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Deep-seated ground deformations measured by robotized system, Roma Metro C Line

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Abstract

The new section T3 of Line C - Rome Metro, crosses its historic and monumental central area. In cooperation with METRO C S.c.p.A., General Contractor responsible for design and construction of the project, a robotized inclinometric system was installed to measure deep-seated ground deformation in three sections. This experimental equipment, allows to measure horizontal deep displacements using a single inclinometer probe driven by a robotic system. This system allows for automatic measurement along the entire length of the borehole with a 50 cm step, double reading, similar to the operator - based measurement. This instrumentation, mainly used in landslides field, is independent from the length of the borehole and is able to reach high frequency measurements (6÷8 measurements/day). The monitoring activities carried out before, during and after the TBM excavation, allowed to collect about 700 measurements in the three sections, characterized by different tube lengths:65, 43, 34m and different lithology. Interesting result were obtained in the 3rd one where a small but clear deformation, induced by tunnel excavation, was observed. Thanks to the high spatial and temporal resolution (50cm, 4 hours) a noteworthy spatial and temporal correlation between TBM progression and inclinometer deformation was obtained.

Keywords

Tunnelling, Heritage, Inclinometer, Monitoring, TBM

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1 Introduction

Historical urban areas, when involved in excavation and tunnelling, should be safeguarded by planning a detailed monitoring network. The value of the heritage monuments is by far greater than the most expensive monitoring strategy. Particularly, in the Roma Metro, Line C, a complex network of automatic sensors was planned, installed and integrated with manual measurements. The aim of the monitoring is the evaluation of the impact of the construction works on the buildings and monuments along with their protection; additionally, the monitoring data were used to validate the design hypotheses. The payed attention is due to the importance of the monuments involved by the works like, among others, Colosseo, Basilica di Massenzio, Basilica di Santo Stefano Rotondo al Celio, Fori Imperiali.

Fig. 1 Study area and the three monitoring sites: 1) Santo Stefano Rotondo al Celio, 2) Fori Imperiali; 3) Basilica di Massenzio. The yellow dashed line shows the excavation track (Background © Google)

2 Materials and Methods

2.1 Robotized Inclinometric System

In the described context, METRO C and CNR-IRPI cooperated in the experimentation of an innovative system for the measure of horizontal deep-seated ground displacements. The goal of the test was the evaluation of the deformations induced by the mechanized excavation activities with TBM. The system was developed and patented by CNR-IRPI (Italian Patent UIBM 0001391881—2012). The TBM advancement and induced deformation were monitored through the use of an experimental instrumentation: the robotized inclinometric system (Fig. 2) which automatizes the traditional inclinometric measurement (Stark and Choi 2008). The peculiarities of the system are: 1) use of only one inclinometric probe; 2) very high accuracy and repeatability; iii) double reading approach (0/180°); 3) high vertical spatial resolution (0.5 m); 4) same equipment for inclinometer tubes with length up to 120m; 5) high frequency of measurement (up to 6 ÷ 8 measurements per day); 6) possibility of rapid transfer and reuse of the instrument (following the excavation progress or in case of too large tube deformations in landslides)..The instrument full description, i.e. components, performances, functioning principles, is explained, in detail, in Allasia et al., 2020. These features, combined with remote control, have made it possible to use the instrumentation for the study of instability phenomena or in large geotechnical work environment. The instrument, in fact, was successfully used in landslide monitoring in different sites across Europe (Allasia et al. 2018; Herrera et al. 2017; Allasia et al. 2021) and was tested in the field of, excavation induced, deformation monitoring.

Fig. 2 Robotized inclinometric system without its protective casing

2.2 Monitoring

The monitoring was carried out in three following steps according to TBM advancement deploying the instrument in different sites (Fig. 1) coincident with renowned monuments:

1. Santo Stefano Rotondo al Celio;
2. Fori Imperiali;
3. Basilica di Massenzio.

In table 1 the main features of each site are summarized. The instrument was easily installed in site 1 in one day thanks to its characteristics and then moved to the next site and reinstalled in less than 4 hours. The monitoring started, at least, one month before TBM passage and ended one week after it. Each duration had been decided, on a site by site basis, in relation to the planned TBM advancement and the real time check of the measured deformations. Thanks to the availability of grid power supply, unlike standard landslide monitoring where the instrument is solar powered, the monitoring frequency reached a maximum of 8 measures per day.

Table 1 Excavation parameters

Site	Tube length [m]	Tunnel axis depth [m]	Distance tube/excavation [m]	Main stratigraphic layer	Total Measures
1	62.5	55	5	Clay	290
2	42.5	36	2.5	Sand	272
3	33.5	28	1.5	Sand	160

3 Results and Discussion

The first two sections did not provide remarkable results in term of deformations/displacements. The borehole-excavation distance, type of stratigraphy and depth excavation induced only a negligible deformation as depicted in Fig. 3.

