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The Horizontal Deformation Analysis of High-rise Buildings

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Abstract. The horizontal deformation analysis of high-rise buildings, quite often is complicated because buildings like chimneys, towers and etc, have complex and asymmetric shapes, consequently there is not always the possibility to apply the method of single points motion analysis. Furthermore, the horizontal deformation analysis is complicated using standard measurement methods like measurements with electronic total stations or optical theodolites. In such case the terrestrial laser scanner could be superior to traditional measurements. However, the terrestrial laser scanner still not widely used to survey building horizontal deformations using high precision measurements. The main aim of this work is to determine the suitability to measure deflections of buildings from the vertical using terrestrial laser scanners and to investigate point cloud data processing. Measurements of horizontal deformation were carried out using the over ground laser scanner and electronic total station. Horizontal deformations of chimneys of thermal power plants were investigated using corresponding methods. Deformation indicators and evaluated measurement accuracies between different methods were compared. Data analysis of terrestrial laser scanning is more complex, time consuming and requires sophisticated hardware resources in comparison with the traditional methods, however results are much more detailed and informative.

Keywords: deformations, vertical deflection of buildings, terrestrial laser scanner, geodetic observations.

Conference topic: Technologies of geodesy and cadastre.

Introduction

Deformation measurements of large structures, especially building tall buildings (chimneys, cooling towers, television towers and poles, water towers, etc.) are one of the most important issues of surveying engineering. A chimney is a necessary part of a heat-producing plant, a refinery and many other types of industrial buildings. It poses potential dangers for human safety and property because if it collapses, it may cause immeasurable damage to human lives and wealth. It is essential to monitor and measure the chimney deformation on a regular basis. The main task of the deformation measurement is to measure inclination of the centerline of a chimney from the vertical, while it only can be determined indirectly (Zheng *et al.* 2012). Measurement devices and techniques in this field are mainly based on the monitoring of discrete points (Kregar *et al.* 2015). Despite of the development of the innovative monitoring engineering techniques, in practice, traditional measurement methods are still widely used. Besides classical techniques, for the recording of surfaces nowadays laser scanners are used, which acquire dense point clouds in very short time (Uchański, Soerensen 2010). Small-scale deformation monitoring using terrestrial laser scanning is gaining considerable attention mainly due to the high spatial resolution of the acquired data (Tsakiri *et al.* 2006). As highlighted in numerous previous research works, TLS can provide surveyors with the means to conduct far more complete (dense) measurements in relatively short time. This would lead to more reliable dimensional control results, despite the fact that single point precision is mostly not sufficient (Girardeau-Montaut *et al.* 2005; Park *et al.* 2007). It appears that precision potential in these applications is not limited by the single point accuracy of laser scanners, since surface elements derived from a large number of points are used for deformation analysis (Tang *et al.* 2010; Bosche, Haas 2008; Schneider 2006).

In article, we present a comparison of TLS and classical deformation measurement of two chimneys. In TLS approach the point cloud was cut into thin layers and projected onto 2D planes in different height levels. Then a cylinder-fit algorithm was applied to these cross section point clouds, where the center points of the cylinders have a much higher precision than single laser scanner points (Akca 2004). The connection of center points of these cylinders at different heights represents the centerline (axis) of the chimney. The comparison with the results from total station measurements also presented.

Measurement methods and research object

The research object is two chimneys of joint-stock company "Vilniaus energija" in small town Trakų Vokė. The height of both chimneys are about 20 m and the diameters at the bottom are 0,74 m and 0,94 m respectively. Chimneys are part of heat producing facility located in Trakų Vokė.

To establish the geodetic control network for chimneys deformation monitoring the benchmarks were measured with GNSS receivers using LITPOS continuously operating GNSS stations network data as reference stations. For classical horizontal deformation measurements electronic total station Leica TCRP1200+, with angular accuracy of 1″ was used, and for TLS measurements laser scanner Leica Scanstation C10 with angular accuracy of 12″ was tested.

