APPLICATION OF FREE TACHEOMETRIC STATIONS IN MONITORING OF MONUMENTAL OBJECTS

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SUMMARY

This paper presents results of investigations concerning utilisation of free tacheometric stations for:

a) **Determination of slip of objects located on escarpments,**
b) **Investigations of deformations of bodies of monumental objects.**

The usefulness of the proposed technology of surveys for implementation of the above tasks has been proved. Results of investigations have been illustrated by results of surveys of displacements and deformations of the St.Ann's Academic Church in Warszawa.

1. INTRODUCTION

In the process of investigation displacements and deformations of monumental objects we deal with many limitations resulting from the difficult access to a particular object or its architectural details, as well as from inability to apply fixed signalling of survey points. Besides, in many cases decisions concerning monitoring of a monumental object are made in emergency conditions; therefore it is not possible to apply labour and time consuming surveys, based on precise levelling and conventional angular-and-linear networks. On the other hand, in case of many monumental objects, various types of sensors are used to perform permanent observations of deformations. Apart from incontestable advantages of such devices, much attention should be paid to their high prices and special installation requirements, which may be hardly met in the case of monumental objects. Conventional surveys may be commenced almost immediately and signalling of controlled points does not have to be connected with injuring valuable architectural details.

This paper presents results of investigations concerning utilisation of free tacheometric stations for:

c) **Determination of slip of objects located on escarpments,**
d) **Investigations of deformations of bodies of monumental objects.**

All test surveys were performed by means of Leica 1202 and Leica TS09 tacheometers.

2. TRANSFORMATIONS OF CO-ORDINATES AS THE BASIS FOR DETERMINATION OF LOCATIONS OF FREE STATIONS (FS)

X,Y,H co-ordinates of a free station may be determined by least squares adjustment or basing on transformation of co-ordinates calculated in the station co-ordinates system,

to the secondary (main) system, defined by reference points. In the case of investigations of displacements and deformations, the main system consists of co-ordinates of reference points, calculated basing on initial surveys.
In the course of determination the FS location with the least squares adjustment, in order to ensure the control of co-ordinates of tie points and not to deform geometry of an observation beam, the *free* type adjustment conditions should be applied.
Identical station co-ordinates will be obtained after transformation of co-ordinates based on Helmert solution, which is known from applications for two-dimensional networks.
The following condition should be realized in the case of 3D transformation:

$$\left[\Delta X_i^2\right] + \left[\Delta Y_i^2\right] + \left[\Delta H_i^2\right] = \min . \qquad (1)$$

where: ΔX, ΔY, ΔZ – transformation residuals of tie points.

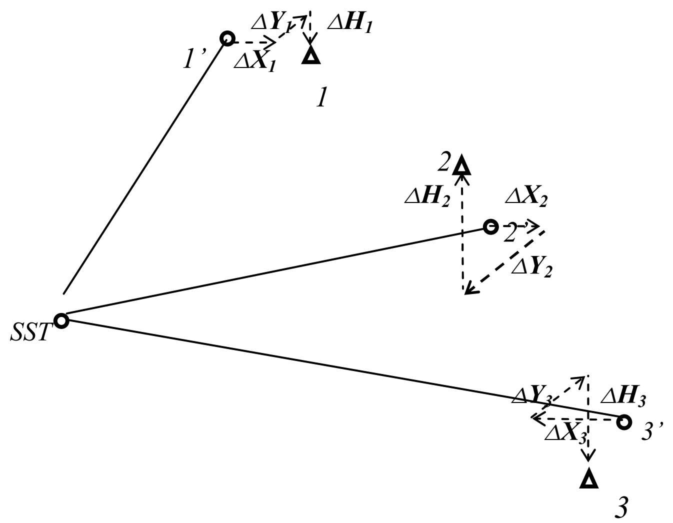

Fig. 1.1. An example of a free station.

