Comparison of monitoring techniques for measuring deformations in an excavation

Comparaison de techniques d'auscultation pour la mesure de deformations dans une excavation

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ABSTRACT: Active monitoring is often suggested as a method to decrease the required safety coefficients in the design stage of a construction. In order to apply active monitoring, precise, reliable and interpretable measurements of the actual behaviour of the structure and soil-structure interaction are required. To obtain this data, accurate and robust monitoring tools should be available at an acceptable cost. An online monitoring test set-up was realized in a railway-infrastructure project site in Anderlecht (Belgium). The braced excavation consists of a nailed jet grout wall with HEB profiles, installed immediately next to a railway track. Both advanced and traditional monitoring equipment is installed to measure the deformation of the jet grout wall, deformations behind the jet grout wall (on the railway tracks) and forces in the nails. The present paper focuses on the results of the measurements in and behind the jet grout wall and on the comparison between the different techniques.

RÉSUMÉ : L'auscultation active est souvent suggéré comme une méthode permettant de réduire le coefficient de sécurité du dimensionnement d'un ouvrage. Afin d'appliquer une auscultation active, des mesures précises, fiables et interprétables du comportement réel des ouvrages et de l'interaction sol-structure sont requises. Afin d'obtenir ces données, des outils d'auscultation précis et robustes doivent être disponibles à un coût acceptable. Un essai de surveillance en ligne a été réalisé sur le site d'un projet d'infrastructure ferroviaire à Anderlecht (Belgique). L'excavation consiste en un mur d'étanchéité cloué, avec des profils HEB, installé à proximité immédiate de la voie ferrée. Des technologies aussi bien avancées que traditionnelles ont été utilisées pour mesurer les déformation du mur d'étanchéité, les déformations derrière le mur (sur les voies ferrées) et les forces dans les clous. Le présent article vise à comparer les résultats des mesures dans et derrière le mur et à comparer les différents techniques de mesure.

KEYWORDS: active monitoring, advanced monitoring techniques, monitoring test site.

MOTS-CLÉS: auscultation active, outils d'auscultation avancés, site d'essai d'auscultation

1 INTRODUCTION.

The Geotechnics Division of the Flemish Government (GEO) realised an online monitoring test set-up to extend the experience with new monitoring techniques and to make a step forward in the application of active monitoring on construction sites. The project was partially funded by the Agency for Innovation by Science and Technology (IWT), allowing 3 firms to develop and perform online monitoring for an excavation. Verification measurements were made by several parties, using both more traditional as well as new monitoring techniques.

1.1 *Main objective*

The main goal of the project is to evaluate different monitoring results and suitability of proposed monitoring schemes for application in interactive design. This implies that accuracy, installation possibilities, reliability and cost are important aspects to be considered.

The monitoring scheme consists of measuring and logging:

- deformation of a vertical wall (x,y,z)
- maximum bending moment in a vertical wall
- deformation of the soil (z) behind a vertical wall
- anchorage forces in nails

1.2 *Site description and applied equipment*

The monitoring site is located in Belgium, Anderlecht (Brussels), where an extra railway track will be constructed alongside of the existing tracks. For the foundation of the new bridge, a nailed jet grout wall was installed next to the existing railway. By doing so, the soil could be excavated vertically and the foundation could be realised in an open construction pit. The excavation depth is 12.5m starting from the railways. The jet grout wall starts 4m below the railway level and has a total length of 21m. HEB profiles with a length of 21m are inserted in the jet grout wall. Five rows of nails are installed over the excavated depth. Figure 1 shows pictures before excavation and after excavation. The excavation is executed in different phases. Each time 2m is excavated and consecutively, a row of nails is installed. After installation of the nails, the contractor waits at least 2 weeks before excavating the consecutive part. More information on the site can be found in Van Alboom et al. 2012 and Verstraelen et al. 2013.

Figure 1. Picture of initial situation (left) and picture of the jet grout wall after excavation (right).

