Deformation Measurement Using Terrestrial Laser Scanning at the Hydropower Station of Gabčíkovo

Thomas SCHÄFER and Thomas WEBER, Germany, Peter KYRINOVIČ and Miriam ZÁMEČNIKOVÁ, Slovakia

Key words: terrestrial laser scanning, HDS 2500, deformation measurement, range accuracy, resolution capability

SUMMARY

So far, terrestrial laser scanning (TLS) in the field of engineering surveying is mainly used for object modelling for as-built documentation purposes and interference checking, as well as small-scaled DTM creation and volume calculation.

In this paper we introduce first operational experiences in the usage of Leica Geosystems HDS[1] 2500 laser scanning system for the determination of surface deformations of several centimeters which can be observed at the lock gates of a hydropower station during the filling and emptying process. For the first time such a multipoint sampling approach allows the visualization of deformations with an accuracy of about one centimeter over the whole area of the gates during different settings of constant liquid levels. The fast data acquisition opportunities of the system also allowed the observation of dynamic deformations during the operation and an animation with a time resolution of 30 seconds was created.

In this paper tests dealing with accuracy and resolution capabilty are introduced and data acquisition and processing methods are described.

[1] High-Definition Surveying is Leica Geosystems new term for the market segment of terrestrial laser scanning.

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1. INTRODUCTION

Located about 40 km south-east of Slovakia`s capital Bratislava the hydropower station of Gabčíkovo retains the Danube over a length of 30 km. The hydro-technical system consisting of several hydraulic engineering constructions, an accompanying dam and a diversion canal. The system was designed in the 1970`s and completed in 1992 with the purpose of flood control and in the slovak-hungarian borderland but also in order to exploit the hydropower potential of the Danube (Kopáčik, Wunderlich, 2004). At Gabčíkovo a difference in water level of approx. 20 m is created powering eight turbines (Fig. 1). To maintain the river navigable for ships two lock chambers were built as well. Measuring 34 m in width, 275 m in length and 32 m in depth the lock chambers suit large cargo ship combinations and are denoted as the biggest in Europe. Due to the immense body of water and the resulting pressure, the four lock gates (each measuring 18 m × 22 m × 2 m and a weight of 435 tons, see Fig. 1, right) situated downstream will experience reversable horizontal displacements of up to 40 mm. Lifting forces will also result in a vertical displacement of a few millimeters.

Fig. 1: Hydropower station of Gabčíkovo (left) and the lock gates (right)

2. HDS 2500 RANGE ACCURACY AND RESOLUTION CAPABILITY

2.1 Artificial Targets

In TLS the term "resolution" mostly describes a scanner's ability to detect small objects in point clouds. In general this is dependent on the smallest possible increment of the angle between two successive mirror positions, the range to the object and the size of the laser spot on the object itself (Böhler et al., 2003). For deformation measurements, this achievable resolution is sufficient. Another aspect of resolution is concerning the range accuracy of a scanning device: the ability to differentiate or resolve two targets that are close together in range. Leica Geosystems HDS uses several artificial targets (Fig. 2) which are used as tie-points for registration purposes of multiple scans to each other or geo-referencing of scans to known control points.

