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DEFORMATION ANALYSIS IN THE CONTEXT OF PHOTOGRAMMETRIC BUNDLE BLOCK ADJUSTMENT BY MEANS OF A STEEL CONSTRUCTION

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1. Introduction

In recent years, photogrammetric methods have become more and more important among measurement technologies. This is especially true for close-range applications, and particularly in industrial applications /10/, /11/, /15/. This is due to the development of efficient computation algorithms (with corresponding progress in the EDP-sector), the associated better capabilities of taking photographs and the purely numerical evaluation technology /25/.

Now it seems to be the right time to start the transfer of technology from the developing university institutes to the industrial user or to continue it where this has already happened. This transfer allows these groups of people to use the photogrammetric measuring techniques for new applications. In this context, photogrammetry should not and must not primarily be viewed as a method competing with purely geodetic methods. It must rather be regarded as a useful c o m p l e t i o n of these methods. If it is used correctly, it offers the user a host of yet unknown applications and advantages.

For surveyers in industry deformation measurements are part of "daily bread". Environmental impact, heavy thermal and/or dynamic loads, but also intentionally produced object changes must (often regularly) be recorded by measurements and have to be made available to the involved mechanical or civil engineer as a basis for their calculations.

Suitable deformation analysis methods have meanwhile firmly taken hold in the geodetic sector /3/, /17/, /18/, /23/, /24/. In the photogrammetric area efficient methods are available too /1/, /7/, /8/, /9/, /11/, /12/, /14/, /22/, /27/, although they are not very much used in practice. The availability of operational program systems, in combination with efficient computer hardware may soon change this situation.

The following is a description of an example of the current capabilities of photogrammetric deformation analysis in combination with bundle block adjustments.

2. Task

Regularly repeated geodetic measurements during the building process of a heavily loaded steel construction (size approx. 43 m * 12 m * 25 m, fig. 1) revealed unexpected, irregular foundation settlements. In order to be able to eliminate the additional stresses resulting from the settling differences that had occurred and hence to preclude follow-up damage to the construction, the construction supported by four foundations was lifted at one support. The lifting process was monitored geodetically at several relevant object points.

The photogrammetric measuring method was supposed to record deformations on the object by measurements before and after the lifting process in order to obtain information on the static behaviour of the steel construction.

3. Surveying concept

Highly accurate close-range photogrammetric measurements today normally are based on the principle of the bundle block adjustment /2/, /16/, /19/, /25/. On the basis of a photogrammetric station configuration which surrounds the whole object of interest, photographs of the signalised object are taken from each station. In this type of applications the photogrammetric exposure stations are only a function of the intersecting ray geometry at the object. The signals reproduced in the photographs are evaluated in a 2D measuring system (comparator). The measurement is made photograph by photograph monoscopically. These measured values (image coordinates) are the main input variables for the bundle block adjustment which produces as a result 3D coordinates of the object points as well as accuracy and reliability information.

3.1 Measures on site

To prepare the photogrammetric measurement approx. 90 artificial signal discs were attached to the object to have measuring points to be clearely identified (fig. 2).

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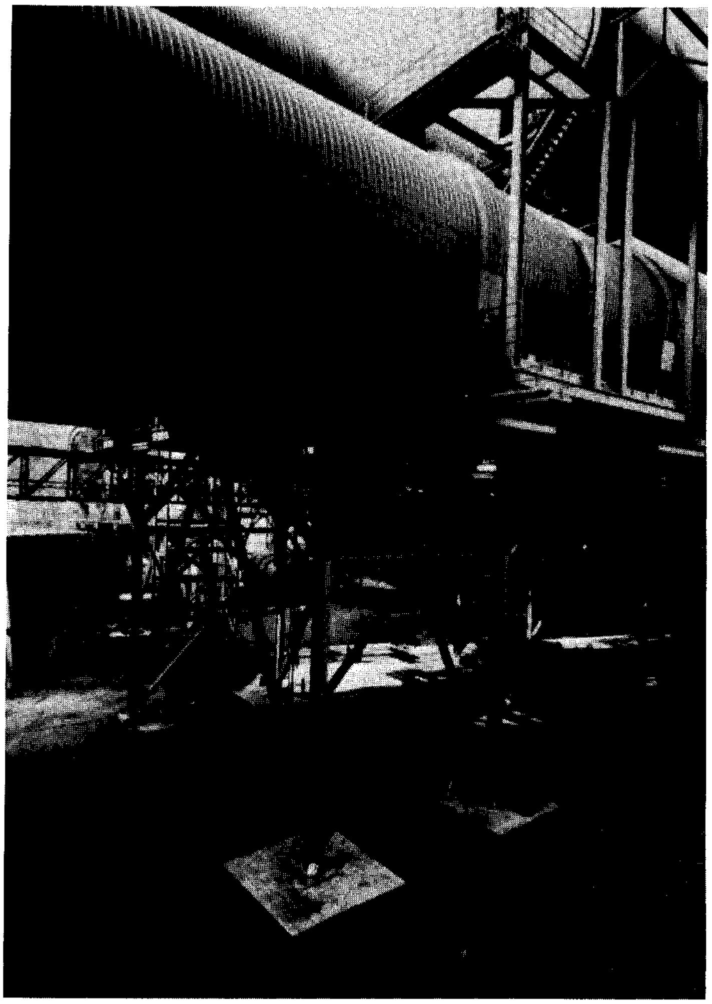


