Improvement of a Terrestric Network for Movement Analysis of a Complex Landslide

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Key words: deformation analysis, landslide, terrestric network

SUMMARY

This paper concerns the installation and evaluation of a terrestrial network, in order to capture the movement of a complex landslide. Based upon past epoch measurements, first deformation analyses are carried out and results are evaluated. Furthermore, the weak areas of the installed network are analysed. Conclusively, the applied deformation analysis methods are scrutinized and an outlook on possibly more complex analysis methods is given.

SUMMARY (German)

Diese Arbeit behandelt die Anlage und Auswertung eines terrestrisch beobachteten Punktnetzes zur Erfassung der Bewegungen eines komplexen Hangrutsches. Dabei werden basierend auf bereits durchgeführten Epochenmessungen erste Deformationsanalysen durchgeführt und die entstandenen Ergebnisse bewertet. Außerdem erfolgt eine Analyse der Schwächezonen des angelegten Netzes. Abschließend werden die verwendeten Deformationsanalysemethoden hinterfragt und ein Ausblick auf mögliche komplexere Deformationsmodelle gegeben.

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1. INTRODUCTION

Landslides cause disasters all over the world. They do not only cause economic damage, but also result in the loss of human lives. To counteract such severe consequences of landslides, it is necessary to develop different strategies, by which the effects of landslides can be reduced or even avoided. One of these strategies is the development of early warning systems that can be used to send advices for actions to the local authorities.
The development of an early warning system for landslides however turns out to be extremely difficult, because the possibilities of a prediction vary significantly. The development and installation of an early warning system, that is placed upon a known historic landslide is thereby quite easy to do. The landslide can be equipped with the necessary monitoring instruments and sensors that indicate a possible reactivation of the landslide. The prediction of new landslides is by contrast extremely difficult.
The aim of the research project ILEWS is the development and testing of a prototype for an integrative landslide early warning system, by that a possible failure of the slope stability can be predicted. This early warning system shall be developed modular and transferable, so that it can be adapted to different governmental organization structures in other regions or countries and to different natural processes like rockfalls and debris flows.

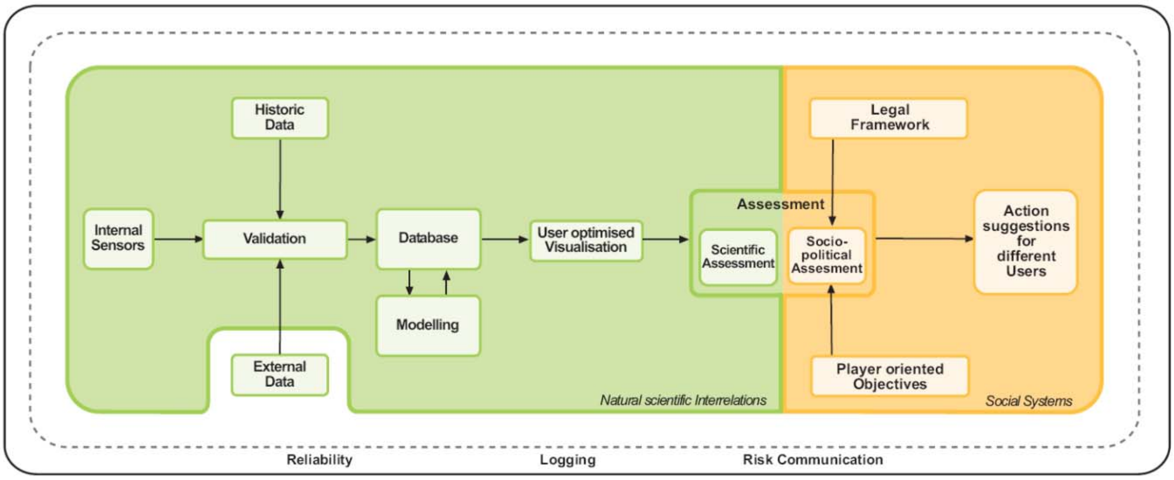

Figure 1: Scheme of the interdisciplinary Project ILEWS

The project ILEWS is funded by the German Ministry for Education and Research for a period of three years. It is divided into three clusters concerning the monitoring of landslides, the modelling of landslides by converting the monitoring results into a reliable early warning and the development and implementation of a communication network between the different actors of an early warning chain. (Figure 1)

