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GEODETIC MONITORING OF SLOW DEFORMATIONS IN A SEISMIC ACTIVE REGION

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Abstract

In the south of Germany one of the seismically most active regions is located in the Swabian Jura, called the Zollernalb. Since the beginning of the 20th century a series of several remarkable earthquakes has started. Buildings are shocked and damaged. The centres run from south to north in several parallel lines crossing an old tectonic structure, the Hohenzollerngraben which appears as a so-called inverse relief. After the large event of 1978, the Geodetic Institute of Karlsruhe University was involved in investigations to find descriptions of the mechanism, direction and amount of the motions.
In a difficult topography (woody mountains) three terrestrial geodetic networks have been established starting in 1983 covering different areas of the seismic zone. In the centre of the seismic zone the network of Onstmettingen was established consisting of 7 pillars in a distance range from 250 up to 900 m. The estimated horizontal deformation amounts to less than 0,1 mm/a and therefore geodetic observations of very high precision were carried out. The design of the networks has been optimised concerning the topography, the tectonic pattern and the sensitivity of the deformation analysis.

1. Introduction

The western Swabian Jura is an intra plate area of increased seismic activity. From 1911 a series of earthquakes started running north and culminated in 1978 by an event of $M_s = 5.7$ located near Onstmettingen. The frequency of recent Swabian Jura events especially in the years 1999 and 2000 can be assessed from available public catalogues (BGR).

Date	Location		Depth (km)	Magnitude
1911-11-16	48° 13'	09° 00'	10	6.1
1943-05-28	48° 16'	08° 59'	9	5.5
1969-02-26	48° 18'	09° 00'	8	4.8
1978-03-13	49° 17'	09° 02	6	5.7
2003-03-22	48° 12'	09° 00'	10	4.4

Tab. 1: Major events within the last 100 years

The earthquake epicentres are arranged near the 9° meridian formed as a belt of subparallel fault planes crossing the rift valley transversely. The focal mechanisms of numerous earthquakes indicate a sinistral shear motion striking 5° or 25° NNO (Schneider, 1971). The foci depths range between 2 and 22 km; Turnovsky (1981) observed depths between 3 and 13 km during the September 1978 swarm. Because of a low width of the graben, varying from 0.9 km to 1.5 km, and the 60-70° tilt of the faults, the base of the graben is found in 2-3 km depth. A detailed description of the present state of knowledge about the neotectonics of this region is given by

Reinecker et. al (2002). The correlation between earthquakes and Hohenzollerngraben and the mechanism behind this intra-plate seismic region are discussed and explained by a new model. Deformations of the surface determined by geodetic measurements and analysis become an important argument in verifying this model. The assumed movements are predicted to be very small at a maximum rate of about 0.1 mm/a.

Against this background, the Geodetic Institute of Karlsruhe University started activities in 1983 to monitor movements in this area related to the seismic pattern. Along the graben structure three geodetic networks (Figure 1) were established in the years 1983 - 1985 crossing the seismic zone. The networks, each labelled after the nearest urban area, consists of 18 points (Tailfingen), 7 points (Onstmettingen) and 5 points (Jungingen).

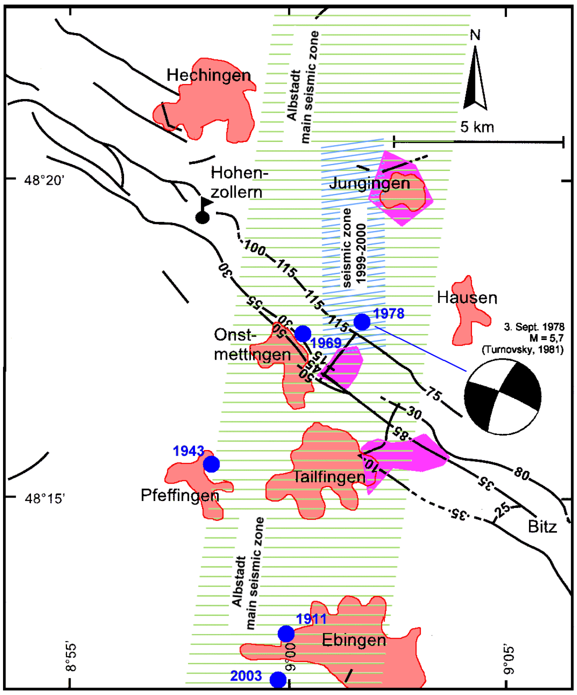

Fig. 1: Structure of Hohenzollerngraben, fault heights and location of the major seismic events and the established geodetic networks.

