The potential of tiltmeters as a low-cost technology in baseline ground movement monitoring

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Abstract

Geothermal energy has received increasing attention in recent decades due to the net-zero emission targets. However, the impact of energy technologies that utilise the subsurface, lacks systematic understanding still. Such an impact is potential ground motion at the surface due to changes (thermal, chemical, pressure) induced at depth. Precise monitoring data and appropriate analysis methods could help on this. This study is part of a wider project on the use of abandoned underground coal mines for energy storage. Here, we test the potential of tiltmeters as a low-cost monitoring system, in providing information on tiny movements of the ground surface that could be used as baseline ground movement for areas that are relatively flat and without any known ground instabilities. We discuss our observations after a full year of measurements, the challenges faced in the analysis of data, mainly due to the effect of temperature on the measurements, and provide considerations on aspects of the monitoring design for similar applications.

Keywords: Ground movement, tiltmeters, temperature drift, time-lag

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1 Introduction

Establishing a ground motion baseline i.e. the movement of the ground due to natural processes only, at a site is significant for energy projects that utilise the shallow subsurface, such as shallow geothermal (Tsilingiridis and Papakostas, 2014) to ensure public confidence and regulatory control. This can then be used as a benchmark to assess the potential impact that works in the shallow subsurface could have on the ground.

This study is part of a wider research project on the use of abandoned underground coal mines for energy storage in Central Scotland. Water from the now flooded coalmines will be used for cooling of a high computing facility and the warm water will be returned back to the mines. The ability of groundwater to retain an almost constant temperature over time is the main principle of this geobattery project: the heat is stored in the flooded underground coal mines and can then be harvested with the use of heat pumps by communities downstream.

The cessation of the activities at underground coal mines and the end of operations of the water pumps lead to the rebound of groundwater in the abandoned coal works. This rebound can take years to reach a new equilibrium stage, and during that period an uplift of the ground surface above has been observed. This has been the case at various sites in Europe and in the UK (Malolepszy et al., 2005; Chambers et al., 2015; Coda et al., 2019), including the area SW of Edinburgh where this geobattery project is focusing on. Todd et al (2019) estimated an uplift of up to 3 mm, based on numerical modelling, as a result of the groundwater rebound at the study area. This is a challenging magnitude to capture with traditional surveying technologies; precise levelling is very time-consuming for the long-term and the precision achieved with total stations is of the same order of magnitude as the ground movement we need to capture.

Tiltmeters on the other hand, are capable to provide information of minute movements. Tiltmeters measure angle deviations (tilt angles) from the gravity vector (Agnew, 1986). They have been used for long-term monitoring to capture ground deformations induced by volcanos and landslides (Lin et al., 2022). In Civil Engineering their applications vary, the most common one being the monitoring of the stability of buildings next to deep excavations. The studies on the use of tilt as a measure of displacement can be dated back to the 1920s (e.g. Jaggar and Finch, 1929) and have since proved the success of tiltmeters in recording small-scale time-series displacement, particularly in a sub-millimetre scale. However, not much information exists on how such technology could be used for baseline monitoring not on slopes, volcanos or vertical walls, but at areas that are almost flat such as these associated with energy projects in the shallow subsurface.

In this paper, we present results from work on the suitability of tiltmeters as a low-cost technology to be used for capturing natural ground movements at the vicinity of the geobattery's site based on analysis of a full year of tiltmeter data. We discuss the analysis methodology and the challenges we faced in the interpretation of the recorded data, as well as their suitability to investigate 3D ground movement. No attempt is made to establish any causative relationships of the recorded displacements with environmental or anthropogenic factors.

2 Field site and monitoring system

2.1 Field site

The field site selected for this study is located in SE of Edinburgh, Scotland. The site is approximately 1.5 km away from the planned abstraction borehole for the geobattery project and within 100 m from the planned monitoring borehole location (Fig. 1a). As this is a feasibility study for the potential of tiltmeters as a monitoring technology for baseline ground movement measurements, being close to the field of the planned abstraction well was not crucial. The collected data are not aimed to serve as a baseline for ground movements on the abstraction well site. The main reason driving the selection of the location for the deployment of the tiltmeters was land access. The chosen site belongs to the University of Edinburgh and the authors had already access to that area. Also the site, being part of a dairy farm, provided access to electricity mains (necessary for powering parts of the monitoring setup as described in more detail in the next section) and an ethernet connection.

