ONLINE-MONITORING OF THE SUBWAY STATION ERDBERG VIENNA

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INTRODUCTION

In modern construction and planning industry, especially renovations (restructuring measures) of old objects, objects in operation etc. the safety aspect becomes more important. A potential source for hazards and damage during renovation respectively conversion can be caused by uncontrolled deformation of directly or indirectly affected object parts. Therefore it is obvious that deformation behavior of these object parts should be investigated as precisely as possible before the rebuild and monitored at best during construction works and to determine its magnitude. Thus in this context about a technique which is not brand new but has not been used all too often – the online geomonitoring- is spoken, where online observations of such deformations using geodetic methods are possible.

Under suitable measuring arrangement nowadays even minor changes to building or plant components can be automatically detected. The Online Monitoring System used by Vermessung ANGST ZT GmbH (in combination with the software GOCA) offers on the one hand an overview of the observed object's condition of change that is retrievable via internet at any time and on the other hand, in case of exceeding the tolerance values, an automatic alert system with optical-acoustical warning for all present on the spot and alerting of those responsible by SMS or e-mail.

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By online monitoring and with responsible chosen tolerance value an exposure can be recognized in a timely manner.

The following is a report on the online- and geomonitoring and alerting in the completed project of the transport hub A4/A23 (“Node Prater”).

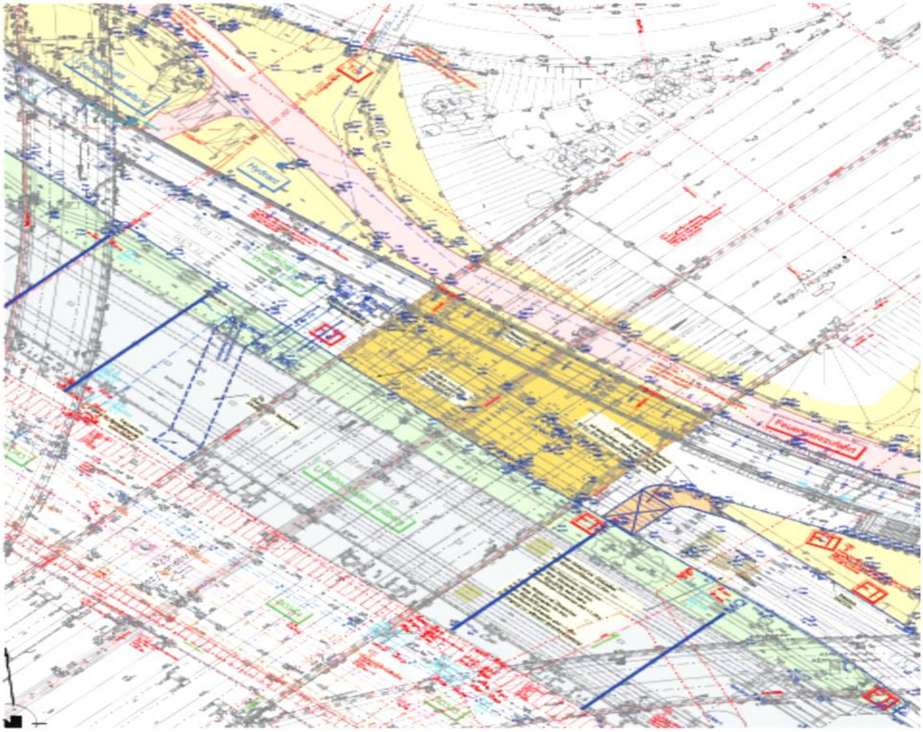

Illustration 1: Project U3-Station Erdberg

1. THE PROJECT:

In course of the renovation program of the transport hub A4/A23 (“Node Prater”) by ASFINAG building work also touched areas which were influencing the area of responsibility of the Vienna Lines (subway station Erdberg). New bridges for crossing Danube Canal were build, too.

Resulting from loads caused by intermediate support as well as loads from temporarily back fillings settlements in the area of the subway were expected. Furthermore surface loads in terms of concrete loads were brought up to the temporarily back fillings.

For monitoring and as well to assess the impact of the construction measures on the affected U3- subway station 'Erdberg' (Fig. 1) a surveying monitoring was planned, which 'Vermessung ANGST ZT GmbH', Vienna, was commissioned to implement. The online geomonitoring was performed from 13.02.2014 until 28.05.2915.

2. INSTALLATION AND OPERATION OF THE ONLINE MONITORING SYSTEM

The distribution of the measuring points within the measuring sections was determined by the responsible structural engineer of Vienna Lines and portrayed in the report on determination of warning and alarm values (Site plan Ill. 1 and Table 1) ([2][3]).
In each measuring sections prism reflectors were set as planned prior to the commencement of work in the U3 subway station Erdberg, in order to enable an automatic observation with total stations. The measuring robots (TC) were mounted on consoles, which were assembled and fixed firmly to the particular wall with screws. Immediately after the online monitoring system's set up the reference measurement was performed.
Measuring interval: In order to receive the fixation of a reasonable epoch interval for the execution of the deformation measurements the measuring robots were set into 24 hours online operation for the reference measurement, the observations were evaluated, visualized and interpreted. After several variable held epoch intervals the further epochs for the execution of the monitoring program were scheduled to once per hour.
Warning values and warning levels: In case of deviations from expected behavior and according to the size of deviation a warning level is disclosed. The warning levels are divided into two levels (see Table 1):
Warning values: when warning values are reached – no compromising stability yet
Alarm values: when exceeding alarm values - compromising stability

