Automated Point Cloud Processing to Increase the Accuracy of Deformation Monitoring

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Abstract. The weather conditions and the loading during operation cause changes in the spatial position and in the shape of engineering structures that affect static and dynamic function and reliability of these structures. Due to these facts, geodetic monitoring is integral part of engineering structures' diagnosis and gives important information about the current stay (condition) of the structure.

Terrestrial laser scanning (TLS) is one of the most effective technology of data acquisition in cases, which require 3D information with high resolution. This potential predetermines the technology of TLS for use in different surveying application even in deformation monitoring of buildings or engineering structures. TLS allows contactless documentation of the behaviour of monitored structure. This fact increasing the safety and the effectiveness of the measurements. The accuracy of determination of the 3D coordinates of single measured points by currently commercially available laser scanners is several millimetres. The accuracy can be increased using suitable data processing.

The paper presents the possibility of defamation monitoring using TLS. To increase the accuracy of results, chosen parts of the monitored structure can be approximated by single geometric entities (small planar surfaces) using orthogonal regression. In this case the position of measured point (part of structure) is calculated from tens or hundreds of scanned points instead of single measurement. An application based on software MATLAB® - Displacement_TLS was developed for automated data processing. The designed method represents a new approach of deformation monitoring. Benefits of the proposed method for data processing are demonstrated by experimental measurements of different structures and building elements (parts).

Keywords. Terrestrial laser scanning, point cloud, automated data processing, orthogonal regression, deformation monitoring

1 Introduction

The advantage of TLS over conventional surveying methods is the efficiency of the spatial data acquisition. It allows contactless determination of the coordinates of measured points lying on the surface of the monitored structure.

Since TLS is available for wider community or surveyors, structural engineers and civil engineers, it is used for deformation monitoring of different kind of objects. TLS is used for structural monitoring (Soni et al., 2015), (Lovas et al., 2008), (Alba et al., 2006). Also for deformation monitoring of bridges (Zogg et al., 2008), (Kopáčik et al. 2013), or for deformation monitoring of dams (Schneider, 2006), (Schäfer et al, 2004).

The accuracy of the achieved results is in most cases limited by the accuracy of the chosen scan system. The accuracy of discrete point coordinate determination by TLS (several millimetres) can be increased by approximation of chosen parts of the monitored object (Kopáčik et al. 2013). In this case the position of the measured point is calculated from tens or hundreds of scanned points (Vosselman et al. 2011). Using regression algorithms in combination with effective calculation software, the data processing can be significantly automated.

The paper presents the possibility of using the technology of TLS in the field of deformation monitoring of engineering structures. The deformation monitoring of a steel pedestrian bridge construction and the monitoring of a parabolic shaped reinforced-concrete roof structure are described.

2 Deformation monitoring using TLS

The determination of the displacements of structures from laser scanning data is relatively simple when the deformation is determined by differential models (as difference between surfaces), or by measuring the coordinate difference between discrete measured points. In both cases the accuracy of the results depending on the accuracy of the position of scanned points (several millimetres). To increase the accuracy of the results, the measured points (monitored parts of the scanned structure) have to be modelled using regression.

The vertical displacements of the measured points can be determined as the difference between the heights of these points in each measurement epoch. The height of the points can be calculated by modelling planes using orthogonal regression. The position of the measured points in the XY plane can be defined by their coordinates in the plane (Fig. 1).

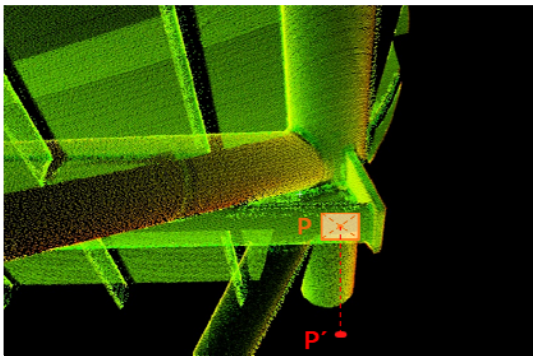

Fig. 1 Determination of the height of measured points

The advantage of this procedure is that the position of the measured points does not change with the thermal expansion of the structure. The heights of the measured points are calculated by projecting the points onto regression planes.

