Challenges in the Analysis of Inhomogeneous Structural Monitoring Data

Werner LIENHART
Institute of Engineering Geodesy and Measurement Systems
Graz University of Technology
Steyrergasse 30, 8010 Graz, Austria
werner.lienhart@tugraz.at

Abstract. The data collected in monitoring projects is typically inhomogeneous and does require new analysis methods. In this paper it is demonstrated that traditional descriptive deformation models are not suitable for the analysis of the monitoring data of complex structures like monolithic bridges. Spatially distributed measurements without connection measurements can only be linked together with cause-response deformation models incorporating a physical model of the structure. If this link can successfully be made in an Integrated Analysis then it is possible to asses if the measured deformations represent the normal structural behaviour caused by changing environmental conditions.

Introduction

The goal of the analysis of structural monitoring data is to separate deformations caused by regular changes (e.g. temperature changes) from deformations induced by damage (e.g. cracks, material deterioration). This analysis does require a comparison of the measured deformations with predicted deformations which can be calculated from a physical model when the causative forces are also measured.

In modern structural monitoring projects data is collected with a wide range of different types of sensors. These sensors may measure different physical or geometrical quantities at different locations on the surface or inside of the structure. Furthermore, the measurement accuracy of the used sensors can be different. Although, the combined analysis appears straight forward at the first glance, problems arise when connection measurements between spatially distributed sensors are missing. In practice the measurements of different sensor types are often carried out by different groups and are rarely made simultaneously. The general situation is therefore given by spatially distributed measurements of different types and scattered in time. The challenges of the analysis of such data are discussed in this paper using external and internal monitoring data of a monolithic bridge.

Licence: http://creativecommons.org/licenses/by-nd/3.0

Traditional Geodetic Deformation Monitoring

Traditionally, geodetic deformation monitoring concentrates on the investigation of deformations of an object in a descriptive manner. These can be rigid body motions (displacements, rotations) which do not change the inner geometry of an object, and distortions (strain and shearing strain, bending, torsion) which change the geometric relation between points of the object. Since deformation cannot directly be measured it is derived from measurements at different times. In geodesy these measurements are made on the surface of the structure. The used instruments can be GNSS receivers, total stations, precise levels, laser scanners and so forth. With those sensors deformations can determined with precisions ranging from a few millimetres down to a few tenth of a millimetre.

The forces which actually cause the deformations are not taken into account in conventional (geodetic) deformation analysis where descriptive deformation models are commonly used. Descriptive deformation models can be further categorised into congruency and kinematic model. The congruency model consists of a purely geometrical comparison of the state of the object at two different points in time [1]. In a first step, the null hypothesis that the coordinates of epochs are equal is tested at a certain confidence level, usually 95%. If the global test of congruence rejects the null hypothesis, a second analysis step identifies points with significant movements. Thus, the result of a deformation analysis with the congruency model is the separation of all observation points into stable reference points and moved object points, see figure 1-left. The displacements of the individual points can further be analysed to identify blocks with similar deformation pattern.

In case of the kinematic deformation model the movements are considered as a function of time [2]. The goal is to find a suitable description of point movements by time functions without considering the causative forces. The results of the analysis are the coefficients of the time function, see figure 1-right. The known time function can also be used to predict deformations into the future. If further measurements are carried out, Kalman-filtering can be applied for updating and predicting the state of the deformation process.

