Vertical Displacements Analysis of Measurements Achieved by Laser Station

Jacek Sztubecki [1], Adam Bujarkiewicz [1], Maria Mrowczynska [2]

[1] Faculty of Civil and Environmental Engineering and Architecture, University of Science and Technology, Kaliskiego 7, 85-796 Bydgoszcz, Poland

[2] Department of Land and Environment Engineering, Institute of Civil Engineering, University of Zielona Gora, Szafrana 1, 65-516 Zielona Gora, Poland

jaceksz@utp.edu.pl

Abstract. Measurements of vertical displacements using geodetic methods consist in the determination of changes in the location of reference points on the object or of its whole components. Such measurements require a high accuracy which can be ensured by the application of appropriate measuring instruments and measurement technologies. Modern measurement methods enable us to undertake tasks which traditional methods could not handle, and the required precision is guaranteed. This article describes an analysis of measurements of vertical displacements taken by means of a coordinate laser station, Leica TDRA 6000, as an alternative for measurements performed by precise levelling. An original approach to the stabilisation of measurement points is presented and technical guidelines for measurements are provided. An analysis of the data obtained from the measurements allowed us to formulate conclusions regarding the measurement technology in question and the accuracy of the results.

1. Introduction

Results of geodetic surveys are particularly important for the identification of the influence of external factors and the impact of the structure on civil engineering structures. They provide information in the form of data describing the behaviour of such structures. Geodetic monitoring, comprising measurements and their interpretation, makes it possible to reach specific conclusions on the dynamic of occurrence of changes in structures [1, 2].

The main symptom of unfavourable changes happening to civil engineering structures is the occurrence of vertical displacements of reference points on a control and measurement network representing the relevant structure [3]. The most common method of determination of vertical displacement in civil engineering structures is precise levelling. In this method, measurements are taken using a high-precision automatic level. The accuracy of the levels ranges from 0.2 mm to 0.7 mm per kilometre double run.

Displacements and deformations of structural components can also be examined using laser stations. Laser technology ensures a high degree of precision, reaching +/- 15 µm + 6 µm/m using a retroreflector, and the operating range of up to 120 m [4, 5]. The Leica TDRA 6000 total station is an example of a measuring instrument of improved accuracy (figure 1).

IOP Conf. Series: Earth and Environmental Science **95** (2017) 032003 doi:10.1088/1755-1315/95/3/032003

Figure 1. Leica TDRA 6000 laser station

The main features which distinguish TDRA 6000 from other total stations is its certified distance measurement with a standard error of ± 0.1 mm and vertical and horizontal measurement with a standard error of 1.3^{c} (0.42”). An accuracy like this is attainable in the high-precision measurement mode with a 1.5” RRR reflector.

This article focuses on the analysis of the measurements of vertical displacements of a network of benchmarks set on a civil engineering structure, taken by means of the above-mentioned laser station. Following lab tests, a few series of field tests were performed.

2. Lab tests

The usefulness of a laser station for the examination of vertical displacements was evaluated through a series of measurements in laboratory conditions. A simple beam model with a length of 1 m was used (a schematic representation of the test model is shown in figure 2) to measure the deflection at its centre point under static load ranging from 0 to 12 kg. The measurements were all taken simultaneously by means of the TDRA 6000 laser station and an Ni 007 automatic precision level. All observations were carried out at a distance of 5 m and 20 m from the model.

In the static test, the results were the readings obtained from a precision level rod by means of the Ni 007 level and from the coordinates of the precision reflector by means of the TDRA 6000 unit.

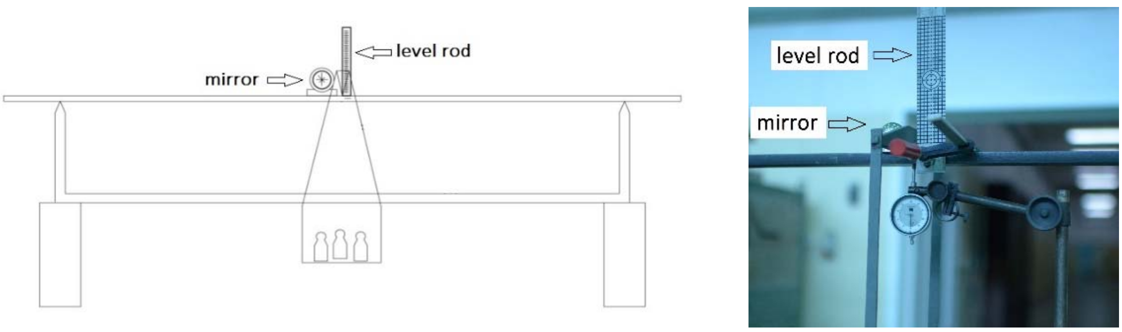

Figure 2. Model of a simple steel beam

Based on the measurements, values of vertical displacement between subsequent states of the loaded beam were calculated. The results are shown in table 1 and diagrams 1 and 2 below.