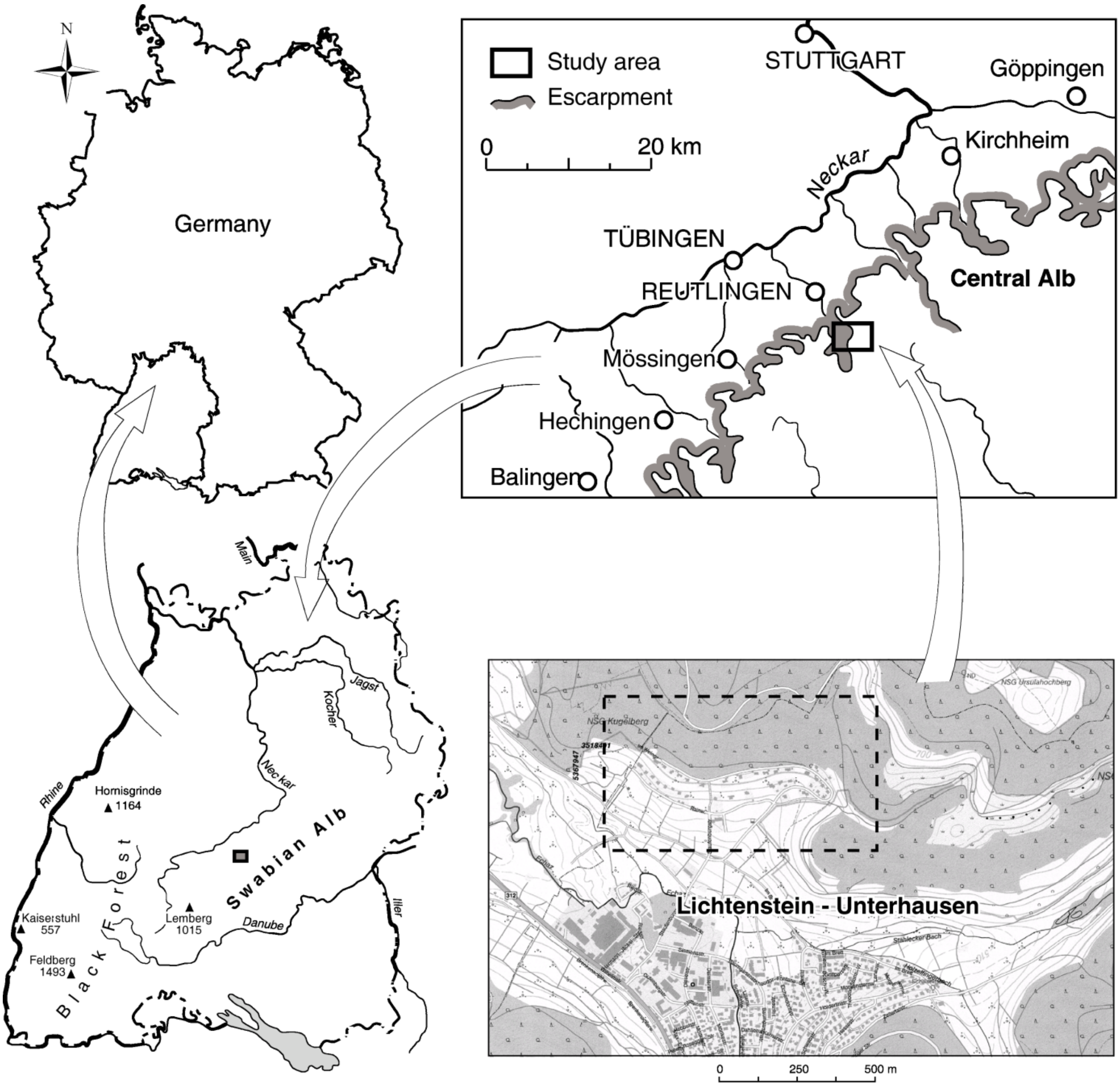

Figure 2: Location of the study area in Lichtenstein-Unterhausen [Bell, 2008]

The study area of the Monitoring Cluster is located in the Swabian Alb, SW-Germany and is part of the southern German cuesta landscape (Figure 2). The region shows significant landslide activity comprising deep-seated rotational and shallow translational landslides as well as creeping and flowing processes [Bell, 2008].

The monitoring of the study area is carried out by multiple sensors measuring meteorologic parameters, soil moisture by geoelectric profiles, TDR-probes and tensiometers, and soil movement by inclinometers and tacheometry.

This paper discusses the geodetic approach to the monitoring of this landslide.

2. INSTALLED POINT NETWORKS

The respective study area was chosen because of the landslide prone slopes, and the fact that one house is showing significant fissures because of ground movements. Additionally the decision to start the project in this area was confirmed by the already existing knowledge and measurement data of inclinometer probes resulting from the previous research project InterRISK, funded by the German Research Foundation [Bell, 2007].
To acquire the expected movements of the landslide two networks were installed, one to acquire the position movements and another one for the height component. Both networks are independent from each other. The possibilities to install the position network were limited by the natural topography and the plant coverage of the hillside as well as the already existing houses. In addition it was necessary to place the majority of the points on public accessible areas, since the access to some parcels was denied by their owners.

2.1 Position network

Figure 3: Position network, installed at the slope of the study area

The points of the position network were placed mainly in the existing streets of the study area (cp. Figure 3). Thereby the points were installed mostly underground in covered protection ducts and allow a positioning precision over the points of a few 1/10 mm because of the usage of precise point signs and positioning methods. Because of the chosen marking method it is expected that the points of the position network are stable towards human influences during the project runtime. At the same time the points are expected to move with the landslide because of its movement depth.