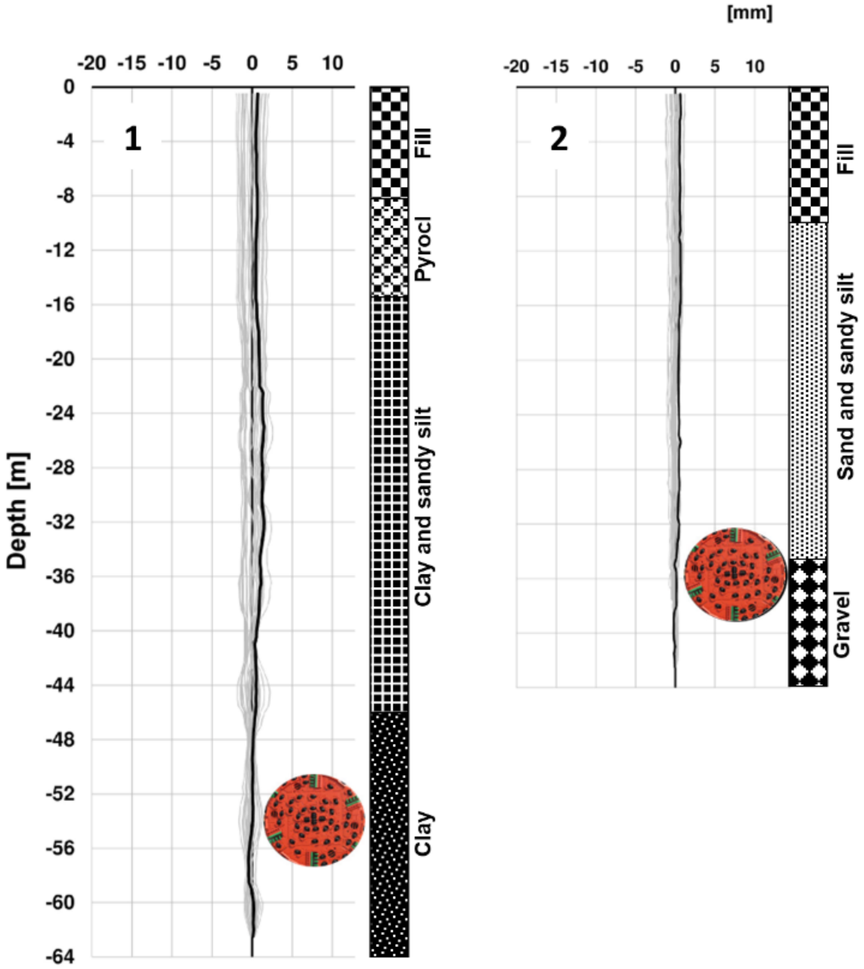

Fig. 3 Plots of cumulated displacements of sites 1 and 2, modified from Allasia et al. 2021. (30 measures are plotted, last measurement is highlighted in bold). TBM image © *https://www.dsd.gov.hk/others/HKWDT/eng/skill.html*

On the other hand, in section 3, due to the reduced spacing, the robotized monitoring was capable of pointing out deformations during the TBM advancement (Fig. 4).

