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DETECTION OF LANDSLIDE BLOCK BOUNDARIES BY MEANS OF AN AFFINE COORDINATE TRANSFORMATION

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Abstract

For a new approach in landslide monitoring, it is important to detect the boundaries between blocks with different directions and rates of movement, so that at these boundaries the changes of movement can be monitored with high precision geotechnical sensors. The idea is to use the displacement vectors (which can be found by a deformation analysis) to split the monitored points into the several blocks.
The assumption is that points lying on one block will have a similar pattern of movement. With the help of the results of an over-determined affine transformation, you can distinguish if all the used points are lying on one common block or if one point of a neighbouring block was taken into account by mistake.
The residuals of the over-determined transformation are a good indicator for this distinction. The analysis of the residuals is done by a fuzzy system which must decide in each step of the iterative algorithm if the searching algorithm should be stopped. The input parameters of the fuzzy system are e.g. the range of the residuals, the change of the standard deviation compared to the last step, and strain parameters. Output of the fuzzy system is a value representing the probability that all the used points are forming one common block.
An example will be given to present the capabilities of this approach.

1. Introduction

Landslides are one of the major types of natural hazards in the world. Especially in Europe, due to the growing tourism in alpine regions, people are living or working more and more in areas with unstable slopes. So the number of people and infrastructure affected by landslides is growing. E.g. in Italy, in the last decade (1990 – 1999) 263 people were killed by landslides.
Due to the complexity of this topic, answers can only be found by a combination of several disciplines, e.g. geology, geodesy, geomechanics, geomorphology, hydrology.

Our approach, OASYS (Integrated Optimisation of Landslide Alert Systems) is an efficient geodetic monitoring system consisting of classical geodetic networks, improved by high precision geotechnical sensors in relevant parts of the slopes.
These relevant parts are the boundaries of different blocks of the landslide. Most of the unstable slopes consist of several blocks moving in different directions with different velocities. The installation of geotechnical sensors across these block boundaries gives important information on the relative movement of the blocks. These permanent observations can be used in a knowledge-based system together with the geodetic measurements to assess (almost in real-time) the behaviour of the slope.
This paper deals with one part of these investigations, the detection of the block boundaries.

2. Affine coordinate transformation

We assume that on the unstable slope and the surrounding stable area a geodetic network has been installed and measured for at least two epochs. If we restrict to 2D, the number of observed points should be at least four per block.
The measurements of the two epochs (GPS and/or tacheometric observations) are used in a geodetic deformation analysis to get the displacement vectors for each observed point.

The basic idea behind the algorithm is to use an over-determined affine coordinate transformation to map the coordinates of the first epoch on the coordinates of the same points of the second epoch. If a certain group of points is lying on one common block then the movement pattern of these points will be similar and the affine coordinate transformation will give good results (i.e. a good standard deviation). If the group of points is lying on different blocks then the standard deviation (and other indicators explained later) will be significantly larger.
For 2D, the transformation can be written as follows:

$$y_{n+1} = a \cdot y_n + b \cdot x_n + c$$
$$x_{n+1} = d \cdot y_n + e \cdot x_n + f$$

where y_n, x_n…coordinates of epoch n
y_{n+1}, x_{n+1}…coordinates of epoch n+1
a,..,f…transformation parameters

The six parameters (a,..,f) can be interpreted as two translations (t_x, t_y), two rotations (w_x, w_y) and two scale parameters (m_x, m_y).

$$a = m_y \cdot \cos w_y \qquad b = m_x \cdot \sin w_x \qquad c = t_y \qquad d = -m_y \cdot \sin w_y \qquad e = m_x \cdot \cos w_x \qquad f = t_x$$

Usually, only one scale parameter is used. Here the two scale parameters are necessary due to the property of landslides that a sliding block will be more distorted in the direction of movement than in any other direction. The second scale parameter has to counterbalance this anisotropy.
For 2D, at least four points have to be used to get an over-determined equation system. Important results out of these transformations are the residuals v and the standard deviation s_0.
The transformation parameters themselves are not very significant due to the small displacements. Fig. 1 shows one of the scale parameters, m_x, taken from the example given in section 5. All possible blocks consisting of 4 points (170 different combinations) were investigated. These combinations can be divided into 3 groups: the correct blocks ('4:0', all 4 points lying on one block) with 31 combinations, and two groups of incorrect blocks ('3:1', 3 points on one block and 1 point on another block with 81 combinations; '2:2', 2 points on two different blocks with 58 combinations). It can be seen that a clear distinction between the different groups can not be made out of this parameter m_x.