2.2 Height network

Figure 4: Height network, installed at the slope of the study area

Next to the position network there was also installed a height network in the study area (cp. Figure 4). The height points were installed in close proximity to the position points and realized by simple height bolts on the roadside. Mostly these height bolts were installed on the valley side of the street (except points 109 and 111). The numbers of these points got the extension -1 during the levelling measurements. If it was necessary to place the position point on the upwards facing side of the street for visibility reasons, a second height bolt was installed to keep the proximity, which then got the extension -2. The eastern part of the position and height network between the point numbers 107 and 208 was not realized right from the beginning of the research project, but was installed after the second epoch because of statements of residents of that area, which described previously unknown movements in that part of the hillside. To enable a datum transformation to a stable point, the section 104 – HB1 – APT was also measured. Thereby the point APT is placed in the fundament of a massive concrete bridge outside of the historic landslide area and is assumed as stable. The section from point 104 to APT was divided by the additional point HP1 because of its length.
The points 301, 302, 305 and 307 are located at inclinometer tubes. Since movements were observed within the inclinometer measurements, it was reasonable to try to combine the different measuring methods. To include the inclinometer tubes in the height measurement an adaption was developed, that gives a stable definition of the height of the inclinometer tube.

For that the tube (red) was equipped with a metal collar (black). On this permanently installed metal collar a cap bedded on three points (grey) was placed during the geodetic measurements, which gives a precise height definition of the tube. (Figure 5)

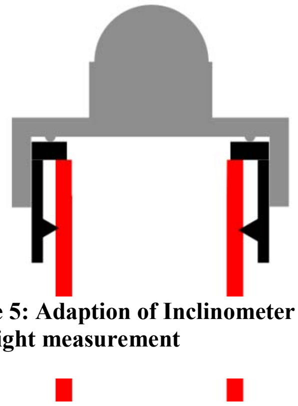

Figure 5: Adaption of Inclinometer tubes for height measurement

3. POSITION MEASUREMENTS

The position network was observed four times so far. (November 2007, March 2008, beginning of August 2008, end of September 2008) The measurements were made with heavy tripods which were centered with high precision optical plummets and cross slides. By that a precision of a few 1/10 mm was achieved. A selected total station TCRP 1201+ from Leica was used for the measurements, in combination with three high precision mekometer prisms. Calibration measurements for this total station showed a precision of the distance measurement unit of ±0,2 mm+0,2 ppm. The measurements themselves were carried out in nine sets on both faces to up to three targets in the set. Additionally automation was applied by using the automatic target recognition (ATR) and the build in set measurement program of the total station. Each of the epoch measurements was adjusted freely.

The deformation analysis was done in multiple 2-epoch comparisons [Welsch, Heunecke, Kuhlmann, 2000]. Figure 6 shows the deformations between the different epochs. The shown confidence ellipses were calculated with a confidence level of $1 - \alpha = 95\%$ and are derived from the epoch comparison 1-4.

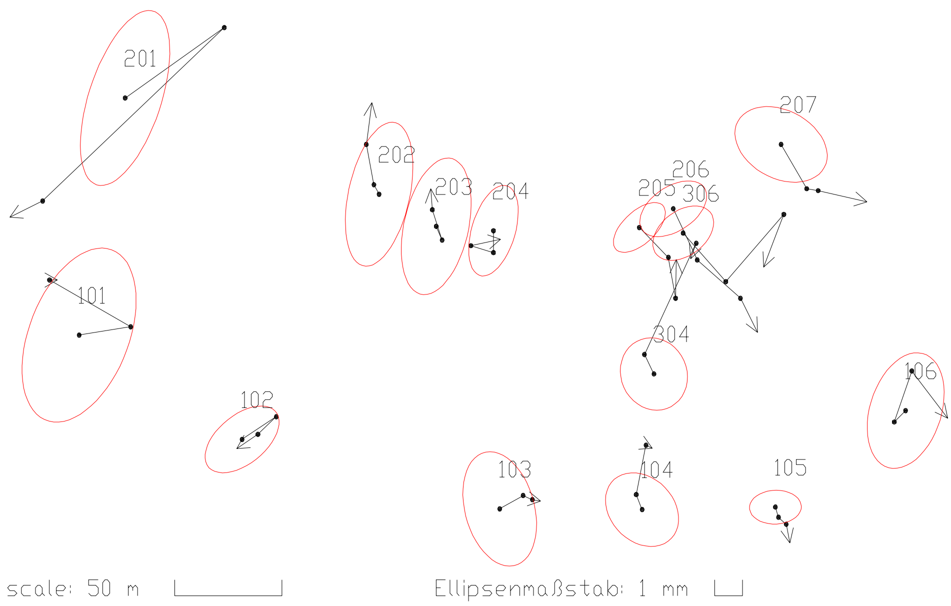

Figure 6: Measured movements in the geodetic position network. The calculated deformations between the measured epochs (Nov 2007, Mar 2008, beginning of Aug 2008, end of Sep 2008) were concatenated and plotted.