Table 1. The results of beam deflection.

No.	Weight	Deflection			
		distance 5m		distance 20m	
		TDRA	Leveling	TDRA	Leveling
	[kg]	[mm]	[mm]	[mm]	[mm]
1	0	0,00	0,00	0,00	0,00
2	2	0,25	0,19	0,28	0,22
3	4	0,44	0,43	0,55	0,49
4	6	0,68	0,68	0,76	0,73
5	8	0,91	0,90	1,05	0,99
6	10	1,16	1,15	1,34	1,21
7	12	1,39	1,40	1,50	1,50
8	10	1,14	1,14	1,30	1,26
9	8	0,92	0,91	1,06	1,02
10	6	0,69	0,68	0,78	0,68
11	4	0,47	0,44	0,58	0,53
12	2	0,20	0,25	0,31	0,27
13	0	0,04	-0,01	0,01	0,00

An analysis of the results demonstrated that with the sight line of 5 m the maximum difference in the deflection obtained using both methods was -0.06 mm, whereas with the sight line of 20 m it was -0.13 mm. The maximum differences fall within the accuracy range of the measurements, which indicates that both methods used for the static test were comparable.

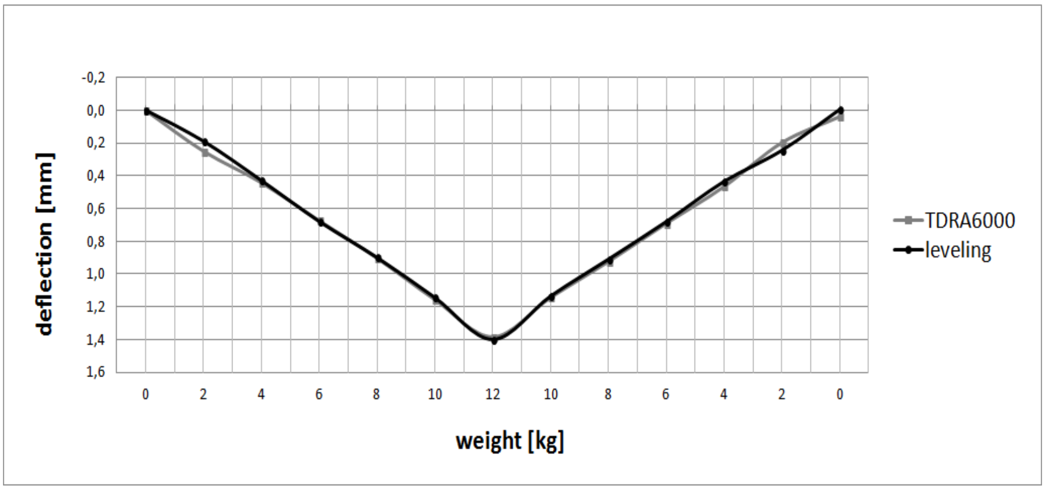

Figure 3. Beam deflection measured from 5 m

For both methods, the standard estimation error in the linear regression was 0.02 mm for the measurements taken at a distance of 5 m, and 0.05 mm for the 40 m distance.

On comparison, it was established that increasing the distance from the measured model led to a greater difference between the results obtained using the two methods. On the other hand, the maximum differences between individual values of deflection measured at the two test sites did not exceed 0.2 mm.

