Classical Concepts for Deformation Monitoring - Strategies, Status and Limitations

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ABSTRACT

Since decades the development and improvement of methods for the mathematical and statistical analysis of deformation measurements is a prominent topic within Geodesy, Surveying and Photogrammetry. But I have seen in several projects that the responsible people lose sight of framework conditions for setting-up a reliable monitoring project. Therefor I try to present some basic parameters, starting with a priori knowledge on the behaviour of the monitoring object, the importance of a stable geodetic datum, the possibility always to use most-modern equipment to determine the object geometry, *i.e.* to change the equipment, if necessary. These framework conditions allows us to avoid well-known problems, to overcome existing limitations and to strengthen the potential of our profession in this monitoring area. In the central section the classical concepts and strategies for deformation analysis are outlined, *i.e.* a comprehensive summary of the well-established rigorous and approximate methods are given in theory and with practical examples. Alternative and modern analysis concepts are summarized, but they are presented in the further papers of this mini-symposium. Finally some considerations are made related to kinematic and dynamic models and the transfer from epochal to continuous data in monitoring projects. This paper should serve as introduction to the mini-symposium on “advanced methods for analysis of deformation measurements”.

I. Introduction

Deformation Monitoring is an emerging methodology for scientists and practitioners in many areas of Geodesy, Surveying and Photogrammetry. Nowadays for our profession it is necessary to manage monitoring tasks adequately and to fulfill the demands for a lot of different monitoring problems.

Our profession is in open competition with other disciplines in this area and we have to convince contracting bodies or customers that we will solve the problems in an optimal way. To do so several framework conditions have to be fulfilled and our competences have to be on a high level.

A. *Deformation, displacement, deteriorations and change detection*

Following a discussion during the FIG Working Week 2021, it seems to be necessary to clarify some terms, used in relation to deformation studies. We have to differentiate between *deformation, displacement, deterioration* and *change detection* to avoid any misunderstanding and to be a competent partner for neighboring disciplines.

As depicted in Figure 1 in general one can differentiate between relative and absolute deformations for structures quite simple.

Relative or intrinsic deformations are changes of the form of and/or tension within an object, often observed at specific/critical points at the structure. In most cases here continuous physical sensors are applied, often managed by structural engineers. If the critical sections have open access, optical sensors can be applied, too. As mechanical models of structural engineers often just cover the object itself, these professionals primarily look at this type of information.

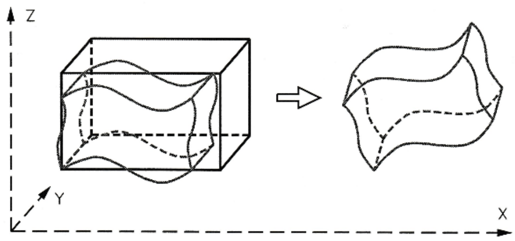


Figure 1. Differentiate between intrinsic deformations and absolute displacements of a body.

The main focus of geodetic sensors is related to *absolute deformations*, *i.e.* to 3D-position changes of an object in relation to its surrounding. If the internal form changes are not in the focus of these studies, one could use the term *absolute displacements,* instead.

Of the selection of points, representing the object, see Section III, allows us to determine relative *and* absolute deformations of the surface of structures.

A third group of displacements are related to building *deterioration*, *e.g.* of historical buildings but also of concrete structures, like bridges and cooling towers, see Figure 2. This flaking of a concrete surface or crushing of edges of mansory or in general material loss cannot be covered by the classical definition of deformations.

Figure 2. Concrete structures, where deteriorations are critical.

Techniques, based on discrete points, are not suited to determine these deteriorations! Here area-based techniques, like laser scanning or ground based SAR systems have to be applied. Methods to analyze the geometry changes of such objects are not fully developed, yet.

To avoid any misunderstanding, we have to separate the before mentioned effects against *change detection*. In remote sensing the term change detection normally is used as the process of identifying differences in the state of an object or phenomenon by observing it at different times. This process is usually applied to earth observation projects, but can be applied to any structure or building, as well.

In my understanding *change detection* is a *yes-or-no-decision*, which is derived from multitemporal images. In Figure 3 this problem is outlined in a simple way. The pixel-values of two images are subtracted to identify the found differences.