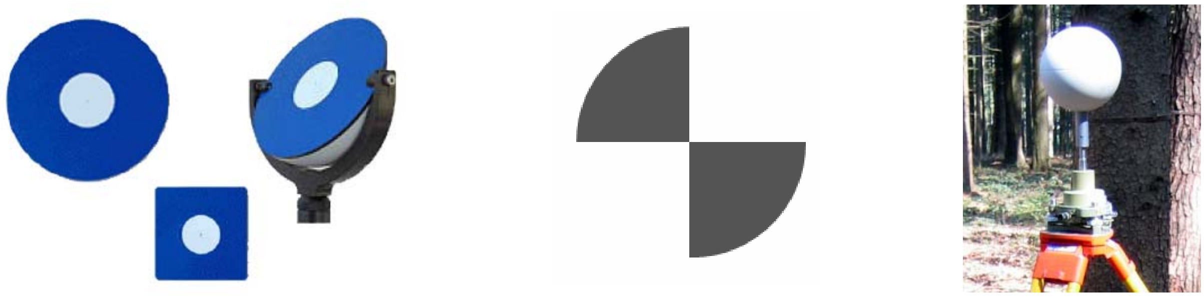

Fig. 2: Artificial HDS-Targets

Planar (Fig. 2, left) and printable (center) targets use designed differences in reflectivity which allow the automatic identification and extraction by Cyclone software, sphere targets (right) use adjustment theory to obtain the centre of the target. Apart from these targets, the Chair of Geodesy at TU München also uses low-cost wooden spheres similar to the Leica spheres. Planar and printable targets can easily be mounted on walls or any kind of surface and surveyed simoultanously by total stations with reflectorless distance measurement, whereas sphere targets can be placed anywhere in the scene of interest on a tripod. However, they can not be observed reliably by classical geodetic instruments.

To verify the resolution capability of the laserscanning system HDS2500, several targets were fixed on a linear guide rail which allows displacements of predefined increments with an accuracy of 1/100 mm. Using displacement increments of 1/10 mm the test targets were acquired during so called fine scans consisting of up to 9000 points per target over a range of 5 mm. Since ranging scanners for distances up to 100 m show about the same range accuracy for any range (Böhler et al., 2003) the series were taken at a distance of 12 m.

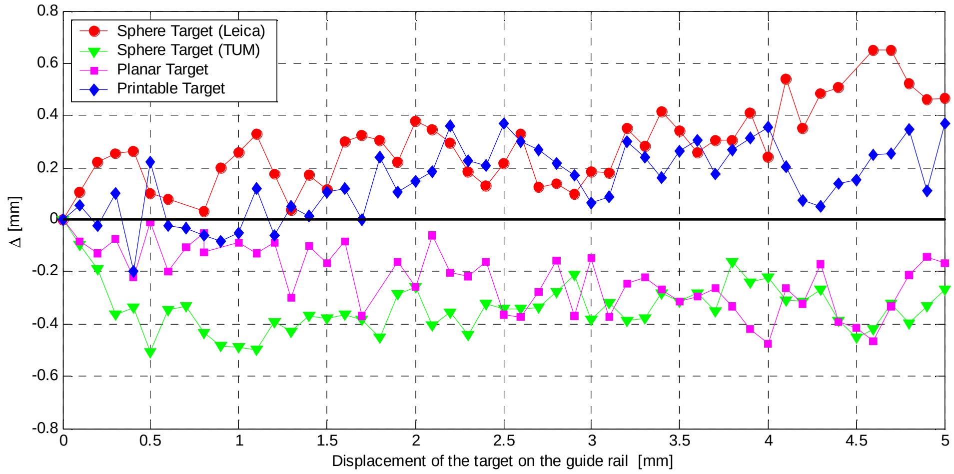

Fig. 3: Difference in range to predetermined nominal value

Fig. 3 shows the difference between actual and detected displacement of the targets. Each series stays within a maximum difference of 0.6 mm. The errors lie within -0.34 to 0.28 mm on average with a standard deviations of about 0.13 mm (cp. Table 1).

Table 1: Mean error and standard deviation

Target	**μ [mm]**	**σ [mm]**
Sphere Target (Leica)	0.28	0.15
Sphere Target (TUM)	-0.34	0.10
Planar Target	-0.22	0.12
Printable Target	0.15	0.14

Due to these results first conclusions on the usability of TLS for deformation measurements can be drawn. Compared to the target acquisition accuracy for planar HDS specified with 1.5 mm by Leica Geosystems, the high accuracy and resolution in range of target acquisition obviously allows reliable deformation measurements.

2.2 Point Clouds

Of course using TLS with target signalling resembles a single point approach. Thus, the methodology does barely differ from traditional tacheometric surveying or close range photogrammetry. However, engineers and architects are increasingly interested in a complete coverage of the object since the exact area of expected deformations might only be partially known from preliminary estimations, or in order to visualize and recognize local variations in deformation amounts. Therefore a multipoint sampling approach should be aspired. Since TLS delivers several thousand points per second the whole information of a point cloud can be used to derive displacement values as well. In that case the above mentioned accuracies and resolutions are invalid because they are derived from many points by adjustment theory or other computational algorithms (e. g. image processing).

