Deformation monitoring with robotic total stations. Pushing the limits

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ABSTRACT

Deformation monitoring using high accuracy surveying methods are techniques widely demanded and used. Even in these conditions, there are several misunderstandings and misconceptions regarding several topics, such as differences in accuracy between the instrument in laboratory conditions and the system running in real conditions, and variations of accuracy in time and space, among others. The paper provides a case study focused on the construction of a new building above an underground transport hub where a deformation monitoring plan was set up to monitor the existing tunnels and structural elements. The monitoring plan included manual precise levelling for monitoring settlement of several pillars in both the building and the transport hub. It also included three robotic total stations (one in each existing tunnel) to monitor displacements and convergences, specifically in sections previously modelled by the finite elements method. According to several as-built uncertainties of the existing tunnel and transport hub and the fact that the new building loads would be transferred via a shared slab, the threshold limits defined for the convergence control were within the limit of the theoretical accuracy of the system, at ±1mm.The paper describes the monitoring system setup, the checks for monitoring performance of the system and an evaluation of changes in accuracy of the systems related to environmental conditions, station-target distance and acquisition geometry. Finally, the paper concludes with an analysis of the resulting challenges faced when dealing with low level thresholds.

I. Scope of the project

The scope of the project in which the monitoring system was installed was to construct an eighth floor building above an existing transportation hub. The building had to be constructed over a pre-stressed slab that also played a major role in the structural behavior of the transportation hub. This pre-stressed slab also acted as the structural roof of the transportation hub itself and below this structure three railway tunnels also existed. At the design stage the information regarding the structural connection between the slab and the tunnels, and the tunnels and the ground were not clear, so- as well as a structural investigation- a monitoring plan was established to manage the design uncertainties (Figure 1).

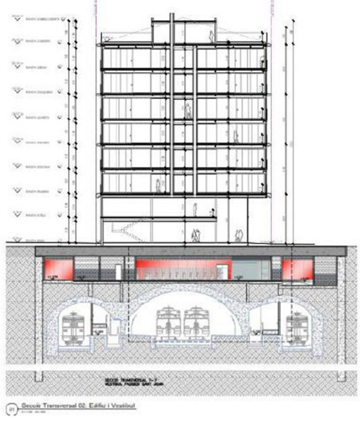

Figure 1. Cross section of the project.

Due to a significant increase in the stress levels on the slab during the construction, a finite element model - FEM - was built in order to assess the stress-strain behavior of the existing structures and the permitted maximum levels of deformation for the hub and the tunnels' structure.

During the first iterations of the FEM a conceptual monitoring plan was defined to address the structural deformation monitoring: fibre optics had to be used for the slab control, precise levelling for pillar control and a robotic total station system for the deformation monitoring of the tunnels.

II. The monitoring plan

A monitoring plan was established to assist with the deformation monitoring of both the existing structural form and the future construction.

The monitoring plan was dependent on the results of the FEM, which ran in the design phase to address the deformation analysis. This FEM was then updated during the construction, as a result of the real values obtained by the monitoring. Here is the logistical challenge: to install the instruments as close as possible to the nodes of the model where the deformation is computed and to update them according to the real deformation measured by the instruments.

The scope of the monitoring plan is to define:

1) The instrumentation systems.
2) The threshold levels in connection with the FEM model.

3) The remediation action in the case that threshold limits are reached.
4) The coordination and cooperation of different administrations and enterprises involved in the project.

At this stage, the project owner tenders the monitoring services with two different packages, one for the fibre optics and another for the deformation monitoring including precise levelling and robotic total stations.

BAC was awarded with the package of the deformation monitoring, therefore, the fibre optics results are outside the scope of this paper.

The allowed limits of deformation were defined according to the FEM results. As the acceptable deformation was "appearance of cracks" and the uncertainty on the real structural connections between elements is quite high, the limits for the tunnel deformation were defined between 0.75 and 1.5 mm for the convergences between prisms. These values are close- even below- the standard defined accuracy of the robotic total station systems, which increase the challenges faced.

A. *Design and implementation of the robotic total station (RTS) network*

The first step was to design the automated control in the tunnels, with an initial visual inspection of the control area to find suitable locations for the RTS. The location of the RTS should consider the following:

- A visual connection with all the control points
- A position no further than 100 m from all the control points
- Be outside the clearance gauge with the trains and other machines circulating through the tunnels

The first deliverable at this stage were the proposed location plans for the prisms and the RTS. The proposal was consistent with the monitoring plan and approved.

The second stage was the implementation of the system and the compilation of the first readings. The system should be fully operational and stable at least two months before the beginning of the construction activities.

Figure 2 shows a plan of the full system, including the location of the RTS and the reference points. Figure 3 shows the distribution of control points in each tunnel.