The basic stage of transformation of co-ordinates (*x,y,h)* from the initial system to the secondary system (*X,Y,H)* consists of calculation of the *C* matrix, which transforms increments of co-ordinates of the initial system on increments of co-ordinates of the secondary system, according to the general formula:

$$C = (\delta^T \delta)^{-1} \, \delta^T \Delta , \qquad (2)$$

where: δ and Δ are the matrices of ordered increments of tie points with respect to a pole in the initial and secondary systems.

In the three-dimensional transformation of co-ordinates, in order to explicitly determine transformation coefficients, it is necessary to know co-ordinates of 4 tie points. Thus, only for 5 points it will be possible to evaluate the correctness of performed surveys, as well as to evaluate the stability of reference points. Additional factor, which makes utilisation of the 3D transformation impossible, may be the non-uniformity of geometry of a spatial network, resulting, among others, from small differences in elevation of reference points.
The influence of the assumed transformation model on the values of deviations of adjustment and displacements of controlled points, will be illustrated using the example of the station No.100 from Fig. 3.2. In the current surveys, non detected, 2-millimetre

displacements of reference points 5 and 7 and zero displacements of controlled points 51 and 52, were simulated. Results of calculations of three-dimensional transformation and independent two-dimensional transformations and transformations of elevations, are presented in Table 2.1.

Table 2.1. Influence of non-detection of displacement of a reference point on the values of deviations of adjustment and displacements of controlled points

	Point number	3D transformation						Independent transformations of 2D co-ordinates and elevations					
		Displacement of p.5 X=2mm, H=2mm			Displacement of p.7 Y=2mm, H=-2mm			Displacement of p. 5 X=2mm, H=2mm			Displacement of p. 7 Y=2mm, H=-2mm		
		X	Y	H	X	Y	H	X	Y	H	X	Y	H
Ref. point.	1	0.2	-0.2	0.3	0.0	0.0	0.0	0.2	-0.2	-0.3	-0.4	-0.2	0.3
	2	-0.3	0.2	-0.3	0.0	0.0	0.0	0.2	-0.2	-0.3	-0.2	0.0	0.3
	3	0.1	-0.1	0.1	0.0	0.0	0.0	0.3	-0.2	-0.3	0.2	0.1	0.3
	4	-0.7	0.5	-0.9	0.0	0.0	0.0	0.3	-0.2	-0.3	0.3	0.2	0.3
	5	0.6	-0.5	0.8	0.0	0.0	0.0	*-1.4*	*0.9*	*1.7*	0.4	0.3	0.3
	7	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.9	-0.3	-0.2	-0.3	*-1.7*
Controll. point	51	*4.1*	*-2.5*	*4.5*	*-0.8*	*-1.7*	*2.0*	-0.2	0.1	-0.3	0.4	-0.8	0.3
	52	*3.9*	*-2.4*	*4.3*	*-0.8*	*-1.7*	*2.0*	-0.2	0.1	-0.3	0.4	-0.7	0.3

From the list of residuals of transformation of points 1-7, as well as from displacements of controlled points 51 and 52 it results that – basing on the 3D transformation – it is impossible to identify displaced reference points basing on the analysis of vectors of apparent displacements. Besides, more reliable results may be obtained basing on transformation of plane co-ordinates, both with respect to reference and to controlled points.

Due to the above it is more effective to independently determine horizontal displacements basing on Helmert transformation of plane co-ordinates and vertical displacements basing on one-dimensional transformation of elevations of reference points.

In that process the following conditions will be independently met for reference points:

$$[\Delta X_i^2]+[\Delta Y_i^2]=\min. \tag{2}$$

$$[\Delta H_i^2]=\min. \tag{3}$$

In the case when distance measurements to all reference points is not possible, numerical implementation of a free tacheometric station may be performed using the least squares adjustment or an approximate method.

3. DETERMINATION OF SLIP OF OBJECTS LOCATED ON ESCARPMENTS

Investigation of slip of objects is resolved to determination of vertical and horizontal displacements of points located in characteristic places of objects and protecting

constructions, such as retaining walls. Vertical displacements are determined basing on observations with the use of precise direct levelling; in order to determine horizontal displacements, incomplete angular-and-linear networks are established. A valuable amendment of investigations are inclinometric observations, which allow for evaluation of displacements of background layers of the landslip. Conventional surveying methods are cost and time consuming. Besides, many limitations occur in the process of establishment of angular-and-linear networks, such as lack of pointing lines, missing permits to permanently fix stations, instability of background in places of planned locations of stations etc.