1.2.1 *Deformation of and bending moments in the jet grout wall*

To measure the deformation of the jet grout wall, both advanced and traditional monitoring equipment is installed:

- Fiber Bragg Grating (fiber optics, FBGS)

- SAAF (In-place inclinometer, Inventec)
- Optical strands (fiber optics, OSMOS)
- Traditional inclinometer (GEO)
- Draw Tower Grating (fiber optics, Belgian Building Research Institute (BBRI))
- BOTDR (fiber optics, Cambridge University)

The equipment for measuring the deformation of the wall or stresses in the wall, is placed on 4 HEB profiles which are lowered over their full length in the jet grout wall. Figure 2 shows a front view of the excavation site and the location of the instrumented profiles is indicated in red. Figure 3 shows a drawing and some pictures of the FBG and BOTDR fibers which are fixed to the HEB profile. The FBG fibers are fixed in small anchor blocks which are welded to the HEB profile (size of the anchor blocks is 18mm x 18mm). Anchors are placed every 0.5m in the upper 8m of the profile and every 2m for the lower part. The BOTDR fibers measure the strain continuously, but are locally glued to the HEB-profile (every 0.5m and 2m) for better comparison with the FBG data. To measure deformations and moments perpendicular to the wall, fibers are placed on the top and bottom flange. To measure possible deformations parallel to the wall, two extra fibers are placed at the sides of the bottom flange. Extra L-profiles, placed above all fibers, are used as a protection during installation.

The other instrumentation was similarly fixed on the HEB profiles by welding or gluing.

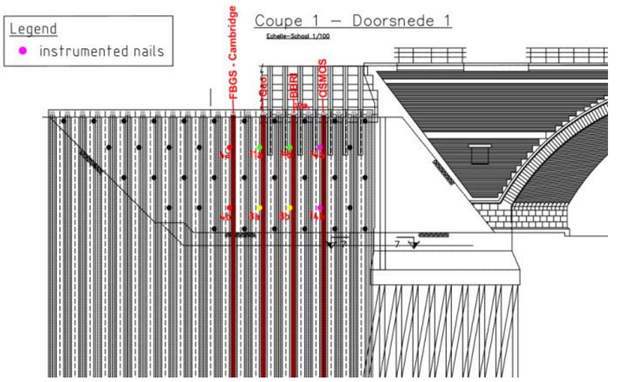

Figure 2. Front view of excavation with indication of instrumented HEB profiles.

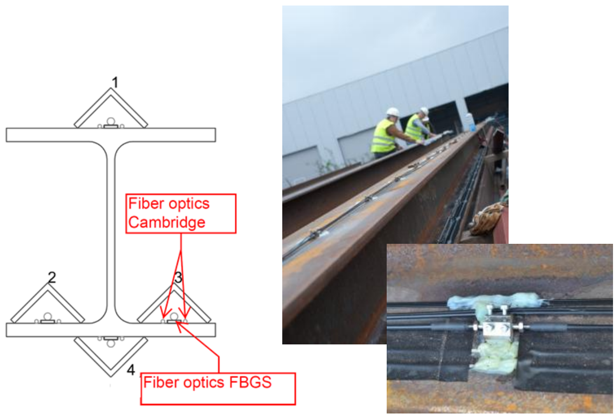

Figure 3. Sketch and pictures of a HEB profile which was instrumented with two optical fiber systems.

1.2.2 *Settlements behind the jet grout wall*

As one of the main concerns during an excavation are the settlements of the soil (and inherently the infrastructure) in the vicinity of the excavation, the vertical deformation of the soil behind the wall is one of the important parameters to be monitored. In this project specifically, deformations of the railroad track are to be avoided.

The deformations behind the wall are measured:

- with two horizontal inclinometers (a traditional one and a continuous SAAF inclinometer) which are placed perpendicular to the wall in the ballast underneath the rails. The inclinometers are attached to a Berliner wall, which is located at one side of the rails. It is assumed that this creates a fixed point;
- topographically: the rails are marked with survey nails along a length of 100m and vertical deformations are measured by topographic levelling at different stages of the project;
- with electrical beam sensors placed on the railway sleepers; the beam sensor consists of an electrolytic tilt sensor attached to a rigid metal beam. The beam, one to two meters long, is mounted on anchor bolts that are set onto the sleepers. The sensors are linked end to end, as to allow displacement values to be accumulated from anchor to anchor to provide a profile of differential movements or settlement.
- with two optical strands, placed at a certain angle with the railway on the railroad tracks .

Figure 4 gives a top view of the instrumentation which is placed on or underneath the railway tracks. It also shows the different HEB profiles which were instrumented.