MQ 1-4			
	Vertical deformations	Warning values [mm]	Alarm values [mm]
		+ 5 /-5	+ 10 /-10

Table 1: Warning and alarm values for the measuring section MQ 1-4 station Erdberg ([2])

In practice in case of exceeding the limit a warning is automatically carried out at the construction side via an optical or acoustical signal (see Ill. 8). At once the persons responsible (Employees of Vermessung Angst GmbH and subsequently the construction management) are informed of a warning state via SMS or e-mail. The automatic transmission of an alarm message – this criticality has never been reached in practice – would have caused the personnel to evacuate of the hazardous area and the station master to immediate close the line.

Control cross-section and measuring points: In the subway station 4 control cross-sections with 6 measuring points each (with these measuring points in each case the 3D wall support movements are captured) had to be processed (see also Illustration 14 and 15 in Annex). A control cross-section is consisting of 6 measuring points (X.1 – X.6), 2 points on top and 4 points at the bottom whose spatial location needs to be captured ([1]).

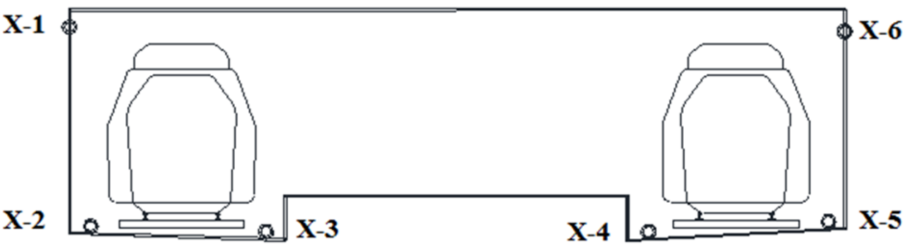

Illustration 2: Measuring point position in the measurement planes in the area of the subway station Erdberg

2.1 Measuring point stabilization and network

To conduct the measurements at the measurement object resp. subway stations the measurement object was provided with a certain amount of measuring points. All measuring points (network and object points) were defined by reflectors, which were firmly attached to the building structure with dowels, precisely defines and ensuring observation possibility for several years. In particular attitude changes of the reflectors based on vibrations caused by subway operation must be avoided.

In order to determine changes to the construction geometry in a result of he construction works, measurement data of the reference and object points were evaluated by means of geodetic network measurements and network adjustment and epoch wise an analysis of the stability behavior via statistically sound deformation analysis was performed. The network was composed of interlaced traverses with 5 reference points each, of which 4 were arranged outside the deformation area (see Ill. 3).

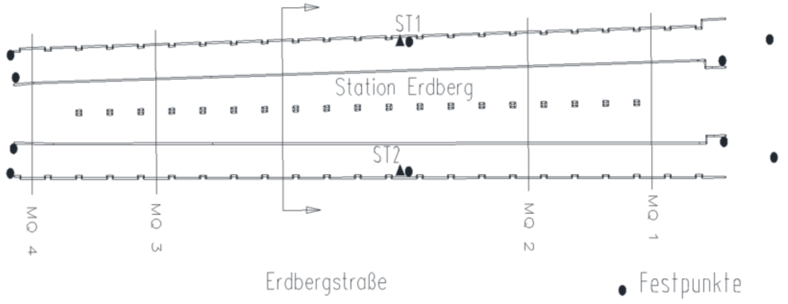

Illustration 3: Fixed point position and measurement plane in the area of subway station Erdberg

3. GEODETIC ONLINE GEOMONITORING SYSTEM GOCA

For the online geomonitoring of the project 'Subway station Erdberg' the application of a monitoring measuring system (MMS) with two total stations was necessary, which were connected to the MMS via a geosensor network. The MMS is to meet the requirements of a geodetic 3D-online monitoring system:

- Online measurements for selected deformation points (see Ill. 7) within determined intervals
- Immediate warning respectively alerting the persons responsible in case of exceeding predefined threshold values (optical, acoustical, telecommunication (Ill. 8))
- Collecting all measurement data in a central database and archiving the data for preservation of evidence and later inspection and re-evaluation

The breakdown of the particular monitoring task ensues interdisciplinary into the components data collection, modeling, reporting and reaction (implementation of an alarm plan) [5]. Central state variable of the above mentioned modeling components in geodetic monitoring is the three-dimensional displacement of object points as position and height changes within a uniform coordinate system.

By means of the mentioned basis components for the used project the data collection and analysis of the data were carried out by the network adjustment-based geomonitoring program GOCA, which has been developed

under the project leadership of Prof. Dr. Reiner Jäger at the Institute of Applied Research (IAF) at Karlsruhe University of Applied Sciences.
The different automatable modules of the GOCA geomonitoring chain (see Ill. 4) replace as complete system the old manual geodetic monitoring methods ([4] [7]).