Orthogonal regression is calculated from the general equation of a plane:

$$\mathrm{a}\cdot\mathrm{X}+\mathrm{b}\cdot\mathrm{Y}+\mathrm{c}\cdot\mathrm{Z}+\mathrm{d}=0 \qquad (1)$$

where: a, b and c are the parameters of the normal vector of the plane, X, Y and Z are the coordinates of the point lying in the plane, d is the scalar product of the normal vector of the plane and the position vector of any point of the plane.

For the calculation of the elements of the normal vector is used Singular Value Decomposition (Čepek et al., 2009):

$$\mathbf{A}=\mathbf{U}\mathbf{\Sigma}\mathbf{V}^{\mathrm{T}} \qquad (2)$$

where: **A** is the design matrix, with dimensions *nx3*, and *n* is the number of points used for the calculation. The column vectors of $\mathbf{U}^{nxn}$ are normalized eigenvectors of matrix $\mathbf{AA}^{\mathrm{T}}$. The column vectors of $\mathbf{V}^{3x3}$ are normalized eigenvectors of $\mathbf{A}^{\mathrm{T}}\mathbf{A}$. The matrix $\mathbf{\Sigma}^{nx3}$ contains eigenvalues on the diagonals. Then the normal vector of regression plane is the column vector of **V** corresponding to the smallest eigenvalue from **Σ**.

The design matrix has the form:

$$\mathbf{A}=\begin{pmatrix}(\mathrm{X}_1-\mathrm{X}_0) & (\mathrm{Y}_1-\mathrm{Y}_0) & (\mathrm{Z}_1-\mathrm{Z}_0)\\ (\mathrm{X}_2-\mathrm{X}_0) & (\mathrm{Y}_2-\mathrm{Y}_0) & (\mathrm{Z}_2-\mathrm{Z}_0)\\ \vdots & \vdots & \vdots\\ (\mathrm{X}_n-\mathrm{X}_0) & (\mathrm{Y}_n-\mathrm{Y}_0) & (\mathrm{Z}_n-\mathrm{Z}_0)\end{pmatrix} \qquad (3)$$

where: $(\mathrm{X}_i-\mathrm{X}_0)$, $(\mathrm{Y}_i-\mathrm{Y}_0)$ and $(\mathrm{Z}_i-\mathrm{Z}_0)$ are the coordinates of the point cloud reduced to a centroid.

The position of the observed points in XY plane is defined as fixed. The Z coordinates (heights) of the measured points are calculated by projecting the points onto regression planes (Fig.1) using formula:

$$\mathrm{Z}_{\mathrm{P}}=-\frac{a\cdot\mathrm{X}+b\cdot\mathrm{Y}+d}{c} \qquad (4)$$

The standard deviations of the results are calculated using uncertainty propagation law, from the standard deviation of the vertical component of the transformation error and the standard deviation of the regression planes:

$$\sigma_{Z_P}=\sqrt{\sigma_{T_Z}^2+\sigma_\rho^2} \qquad (5)$$

where: σ_{T_Z} is the vertical component of the error of the data transformation and σ_ρ is the standard deviation of the calculated regression plane. The transformation of the point clouds in each measurement epoch is needed to obtain data in a common coordinate system in each measurement epoch. The accuracy of the transformation is given by the differences (ΔX, ΔY, ΔZ) between the identical reference points after the transformation of the scanned point cloud of the current measurement epoch into the coordinate system of the initial measurement epoch. The standard deviation of the regression planes is calculated from the orthogonal distance of the points of point cloud from these planes. Dispersion of the points around the plane reflects the random error (noise) of the distance measurement by TLS (coordinate determination) mainly. To eliminate the effects of systematic errors it is recommended to perform the measurements in the same conditions in each epoch (position of the scanner, temperature, etc.). The effect of the