Figure 3. Image Algebra Change Detection: Substraction of pixel-values of two images to identify the differences (FIS, Uni Bonn).

B. *Point related to area oriented monitoring*

The classical paradigm of geodetic monitoring is the approximation of the object under discussion by an adequate number of discrete points, normally realized by well-defined physical marks attached to the surface. Of course, for sensors like total stations, levelling and GNSS the exact relation between the origin of the sensor and these physical marks is necessary.

Within this concept, depicted in Figure 4, the study object is approximated by a quantity of points, which have to be sufficient in number and selected carefully to cover all critical areas, see Section III. For these points the displacements are determined in two or more epochs and then - in a final and really important step - the deformation pattern of the complete study area has to be derived.

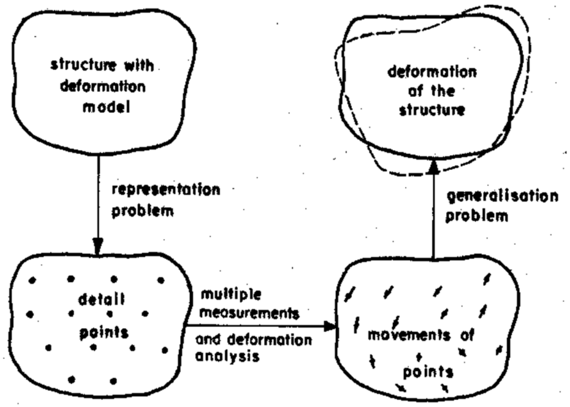


Figure 4. Classical point concept for deformation studies.

Actual developments of theodolite-based so-called *multi stations* make it possible to avoid physical marks. They capture laser scanner data and image data with the same instrument. Both data sets are merged: The scan data are sensitive to distance variations inline of sight, while object movements perpendicular to this viewing direction can be detected by the image data. This allows to define a point not by a manually attached mark, but by structural correspondence at the surface of an object, see Figure 5. The identified point can serve as regular monitoring point in both epochs.

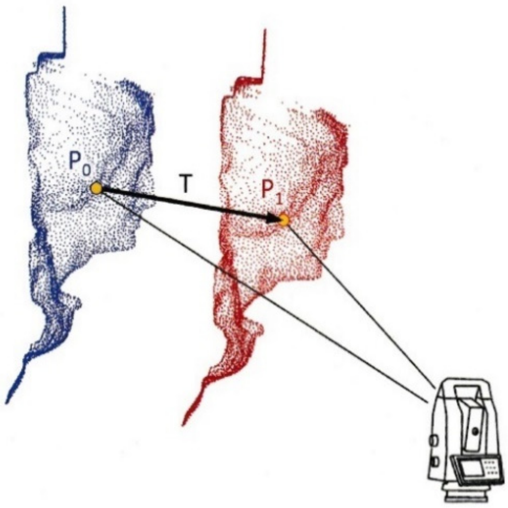


Figure 5. In structure matching of the point cloud between two epochs (blue and red) (Wunderlich et.al, 2020).

Coming to the application of modern sensors, like Laser scanners, InSAR, GBSAR, the surface of an objects is captured by a huge amount of points. But here the surface is scanned in some regular pattern, independent of surface structure and areas of interest, see Figure 6. A defined point, which can be reobserved in a second epoch, does not exist!

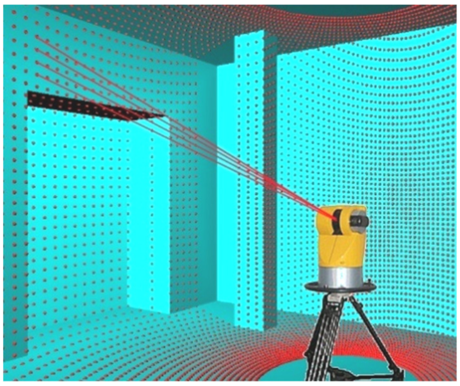


Figure 6. Regular pattern of undefined laser scanning points at a regular surface.

In Section V C concepts are presented to apply classical congruency tests to these area-oriented capturing methods, as well.