Fig. 1 Steel construction with duct loads. The support at the right in the pictures was lifted.

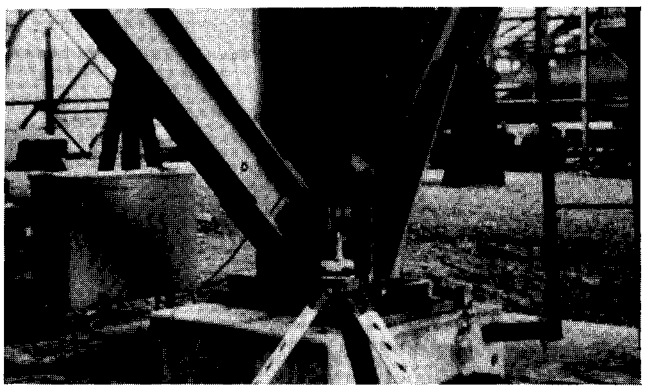


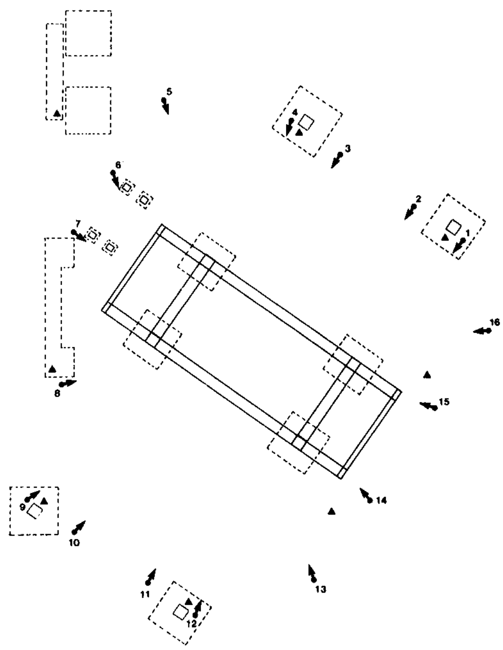
Fig. 2 Targets to define the object points

Since the photogrammetric measuring process is only able to give information about the geometry (shape) of the object, scale and location are determined by the combination with geodetic measurements. For this purpose, suitable control points were located by surveying with respect to position and height right of the steel construction.

Geodetic measurement of control points and photogrammetric measurement of both epochs were carried out simultaniously. Fig. 3 shows the position of the control points on neighbouring buildings as well as the stations of the photogrammetric camera (Zeiss Jena, UMK 10/1318). In order to get also an unimpeded view of the higher parts of the steel construction the pictures were taken from the platform of a lift truck (fig. 4). Altogether, the measurements took approx. 7 hours per epoch.

In this context it might be of interest that the geodetic ground surveying for the control point measurement (13 points) took approx. the same time as the photogrammetric measurement (approx. 90 points), where as twice as much people were required (4 geodesists - 2 photogrammetrists)!

In order to minimize the impact of temperature and insolation on the measuring result both epochs were recorded at the same times and under comparable outdoor weather conditions. Accompanying temperature measurements over the day showed differences < 5°C. The maximum temperature-induced changes depending on an expansion coefficient for steel of $0.0115 * 10^{-3}$ (per meter and °C) are indicated in table 1 for the measures of the object in question.



