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11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

Wireless Monitoring Solutions as an early warning tool to manage growing risk of Alpine slope stability failures: a case study from a hotel construction project in Salzburg, Austria

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Abstract

Risk, by definition, is the probability of the occurrence of an event that is not supposed to happen. This principle gives the impression that corresponding events always occur unexpectedly, i.e. without any recognisable signs. With careful observation of relevant parameters, however, many events announce themselves as a trend more or less in the long term and can, if necessary, be averted by suitable and, above all, timely countermeasures.

The International Tunnel Association ITA declares deformation monitoring as an "integral part of risk management" (WG2-Research, 2011).

The global temperature rise is changing the face of the Earth at rates without precedent in human history. The consequences of climate change are particularly evident in alpine regions around the globe and have an impact on land use designation and construction projects.

Sophisticated geotechnical design and monitoring systems are required to guarantee safety of structures and the environment.

Traditional monitoring techniques like manual levelling and inclinometer measurements are used and combined with data from INSAR and automatic monitoring systems to understand the ground conditions and possible impact of constriction activities. A new way to establish early warning systems is the use of wireless technology.

These so called “intelligent monitoring systems”, like Senceive’s InfraGuard™ solution, are based on the use of wireless “MEMS” tilt sensors installed on stakes driven into the ground allow the detection of relative movement of a slope. The sensors take readings in a defined interval and are triggered by a sudden event and take additional readings, trigger adjacent sensors and increase the monitoring frequency. The system can also be combined with a camera which is also triggered by this event and allows visual inspection remotely. The case study shows the use of such a system and compares the results with data from other monitoring techniques which are used in parallel for verification.

Keywords: Slope Stability, Risk Management, Remote Condition Monitoring

1. Introduction

The construction site is located in the cadastral commune of 57317 Viehhofen in Salzburg, Austria. An overview of the geographical location is given in Figure 1. The project site is located at an altitude of approx. 900 m.a.s.l. On the parcels with the property numbers 621/25 and 621/31 of KG 57317 Viehhofen, a building complex consisting of four buildings (house A, B, C, D) is erected. In 2018, the structural engineers of MJP-ZT carried out the design as well as the calculation of the design and calculation of the excavation support for the construction of House A and B.

For the execution phase, the structural engineers of MJP-ZT carried out the structural analysis of the excavation support. This was essentially based on the results of the investigations carried out during the tendering phase, adapted to the final design. The construction is carried out in two phases. Phase one is the construction of buildings A & B (Fig. 2), currently under construction and phase two will be the construction of buildings C & D.

Figure 1: Project Location

Based on existing documents and the available historical documentation of this construction project, a low-deformation excavation support was designed. The following work procedure has been selected:

- The excavation work within construction sections 1 and 2 is adapted to the results from the monitoring carried out. The excavation pits are only excavated over half their length. Only after backfilling of the first, the second section is excavated.
- The detailed planning for construction phase 2 (houses C & D) will take place after the implementation of construction phase 1.

Figure 2: Construction site in September 2021

For the implementation of the planned construction activities, the construction of excavation pits with a maximum depth of approx. 12 m is required. The subsoil conditions - soil layers and slope water - at the project site are complex due to their genesis. The calculation and dimensioning of the excavation support, which represents a permanent support measure, was carried out on the basis of extensive investigations and cautious parameters derived from them. Due to the complexity of the ground conditions, the construction project is carried out according to the design and supported data collected using the observation method of EC 7. This consists of the following measures:

- Building condition survey
- Optical 3D displacement monitoring and levelling of structures and the slope (automatic and manual)
- Inclinometer measurements (manual)
- Installation and monitoring of load cells on excavation support (manual)
- Groundwater monitoring of wells (manual)

2. Ground investigation and design

2.1 Ground conditions

The genesis of the subsurface conditions is extremely complex and allows only a rough delimitation into geological layers. These are briefly described again below with photos from the drill cores.

Figure 3: GA1 - Weathered material / slope rearrangement (KB 1/11, 0-3m); GA2 - Greywacke schist, predominantly deconsolidated (loose rock character) (KB 1/11, 8-11 m);

Figure 4: GA3 - Kakirite (KB 1/11, 18-24 m); GA4 - Greywacke schist, predominantly stratified, clearly deconsolidated (KB 2/11, 17-21m)

Figure 5: GA5 - Greywacke shale, in stratigraphy, dissected, weathered (KB 1/11, 29-. 30,8m);

Figure 6: GA6 – Greywacke schist, stratified, un-weathered

2.2 Geotechnical Model

Based on the available documentation, the geological model, laboratory results, historical inclinometer measurements and ground water monitoring, a geotechnical model was developed, which allows to calculate the excavation and construction support.