II. Monitoring Objects

In this section the focus is laid on typical monitoring objects resp. problems to identify, why and under which conditions our profession can participate.

A. *Engineering structures*

The monitoring of large engineering structures is the classical sample for monitoring in engineering surveying. The classical two-step network set-up for these tasks is given in Figure 7. The advantage of geodetic monitoring is the ability to derive absolute displacements and this requires reference stations outside the structure itself. Typical structures are dams, bridges, tunnels, high rise buildings, harbour cays, but also linear infrastructure objects, like traffic and energy systems.

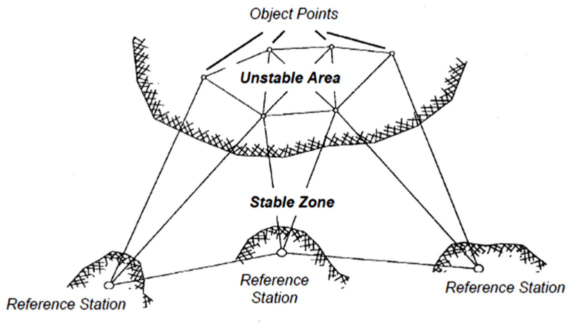


Figure 7. Typical two-step network design with object points to represent the structure and reference stations.

Here a close cooperation with people from civil engineering, structural analysis, rock mechanics and business administration is necessary. The outcome of our monitoring has to have an additional value for the safety and management of the structure.

We have to differentiate between monitoring tasks *during construction*, *i.e.* for jobs associated with the so-called observation method (EC7) and tasks *after completion of a building*, *i.e.* to study the behaviour of structures for years or decades, to guarantee the functionality and safety during the operation phase.

Our classical field are the long-term tasks, and most observation and analysis methods are oriented to these tasks, but due to advanced sensors and almost online processing and analysis we can realize substantial projects for the monitoring during construction, as well.

B. *Sections of the Earth surface*

A second group of objects for monitoring are related to local, regional and even larger sections of the earth surface.

Typical monitoring examples are related to natural or artificial slopes, dykes, areas with groundwater withdrawl and mining activities, but as well to tectonic resp. volcanic active areas. In addition, in relation to climate change the study of vertical movements in coastal zones is an important task, too.

For an example as depicted in Figure 8, some a-priori knowledge on the location of the fault is necessary. Then we have to establish a system with sufficient monitoring stations in the surrounding to be able to detect any type of displacement in this area.

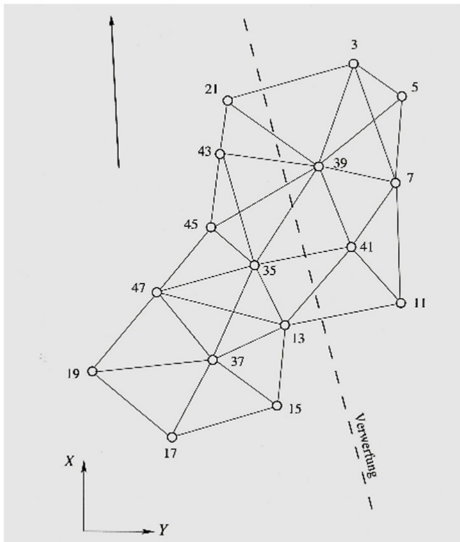


Figure 8. Typical network to monitor specific parts of the earth surface. Sometimes a fracture zone is known.

C. *Industrial objects*

A third group of projects for monitoring is related to industrial objects resp. tasks. Typical examples are assembly lines, manufacturing cells, steel beams, quality control of prefabricated industrial parts and radio telescopes.

Each problem requires a specific solution, derived out of the prior information, we have on this problem.

III. Prior Information

In general the statement hold:

"No prior information – no adequate monitoring"

If any professional from Surveying, Geodesy or Photogrammetry is involved in a monitoring project, the first questions during the design phase of a monitoring project are related to the available prior information on the behaviour of an object:

1. What is size/extension of the object?
2. What is sufficient number of monitoring points to approximate the surface or parts of interest?
3. Is separation between deformable body and stable surrounding possible?
4. What is known on expected displacements or internal deformations?
   - Absolute values and critical directions
   - Temporal development of deformations, just as a function of time or of specified external forces?
5. Time to compute the deformation rates: online or offline solutions?