In most cases, deformation monitoring is performed by using electronic total stations. First of all the exact coordinates and heights of the monitoring benchmarks are derived and adjusted using geodetic methods. From these benchmarks the cross-sections at selected heights are measured. It is important that measurements from all stations is performed bisecting the same height (cross section) of the chimney. Chimney deformation is reflected by center displacement of each chimney cross-section. Measurements were carried from two stations at 6 cross-sections evenly distributed along the chimney (Fig. 1).

Terrestrial laser scanning is considered faster and more progressive geodetic measurement method. The terrestrial laser scanner position and orientation was set using three high reflective targets. Position of these targets was measured with electronic total station from the same geodetic control network points used in classical approach. The targets were positioned in a way that they will be visible from both measuring stations, and provided good geometric distribution for scanner position determination. Observations with the terrestrial laser scanner covered whole chimneys, not just chosen cross-sections (Fig. 2).

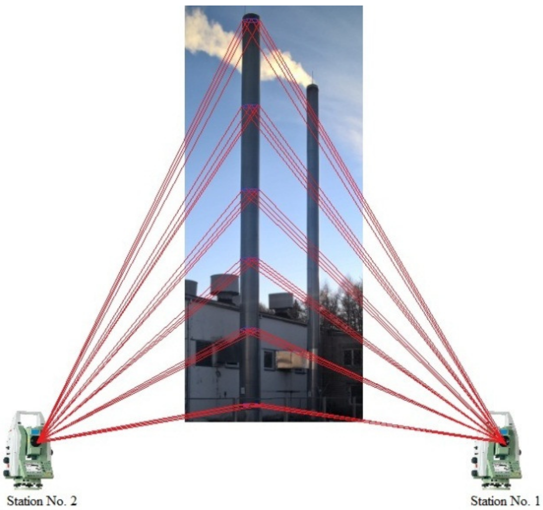

Fig. 1. Measurement setup using electronic total station

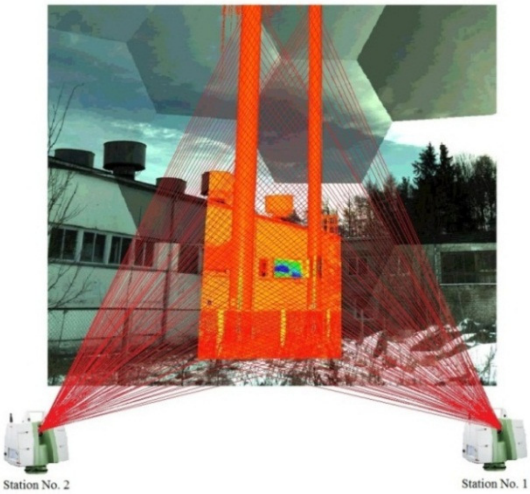

Fig. 2. Measurement setup using terrestrial laser scanner

Processing of measurement data.

The observed chimneys have cylindrical shape, therefore cross-sections has a circular form. In order to determine deviations from the vertical it is necessary to calculate the centers of the circles of each cross-section from measured points. The circle center coordinates are calculated according to the following formulas.

Circle arc points and the coordinates of the center can be linked with the radius by the equation:

$$(x_i - x_C)^2 + (y_i - y_C)^2 = R^2.$$

Here x_i and y_i – coordinates of chimney surface points in the corresponding cross-section, x_C ir y_C – the coordinates of a center of the cross-section, R – radius of the chimney cross-section.

After performing some mathematical operations:

$$x_i^2 - 2x_i x_C + x_C^2 + y_i^2 - 2y_i y_C + y_C^2 - R^2 = 0;$$

$$\tau_1 = 2x_C;$$

$$\tau_2 = 2y_C;$$

$$\tau_3 = x_C^2 + y_C^2 - R^2;$$

$$l_i = x_i^2 + y_i^2.$$

For each measured point we receive correction equation:

$$v_i = -x_i\tau_1 - y_i\tau_2 + \tau_3 + l_i.$$

Applying correction equations for each measured point and using the least squares approach to find unknowns τ_i we can estimate radius and center coordinates of the circle:

$$\begin{cases} x_C = \frac{\tau_1}{2} \\ y_C = \frac{\tau_2}{2} \end{cases};$$

$$2R = \sqrt{\tau_1^2 + \tau_2^2 - 4\tau_3}.$$

Using the formulas above, cross-section center coordinates of both chimneys was calculated and chimneys deviations from the vertical were estimated. Deviations were estimated in each cross-section with respect to the lowest cross-section.