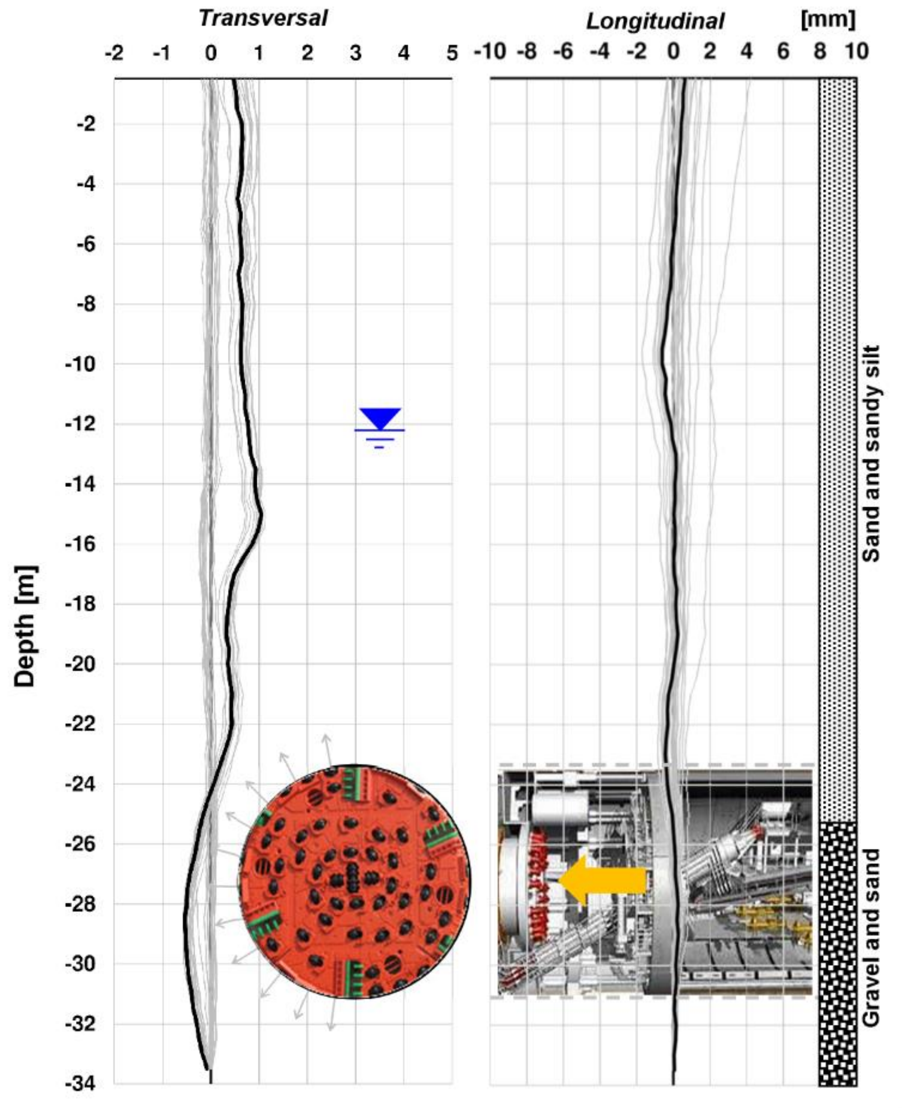

Fig. 4 Plot of cumulated displacement, modified from Allasia et al. 2021. (30 measures out of 160 are plotted, last measurement is highlighted in bold). TBM images © *https://www.dsd.gov.hk/others/HKWDT/eng/skill.html* and *https://www.youtube.com/watch?v=1DrLQGxpj1Q*.

Although the measured deformations are limited, at excavation depths, deformations were clearly observed with a definite curvilinear shape induced by mechanized excavation in overpressure (Beghoul and Demagh 2019). The progression of this curvature was observed with as the TBM approaches, starting from a distance of approximately 20 ÷ 22 meters (equal to about $2.7xD_{excavation}$). The maximum value of the displacement, equal to about 0.5mm, was measured roughly at the axis of the tunnel and did not show further changes after the TBM progression (Fig. 5).