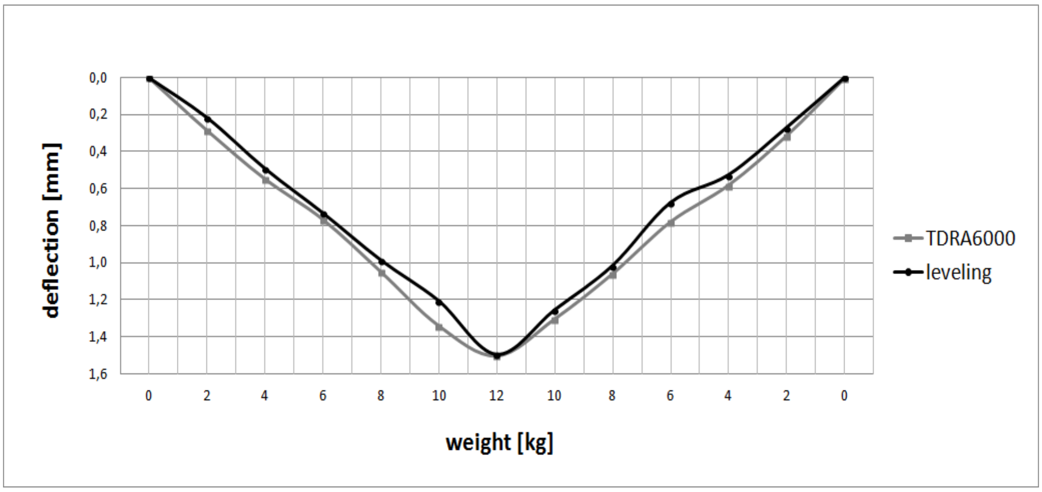

Figure 4. Beam deflection measured from 20 m

3. Field tests

Considering that the static load results obtained on the simple beam model in laboratory conditions were very promising, it was reasonable to verify these on an actual civil engineering structure. Therefore, four series of measurements were taken on a network of marked benchmarks on Building No. 3.1 of the University of Science and Technology in Bydgoszcz, shown in figure 5.

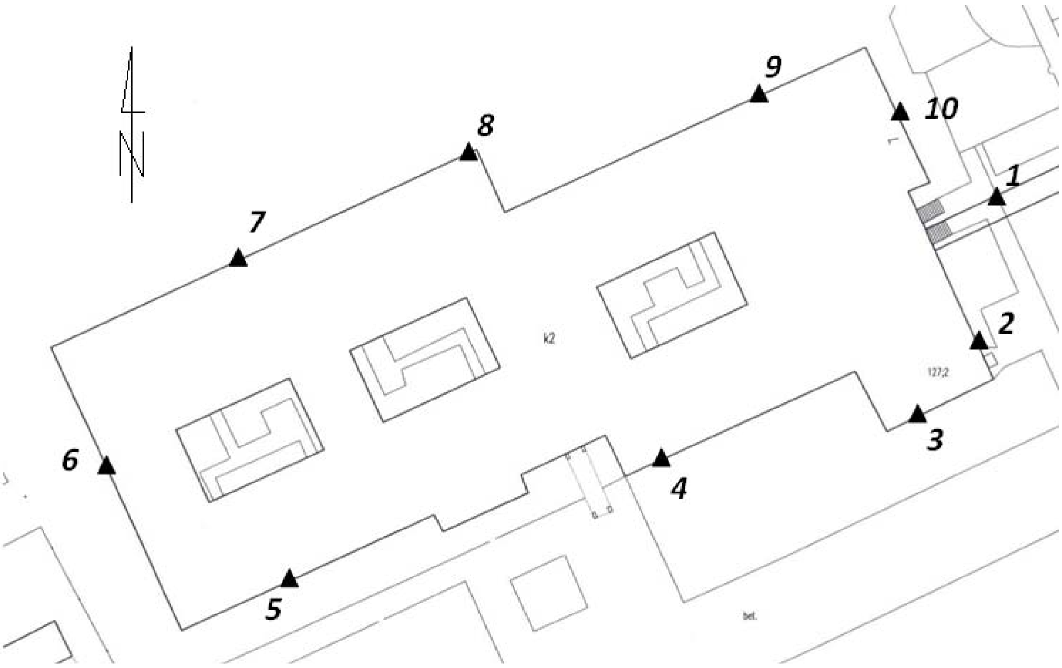

Figure 5. Benchmark network

Measurements were taken by means of the above-described Leica TDRA 6000 total station. To this end, a milled nut was fixed to each benchmark to serve as a stable base for the 1.5” RRR prism. Figure 6 shows a representative arrangement.