The rock types GA1 (weathered material / slope overburden) and GA2 (greywacke shale, predominantly deconsolidated, loose rock character) together show a layer thickness of 15-28 m. Due to the strongly heterogeneous structure of the two layers and the comparable mechanical properties from a geotechnical point of view, a layer boundary of approx. 8.0 m below ground level was drawn and used in the calculation model.

The layer boundary was based on the slope water courses described in the geological model and the measured water levels in the open stand pipes (7 - 8 m below ground level). In order to be able to take the diffuse slope water courses into account mathematically, the shear parameters were reduced in the soil layer from 8 m below ground level ("slope overburden heavily wetted"). The evaluation of calculated deformations was carried out based on this system.

In the model, "worst case considerations" were made to ensure sufficient system load-bearing capacity of the designed support. A complete saturation of the saturated slope bedding was assumed and the reinforcement and the supporting means were designed according to this .assumption

For the execution, some adjustments were necessary. The most important factor here was the required excavation depth, which was increased by around 60 cm from approx. 889.22 m.a.s.l. to 888.63 m.a.s.l.. In the middle section (staircase) directly adjacent to the house A+B, the bored pile heads can pass through at the same level.

The calculation of the bored piles was adjusted to reflect these changes. For the design of the bored piles, significantly higher cutting forces occur, in particular due to the changed excavation pit height and under unfavourable subsoil conditions. Therefore, the following load cases are considered for the execution:

- LC1 Dry substrate – design with φ=28° and crack width
- LC2 Water saturated – design with φ=30° and crack width

If the subsoil conditions were less favourable during implementation (high proportion of fines and high water saturation as well as deformations in the order of magnitude of the LC 2 model), the loads would have been transferred to the footing area and an additional anchor beam including a pre-stressed anchor would have been installed. Any required design adjustments were made following the construction activities.

2.3 Result – Load Cases

In accordance with the calculations, the deformations were mapped over the building conditions for the two investigated load cases. In addition to the points at the excavation support and at the Holzer building, the following analysis is extended by some points in the slope between house A/B and the Holzer building (Fig. 7).

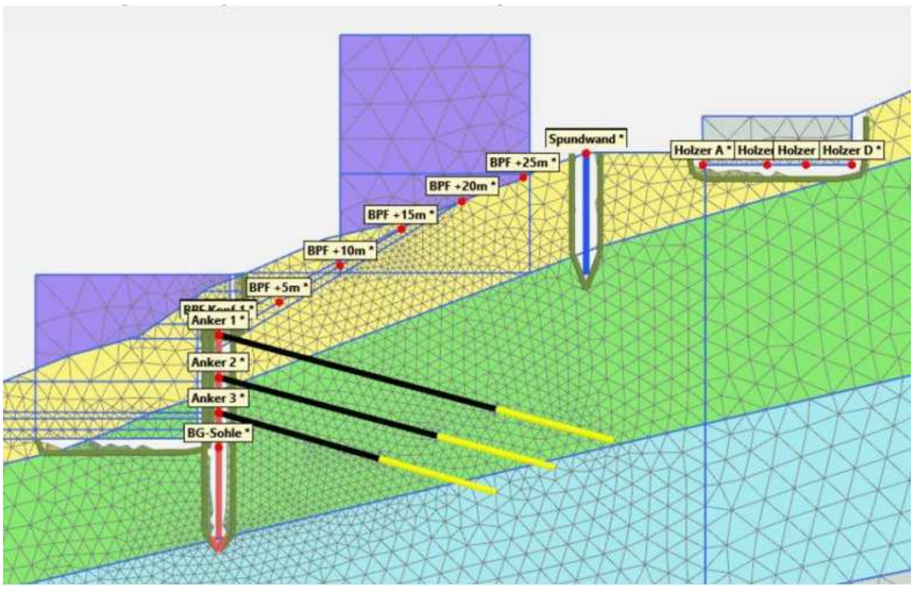

Figure 7: Section deformation mapping construction area

The two load cases (LC1 and LC2) differ mainly in the displacements ux during the advance excavation phase (Fig. 8). Therefore it was necessary to install additional monitoring targets on the Holzer building and on the sheet pile wall before the advance excavation started.