First results were reported by Brezing et al (1996). Because only a short time period passed since the first measurements, no significant results could be presented. Meanwhile, about seven years later, especially the network of Onstmettingen is in focus of new neotectonic investigations and modelling (Reinecker et al., 2001). This network covers parts of the southern fault and is close to the epicentres of 1969 and 1978 earthquakes and the maximum fault height of the Hohenzollerngraben of about 115 m (Figure 1). It consists of 7 reinforced concrete pillars. The supposed fault pattern is very uncertain, the topography like a flat depression and surrounded by an old forest. There is no possibility to extend the network in any direction. The pillars of the network are based on bedrock, have a footprint of 150 x 150 cm² and an average height of 150 cm. In each corner a benchmark is delimited to provide control measurements by levelling. The pillars were equipped with fixed forced centrings and protected against destruction. The results of new measurements carried out in this network in 2001 and 2002 are reported in this paper.

2. Observation method

Due to the low deformation rate only a very precise observation technique was suitable to get information about the movements. At the beginning of the project, it was decided to use the optical distance meter Mekometer (ME 3000 in 1983-1987, ME5000 in the following years) and to optimise the network design for distance measurements. The inner accuracy of the Karlsruhe

Mekometer ME5000 amounts to k = 0.2 mm estimated by measurements on a calibration line (Dieterle, 2002). This accuracy is confirmed in a long time period starting in 1987.
This fixed uncertainty given by each instrument is completed by the distance dependent error caused by the meteorological conditions. It is well known that the unknown changes of refraction increase the distance inaccuracy up to a scale error of 1mm/km. Although it is possible to correct the raw Mekometer measurements in subject to dependence on temperature and air pressure it seems to be much more reliable to use an observation technique neglecting these influences.
In order to eliminate the meteorological effects extensively the observation technique "distance ratio" has been applied in all epochs. The formulation of distance ratio assumes a common scale factor to the measurement of two distances from the same viewpoint within a short time span and covering similar topography. In the ratio of both distances the scale factor is eliminated and yields the advantage that the frequency calibration and recording of meteorological data is no more necessary (Jäger, 1985). The disadvantage is an elaborate program to perform the observations which include more distance observations in opposite to a traditional simple distance measurement. The independence of pairs of distance ratios (Fig. 2) have to be taken into account particularly.

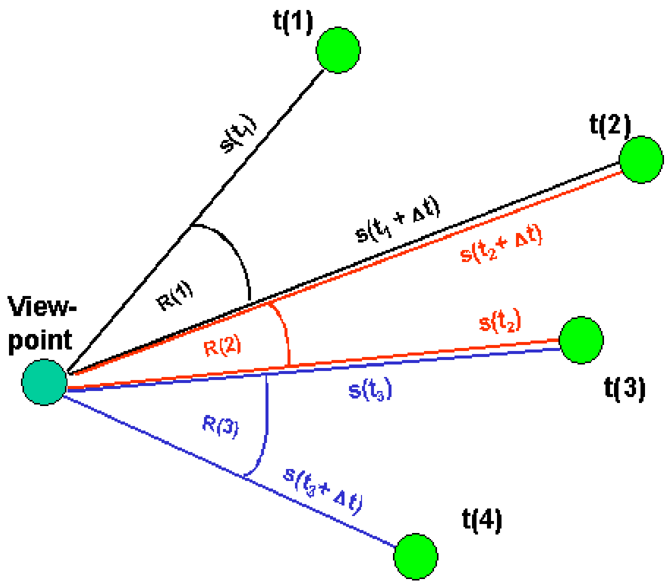

Figure 2: sequence of the distance ratios R(1), R(2) and R(3) and one order of independent observation