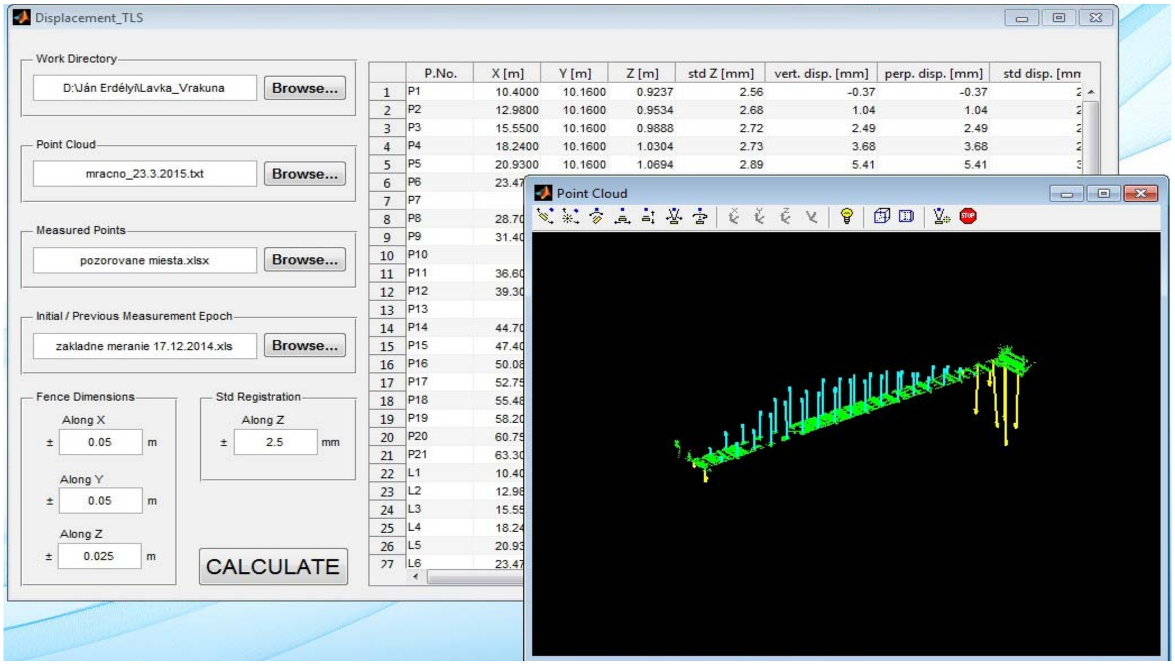

Fig. 2 Print screen of the Displacement_TLS dialog window

systematic errors is included in the accuracy of determination of coordinates of the reference points (stable objects in each epoch).

To get a better imagination about the behaviour of the monitored structure, the vertical displacements can be transformed into the direction of the normal vectors of the regression planes.

An application based on software MATLAB® - Displacement_TLS (Fig. 2) was developed for automated data processing. The above mentioned computational procedure is performed and controlled with help of the graphical user interface of the application. The application was created as a standalone app; however the Matlab Runtime is necessary to be installed. The work with the app is as follows: In the first step the user can choose a work directory in which the resulting files will be saved. The second step is the point cloud file loading in *.txt or *.xyz file format which contains the coordinates of scanned points. The measured points can be arranged in *.xls or *.xlsx file defining the coordinates of the monitored points. The vertical displacements are calculated in the points defined by the mentioned file and are transformed to perpendicular displacements using the normal vectors of planar surfaces. The user can load the resulting file of the previous measurement epoch in the Initial / Previous Measurement box (for comparison of point heights). Without this file the result will be an *xlsx file containing the heights of the measured points. The fencing boxes, selecting part of the point cloud around the measured points (loaded in the Measured Points box), are defined by its dimensions along axis X, Y and Z. The standard deviation of the registration (transformation of point cloud) is necessary for the calculation of the standard deviation of the results using the uncertainty propagation law using (5). The results are shown in the table on the right side of the app's dialog window and are saved into an *.xlsx file in the work directory. A figure which shows the point cloud and the displacement vectors in a relative scale is created for the better imagination of the results.