Utilisation of free tacheometric stations is particularly advantageous in case of measurements in areas of limited visibility, e.g. due to densely built-up areas or high vegetation.

Within the frames of the presented work two cases of utilisation of the FS for determination of vertical and horizontal displacements have been analysed. In the first case, the FS was located far from the controlled object – in the location of one of stations of a conventional angular-and-linear network (Fig.3.1). In the second case two free stations were located close to the monitored object (Fig.3.2). Tables 3.1 and 3.2 present lists of components of vectors of displacements, calculated basing on surveys performed from the station No.102 and mean errors of transformations; differences between displacements calculated using the FS method and performed in a conventional angular-and-linear network and the precise levelling network.

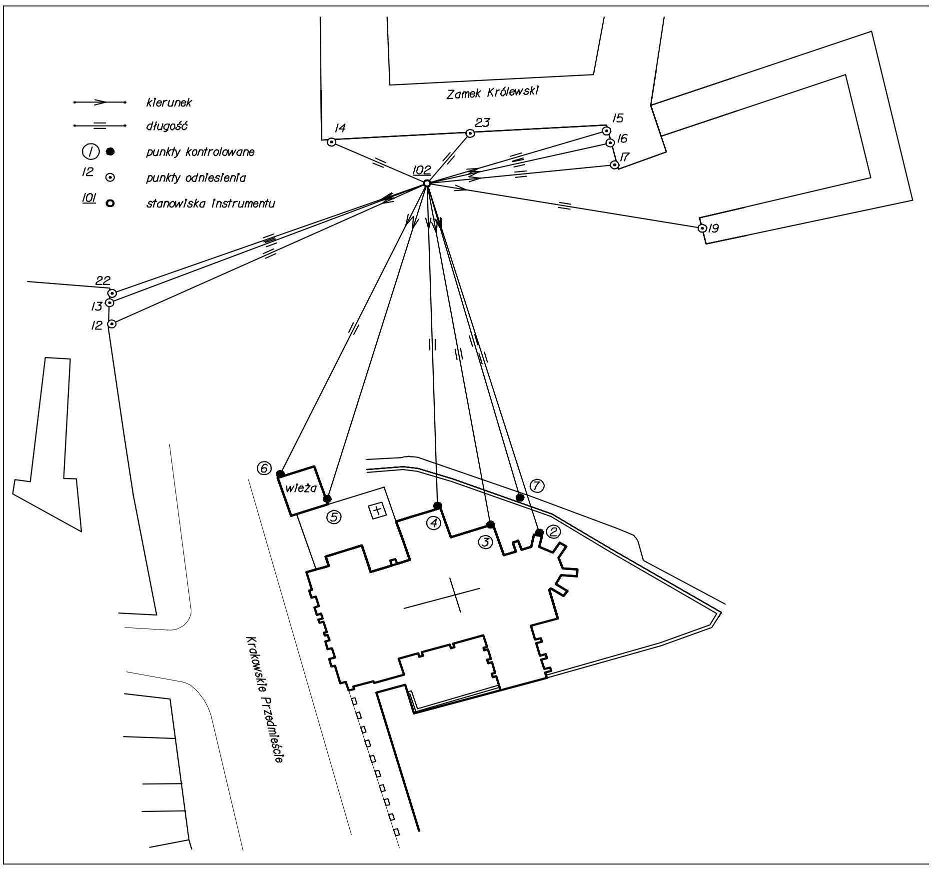

Fig. 3.1. Sketch of observations from a free station located close to reference points.

Differences of displacements obtained from conventional and FS methods, which are characterised by constant signs, point to the torsion of an observation beam in the process of transformation and to various scales of linear observations.

