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Interpolation of landslide movements to improve the accuracy of 4D geoelectrical monitoring

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ABSTRACT

Measurement sensors permanently installed on landslides will inevitably change their position over time due to mass movements. To interpret and correct the recorded data, these movements have to be determined. This is especially important in the case of geoelectrical monitoring, where incorrect sensor positions produce strong artefacts in the resulting resistivity models. They may obscure real changes, which could indicate triggering mechanisms for landslide failure or reactivation. In this paper we introduce a methodology to interpolate movements from a small set of sparsely distributed reference points to a larger set of electrode locations. Within this methodology we compare three interpolation techniques, i.e., a piecewise planar, bi-linear spline, and a kriging based interpolation scheme. The performance of these techniques is tested on a synthetic and a real-data example, showing a recovery rate of true movements to about 1% and 10% of the electrode spacing, respectively. The significance for applying the proposed methodology is demonstrated by inverse modelling of 4D electrical resistivity tomography data, where it is shown that by correcting for sensor movements corresponding artefacts can virtually be removed and true resistivity changes be imaged.

1. Introduction

Landslides constitute one of the greatest natural hazards, causing tremendous damage every year and posing a significant risk to communities and infrastructure. Moreover, there is the potential that landslide occurrences may increase in the future due to changes in climate (Dijkstra and Dixon, 2010), the effects of which are yet to be investigated and understood. A major focus of international research is therefore to gain an improved understanding of triggering mechanisms and failure potentials, with the aim of developing landslide forecasting methodologies. Physical or process-based landslide models not only offer the best foundation to help in understanding the triggering mechanism, but also require a set of input parameters that have to be determined accurately to characterise the hydrological conditions of the slope (Dai et al., 2002; Dijkstra and Dixon, 2010).

Those data are obtained using techniques ranging from point sensors measuring, for example, moisture content or water potential, to volumetric monitoring of moisture movements using time-lapse electrical resistivity tomography (ERT). The latter is an approach that only very recently has become applied to studying landslides and unstable slopes in general (e.g., Gunn et al., 2014; Chambers et al., 2014; Supper et al., 2014). Due to its high sensitivity to lateral and temporal changes in moisture content, ERT is the geophysical technique that is most frequently applied to landslide investigations (Jongmans and Garambois, 2007; Jomard et al., 2007; Lebourg et al., 2010; Chambers et al., 2011).

However, due to the nature of ERT data interpretation, the locations of the individual electrodes within the ERT imaging array have to be known accurately to robustly interpret the measured data. In the case of a permanent installation on a landslide, electrode locations would have to be corrected for movements, which currently is not part of common processing workflows. Yet, misplacement of electrodes is known to cause severe artefacts in the resulting resistivity models (Zhou and Dahlin, 2003; Oldenborger et al., 2005; Szalai et al., 2008; Wilkinson et al., 2010), masking true resistivity variations due to changes in, e.g., moisture content. Changes in the separations of the electrodes change the measured potentials, which in turn affect the inverted resistivity models. Fig. 1 shows ratios of inverted resistivity models (commonly used to highlight changes in resistivity) obtained from data acquired on a natural landslide in North Yorkshire, UK (i.e., Hollin Hill), before (March 2008) and after movement (March 2009). In Fig. 1a the electrode locations of 2008 were used for both the 2008 and 2009 resistivity data, while in Fig. 1b electrode locations measured

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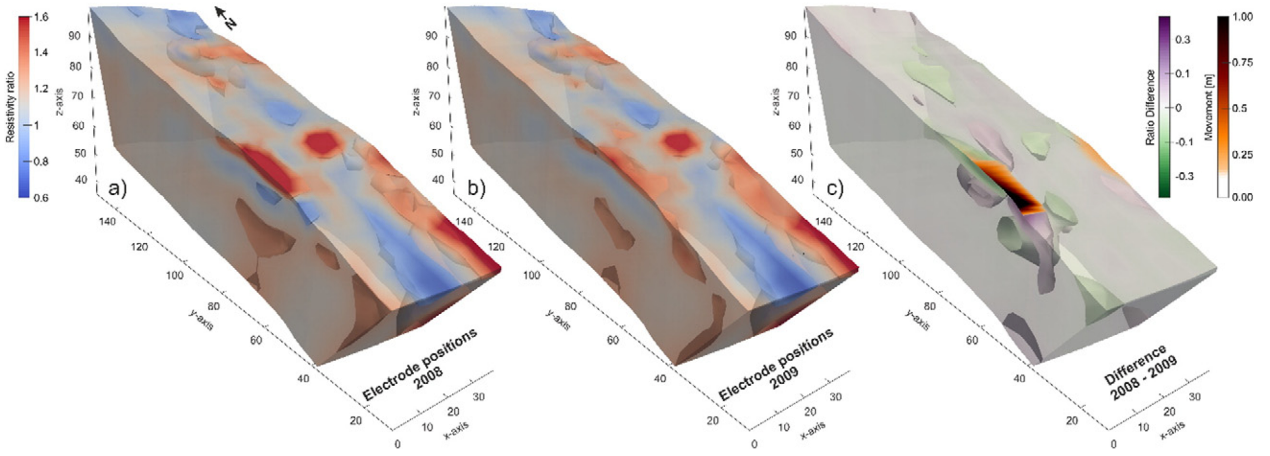