In each cross-section 8 surface points of the chimney were measured using total station. Estimated vertical deviations of the chimneys from total station measurements presented in tables 1 and 2, and figure 3 and 4.

Table 1. Vertical deviations of chimney No.1 (total station measurements)

Cross-section No.	Center coordinates, m		Height of the cross-section, m	Cross-section height from the chimney base m	Deviation from the vertical, mm			Azimuth	Orientation
	x_C	y_C			Δx_T	Δy_T	Δl_T		
bottom	–	–	154,36	0,00	–	–	–	–	–
1	6 055 318.673	571 389.061	154.45	0.09	0	0	0	0°	–
2	6 055 318.661	571 389.062	157.82	3.46	–12	1	12	175°	SE
3	6 055 318.674	571 389.076	161.39	7.03	1	15	15	86°	NE
4	6 055 318.695	571 389.088	165.00	10.64	22	27	35	51°	NE
5	6 055 318.687	571 389.108	168.58	14.22	14	47	49	73°	NE
6	6 055 318.724	571 389.126	172.18	17.82	51	65	83	52°	NE
top	–	–	173.83	19.47	–	–	–	–	–

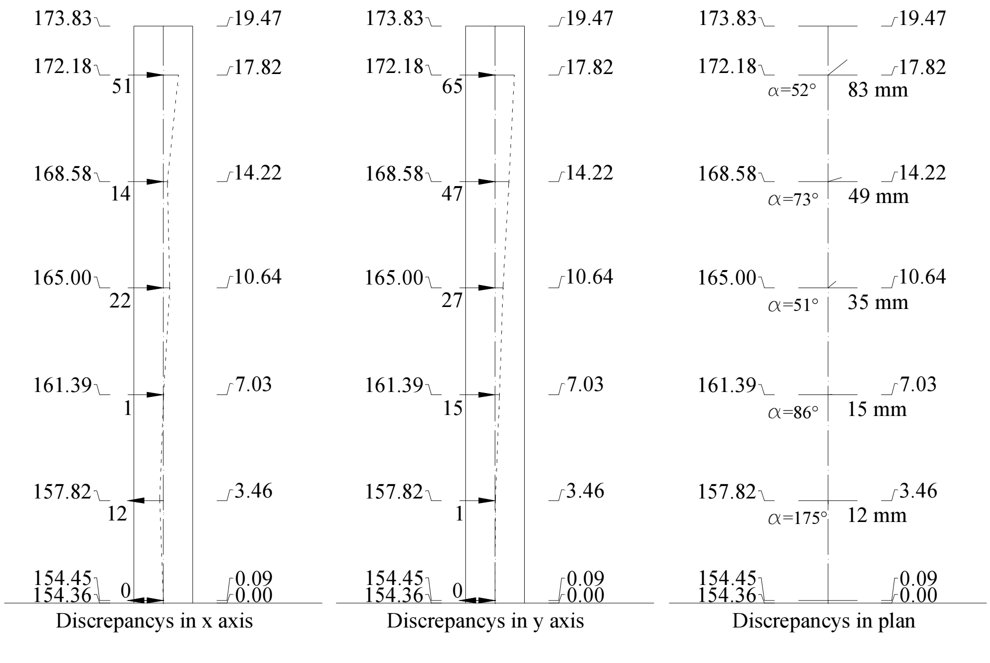

Fig. 3. Vertical deviations of chimney No. 1 (total station measurements)

Table 2. Vertical deviations of chimney No. 2 (total station measurements)