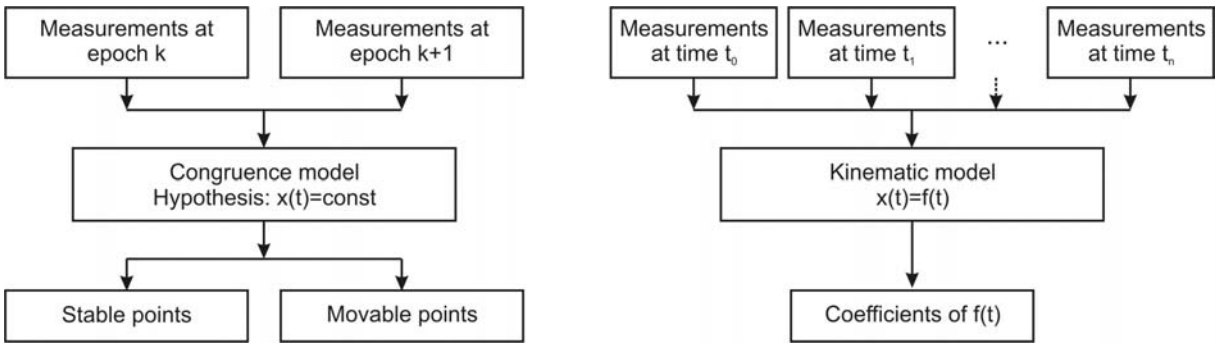

Figure 1. Conventional geodetic deformation analysis: congruency model (left), kinematic model (right)

As will be shown in the following section traditional geodetic deformation models are not suitable for the analysis of the monitoring data of complex structures like monolithic bridges.

Monitoring of the Monolithic Bridge Minkelkehre-Adlerhorst

2.1 Bridge Design

In 2002 a new bridge design for the widening of alpine roads was built near Schladming (Austria) for the first time. The concrete deck of the bridge is 150m long and does not contain any expansion joints or bridge bearings. Furthermore, the bridge deck is connected to the existing road without expansion joints. The bridge deck is linked to the slope with 30 concrete piles of about 8m depth. The reinforcement of the piles was extended into the bridge deck, thus generating a monolithic structure. Figure 2 shows the curved shape of the finished bridge. In the central section as well as on both ends the bridge deck rests entirely on the old road. More details about the construction can be found in [3]. This bridge is referred to as Monolithic Bridge in this paper.

Figure 2. Top (left) and bottom (right) view of the finished Monolithic Bridge

2.2 Measurement Program

The measurement program of the Monolithic Bridge consists of traditional geodetic techniques but also includes internal strain measurements with fiber optic sensors and tilt measurements with borehole inclinometers. Height changes of the concrete deck were determined by precise levelling at more than 20 points. The positions of these points are indicated in figure 3. To measure the length changes of the entire bridge, four bolts for mounting reflecting targets were installed in the bridge deck, see figure 3. For the computation of absolute deformations, the geodetic measurements need to be connected to stable reference points which were established to the west and east of the Monolithic Bridge.

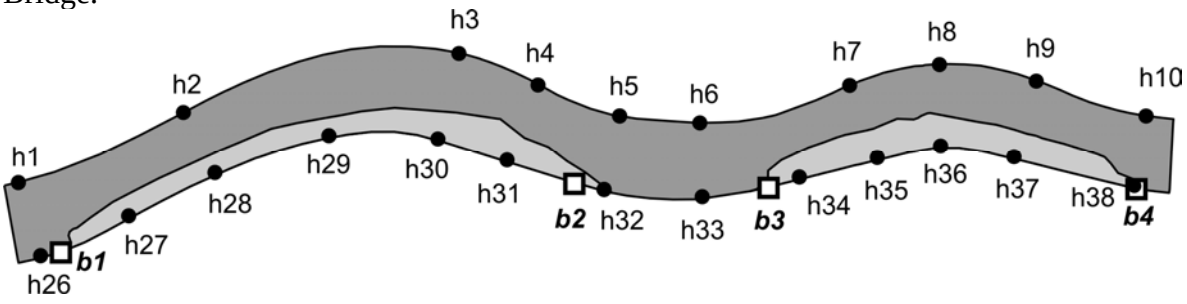

Figure 3. Top view of the Monolithic Bridge with cantilevered (bright grey) and non cantilevered areas (dark grey). Positions of levelling points (black circles) and four traverse points (white squares)

For the internal strain monitoring of the Monolithic Bridge 8 SOFO sensors with a length of 5m were embedded in the bridge deck. Considering the measurement precision of 2μm and the sensor length of 5m, strain values can be determined with a precision of $4 \cdot 10^{-7}$. The sensors were placed in three measurement profiles (MP) in the curved sections of the bridge, see figure 4. In order to separate temperature effects from the measured strain values, resistance temperature detectors (RTD) were also embedded. Three pairs of platinum RTD sensors were installed in the measurement profiles MP2 and MP3. Each pair consists of two vertically separated sensors to compute vertical and horizontal temperature gradients. Furthermore, inclinometer tubes were installed in two piles to monitor shape changes of the piles.