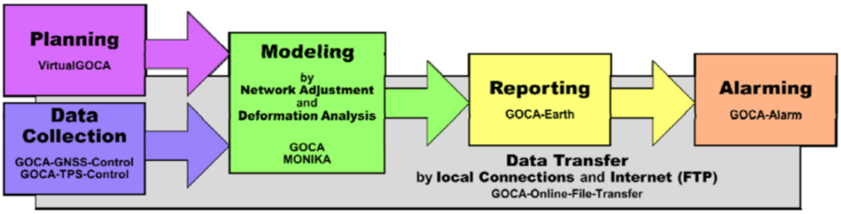

Illustration 4: Components of the geodetic geomonitoring chain using the example of GOCA system ([4] [5])

3.1 Used hardware and software

An online monitoring system for automatic monitoring of construction movements consists of the following basis components:

- Measuring sensor (motorized precision total station with automatic target recognition to prism, see Ill. 7)
- Communication box with computer and GOCA-TPS-Control to control the measuring sensor inclusive automatic measurement data collection (geomonitoring component 1, Ill. 4)
- GOCA-Software and GOCA-Alarm for network adjustment based deformation state estimation, visualization and alarming (geomonitoring component 2,3 and 4, Ill. 4)

In addition to the efficiency of the precision total station especially the service spectrum of the analysis software (geomonitoring component 2, 3 and 4, ill. 4) is a central criterion for the complete system ([4] [5]).

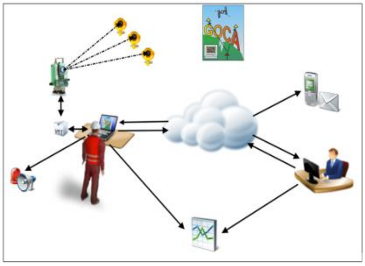

Illustration 5: General overview of the measuring system ([from 6, S. 61])

3.2 Geo-sensor networks

The superordinate term 'sensor networks' refers to a bundling of several sensors to a network, in order to determine common or specific condition information. The term geo-sensor networks includes sensor types for monitoring tasks in geoscience disciplines (Meteorology, hydrology, geodesy, geology, geophysics, etc.), which comprise different sensor types (geodetic sensors, geotechnical sensors, meteo sensors etc.) depending on complexity resp. the interdisciplinary character of the state estimation. The accuracy of georeferencing the sensors is problem- and sensor specific of varying importance. In classical geodetic deformation analysis – as a task of permanent monitoring of displacement states (PELZER, 1971, 1976) in a geodetic sensor's network – the continuous sensor georeferencing in terms of high-precision sensor positioning is assumed respectively base state variable for additional state estimations at the same time (Ill. 2) ([7]).

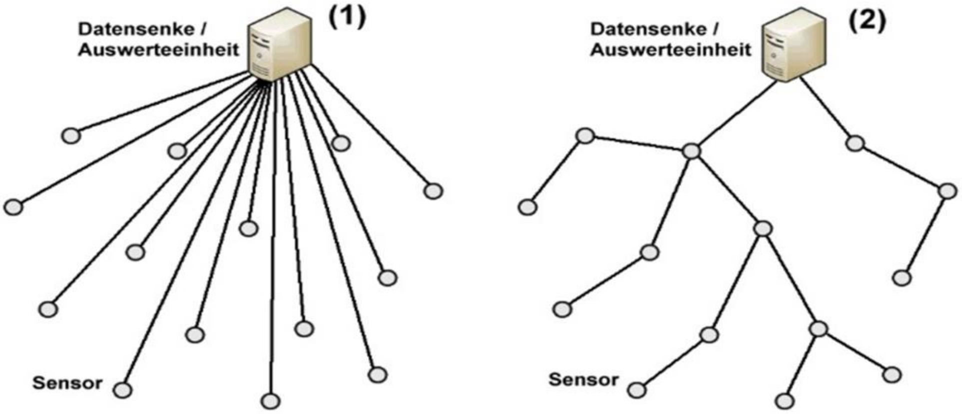

Illustration 6: (1) Direct data link [7], (2) manually configured data network [7]

Common name	Range (Ø / max.)	Extensibility / to	Data medium (Cable / Radio)	Comments
LAN / Ethernet	100 m / 80 km	yes / ∞	Data cable / fiber optic cable	

Table 2: Approximate ranges for direct data connections (table excerpt from [7, S.97])

The data transfer from the sensors to the data sink/evaluation unit in geo-sensor networks can result from direct connections on the one hand (star topology, see ill. 6 (1)). According to scheme illustration 6 (1) (Direct data link) the two instruments (Topcon IS 301) used in the area of the subway station were directly linked. Besides these instruments further sensors e.g. meteorological sensors were considered.

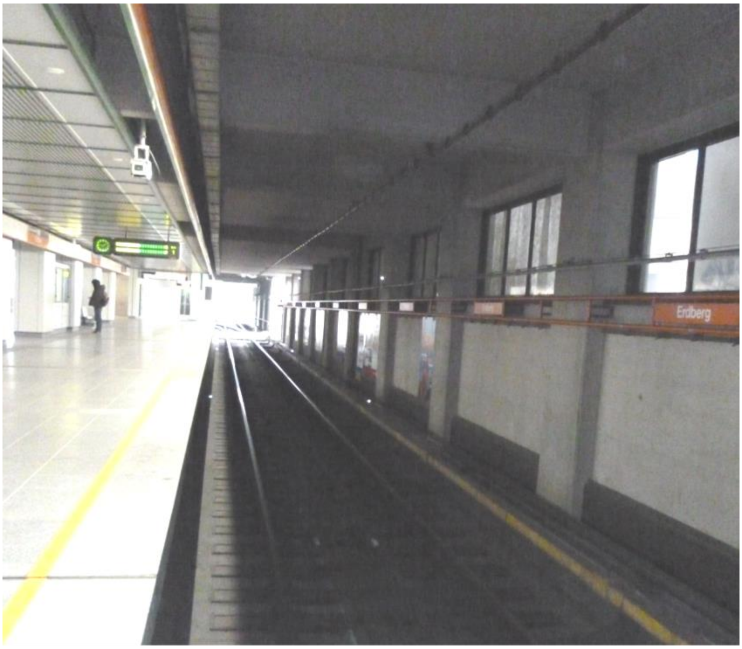

Illustration 7: Measuring station ans measuring section example - subway station Erdberg