All the tunnels have their own particularities, but have one feature in common: one section control is located in the tunnel, one is located in the station and another one in the transition zone between the station and the tunnel. Aside from the geometric considerations and the difficulties of establishing one appropriate line of sight for all the prisms, the environmental conditions of the tunnel (air temperature, humidity and atmospheric pressure) are more stable, whilst in the transition zone and specially the station there were more significant changes.

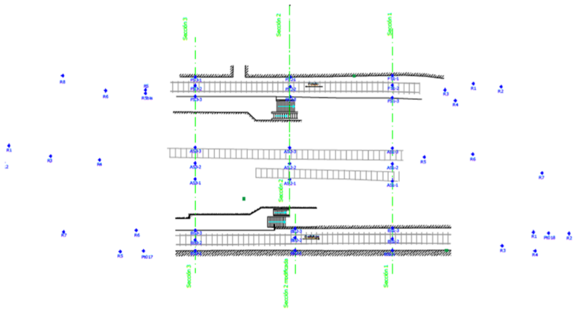

Figure 2. Monitoring area, control and reference points.

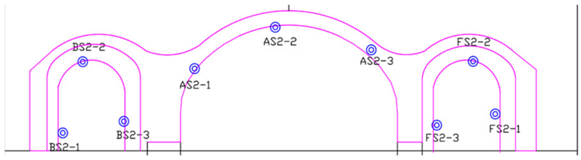

Figure 3. Distribution of monitoring points.

Regarding the line of sight, all the robotic total stations have to be placed in the tunnel section for the sake of security of the instruments. This means in all cases that the section located in the station can be further than 100 m. Additionally, according to the need for a proper distribution of the references (see for example, NWI PRE ISO 18674-9), between 4 to 6 references- half of the total- are further than the limit of 100 m. This means that according to the border conditions of the tunnels, some prisms will have less accuracy than required.

All the robotic total stations used were of the model TOPCON MSAXII and the calculation routine used was that which was implemented within the package of TOPCON monitoring Delta Live and Delta Watch.

The measurement routine was established with one measurement every two hours so that the number of points to be measured per each station was not excessive.

Table 1 shows the geometry of measurement of all the targets- reference and monitoring points- in terms of distance and horizontal and vertical angle from the robotic total station.

The main findings and characteristics of this distribution are:

- Central tunnel:
  - All the control points are close to the total station less than 30 m, but all the references are far away between 37 and 56 m.
  - References are well distributed in terms of horizontal angles but have a worse distribution in terms of vertical angle.
  - Control points are well distributed in terms of horizontal angles but have a worse distribution in terms of vertical angle.

- Lateral-B tunnel:
  - All control points are close enough to the total station maximum around 60 m. Good distance distribution among reference points, with distances between 15 and 70 m.
  - References distribution in terms of horizontal angles are split in two groups, one around 25 and another around 200. Regarding vertical angles, all the points are around 100.
  - All the monitoring points have similar horizontal angles around 20 and vertical angles around 100.
- Lateral- F tunnel:
  - All control points are close enough to the total station maximum around 30 m. Good distance distribution among reference points, with distances between 15 and 63 m.
  - Reference points in terms of horizontal angles are in one single group around values of 300. Regarding vertical angles, all the points are round 100, except for one single point at a value of 300.
  - All the monitoring points have similar horizontal angles around 100 and vertical angles around 100.

B. *Design and implementation of precise levelling network*

As defined in the monitoring plan, the precise levelling network was to be carried out with manual readings and the results to be used as a comparison and calibration for the fibre optic sensors.

The levelling points were to be installed in specific pillars. Some new construction pillars close to the contact with the slab and others that have continuity in the transportation hub level. Also, the upper surface of the existing walls (constructed during the execution of the construction hub) are levelled with the same instruments.

The installed levelling points are those shown in Figure 4.

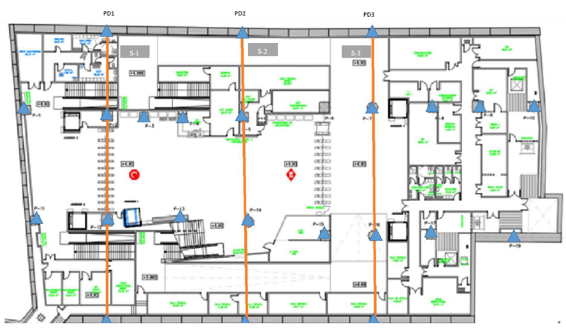

Figure 4. Levelling control points.

The system requires external references to perform the computation. Those references were installed outside the construction site.

Figure 5 shows results of settlements points to help understand the type of movement measured in the project.