Surveying station and direction ▲ control point (location and height)

Fig. 3 Surveying stations and directions as well as position of the control points

		Max. longitudinal deformation
length	43 m	2.0 mm
height	25 m	1.2 mm
width	12 m	0.6 mm

Table 1 Temperature-induced longitudinal deformation of the object

The temperature impact on the result is nearly completely eliminated by taking into account that the measuring time for both epochs was equivalent. Furthermore the computations of differences between the two epochs eliminate the temperature induced effect.

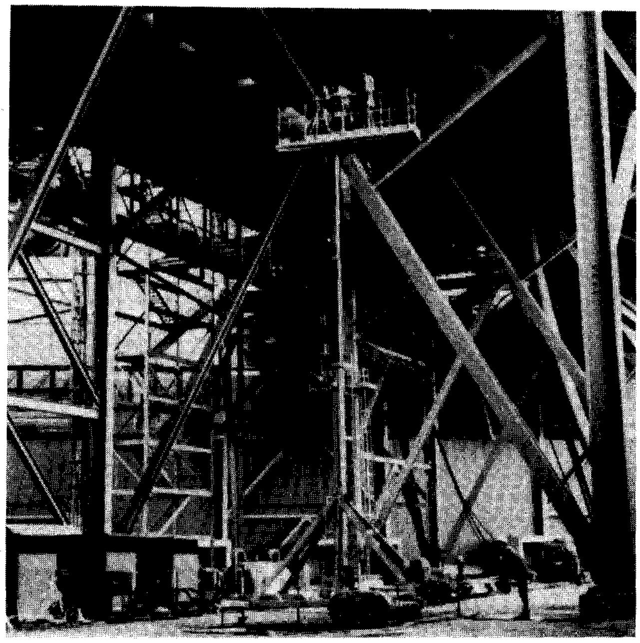


Fig. 4 Photogrammetric surveying by lift platform from an elevation of approx. 15 m

4. Evaluation and results

4.1 Geodetic netadjustments and deformation analysis

To prepare the bundle block adjustment, the control points of both epochs were determined by geodetic netadjustment /20/. The estimated accuracies of the position coordinates as well as of the heights, determined by levelling can be taken from table 2.

Epoch	1	2
	0.3 mm < $sigma_x$ < 0.7 mm	0.3 mm < $sigma_x$ < 1.1 mm
	0.3 mm < $sigma_y$ < 0.9 mm	0.3 mm < $sigma_y$ < 0.8 mm
	$sigma_z$ = 1.0 mm	$sigma_z$ = 1.0 mm

Table 2 Standard deviations of the control point coordinates

The subsequent deformation analysis of both geodetic measurements revealed movements of two position control points (3 and 8.8 mm respectively).

4.2 Photogrammetric bundle block adjustment and deformation analysis

4.2.1 Individual adjustment of the photogrammetric epochs 1 and 2

The results of the photogrammetric bundle block adjustment of both epochs are shown in table 3. About 10 % of approx. 90 originally signalled points had to be discounted as utterly false observation because they were hidden or badly illuminated or were proved wrong by the adjustment.

The improved precision in the 2nd epoch is primarily attributable to a higher number of intersecting rays per point (epoch 1: 3.6; epoch 2: 4.1).

Epoch	1	2
$sigma_x$ (mm)	1.6	1.3
$sigma_y$ (mm)	1.9	1.4
$sigma_z$ (mm)	1.1	0.9

Table 3 Standard deviations (RMS) of the object point coordinates
Sigma $_{x,\,y}$ - position sigma $_z$ - height

A complete camera calibration could be carried out simultaneously with the object point determination /21/. The used exposure station arrangement as well as the object geometry in combination with a special camera orientation at a few stations (rotation of 180° around the camera axes) permit a high precision for the adjusted parameters of the interior orientation of the surveying system (table 4).