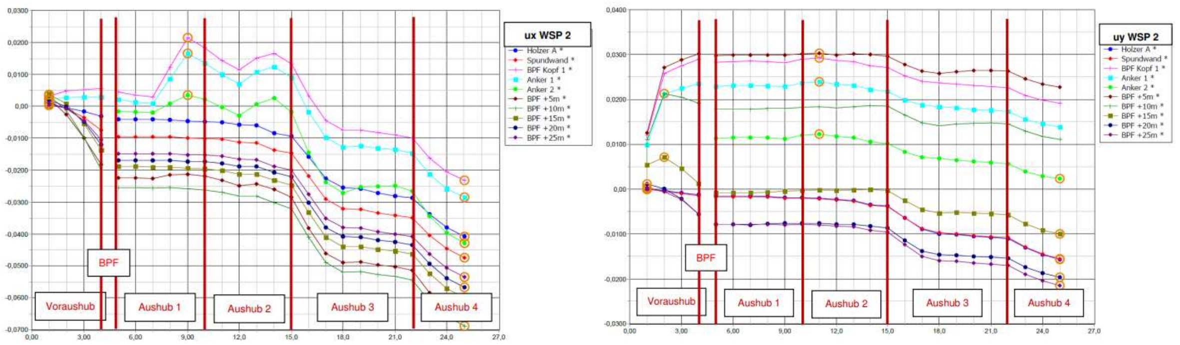

Figure 8: LC 2 displacement model

The calculated deformations for the BPF phase (installation of the bored piles) result from the necessary inferfacing of the piles. In principle, small deformations are to be expected in this phase, but these are mainly based on the influences from the construction operations or from the pile construction process, which cannot be predetermined mathematically.

The main differences in the two calculation models (LC 1 and LC 2) can be seen in the horizontal displacement in the various calculation phases. This differentiation is supposed to be already apparent in the phase of the 2nd excavation. The difference in the displacement of the bored pile head between the two models is approx. 3mm. A differentiation between the two models can also be made via the uphill extensions of the displacements. Therefore, it was necessary to establish surface measurement points on the slope. The calculated displacements of the points BPF +15m / BPF +20m / BPF +25m differ only slightly. Therefore, the points BPF +5m / BPF +10m and BPF +20m as well as the sheet pile wall, Haus Holzer, the pile head and the three anchor beams were used for monitoring. For the point BPF +5m, the influences from construction operations must be taken into account in the assessment.

3. Monitoring system

3.1 Overview

A total of five profiles were defined for the excavation support. Five geodetic measuring prism were required at each anchor beam and at the bored pile head. In addition, three sections of three surface measuring points (bored pile +5m / +10m / +20m) as well as three measuring points on the sheet pile wall and the inclinometer heads were installed. 2 geodetic measuring points were installed on the lateral shotcrete walls. The surface measuring points consist of e.g. driven-in steel stakes, the driving depth was at least 1.0m, in case of soft ground conditions at least 1.5m.

The monitoring prisms were mounted to these stakes. The distance above ground level was max. 0.5m. The surface measuring points in the slope were installed and baselined before the excavation of the first anchor beam started.

Geodetic monitoring at the excavation pit and at the buildings located to the side of the project site (GN 621/24, 621/22, 627/1, 627/2) was done in real time using a robotic total station based system (TOPCON Delta, Topcon MS05AXII). The monitoring frequency was set at two hours with two sets of readings in two phases.

The buildings 621/7, 621/4, 640/8 and 627/1, the sheet pile wall and shaft will be geodetically surveyed in their position before the start of construction. In addition, a levelling of the above-mentioned properties, the sheet pile wall and the shafts was necessary for the ongoing monitoring of the buildings. For this, at least 3 points were necessary on each building, at least 4 points on the Holzer house (Fig. 9). The interval for levelling depended on the progress of construction; during the excavation phase weekly checks were necessary. A geodetic control measurement of the buildings was carried out depending on the measurement data from the robotic total station.