Illustration 8: Box for central computer and control system inclusive alarm system (optical and acoustical)

In this way the two Topcon instruments could get put into operation, driven and controlled continuously from one of the central computers via the internet (e.g from the office). The central computer system also has exceeding time and cost-saving affects compared to former installations.

3.3 Topcon instruments and course of measurements

For position and height measurements two precision total stations (Topcon IS 301) were used. By means of Automatic Target Recognition (ATR) and TPS Control programs the three components (horizontal angle (Hz), zenith angel (V) and distance (D)) were simultaneously determined and registered in online mode. These instruments show a certificated distance accuracy of σs = ±0,3 mm + 1 ppm, the certificated horizontal and zenith angel accuracies are σHz = ± 0,06 mgon respectively σV =±0,10 mgon.

The Topcon total stations generally possess really good performance specifications. Working with Topcon IS-series instruments is extremely beneficial due to structured menus and very short recording time (Change in targeting points and measurements in both faces). The existing robotic mode (Online mode) enables a very rapid provision of the individual measurement cycles of the measurement program given by the customer in connection with the remote control of the TPS-control program (Prof. Jäger, HS Karlsruhe).

In order to fulfill all special requirements regarding the monitoring the automatically operating Online-MMS “GOCA” was installed. The Online monitoring is taking place with two high-precise Topcon total stations. In each measurement run the prisms were measured in given measurement cycles in two faces and forwarded to the following analysis.

The GOCA software enables the computation of absolute displacements in the form of online displacement estimations referring to a common coordinate system of the fixed points (reference point coordinate system) in the submillimetre range.

Employees of Vermessung Angst GmbH observed online from their office the behavior of the object and provided the construction management with relevant measurement results (information about the object's behavior), whereat also a daily measurement report (Reporting part in the above shown geomonitoring chain, see Ill. 4) is sent via email. The result were visualized in real time on the server of Vermessung Angst ZT GmbH. The access was made available for all corresponding participants via log-in and password. The customers were able to retrieve actual changes in position of the object during construction works at any time or place. During visualization a focus was set on the quick and clear detection of deformations (marking tolerance values in striking color) of the individual object points on the start page.

All measurement values, the computed coordinates and additional information were archived in a database. Thereby consistency and plausibility can be checked as required.

4. DEFORMATION ANALYSIS, MODELING AND ANALYZING MEASUREMENT DATA

4.1 Basics

The concept of geodetic geomonitoring – the following treated state estimation instances based on data from linked sensors (see Ill. 6) single- or multistage geodetic network adjustment- has remained unchanged since the basic setting and technical definition of the mathematical modeling of deformation analysis [9] more than forty years ago, see also [8], [4], [5], [6], [7], [10], [13] and [14]. The technical innovations in the age of IT allow for from now on three decades in different stages of deployment a continuous automation respectively real-time capability of the geomonitoring chain (Ill. 4) and thereby a local staff-free, permanent real-time geodetic geomonitoring system such as GOCA [5] for civil protection and as early-warning system in building industry.

In network adjustment based deformation analysis the sensor points which are regarded as stable reference points $\mathbf{x}_R$ form the uniform 3D coordinate system for computation and modeling of the object point positions $\mathbf{x}_O$ in one or several associated figuline object areas (ill. 7). The stability and congruency of the reference points $\mathbf{x}_R$ can also be statistically analyzed and proved [10].

In the network adjustment based concept of GOCA GNSS and LPS sensor data are processed online or near-online (for epochal measurements also post-processed) in a 3 stepped adjustment concept ([4],[6],[7],[10],[13]) as least squares estimations as well as robust M-Estimator ([11], [12]). The initialization step 1 serves as determination of the 3D reference point frame $\mathbf{x}_R$ and its covariance matrix $\mathbf{C}_{X,R}$. Step 2 includes – in regards to the presented (2D/1D) concept in this report (1a-e) – the continuous adjustment of the GNSS calculations (spatial vectors) and LPS data (slope distance, directions, zenith distances and leveled height differences) mapped to appropriate position and height components. Thereby the 3D georeferencing of the object points $\mathbf{x}_O(t)$ with covariance matrix $\mathbf{C}_O(t)$ is carried out in the reference point datum $\mathbf{x}_R$. Central state variable of the modeling component, but also for reporting and alarming within the geodetic geomonitoring chain (Ill. 4), is the 3D displacement vector $\mathbf{u}$ of the object points $\mathbf{x}_O(t)$ (see Ill. 9) derived from the sensor data as well as its velocity and acceleration component $\dot{\mathbf{u}}$ and $\ddot{\mathbf{u}}$. The georeferencing of the object point time series $\mathbf{x}_O(t)$ and the object state variable $\mathbf{y}(t) = [\mathbf{u}(t), \dot{\mathbf{u}}(t), \ddot{\mathbf{u}}(t)]^T$ takes place in a consistent reference point coordinate system $\mathbf{x}_R$.