Interior Orientation	Epoch 1	Epoch 2
c / $sigma_c$	99.649 ± 0.004	99.637 ± 0.004
x_H / $sigma_{xH}$	-0.003 ± 0.004	0.001 ± 0.004
y_H / $sigma_{yH}$	0.003 ± 0.003	0.006 ± 0.003
R1 / $sigma_{R1}$	0.847D-07 ± 0.12D-07	0.621D-07 ± 0.89D-08
R2 / $sigma_{R2}$	-0.587D-11 ± 0.15D-11	-0.409D-11 ± 0.11D-11

Table 4 Interior orientation parameters

c - focal length
x_H, y_H - principle point
R1, R2 - parameters of radial-symmetric distortion

The aim of the individual adjustments is the removal of gross errors. These blunders are identified by means of a statistical test and are subsequently eliminated.

Since various observations are included in the adjustment, it is useful to carry out a variance component estimation. The variance component estimation is a procedure which puts weights of the various groups of observation in the correct relation to each other; this is done by an iterative estimation process /5/, /6/.

The following observations are of particular relevance:

- image coordinates
- distances
- "observed" control point coordinates
- "observed" parameters of interior orientation.

The control point coordinates computed within the geodetic ground adjustment are not inserted as errorfree data into the bundle block adjustment, but the ascertained standard deviations are rather included via the weights of the "observed" coordinates. The interior orientation parameters are treated in the same way; the values from the calibration report are only approximate values which are improved during the adjustment process. Here again, the standard deviations of these variables, given by the calibration report, define the weights.

Since the datum is not defined via fixed points but via the weighted control points, photogrammetry also permits a check of the control points obtained from the geodetic ground adjustment.

4.2.2 Joint adjustment of the photogrammetric epochs 1 and 2 with simultaneous deformation analysis

Once blunders have been removed from the respective epochs by the individual adjustments, a joint adjustment is carried out. As in case of individual adjustments before, the datum (scale and orientation) is defined here via weighted control points of the individual epoch. It can be assumed that the control point coordinates of each epoch belong to the same coordinate system. This was ensured through the geodetic deformation analysis (chapter 3.1). For this reason a deformation analysis at the control point under the photogrammetric calculations is no longer required and is therefore dispensed with.

Pseudo-observations are introduced at all points to be analysed to carry out the deformation analysis. In the present case, where shifts in height and position are to be discovered, these are height differences and horizontal distances. The pseudo-observations connect identical points of different epochs; the following expressions hold:

$\Delta h_i = 0$ as well as $\Delta s_i = \varepsilon$ ($\varepsilon \sim 0$, for numerical reasons $\varepsilon \neq 0$ must hold).

These are pseudo-observations because firstly they were not observed in reality and secondly are included in the adjustment with the weight $p_i = 0$ and have therefore no constraining influence. The introduction of the weightless pseudo-observation makes no sense in terms of the adjustment. However, since the used bundle adjustment program MOR-S employs a special sparse-technique /13/, this introduction is required for calculation purposes only. By using the pseudo-observations the program calculates standard deviations for each pseudo-observation.

The introduction of the pseudo-observations with the value 0 corresponds to the hypothesis that all points are not deformed!

The second adjustment of both epochs is again carried out in two steps.

First a joint adjustment is carried out without the pseudo-observations. Here again, the coordinate system is defined by the geodetic control point system. With this joint adjustment in the model of the variance component estimation the weight relations of the observations of the two epochs are estimated. In doing this, it is also ascertained whether for example the measurements of the image coordinates of both epochs were carried out with the same precision. The weight relations estimated in this way are then included in the original observations.

The joint adjustment of both epochs with the pseudo-observations is then carried out with this preliminary estimation of the weight relation. A variance component estimation is not carried out anymore at this point because the weight relations among the real observations are already known and the pseudo-observations ($p_i = 0$) have no effect. Since the weights are included in the weight matrix without any factor, the variance of the weight unit may be set $\sigma_0 = 1$. This makes sure that no falsification of the redundancy occurs as a result of pseudo-observations and the estimated standard deviations result from the joint adjustment without pseudo-observations.