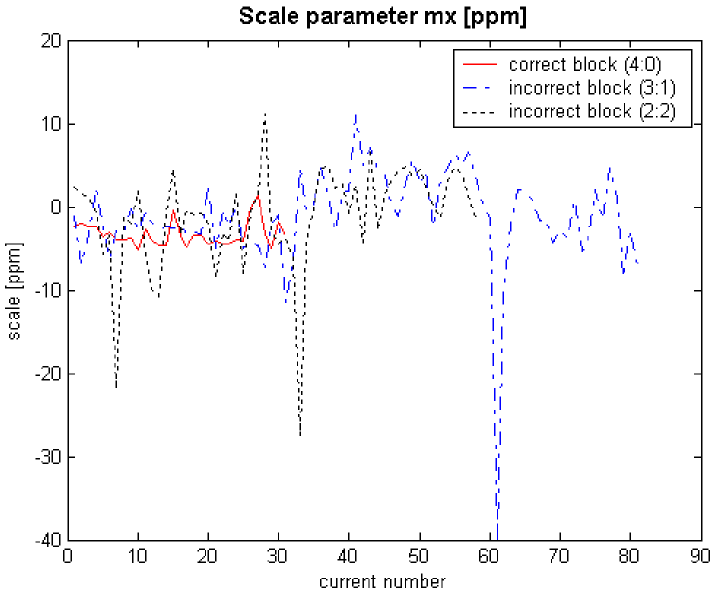

Fig. 1: Scale parameter m_x for the different cases: correct block (4:0), incorrect blocks (3:1 and 2:2).

Welsch (Welsch, 1982) has shown that the affine coordinate transformation is equivalent to a strain analysis (assuming homogeneous infinitesimal strain). So the six transformation parameters can also be interpreted as two translations plus 4 parameters of the strain tensor E:

$$E = \begin{bmatrix} e_{xx} & e_{xy} \\ e_{yx} & e_{yy} \end{bmatrix}$$

with e_{xx}, e_{yy}... rate of change of length per unit length in direction of x-axis resp. y-axis
e_{xy}, e_{yx}...rate of shear strain

A better interpretation of the strain parameters can be reached by the transformation into the principal strain axes system, represented by the strain ellipse (Tissot indicatrix). The calculation of the strain ellipse is analogous to that of the geodetic point error ellipse. So the six parameters can be seen as two translations and one rotation of the block (rigid body movement) plus the distortion represented by the strain ellipse: e1, e2 (the semi-axes) and θ (the orientation of e1).

Welsch mentions that the translations should not be used in a strain analysis, but in the case of landslide monitoring the model of a rigid body (with small inner distortions) moving downwards is the most practicable one. Without the two translational parameters, the strain parameters would be falsified because they would have to counterbalance also the translational part of the block movement.

3. Algorithm

The basic scheme of the algorithm can be found in fig. 2. Based on the residuals v and the standard deviation s_0 of all possible transformations a minimal block consisting of four neighbouring points is chosen. Additionally, the two semi-axes of the strain ellipse have to be within a user-defined limit (to ensure small and rather isotropic distortions).
In the following step the most suitable one of the neighbouring points has to be included into the minimal block. For all combinations with 5 points the transformations are calculated; the block with minimal s_0 (and again, e1, e2 within some limits), is chosen. At the same time, it has to be

checked if this block is still `correct`, i.e. if all points are lying on this block. This analysis is done by a fuzzy system (cf. later).
If the block is `correct` then the algorithm is searching for the next suitable point within all neighbouring points, until the fuzzy system rejects the test of `correctness`. In this case the last point has to be removed and the next minimal block of four points has to be found out of the remaining points.

