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Real-Time Insight in Geotechnical Risks; Monitoring During the Observational Method

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Abstract. Designing challenges engineers to develop both economically attractive and safe designs. This might seem a paradox, but with the application of the observational method, wherein safety is checked by real-time monitoring, economic design and safety are united. The observational method is recently successfully applied in the Netherlands during the excavation works of the double layered tunnel across densely populated central Maastricht. The uncertainties in the limestone conditions and possible karst holes, combined with a length 2.5 km of tunnel, made the observational method very applicable. This paper outlines the application of state of the art real-time monitoring techniques as vital part of the observational methods' success. The individual components of the monitoring network will be discussed with an emphasis on reliability and availability of data. Actual data is presented and attention is paid to the essential relation of the monitoring team with the geotechnical engineers and excavation crew.

Keywords. Observational Method, monitoring, limestone, measuring passive resistance, strut forces, strain measurements, water pressure measurements, dewatering, economically attractive design.

1. Introduction

The design of a 2.5 km long double layered highway tunnel across the urban area of Maastricht, south-eastern Netherlands, faced engineers with uncertain ground conditions. Peat, clay and sand are common Dutch soils, however, the tunnel trajectory consists of limestone and gravel. Despite extensive research into soil conditions, uncertainties remained concerning the conditions of the limestone (i.e. cohesion, permeability) and possible karst holes. These uncertainties called for careful consideration.

To avoid a conservative design, *Avenue2* decided to adopt the Observational Method [OM] to obtain a less conservative design which would be nonetheless safe. Using this approach, safety factors are reduced by adding real-time monitoring. For more details of the geotechnical considerations, reference is made to the paper "Observational Method, Case A2 Maastricht", Dalen (2015), to be found elsewhere in the conference proceedings.

2. Monitoring Focus

This paper discusses the system that is designed to monitor the major risks of the design:

1. Lower cohesion of the limestone than anticipated;
2. Aquiferous karst holes or otherwise higher water flow rates, endangering the stability of the building pit.

The building pit consists of sheet piles placed in a cement-bentonite suspension, excavated stepwise and reinforced with girders and several strut levels, visualised in Figure 1.

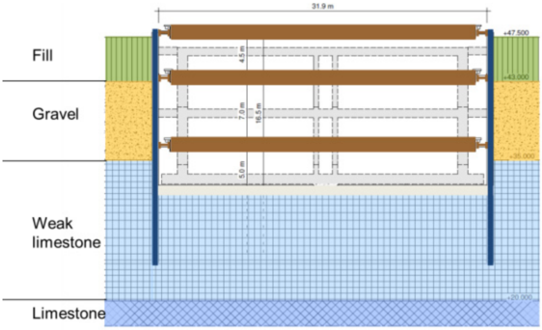

Figure 1. Cross section of the building pit with struts and girders. The final construction is represented by dashed lines.

The vital role of the limestone (in the absence of underwater concrete) is to form the lower 'strut', hence, the sheet piles need to mobilise sufficient passive resistance.

2.1. Monitoring components

Since passive resistance is not a directly measurable quantity, indirect quantities have to be monitored to disclose the level of safety:

1. Strut forces as a measure for the load transfer from the limestone towards the struts;
2. Water pressure as a measure for the effectiveness of water extraction and as an indicator for overpressure / effective grain stress;
3. Inclination of the sheet piles: movement of the sheet piles' toe indicates low passive resistance;
4. Settlement of adjacent buildings.

The next chapters will discuss the individual monitoring components.

3. Strut Forces

To monitor strut forces, several techniques are available i.e. flat jack, hydraulic jack, pressure cells, strain gauges, fibre optics and etcetera. The techniques fall into two categories: incorporated within the strut head or applied on the strut. Diligence and effort is required when installing hardware into the strut. In particular the strut design may require changes if hardware was not taken into account in the original design.

Besides lower costs, major benefit of non-strut head applications is the independence from the logistic process. The hardware can be pre-installed on the strut or can be installed in the building pit after strut placement. Flexibility, experience and relatively low costs led to the final decision for strain gages.

3.1. Testing of strain based force system

The performance of the whole system was tested during the excavation of the southern trajectory with stronger soil conditions. The OM was only applicable on the weaker northern part of the tunnels trajectory, Dalen (2015).

The test strut was adapted to fit four very stiff hydraulic jacks equipped with calibrated pressure sensors. The excavation was simulated by increasing the oil pressure. Knowing the exact surface area of the jacks, the force could be calculated and should comply with the average force calculated from the recorded strains.

Figure 2 shows almost identical results for both strain and pressure based force calculations at both 1000 kN and 3000 kN.