The theoretical advantages of distance ratios are tested in the Onstmettingen network and could be confirmed in all epochs. Using the results of a network optimisation concerning accuracy and sensitivity with respect to the deformation analysis the observations schema is fixed and consists of nearly the same number of observations beginning from the first epoch. For example, the network of epoch 2001 (Steidl, 2001) consists of 43 distance ratios observed within two days under difficult conditions.
Starting the geodetic monitoring of the Onstmettingen area in 1983 GPS was not yet available as a well known, high precision method. The first GPS-measurements started in 1988 and were four times repeated until 1995. Because of the restricted accuracy (5-10 mm) of the equipment available Brezing et al. (1996) could not analyse significant deformations from GPS. Due to the enhancement of accuracy in the last years, GPS increases in importance for the continuing measurements in future, simultaneously to distance ratios obtained by Mekometer measurements and especially after the end of the Mekometer period.

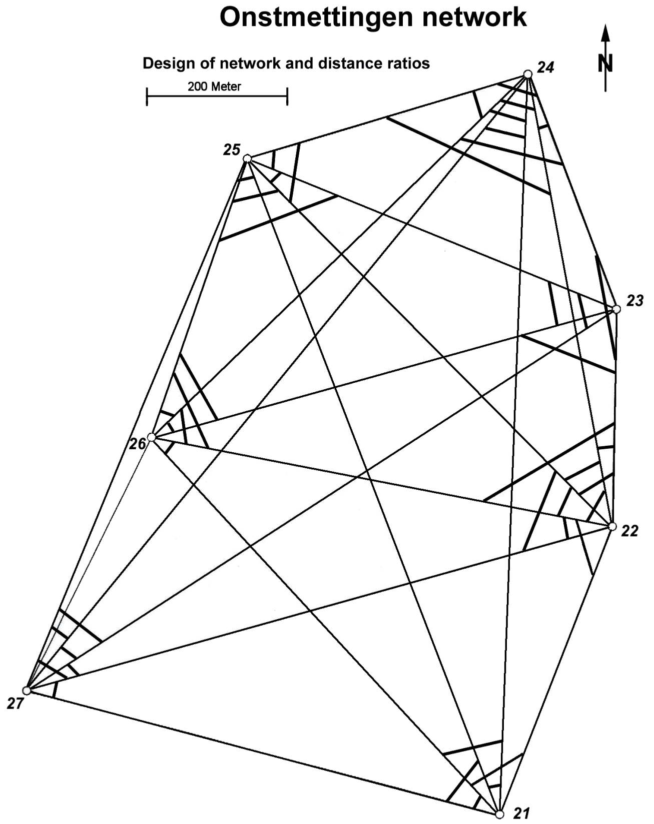

Fig. 3: The design of Onstmettingen network and the configuration of used distance ratios.

3. The analysis

The task of the following conventional deformation analysis is the investigation of movements and displacements of the pillars with respect to space and time. Welsch (2002) gives an overview of advanced deformation analysis, trends and the capacity of up-to-date geodetic surveillance. Because the observations of all epochs are carried out in a short time and the causative forces and the physical properties of the network investigated are unknown the used deformation analysis is a so-called congruence model giving information about the points movements and their statistics.
The Karlsruhe Approach is a stepwise procedure partitioned in different steps. Nkuite et al. (1994) describe the principle which is realised in the software package CODEKA2D. Within the COordinate referred DEformation-analysis based on Karlsruhe Approach (=> CODEKA) the adjustment of the single networks gives estimated coordinates $\mathbf{x_i}$ of epoch i, their covariance matrix $\mathbf{C_{xi,i}}$, the sum of redundancies $\mathbf{r_i}$ and the total sum of the quadratic forms. Using a minimum norm solution the same approximate coordinates have to be used in all epochs. By these terms the design and the quality of network can be described.
CODEKA uses the results of the single epochs to form the equations of the deformation analysis.

$$x_i + v_{x,i} = D_i \cdot dx + x_0$$

functional model (1)

D_i = (0,1) matrix
x_O approximate coordinates of all epochs

$$P_{x,i} = s_0^2 \, C_{x,i}^+$$

stochastical model

$C_{x,i}$ covariance matrix of unknowns $\mathbf{x}$ of epoch i

The unknowns of the coordinates are partitioned to control/reference points valid for all epochs and uncertain points of the object/network estimated by each epoch separately.

$$\mathbf{dx} = \begin{pmatrix} \mathbf{dx_r} \\ \mathbf{dx_{o,1}} \\ \mathbf{dx_{o,i}} \\ \mathbf{dx_{o,n}} \end{pmatrix} = \begin{pmatrix} \textbf{shared reference points} \\ \textbf{object points epoch 1} \\ \textbf{object points epoch i} \\ \textbf{object points epoch n} \end{pmatrix} \qquad (2)$$

Statistical tests (Nkuite et al, 1994) in formulation of a congruency test enable to know whether during the whole investigation period anywhere in the network or part of it significant modifications in the coordinates have occurred or not. Rejecting the assumed null hypothesis H_0 (all points are unmoved) the group of control/reference points has to be identified to be stable. It is one of the advantages of a coordinate based deformation analysis to check all control points in only one adjustment and to identify unstable control points which have to be added to the group of object points. Balancing the probability of errors the results of the different statistical test are not contradictory.

4. Recent Results

In the Onstmettingen network up to nine epochs of distance ratio measurements are available. Due to the observation of distance ratio no scale factor is assumed in the stochastic model. Table 2 gives information about the adjustments of the static epoch adjustments using the NETZ2D software package. The stochastic model of Mekometer ME3000, used from 1983 to 1987, is separated in range I and range II. The values are provided by Kern. No outlier is found by "data snooping" in the data sets.

Epoch	Instrument	stochastic model	mean point error [mm]
1983	ME 3000	0.3 mm / 0.6 mm	0.15
1984	ME 3000	0.3 mm / 0.6 mm	0.16
1985	ME 3000	0.3 mm / 0.6 mm	0.17
1986	ME 3000	0.3 mm / 0.6 mm	0.14
1987	ME 3000	0.3 mm / 0.6 mm	0.15
1988	ME 5000	0.2 mm	0.06
1989	ME 5000	0.2 mm	0.04
1995	ME 5000	0.2 mm	0.08
2001	ME 5000	0.2 mm	0.07
2002	ME 5000	0.2 mm	0.10

Tab. 2: The epochs of observation, the used distance meter and stochastic model and the mean point error as criterion of network accuracy

It is remarkable that changing the Mekometer ME3000 to ME5000 the accuracy of coordinates is increased by a factor of two.
Because all pillars are marked by a benchmark in each corner of the base plate a control levelling indicate tilt of the pillar which could result and misinterpreted as a deformation. In each epoch this control levelling is carried out and no tilt could be found at any pillar. Figure 4 shows a graph demonstrating the stability of pillar 22 with respect to tilt.

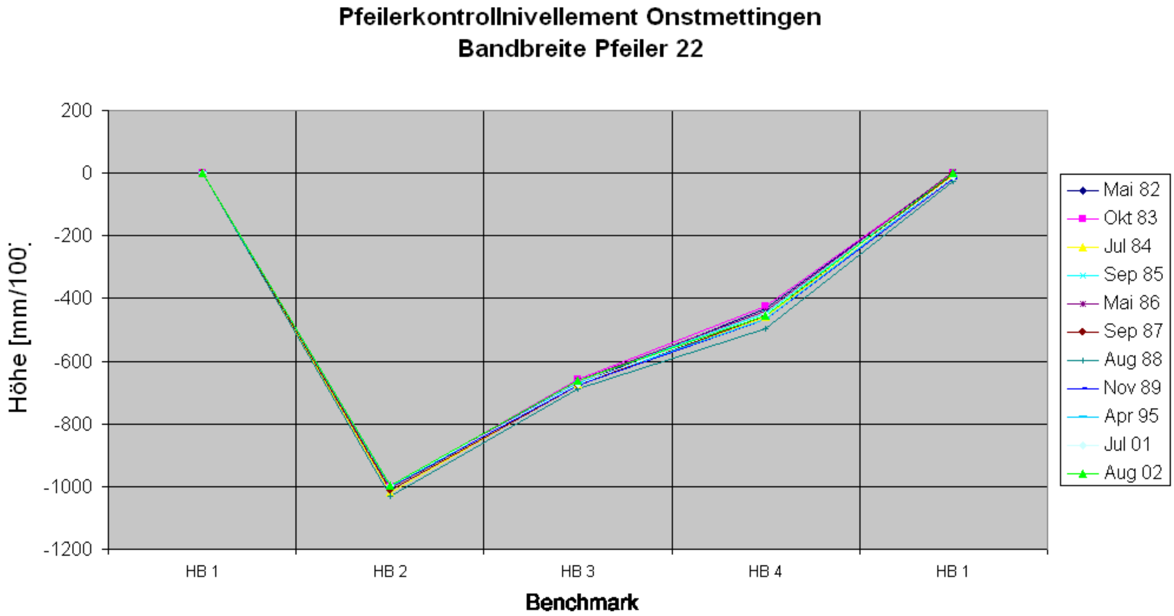

Fig. 4: Results of control levelling around pillar 22 i.e.

The deformation analysis was done by the CODEKA2D software package using a data flow from the output of NETZ2D software. In opposite to Brezing (1996) only the points 22, 23 and 24 are confirmed as stable reference points. Table 3 gives the results of the congruency tests.

reference points	critical value	test value	acceptance
22, 23, 24, 26 (Brezing, 1995)	1.03	1.92	no
22, 23, 24	1.15	0.864	yes

Tab. 3: Results of congruency tests using different reference points

The following single point analysis can be done in two ways:

- Analysing the deformations from epoch to epoch will give an overview of the differences between the epochs. The results can be interpreted easily like the trace of the movements which have take place. This graph consists of n-1 vectors (n = number of epochs) and the single deformations are not significant in the Onstmettingen network.
- Analysing the deformations from the first epoch to a certain epoch **i** gives the total deformation in this time. This total value can be used to decide the point is moved because the vector crosses the calculated confidence ellipse.

In Figure 5 the recent results of deformation analysis the Onstmettingen network are presented. Although the run of the assumed faults is not very precise all the stable points are located on the same block certainly. The movements of the unstable points are very irregular and difficult to interpret. After first interpretations only the changes in the points 21 and 25 extend the confidence ellipse which marks the critical line of statistical significance of movement. It is safe to say point 25 is moving towards SW. The points number 26 and 27 show very irregular deformations changing their direction random. Sometimes the changes of coordinates seem to become significance to be reduced or varied in the next epoch.
But a second interpretation gives same remarkable indications. Within the first epochs (4 years) point 21 changes about 1.4 mm in 105° and turns to 1 mm in 330° in the following years (15 years). The first movement (0.35 mm/a) crosses the confidence ellipse and become significance, the second movement (0.07 mm/a) seems to be very straight but not yet significant due to the unfavourable graph of the confidence ellipse. A geological interpretation of this unusual

deformation behaviour is not yet available. Interpreting the movement of point 25 you can recognise mainly a cross of the critical line of the confidence ellipse.