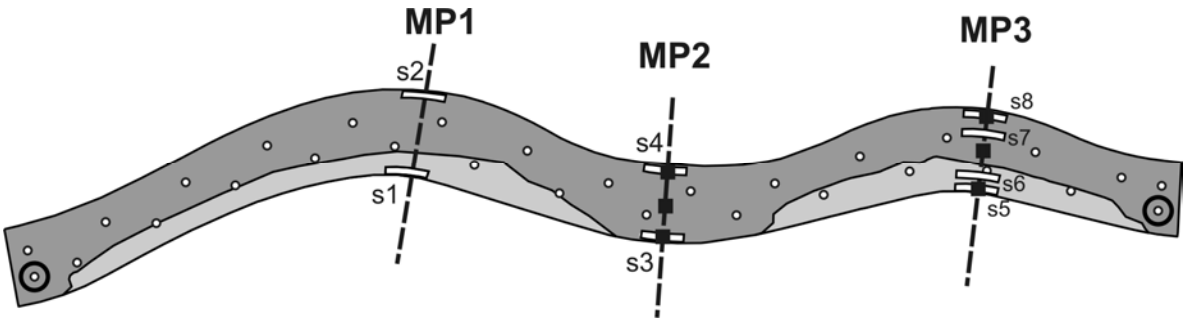

Figure 4. Positions of eight SOFO sensors (white) in three measurement profiles (MP), six pairs of resistance temperature sensors (black squares) and two inclinometer tubes (black circles). White circles indicate the 30 bridge piles supporting the bridge deck.

Analysis of the Inhomogeneous Monitoring Data

3.1 Analysis of Individual Measurement Epochs

At each measurement epoch all measurements were carried out in an over-determined manner. Thus the least squares method can be applied to estimate the best result in terms of minimum sum of squares of the residuals. The measurements were used to determine the horizontal coordinates of the points of the horizontal geodetic network, the height values of the levelling points, the length differences of the fibers in the SOFO sensors and the horizontal positions of the inclinometer tubes at various depths. Altogether 162 parameters had to be estimated for every epoch. The estimated parameters $\hat{\xi}$ and their variance co-variance matrix (VCM) $\Sigma_{\hat{\xi}\hat{\xi}}$ are the core elements of the subsequent deformation analysis.

As it is shown in [4] the normal equation system of the least squares estimation collapses into individual subsystems due to missing connection measurements between external measurement points and embedded sensors. Thus, the measurement data of different instruments could only be analysed independently. This is a general problem in structural monitoring. Often it is very difficult to establish connection measurements between different sensor types. In case of embedded sensors it is mostly impossible to link different sensors.

3.2 Deformation analysis with descriptive deformation models

The results from two individual measurement epochs *i* and *j* can be used to calculate the deformations *d*. The variance co-variance matrix Σ_{dd} of the deformations can also be derived and is given by the sum of the variance co-variance matrices of the individual measurement epochs. As already described section 1 the deformations are tested for significance in a global congruency test. Figure 5 summarizes the standard procedure.