The above mentioned procedure increases the efficiency of the measurement, since it is not necessary to define the measured point during the scanning (no stabilization no signalization), it is enough to scan the bottom side of the whole structure monitored. The automated data processing using the app Displacement_TLS significantly decreases the time needed for the data processing, which takes only several minutes, since the calculation described in the second section of the chapter is executed automated for all measured points at once. The accuracy of the results increases using the app, too (Chapter 3 and 4).

3 Monitoring of a steel bridge structure

The monitored construction was a pedestrian bridge over the river Malý Dunaj in Bratislava – Vrakuňa (Slovakia). The bridge connects the residential zone with the recreational area of Vrakuňa Forest Park. The substructure consists of two abutments from reinforced concrete in which the supporting pylons are anchored (Fig. 3).

Fig. 3 Pedestrian bridge over the river Malý Dunaj in Bratislava, Slovakia

The main field (54 m length) of the bridge is divided into 10 sections by suspensions. The deck is composed of metal plate (thickness of 10 mm), of steel cross-girders (IPE 270) located in transverse direction in axial distance of 2 m and longitudinal girders (IPE 360 on the sides and IPE 270). The clearance of the bridge deck is 2360 mm. The superstructure is suspended on four pylons (Fig. 3).

3.1 Deformation monitoring of the bridge

Monitoring was performed in two measurement epoch, in December 2014 and in March 2015 using TLS Leica ScanStation2. The instrument is able to scan up to the range of 300 m with a scan rate up to 50,000 points / second. The accuracy of single point measurement is defined at level of 6 mm at 50 m range (one sigma) by the producer (Leica Geosystems).

The bottom part of the suspension bridge deck was scanned from a single position of the scanner (under the deck approximately in the longitudinal axis). The scanner was located in each epoch approximately in the same position to ensure same conditions of the measurement (distance from the instrument, angle of incidence of measuring signal). The reference network consists of four control points stabilized on the abutments of the bridge. All of them were signalized by Leica HDS targets. The points of the reference network define a local coordinate system for the deformation monitoring of bridge. The Z axis of the coordinate system is vertical (defined by the dual axis compensator of the instrument) and the X axis is parallel with the longitudinal axis of the bridge. The minimal point density was 3 mm x 3 mm on the surface of the scanned part of the structure. The weather conditions (air temperature) and temperature of the structure were also measured during the process of the scanning.

The data obtained by the TLS were transformed to the local coordinate system of the bridge. The accuracy of the transformation is given by the differences (ΔX, ΔY, ΔZ) between the common identical reference points after the transformation. The main task of the data processing was to determine the vertical displacements of the bridge. It was performed by modelling of the movement in Z direction of the chosen parts (represented by the measured points) of the structure in each

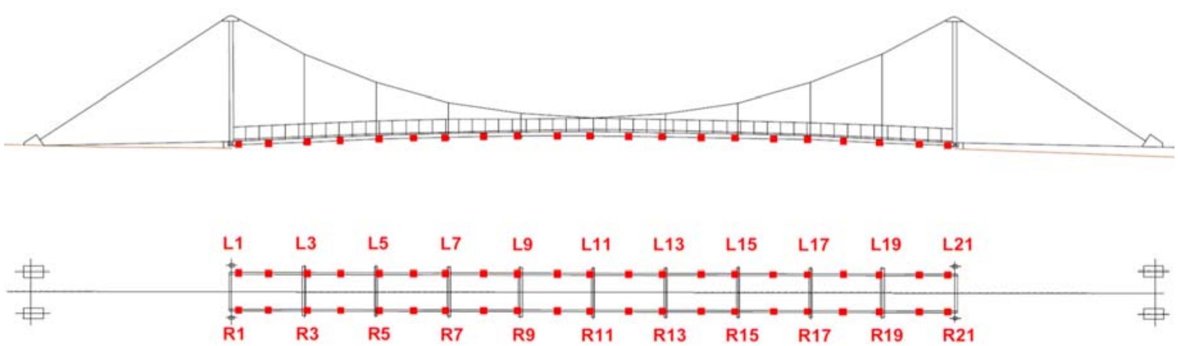

Fig. 4 Scheme of the bridge with the position of measured points

measurement epoch. These points are located on the bottom part of the bridge desk on the side girders IPE 360 at the beginning, in the centre and at the end of each bridge section (Fig. 4). The total number of observed points is 42.