Table 1. Coordinates of control and reference points

Target ID	Coordinates		
	H. Angle [^{g}]	V. Angle [^{g}]	Distance [m]
AR1	196.0106	98.788	45.696
AR2	204.3329	98.9068	45.5921
AR3	198.9278	98.2008	37.2231
AR4	197.7127	97.5916	27.8815
AR5	23.481	104.0164	34.8308
AR6	22.3561	104.0572	44.0438
AR7	12.7493	103.5963	56.474
AS1-1	7.9159	102.3895	27.6962
AS1-2	16.1558	97.0723	27.888
AS1-3	27.4242	102.7751	28.7582
AS2-1	394.4046	107.4128	8.5841
AS2-2	36.1424	91.0596	8.8559
AS2-3	67.1827	103.527	12.5245
AS3-1	208.8988	100.9946	9.1215
AS3-2	177.5896	91.5498	10.3815
AS3-3	156.5435	100.7418	12.9032
BR1	207.8099	106.1259	17.8787
BR2	211.5806	105.9328	24.4881
BR3	216.81	93.7674	11.0199
BR4	222.0319	106.2988	17.2676
BR5	18.6843	102.1682	62.9229
BR6	23.078	103.654	59.4367
BR7	22.2705	102.9023	73.584
BS1-1	17.2692	115.596	10.5811
BS1-2	27.759	93.4013	10.5042
BS1-3	41.6912	101.9613	10.5326
BS2-1	18.4523	107.2776	29.8638
BS2-2	21.2619	97.4655	29.3786
BS2-3	27.086	105.924	28.6305
BS3-1	18.6738	103.3953	47.2741
BS3-2	20.8087	97.9384	46.7211
BS3-3	23.4074	97.5963	47.3293
PT018	209.8563	103.6269	20.614
PT017	18.5985	103.531	58.4337
FR1	296.8986	103.8799	21.5699
FR2	298.4373	102.1154	26.5772
FR3	303.4265	92.9511	16.272
FR4	310.154	106.1325	18.6403
FR5	288.739	296.2545	38.6499
FR5BIS	87.8678	104.4789	38.7959
FR6	289.7147	296.8385	45.7863
FR7	93.8498	97.8119	53.3053
FS1-1	290.8668	111.3271	7.421
FS1-2	307.0931	84.6962	7.5075
FS1-3	325.4728	111.7009	8.2654
FS2-1	94.6325	107.7206	12.4479
FS2-2	87.017	90.4514	12.5364
FS2-3	75.2796	110.7454	13.2156
FS3-1	94.7095	102.6907	29.7767
FS3-2	92.2798	96.0385	30.2484
FS3-3	85.3848	95.1756	30.3254

III. Results

As defined in the monitoring plan, deformation monitoring for the tunnels has to be computed and plotted in terms of convergence. Those convergences have different trigger values per each tunnel, each section and each convergence line, as shortening and elongation results should cause a different behavior in terms of crack appearance.

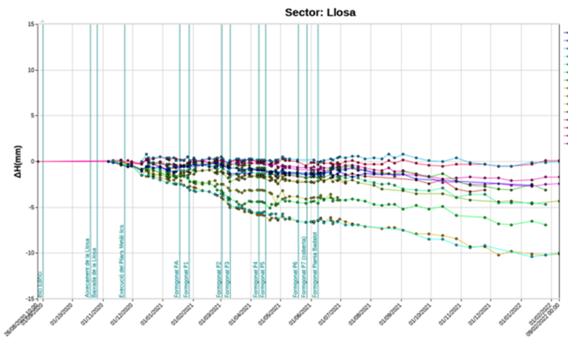

Figure 5. Levelling point results.

Fortunately, the system could be set up and run for almost three months before the construction activities started. This was of great help in order to understand and interpret the stability of the whole system.

From the very beginning all the sections located in the central tunnel showed better stability and better levels of standard deviation.

The most critical sections in terms of the relationship between standard deviation and threshold limit were sections 2 and 3 in the lateral -B tunnel and section 3 in lateral- F tunnel.

As a summary of these initial findings, Figure 6 shows the results of one section of the central tunnel, whilst Figure 7 shows the results of section 2 of the lateral- B tunnel, and Figure 8 shows the results of section 3 in the lateral- F tunnel.

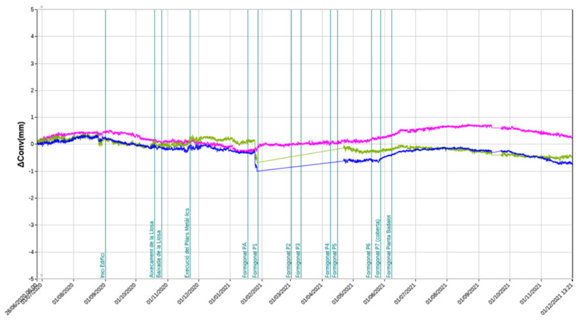

Figure 6. Convergence results. Central tunnel.