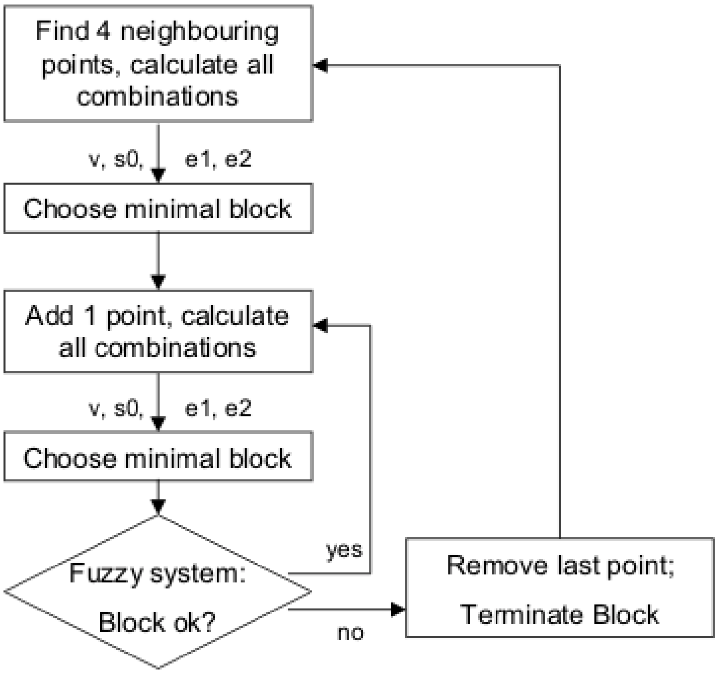

Fig. 2: Scheme of the detection algorithm

4. Short description of the fuzzy system

The fuzzy system was implemented in MATLAB. Matlab provides an initial fuzzy system, where many necessary functions (membership functions, aggregation and defuzzification methods) are already implemented. It is necessary to choose the input parameters and the output with their most suitable membership functions and the several calculating methods.
The input parameters implemented at the moment are:

- Rate of change of the standard deviation between subsequent steps: If a point from another block is included into a correct block, s_0 becomes larger. This rate of change can be tested.
- Semi-axes of the strain ellipse: e1, e2.
- Rate of change of e1 and e2 between subsequent steps.
- Interquartile range of the residuals (used in the exploratory data analysis). Fig. 3 represents the variation of the residuals. For the 170 possible cases (analogous to fig. 1) the interquartile range was investigated. It can be seen, that there is a clear distinction between the correct cases (‘4:0’) and the incorrect cases (‘3:1’ and ‘2:2’).
  The higher this input parameter the higher the probability that the block is incorrect.

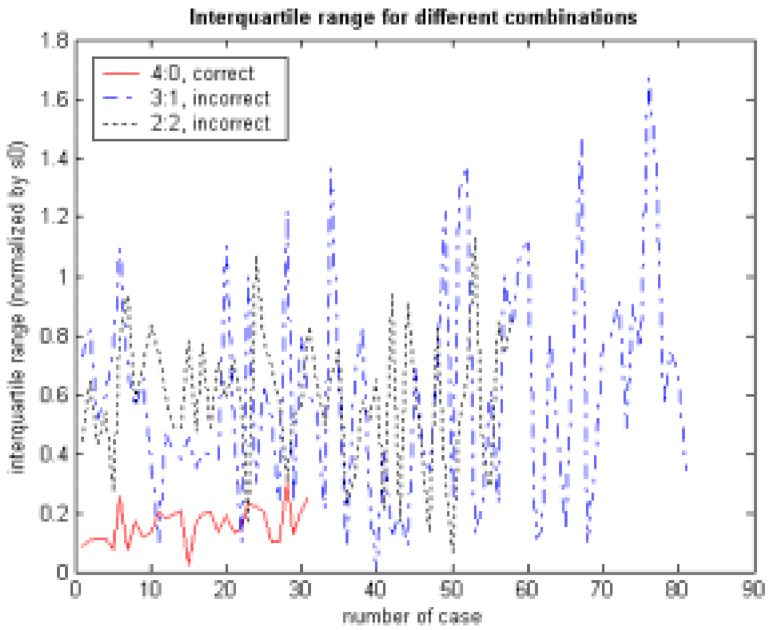

Fig. 3: The interquartile range of the residuals for the different cases: correct blocks (4:0), incorrect blocks (3:1, 2:2).

5. Example

The simulated raw observations for the example investigated were published in (Welsch, 1983), where several methods for deformation analysis and block detection were tested on the same data. In our investigation, epochs 1 and 3b were chosen and a geodetic deformation analysis was calculated to get the displacement vectors (see fig. 4).