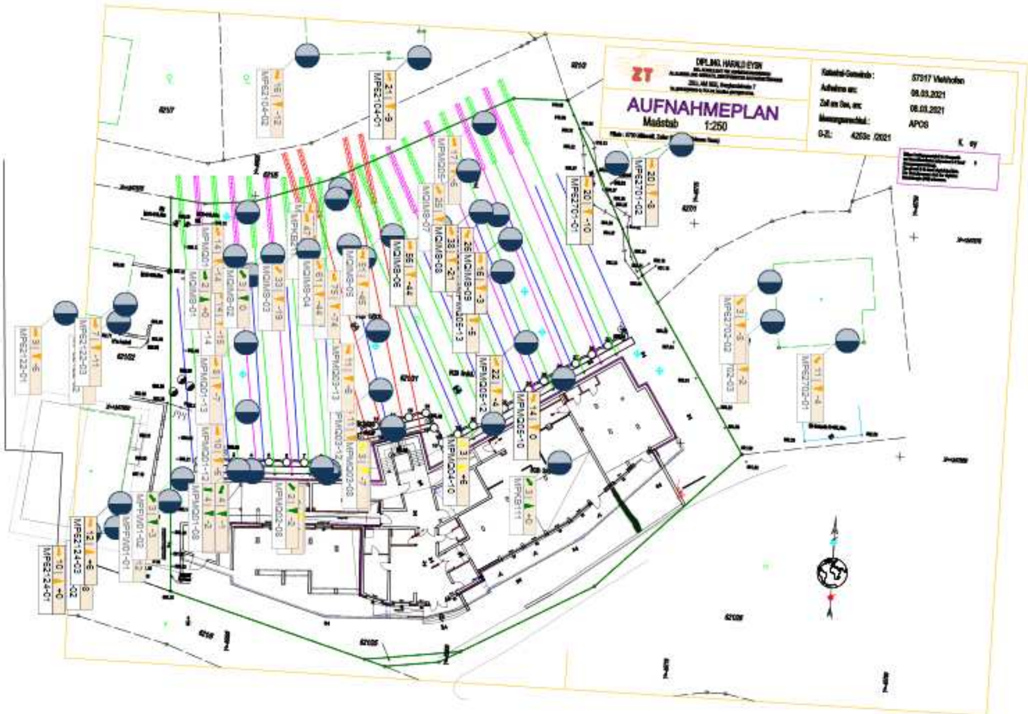

Figure 9: Plan view monitoring points on site

The robotic total station and monitoring prisms were installed in April 2021 and the system has been taking automatic readings since then.

Two inclinometers KB 1/11 and KB 2/11 with historical data were available at the construction site. In addition, inclinometers were installed in three bored piles. The inclinometers were measured manually in a frequency defined by the construction progress.

Weekly ground water monitoring was carried out at an open standpipe on site (Fig. 10).

Figure 10: Monitoring installations on site

In September 2021, a measurement system based on triaxial tilt sensors – Senceive InfraGuard™ - was installed, in addition to the geodetic measurement system. The triaxial tilt sensors were installed on structures, on the anchor beam and on stakes. Additional measuring points were installed on the stakes and included in the geodetic measuring program. The purpose of this system was to provide reliable information on slope movement and allow the direct comparison of the results from geodetic monitoring and results derived based on the data from the tilt sensors installed on stakes (Fig. 11).

The advantage of this additional system was that it provide reliable data every 1 min and it was not impacted by the site traffic, as the site traffic and construction progress started to block the line of sight from the robotic total station to the monitoring prisms.

Figure 11: InfaGuard™ installations on site

3.2 InfraGuard^{TM} – intelligent monitoring system

The installed measuring system is an intelligent measuring system from the manufacturer Senceive. The measuring system consists of wireless triaxial tilt sensors that are connected to a gateway via FlatMesh^{TM} (2.4 GHz) communication, from where the data is sent to a central server for further evaluation and visualisation.

In addition, a 4G camera was installed that takes a picture of the construction site every 6 hours and will also be triggered to take a photo if spontaneous movement occurs.

These systems have been widely used since 2019 to monitor earthworks next to railroad tracks to detect possible slippage onto the tracks and to be able to stop a train before a rail vehicle derailment occurs (Fig. 12). A variety of sensors can be integrated into this system.

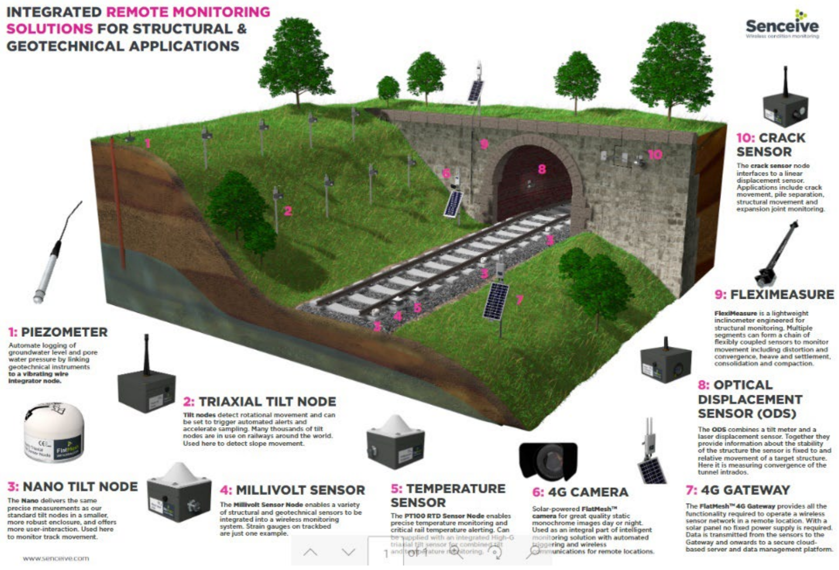

Figure 12: Example intelligent monitoring system in a rail / embankment environment