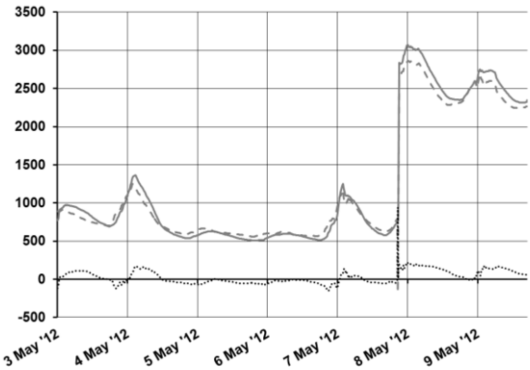

Figure 2. Jack force, strain based force (dashed) and force difference (dotted) [kN]

Expected intervention loads during the OM could double, up to 6000kN. The ultimate load during the jack test was lower so as to not introduce too much displacement in the building pit. The presented comparison gave enough confidence to apply the system based on strain gages (minor differences could mainly be explained by different time dependent temperature effects).

3.2. System lay-out

The strain gauge system per strut consists of four full bridge strain gauges (Figure 3) over the cross section with a data logger per strut, incorporating stabilised power supply for accurate measurements. Although it was argued that two sensors could give sufficient information, it was decided to install four sensors to provide both redundancy and information about asymmetric load introductions.

The strain recordings were zeroed after placement of the struts to exclude any bending strains due to the struts dead weight.

Figure 3. One out of four covered strain gages on a strut during critical excavation

3.3. The first section

In the OM trajectory, almost 170 struts were placed on the lowest level. To avoid measuring all the struts, six subsequent struts, i.e. all the struts between one girder length, were instrumented to see if measuring only two struts would give a representative image. Figure 4 depicts one month of force measurements.

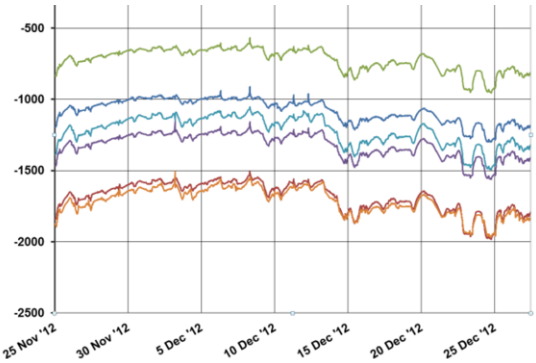

Figure 4. One month registration of six strut forces in section 86, excavated situation [kN]

It could be concluded that a fairly large spread in the force results is apparent, although there is a clear average. The differences could be explained by the number of fill plates that were used between strut and girder: the more plates, the more residual space that could not be grouted. As a consequence, struts with more residual space react less stiff and attract less force. It was concluded that the number of filling plates had to be kept to a minimum by accurately measuring the spacing before assembling the strut. No other dependencies were discovered, making it acceptable to measure only two struts per section (6 struts).

3.4. Weekly routine

Gauges were fitted to a total of 52 struts, covering a length of roughly 700 meters of tunnel (224 sensors). Every week, a new section with six struts was produced, including two pre-equipped sensor struts.

A typical registration is depicted in Figure 5, were the compression force increases during the step by step excavation.

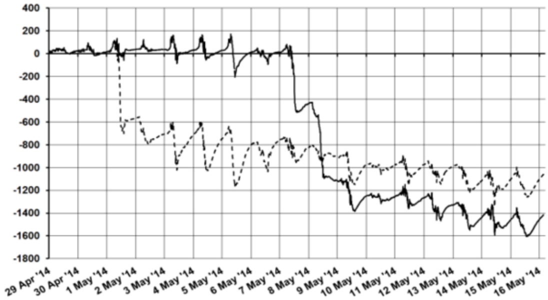

Figure 5. Force registration of strut number 64-35 and 64-32 [kN]. Limestone underneath strut 64-35 (dashed) was excavated a week before strut 64-32.

Each strut consists of two load introduction plates per side. From figure 6, it becomes clear that the plates are equally loaded, although the lower part of the strut carries more load than the upper part.

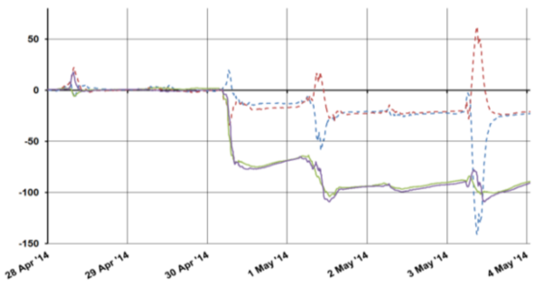

Figure 6. Strain registration under excavation of strut number 65-35 [µm/m]. 2 upper sensors [dashed] and 2 lower sensors.