Cross-section No..	Center coordinates, m		Height of the cross-section, m	Cross-section height from the chimney base m	Deviation from the vertical, mm			Azimuth	Orientation
	x_C	y_C			Δx_T	Δy_T	Δl_T		
bottom	–	–	154.50	0.00	–	–	–	–	–
1	6 055 325.391	571 388.992	154.55	0.05	0	0	0	0°	–
2	6 055 325.389	571 389.011	157.92	3.42	–2	19	19	96°	SE
3	6 055 325.382	571 389.016	161.48	6.98	–9	24	26	111°	SE
4	6 055 325.390	571 389.023	165.05	10.55	–1	31	31	92°	SE
5	6 055 325.403	571 389.023	168.67	14.17	12	31	33	69°	NE
6	6 055 325.420	571 389.010	172.28	17.78	29	18	34	32°	NE
top	–	–	173.92	19.42	–	–	–	–	–

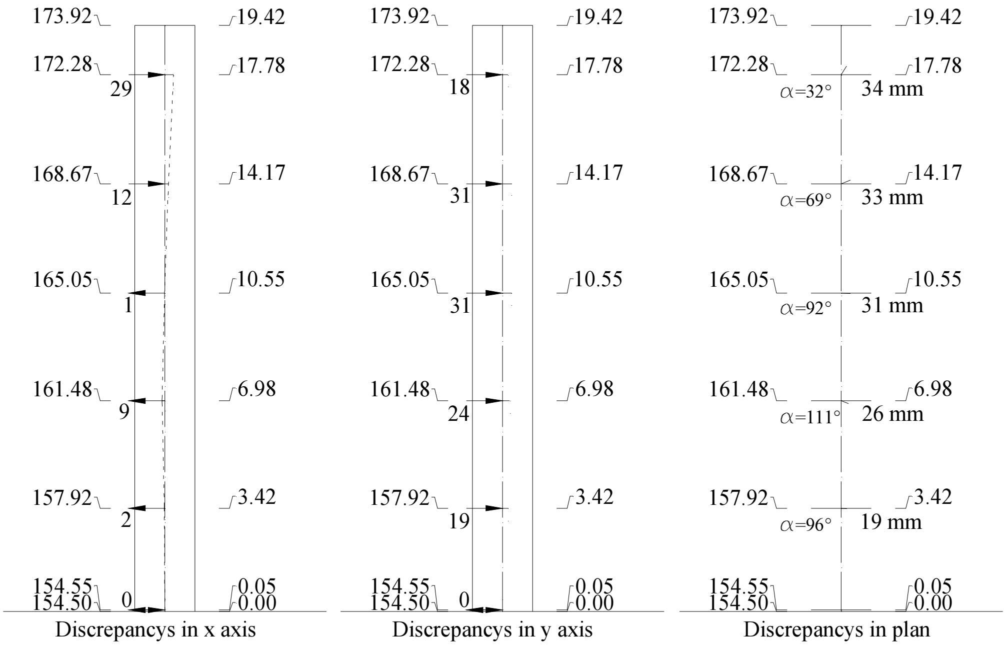

Fig. 4. Vertical deviations of chimney No. 2 (total station measurements)

Measurements with terrestrial laser scanner were performed with density 1point/1mm^2 across all surface of the chimney. From the point cloud 8 thin layers in different height levels (the same heights as total station measurements) was cut and center coordinates of these point cloud cross-sections were estimated. Center coordinates of each cross-section were computed from around one thousand points.

Estimated vertical deviations of the chimneys from TLS measurements presented in tables 3 and 4, and figures 5 and 6.

Table 3. Vertical deviations of chimney No.1 (TLS measurements)

Cross-section No..	Center coordinates, m		Height of the cross-section, m	Cross-section height from the chimney base m	Deviation from the vertical, mm			Azimut h	Orientation
	x_C	y_C			Δx_S	Δy_S	Δl_S		
1	2	3	4	5	6	7	8	9	10
bottom	–	–	154.36	0.00	–	–	–	–	–
1	6 055 318.677	571 389.065	154.48	0.12	0	0	0	0°	–

End of Table 3

1	2	3	4	5	6	7	8	9	10
2	6 055 318.666	571 389.062	157.81	3.45	–11	–3	11	195°	SW
3	6 055 318.680	571 389.077	161.34	6.98	3	12	12	76°	NE
4	6 055 318.700	571 389.093	165.01	10.65	23	28	36	51°	NE
5	6 055 318.694	571 389.109	168.58	14.22	17	44	47	69°	NE
6	6 055 318.730	571 389.128	172.18	17.82	53	63	82	50°	NE
top	–	–	173.83	19.47	–	–	–	–	–