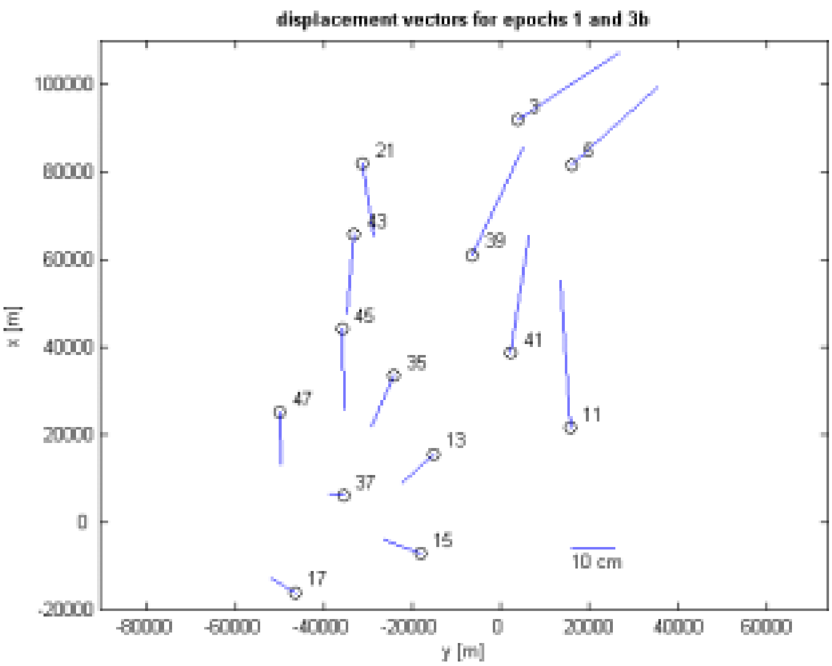

Fig. 4: displacement vectors between epochs 1 and 3b

In the first step of the algorithm all transformations of 4 neighbouring points are calculated. The best suitable block is chosen based on the analysis of the standard deviation s_0 and the strain ellipse parameters e1, e2. The idea is that a correct block will not be very distorted, so e1 and e2 should be within some user chosen limits (depending on the actual geological conditions).
In this example the points 3, 5, 11, 41 were chosen because of the minimal standard deviation of 9.9 mm. Now the iterative algorithm starts to find the next suitable point. All transformations with 5 points (i.e. the chosen block of 4 points + one neighbouring point) are calculated, and the combination with the minimal s_0 is chosen (tab. 1).

Point id					s_0 [mm]
3	5	11	41	13	78.3
				15	59.5
				21	52.6
				35	66.2
				39	**12.8**
				43	55.8

Tab. 1: Possible candidates for the 5th point.

Point id						s_0 [mm]
3	5	11	41	39	13	94.4
					15	72.3
					21	**71.3**
					35	86.9
					43	76.4
					45	76.7

Tab. 2: Candidates for the 6th point.

After choosing point 39, the fuzzy system calculates all the necessary indicators used for the assessment of the block. The result of the analysis in the fuzzy system is a probability of 30 % that the block is not correct (i.e that the last point taken into account should be on another block). So the next step in the iteration is started, the sixth point of the block is searched for. The possible candidates can be seen in tab. 2, and due to the minimal standard deviation s_0 point 21 is taken into this block. (Note the rate of change of s_0 between the two steps of iteration). Again, the fuzzy system is used to analyse the new situation. The output is 72 %, that means that the block is not correct any longer, and point 21 has to be removed. So the correct block consists of the points 3, 5, 11, 41, 39.
Out of the remaining points, the search for the next block can be started. The minimal block consists of points 13, 15, 17, 35 with s_0 = 12.0 mm. The results of the several iterations and the output of the fuzzy system can be found in tab. 3.

Number of iteration	Points included in the actual block									s_0 [mm]	Probability of termination (fuzzy system)
1	13	15	17	35						12.0	
2	13	15	17	35	47					11.9	0.30
3	13	15	17	35	47	45				11.0	0.30
4	13	15	17	35	47	45	37			17.1	0.39
5	13	15	17	35	47	45	37	43		24.3	0.48
6	13	15	17	35	47	45	37	43	21	31.6	0.50

Tab. 3: Results of the different steps of iteration starting with a minimal block of 4 points (13, 15, 17, 35). The output of the fuzzy system shows that all the blocks are correct.

Here the algorithm stops because all points have been used, so the second block consists of the points 13, 15, 17, 35, 47, 45, 37, 43, 21.

Comparing this result with the several methods presented in (Welsch, 1983) it can be seen that all the algorithms give the same blocks.

6. Conclusion

The human mind is strongly influenced by visual pattern recognition. Looking at figures like fig. 4, it seems obvious to divide the situation in two blocks. The comparison with the result of our detection algorithm shows that the fuzzy system is able to reproduce the human way of thinking.

But a lot of work has to be done, e.g. within the fuzzy system. It is planned to implement some other parameters: The degree of freedom of the over-determined transformation, because the significance of the F-test in the background is the better the bigger the number of degree of freedom. Some geological parameters to assess the actual geological conditions will also be necessary.

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