Table 3.1. Horizontal and vertical displacements in the period 9.02-8.06.2010 - station No.102

Displacements of points on a church (p.2,3,4), a tower (p.6), and a retaining wall (p.7) *[mm]*									
Point	**Components of vectors of displacements**			**Mean errors of transformation**			**Differences of displacements from conventional methods and the FS method**		
	ΔX	**ΔY**	**ΔH**	$m_{\Delta X}$	$m_{\Delta Y}$	$m_{\Delta H}$	$\varepsilon_{\Delta X}$	$\varepsilon_{\Delta Y}$	$\varepsilon_{\Delta H}$
2	**0.1**	**5.9**	**0.9**	**0.6**	**0.8**	**1.1**	**3.0**	**-3.4**	**-1.2**
3	**-0.1**	**4.8**	**0.6**				**3.7**	**-1.9**	**-0.8**
4	**-0.7**	**3.5**	**0.3**				**4.0**	**-1.9**	**0.5**
5	**-1.0**	**0.8**	**1.6**				**2.6**	**2.5**	**-1.7**
6	**-3.5**	**4.1**	**-**				**4.1**	**-1.1**	**-**
7	**0.4**	**5.0**	**-1.2**				**2.6**	**-3.4**	**0.9**

Table 3.2. Horizontal and vertical displacements in the period 9.02-9.09.2010 - station No.102

Displacements of points on a church (p.2,3,4), a tower (p.6) and a retaining wall (p.7) *[mm]*									
Point	**Components of vectors of displacements**			**Mean errors of transformation**			**Differences of displacements from conventional methods and the FS method**		
	ΔX	**ΔY**	**ΔH**	$m_{\Delta X}$	$m_{\Delta Y}$	$m_{\Delta H}$	$\varepsilon_{\Delta X}$	$\varepsilon_{\Delta Y}$	$\varepsilon_{\Delta H}$
2	**0.4**	**6.1**	**-0.3**	**0.8**	**0.7**	**1.2**	**1.2**	**-1.2**	**0.2**
3	**0.8**	**4.4**	**1.1**				**1.9**	**-0.2**	**-1.1**
4	**-0.2**	**4.1**	**0.0**				**2.0**	**-1.2**	**0.5**
6	**-2.7**	**2.9**	**1.9**				**1.7**	**-1.0**	**-1.8**
7	**1.6**	**4.2**	**-0.7**				**0.9**	**-1.2**	**0.6**

Below /table 3.3 and table 3.4/, results of surveys from another two free tacheometric stations are presented; locations of those stations are presented in Fig. 3.2.

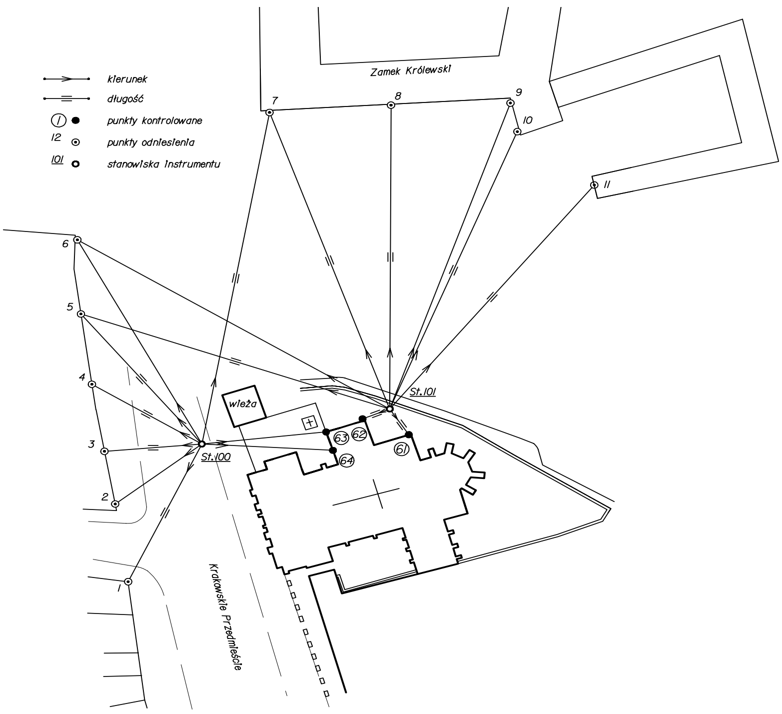

Fig. 3.2. Sketch of observations from a free station located close to an investigated object.