4.2 GOCA network adjustment concept and adjustment steps 1 and 2

The functional model of the position and height adjustment in the GOCA adjustment steps 1 and 2 is based on the following correction equations:

GNSS position baselines:
$$\begin{bmatrix} \Delta x_{ij} \\ \Delta y_{ij} \end{bmatrix}_{GNSS} + \begin{bmatrix} v_{\Delta x,ij} \\ v_{\Delta y,ij} \end{bmatrix}_{GNSS} = \begin{bmatrix} \Delta \hat{x}_{ij} \\ \Delta \hat{y}_{ij} \end{bmatrix} \tag{1a}$$

Horizontal distances:
$$s_{ij} + v_{s,ij} = s \cdot \sqrt{\Delta \hat{x}_{ij}^2 + \Delta \hat{y}_{ij}^2} \tag{1b}$$

Directions:
$$r_{ij} + v_{r,ij} = \arctan\left(\frac{\Delta y_{ij}}{\Delta x_{ij}}\right) - o_i \tag{1c}$$

GNSS height baselines:
$$\Delta h_{GNSS,ij} + v_{\Delta h,_{ij}} = \Delta \hat{h}_{ij} \tag{1d}$$

Terrestrial height differences:
$$\Delta H_{terr,ij} + v_{\Delta H,ij} = \Delta s_h^m \cdot \Delta \hat{h}_{ij} + (\hat{a}_{00} + \hat{a}_{10} \cdot x_j + \hat{a}_{01} \cdot y_j)^m - (\hat{a}_{00} + \hat{a}_{10} \cdot x_i + \hat{a}_{01} \cdot y_i)^m$$
… (1e)

'm' in (1e) is referring to the area index and with Δs_h^m resp. a_{ik}^m the scale difference resp. the area polynomial coefficients for modeling the local height reference surface in the area m. Concerning GNSS, the GOCA software component GOCA-GNSS-Control (see Ill. 4) can work in RTK and in near online mode (RINEX data). As a result of chain link 1 (see Ill. 4) regarding GNSS the 3D baselines (1a, e) - besides the terrestrial sensor data (LPS) - are passed on in so-called GKA format [5] for continuous network adjustment and deformation state to the GOCA deformation analysis software (chain link 2, Ill. 4). The 3D baselines are converted to 2D/1D baselines and processed according to (1a, e).

4.3 GOCA Adjustment step 3 and deformation state estimation

The deformation analysis in GOCA adjustment step 3 is based on the simultaneously from online GOCA network adjustment step 2 arising object point time series and their covariance matrices:

$$\mathbf{x}_O(t) \text{ and } \mathbf{C}_O(t) \qquad (2a, b)$$

Illustration 9 shows the object point time series $\mathbf{x}_O(t)$ (2a), the result of network adjustment in GOCA step 2 by the example subway station Erdberg, Vienna.

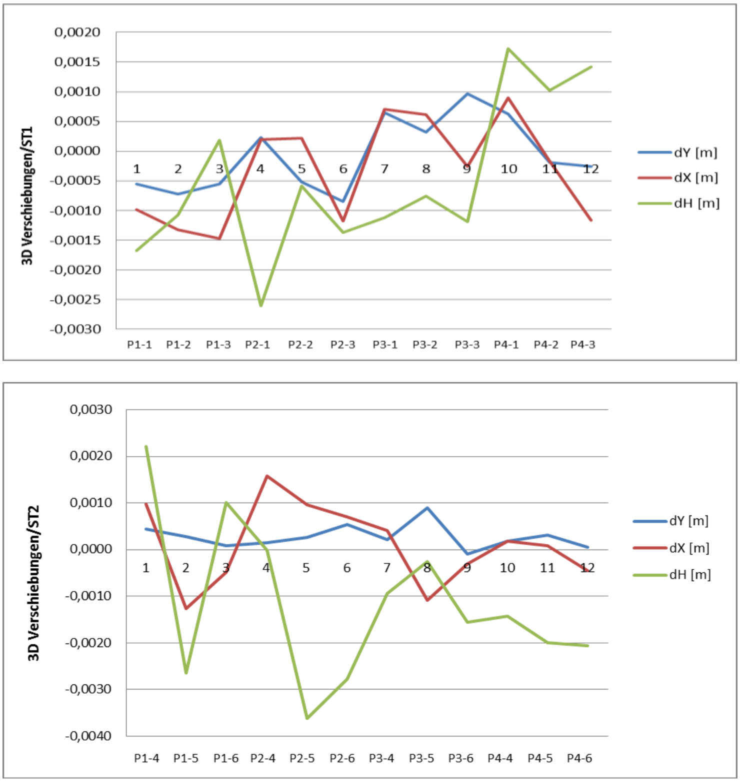

Illustration 9: Visualization of raw object point time series $x_O(t)$ *(2a) on a daily base by the example of one object point of the geomonitoring network U3 station Erdberg, Vienna*

The expected movements/deformations are about a quasi even process (except the last measurements), so that the chosen sample rate of respectively in measuring epochs 1/day was sufficiently.