The most significant movement in the study area shows the point 201. Eye-catching is thereby the uphill movement between the epoch 1 and 2 during the winter 2007/08, that inverts during spring and summer 2008 and becomes a significant downhill movement of about 1 cm. At present these movements are interpreted as an effect of swelling and shrinking of in the clayrich soils, following dry and wet periods. For validation of this hypothesis, more measurements must be conducted. Integrating the results of the soil moisture sensors, which provide data continuously since August 2008, will improve understanding and correct interpretation of the measured movements.

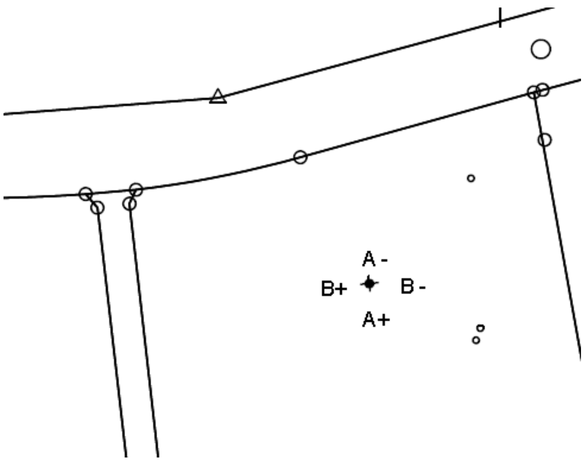

Figure 7: Position and measuring direction of the inclinometer 305, which is closely located to point 306

Noticeable are movements at the points 205-207 and 306. These points are placed in a grassland area. Due to steep slopes in that area and the bumpy topography landslide activity can be anticipated also from a geomorphologic perspective. Extraordinary is especially the sidewards movement of the point 306 between the epochs 2 and 3, and the starting back movement towards epoch 4. These measurement values are no deviations in the observation, because identical movements can be recognized in the results of the measurements of inclinometer 305 (in measurement direction B), placed about 2 meters next to point 306 (cp. Figure 7).

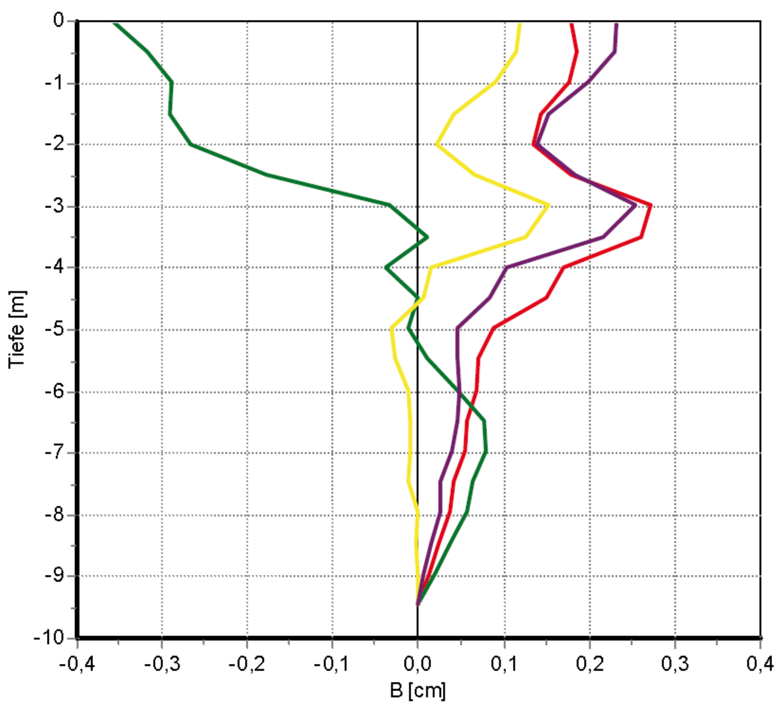

Figure 8: Horizontal movements, measured orthogonally to the slopegradient (direction B, cp. Figure 7), at the inclinometer 305, near to point 306. Measurement dates: 6.5.2008 (red), 17.6.2008 (green), 9.11.2008 (yellow) and 12.2.2009 (violet)

Figure 8 shows these measuring results. The movement at the surface shown there is similar in size and direction to the deformation analysis results of the geodetic position network. The geodetic network shows a sideward movement of about 4 mm from epoch 2 (march 2008) to epoch 3 (august 2008). This sideward movement is identically found in the inclinometer (epoch red to green). The back movement can also be detected in the inclinometer 305 as well as in the geodetic measurements from epoch 3 (august 2008) to epoch 4 (September 2008). Due to the short time period between the epochs 3 and 4, these geodetic measurements do not capture

the whole back movement, shown in the inclinometer.
For the registered movements at further points, especially for the uphill movement of point 304, smaller but similar also in point 104, and for the sideward movement in point 101 at the moment a final interpretation is still missing. For an unambiguous definition of the movements of these points further epoch measurements are necessary.