The Z coordinates of the measured point were modelled using small planar surfaces of 0.1 m x 0.1 m using the app Displacement_TLS described in the chapter 2. The position of the measured points in the XY plane is defined as fixed (Fig. 5). From the selected sets of points regression planes were calculated and by projecting the measured points onto this planes their Z coordinates were obtained. The vertical displacement of the points was determined as the difference between the Z coordinates of these points.

The Figure 6 shows the results of the monitoring. The vertical axis represents the vertical displacements of the measured points. The second axis represents the temperature difference between the initial measurement and its change during the scanning (1.5 h). The positive values mean lower temperature in the control measurement epoch. The grey area represents the standard deviation of the displacement in each point (one sigma), it reaches from 2.2 to 3.5 mm (instead of 6mm for the discrete point measurement).

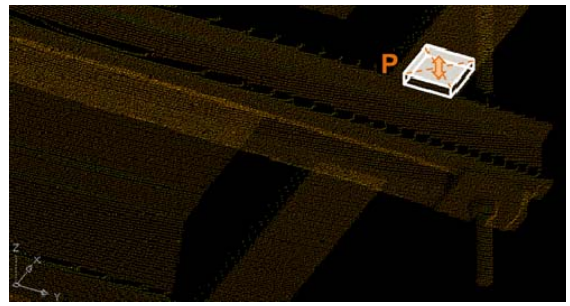

Fig. 5 Definition of the measured point position by fencing box

The displacements towards the centre of the bridge increase and have positive values. In the middle of the bridge they reach values of 7 mm. This is caused by the lower temperature of the structure in the control epoch of the measurement and it corresponds with the theoretical values of deformation. For example: Due to the temperature