Apparently, the load is not being redistributed over the cross-section. To check the distribution over the length, some struts were equipped with sensors at both strut heads and midspan. The comparison of sensors at three different cross sections revealed that there is no redistribution or second order effect, proving the sensor location near the strut head is a representative location for measurements.

To give an impression of the overall strut forces recorded during the observation period, the force per section is plotted in figure 7 as percentage of the predicted force.

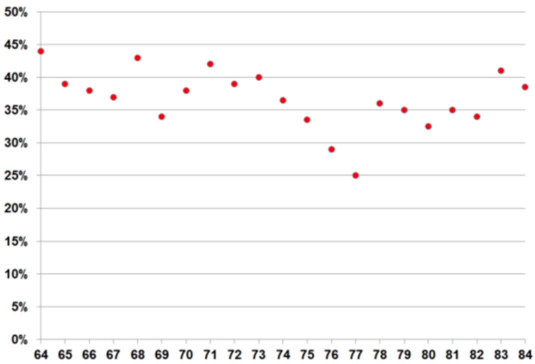

Figure 7. Strut forces per section number as a percentage of the predicted load.

3.5. Data acquisition of strut forces

After correctness of data, data availability had the highest priority. The data acquisition system was split up in completely independent sections of six struts, each with individual power supply and wireless data transmission to avoid short circuits in the whole system. By alarming on data gaps per section, defects could be directly traced to a relatively small section. This, and the availability of spare parts meant that down time was minimised to less than 1%.

Although data cables were protected by steel tubing, neighbouring welding activities damaged data lifelines twice, triggering data gap alarms and activating the monitoring intervention team. The overall sensor failure was six out of 224 sensors, were two sensors suffered from water intrusion after damaging of the cable (welding activities) and four sensors malfunctioned after installation. The sensors were not replaced since the system was designed with redundancy.

To secure the data, local storage was combined with hourly backups on the head offices' central data server, running in raid modus. A real time strut force data viewer was available online and alarms were active on all critical struts. All the data was automatically processed in daily reports to get an immediate overview of the current conditions.

From figure 7 it becomes clear that the measured strut forces were lower than anticipated. Fears existed that uneven stiffness distribution would cause the second strut layer to be excessively loaded. This was checked by measuring a strut in the second strut layer. The results showed that the forces were again more than 50% lower than predicted.

4. Water Pressure

To monitor water pressure in the limestone, four monitoring wells were placed per 24 m^1 building pit. Each well was equipped with a sensor and autonomous data logger, taking readings every minute and sending information using a mobile network, every 15 minutes. The alarm checks were incorporated in the logger, providing a 'real-time' alarm trigger. During the peak of the OM, 120 sensors were active within the whole building pit. The environment was covered with another 80 sensors.

The water pressure, measured at several depths, provided information about the height profile of the pore pressure, indirectly providing information of effective stress, as indicator for the building pits' stability.

Moreover, the information was used for monitoring the effectivity of the dewatering system; a malfunctioning deep well could easily be detected and the overall performance could be checked by comparing actual water pressure and desired water pressure.

Traditional monitoring wells are very vulnerable during excavation: chops of soil around the well easily crumble off, damaging the wells beyond repair. During the OM, unavailability of wells was unacceptable since safety could then no longer be addressed. To avoid damage, the wells were pre-installed during the digging process of the cement-bentonite [CB] walls. Large steel casings were welded onto the sheet piles and at the desired monitoring depth, the casings were curved, pointing towards the building pit. The obtained casing was sealed watertight, preventing CB from flooding the casing. Once the CB was hardened, the wells could be connected with the limestone, using a high water pressure nozzle.

4.1. Periscope

The performance of the obtained alternative monitoring well, called the periscope, was checked by placing a traditional well close to the periscope just before starting the water extraction. The periscope gave a nearly identical response to the water extraction when compared to the traditional well, proving its performance and reducing the risk of unavailability.

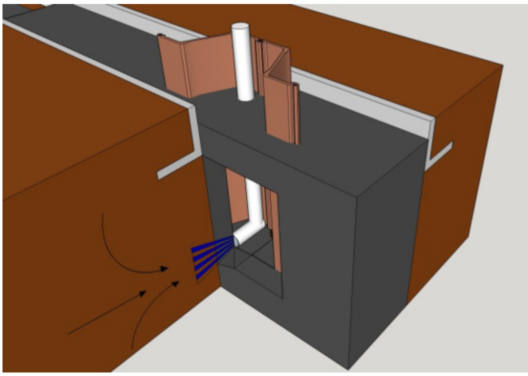

Figure 8. Periscope principle in a CB-wall with sheet-pile.

From 80 periscopes, two became unusable due to obstructions with gravel due to lost protection caps. Some periscopes were leaking, causing the periscope to flood with CB, these periscopes could be cleaned with the water pressure nozzle, flushing all the CB upwards. A more serious threat is flushing too little limestone away, leaving a small periscope opening that can easily get clogged with fine limestone particles. This issue can be detected by observing an unrealistically stable water level.