This system can also be used for monitoring areas of possible slope failure, where early detection is required and visual inspection and rapid assessment of the potential risk is needed. Possible applications also arise in alpine areas after heavy rain events or in construction projects where there is a risk of slope movement.

This installation represents such an application (Fig. 13). The direct comparison between geodetic measurements and the measurements of the triaxial tilt sensors is interesting. The advantages of the tilt sensors compared to the geodetic measurements are a higher measuring frequency, the possibility of integrating the camera for visual inspection, and the fact that the measurements are not disturbed by construction activity. With the geodetic measuring system, a line of sight between the theodolite and the measuring point is necessary.

Fig. 13: Installation of camera at site (picture taken by 4G camera day and night).

These measuring systems and their components are generally supplied pre-configured. Even if only one sensor type was planned in the original project, the system can later be extended to include any number of sensors and sensor types. For example, a FlatMesh™ gateway can manage up to 100 nodes. Within a project, the number of nodes and gateways is practically unlimited.

A key feature of the system is its extremely simple and therefore fast installation and self-sufficient operation. In general, the nodes are simply glued to the sleepers. Further configuration can then be carried out via remote access.

Automated monitoring in general and these systems in particular are especially economical where access to the monitoring zone is difficult, restricted or dangerous, where either the required sampling rate is too high from a technical and economic point of view, or very long observation periods make fixed installations seem efficient.

It is obvious that absolute values of landslide are not obtained by inclination sensors. However, Uchimura [2015] has shown that the occurrence of future landslides can be inferred based on the entry velocities of movements.

However, the direct comparison between these systems and geodetic systems already allows conclusions about the amount of movement.

3.3 Information on the interpretation of measurement results

The illustration in Fig. 14 shows the displacement directions defined in the project. The longitudinal direction of the geodetic measurement system corresponds to the x-axis of the tilt sensors and the lateral direction corresponds to the y-axis of the tilt sensors.

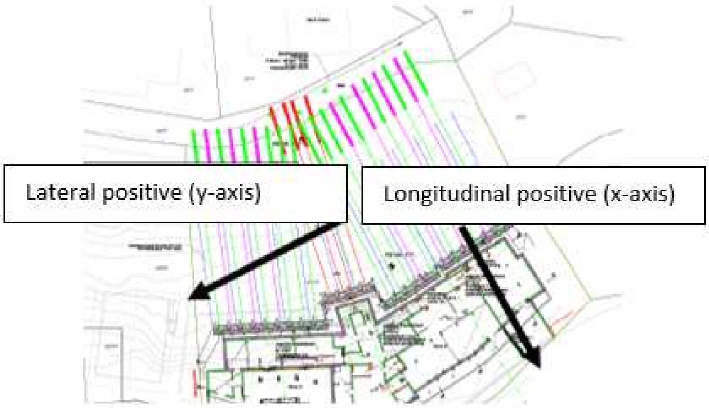

Fig. 14: Displacement directions in the project (longitudinal direction corresponds to X-axis inclination)

The tilt sensors mounted on the earth stakes measure the tilt in degrees, by assuming that the earth stake protrudes 1 m from the ground, the displacement can be converted into mm and a comparison can be made with the result from the geodetic measurement (Fig. 15).