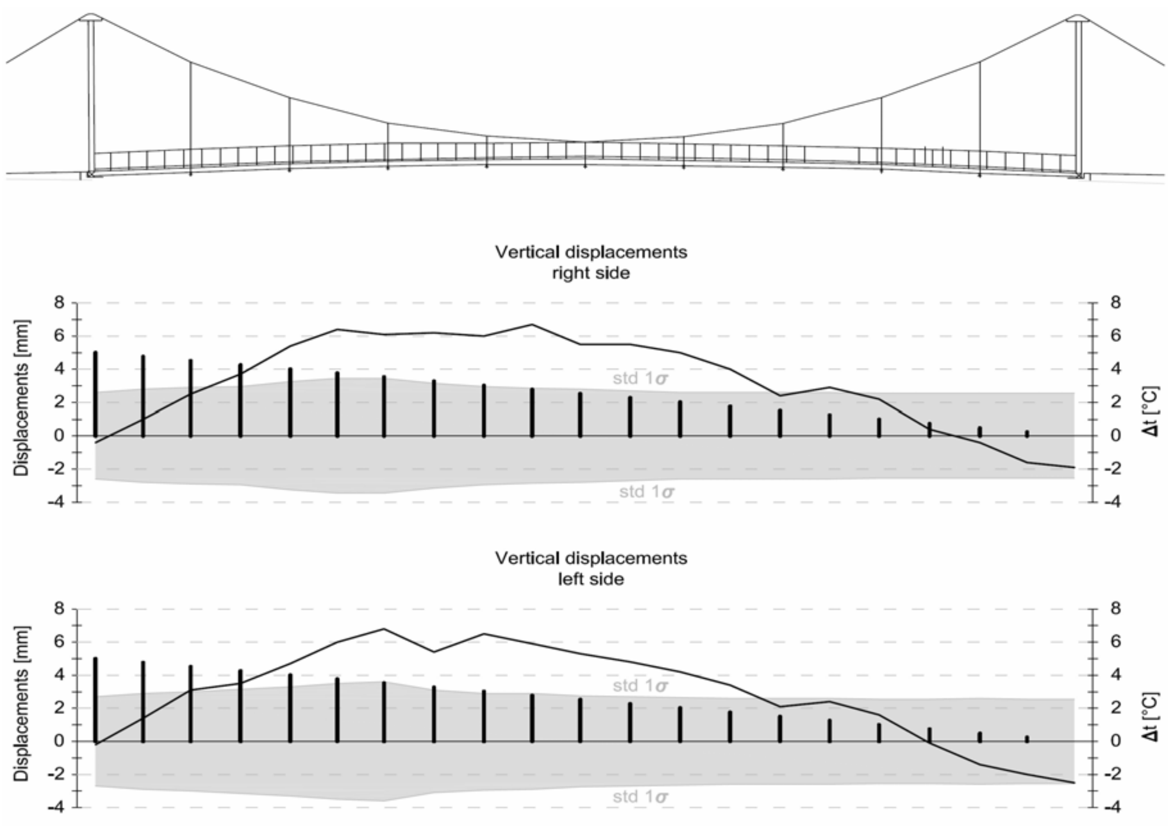

Fig. 6 Vertical displacements of the pedestrian bridge

changes about 3°C, the theoretical value of a displacement in the middle of the bridge deck at the position of anchorage of suspension cables (point No.R11 and L11) is 4 mm. The displacement determined by the measurement is 5 mm on the both sides of the deck (Fig. 6). The difference between the theoretical values and the measured displacements is approximately 20% which is caused by the inaccuracy of static model of the structure. The values of the displacement increase with the temperature difference, too.

4 Monitoring of a parabolic shaped reinforced-concrete roof structure

The measured object is used for storage of fertilizer in the chemical company Duslo, Ltd., Šaľa, Slovakia. It consists of a reinforced concrete structure with dimensions 30 m x 170 m and with height 14 m. On the roof in the middle part of the structure is situated a conveyor along the whole warehouse. The warehouse is founded on foundation strips (with dimensions 3.7 m x 172.0 m x 1.5 m) and is divided into 5 blocks (Fig. 7).

The roof consists of a parabolic shaped reinforced concrete structure with parabolic transverse beams (with axial distance 4.8 m). The warehouse was built in year 1960. The operation load of the conveyor, and the weather conditions caused deformation of the roof structure during the decades of operation. The mentioned reasons caused a shift approximately 150 mm between the 1st and the 2nd block, which is visible at the dilatation.

The aim of the measurements was the geodetic monitoring of the parts of the roof structure near the dilatation joints, and the determination of the rate of changes.

Fig. 7 The structure of the warehouse

4.1 Deformation monitoring of the roof

Considering the unclear cause of deformations, the monitoring was designed to be able not only to quantify the movements of the mentioned parts of the roof structure, but even the eventual motions of foundations. The measurements were done in 5 epochs during 2 years, in October 7th 2013, October 21st 2013, December 2nd 2013, March 6th 2014 and October 2nd 2014. The aim of the monitoring was to determine the rate of the displacements, and to determine their influence to the secure operation. The deformations of the roof structure were monitored using terrestrial laser scanning, and the behavior of the foundations was measured by precise levelling.

The height of 8 measured points (N1.1-N2.4) was determined relative to the height of 3 control points (VB1-VB3) by precise levelling in a local height system. The control points are situated near the monitored object, in the footings of the pylons of a pipeline nearby the warehouse. These are stabilized by ground benchmarks. The stability of the reference net was determined comparing the height differences between the points in each epoch.