Figure 1. (a) Location map of the field site and surrounding landscape features (background map based on Google Earth). Inset: Location of field site in Scotland (created using GIS, boundary layer of Scotland downloaded from Office for National Statistics (https://geoportal.statistics.gov.uk/datasets/ons::counties-and-unitary-authorities-december-2019-boundaries-uk-bgc/about)), (b) Locations of the tiltmeters and GNSS receiver on site (background map based on Google Earth). (c) Graphic representation of monitoring setup for data collection and transmission.

The chosen location comes with challenges. It is an area characterised by gentle sloping of the ground (< 5%) and consisting of fields used for grazing. No ground movements or slope failures have been observed previously for that area. The farm is close to a main road and a secondary road at distances of 650 m and 200 m, respectively (Fig.1a). There is an industrial estate at a distance of approximately 800m from the field site.

The farm fields are bounded in the South and East by Kill Burn (Fig.1a; 200 m from closest tiltmeter, ~15 m elevation difference) and in the North, by Bilston Burn (475 m from the nearest tiltmeter, 12 m elevation difference). North Esk river lies further SE (1280m from closest tiltmeter, ~53 m elevation difference). The daily activities around the farm buildings which are 150 m away from the central tiltmeter, include the use of tractors and pickup trucks along the farm access roads as well as daily movement of livestock between the grazing fields and the farm sheds between the months of April to August. These activities can induce additional noise in measurements during the peak activity hours between 6am and 2pm.

The local geology consists of layered sedimentary rocks mainly of both the Clackmannan Group deposited during the Carboniferous Period (Tulloch and Walton, 1958). The bedrock is covered by sediments with thickness ranging from 0 m to ~25 m. The overlaying sediments are mainly characterised as diamicton, sand and gravels (Geological Map Data BGS © UKRI 2024). Some are naturally deposited sediments while there are also large areas covered with made ground following the cessation of mining and the reclamation of the land.

The uplift of the area above the coal mines is evident from InSAR data. Based on the ortho dataset provided by the European Ground Motion Service (2025) for the 9 available InSAR points located at the field site (40jJdYRMRv, 40jJiF6be0, 40jJiF6be1, 40jJdYRMRw, 40jJdYRMRx, 40jJYrm7Fr, 40jJYrm7Fs, 40jJYrm7Fs, 40jJUB6s3n) the average rate of uplift during the period 2019-2023 is 1.42 mm/year.

2.2 Monitoring system

At the beginning of the geobattery project, our hypothesis was that using tiltmeters (1) would allow us to capture minute ground movements (< 1mm). And (2) although these ground movements refer to a horizontal plane, adopting a specific deployment geometry for the tiltmeter network and through the combination and comparison of the observed movements, we should be able to derive conclusions as to any potential ground movements on site along the vertical direction (uplift or subsidence).

In order to confirm or reject this hypothesis, and based on the desire for a low-cost solution, we deployed 5 tiltmeters (LS-G6-TIL90-X), thereafter referred to as Tilt 1, Tilt 2, Tilt 3, Tilt 4, and Tilt 5 (Fig. 1b) along 2 lines heading SW-NE (Tilt 1-2-3) and NW-SE (Tilt 4-2-5). The coordinates of the tiltmeters were obtained using Network RTK. Each tiltmeter can record inclination with respect to gravity's direction along 3 axes. This does not mean that all three axes are used for monitoring at the same time. Any tilts are only recorded along 2 directions (referring to the movement of a horizontal plane). But a 3-axes tiltmeter allows for its deployment in any orientation. In our study, the two axes used for monitoring were oriented towards North and East, respectively. This was achieved by the use of a compass. The tiltmeter data (tilt angles in degrees) are transmitted to a gateway (located in one of the farm buildings and powered by mains electricity, 500 m from the furthest tiltmeter) through a wireless link. The gateway then sends the recorded data to the database (Trimble 4D Control) using a mobile phone network (Fig. 1c). The tiltmeters used in this study have an accuracy of 0.0025° for angles within ± 2°. The stability of the tiltmeters is reported better than 0.003° at 14 hrs (https://info.worldsensing.com/ datasheet_Tilt90_EN). This parameter is associated with the sensor. The stability was determined in a lab using a rotary table that complies with EU standards. This is a common parameter monitored for a limited amount of time; running the test for longer periods is not common practice (personal communication with Mounir Ajrouche, Trimble Geospatial, on 13/02/2025). All technical specifications above refer to ideal conditions and factors such as temperature are not considered.