In GOCA step 3 – based on the results $\mathbf{x}_O(t)$ and $\mathbf{C}_O(t)$ (2a, b) from GOCA step 2 and individual settings for critical values and statistical parameters for object points $\mathbf{x}_O$- the following online estimations for deformation analysis of the object area as least squares and robust Huber ans L1 estimation are possible:

- moving average in position and height
- online displacement estimation at different epoch definitions (see Ill. 3)
- Kalman filtering for displacement, velocity and acceleration [12]

The functional model of the above mentioned displacement estimation (see Ill. 10) between two epochs and periods t_0 and t_i reads as follows:

$$\begin{bmatrix} l_{t_0} \\ l_{t_i} \end{bmatrix} + \begin{bmatrix} v_{t_0} \\ v_{t_i} \end{bmatrix} = \begin{bmatrix} E_1 & 0 \\ E_2 & E_2 \end{bmatrix} \cdot \begin{bmatrix} \hat{x}_0 \\ \hat{u}(t_0, t_i) \end{bmatrix} = A \cdot \hat{y}$$

with $\hat{y} = [\hat{x}_0(t_0), \hat{u}(t_0, t_i)]^T$ (3a,b)

Each epoch time t_0 and t_i marks the middle of a discrete epoch interval in each case (e.g. 1 hour or 1 day, ill. 10) and both observation groups l_{t_0} and l_{t_i} are derived directly from the object time series $\mathbf{x}_O(t)$ from GOCA adjustment step 2 (2a, b). The observation corrections are referred to as v, furthermore $\hat{x}_0(t_0)$ and $\hat{u}(t_0, t_i)$ are referred to as the object point position at starting point t_0 respectively the occurred displacement at time t_i as part of the parameter vector to be estimated.

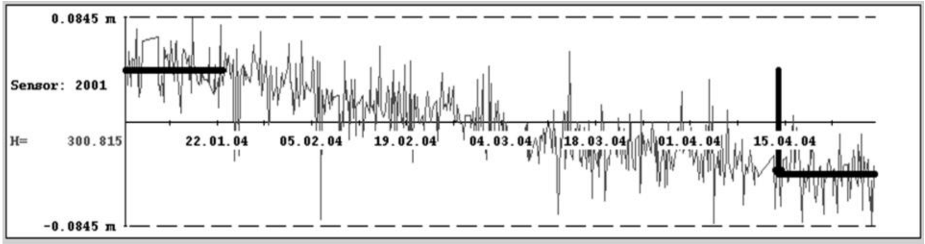

Illustration 10: GOCA visualization of time series $x_O(t)$ of an object point (adjustment step 2) and displacement estimation (adjustment step 3) by the example of a subsidence

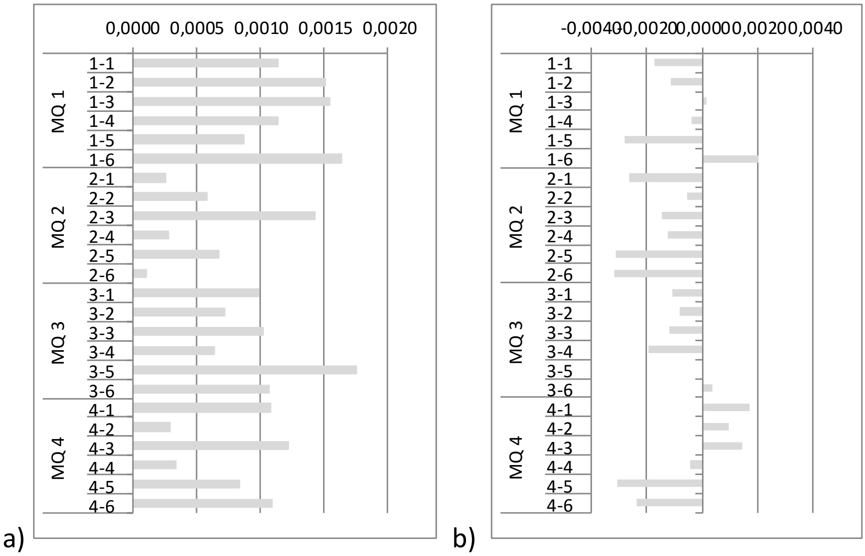

Illustration 11: Graphics displacement horizontal [m] a) and determined height displacement resp. settlement absolute vertical [m] b)

The GOCA Kalman filtering ([12], [14]) – as additional component of the state estimation in GOCA step 3 in chain link 2 (Ill. 4) – is based on the following state transition matrix $\mathbf{T}(t)$ for the state vector **y**(t). For its transition from previous $t-\Delta t$ to present time the following applies:

$$\mathbf{y}(t) = \mathbf{T}(t) \cdot \mathbf{y}(t-\Delta t) \qquad (4a)$$

with

$$\begin{bmatrix} \mathbf{u}(t) \\ \dot{\mathbf{u}}(t) \\ \ddot{\mathbf{u}}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{I} & [\Delta t] & \left[\frac{1}{2}\Delta t^2\right] \\ \mathbf{0} & \mathbf{I} & [\Delta t] \\ \mathbf{0} & \mathbf{0} & \mathbf{I} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u}(t-\Delta t) \\ \dot{\mathbf{u}}(t-\Delta t) \\ \ddot{\mathbf{u}}(t-\Delta t) \end{bmatrix} \qquad (4b)$$

and

$$\mathbf{y}(t) = [\mathbf{u}(t), \dot{\mathbf{u}}(t), \ddot{\mathbf{u}}(t)]^T . \qquad (4c)$$