All this information is necessary to set-up a monitoring system, to select the sensors resp. equipment, to design the network with reference to stable areas and to develop the processing and analysis chain.

But often this information is hard to get from the customer. In discussions with civil or structural engineers or with geoscientists, we have to find out, what is known on all the parameters, listed above. Best for this discussion is competence in those areas, *i.e*. at least some knowledge on the thinking and strategies of neighboring disciplines.

Sometimes it helps to set-up more than one monitoring concept, *i.e*. to explain, which effort is required for which results. In any case the prior-knowledge on the monitoring project has to be formulated, to avoid later misunderstandings.

IV. SET-UP OF MONITORING SYSTEM

Nowadays we have a huge amount of sensors that can be and are used in monitoring projects. With solid prior information we can select the optimal sensor or combination of sensors to determine geometric changes of the object under discussion. For long-term projects we have to be aware that technology is changing and in some years different sensors exist!

A. *Network set-up*

For most applications the establishment of a monitoring network is the right choice, see Figures 7 and 8. That means, a number of points/stations are positioned on the monitoring object itself, while a number of external reference stations allows to derive the displacements of the object in an almost absolute manner, *i.e*. relative to the outer world. Here well-known aspects from network theory have to be applied, *e.g*. network optimization in respect to precision and reliability. In addition, the sensitivity of a network to be able to detect the requested displacements, is an important aspect.

B. *Datum problem*

A further problem, often difficult to solve, is the establishment of a *stable geodetic datum*. Most of our sensors give relative information, *i.e*. distances and angles between From- and To- stations or height differences between benchmarks. The same is valid for Laser scanning and GBSAR, the derived information is related to the position of the instrument setup.

For GNSS some people believe that the datum is given by precise ephemeris and by the ITRS and that this is sufficient as basis for a datum. In Niemeier and Tengen (2022) we explain, why it is better to have a group of ground-based stable reference points, instead.

The challenge is to have - in any case - a sufficient number of stable reference stations, as otherwise the derived displacements are no longer reliable.

As example the monitoring network for a dam in Luxembourg is given in Figure 9, where in total 6 reference stations are set-up to guarantee a sufficient network of reference points and by this a stable datum. Of course, the stability of this group of stations has to be analyzed in a rigorous way, see Section VI.

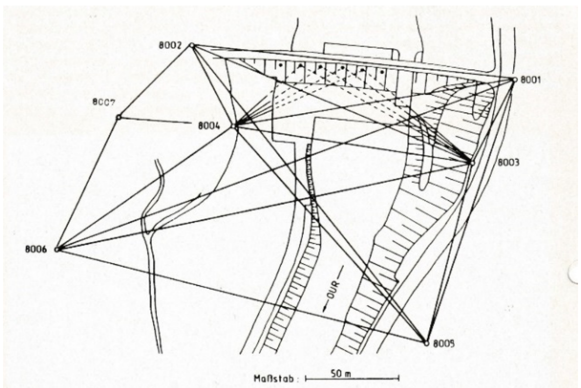


Figure 9. Two-step monitoring network for the Lohmühle dam in Luxembourg.

C. *Discrete or continuous observations*

The adequate *frequency of observation cycles* is responsible for the type of instrument and recording set-up: For taking the observations in epochs/campaigns the normal case is to install instrumental pillars and to position manually the sensors in each campaign via forced centering. The data storage is done by the sensors automatically and after each campaign the processing and analysis of the data is performed.

For permanent installation of sensors and continuous recording the transfer of monitoring data in online modus is the best choice, but not always possible to realize, *e.g*. if power supply is difficult and a radio link is difficult to achieve.

D. *Prerequisites from practice*

Several prerequisites have to be covered by the monitoring approach, before one can claim it to be rigorous and applicable in practice:

i. The original configuration of points may be different from epoch to epoch, because points are lost and/or added in the course of time.
ii. For long-lasting monitoring projects the type of geodetic sensors can change: Some decades ago total stations and levelling were the only adequate sensors, later GNSS was included, followed by laser scanning and radar systems. Actually digital images from aircrafts and drones come into play.
iii. The approach has to be applicable independently of the dimensions of the network, *i.e.* for 1D, 2D or 3D monitoring tasks.
iv. Nowadays it is often necessary to provide analysis results to the client after each epoch. These results have to be reliable and final, to allow the client to evaluate the stability of the monitoring object.