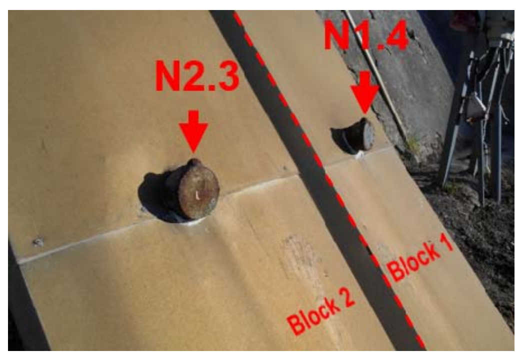

Fig. 8 Measured points – precise levelling

The measured points are situated on the beginning and end of 1st and 2nd block on the both sides of the warehouse. The points are stabilized by wall benchmarks in the bottom part of the parabolic transverse beams (Fig. 8). The vertical displacements of these points were determined as the difference between the heights of these points in each epoch. The statistical significance of the displacements was determined on the basis of the statistical analysis using interval estimates.

The measurement did not shown any displacements of the observed points. Due to the results of precise levelling, it can be assumed that

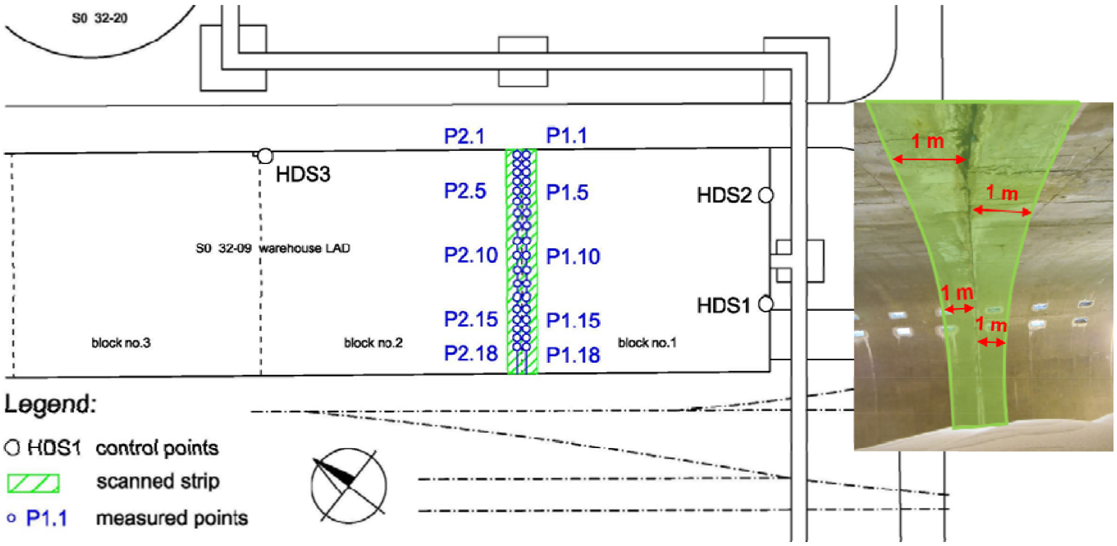

Fig. 9 Position of measured points – TLS

the foundation strips of the structure are stable, or the movements are slow without influence to the security.

The monitoring of the roof structure was performed using TLS Leica ScanStation2. The bottom side of the roof was scanned from a single position of the scanner in each measurement epoch. Scanned was a 1 m wide strip on the both sides of the dilatation (Fig. 9). The scanner was positioned in each epoch approximately in the same position to ensure same conditions of the measurements (distance from the scanner, angle of incidence of the measuring signal).

The reference network consists of 3 control points stabilized on the pillars of the warehouse frame by metallic fasteners (it was possible due to the stability of the foundations). All of the control points were signalized by the Leica HDS targets. To improve the efficiency of the measurement, a simple script was defined before the scanning in each epoch. The script defines separate field of scanning for different parts of the structure, the scan resolution in each field, and the target acquisition. The minimal point density on the surface of the roof was 10 mm x 10 mm.