4. LEVELING MEASUREMENTS

The surveying of the height network was carried out by precise levelling. For this a DiNi 12 from Trimble and two invar-band rods were used. The measurements in every epoch were conducted as double measurements. The height network was observed always at the same time as the position measurements took place (November 2007, March 2008, beginning of August 2008 and end of September 2008). Thus, at present four measured epochs are available. These epochs were, similar to the position network, adjusted freely and then compared in multiple 2-epoch comparisons. During this deformation analysis the changed points from one epoch to the next are identified by a hypothesis test and then removed out of the datum definition by an S-Transformation [cp. Welsch, Heunecke, Kuhlmann, 2000]. Finally by analyzing the results of the deformation analysis, the network can be divided in three major parts. The first part consists of a connection levelling from the bridge bolt to the point 104-1 at the lower street of the study area. The second and third part is the levelling measurement along the lower and the upper street (cp. Figure 4).

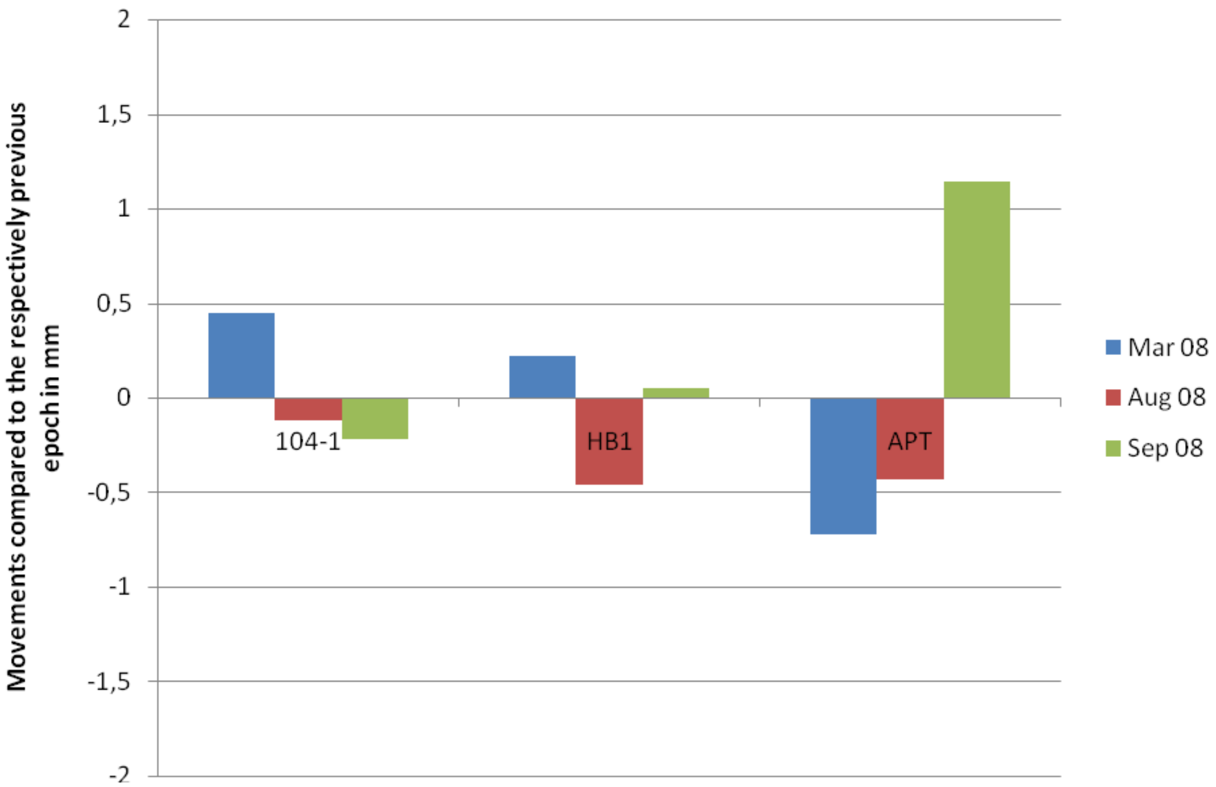

Figure 9: Deformation analysis results for the levelling to the anchorage point

For the first part of the levelling the hypothesis test identified point APT as changed between the epochs 1 to 2 (March 2008) and 3 to 4 (September 2008) (cp. Figure 9). Obviously also a height change has happened at point 104-1 between the epochs 1 and 2. Thus, the point was removed out of the datum definition. Out of these measurements results the question, if the decision to assume the point APT as stable and outside of the landslide area was correct. A final valuation of the stability of this anchorage point cannot be conducted at present; therefore further epoch measurements are necessary.