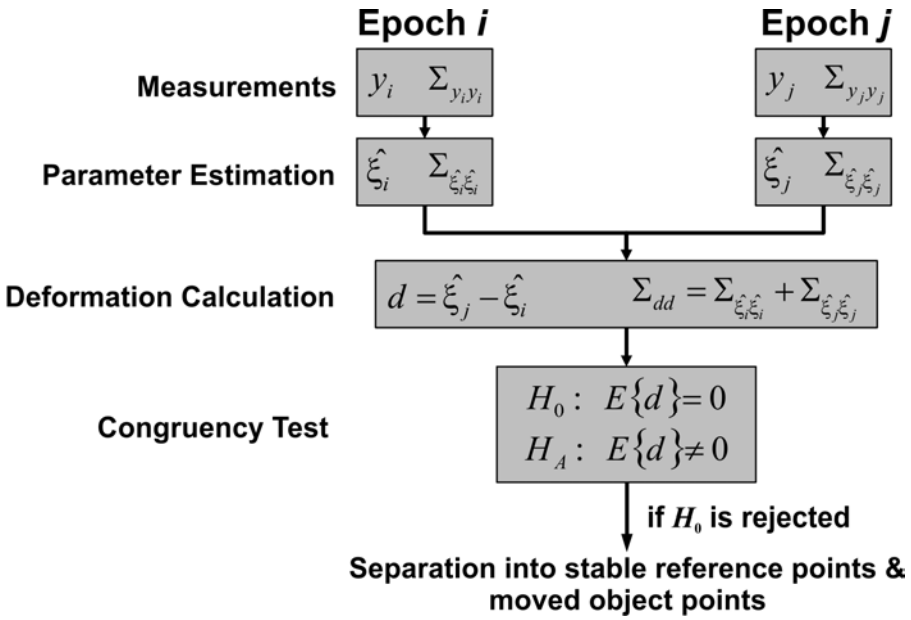

Figure 5. Deformation analysis using the congruency model

The congruence model was applied to the monitoring data of the Monolithic Bridge. Figure 6 shows the deformations of the points of the horizontal network between November 2003 and July 2004.

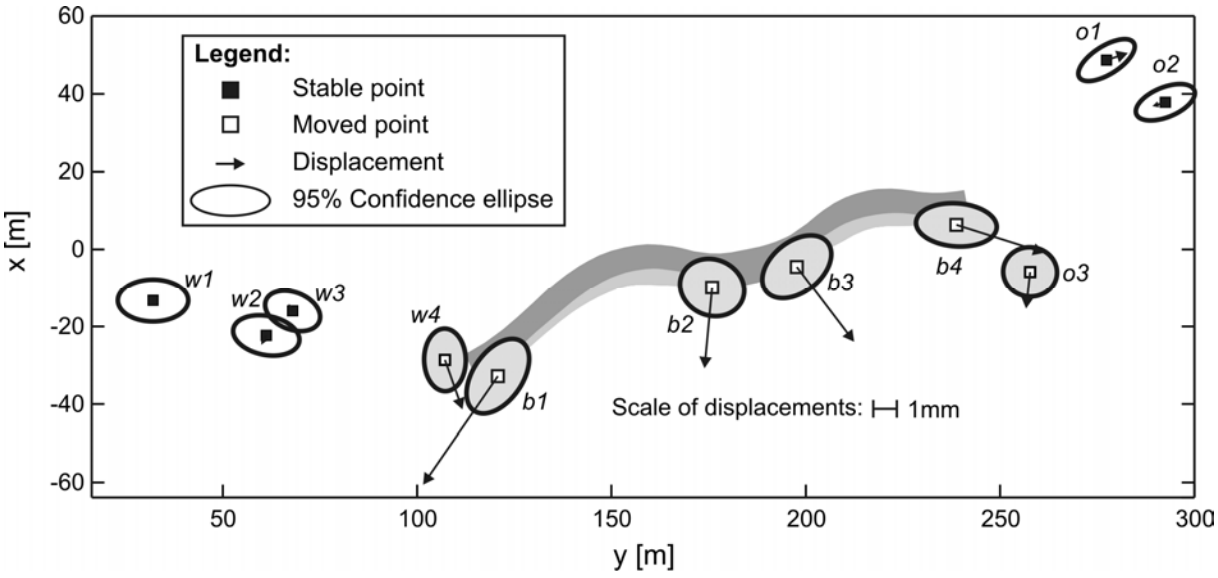

Figure 6. Displacements between Nov. 2003 and July 2004

The data analysis reveals significant displacements of the points on the bridge deck (*b1* to *b4*). Also the initially assumed stable datum points *w4* and *o3* show significant displacements and had to be removed from the group of stable points. The direction of the displacements seems to be reasonable assuming a temperature increase from November to July.

Contrary to the horizontal displacements the height changes cannot be interpreted in such a simple way. Figure 7 shows the height changes derived from precise levelling in November 2003 and July 2004. The datum points are stable but the height of the points on the valley side of the bridge deck decreases significantly. However, from the deformation pattern it cannot be assed if the deformations represent the normal behaviour of the bridge. Point 30 for instance shows a different behaviour compared to the other points.