The distance between neighbouring Tilts is around 200 m. All tiltmeters are mounted on 80 cm long angle steel posts concreted in a 30 cm × 30 cm block at 0.5 m depth below the ground surface (Fig. 2a, b). The tiltmeter case sits at 20 cm above the ground surface (Fig. 2c). All relevant lengths were measured with a measuring tape and marked on the posts to ensure that these lengths remain true during installation. The maximum height difference between the tiltmeter at the highest (Tilt 4) and lowest elevations (Tilt 5) is 9m over a distance of 450m. Tilts 1, 2 and 4 are established on almost flat ground. Tilt 3 is established at the bottom of a gentle slope (<5% gradient, ~95° direction), while Tilt 5 has the lowest elevation and is located on the crown of a steep slope (>20% gradient, direction 140°).

All tiltmeters are located within fields used occasionally for grazing by livestock. They are protected with wooden fences and Tilts 2, 3 and 5 are also covered with large PVC covers (approx. dimensions: 50 cm × 50 cm × 50 cm).

Figure 2. Installation of tiltmeters: (a) a 80 cm angle steel beam is fixed in a 30 cm × 30 cm × 30 cm posthole using postcrete and buried at 50cm depth, (b) a mounting plate is firmly fixed on the angle steel, (c) the tiltmeter is mounted onto the plate. Final position at 20 cm above ground surface.

To complement the network of the tiltmeters, we established a GNSS station on site close to the location of Tilt 4 (see Fig. 1c). A GNSS antenna (Trimble Zephyr Geodetic) was mounted on a pole fixed on the wall of one of the existing buildings. The pole extends approximately 1 m above the roof. The antenna is connected to a Trimble NetR9 receiver. Raw data are sent via an ethernet connection to the database (Trimble 4D Control) in real-time.

2.3 Available data

The tiltmeter data used in this paper cover the period from 15 October 2023 to 14 October 2024 with a sampling interval of 10 minutes. This is a sampling frequency with high redundancy. The reason was that we had very limited previous knowledge as to the type and magnitude of natural ground movements we should expect and such a high sampling rate was deemed appropriate to capture any potential transient ground movements along with seasonal/more regular ground movements. It also allowed us to look into more details on parameters, other than actual ground movements, that might affect the recordings and supported the quality assessment of the data.

Figure 3 shows the time histories of the calculated tilt values (differences between reference tilt value on 15th October 2023 and any subsequent tilt value) along the East-West (EW) and North-South (NS) directions. Positive values indicate a tilt toward East and South, respectively. Negative values reflect a tilt towards West or North. The gaps that appear at times in both plots for different tiltmeters reflect times when transmission of data was interrupted due to damage on the tiltmeter radio anntenae. Tilt 1 and 5 exhibit maximum tilt values out of all 5 tiltmeters for both the EW and NS directions.

The GNSS data cover the period from 8th Feb 2024 to 14th Oct 2024. Data are recorded every second and streamed in real-time. The GNSS positions are calculated using a base station and a 1.5 km baseline with positions processed every 12 hours. Raw data and processed positions are saved in a database (Trimble 4D Control). The post-processing provides a position within a precision of ~3.5 mm.

2.4 Accuracy of measurements

For the tilt which is computed as the difference between the reference tilt angle $T_{tilt,0}$ and every subsequent tilt angle $T_{tilt,i}$, the corresponding accuracy is given by Eq. (1) (Bonford, 1971):

$$\sigma_{tilt} = \pm\sqrt{\sigma_{tilt,i}^2 + \sigma_{tilt,0}^2} \quad (1)$$

where
σ_{tilt} accuracy of the tilt.
$\sigma_{tilt,i}$ accuracy of the tilt angle in epoch *i*, equal to the accuracy of the tilt measurement, 0.0025°
$\sigma_{tilt,0}$ accuracy of the reference tilt angle, equal to the accuracy of the tilt measurement, 0.0025°

Using Eq. (1), the accuracy of the resulting tilt is found equal to ± 0.0035°. This threshold reflects the uncertainty in the calculated tilt values, i.e. any tilt values outwith the ± 0.0035° threshold represent changes against the reference value that are not due to the measurement limitations of the tiltmeters. This should not be confused with the significance of the mean of measurements against random errors which would assume that the data follow the normal distribution and would consider a 3 sigma threshold. From Fig. 3 it is shown that the EW tilt values for Tilt 1 and 4 exceed the accuracy threshold for almost the full time period examined, while Tilt 5 values exceed the threshold during most of the monitoring time. The values for the EW tilt for Tilt 2 and 3 fluctuate within the accuracy thresholds up until end of June 2024 for Tilt 3 and beginning of August 2024 for Tilt 2. Specifically for Tilt 2, the sudden increase in the tilt value is due to agricultural activities in the field. All tilt values along the NS direction for all tiltmeters are significant for the full time period.