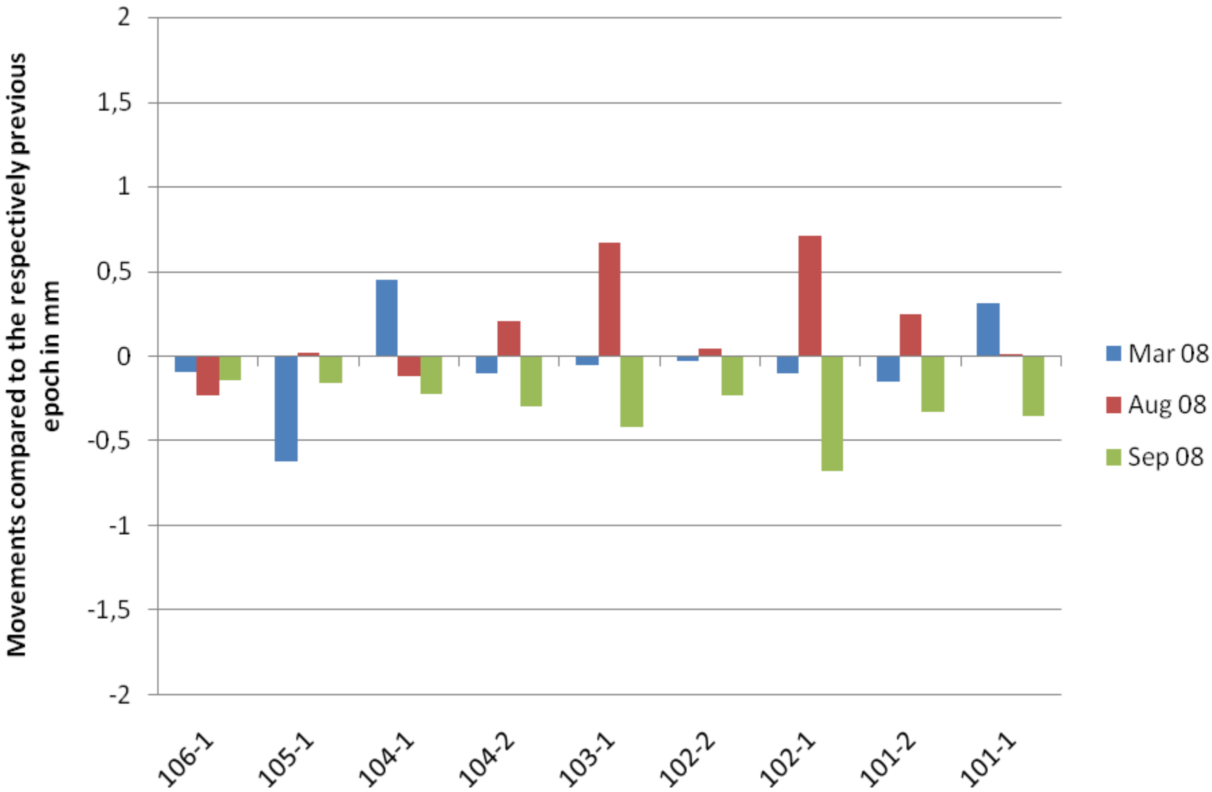

Figure 10: Deformation analysis results for the lower street

The deformation analysis based upon hypothesis tests has shown for the second part of the levelling (the lower street) that next to the already mentioned point 104-1 also the points 105-1 from the first to the second epoch (March 2008) and the point 103-1 from the second to the third epoch (August 2008) was moved. In Figure 10 the movement at point 102-1 during the epochs 2 over 3 to 4 stands out. These movements at point 102-1 cannot be interpreted finally, but may be reasoned by a measuring error during the third epoch. There, the movements from the second to the third epoch have the same size but the opposite direction as compared to the movements from the third to the fourth epoch. Thus, these values eliminate each other.

Figure 11: Deformation analysis results for the upper street

For the eastern part of the height network a deformation analysis is not reasonable at present, since only data of the epoch 3 and 4 is available, but more epochs are needed for the analysis. The deformation analysis recognises for the first two epoch comparisons that all points on the upper street have changed. Outstanding in these movements are the heights of the points 201-1 and 204-2, followed by the points 206-1 and 204-1 (cp. Figure 11). For the point 201-1 this movement is reasonable, since this point shows a significant movement also in the position. The significant height increase during the winter (comparison epochs 1-2) and the following height decrease during the summer (comparison epochs 2-3-4) supports the hypothesis of shrinking and swelling of clay minerals in the subsurface around this point.

A similar behaviour can be found at the points 204-1 and 204-2 (cp. Figure 11). Even if the position measurements for the point 204 do not show a conclusive movement pattern until now, so shows a house in direct proximity to these two points significant fissures that proof strongly the ground movements (cp. Figure 12). Maybe in the future a causal connection between soil moisture contents, geodetic measurements, inclinometer measurements and changes in the fissure sizes of the house can be derived.