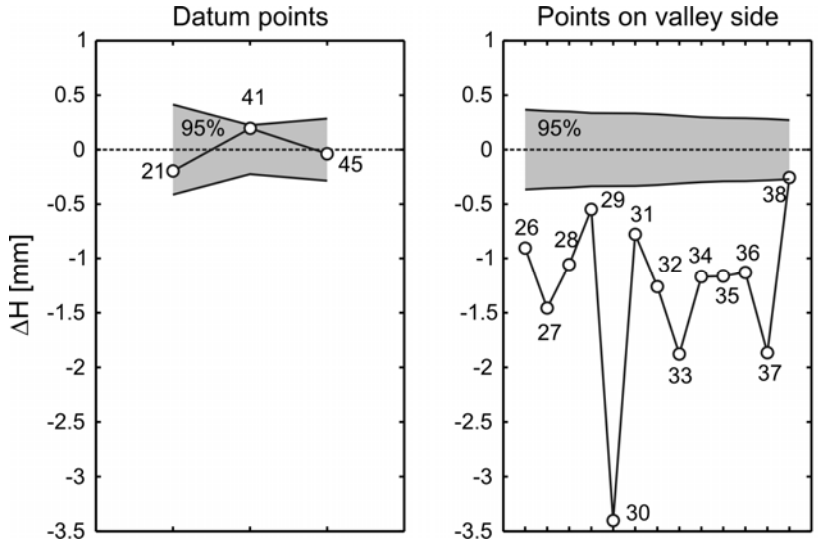

Figure 7. Height changes between Nov. 2003 and July 2004. The grey area indicates the 95% confidence interval

3.3 Deformation analysis with cause-response deformation models

In order to understand the deformation behaviour of such a complex structure the Monolithic Bridge has to be treated as dynamic system which converts acting forces into deformations, see figure 8.

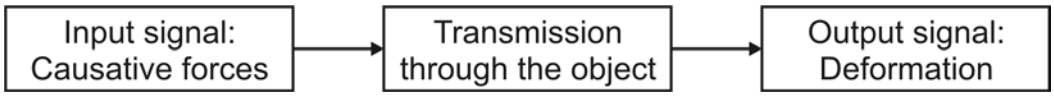

Figure 8. Deformation as output of a dynamic system [5]

The main source for natural deformations of the Monolithic Bridge between Nov. 2003 and July 2004 are temperature differences. As already described the internal temperature of the bridge deck was measured at 12 positions. These temperature measurements f_{MEAS} are used as input signal. The reaction of the bridge to temperature changes can be investigated with a finite element model (FEM) of the structure. The FEM calculation delivers nodal displacements *u* from which calculated deformations d_{FEM} can be derived. These predicted deformations can be compared with the actually measured deformations d_{MEAS} which were derived in section 3.2. In general d_{FEM} will differ from

d_{MEAS}. The significance of this difference δ has to be verified by a statistical test. In order to perform this test, the variance co-variance matrix $\Sigma_{\delta\delta}$ has to be known. This matrix is the sum of the VCM of the measured deformations and VCM predicted deformations. The VCM of the predicted deformations has to be derived from the VCM of the acting forces Σ_{ff} by variance propagation through the model and does also include the model uncertainties.