Fig. 1. Resistivity ratios between measurements acquired on an active landslide from March 2008 and March 2009. Between these measurements electrodes in the western part of the model ($x < 10$ m) moved by up to 1.6 m. a) Shows the resistivity ratios for uncorrected electrode positions; in b) RTK-GPS measurements of the moved electrodes were included. The differences between the resistivity ratios (indicating the effect of electrode movement) are shown in c); artefacts in the resistivity ratios align with areas of severe movements.

in 2009 were used to invert the 2009 resistivity data. The difference between the two ratios (Fig. 1c) shows the effects of electrode misplacement on the resistivity ratio. In the area of movement ($x < 10$ m, $40\ \text{m} < y < 80$ m; shown by surface overlays with orange to black colours indicating progressively greater movement), the differences in resistivity ratio exhibit large variability with values ranging from −0.6 to +0.5. The largest differences occur close to the surface. These are positive (increased ratios) just beneath the northern part of the moving area ($55\ \text{m} < y < 80$ m), and negative (decreased ratios) in the southern part. Below these near surface artefacts (>2 m depth), deeper features of the opposite polarity are found extending to a depth of about 7 m below ground level (bgl). As resistivity ratios are commonly used to show changes in moisture conditions (Jomard et al., 2007; Chambers et al., 2014) which, in terms of landslide monitoring, can be used as proxy to slope stability (Lebourg et al., 2010), methodologies have to be developed to estimate electrode movements to minimise these artefacts and improve ERT monitoring applied to landslides.

While 2D ERT monitoring usually employs less than 100 electrodes, 3D ERT monitoring systems easily exceed this number. Manual monitoring of each electrode position with high spatial and temporal resolution is generally not practical due to the prohibitive time and number of site visits this would require. If the electrodes have been buried, resurveying the electrodes is not possible at all. Therefore, we propose a methodology for which only a small set of reference points is monitored with high spatial accuracy (i.e., centimetric), using e.g., real-time kinematic (RTK) GPS surveying, with only limited temporal resolution. The movements of the reference points are then interpolated to a larger set of points of interest or to regular grids. In this study we compare the performance of three different interpolation techniques.

To validate the approach, we apply these techniques to 4D (i.e., 3D time-lapse) ERT monitoring problems, both on a synthetic model and a real installation on an active landslide. Techniques to estimate landslide movements are especially important for this application, since electrodes are usually buried underneath the surface. Therefore, repeated surveying of their locations is not possible. In the examples we interpolate the movements of reference points to a regular grid of points, where the ratio between known and interpolated points is about 1/5 and 1/4, respectively. Due to their complexity, including build-up of fissuring and sudden movements, interpolation of landslide movements can only deliver an estimate of true electrode displacements. However, for ERT measurements it is crucial to estimate these displacements to limit their effects on the resistivity data, inversions and subsequent interpretations.

2. Methodology

Discrete measurements of landslide movement are commonly used to derive velocities or displacements at the actual measurement points only (e.g., Mora et al., 2003; Corsini et al., 2005; Gance et al., 2014). However, for applications using a large set of points, e.g., ERT time-lapse imaging, monitoring of the movement of every single point is not feasible and a need arises to interpolate movement information of a sparse set of reference points (RP) onto a larger set of points of interest (PI) or regular grids, the positions of which are unknown.

Although this problem applies to a range of applications employing point sensors or sensor grids placed on a landslide, in this paper we will focus on 4D ERT. Note, however, that the methodology may be applicable for any other type of monitoring system.

A general procedure to monitor and interpolate landslide movement can be outlined as follows:

1. Install/define points of interest (e.g., electrodes) E_i and a set of reference points R_j.
2. Survey initial locations $E_i(x,y,z)$ and $R_j(x,y,z)$ at the initial time t_0.
3. Repeat survey of $R_j(x,y,z)$ at time t_1.
4. Calculate directional movements dx_j, dy_j, dz_j at each R_j-location.
5. Interpolate the set of dx, dy, dz to $E_i(x,y,z)$ using a suitable method.
6. Update $E_i(x,y,z)$ by adding interpolated movement components dx_i, dy_i, dz_i.
7. Repeat steps 3 to 6 for subsequent time steps.

After a certain time, and if the E_i are accessible (e.g., not buried underneath the surface), the system can be recalibrated by surveying both the locations of E_i and R_j. To obtain locations of E_i for a time t_k for which no actual R_j data is available, an interpolation of R_j to t_k between the two adjacent measurements is proposed. Considering the type of movement observed at translation- or flow-dominated landslides in the UK (Uhlemann et al., in revision), a linear interpolation in time is usually sufficient.

A priori information, e.g., direct measurements of E_i locations over time or areas where the E_i are known to be static, can be included in the calculation of the updated E_i. This can be achieved by using this direct information instead of estimating the movements at the corresponding locations or by introduction of known boundaries of differential movement.

In the following we will discuss three different ways to interpolate the movements of the RPs to a larger set of PIs.