The state vector comprises in the parameters **y**(t) (4c) the 3D displacement $\mathbf{u}(t)$, the 3D velocity $\dot{\mathbf{u}}(t)$ and the 3D acceleration $\ddot{\mathbf{u}}(t)$ of the object points $\mathbf{x}_O(t)$ in between two sequenced time intervals Δt. The state transition model (4a, b) implied a Taylor expansion truncated after second term of the unknown displacement function $\mathbf{u}(t)$ and thus the assumption of a constant acceleration $\ddot{\mathbf{u}}(t)$ within a short filter time interval Δt. This assumption is – by appropriate high sampling rate or naturally slowly moved (static) processes – almost always feasible resp. given in geodetic geomonitoring for many objects (construction, dams, landslides, mines etc.). The covariance matrix $\mathbf{C}_y$ of the prediction $\mathbf{y}(t)$ (4b) – as stochastic Gauß-Markov-Model [11] component of the actual estimation at time t – is calculated according to the law of error propagation applied to (4b) on the basis of the covariance matrix from the previous estimation of the state vector $\mathbf{y}(t-\Delta t)$. As observation component **l**(t) for the Kalman filter predictions **y**(t) (4c) come up the GOCA based displacements $\mathbf{u}(t)$ within the interval Δt, referring to the same state vector **y**(t) (4c), with appropriate covariance matrix. This observation component **l**(t) at time t and the stochastic model $\mathbf{C}_l$ are as follows:

$$\mathbf{l}(t)=\mathbf{l}(\mathbf{y}(t))=:\mathbf{u}(t)=\mathbf{x}_0(t)-\mathbf{x}_0(t_0) \qquad (4d1)$$

with

$$\mathbf{C}_l=\mathbf{C}_{x_0}(t)+\mathbf{C}_{x_0}(t_0)\,. \qquad (4d2)$$

The observations $\mathbf{l}(t)$ (4d1) are the differences between the present object point position $\mathbf{x}_O(t)$ (2a, b) from GOCA adjustment step 2 (FIN files) minus the position $\mathbf{x}_O(t_0)$ to the reference date for the displacement of the Kalman filtering. The Kalman filter estimation ([4], [10], [12], [14]) itself is equivalent to the Gauß-Markov-Model [11] of a common adjustment on prediction $\mathbf{y}(t)$ (4a, b, c) and observation component (4d1,2) at time t.

The above results of adjustment step 2 and 3 are provided both numerical and visualized in a graphics window (Ill. 9 and 10). They are also available as general output interface, e.g. for virtual sensor modeling or 'integrated deformation analysis' (also 'system analysis' or structural health monitoring') ([4], [14]). An alerting (acoustical, SMS, email etc.) can result from direct comparison of the estimated numerical values of the deformation parameters (such as e.g. $\hat{\mathbf{u}}(t_0, t_i)$ (3b)) with the appropriate critical state variable (see Tab. 1), from statistical significance of the deformation parameters as well as logical AND resp. OR operation of both cases.

4.4 Robust M-Estimation

Sensor data errors and systematical error (e.g incorrect ambiguity resolution for GNSS) would involve defective results in the above deformation analysis for a fully automated GOCA real time adjustment step 2 and 3. False alarm or a high risk to erroneously suppressed alarm situations in a critical state would be the consequences. In order to eliminate this risk or keep it as small as possible the parameter estimation in GOCA deformation analysis in the adjustment steps 2 and 3 are based on the concept of robust M-Estimations ([11], [14]).

4.5 Current development of the GOCA system

The current development in the GOCA system included the implementation of a quasi-integrated 3D network adjustment ([14], [15]) in geometry and gravity space in 2015. The 2D/1D modeling (1a-e) persists unchanged, e.g. in order to cover 1D leveling networks further on. The quasi as well as the fully integrated 3D model in contrast to the 1D/2D model and so-called 'geometrical' 3D models can parametrize all available geoinformation and sensor data, i.e. gravity field models (e.g EGM 2008), gravimetry, GNSS total stations (TPS), leveling, laser scanners, radar sensors, geotechnical sensors up to photogrammetric data from modern video tachymeters – for geomonitoring geodynamical, natural and structural processes resp. objects. That is why both above mentioned integrated 3D models have a key role in actual and prospective research and development.