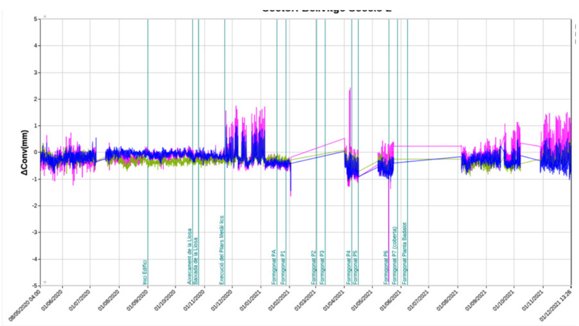

Figure 7. Convergence results. Lateral- B tunnel.

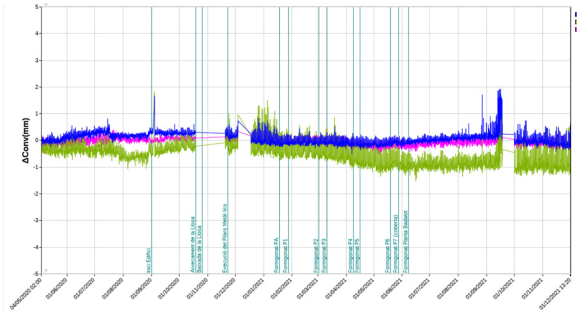

Figure 8. Convergence results. Lateral- F tunnel.

Figures 9 to 11 show the vertical displacement component results of the references for each one of the tunnels. It is clear to see that the central tunnel references are as stable as the monitoring points, with standard deviations between +/-1mm. On the other hand, the lateral-F tunnel references show significant differences in the standard deviation values (in the range +/-2.5mm). The performance of the Lateral- B tunnel references started well- even better than those located in the central tunnel. However, as the project advanced, the standard deviation levels increased.

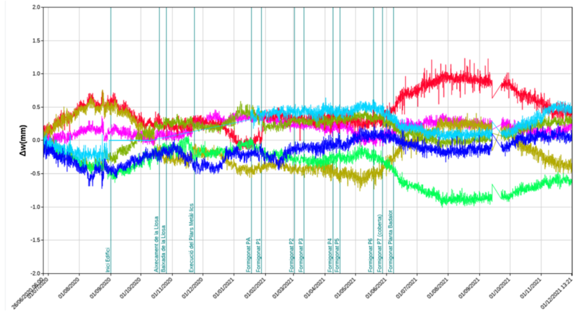

Figure 9. Reference performance. Central tunnel

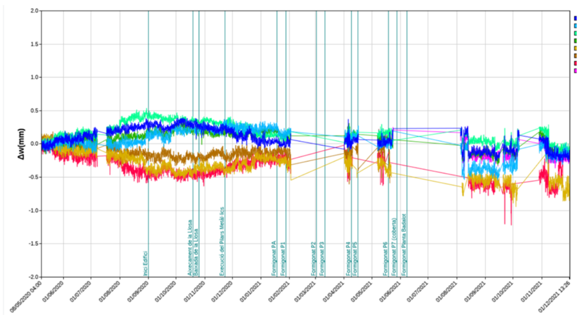

Figure 10. Reference performance. Lateral- B tunnel.

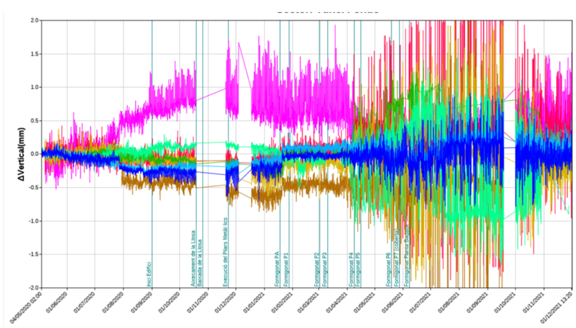

Figure 11. Reference performance. Lateral- F tunnel.

IV. Concluding remarks

As evidenced above, it is essential to design a deformation monitoring system with a robotic total station based on distances and distribution of RTS, control and reference points, in accordance with ISO 18674/9.

According to the border conditions of the project, the above may not always be possible. In this case, the system should be set up prior to the start of the construction activities to understand the real standard deviation levels of the measurements.

The standard deviation is influenced by environmental changes (see references) particularly related to temperature, density and humidity of the air. These environmental changes are an inherent part of the project, cannot be changed, and should be considered and properly addressed throughout the project.

Finally, the standard deviation of the measurements may be affected by physical obstacles and other visual barriers that can be present in the project. The geometry of acquisition should also be checked throughout the project.

Taking into account the above points, it is clear that the standard deviation of the measurements may change with time in the same project and this needs to be continuously assessed for the success of the project.

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