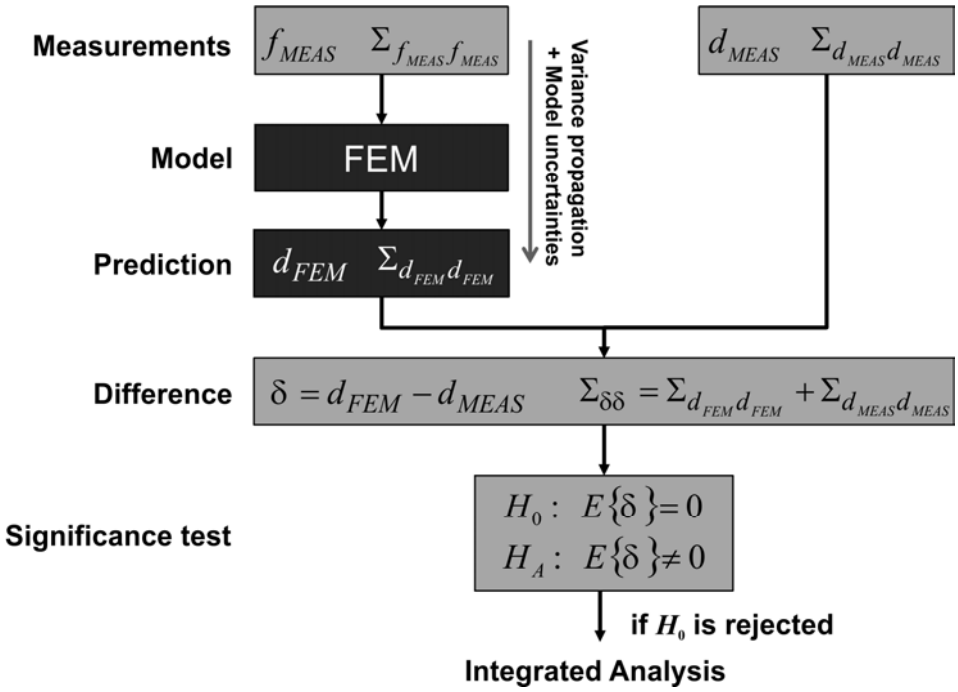

Figure 9. Comparison of calculated and measured deformations

Unfortunately with many commercially available FEM programs it is not possible to calculate the precision of the nodal displacements when the precisions of the acting forces and the model parameters are known. In such a case the variance propagation has to be performed by the user. The required partial derivatives can be approximated by numerical differentiation. The partial derivatives of the displacements with respect to parameters can be determined by repeating the FEM calculation with slightly changed parameters. The difference between the original result and the now calculated displacements divided by the amount of change is the numerical approximation for the partial derivative.

In case of significant differences an Integrated Analysis has to be performed. The Integrated Analysis can be based on adaptive Kalman-filtering [6] if continuous measurements are available or can be based on the Integrated Analysis Method (IAM) presented by [7] in case of a small number of measurement epochs. In the IAM the design matrix is extended and does include an additional system part which connects the measurements and the calculated deformations. This block contains the partial derivatives of the deformations *d* with respect to the nodal displacements *u*. The connection between the displacements, the material parameters and the forces is established by another block which contains the partial derivatives of the nodal displacements with respect to the model parameters and the acting forces. In case of the Monolithic Bridge functional relations are established between previously unconnected sensors. Therefore, the individual fiber optic sensors can now be linked together. Furthermore, connections between the fiber optic sensors and other observation points can be established.

The Integrated Analysis does deliver a calibrated physical model taking all available stochastic information into account. This is especially important when the monitoring data

does include measurements with highly different precisions. In case of the monitoring of the Monolithic Bridge the highest precision can be achieved with the embedded fiber optic sensors. The precision of these internal measurements is about 100 times higher than the precision of the geodetic measurements.

Figure 10 and 11 show the final results of the Integrated Analysis. It can be seen that the calculated deformations using the calibrated model correspond well with the deformations derived from the measurements. Also the height differences of point 30 can be predicted well with the calibrated model using the measured internal temperature changes as input. Therefore, it can be concluded that the large height changes of point 30 are solely caused by temperature changes.

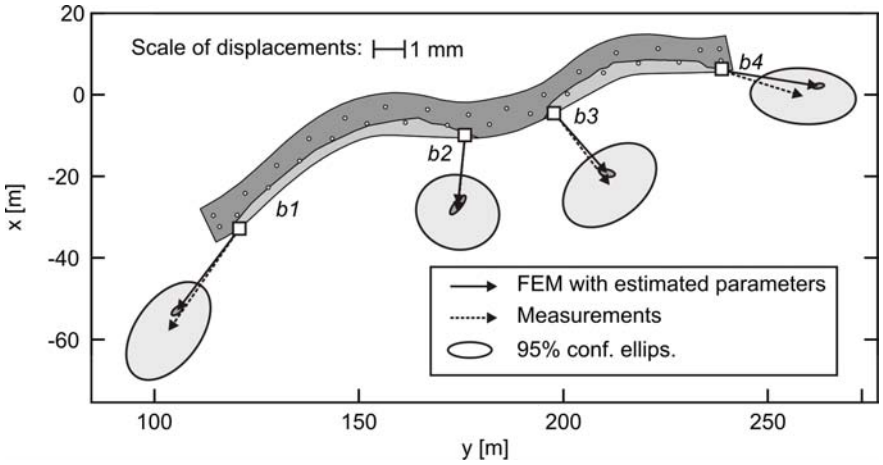

Figure 10. Calculated displacements (calibrated model) and displacements derived from measurements