The station No.100 has been located within the central between the controlled object and reference points. The station No.101 has been located in the distance of several metres from the investigated object. Observations were performed at those stations by students of the Faculty of Geodesy and Cartography of the Warsaw University of Technology, using Leica TS09 instrument.

Table 3.3. Horizontal and vertical displacements in the period 12.07-8.09.2010-stations 100,101

Displacements of points on a church (p.2,3,4), a tower (p.6) and a retaining wall (p.7) *[mm]*									
Point	Components of vectors of displacements			Mean errors of transformation			Differences of displacements from conventional methods and the FS method		
	ΔX	ΔY	ΔH	$m_{\Delta X}$	$m_{\Delta Y}$	$m_{\Delta H}$	$\varepsilon_{\Delta X}$	$\varepsilon_{\Delta Y}$	$\varepsilon_{\Delta H}$
51	-0.8	0.1	0.3	1.6	1.6				-0.6
52	-0.6	-0.2	0.1						-0.2
61	-0.7	-1.0	-0.1	0.8	0.8		-0.2	2.3	-0.1
62	-0.7	-0.8	-0.2				-0.8	2.1	-0.1

Table 3.4. Horizontal and vertical displacements in the period 12.07-3.11.2010-stations 100,101

Displacements of points on a church (p.2,3,4), a tower (p.6) and a retaining wall (p.7) *[mm]*									
Point	Components of vectors of displacements			Mean errors of transformation			Differences of displacements from conventional methods and the SST method		
	ΔX	ΔY	ΔH	$m_{\Delta X}$	$m_{\Delta Y}$	$m_{\Delta H}$	$\varepsilon_{\Delta X}$	$\varepsilon_{\Delta Y}$	$\varepsilon_{\Delta H}$
51	-0.6	0.4	1.3	1.3	1.3				-1.5
52	-0.8	0.0	0.3						-0.4
61	-1.1	-1.8	0.5	1.7	1.7		-1.9	-0.8	-0.7
62	-1.3	-1.2	0.2				-0.5	0.0	-0.4

The above presented results of surveying experiments, performed by the authors and by the students, confirm the possibility to determine components of vectors of horizontal displacements with the mean errors of about 1-2mm, and vertical displacements – with the mean error of about 0.5-1.0mm.
The above accuracy will depend on the stability and distribution of reference points, lengths of aiming lines and the accuracy of measuring instruments. The most advantageous results were obtained from the station located close to the investigated object.
Satisfactory accuracy of surveys are obtained basing on observations performed in 2 survey series.
Software of electronic tacheometers and the process of numerical processing allow to obtain information about occurring displacements almost immediately after completion of observations.

4. INVESTIGATIONS OF DEFORMATIONS OF SOLID OF MONUMENTAL OBJECTS

Objects located within areas of landslide are the subjects of horizontal, as well as vertical displacements. Numerous deformations inside each object occur in the course of sliding. The question arises: to what extent is it possible to detect them and describe basing on conventional surveys? Previous experiments confirmed the high accuracy of measurements of short sides using contemporary electronic tacheometers. The accuracy

of angular measurements – in the case of short aiming lines – is mostly influenced by errors of setting up instruments. Therefore, the technology applied should be released from impact of such factors. The measuring experiment, based on utilisation of the FS technique was performed in the main nave of the St. Ann's Academic Church (Fig.4.1). Controlled points, in the form of reflective sign, were located around the church's main nave at various levels.

Fig. 4.1. Measurements performed from a free station in the main nave.