HDS 2500 specifications estimate a range accuracy of a single point with ±4 mm (1σ) at a distance of 50 m (Leica, 2004). Own test series conducted at TU München were done by scanning a plane board perpendicular to the observation direction at a distance of 12 m with approx. 3800 points (Schölderle/Ratke, 2004). Fig. 4 shows a typical histogram with a Gaussian distribution of the range errors (noise) in reference to a best fit plane. The single point range accuracy thereby is ±2.6 mm (1σ) with a maximum error of ±9 mm.

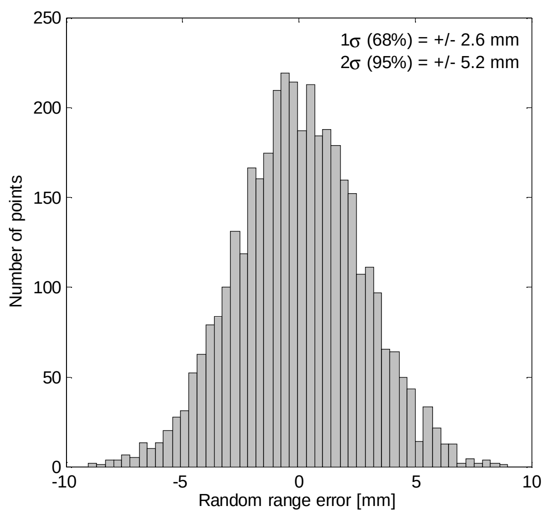

Fig. 4: Range accuracy of single laserscanning points

Since deformation measurements always consist of two subtracted measuring epochs, the accuracy for derived deformations in range direction of point clouds can be estimated by error propagation law from ±3.7 mm to ±5.7 mm (1σ).

3. DEFORMATION MEASUREMENT

3.1 Configuration and Execution

The HDS2500 was positioned outside the lock chamber on an existing platform outside a window of the concrete wall (Fig. 5). For synchronous control measurements a total station (Leica TC1800) was positioned on the corresponding platform across the waterway observing six points arranged in three vertical sections.