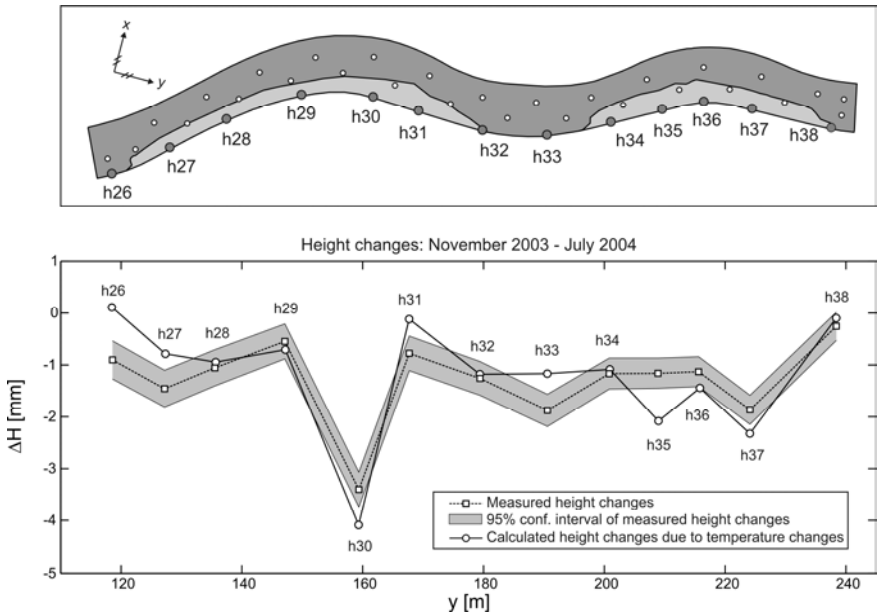

Figure 11. Calculated height changes (calibrated model) and height changes derived from measurements

Conclusion

The data in structural monitoring is often inhomogeneous. Measurements are made at different positions within the structure or on its surface using different types of sensors with different precisions. As a result traditional deformation models are not appropriate because the normal equation system collapses and does not allow an integrated analysis of all available data. As was demonstrated in this paper cause response models are required to asses if measured deformations represent the normal structural behaviour caused by changing environmental conditions. Nowadays, the focus of modern analysis shifts from statistically verifying if deformation has occurred to comparing predicted calculations with measured deformations. It has to be pointed out that this comparison has to be realized by a statistical test. However not all FEM programs deliver all the necessary information in order to perform such a test.

References

[1] Pelzer H (1971) Zur Analyse geodätischer Deformationsmessungen. Deutsche Geodätische Kommission, Reihe C, 164, Munich, Germany, 86 p.

[2] Pelzer H (1987) Deformationsuntersuchungen auf der Basis kinematischer Bewegungsmodelle, AVN, 94, pp. 49 – 62

[3] Högler H, Lienhart W (2003) Integrales Brückenbauwerk zur Straßenverbreiterung und erste Deformationsmessungen mit faseroptischen Sensoren. VDI Berichte, 1757, pp. 221-231

[4] Lienhart W (2007) Analysis of Inhomogeneous Structrual Monitoring Data, Series: Engineering Geodesy – TU Graz, Shaker Verlag, Aachen, Germany, 300 p.

[5] Welsch W, Heunecke O (2001) Models and Terminology for the Analysis of Geodetic Monitoring Observations. Proc. 10th international FIG-Symposium on Deformation Measurements, Orange, California, USA, March 2001, pp. 390-412

[6] Heunecke O (1995) Zur Identifikation und Verifikation von Deformationsprozessen mittels adaptiver KALMAN-Filterung. Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, 208, Hannover, Germany, 185 p.

[7] Lienhart W, Brunner FK (2007) Integrated Analysis of Inhomogeneous Structural Monitoring Data of a Monolithic Bridge, Proc. 3. International Conference on Structural Health Monitoring of Intelligent Infrastructure, Vancouver, Canada, 12 p.