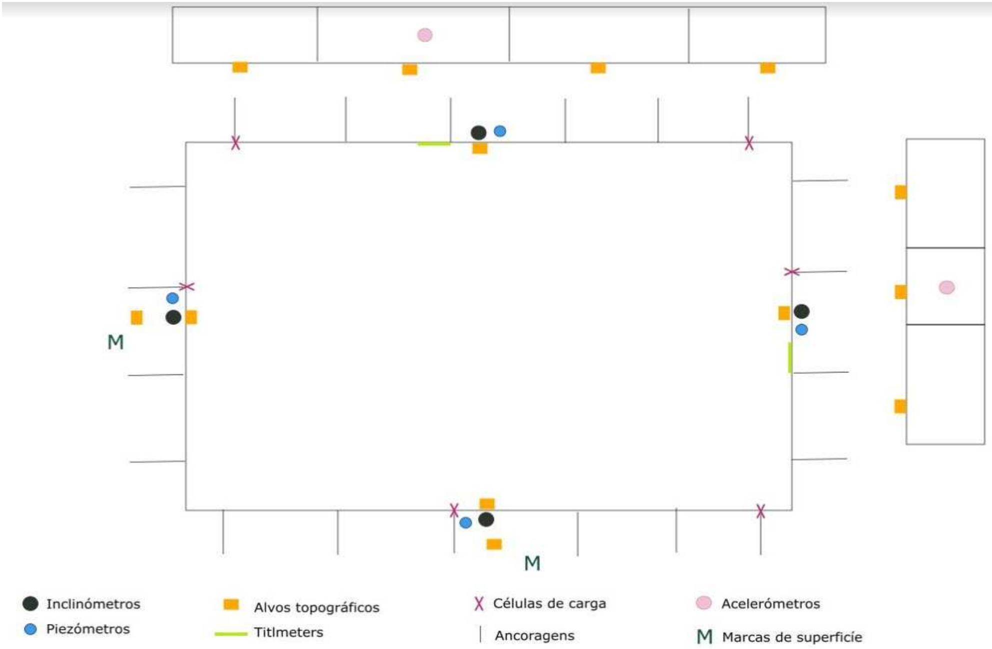

Figure 1 - Location of field instruments in a rectangular superficial excavation (20 m x 10 m)

3.2 Frequency of readings and alert and alarm criteria

The frequency of readings will depend on the type of system adopted (manual or automatic) and on the phase of the construction works. During excavation, which it is the most critical moment for a building, the readings should have a higher frequency. For the automatized instruments, it is possible to get readings several times during the day. This shows the added value of automatic equipment when compared to manual equipment.

Table 3 includes the estimated frequencies generally used during the different construction phases.

Construction phase	Frequency of readings	
	Manual readings	Automatic readings
Beginning of excavation	Weekly	Weekly
Until completion of excavation	Daily	Every hour
Infrastructure construction	Bi-weekly	Every two hours
Until beginning of superstructure	Two in two weeks / monthly	Daily
After conclusion	Monthly / tow in two months	Weekly

Table 3 - Estimated frequency of readings for the field instrumentation of a superficial excavation

In association with the field instrumentation, an extended visual inspection of the targeted area should be regularly performed. Whenever it is obstructed, whether physical or visual, the use of a UAV (i.e., drone) should be envisaged to complement the visual inspection but considering the good practice of the usage of such device near people.

The alarm and alert criteria are defined in the design phase, depending on the level of deformation that the ground and structures are estimated to efficiently support, when these limits are reached or exceeded, some contingency measures (and type) should be implemented. Usually, for deformations equal or greater than 25 % and lower than 50 % than the ones predicted, the project should be reviewed, and for deformations equal to or greater than 50 % of the maximum predicted deformation, the works should be stopped, and the contingency measures implemented. These measures encompass reinforcement of the horizontal restraint of the retaining walls, ground reinforcement and/or improvement of the drainage conditions.

3.3 Information circuit

Figure 2 presents the scheme for an efficient information circuit associated with a monitoring plan, and for that it is necessary that the analysis be carried out by a specialist in geotechnical instrumentation. The treatment and the availability of information should be done quickly and effectively, enabling all those involved in the project to be aware of the stability of the site and the surrounding area. For this purpose, it is important to implement and manage the systems that will allow a continuous availability and a quick exchange of information, if necessary.

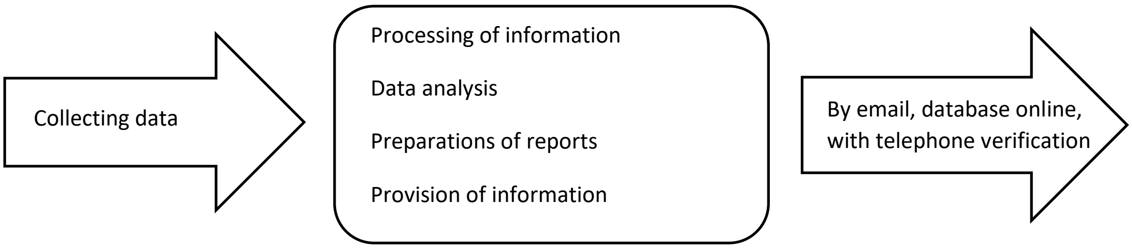

Figure 2 - Scheme of an efficient information circuit

The transmission chain of information can be done by direct data entry into online databases or by e-mailing the reports. In case of changes in the stability conditions, it must be necessary a confirmation (e.g., a receipt of information) by all the concerned entities, so a contact by phone is the best option.

4. Conclusions

Manual instrumentation systems are the most used in monitoring plans, which sometimes makes the observation insufficient. Incorporating manual and automatic instruments present the advantages of a higher frequency of readings, which enables better monitoring, decreases the eventual errors, and provides an early prediction of the behaviour of ground or structures.

In some projects, there may be budget restrictions that could limit the option for an automatic system, so the solution will be the use of minimum automatic instrumentation complemented with manual instrumentation allowing for the redundancy of results, fundamental in this type of geotechnical observation.

The importance of a standard instrumentation plan that can be adapted to all types of excavation works in consolidated urban centres, since it is noted to promote not only safety, but also the use of instrumentation in any type of building, so it reduces the potential cases where it will not be implemented.

Acknowledgements

The research was developed for a master thesis (Earth Sciences Department of the NOVA School of Sciences and Technology) and Paula F. da Silva work was supported by FCT - project GeoBioTec/NOVA UIDP/GEO/04035/2020.

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