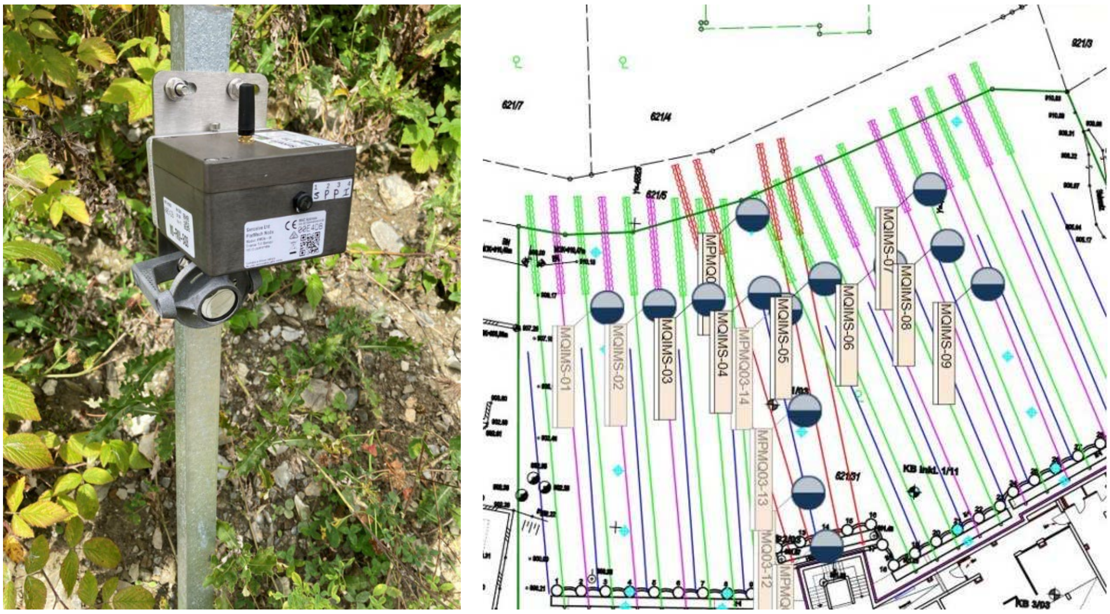

Fig. 15: Example installation tilt sensor and monitoring prism on stake; position of measuring points on stakes

The location of the installed tilt sensors is shown in Fig. 13. Each stake was equipped with one sensor and one point of measurement. Nine sensors were installed in the area of the slope above the bored piles.

3.4 Interpretation of results

The comparison of the geodetic measurement data with the data of the inclination sensors shows that longitudinal displacement and settlement occurred in the central area of the slope from November 3, along measurement/cross-section 3.

This is shown by the data of the measurements of the prisms at the stakes, the measurable prisms at the original points at cross section 3, as well as the values of the tilt sensors. Figure 16 shows that the geodetic measurements at the stakes with tilt sensors show an increase in longitudinal displacement and settlement starting on November 3.

The first event on November 3 shows a longitudinal displacement of up to 20 mm and a settlement component of 15 - 17 mm. The second event on November 5 shows an increase in longitudinal displacement of another 20 mm and an increase in the subsidence component of another 15 - 17 mm.

The most extreme values are shown by the measuring points MQIMS-04 and MQIMS-05, while a lower value is shown by the measuring points MQIMS-03 and MQIMS-06.

Figure 17 shows that the geodetic measurements of the measurement points of measurement cross section 3 also show an increase in longitudinal displacement and settlement from November 3.

The first event on November 3 shows a longitudinal displacement of up to 15 mm and settlement of 10 - 12 mm. The most extreme values are shown by measurement point MPMQ03-14, which is just above measurement points MQIMS-04 and MQIMS-05. Measurement point MPMQ03-15, located at the sheet pile wall, shows only a slight increase in longitudinal displacement of 5 to 7 mm.

The second event on November 5 shows an increase in longitudinal displacement of another 25 mm and an increase in the settlement component of another 20 mm. The most extreme values continue to show measuring points MPMQ03-14. The measuring point MPMQ03-15 shows only an increase in longitudinal displacement of 5 to 7 mm.