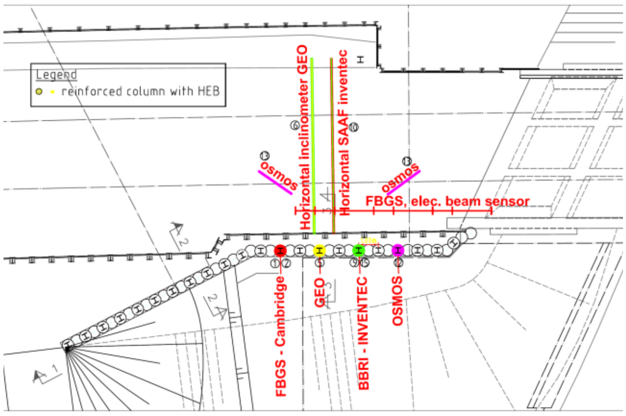

Figure 4. Top view of installed equipment.

A more detailed description of all installed equipment is given in Van Alboom et al. 2012.

1.3 *Design of the jet grout wall*

Calculations of the jet grout wall are implemented in FLAC2D by TUC Rail. They result in a maximum horizontal displacement of 21 mm, a maximum moment of 81KNm/m and a maximum settlement of 9mm behind the wall in the final excavation phase. A more detailed description of the calculations is given in Verstraelen et al. 2013.

1.4 *Sequence of the execution phases*

Table 1 gives the sequence of the execution phases, retrieved from photos made on site every hour. As continuous monitoring was performed, the influence of the executed works on the movement of the soil can be assessed.

Table 1. Execution phases.

Date	*information*
22-23/10/2011	Installation of the instrumented HEB profiles in the jet grout wall
3/11/2011	Excavation up to 1,25m below the top of the concrete beam
06-09/11/2011	Installation of the first row of nails
06-07/12/2011	Excavation up to 3m below the top of the jet grout wall

08-12/12/2011	Installation of the second row of nails
11/01/2012	Excavation up to 5m below the top of the concrete beam
17-20/01/2012	Installation of third row of nails
01-02/02/2012	Excavation up to 7m below the top of the concrete beam
14/02/2012	Putting in gravel for ground improvement
17-21/02/2012	Installation of fourth row of nails
27/02/2012	Installation load cells GEO
08-09/03/2012	Unspecified drilling activity
12-13/03/2012	Excavation up to 8,5m below the top of the concrete beam
13-14/03/2012	Installation of 5th row of nails

2 MEASUREMENTS

The measurements made by the 3 tenderers are continuous and data is transferred over the internet. The verification measurements, both with traditional equipment and innovative techniques are performed at discrete moments in time.

2.1 *Deformation of the jet grout wall*

The instrumentation is placed on the HEB profiles which are lowered in the jet grout wall. The traditional inclinometer and the SAAF measure the inclination of the profile every 0.5m, allowing direct derivation of horizontal deformation of the wall.

Figure 5 shows the horizontal deformation of the HEB profiles, measured with the traditional inclinometer and the SAAF. These measurements are both made on the same date and are taken after the installation of the fourth row of nails. The excavation depth at that time is 7m. The data fit very well together. The data from the SAAF start above the reference zero level (which is the top of the grout wall), as the HEB profile did not reach full depth and protruded about 1.7m above the top of the grout wall.

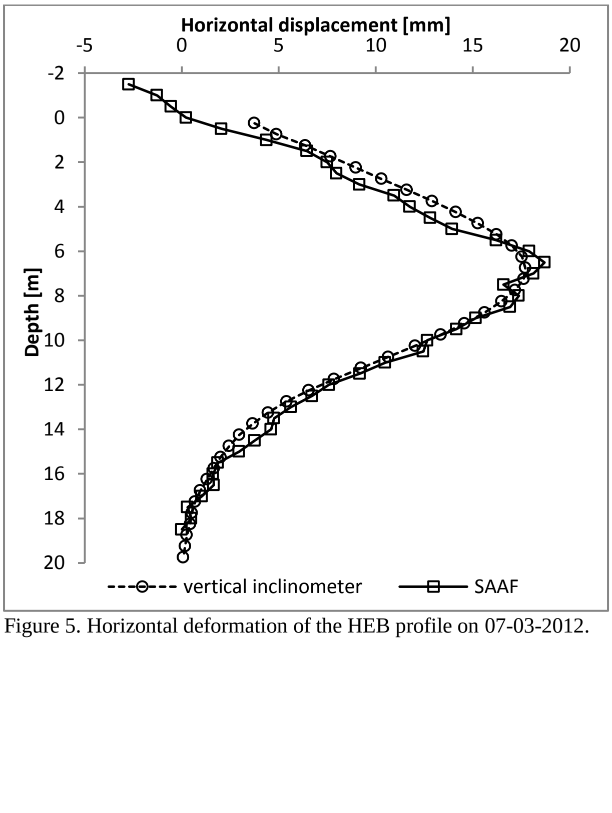

Figure 5. Horizontal deformation of the HEB profile on 07-03-2012.