Because of the low vertical permeability of the limestone, water extraction went slower, resulting in higher water pressure than anticipated. Although there was little to no overpressure, the recorded levels were above the signalling values, almost following a hydrostatic evolution. Since the strut forces were relatively low, the passive resistance was still sufficient, resulting in a safe but unpractically wet building pit.

5. Inclination

Besides water pressure and strut forces, the inclination of the sheet pile toe was monitored to check for horizontal shift. Shift of the toe would imply low passive resistance and could therefore be an indication of instability of the building pit. The traditional inclinometer system based on hand readings (not real time; it's a secondary check) was used in combination with a specifically designed software tool to be able to define a strut layer as a fixed point. In regular building pits, the fixed point is the sheet pile toe since there is no discussion about passive resistance.

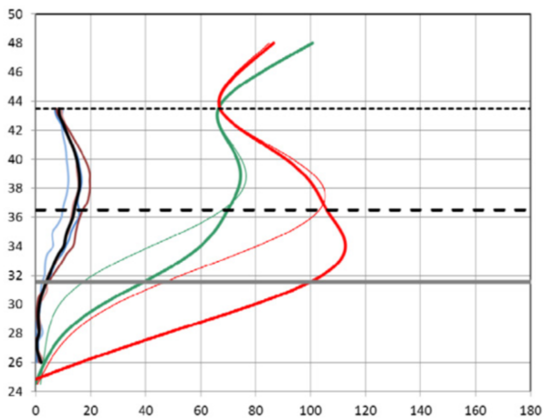

Figure 9. Measured deflections over the depth in section 66 (left) and signaling- and intervention levels (right).

6. Settlement of Adjacent Buildings

Automated survey equipment hourly checked 50+ critical objects throughout the project.

7. OM Management

Acquiring data is only one vital link in the OM chain. The OM can only be successful if a dedicated team works together in tight collaboration. In the next paragraphs, the key roles in the observational methods' team will be discussed. Each key role comes with a cell phone, managed by the person on active duty, contactable 24/7. With this approach, no uncertainties remain about who is on duty or which number to dial.

7.1. Geotechnical (site) engineers

After translating the design philosophy into a monitoring strategy, site engineers need to evaluate the data on a daily basis, combined with daily inspections in the building pit. After these checks, further excavation can take place.

7.2. Monitoring team

Monitoring should be considered from the very start of the design phase, allowing implementation of innovative solutions. Together with geotechnical engineers, the feasibility of the chosen monitoring strategy needs to be discussed. The monitoring team is responsible for the correct application of all tubing and sensors. For the A2 tunnel project, a stunning 10 km of monitoring tubes were installed. The quality control during this phase is essential to ensuring the timely replacement of faulty tubes or sensors.

During the OM a 24/7 alarm check on all critical values was active, including a permanent check of new data file production. Managing 500+ sensors in real time is only achievable if the systems generate reports automatically. The monitoring team keeps all the sensors online and follows up every alarm by checking the correctness of data and if necessary, call the OM team manager.

7.3. OM team manager

The responsibility of the OM team manager is to translate the input of team members into concrete decisions, while maintaining an overview of the situation. Having only one person in charge, simplifies fast decision making when necessary. The manager can consult team members 24/7 for support, including the external dewatering team. The follow up of unpredicted events is coordinated by the team manager, unless no time is available for deliberation. Predefined mitigation measures (Dalen (2015)) can be initiated by the OM manager. The OM manager is also in charge of the external communication.

7.4. Excavation crew and site manager

After the inspection of the geotechnical engineers, the site manager is authorised to release the pit and give instructions to the excavation crew. The excavation crew is the first pair of eyes in the pit. They can spot irregularities that would indicate the presence of karst holes. This is an essential role that requires clear instructions and communication lines.

8. Conclusions

The application of the OM in Maastricht showed once again that information about actual geotechnical parameters gives insight in the level of safety. An already optimised design proved to have enough capacity for further optimisations. A modular building pit design facilitates real-time construction optimisation, depending on measured quantities.

Strain based force measurements on pre-equipped struts proved to be a reliable technique. Independent circuits drastically improved detectability of errors, increasing availability.

The periscopes are a robust alternative monitoring well, when sufficiently jetted. The periscopes were extremely useful in detecting defects in the dewatering system.

The data flow can only be managed with automated systems, there is no time for manual data processing in real-time systems.

Of utmost importance is the interaction between disciplines and the way communication is organised. There is no time for confusion when intervention is necessary and acuity of all disciplines is a requisite throughout the project. The latter may become a pitfall after a few repetitions.

References

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