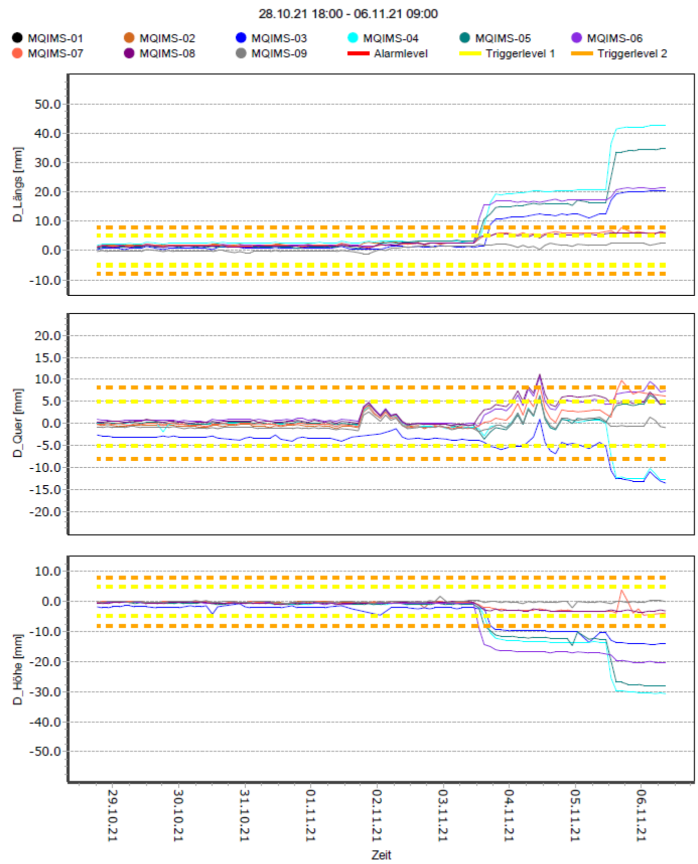

Fig. 16: Geodetic measurement of the prisms on the stake mounts with tilt sensors

Comparing these results with the data from the tilt sensors (Fig. 18), the following picture emerges.

The tilt sensors on the stakes show an increase in inclination in the x-direction, which can be correlated in time with the measurements of the geodetic measuring system. Thereby, the inclination sensors E4DF, E4F0 and E500 show the most extreme values, which corresponds to the geodetic measurement points MQIMS04, MQIMS-05 and MQIMS-03.

The longitudinal displacement calculated from the inclination values shows a lower value than the results of the geodetic measurement, because the base for the calculation was assumed to be 1 m, which, however, is only an approximate value and was not determined for the individual points on the site.

The calculated values of longitudinal displacement give a maximum value of 5 mm for the first event on November 3, and a maximum increase of 6 - 7 mm for the event on November 5, i.e. an absolute value of longitudinal displacement of 12 mm.

This shows that the system detects the events, however the calculated value of the displacement is lower, which can be improved by refining the calculation and adjusting the real length of the beam.