Figure 12: Picture of fissure in a house near to point 204

5. EVALUATION AND NETWORK OPTIMIZATION

5.1 Design and precision of the installed networks

5.1.1 Position network

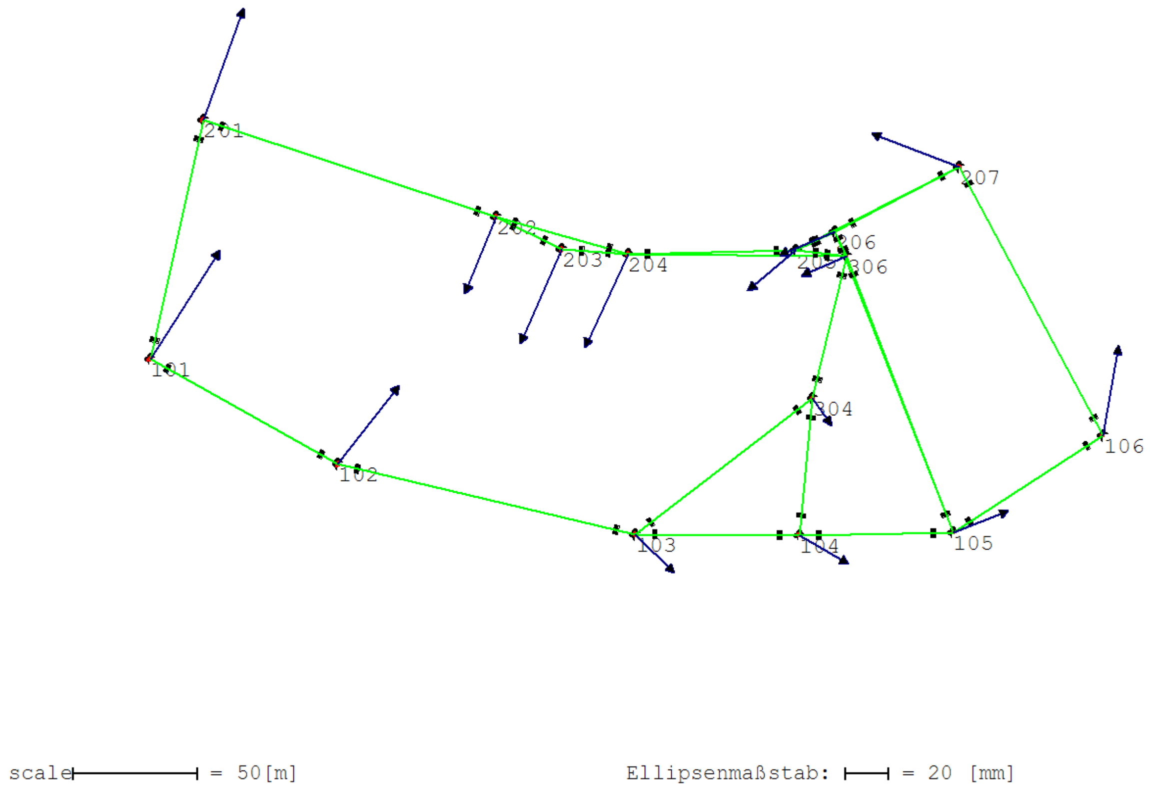

Figure 13: Main component analysis of the installed network (Ellipsenmaßstab = ellipse scale)

Using a principal component analysis of the position network [cp. Welsch, Heunecke, Kuhlmann, 2000], the principal component vectors in the western part of the geodetic network are noticeable (cp. Figure 13). Here, the problem is that these vectors are quite parallel to the slope gradient. Thus, in this area it is possible that random coordinate changes out of measurement variances show deformations that never happened. Therefore, the western part is a weak area of the installed network. This is also represented in the confidence ellipses of the western part of the network.