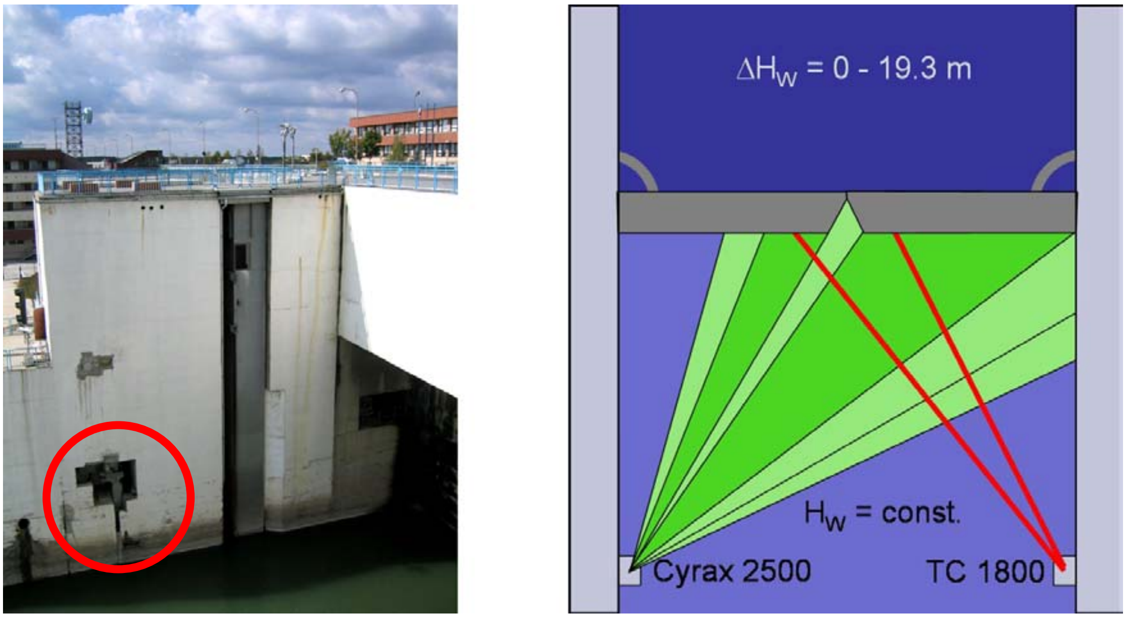

Fig. 5: Observation platform and configuration

In permanent consultation with the lock's commander, it was possible to realize complete measurements during five different settings of constant liquid levels ranging from 0.0 m (as the reference epoch) to a maximum of 19.3 m. The complete lock gates were scanned with a spatial resolution of 100 mm × 100 mm which took 150 seconds. Beside this "static" observation, a new task and situation was given. It was also possible to observe the gates during a usual "dynamic" filling and emptying process. To fill the chamber only takes 12 minutes which corresponds a change in liquid level of 1.6 m per minute. To make sure one scan cycle takes place at a fairly constant level of liquid, only a detail (a vertical stripe in the centre, 3 m wide) of the lock gate was scanned. With a resolution of 80 mm × 80 mm these scans only took 30 seconds. After a necessary re-sampling process (see section 3.2), every point cloud was available with a spatial resolution of 50 mm × 50 mm.

To describe local deformations a geodetic network related to the area outside of expected deformations has to be created. Usually such a network is realized using control points (respectively HDS-targets as shown in Fig. 2). Due to the limited field of view of the scanner and the construction itself, it was not possible to fix targets in the sorrounding. Therefore, a virtual reference frame was created by surface modelling. The laser points that hit the rigid concrete walls in the upper right corner (Fig. 6) were selected and three best fit planes were calculated. The point of intersection hereby represents the centre of the coordinate system. The orientation was chosen with the y-axis perpendicular to the vertical plane parallel to the lock gates. Hence, the direction of deformation is represented by the y-component of each point of the cloud (Schäfer, 2004).