3 Data analysis and Results

The field site is a relatively flat/ very gentle gradient area with no known ground instabilities, other than gradual ground uplift due to the rise of groundwater level within the abandoned coal mines evidenced by InSAR data.

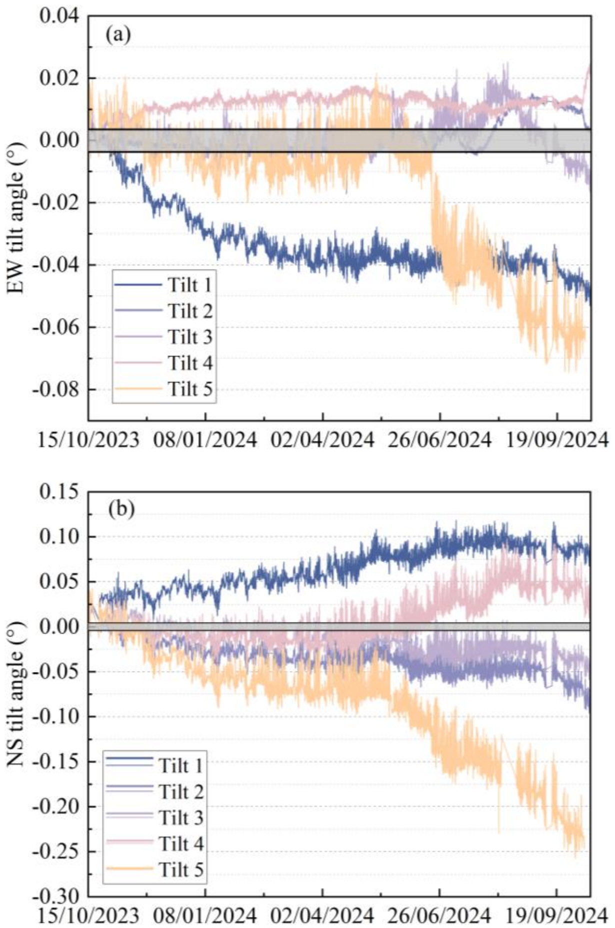

Figure 3. Calculated tilt in the (a) EW and (b) NS direction for all 5 tiltmeters. The highlighted grey areas indicate the accuracy threshold of the tilt values as calculated by eq. (1).

3.1 Calculation of displacements from the tilt angles

Instead of working with tilt values (degrees), we decided to work with values of displacements as these are commonly used in engineering to describe ground movements. This was done based on the equations below:

$$Deviation = sin(Tilt_{degree}) \times gauge\_length \quad (2)$$

$$Displacement = Deviation_{current} - Deviation_{initial} \quad (3)$$

where *gauge_length* is 700 mm for this study, and $Deviation_{initial}$ indicates the reference value based on the tilt angle reading on 15th Oct 2023. Both *Deviation* and *Displacements* are calculated in mm. It should be noted here that the tiltmeters were deployed at the end of September 2023. We decided to start using the data from two weeks later than the deployment date to ensure that the tiltmeters had settled. Based on the ground and weather conditions at that time and the evolution of tilt values during that 2-week period this duration was sufficient in our case. The reference value should be chosen with caution as it may be systematically distorted despite the two-week wait time, which will affect the relative evaluation. In general, depending on the ground conditions and weather conditions, a two-week wait might not be suitable and a longer 'wait' time might be required.

Based on the tilt values shown in Fig. 3, the gauge length of 700mm and Eqs. (2) and (3), the range of the displacements (absolute values) is between 0 and 0.733 mm in the EW direction and 0 and 3.05 mm in the NS direction.

In an engineering context, this order of magnitude for displacements is negligible in terms of risk on the structural integrity of infrastructure. Not the full range of these amplitudes reflect real movements. Some correspond to noise induced by various factors, the main of which is temperature.

3.2 Temperature drift

Tiltmeter recordings are affected by temperature variations (Chrzanowski and Secord, 1999**)**. The tiltmeters used here have a temperature offset of ± 0.002°/°C (WorldSensing, 2025**)** but a temperature correction is not straightforward to apply as it can have both a negative or a positive effect for the same amount of temperature rise **(**Battista et al., 2024).