**The horizontal projection of the implemented test network is presented in Fig. 4.2.
The initial and current surveys were performed by various surveyors, within a short period from various stations. Determined relative displacements should be equal to 0.**

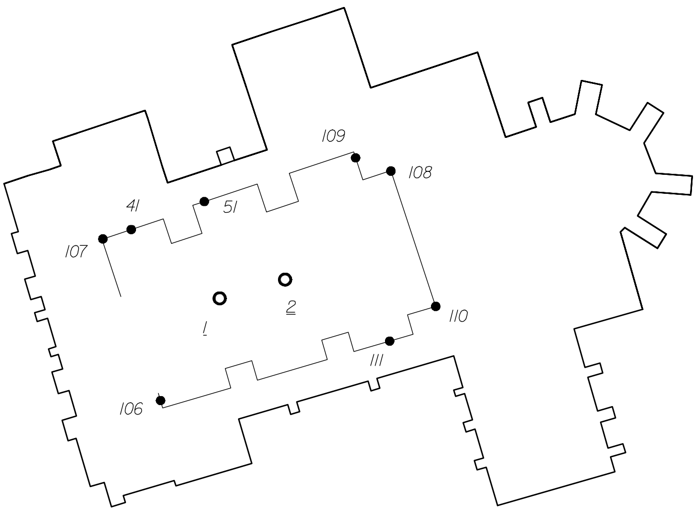

Fig. 4.2. Sketch of location of stations and controlled points inside an object.

In order to illustrate that issue, Table 4.1 presents displacements of points 108 and 110, located in the presbytery, with respect to points located in the main nave.

Table 4.2 presents displacements of points 41, 51, 109 and 108 located on the north wall, with respect to points located on the south wall. Point 41 and 51 are located under the ceiling, at the elevation of 13m. The relative displacements were calculated from independent transformations of 2D co-ordinates and elevations.

Table 4.1. Displacements of the presbytery with respect to the main nave *[mm]*

Point	Components of vectors of relative displacements			Mean errors of transformation			True errors of displacements		
	ΔX	ΔY	ΔH	$m_{\Delta X}$	$m_{\Delta Y}$	$m_{\Delta H}$	$\varepsilon_{\Delta X}$	$\varepsilon_{\Delta Y}$	$\varepsilon_{\Delta H}$
108	0.1	-0.7	-0.1	0.2	0.2	0.6	0.1	-0.7	-0.1
110	0.1	-0.4	0.0				0.1	-0.4	0.0

Table 4.2. Displacements of the north wall with respect to the south wall *[mm]*

Point	Components of vectors of relative displacements			Mean errors of transformation			True errors of displacements		
	ΔX	ΔY	ΔH	$m_{\Delta X}$	$m_{\Delta Y}$	$m_{\Delta H}$	$\varepsilon_{\Delta X}$	$\varepsilon_{\Delta Y}$	$\varepsilon_{\Delta H}$
41	-0.3	0.2	0.2	0.1	0.2	0.4	-0.3	0.2	0.2
51	-0.5	-0.4	-1.1				-0.5	-0.4	-1.1
109	0.4	-0.2	0.1				0.4	-0.2	0.1
108	0.1	-0.6	-0.2				0.1	-0.6	-0.2

Above results confirm the possibility to determine, with the high accuracy, the relative displacements basing on simple surveys. An exception is point 51; the half of the surface of the reflective sign was covered on that point.

5. CONCLUSIONS

In case of observations of short sides and steep aiming lines to points, which are signalled by means of reflective sign, electro-optical distance meters of narrow laser beam should be applied.
Electronic tacheometers may substitute many expensive, special instruments, which are usually designed for individual tasks.
Measurements of slips of a construction, using FS method is a fast and inexpensive process, which does not require special stabilization of points. The obvious advantage of this method is independent selection of location of the station for each measuring cycle.
The FS method may be also applied in surveys of local deformations of objects, as well as changes of the width of slits, which are inaccessible for direct measurements.
The obtained results of the test measurements and numerical simulation confirm the common opinion that the results of 3D transformation are highly influenced by the topography of connecting points.
Due to small differences of elevations in the majority of surveys, which result from small differences in terrain elevation, independent determination of horizontal displacements basing on Helmert transformation of plane co-ordinates and vertical displacements basing on one-dimensional transformation of elevations of reference points, is more advantageous.

REFERENCE

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