The data obtained by the TLS were transformed to a local coordinate system. The accuracy of the transformation was calculated from the differences between the common identical points after the transformation. The main task of the data processing was modelling the vertical displacements of the measured points using the app Displacement_TLS (modelling by small regression planes 0.1 m x 0.1 m). These are positioned on the bottom side of the roof every 2 m on the both sides of the dilatation (Fig. 9). Their XY coordinates were defined as fixed. The app selects approximately the same set of points around of these points in each measurement epoch. Their Z coordinates were calculated by projecting their positions in the XY plane onto the regression planes. The vertical displacements were calculated as the differences between the Z coordinates of measured points in initial and current measurement epoch. The vertical displacements were transformed to orthogonal displacements along the normal vector to the surface in each part of the structure. The statistical significance of the displacements was determined on the basis of the statistical analysis using interval estimates. The standard deviation of the displacements was less than 2.5 mm in any cases (instead of 6mm for the discrete point measurement defined by the producer of the instrument used). The Fig. 10 shows the graphical representation of the displacements of the selected points between the initial measurement (October 7th 2013) and the 2nd measurement epoch (October 21st 2013). The results of all measurement epoch confirmed that the displacements (movements) of the structure does not influence the safety operation of the warehouse. The changes are caused mainly by weather conditions. The above mentioned shift of 150 mm is caused by other factor, which was the part of the research of structural engineers.

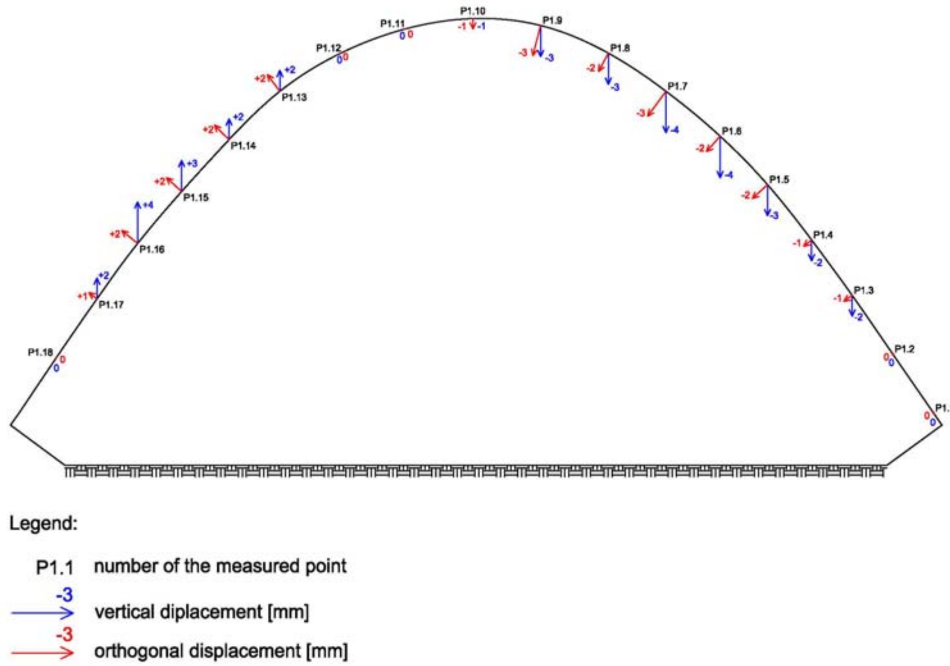

Fig. 11 Vertical and perpendicular displacements of the roof structure

5 Conclusion

The results of the experimental measurements described in this paper show that TLS technology can be used to determine the displacements of different structures. To increase the accuracy of the results, selected parts of the monitored structure have to be approximated by single geometric entities using regression. An application based on software MATLAB® - Displacement_TLS was developed for automated data processing. The designed method represents a new approach of deformation monitoring. Benefits of the proposed method for data processing are demonstrated by experimental measurements of a steel pedestrian bridge structure and a parabolic shaped reinforced-concrete roof structure.

„This work was supported by the Slovak Research and Development Agency under the contract No. APVV-0236-12“.

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