The final deformation analysis with the bundle adjustment program is fairly simple because standard deviations for all observations and pseudo-observations are calculated. In order to check whether a pseudo-observation differs significantly from zero, the residual of the pseudo-observation must be divided by the standard deviation of the adjusted pseudo-observation and must be compared with the fraction value of the t-distribution.

$$\frac{v_{pi}}{\sigma_{pi}} > t_{1-\alpha;\ u-q} \quad \longrightarrow \text{deformation} \qquad p \equiv \text{pseudo}$$

The assumption of $\alpha = 5$ % as the level of significance, resulting in a 95 % reliability likelihood of the test, combined with a redundancy of $(u-q) > 120$, is followed by a fraction value of the distribution of

$$t_{95;\infty} = 1.96$$

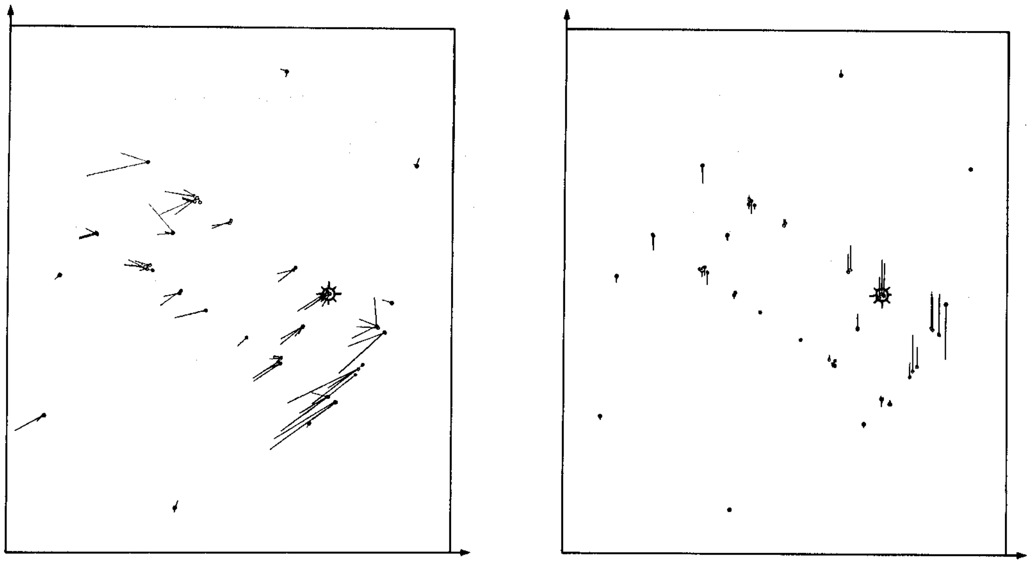
If the residual is approximately twice as high as the standard deviation of the adjusted observations, this means there is a deformation (it should be explicitly pointed out that the standard deviation of the adjusted observation is not equal to the standard deviation of the residual). The result of this test can be taken from table 5. Significant deformations were found in altogether 52 points.

Deformation (mm)	position	height
min.	1.0	2.2
max.	21.9	11.0

Table 5 Maximum and minimum deformation amounts

Fig. 5 a and b give a global overview of the deformations including those identified as not significant. Exclusively significant (i.e. identified by the test) deformations are depicted (in various horizontal and vertical projection planes) in fig. 6 a - 6 c.

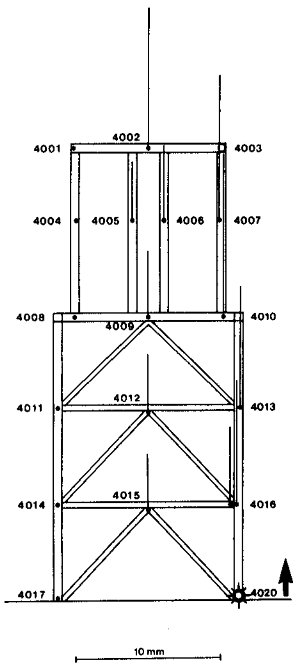
Moreover, it seems to be justified in the present case to use an analysis method with a strict hypothesis towards zero because the points to be analysed are permanently marked with targets. Centering errors, possible e.g. in the case of geodetic measurements, are not relevant therefore /17/.