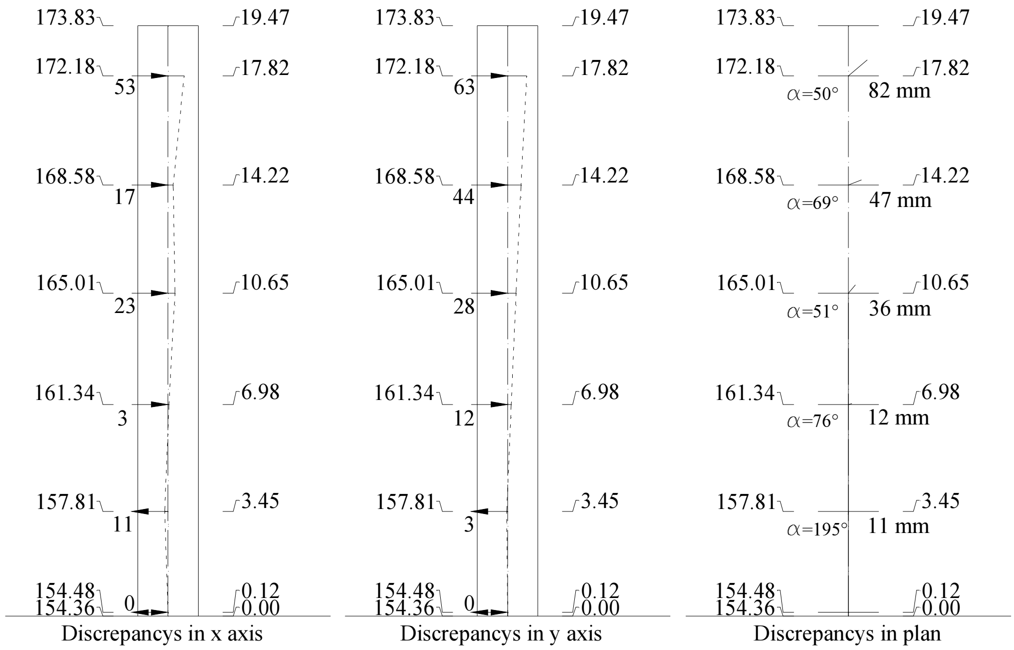

Fig. 5. Vertical deviations of chimney No. 1 (TLS measurements)

Table 4. Vertical deviations of chimney No. 2 (TLS measurements)

Cross-section No..	Center coordinates, m		Height of the cross-section, m	Cross-section height from the chimney base m	Deviation from the vertical, mm			Azimuth	Orientation
	x_C	y_C			Δx_S	Δy_S	Δl_S		
bottom	–	–	154.50	0.00	–	–	–	–	–
1	6 055 325.394	571 388.993	154.61	0.11	0	0	0	0°	–
2	6 055 325.392	571 389.011	157.96	3.46	–2	18	18	96°	SE
3	6 055 325.386	571 389.017	161.43	6.93	–8	24	25	108°	SE
4	6 055 325.394	571 389.023	165.01	10.51	0	30	30	90°	E
5	6 055 325.407	571 389.027	168.67	14.17	13	34	36	69°	NE
6	6 055 325.425	571 389.013	172.28	17.78	31	20	37	33°	NE
top	–	–	173,92	19,42	–	–	–	–	–