The maximum horizontal displacement, measured after full excavation, amounts to 21 mm (26/04/2012) at a depth of 6.5m below the top of the grout wall for the inclinometer and 21.6mm for the SAAF. This lies very close to the calculated value of 22mm. It is found however that the direction at which the maximum deformation is found for the SAAF deviates slightly from the expected angle (perpendicular to the wall). This is probably due to a very small twist in between the different elements of the SAAF.

The other optical fiber instrumentation measure the strains in the HEB profiles and derivation of deformations can only be achieved by integration of the measured strains. Furthermore, the stiffness of the combination jet grout wall and HEB-profile needs to be estimated to obtain the deformation. It was found that there are a lot of assumptions which need to be made to obtain a reliable result. Further analysis will be attempted in the future.

2.2 *Moments in the jet grout wall*

For the inclinometers, the bending moment can be derived as:

$$M = EI\frac{d\alpha}{dx} \qquad (1)$$

With E Young's modulus, I the moment of inertia of the HEB profile and α the inclination.

For the fiber optics, which measure strains at regular intervals, the bending moment can be obtained as:

$$M = \varepsilon EW \qquad (2)$$

With ε measured strain and W the section modulus. All fiber optics are mounted on the top and bottom flange of the HEB profile. Strains resulting from temperature differences or normal forces can thus be excluded and only the bending strain is withheld.

For the optical strand, measuring only 1 strain over its full length (top 10m of the HEB profile), the moment can also be derived with Eq.2, only this will result in 1 single bending moment and not in a bending moment as a function of depth.

Figure 6 shows the bending moments derived according to Eq. 1 and Eq. 2 for the different measuring techniques (except for the optical strand, as this does not result in a bending moment as a function of depth). Unfortunately, a lot of breakage of the FBG sensors placed by FBGS was observed during the first weeks after installation. For this reason, they are not included in the graph. For the stiffness of the wall, the stiffness of the HEB profiles was used, as the instrumentation is placed on these profiles.

There is some time shift between discontinuous and continuous measurements. However, all measurements are made after the final excavation phase.

Figure 6 shows that all derived bending moments give comparable values, except for the SAAF. This can be explained by the fact that the deformation measurements of the SAAF are less "smooth". As the bending moment is a result of the derivative of the measured inclination, this results in unexpected peak values.

A maximum bending moment of about 55 kNm is derived from the measurements. This is again in the same order of magnitude of the calculations (maximum calculated bending moment of 73 kNm). For the optical strand, the derived bending moment is about 35kNm, which is considerably lower than the other measurements. Due to the smoothing which is used for the BOTDR measurements, the peak bending moment is also reduced and has a value of 39kNm, which is also less than the value obtained by the inclinometer and the FBG technique from the BBRI. The shape of the bending moment curve however, is comparable to the other results.

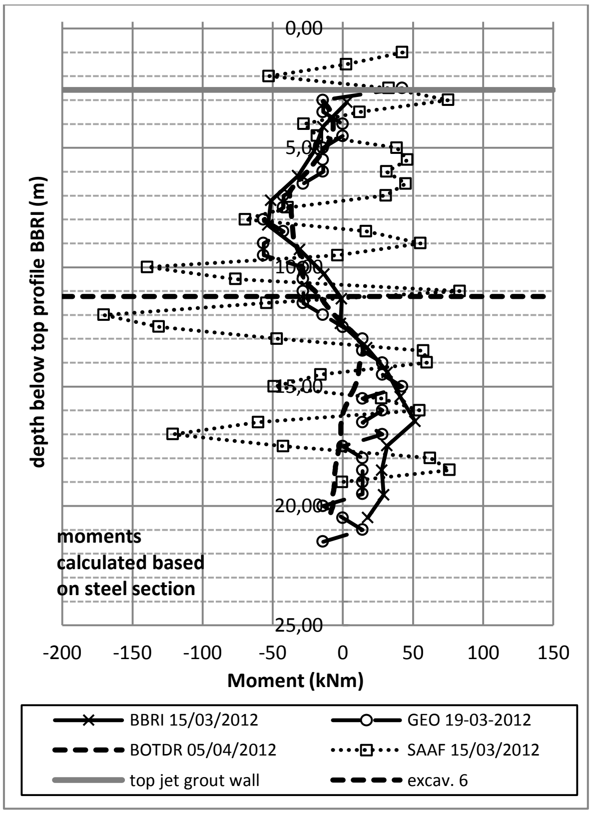

Figure 6. Bending moment HEB profile after the last excavation.