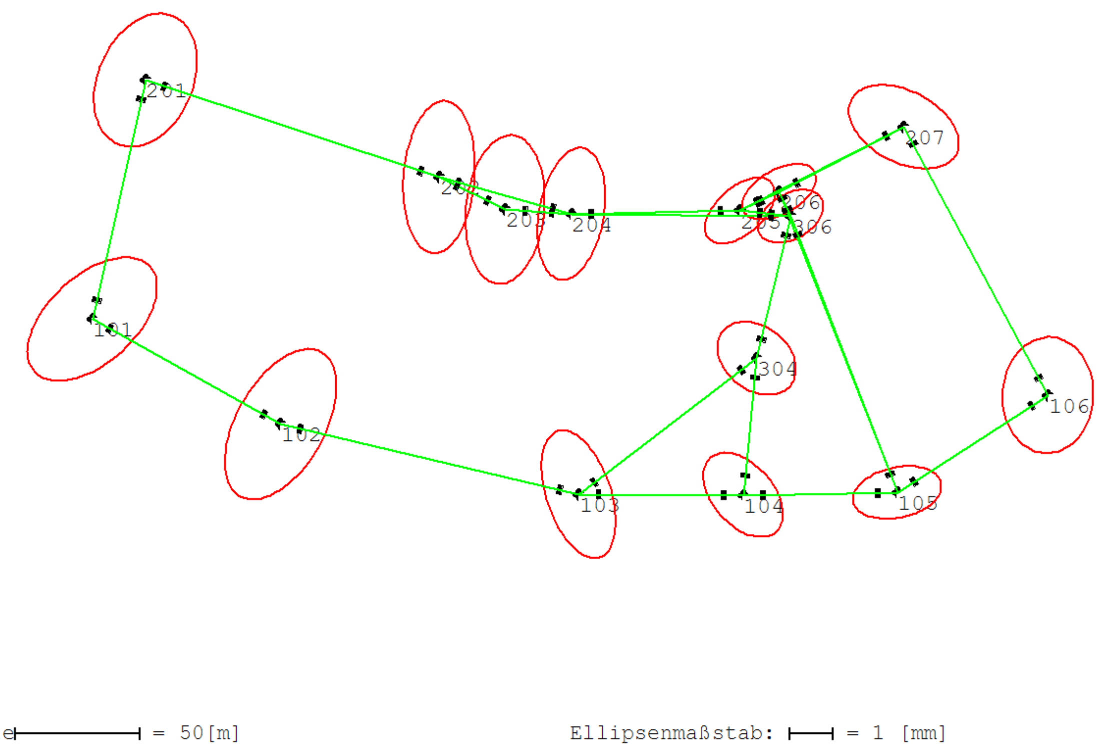

Figure 14: confidence ellipses of the installed position network at a significance level of 95 %. (Ellipsenmaßstab = ellipse scale)

The confidence ellipses of the position network shown in Figure 14 were calculated with a standard deviation of $\sigma =$ 0.8 mgon in the angle measurement and $\sigma =$ 0.4 mm in the distance measurement, derived from a variance component estimation during the free adjustment of the network [cp. Welsch, Heunecke, Kuhlmann, 2000]. For the drawing of the confidence ellipses the significance level was set to 95 %. Because of that significant inaccuracies at the point determination in the direction of the slope gradient occurred in the western part of the net. A stabilization of the western part of the network could have been achieved by the measurement of additional cross beams, which were not possible due to the topographic situation of the landslide. However, a sensitivity analysis for the point 201 shows a minimal length of the deformation vector that is necessary for a deformation to be recognized between two epochs of about 2 mm in slope direction. Until now the size of the measured deformation exceeds this minimal recognizable deformation by a factor of 2-4. It seems that the network has a sufficient sensitivity, to capture the expected movements despite the weakness in the western part.

5.1.2 Height network

In the used height network a significant quality and reliability increase was achieved by the densification of the network installed in the eastern part of the research area at the beginning. Because of the reduced amount of change points between two network points the probability to discover measurement errors is increased and the repeat time for faulty measurements was

reduced. Due to this reason also a densification of the points in the connection levelling to the anchor point at the concrete bridge should be considered.
A significant reliability increase could also be achieved, if it would be possible to survey a cross beam between the lower and the upper street. This was also inhibited by the topography of the study area.

5.2 Evaluation strategy

The normal proceeding for the determination of a deformation between multiple epochs is the usage of multiple 2-epoch comparisons. This strategy was applied for the analysis of the epochs in this study. The results of such an evaluation strategy though are often difficult to interpret. Because of that a strict multi-epoch comparison for a simultaneous analysis of all measuring epochs is desirable. The programming of an application using this evaluation method is currently in progress.
This application will also be the base for future kinematic analyses of the measured epochs. In the research project ILEWS it is planned to measure up to 10 epochs covering 2.5 years, which is supposed to be a sufficient data basis to do a kinematic analysis of the landslide. At present, the available data covers hardly a year and does not contain sufficient information to describe cyclic movements based upon annual changes of the soil moisture content that can be anticipated in the measurements already carried out.

6. CONCLUSION AND OUTLOOK

The installed measuring network shows a weak area in the western part. A workaround for that is not possible due to the given situation in the study area. However, the actual measuring precision seems to be sufficient to discover the ongoing movements in this part of the study area.
Integrating all data from the project partners like data from inclinometers, soil moisture sensors, geoelectric profiles and the weather station, there might be the possibility to conduct a dynamic modelling of this landslide. This model will then be based not only upon geodetic measurements, but will also respect the causal connection between geological and meteorological influence variables and the observed landslide movements.
The deformation model used until now, which is based upon multiple 2-epoch comparisons, becomes more insufficient with every new epoch measurement. It will be replaced by a multi-epoch analysis, a kinematic analysis or even a dynamic model in the future.

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