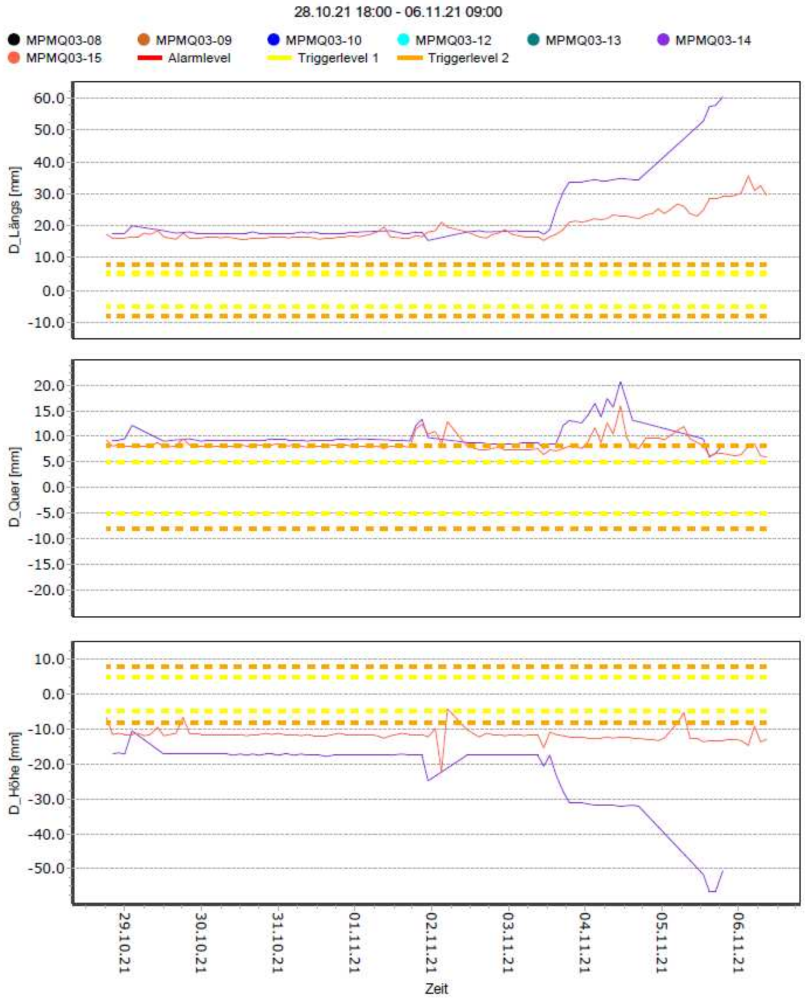

Fig. 17: Geodetic measurement of the measurable prisms of cross section 3

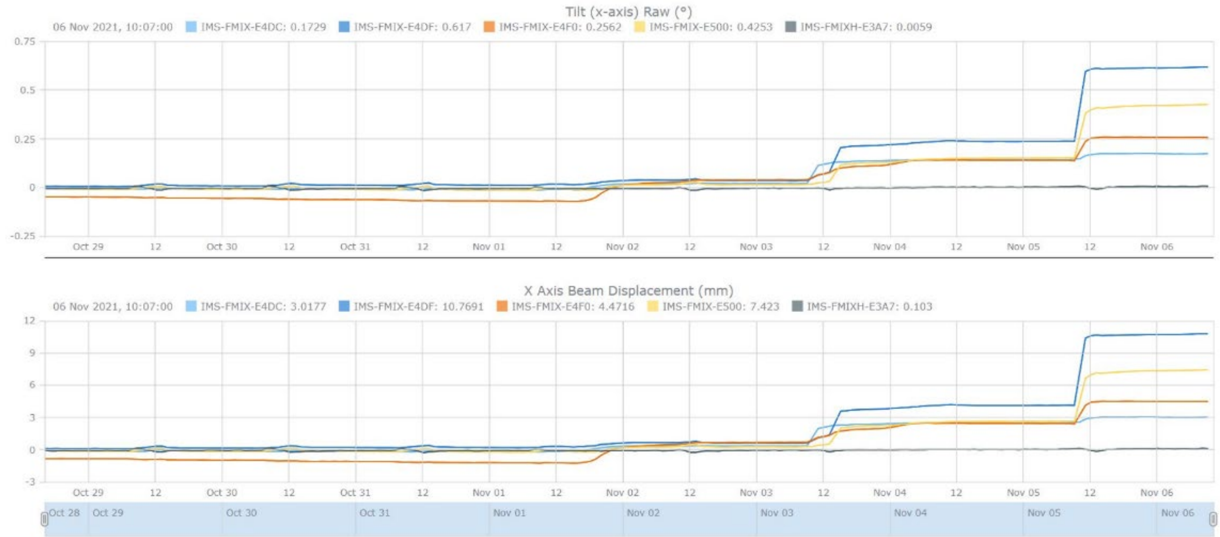

Fig. 18: Result of the tilt sensors and derived displacement in the longitudinal direction (x-axis sensor)

4. Conclusions

The advantage of the tilt measurement system is that it can detect the displacement events and trigger the camera regardless of weather or construction activity, which allows for immediate remote visual confirmation. The measurement reporting rate can be automatically increased to 1 Hz by a displacement event, which is not possible with a geodetic measuring system.

The system can be used to monitoring construction areas and remote locations 24/7 and allows visual inspection of the site any time, also when no personnel is on site – also during the night. In addition, this system provides reliable data because, unlike geodetic measurement systems, there are no limitations due to extreme weather conditions or construction activity.

During the presented construction project the system allowed to continue with the works also when there was no data from the geodetic monitoring system available. It detected movement when excavation works and micro piling works at excavation level 3 were not carried out according to design. This caused longitudinal movement of the slope in the central section staring on the 3rd of November, continuing on the 5th and 10th of November (Fig. 19).

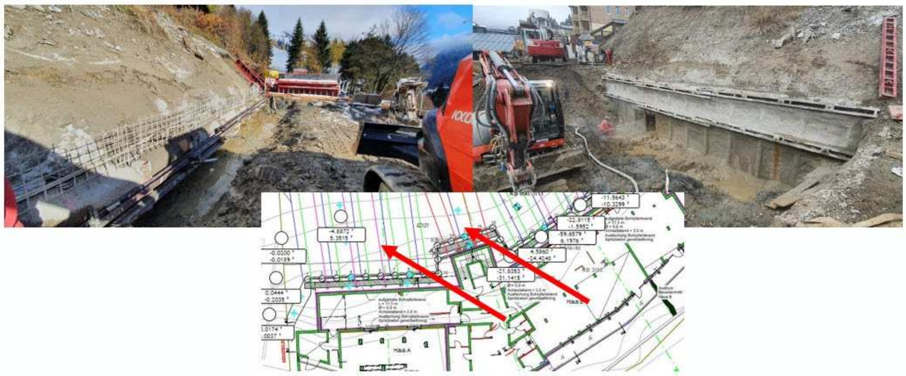

Fig. 19: Excavation and micro piling works November 2021

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