V. Long term usability of monitoring system

A. *Coordinate approach*

As we normally try to apply the most-modern sensors to solve the often sophisticated monitoring tasks, the analysis methodology has to take into account a change of the sensor type and by this in the achievable original or raw information.

This mean that an analysis approach using original observations never could be constructive here, while in specific tasks, esp. in Geophysics, such approaches were used sometimes.

We recommend an intermediate approach based on 1D-, 2D- or 3D-coordinates of stations or surface parameters for area based sensors. Even if some problems occur with this concept, the advantages predominate the shortages by far!

B. *Datum-Free concept*

The next problem has something to do with the effectiveness of geodetic observations to determine form and size of an object. Following Baarda (1968) our observations are very well suited to derive *form and form changes*, but the determination of the absolute size of an object is limited. In elder projects sometimes just one distance observation was made per epoch. Due to limitations of the absolute scale of a distance meter and the atmospheric effects, the determination of absolute size of a network is limited.

To overcome this problem, we recommend always to use the *datum-free approach* (see *e.g.* Niemeier, 2008), *i.e.* to analyze always with maximum number of possible datum parameters and by this to restrict the analysis to form changes. For a pure triangulation the datum defect is 4, in a triangulation or mixed network we include for distances a scale factor and come up with a datum defect of 4, as well. For GPS-information in 3D-network, being it sets of absolute coordinates or baselines, we would introduce 3 orientation parameters and 1 scale factor.

By this datum-free approach we are able to combine all types of information, coming from traditional or most modern sensors!

C. *Datum-free concept*

As mentioned before, nowadays new sensors and methods for data capture come into consideration, most of them give unstructured, area-based data, as depicted in Figures 6 and 10 for laser scanning.

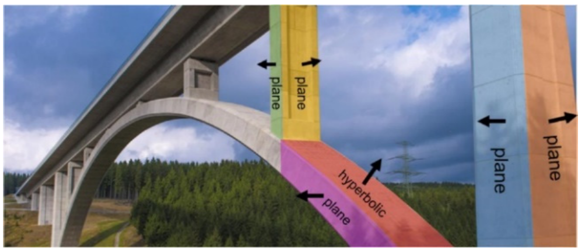


Figure 10. Segmentation of laser scanner data to define specific surface elements of a bridge (Wunderlich *et al.*, 2016).

One possible solution (Wunderlich *et al.*, 2016) is to use segmentation algorithms for the laser scanner raw data to define specific surface elements and then to approximate these surfaces by parameters.

This allows to use the classical congruency tests to derive significant changes of these surfaces between epochs.

VI. Data and model driven analysis

A. *Data driven analysis*

Normally, in our profession we restrict ourselves to the data that are directly available to us, *i.e.* our own observations resp. results. With proper knowledge and processing of our sensor data we come up with precise and reliable results for each new observation epoch.

Any advanced analysis based on just these data has to be restricted to simple models, *e.g.* just linear deformations, which are called kinematic models, see Heunecke *et al.* (2013).

Of course, during the design phase we use knowledge on the possible behavior of the monitoring object to select adequate points, sensors and critical values for displacements.

However, as long as we do not include a geological or physical model on possible displacements, we remain with a data driven analysis.

B. *Model driven analysis*

An extension of this concept is the inclusion of prior information into the analysis approach itself. For most monitored objects some physical model exists.

For engineering structures such a model may consist of knowledge about the behavior during the consolidation phase of a foundation, which normally is given by a consolidation function. Alternatively, a mechanical model for the behavior of a structure may have been derived during the design phase, *e.g.* a model of the bending of a dam due to the actual water level.

For monitoring of sections of the earth's surface this prior information may consist of knowledge about the existence of active tectonic fissures, the boundary of a landslide effected area or current underground mining activities.