2.3 *Settlements behind the jet grout wall*

The calculated settlement prior to installation is 5mm. The measurements indicate a maximum settlement varying between 50 mm and 70mm for the different measuring techniques, which is much larger than the calculated value. Figure 7 shows the maximum settlement value measured by the SAAF in time. It demonstrates the great advantage of measuring continuously.

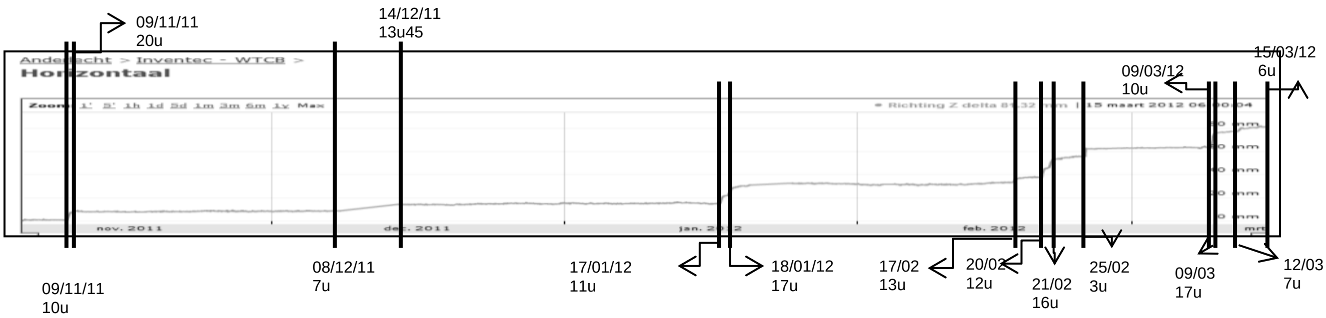

Figure 7. Maximum settlement as a function of time for the horizontal SAAF.

When comparing Table 1 with Figure 7, it can be seen that the discontinuities in the settlement curve correspond each time with the installation of the nails. In Verstraelen et al. 2013, it is explained that this is due to the execution of the jet grout nails. The settlement on 25/02/2012 is caused by lifting the tracks, due to which the inclinometer was locally displaced.

Figure 8 shows the settlement measured by the horizontal inclinometer and the SAAF on two different dates. The zero settlement point corresponds with the fixed point on the Berliner wall. A significant difference between the settlements measured with the two techniques can be observed (approx. 30%). When comparing with the topographical levelling, it can be concluded that the measurements made with the horizontal SAAF are closest to the real settlements. This can be explained by the limited length of the inclinometer tubes (8m) and the fact that the stiffness of a traditional inclinometer tube is quite high for such a short distance (and large settlements).

The “bump” in the measurements of the SAAF (circled in Figure 8) is caused by the lifting of the tracks on 25/02/2012, as explained above. This “bump” has no influence on the settlement which is measured at the end of the railway tracks.

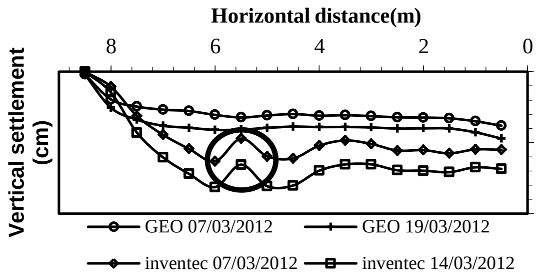

Figure 8. Settlements measured with hor. SAAF and hor. inclinometer.

The measurements made with the electrical beam sensors give comparable results to the measurement of the SAAF. The data measured with the optical strands appears to be uninterpretable. This is probably because it was in no way connected to a fixed point.

3 CONCLUSION

An extensive monitoring program was set up to compare different monitoring techniques. It appears that both new and traditional techniques can lead to the same result, when sufficient care is taken to the installation and interpretation. A significant advantage can be seen when continuous monitoring is applied, as the link with execution phases can be made.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

Van Alboom G., De Vos L., Haelterman K. and Maekelberg W. 2012. Innovative monitoring tools for on line monitoring of building excavations. A monitoring test site. *ISSMGE- TC 211 International Symposium on Ground Improvement,* Brussels, IV-327 – IV-338.

Verstraelen J., Maekelberg W., De Vos L. 2013. Design and performance of a jet grout retaining wall in a railway embankment on soft soil. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris