Journal of Applied Geodesy 1 (2007), 17–25 © de Gruyter 2007. DOI 10.1515/JAG.2007.003

Fuzzy system based analysis of deformation monitoring data at Eiblschrofen rockfall area

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Abstract. In 1999 a rockfall occurred at the Eiblschrofen, near Schwaz (Tyrol, Austria). Immediately after this event, a monitoring system consisting of GPS, geodetic and geotechnical sensors was installed in this area. The data of this different group of sensors are now for the first time analysed together within a hybrid assessment tool. This tool shall imitate the knowledge and decision making process of a human expert looking at different data. Therefore a fuzzy-based approach is chosen to implement the assessment tool. The paper describes the situation at the Eiblschrofen area, the monitoring system as well as the first implementation steps for the fuzzy-based assessment tool.

Keywords. Deformation, rockfall, geodetic and geotechnical monitoring, fuzzy theory, assessment.

1. Introduction

Eiblschrofen is one of the most well-known rockfall areas in Austria. It is located near the city of Schwaz, Tyrol (see fig. 1).

Schwaz has a very long tradition in mining. Since the middle ages, silver was mined at Eiblschrofen and its surrounding area. In the 15th and 16th century, Schwaz was the second largest town in Austria (30000 inhabitants) and the center of silver mining in Europe. This period ended when "cheap" silver was brought to Europe from the Americas. Since the 1950ies dolomite has been mined at Eiblschrofen area.

After the rockfall in 1999, a monitoring system consisting of several different sensors was installed in this area. In 2005, the responibilities for these groups of instruments were centralized at one local surveying office. The idea was then to build an integrated, 'intelligent' data assessment, where all data collected is processed together to feed an alarm system. Due to the properties of the different data types we decided to use fuzzy techniques for the assessment. These fuzzy techniques and other methods of artificial intelligence are just beginning to be used in geodesy (see e.g. Chmelina 2002, Wieser 2002, Haberler 2005). So, the basics of fuzzy system based decision making are also presented here to give the opportunity to get familiar with this promising technique.

Figure 1: Location of the Eiblschrofen, Schwaz, Tyrol, Wikipedia 2006.

2. Geology

The geological situation at the Eiblschrofen area is rather complex. Three materials form this area (Brandner and Reiter 2001):

- Dolomite forms the basic block of the Eiblschrofen. Here, the mining took place, so the dolomite has many excavations below ground.
- The bedding of the dolomite at the toe of the Eiblschrofen is formed by sandstone.
- Schist lies on top of the dolomite. The loading of the schist causes a compression which results in tilting and toppling of the dolomite at the tear-off zone.

3. The rockfall and the monitoring system

On July 10th, 1999 a rockfall (thousands of m^3 material) at the Eiblschrofen endangered the inhabitants of Schwaz. About 50 buildings and 16 companies had to be evacuated in the risk area below the Eiblschrofen. As a first measure some protection dams were built. To protect the people during the construction work and to observe the situation at the top of the rockfall, a monitoring system had to be installed immediately in the area.

3.1. Terrestrial measurements

A geodetic network consisting of approx. 20 points was established immediately after the rockfall. In the first weeks after the rockfall, measurements were carried out every day, but after the stabilization phase the interval between the measurements was increased by and by to two times a week. Today the geodetic network is observed once per year (see fig. 3 in dashed black).

3.2. GPS Measurements

For an efficient monitoring of the rockfall area, a permanent monitoring system proved to be necessary. So, in 2003 three stations were equipped with L1-frequency GPS receivers (see fig. 3, in green). The reference station (dual frequency receiver) is approximately 1.5 km away. For the monitoring of the movements of this reference station, it was connected into the Tyrolean reference network TIREF.

The measurements for the reference epoch were done in October and November 2003; since November 2003 the data of the four stations have been transmitted to the office of the responsible surveyor by WLAN. As an analysis software, Leica Spider was chosen.

After the testing phase, hourly data is sent to the office; the processed results are then averaged to get two positions per day.

3.3. Geotechnical equipment

Shortly after the rockfall, a continuous monitoring system consisting of several geotechnical sensors was installed at the top of the Eiblschrofen. The aim was firstly to protect the workers building the dams at the toe of the rockfall area and secondly to monitor the longterm behaviour of the Eiblschrofen.

The following sensors have been installed since 1999 (Gillarduzzi 1999, Kandler and Obex 2004, ARGE Monitoring Eiblschrofen 2005):

- Extensometers: Up to 11 wire extensometers (Hottinger) have been installed since 1999; at the moment 5 of them are active.
- Crackmeters: a maximum of 12 crackmeters (Hottinger) have been installed; 7 of them are active at the moment.
- Tiltmeters: 3 out of 7 tiltmeters (dual-axis, Althen) are still active.

3.4. Assessment of the existing monitoring system

The existing monitoring system consists of three different parts (see 3.1–3.3) which cannot directly be combined to obtain a hybrid result. The data can be distinguished by several properties:

- Different data rates: The coordinates calculated from the geodetic terrestrial measurements are available once per year. GPS coordinates represent hourly mean values of the permanent monitoring. The continuously monitored data of the geotechnical sensors is archived by three-hour-values. In case of anomalies the data saving rate can be increased, e.g. to 10-minutes-intervals.

Figure 2: The Eiblschrofen, July 2006. The tear-off zone can be seen as the light shaded area at the top of the mountain.

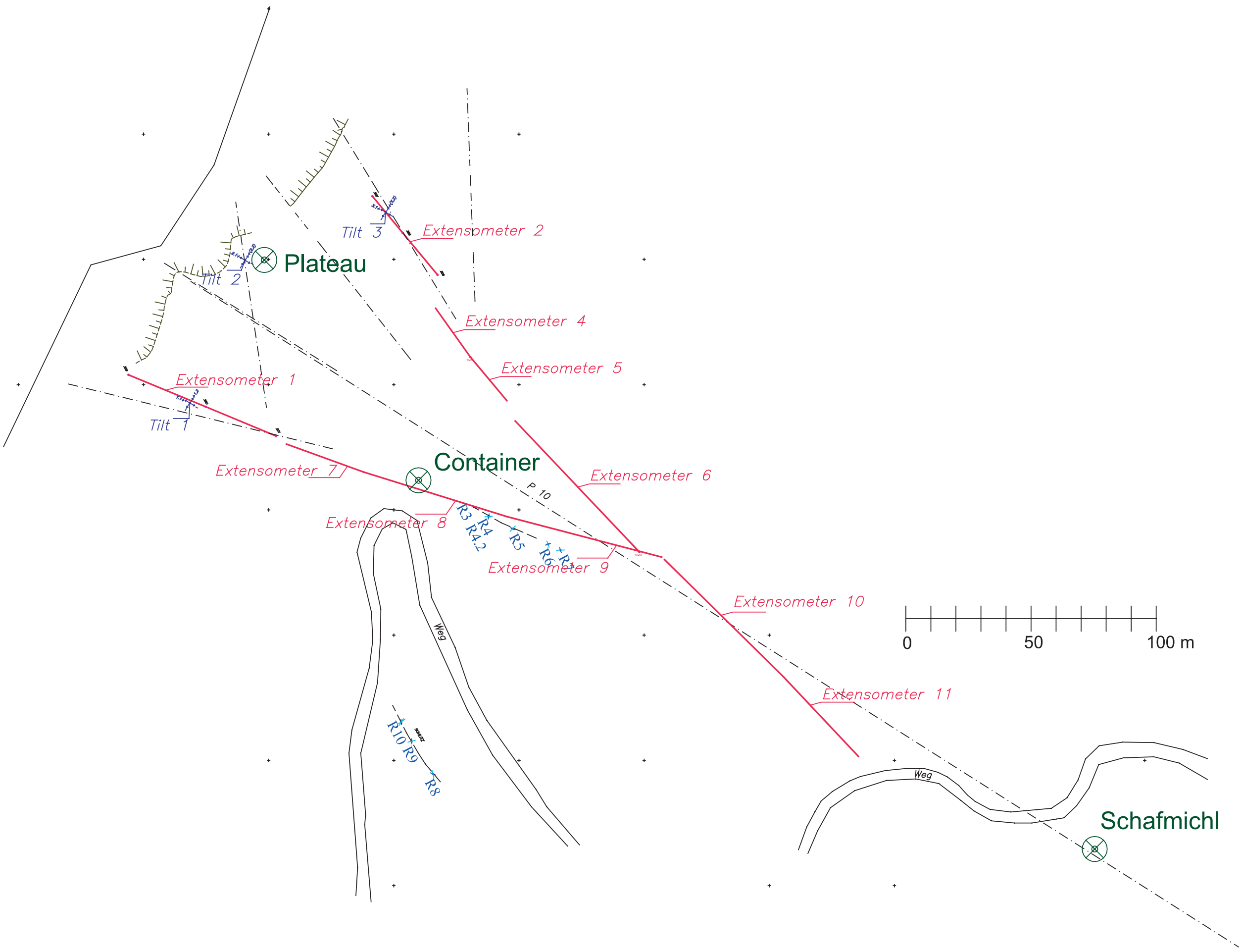

Figure 3: Overview of the installed measurement systems. The tear-off zone is at the upper left corner of the figure. GPS measuring points shown in dark green, tacheometric profiles in dashed black lines, extensometers in red, tiltmeters and crackmeters in blue, based on Gillarduzzi 1999.

Figure 4: GPS point 'Plateau' with tiltmeter and WLAN antenna.

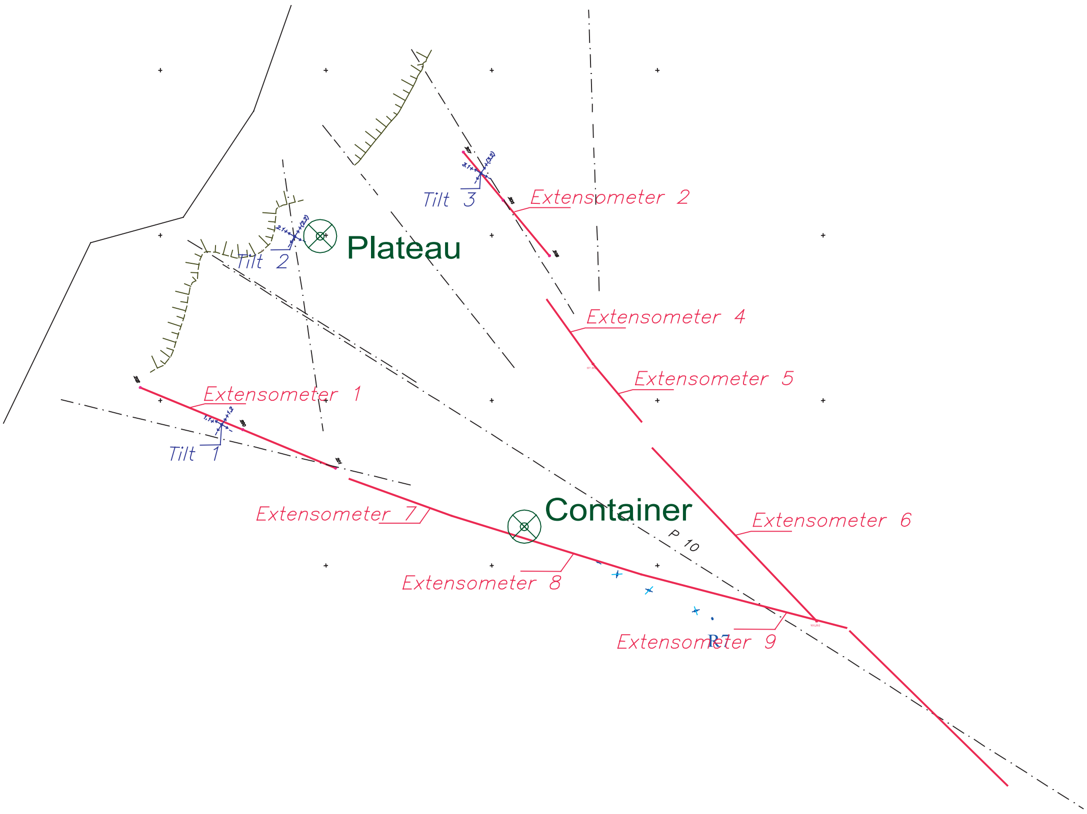

Figure 5: Detail of the installed monitoring system. 2 GPS points in dark green, extensometers in red, tacheometric profiles in black dashed, tiltmeters in blue, based on Gillarduzzi 1999.

- Different data types: GPS and terrestrial measurements result in (absolute) coordinates of the observed points. The geotechnical sensors can only provide relative information like changes in length or tilt.
- Different reference frames: The reference frame for the GPS stations is the TIREF, the Tyrolean representation of the ITRF. The geodetic terrestrial measurements are calculated within the Austrian reference frame, which is a Gauss-mapping of the Austrian Bessel-ellipsoid. The measurements of the geotechnical sensors can only be described in this reference frame, if the local ties have been considered, i.e. the connection between the sensors and at least one geodetic point in the vicinity of the sensors.
- Different accuracy: the geotechnical sensors give data with the greatest accuracy, usually in the range of approximately 0.1 mm or better. The accuracy of GPS and terrestrial measured coordinates is usually about 1 cm.
- Different software: for every group (terrestrial measurements, GPS observations, geotechnical sensors) a different software package is used for data collection, processing and archiving.
- Different authorities: in the beginning, different companies were responsible for the measurements and sensors. Now this will be unified so that one local surveying office is the contact point for the monitoring of the Eiblschrofen.

4. Fuzzy based data analysis system

4.1. Basics of fuzzy-based decision making

The task is to develop an analysis and assessment tool for the various monitored data gained at the Eiblschrofen. The Matlab fuzzy toolbox is used due to its broad mathematical functionalities.

The individual software for each group of sensors is still used for the data transfer and first processing of the data in the office. Then the data is exported to the fuzzy analysis tool. The aim is to combine the corresponding data within the analysis tool to imitate the human expert who does this combination in his mind while looking at the different sensor diagrams.

Using a rule-based decision making system like the Matlab fuzzy toolbox, the rough procedure is as follows:

- Input and output parameters

In a first step the desired output parameter(s) and the therefore necessary input parameters have to be identified (in most cases by empirical methods).

- Modelling of parameters

The parameters have to be modelled by at least two terms. In most cases 3 to 7 terms are used (e.g. fig.

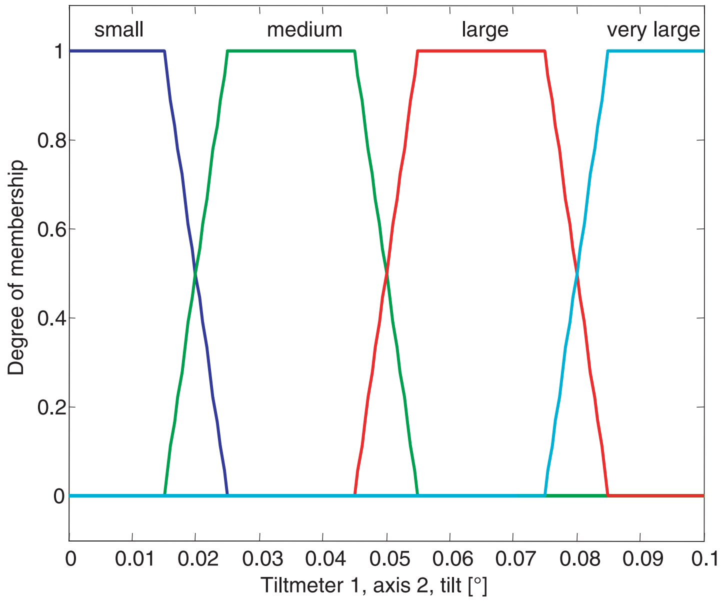

Figure 6: Example of the modelling of the parameter 'tilt of tiltmeter 1, Axis 1.2' with 4 terms (small, medium, large, very large).

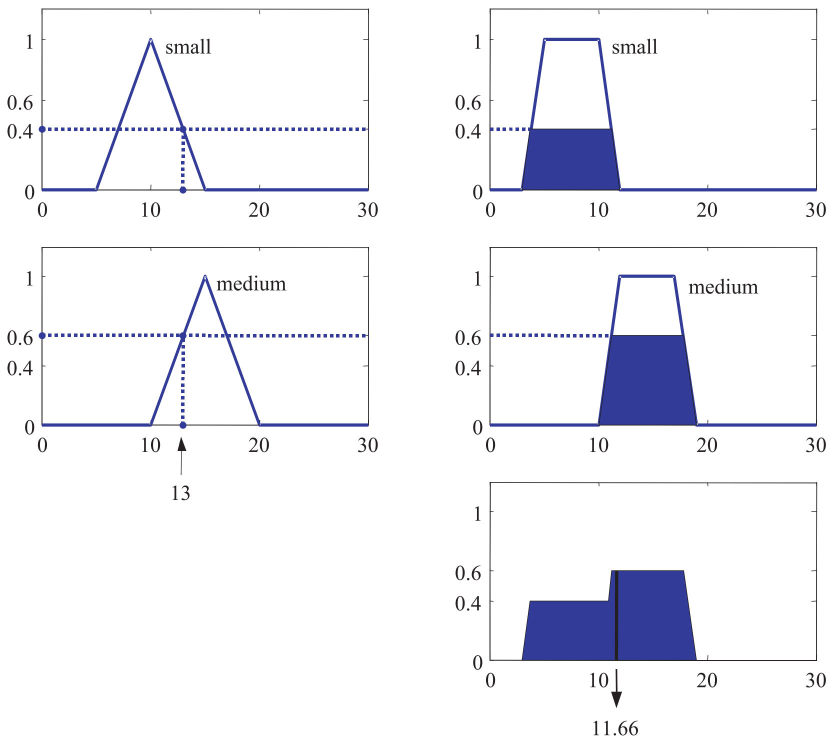

Figure 7: Simple general example illustrating 2 rules (= first 2 rows); in the left column the input value ('13') results in degrees of membership of 0.4 and 0.6 resp. In the right column the truncated output set for the current input value is shown. The lower right figure shows the fuzzy output set after aggregation (in blue) and the defuzzified distinct output value (11.66, CoG-method).

6); the more terms the finer will be the decision making process, but also the more rules are needed to describe the system. The membership functions are defined empirically in most applications.

- Rules

The if-then-rules connecting input and output have to be collected (e.g. by means of interviews with experts). The rule-base represents therefore the expert knowledge. As an example, the rule base shown in fig. 7 consists of the following rules:

IF input = small THEN output = small.

IF input = medium THEN output = medium.

- Weighting

The rules can get different weights according to their influence on the decision (i.e. output).

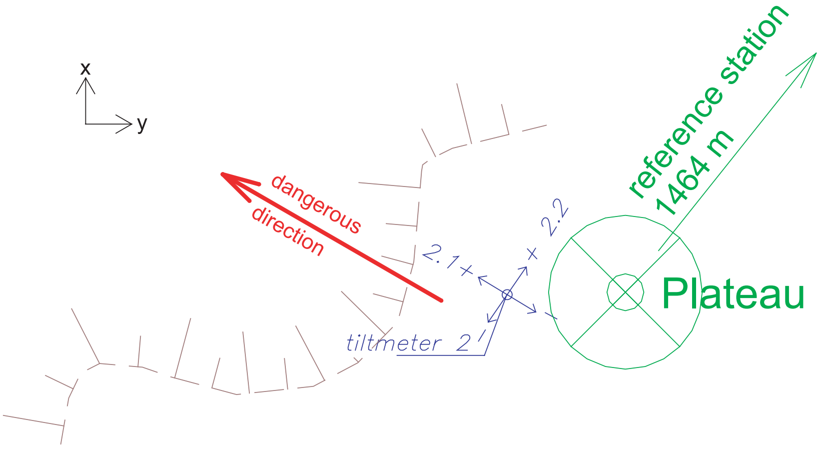

Figure 8: Example of the relation between the GPS station 'Plateau' (in green) and the tiltmeter number 2 (in blue), based on Gillarduzzi 1999. The critical direction is shown in red.

- Decision making

For the calculation of a new output (= decision), the actual/current input parameters are fed into the system. Each rule is evaluated and gives a contribution to the final output according to the degree of accordance. All these sets are merged ('aggregation'), and a final (distinct) output value is calculated out of the aggregated fuzzy set ('defuzzification'). In most cases, the 'Center of Gravity'-method (CoG) is used for this task.

In fig. 7 the decision making is shown for an example: the current input value of '13' is fed into the small system mentioned above. It gives degrees of accordance of 0.4 resp. 0.6 for the first resp. second rule. These degrees of membership are transferred to the output and used to cut the corresponding fuzzy set (right column). These output sets are aggregated, and the center of gravity is calculated, which gives a defuzzified output value of '11.66'.

For further information on fuzzy set theory and the application in geodesy see e.g. Bandemer 1997, Kahlert and Frank 1993, Chmelina 2002, Wieser 2002, Haberler 2005.

4.2. *Results of the fuzzy-based analysis of monitoring data*

From the longterm monitoring data at the Eiblschrofen, a time interval of two months was chosen for the design of the system. As a first step, the relations between the different sensor groups had to be identified, taking into consideration the geological situation. This means that if one sensor shows an increasing movement, some other sensors must show the same tendency so that the situation is assessed as potentially dangerous. If only one sensor indicates a movement and the other related instruments are stable, then another reason must be found, e.g. measurement errors or an animal touching the instruments. For the synchronization of the data a time interval of 3 hours was chosen.

During the data import blunders like bad GPS positions due to bad satellite constellations were removed from the data. Then the relationships between the various sensors were investigated and implemented ('rule-base'). One of these relations (= rules) exists e.g. between the GPS point 'Plateau' and the tiltmeter number 2 just beside the GPS station:

> If the x-coordinate of GPS point 'Plateau' is increasing and the y-coordinate is decreasing and tiltmeter 2 shows a tilt in the same direction (increase of measurement values of axis 2.1) then a toppling of the front part of the Eiblschrofen could be the reason (see fig. 8).

Note: Usually, the geotechnical sensors are oriented relative to the critical direction of the movements (see tiltmeter in fig. 8). The coordinates of the GPS receiver are calculated and archived within the official Austrian coordinate system. Therefore, the movement of the GPS point must be modelled by the movements in x- and y-direction.

Whenever a new epoch of input values is provided by the monitoring system, the fuzzy-based tool checks the suitable rules available in the implemented rule base. As a result, the potential of danger is assessed for the Eiblschrofen area with a rating between 0 and 1 (for details of the processing see the following example).

Note: due to the actual small movement rates at the Eiblschrofen, the measurement values had to be enlarged to get a potentially critical situation for this simulated example.

The input data for this example consists of the x- and y-coordinate of the GPS-point 'Plateau' and the corresponding measurement values of the inclinometer 2 for a time interval of 60 days (see fig. 9, 10 and 11, moving average with a window of 11 values).

The time series show the original data until day 30, then a dangerous situation was simulated by overlaying larger movement rates:

- days 30–37 (phase 1): increase of the movement rates (approximately 5 cm per day)

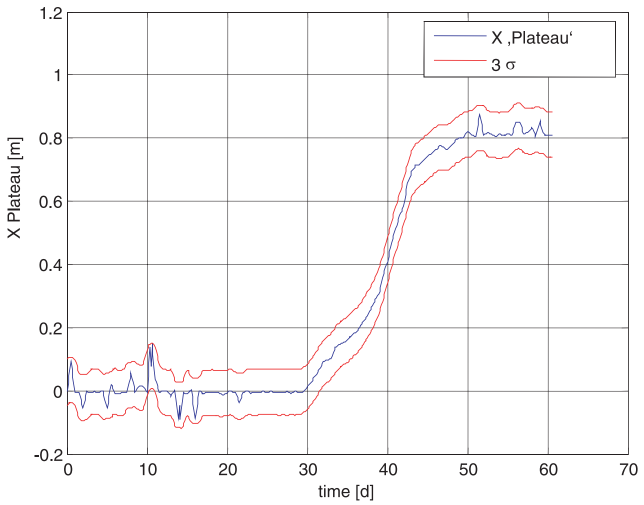

Figure 9: Movement for the x-component of the GPS-point 'Plateau' (in blue, simulated by overlaying the original data with assumed movement rates).

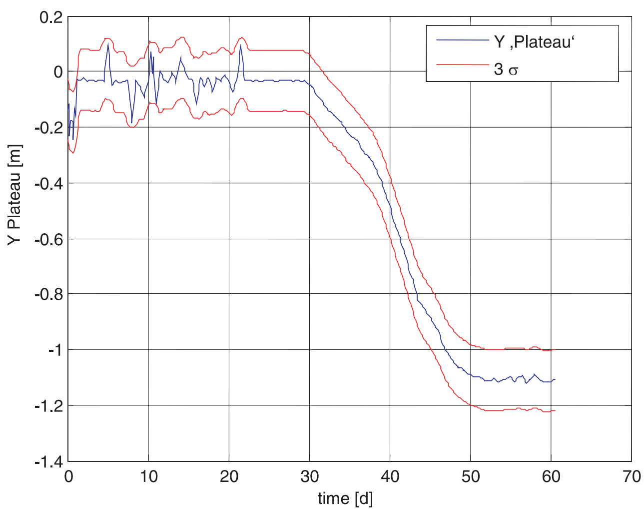

Figure 10: Movement for the y-component of the GPS-point 'Plateau' (in blue, simulated by overlaying the original data with assumed movement rates).

– days 38–43 (phase 2): stronger increase of the movement rate (approximately 7 cm per day)
– days 44–50 (phase 3): smaller movement rates, transition to original data
– days 50–60: original data (with a vertical offset due to the simulated movement)

From the measurement data, the input variables for the fuzzy based analysis are derived. For each sensor, the measurement value itself and the change of the measurements from the last to the current epoch are calculated. For the example shown here, 8 input variables are defined and modelled (x- and y-component of the GPS-point, 2 axis of the corresponding tiltmeter). Fig. 12 gives an example for the modelling: if the movement of the x- resp. y-component of the GPS-point (relative to the reference measurement) is

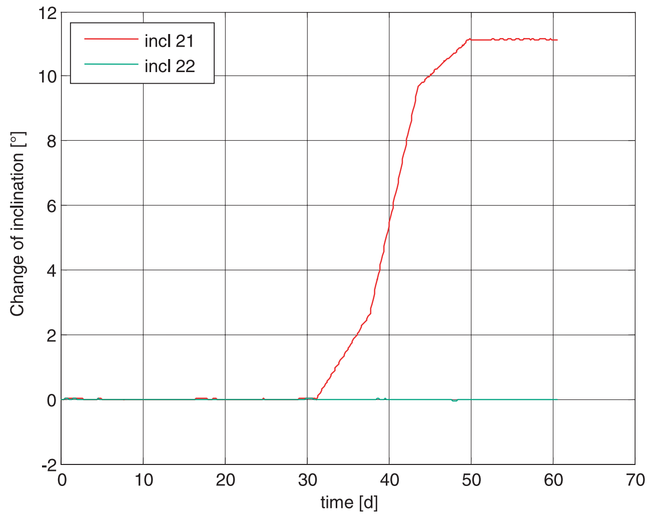

Figure 11: Simulated changes of the inclination of the inclinometer (critical axis 2.1 in red). According to the scenario, a toppling of this area, the changes of the inclination were calculated and superimposed to the original data. Axis 2.2 (in green) shows the original measurement data (no movement).

up to about ±3 cm, the movement is said to be 'small'. Are the movements in a range of about ±5 to 7 cm, the input is described as 'medium', etc.

In the analysis, the derived input variables are fed into the fuzzy system epoch by epoch ('fuzzification'). All matching rules within the rulebase are applied and evaluated according to the input. The final output value is calculated using aggregation and defuzzification methods (see before). For the discussed application, the output variable 'potential of danger' within a range of 0 to 1 is defined, where '0' means 'no danger' and '1' stands for a potentially dangerous situation. The output is calculated using a rulebase of 189 rules; one of them, indicating a critical situation, was mentioned before. Fig. 13 shows the output values calculated for each epoch of the time series. Looking at this figure, the 'potential of danger' can be interpreted as follows:

At day 30, the potential of danger is increasing according to the increasing movement rates. Since the movement rates are quite constant in this first phase, the potential of danger shows a stabilization, until the movement rates are increasing again (phase 2). There, the output value rises to 0.7 which indicates a potentially dangerous situation. Phase 3, indicating a stabilization of the situation, brings the output values slowly back to a normal level (0.1 to 0.2).

Note: the extreme values 0 and 1 cannot be reached in this analysis due to the defuzzification method 'Center of Gravity'. The center of gravity of the output set is calculated, so the actual minimum and maximum values depend on the size and the shape of the membership functions of the modelled output parameter. E.g. in this case (see fig. 13), the actual lowest value that can be reached is 0.07.

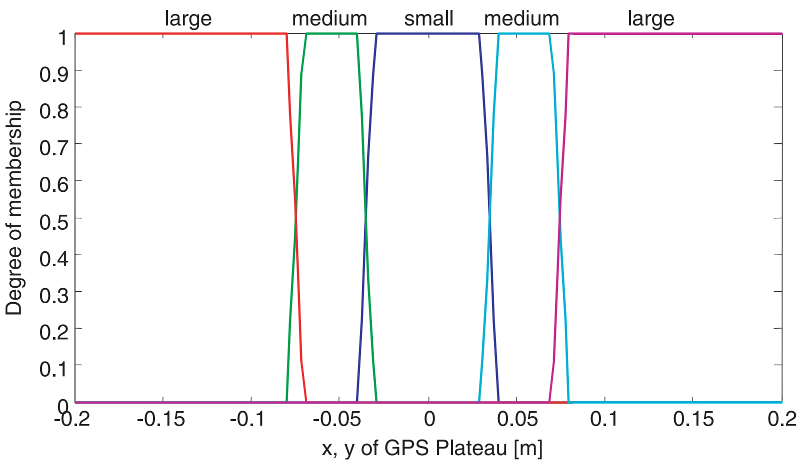

Figure 12: Modelling of the input variables x- resp. y-component of the GPS-point 'Plateau', relative to the reference measurement.

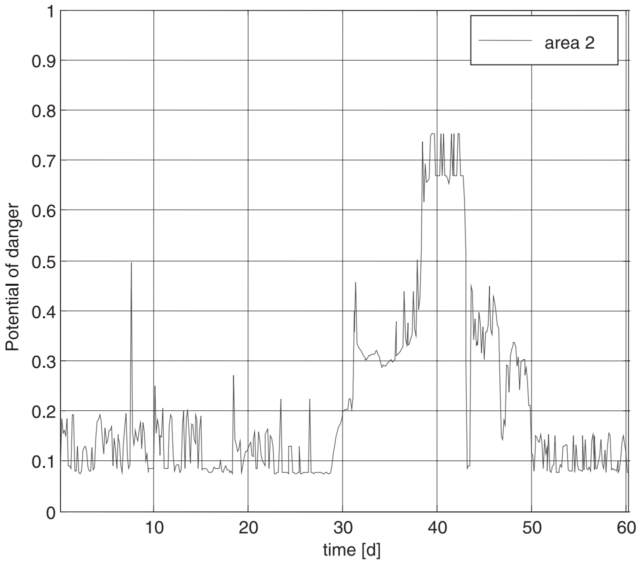

Figure 13: Diagram showing the 'potential of danger' (range: 0 = small to 1 = large) calculated by the fuzzy analysis tool for the investigated data (2 months). According to the simulated scenario, the potential of danger increases reacting to the different movement rates.

Note: One output value of day 7 (nearly 0.5) shows the sensibility of the developed fuzzy system: At this epoch, all input parameters show the same tendency as a critical situation compared to the last epoch (x- and y-coordinate of the GPS-point slightly increasing and decreasing, very small increase of the inclination regarding to the last epoch). These 'changes' are of course random variations, but the system recognizes this tendency and reacts to draw the attention of the human expert to this situation.

5. Conclusions and outlook

The first steps in design and modelling show a great potential for an 'intelligent' fuzzy-based analysis and assessment tool for geodetic monitoring data. The relations between different sensors for the situation at Eiblschrofen have been found and implemented in the fuzzy system, but further investigations are necessary to build an efficient assessment tool. After the implementation phase, the analysis tool was tested with data from other time intervals collected by the Eiblschrofen monitoring system. The fuzzy system is still a post processing routine, the final assessment tool shall of course work in near real-time. Then, the local surveying office can start testing the tool under real conditions.

The analysis tool uses the geodetic and geotechnical measurement values available at Eiblschrofen, which is a pure geometrical information. The method of fuzzy systems allows very well for an integration of other types of data, e.g. geology in this case. An extension of the analysis tool taking into account other than geodetic data can be a task for future work.

Acknowledgements

We would like to thank Verbundplan (Salzburg), Vermessung Weiser + Kandler (Schwaz) and TIWAG (Innsbruck) for providing the monitoring data.

References

ARGE Monitoring Eiblschrofen, Jahresbericht 2004, unpublished report, 2005.

Bandemer H., Ratschläge zum mathematischen Umgang mit Ungewissheit, Teubner Verlag, Stuttgart, 1997.

Brandner R., Reiter F., Strukturgeologische Untersuchungen und Erläuterungen zur geologischen Kartierung des Eiblschrofen, unpublished report to the Forsttechnischer Dienst für Wildbach und Lawinenverbauung BMLFUW, 2001.

Chmelina K., Wissensbasierte Analyse von Verschiebungsdaten im Tunnelbau, Dissertation, Geowissenschaftliche Mitteilungen, Schriftenreihe der Studienrichtung Vermessungswesen und Geoinformation, Technische Universität Wien, Heft 62, 2002.

Gillarduzzi K., Geodätische Deformationsmessungen Eiblschrofen, unpublished report, TIWAG, 1999.

Haberler M., Einsatz von Fuzzy Methoden zur Detektion konsistenter Punktbewegungen, Dissertation, Geowissenschaftliche Mitteilun-

gen, Schriftenreihe der Studienrichtung Vermessungswesen und Geoinformation, Technische Universität Wien, Heft 73, 2005.
Kahlert J., Frank H., Fuzzy-Logik und Fuzzy-Control, Vieweg Verlag, Braunschweig, Wiesbaden, 1993.
Kandler C., Obex M., Deformationsmessungen Eiblschrofen, unpublished reports, ARGE Monitoring Eiblschrofen, 2004.
Wieser A., Robust and fuzzy techniques for parameter estimation and quality assessment in GPS, Shaker Verlag, Aachen, 2002.
Wikipedia, http://de.wikipedia.org/wiki/Schwaz (last date accessed: Nov 2006).

Received: Aug 28, 2006 Accepted: Nov 17, 2006

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