In general, these behavior models do not have the same level of confidence as our geodetic results. They are based on well-founded assumptions or derived from theoretical considerations, but they are not severely tested for a realized project.

Such a model has to contain information on aspects, that are listed in Section III as prior information.

Different methodologies exist to treat prior information. In Section VIII the Dutch concept is outlined to use prior information to setup alternative hypotheses. The validity of these hypotheses can be checked by the adequate tests.

VII. Classical congruency test

A. *Starting information*

This standard procedure for deformation analysis was developed by Pelzer (1971), applying the variance analysis method, developed by Scheffé.

This testing method is based on the *coordinate approach,* as introduce in Section V, as it is the most flexible method and allows for a good interpretation of the displacements and geometry of an object.

The coordinate approach requires that, as a first step, for each individual epoch a set of coordinates X_i and covariance matrices $\sum_{xixi}$ is determined by a least squares adjustment. This set has to include both object points and reference points.

For geodetic professionals it is clear that these adjustments have to be carried out according to adjustment theory and principles, *e.g.* outliers are detected and by variance-component estimation all is applied properly.

As starting point for this paper we have for a series of epochs t_1, t_2, … t_k as starting information (Eq. 1):

$$\begin{array}{ll} \text{Epoch } t_1: & \hat{X}_1,\ \hat{\sigma}_{01}^2,\ Q_{x1x1},\ f_1 \\ \text{Epoch } t_2: & \hat{X}_2,\ \hat{\sigma}_{02}^2,\ Q_{x2x2},\ f_2 \\ \vdots & \vdots \quad \vdots \quad \vdots \quad \vdots \\ \text{Epoch } t_k: & \hat{X}_k,\ \hat{\sigma}_{0k}^2,\ Q_{xkxk},\ f_k \end{array} \tag{1}$$

Here the covariance matrices $\sum_{xixi}$ are split up into cofactor matrices Q_{xixi} and variance factors σ_{0i}^2 (Eq. 2):

$$\textstyle\sum_{xixi} = \sigma_{0i}^2\, Q_{xixi} \tag{2}$$

This split up allows for testing the *basic hypothesis* of deformation studies: All quantities $\hat{\sigma}_{0i}^2$, derived with f_i degrees of freedom, have to be estimates of the same theoretical variance factor σ_0^2. Additionally, it allows to use theoretical as well as empirical estimates for σ_0^2 within the analysis.

As starting point we include **all** points of the monitoring network into the analysis, coordinate estimates for all points have to be considered, leading, in general, to a singular adjustment model and by this to singular cofactor matrices Q_{xixi}.

For two-step networks the analysis is separated in two steps, as well: At first the group of reference stations is tested on stability, then the group of object points is analyses, where the displacement vectors have to be related just to the subset of stable reference stations.

B. *Global congruency test for two epochs*

As a first step one can restrict the statistical analysis to the classical *congruency problem*, *i.e*. to the question, whether or not statistically significant deviations exist between the geometry of networks in epochs t_1 and t_2.

The term *congruency test* was introduced by Niemeier (1981), following the general definition that congruency means the quality of correspondence.

Rigorous and approximate approaches for this classical deformation analysis problem can be found in Pelzer (1971; 1985), Niemeier (1979; 1981; 2008), Chrzanowski *et al*. (1981), Heunecke *et al*. (2013), Lösler *et al*. (2017) and elsewhere.

With reference to Figure 11 a rigorous congruency analysis answers the question, whether or not the deviations between the geometric locations of points are caused by real displacements or are just the effect of uncertainties of the observations, *i.e*. lay within the unavoidable uncertainty level of the networks under consideration; *i.e*. the level of correspondence is tested.

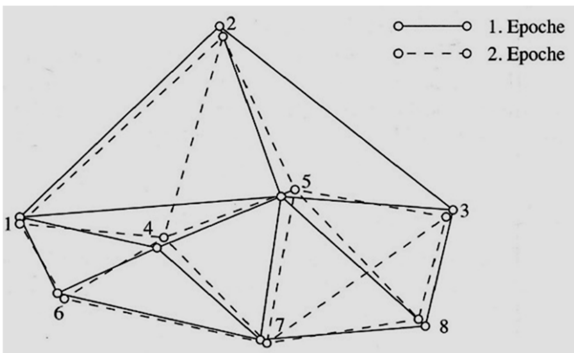


Figure 11. Principle of congruency analysis (Niemeier, 2008).