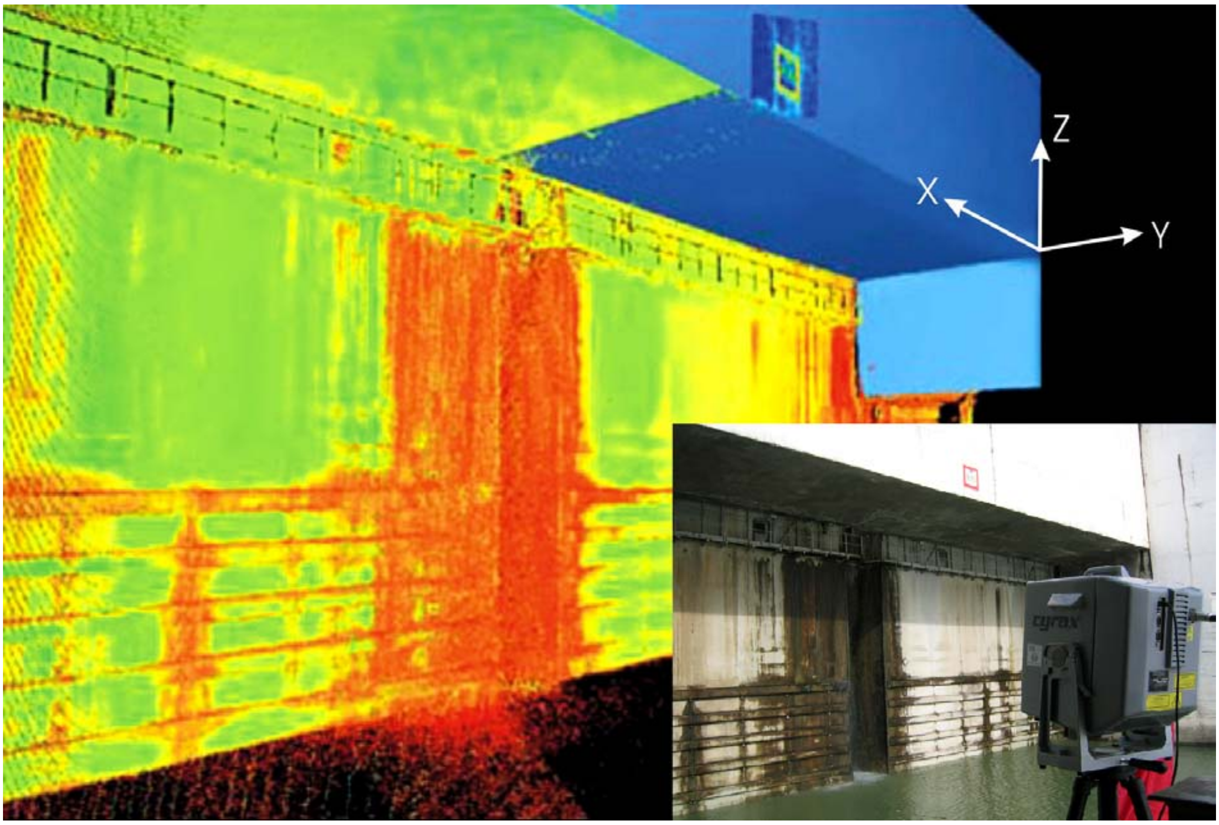

Fig. 6: The lock gates as point cloud viewed from the observation platform with the definition of a local reference frame using three perpendicular planes of the the rigid conrete walls.

3.2 Re-sampling Process

After installing a reference frame characteristical points of the object have to be selected and marked with targets (Welsch et al., 2000). Their initial positions can then be compared with positions of further measurement epochs. The marked targets herby define identical points. With TLS however, it is not possible to point at identical points since there is no opportunity of setting the mirror positions to defined angles etc. Therefore, raw point clouds have to be post-processed. With the help of a Delaunay-Triangulation it is possible to calculate an uniform and regular grid (e.g. for the x- and z-coordinates) that is identical to every point cloud (Fig. 7). Then, for each sampling point, a new value (y`) can be interpolated. The differences of two corresponding y`-coordinates now represent the amount of deformation.

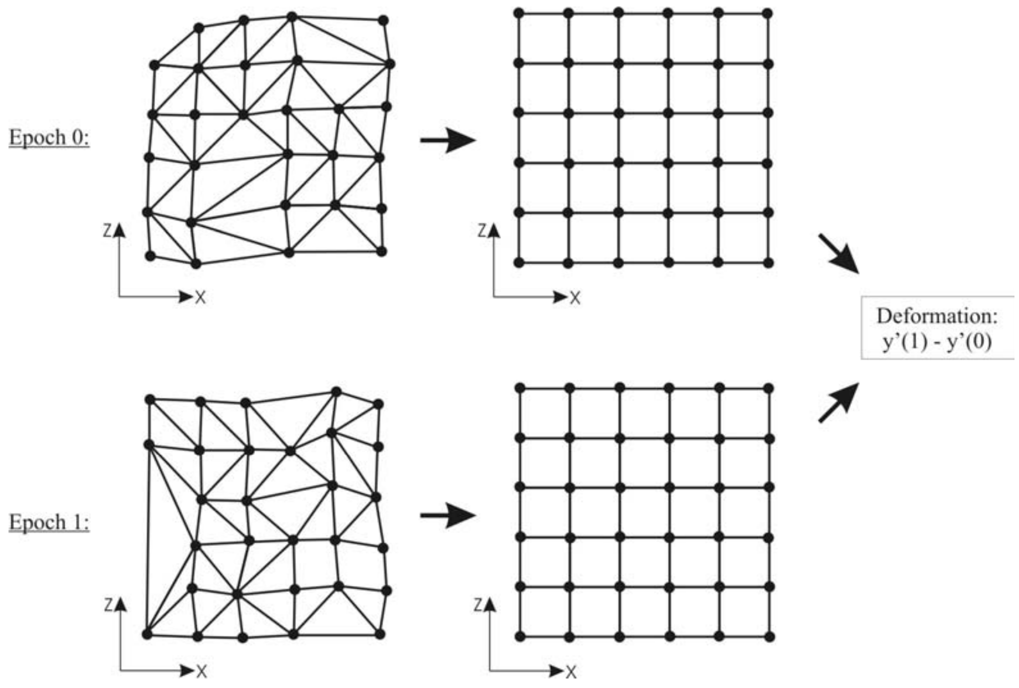

Fig. 7: Raw point clouds with an irregular and non-uniform sampling (left) and the interpolated grid (right) identical for every point cloud (epoch). The difference in y-direction represents the deformation.