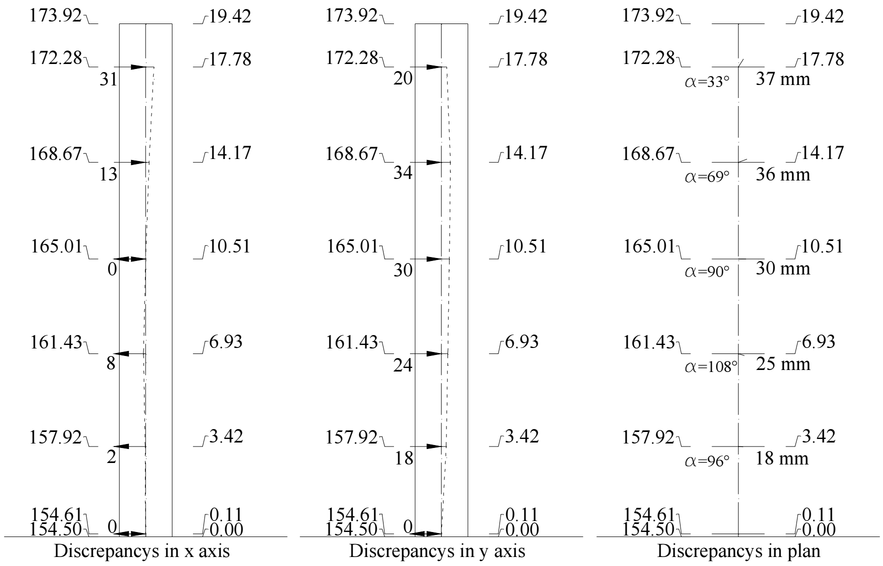

Fig. 6. Vertical deviations of chimney No. 2 (TLS measurements)

In the tables above, the center coordinates of the cross-sections expressed in LKS94 coordinate system, normal heights in LAS07 height system and the relative heights of the chimney expressed in relation with the bottom of the chimney. There are coordinate differences (chimney deviations from the vertical) in x and y components and linear deviation presented as well.

Comparison of the results

We compared estimated chimney deviations of the vertical from different measurement methods.

Deviation determination was done using the two methods and assuming that they have more less same accuracy, chimney deviation accuracy assessment was carried out by double measurements differences.

$$m = \sqrt{\frac{\sum_{i=1}^{n} \varepsilon_i^2}{2n}},$$

where: ε – differences of double measurements, n – number of differences.

It is also possible to calculate the deviations from the averages from the two methods, then the mean squared error of the deviation is:

$$m_v = m/\sqrt{2}.$$

Deviation accuracy assessments presented in tables 5 and 6.

Table 5. Deviation accuracy assessment of chimney No.1

Cross-section No.	Deviation from the vertical from total station measurements, mm			Deviation from the vertical from TLS measurements, mm			Differences of deviations		
	Δx_T	Δy_T	Δl_T	Δx_S	Δy_S	Δl_S	ε_x^2	ε_y^2	ε_l^2
1	0	0	0	0	0	0			
2	–12	1	12	–11	–3	11	1	16	1
3	1	15	15	3	12	12	4	9	9
4	22	27	35	23	28	36	1	1	1
5	14	47	49	17	44	47	9	9	4
6	51	65	83	53	63	82	4	4	1
						Σ	19	39	16
						m	1.4	2.0	1.3

Table 6. Deviation accuracy assessment of chimney No. 2

Cross-section No.	Deviation from the vertical from total station measurements, mm			Deviation from the vertical from TLS measurements, mm			Differences of deviations		
	Δx_T	Δy_T	Δl_T	Δx_S	Δy_S	Δl_S	ε_x^2	ε_y^2	ε_l^2
1	0	0	0	0	0	0			
2	–2	19	19	–2	18	18	0	1	1
3	–9	24	26	–8	24	25	1	0	1
4	–1	31	31	0	30	30	1	1	1
5	12	31	33	13	34	36	1	9	9
6	29	18	34	31	20	37	4	4	9
						Σ	7	15	21
						m	0.8	1.2	1.4

Differences in chimney deviation results do not exceed 4 mm. The calculations shows that root mean square (RMS) error is less than 2 mm then single method is used, and RMS error does not exceed 1.4 mm then the average of the both methods is used.

Conclusions

1. The analysis and comparison of deviation results suggests that TLS is suitable tool for deformation monitoring
2. A measurement with terrestrial laser scanner allows more precisely determine the center of the cross-section due to huge amount of points, despite the fact that single point precision is lower than total station.
3. Using point cloud data we can calculate any required cross-section at any height. Overall scan creates much more detailed and complete data set.

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