For simplicity, here we assume that the number of points is identical in all epochs and both epochs are adjusted within the same S-System (see: Baarda, 1968).

The *zero-hypothesis* H_o of this global congruency test is given by (Eq. 3)

$$H_0: \qquad E(\hat{X}_1) = E(\hat{X}_2) \quad , \qquad (3)$$

i.e. under H_0 the statistical expectation *E(..)* of the coordinate estimates of both epochs are equal.

The common *alternative hypothesis* H_A is (Eq. 4):

$$H_A: \qquad E(\hat{X}_1) \neq E(\hat{X}_2) \quad , \qquad (4)$$

what means that there are significant differences between the epochs, if H_A holds. Normally nothing more is specified for a congruency test.

As a first step for the testing procedure itself the difference vector *d* is computed (Eq. 5)

$$d = X_2 - X_1 \qquad (5)$$

The corresponding covariance information for this difference vector *d* is (Eq. 6):

$$\mathrm{Q}_d = \mathrm{Q}_{\mathrm{x2x2}} + \mathrm{Q}_{\mathrm{x1x1}} \qquad (6)$$

The basic test statistic for this global congruency test is given by the ratio, see Niemeier (2008) (Eq. 7):

$$F = \frac{d^t Q_d^+ \, d}{\sigma_0^2 \; h} \qquad (7)$$

where the "+" indicates the pseudo-inverse, *t* indicates the transposed vector, and *h* is the rank of the cofactor matrix Q_d. Other generalized inverses can be used here, but the pseudoinverse makes it clear that all points are included into the analysis.

Remark: In a two-step network at first the group of reference stations is considered. This requires to transfer the datum on this group, see Niemeier (2008).

If this empirical quantity F exceeds the 95% quantile of the statistical F-distribution with *h* and ∞ degrees of freedom, the coordinate estimates between the epochs *1* and *2* differ statistically significantly.

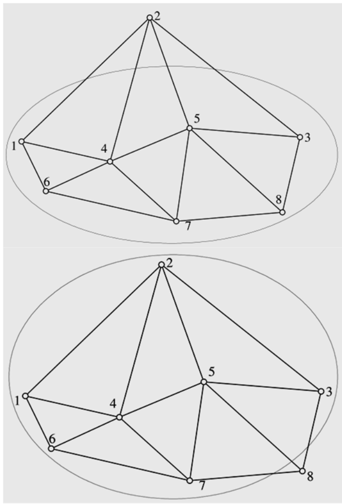
Remark: Especially the use of the theoretical variance factor σ_0^2 is discussed: Several authors recommend to use a combined empirical estimate $\hat{\sigma}_0^2$, instead, to account for the empirical situation more adequately.

C. *Localisation of points with significant movements*

The next step of a complete congruency analysis is the *localization* of significant movements for individual points, see Niemeier (2008).

The principle of this *successive elimination approach* is depicted in Figure 12. The concept of the global congruency test is maintained, here applied to a subset of point, where in each step on of the original points is eliminated. In the computational realization, *e.g*. with the software package PANDA (www.geotec-gmbh.de), this elimination is done by relating the network geometry successively to each subset of points by datum transformation.

This principle to eliminate in each localization step one individual point, corresponds to the global test in the equation. In Figure 12 this elimination of points 2 or 8 and its corresponding test statistics are depicted. The individual point, that has led to the major reduction, is considered as having significant movements!



$$F_{\backslash 2} = \frac{\mathbf{d}_{\backslash 2}^{T}\mathbf{Q}_{dd\backslash 2}^{+}\mathbf{d}_{\backslash 2}}{\hat{\sigma}_0^2 \cdot (h-2)}$$

$$F_{\backslash 8} = \frac{\mathbf{d}_{\backslash 8}^{T}\mathbf{Q}_{dd\backslash 8}^{+}\mathbf{d}_{\backslash 8}}{\hat{\sigma}_0^2 \cdot (h-2)}$$

Figure 12. Localisation procedure: Successive elimination of individual points.