Visual inspection of random segments of the time histories between the calculated tilt and the tiltmeter temperature indicates a strong correlation between the readings, i.e. it appears that the tiltmeter responds immediately to the temperature change (Fig. 4) and thus indicating a linear relationship between the two.

Given the very small magnitude of the recorded tilts and consequently the calculated displacements, one can assume that these displacements are just noise, a mere response of the tiltmeter to the temperature (as recorded by the tiltmeter) changes.

To provide some context, the average annual temperature in the area is about 10 °C (COSMOS UK, 2025). The coldest months are January and February with the average temperature around freezing level. For the time period considered in this paper, the maximum recorded air temperature was on 11th May 2024 at 23.2 °C and the minimum on 2nd December 2023 at -7.9 °C. The recorded tiltmeter temperature values vary. Tilt 1 ranges from

-3.5 to 31 °C. Tilt 2 ranges from -9.4 to 36.6 °C. Tilt 3 ranges from -2.5 to 36.5 °C. Tilt 4 ranges from -3.8 to 40.9 °C. Tilt 4 ranges from -3.5 to 35.8 °C.

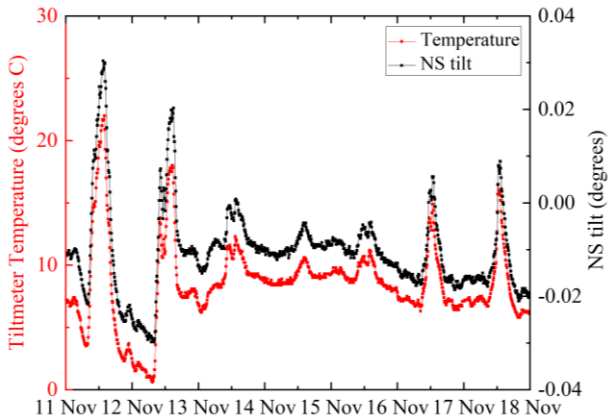

Figure 4. Variation of tiltmeter temperature and NS tilt over the span of one randomly selected week as recorded by Tilt 5. The tilt values appear to be in perfect sync with temperature.

In order to further investigate the displacement-temperature relationship, we propose a simple to implement approach. We applied the Continuous Wavelet Transform (CWT; Percival and Walden, 2000) to identify the dominant periods in the computed displacements and tiltmeter temperature data. This analysis showed that both the tiltmeter temperature and the displacements have their dominant frequency at the period of 23.53 hrs, a classic diurnal cycle. However, CWT does not provide information on the type of the relationship (e.g. linear) between the two parameters. The Wavelet Coherence (WTC; Grinsted et al., 2004) is a method that could address this. It enables the identification of common power spectra and wavelet coherence between two time-series datasets (Grinsted et al., 2004). Using the phase information provided from WTC, we were able to calculate existing time-lags between tiltmeter temperature and displacements over the full year of measurements. We extracted the phase difference from the WTC results at the dominant period of 23.53 hrs through the whole monitoring period. This parameter measures the relative phase shift between two time-series at different time scales. The time-lag can be obtained by dividing the phase difference by a full cycle of 2π (the phase is given in radians by the WTC analysis) and then multiplying by the time scale (23.53 hrs period in this study).

Fig. 5 shows that assuming a linear relationship between the tiltmeter temperature and the calculated displacements is not correct. Here we use the displacements along the NS direction that have larger values compared to those in the EW direction for all Tilts. The time-lag evolution over time for Tilt 1, 2 and 4 appear to be consistent: the actual values are different but the pattern is very similar. This is not the case for Tilts 3 and 5. A possible explanation could be that these tiltmeters were in fields that were frequently used by livestock. Livestock frequently caused damage to the radio antennae. To avoid this, we covered both tiltmeters with large PVC boxes which influence the temperature values recorded by the tiltmeter inside the box.

Note that in Fig. 5 time-lags between 0 and 10 mins can be regarded as zero. This is due to the sampling rate of 10 minutes that does not allow to distinguish between time-lags with values in the range from 0 to 10 minutes. Positive values of the time-lag represent a delayed response of the tiltmeter to a temperature change, i.e. a rise in the temperature is followed by an increase in the tilt value some time later. This behaviour can be either (a) a temperature drift or (b) reflect real ground movements due to temperature rise (Loria and Coulibaly, 2021). In addition, there are time periods where the time-lag values become negative (i.e. change in the displacement value precedes change in tiltmeter temperature). In this case, the calculated displacements are not correlated to temperature in any form. They are not due to temperature drift, nor induced by temperature.