4. RESULTS

Fig. 8 shows the determined deformations at the four different constant levels. At the first picture (level 4.4 m) no deformation is recognizable. At a level of 9.4 m first significant deformations ranging from 1.5 cm to 2.5 cm are visible increasing to 1.5-3.0 cm at a level of 13.0 m and finally up to 3.0-3.7 cm at a maximum level of 19.4 m. These results differ (within 3 mm) from the TC1800 data. Under consideration of both, the limited range accuracies of HDS 2500 and the fact, that these two techniques could not use identical points, the data is consistent.

All stages still show a noise of several millimetres due to the range accuracy. Filter algorithms (Schäfer, 2004) such as known from digital image processing or free-form surfaces can be used to reduce noise.

As expected, the largest deformations occur in the lower part of the lock gate due to higher pressure. At the top of the gate, no deformations are recognizable, because the lock is in contact with the upper concrete wall. Remarkable however, local variations of deformation can be seen in the upper part of the gate. Clearly a regular pattern is visible (see marked ellipses in Fig. 8). These contours show a high correlation to the inner framework of the construction. This information has been derived for the first time due to the complete coverage of the lock gates using TLS.

The coverage of a part of the gate during dynamic filling and emptying process particularly shows the change of deformation depending on the change in water level. With a time resolution of 30 seconds an animation consiting of 50 single frames was created for the first time. The animation can be viewed on the website of the Chair of Geodesy.