IOP Conf. Series: Earth and Environmental Science **95** (2017) 032003 doi:10.1088/1755-1315/95/3/032003

Figure 6. Placement of the 1.5” RRR reflector on a benchmark

The difference of height between individual benchmarks was measured at fixed sight lines, not exceeding 30 m. At each site, measurements were taken with the height of the laser station changed at least twice, making sure that the relevant deviation fell within the permissible limits. After each point of the network was measured, an initial verification of the survey was carried out, adding and comparing the height differences in the loop. The results are listed in Table 2

Table 2. Results of measurement.

Point No.	**Height difference [mm]**				**Point No.**
	Measurements and dates				
	1st 2016.12.12	**2nd 2016.12.31**	**3rd 2017.04.04**	**4th 2017.05.12**	
1					1
	-18.0	-18.1	-18.3	-18.3	
2					2
	377.2	377.2	377.0	376.8	
3					3
	1223.6	1224.2	1224.0	1223.7	
4					4
	5.1	5.1	5.0	3.9	
5					5
	-295.7	-295.7	-295.5	-295.4	
6					6
	253.0	253.0	253.5	253.6	
7					7
	-178.2	-178.3	-178.4	-178.3	
8					8
	62.8	62.8	63.2	63.8	
9					9
	-321.2	-321.2	-321.2	-321.0	
10					10
	-1108.6	-1109.1	-1108.9	-1108.5	
1					1
Total	**0.0**	**-0.1**	**0.4**	**0.3**	

When looking into the results of the verification, it is noticeable that the maximum deviation from the closed-loop was 0.4 mm, which – transferred into a mean measurement error – is 0.13 mm.

A differential method is usually applied to examination of displacements, as it largely eliminates the influence of systematic errors [1]. Using the differences in observed results the values of displacement should be obtained through appropriate conversions, provided that the reference system is correctly defined. The determination of vertical displacements was effected by adjusting the changes in height differences of the control and measurement network using an intermediate method at minimum restriction of the degrees of freedom, presuming that Point No. 3 is constant [6].

In the process of adjustment, the values of vertical displacement of the control and measurement network points were determined, as well as the errors of height differences and the errors of obtained displacement values, which were critical for this paper. The values of the error of height difference were as follows:

- 0.03 mm from the adjustment of *Measurement 1 – Measurement 2*,
- 0.12 mm from the adjustment of *Measurement 1 – Measurement 3,*
- 0.09 mm from the adjustment of *Measurement 1 – Measurement 4*.

The values of the error of height differences did not exceed 0.12 mm, which is consistent with the mean error of height difference obtained on the basis of the non-closed loop, as above.

All values of the error of obtained displacements are presented in Table 3.

Table 3. Errors of obtained displacements.

Point No.	**Displacement error [mm]**			**Point No.**
	Measurements			
	1 – 2	**1 – 3**	**1 – 4**	
1	0.04	0.16	0.12	1
2	0.03	0.12	0.09	2
4	0.03	0.12	0.09	4
5	0.04	0.16	0.12	5
6	0.05	0.18	0.14	6
7	0.05	0.20	0.15	7
8	0.04	0.18	0.13	8
9	0.05	0.20	0.15	9
10	0.05	0.18	0.14	10

The values of the obtained error of displacement did not exceed 0.20 mm, which falls within the generally accepted accuracy of measurement.

4. Summary and conclusions

More and more advanced technologies used in measuring instruments make them applicable to new and unusual tasks. This article shows some possibilities of using the Leica's TDRA 6000 total station to determine vertical displacements. Measurements were taken both in laboratory conditions and on actual structures. In lab tests, the deflection of a simple steel beam under load was measured. The tests demonstrated that the results obtained using the laser station were very consistent with the deflection values read by means of an Ni 007 precision level. The maximum difference in displacement measured from 20 m was 0.13 mm.

In field tests, the laser station was used to measure a network of benchmarks forming a closed loop. It was confirmed as early as at the verification phase (checking of the loop closure) that the measurements were as accurate as assumed, with the mean error of the height difference not exceeding 0.13 mm. Further analysis involved the determination of the error of observation and strict adjustment unknowns in the measured network. It was ascertained that mean errors of height differences did not exceed 0.12 mm and the error of obtained displacement did not exceed 0.20 mm.

Summing up the results, both the laboratory tests and the field tests demonstrated that the accuracy of measurement of vertical displacements taken by means of the TDRA 6000 laser station was comparable to the accuracy of measurements performed using traditional methods.

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