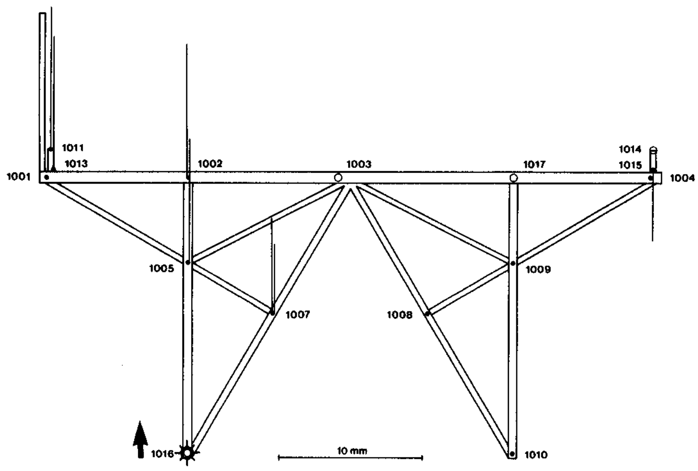


a) position component

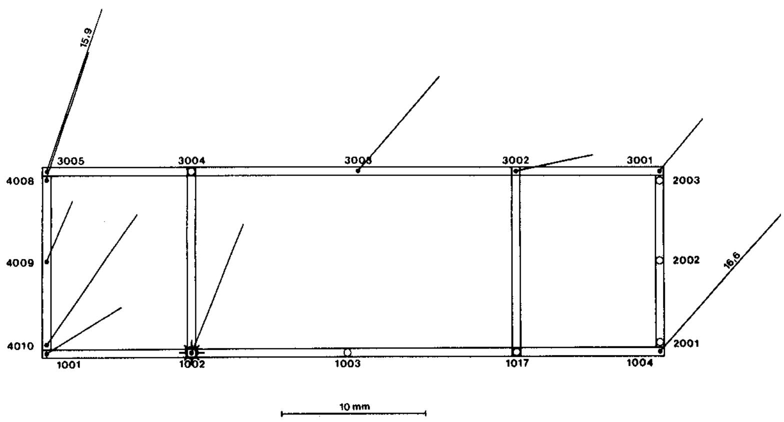
b) height component

Fig. 5 Comparison of epochs 1 and 2 including the deformations identified as not significant (depicted in the horizontal plane).
☼ - lifted support





height component



position component

Fig. 6 a - c Depiction of only significant deformations in horizontal and vertical projection
☼ - lifted support

5. Conclusion

It could be demonstrated by means of steel construction that the applied photogrammetric method can determine points with high accuracy and homogeneity. Furthermore, reliable information on deformations of the object can be obtained by means of statistical tests.

Apart from the short duration of the surveying and the large number of recordable object points, a virtually free surveying arrangement is particularly advantageous compared with purely geodetic methods. In this way, elevated stations can also be used, so even points can be recorded which in case of geodetic observation could either not be seen at all or only with difficulty.

The photographs available are not only an extensive photo documentation but can also be evaluated at a later date possibly for different purposes.

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AVN - Allgemeine Vermessungsnachrichten
ZfV - Zeitschrift für Vermessungswesen

ABSTRACT

For surveyers in industry deformation measurements are part of "daily bread". Resulting from this suitable deformation analysis methods have meanwhile firmly taken hold in the geodetic sector. In the photogrammetric area efficient methods are available too, although they are not very much used in practice.

This paper gives an example of current capabilities of photogrammetric deformation analysis combined with bundle block adjustments.

The presentation of the task and surveying concept is followed by a brief description of the analysis method realized in the program system MOR-S.

In addition graphics show the results of the adjustment and analysis.

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DEFORMATIONSANALYSE AM BEISPIEL EINER STAHLKONSTRUKTION IM RAHMEN PHOTOGRAMMETRISCHER BÜNDELBLOCKAUSGLEICHUNGEN

ZUSAMMENFASSUNG

Deformationsmessungen gehören für den in der Industrie tätigen Vermessungsingenieur zum "täglichen Brot". Hieraus resultierend haben sich geeignete Deformationsanalyseverfahren zwischenzeitlich auf dem geodätischen Sektor fest etabliert. Auch im photogrammetrischen Bereich sind leistungsfähige Methoden bekannt, in der Praxis jedoch weitestgehend ungenutzt.

Der Aufsatz vermittelt bereits heute bestehende Möglichkeiten photogrammetrischer Deformationsanalysen in Verbindung mit Bündelblockausgleichungen.

Der Darstellung von Aufgabenstellung und Aufnahmekonzept folgt die Beschreibung des Analyseverfahrens mit dem Programmsystem MOR-S. Graphische Darstellungen erläutern ergänzend das Auswerteergebnis.

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