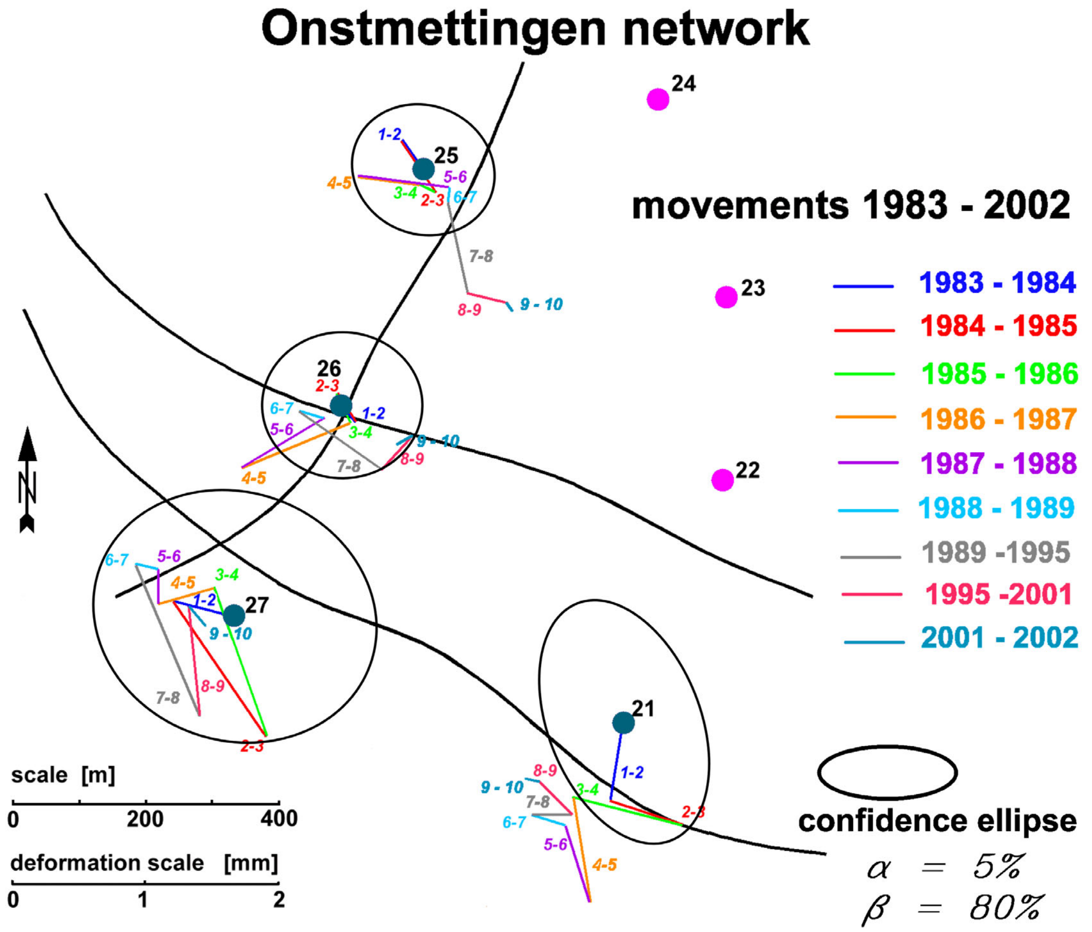

Fig. 5: Results of deformation analysis in the Onstmettingen network. A series of deformation vectors from epoch to epoch identifies the changes taken place. The confidence ellipses give a critical value the deformation can be evaluated to be significant. The scale of confidence ellipses is in accordance to the deformation scale.

by the total movement. In detail the beginning of the deformation graph shows small unsteady movements in the years 1983 to 1987 but after this date the point changes in 140° nearly straight ahead. In the period from 1987 to 2002 the changes accumulate to 1.6 mm respectively about 0.1 mm/a in SW.

Similarly starting in 1987 the movements of point 26 are very small and inconsistent over 4 years. In the following time period the point moves about 1.3 mm in 80° straight ahead to a greater or lesser extend. Evaluating the total time of observations no significant deformation can be found but starting in 1987 the estimated movement becomes interest. The annual rate increases to 0.08 mm/a and is in the range of geological assumptions but the direction is surprising within this first interpretation.

The confidence ellipse of point 27 is out of scale. The reason may be the loss of sight to the adjacent point 26 because of growing forest in the last years. Contrary to the other points no time dependent changes are recognisable in the deformations. The movements vary between S and W and are alternating.

The discussed deformations in the Onstmettingen network have to be presented and interpreted by geologists and seismo-tectonic experts to find accordance to their models of the seis-mically active region of the Hohenzollerngraben. In order to detect movements less than 0.1 mm/a a special geodetic observation technique and a successful deformation analysis was necessary.

5. Conclusions

The Onstmettingen network is an example of a deformation network to demonstrate the high quality of geodetic observations and modelling. Using a Mekometer ME5000 and the observation type "distance ratio" and the CODEKA2D software package the verification of very small deformation was successful within 20 years of observation.
The estimated deformations have to be verified by different models. Additional analyses with observations starting 1987 have to examine carefully the detailed time dependent interpretations. In the future Mekometer distance ratio observations will be carried out simultaneously to GPS measurements of high precision. The discussion of the results to geologist is necessary.

This paper is based on the work of the students R. Steidl and R. Dieterle who carried out the field work of the latest epochs, re-organised the data of the former measurements and prepared the deformation pictures. This help is acknowledged gratefully.

Note:
This paper with all figures available in color and at full scale is free for download at
http://www.gik.uni-karlsruhe.de/~zippelt/pub/albstadt-1

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