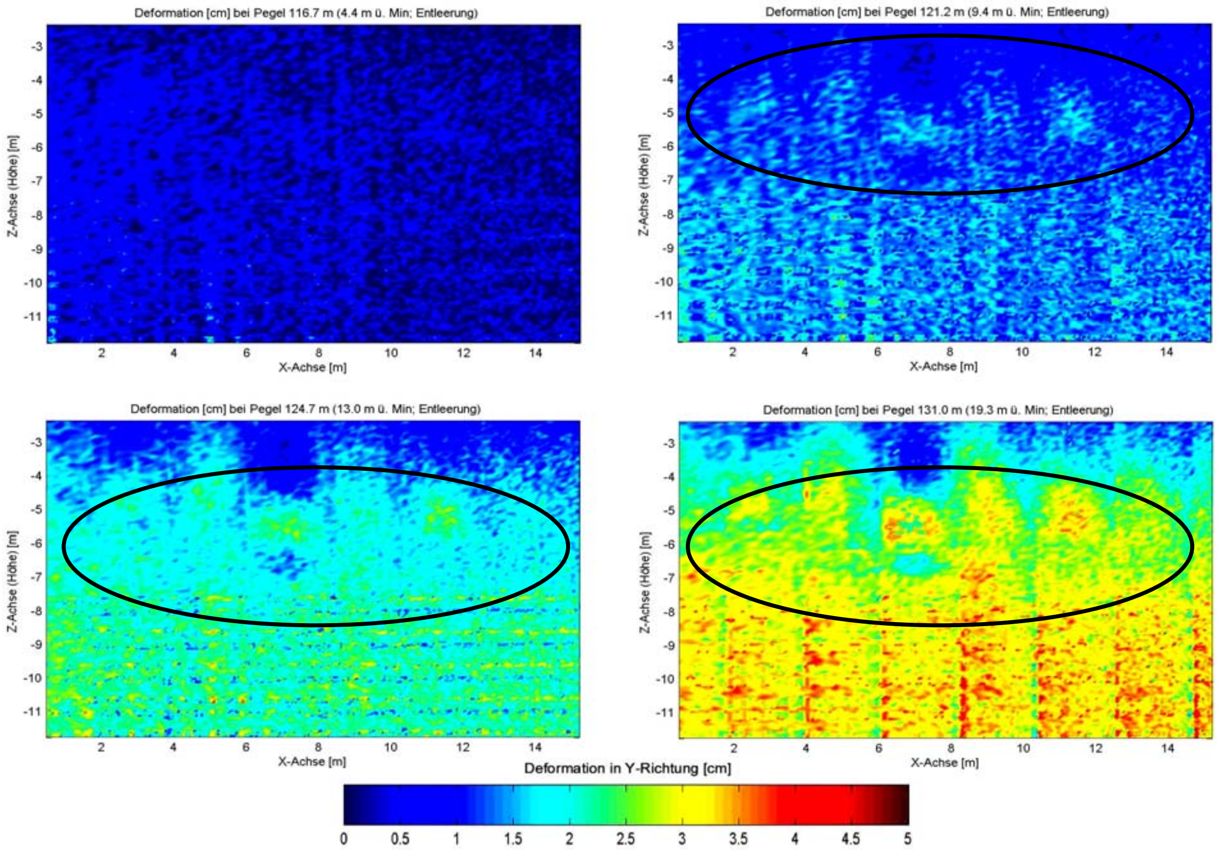

Fig. 8: Deformations observed at constant liquid levels of 4.4m (upper left), 9.4 m (upper right), 13.0 m (lower left) and 19.3 m (lower right).

5. CONCLUSION

The high accuracy and resolution capability of target acquisition with TLS allows the detection of small displacements. Since target signalling is necessary this methodology is closely related to classical geodetic deformation monitoring. Using TLS without target signalling, however, it is possible to derive full coverage (with almost unlimited spatial resolution) deformation values of objects along one axis according to the processing method introduced in this paper. Due to the fast and automated scanning process it is also possible to observe dynamic deformations which enable new insights into strain and stress conditions during operational activity in industrial environments. Thus, deformation measurement can be regarded as a new field of application of TLS with a high technological and economical potential.

With a range accuracy of ±4 mm (1σ) at a distance of 50 m TLS-Systems working with the principle of time of flight noise is still limiting possible applications. But observed deformations at the lock gates of almost 40 mm could be detected by HDS 2500 significantly and agree with tacheometric control measurements. For deformation monitoring in industrial environments short- and medium-range scanners applying the principle of triangulation like e.g. S10/S20 (formerly Soisic) with point accuracies from 0.2 mm to 0.6 mm at maximum distances of 10 m/25 m (Mensi, 2004) might be more reliable and appropriate.

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BIOGRAPHICAL NOTES

Dipl.-Ing. Thomas Schäfer
Study Geodesy at TU München 1997-2003. Awarded Harber-Prize by the German Association DVW in 2003. Scientific employee at the Chair of Geodesy since 2003. Is involved in the research project BayFORREST (F248) on Laserscanning for CAFM.

Dipl.-Ing. Thomas Weber
Study Geodesy at TU München 1994-1999. Scientific assistant at the Chair of Geodesy since 2000. Author of several publications in various journals and conference proceedings.

Peter Kyrinovič, MSc.
Study Geodesy and Cartography SUT Bratislava 1993-1998. Lecturer at the Department of Surveying at SUT since 1999 – Surveying, Engineering Surveying. Takes part in solution of grant project VEGA 1/0318/03. Author of several publications in various journals and conference proceedings.

Miriam Zámečníková, MSc.
Study Geodesy and Cartography SUT Bratislava 1997-2002. Doctoral study at the Department of Surveying at SUT since 2002 – Surveying. Takes part in solution of grant project VEGA 1/0318/03.

CONTACTS

Dipl.-Ing. Thomas Schäfer
Technische Universität München, Faculty of Civil Engineering & Geodesy, Chair of Geodesy
Arcisstraße 21, D-80290 Munich
GERMANY
Tel. + 49 89 289 22850
Fax + 49 89 289 23967
Email: th.schaefer@bv.tum.de
Web site: http://www.geo.bv.tum.de

Ing. Peter Kyrinovič
Slovak University of Technology, Faculty of Civil Engineering, Department of Surveying
Radlinského 11, 813 68 Bratislava
SLOVAK REPUBLIC
Tel. + 421 2 59274 310
Fax + 421 2 52494 334
Email: peter.kyrinovic@svf.stuba.sk
Web site: http://www.svf.stuba.sk/kat/GDE/

Dipl.-Ing. Thomas Weber
Technische Universität München, Faculty of Civil Engineering & Geodesy, Chair of Geodesy
Arcisstraße 21, D-80290 Munich
GERMANY
Tel. + 49 89 289 22850
Fax + 49 89 289 23967
Email: th.weber@bv.tum.de
Web site: http://www.geo.bv.tum.de

Ing. Miriam Zámečniková
Slovak University of Technology, Faculty of Civil Engineering, Department of Surveying
Radlinského 11, 813 68 Bratislava
SLOVAK REPUBLIC