Remark: Several approaches exist, which can be used for localization of individual points, groups of points or even coordinate components. The here presented method is straightforward and is proven to be statistically correct.

The subset of points, which reduces the primary value of F in Equation 7 most, is maintained for the next analysis cycle, where the same procedure is applied to the remaining points. If after several cycles the test statistics F finally falls below the critical value, the procedure stops and all remaining points can be considered as being stable.

VIII. Further developments

A. *Sequential multi-epoch analysis*

The starting model for the congruency analysis of k epochs is given in Niemeier (1979; 1981; 2008) as (Eq. 8):

$$\begin{bmatrix} l_1 \\ l_2 \\ \vdots \\ l_k \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_k \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 & 0 \\ 0 & A_{22} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & A_{kk} \end{bmatrix} \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \vdots \\ \hat{x}_k \end{bmatrix} \qquad (8)$$

This equation considers the normal situation within an adjustment that one has to linearize the functional model, leading to the incremental observation vectors l_i, the residual vectors v_i, the design matrices A_{ii} and the incremental coordinate estimates $\hat{x}_i$. Here no functional relations between the epochs are included; each epoch in itself can be adjusted and pre-analyzed.

The corresponding stochastic model is given by (Eq. 9):

$$\Sigma_{ll} = \sigma_0^2 \, Q_{ll} = \sigma_0^2 \begin{bmatrix} Q_{11} & 0 & 0 & 0 \\ 0 & Q_{22} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & Q_{kk} \end{bmatrix} \qquad (9)$$

In this stochastic model no correlations between the epochs exist, *i.e.* no remaining effects from non-modelled atmospheric conditions are considered. More complete concepts may include these correlations, but this is without the scope of this paper.

A common approach to handle k measuring epochs is repeated application of two-epoch congruency tests. The possible two strategies of Table 1 can be followed.

Table 1. Strategies for a sequential multi-epoch analysis:

Congruency tests for consecutive epochs	*Congruency test of each epoch against epoch 1*
1 - 2 2 - 3 ... k-1 - k	1 - 2 1 - 3 ... 1- k

An important aspect here is the existence of a sufficiently large group of stable reference points during the complete monitoring project. For two-dimensional networks from our practice we consider to have at least 4 stable reference points over all epochs!

B. *Hypothesis constrained multi-epoch analysis*

As mentioned above, one possibility to deal with prior information is to use hypotheses that account for the available displacement models. By this concept it is possible to test several alternative hypotheses, corresponding to various behavior models.

These hypotheses constrain the adjustment model for two or several epochs (Velsink ,2018; Niemeier and Velsinck, 2019).

C. *Clustering*

A promissing concept for further analysis is custering, which allows to identify automatically groups of points with similar behavior. Fletling (2010) has applied this method to the famous simulated test net Delft, given already in Figure 8. Classification was done by using formal criteria of displacement vectors:

- Length
- Azimuth

As result Fleting (2010) could differentiate between 3 clusters, as given in Figure 13. The fault line, assumed to split-up the study area, came out clearly, the lower subset of the left point group was not no obvious in other studies.

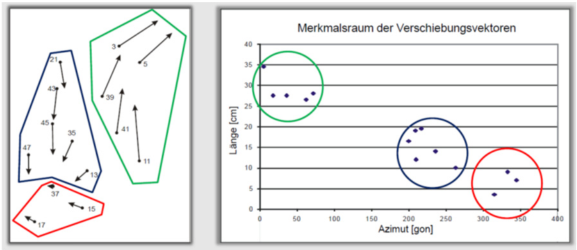


Figure 13. Results of clustering to test network Delft (Figure 8).

D. *Advanced concepts*

During this symposium various general and specific concepts and methods will be presented, that give the state-of-the-art in deformation studies, the details can be found there.

IX. Conclusion

The *global congruency test* is established standard procedure in deformation analysis, as it is applicable for networks with variations in the configuration and changes of sensor types.

It is important to consider the here outlined and discussed prerequisites in any application. Otherwise no reliable results can be achieved.

The analysis of deformation measurements is within the focus of our discipline since decades, but future research and development is necessary to fulfill the requirements of the modern world.

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