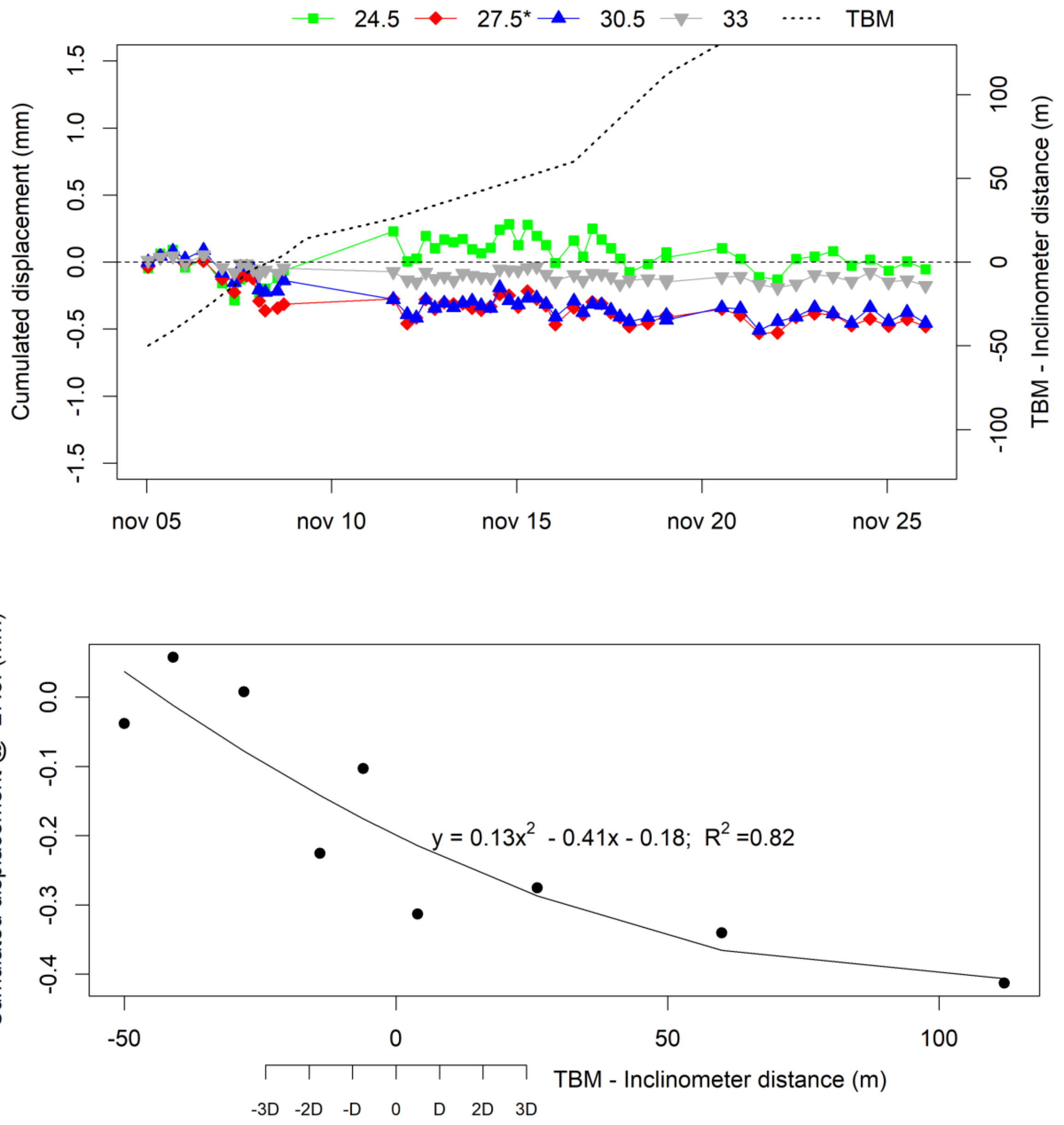

Fig. 5 Time series of transverse cumulated displacement at significant depths and TBM excavation advancement (up). Relationship between TBM advancement and deformation measured at tunnel axis (down)

Concerning perturbation's vertical extension, the curvilinear trend tends to run out few meters over the top of the tunnel shell. At a depth of about 16m - 8m above the excavation - some minor displacements were also detected probably due to defects in the inclinometer tube cementation. About the longitudinal plane, no noticeable changes were observed. Similar results were observed on the surface, where, the integration from below shows millimetric values for both measurement planes (transversal and longitudinal).

To validate the result, inclinometric measures were compared with data obtained from a TRIVEC system located in a borehole 2m far from the inclinometer. Data acquired with this system showed the same, even if slightly overestimated in modulus, type of curvilinear trend. Such differences may be explained by the different type of instrumentation; additionally, the measurement was carried out in another, though very close, tube. Orientation and concavity of the curve are the same as those measured by the inclinometer. Both measured deformations are to be considered almost completely plastic as no appreciable deformation decreases were observed with the progress of the excavation and subsequent processing. The behavior observed in section 3 appears fully compatible with the overpressure excavation methods (Beghoul and Demagh 2019) and with the very small distance between the excavation/processing boundary and the inclinometer tube.

During the monitoring campaign, the probe encountered two critical failure induced by the reduced borehole diameter (i.e. 60 mm) which stressed wheel assembly spring resulting in two breakages. Thanks to the load cell installed in the instrument and the remote link it was possible to detect the issue in real time and solve it in less than one day by repairing the spring and keeping the same probe for the next measurement. This precaution allowed to keep the measurement uniform in time and assure their comparability.

4 Conclusions

The robotized system proved its effectiveness and reliability in the monitoring campaign. Deformations induced by TBM excavation was detected earlier than its passing at the instrument section. This early detection may allow the activation of procedures in order to increase the monitoring frequency of surface instruments and to alert inspection squads to check monuments status while the TBM is approaching. Type of stratigraphy, depth of tunnel and closeness of the borehole to the excavation was probably a key factor to acquire measurement with meaningful data. In fact, only in the third section (the closest to the TBM) not negligible deformations have been measured. These values, although appreciable from instrumental and metrological point of view, were considered normal and into the design parameters.

Concerning the instrument operability, it confirmed its reliability and usability. The remote access allowed for real time monitoring of its functioning and to detect failures to plan for maintenance or instrument removal. The re installation, thanks to several improvement in the previous years, took only few hours and the instrument was immediately ready for the next monitoring.

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