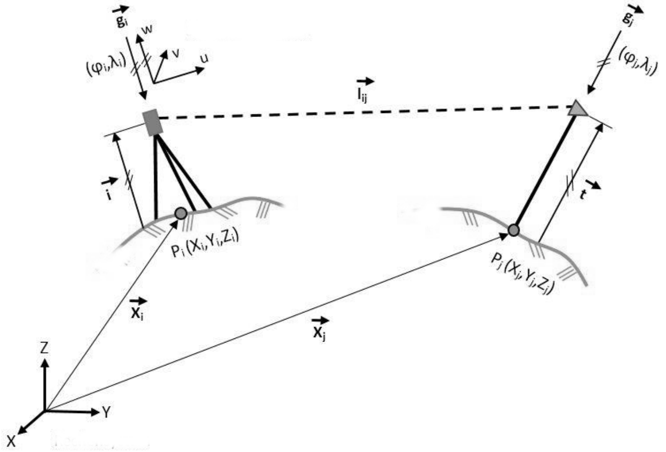

Illustration 12: Vector summary for quasi-integrated 3D modeling for total station observations (TPS) with skewed gravity directions in standpoint and target point system

Illustration 12 shows the gravity filed integrated 3D modeling by the example of total station observations (TPS). For skewed gravity directions (φ_i, λ_i) resp. (φ_j, λ_j) in standpoint system (instrument height i) resp. in target point system (reflector height t) the vector summary adds up to:

$$\mathbf{x}_i + \mathbf{i} + \mathbf{l}_{ij} - \mathbf{t} - \mathbf{x}_j = \vec{\mathbf{0}} \qquad (5a)$$

Based on (5a) the significant observation vector $\mathbf{l}_{ij}^{i}$ for TPS observations (directions, zenith distance and slope distance) in the standpoint system (I) is as follows:

$$\mathbf{l}_{ij}^{i} = \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta w \end{bmatrix}_{ij}^{i} = \mathbf{R}_{e}^{i}(\varphi_i, \lambda_i) \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix}_{ij} - \begin{bmatrix} 0 \\ 0 \\ i \end{bmatrix}^{i} + \mathbf{R}_{e}^{i}(\varphi_i, \lambda_i) \cdot \mathbf{R}_{j}^{e}(\varphi_j, \lambda_j) \cdot \begin{bmatrix} 0 \\ 0 \\ t \end{bmatrix}^{j} \qquad (5b)$$

The vector components ($\Delta u_{ij}^{i}, \Delta v_{ij}^{i}, \Delta w_{ij}^{i}$) from $\mathbf{l}_{ij}^{i}$ enable an easy parametrization for the above mentioned TPS observations and with (5b, right part) a transformation in an earth-fixed (e) geocentric Cartesian calculation system (x, y, z) [15]. The GNSS baselines are directly parametrized as coordinate differences within the uniform earth-fixed geocentric Cartesian calculation system (x, y, z). Already this example shows the superiority of the integrated 3D model compared to the 2D/1D approach and other 'geometrical' 3D models, because for combined GNSS terrestrial networks only a linked sensor network (ill. 7) is provided. The demand for additional 'identical' points for GNSS and terrestrial sensor nodes and components expires for the integrated 3D models. In the quasi-integrated 3D model (GOCA Software version 5.3) the parameters of the vertical directions (φ_i, λ_i) resp. (φ_j, λ_j) (5b) are pairwise introduced as unknowns and -via the integrated gravity field model – as direct observations at the same time. In a fully integrated 3D model the parametrization of the gravity filed and also the parameters of the vertical directions (φ_j, λ_j) (5b) of the individual network points result from regional spherical cap harmonics.

The 3D modeling, integrated as additional option in the GOCA software, affects only step 1 and 2 within the GOCA concept of stepwise adjustment (chapter 4.2 and 4.3). The deformation state estimation stays unaffected.

In 2016 in cooperation with TOPCON the photogrammetric component of the geomonitoring system GOCA is continued with the above mentioned quasi-integrated 3D adjustment model implementation. With regard to encoded measure marks and their modeling via image processing a recourse to developments within precise navigation (www.navka.de) is possible. The integration of image data received from TOPCON video tachymeters in the GOCA system implies a multi-sensory supported bundle block adjustment I the 3D adjustment.

SUMMARY

The presented project 'Subway station Erdberg' in Vienna clearly demonstrates, that a fully automated operation of a geomonitoring system by means of the geomonitoring system and the software GOCA is possible. The geomonitoring serves primarily for estimating the probability of damage occurring. The results are available in real time and – enabled by the internet – available at any locations.

Determining geometric changes resp. 3D deformations in form of settling and position displacement and their chronological sequence were of particular interest, on the one hand for ensuring the employees safety at the building site and to guarantee a safe and from the building site unaffected run of the subway lines.

Particularly worth mentioning is the extremely high profitability of the measuring system, especially the low effort for capturing many measuring cycles with little temporal and staff assignment. This enables the metrological online monitoring of construction works during current operations of ÖBB trains and subway lines.

On that basis the fully automation of epoch measurements as step 1 of the geomonitoring chain (see Ill. 4) in case of tachymeter sensors (TPS) by the usage of several simultaneously monitoring ATR tachymeters with precision prisms and WLAN data transmission to the GOCA software components responsible for steps 2, 3 and 4 can be achieved.

The continued deformation process modeling and the alarm management building upon that shall guarantee that the construction-related additional occurring displacements remain within safe limits, resp. a timely evacuation of the inhabited housing complex is ensured during construction works.

The use of observation measurements, GOCA software and communication systems were really important for this project, because the high-precision measurements provided the requested information for the state of the tunnel and subway station based on the construction work fully automated. The risk is minimized not only for the tunnel and the subway station, but also for the involved people and public safety. Without the high standards of measuring technologies with high precision instruments and the reliable software

GOCA which enables an automated deformation monitoring, this project would not have been feasible.

Attention should be paid to the fact that applying such automated observation software can not replace geodesists as experts but can be used there to support his performance.

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