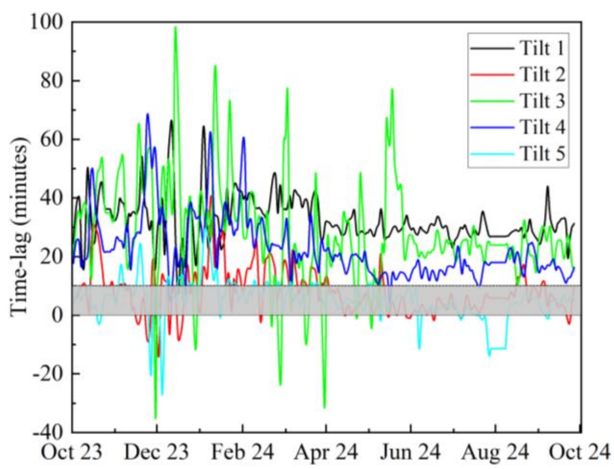

Figure 5. Time-lag between temperature and tilt over time. The grey highlighted area represents a zone where the time-lag values can be essentially regarded zero.

The next step in this analysis would be to develop a methodology to remove the temperature drift and to look at the mechanisms that could be triggering such behaviours: positive time-lags or negative time lags. One of these factors could be rainfall that can result in increase in the soil surface moisture (Chen et al., 2017) and movement of the ground. Another cause could be rise of groundwater level. The exact determination of the cause is the focus of an ongoing research.

3.3 GNSS observations

The deployment geometry of the tiltmeter network we adopted in this study did not allow any conclusions for movement in the vertical direction. For this, we look into the GNSS monitoring data as shown in Fig. 6. A linear trend was fitted to the GNSS positions along the vertical direction. The slope of the trend was found equal to 10 mm/year. This value is 10 times larger than the average rate of uplift reported for the farm site from the InSAR data. This is not only due to the different accuracies of the two technologies but mainly due to the different duration of data used. Our GNSS data only cover a period of 8 months. The InSAR data refer to an average uplift rate over a 5-year long period. The rate we report from our data is halved to 5 mm/year if we take into account the period up to beginning of March 2025. This value is expected to drop even further if we use data covering a longer time period. It is likely that the rate is affected by what looks like a seasonal effect, with the dH values showing an increase during the months May to September. This however, cannot be documented with just 8 months of data. Monitoring for a longer time -period would allow for more robust conclusions. In any case, the GNSS data over the time period examined in this paper support the overall trend of ground motion in the vertical direction, representing an uplift trend in agreement with the InSAR observations.

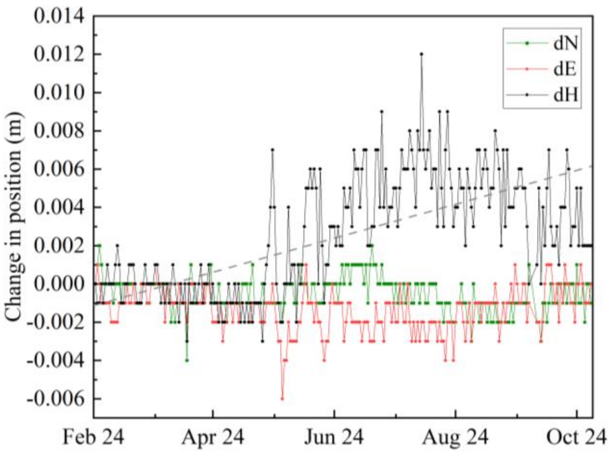

Figure 6. Change in the position for the GNSS monitoring point in Northing (dN), Easting (dE) and Elevation (dH). The dashed grey line represents the linear trend of the dH values with a slope of 10 mm/year.

4 Discussion and Conclusions

This study focused on the potential of tiltmeters as a low-cost technology to monitor minute ground movements over a relatively flat area, which could be the case for energy projects that utilise the subsurface. Tiltmeters is a low-cost technology and have been extensively used in a number of applications, so at first, this idea seemed to be straight forward to implement.

The truth ended up being very different. Referring back to the original hypothesis on the use of tiltmeters to capture ground movements along the vertical direction, our study showed that for such applications, a small number of tiltmeters, like the one used here, at distances of > 50 m, is not enough to derive conclusions on movement along the vertical direction. Especially in cases where the ground gradient is relatively flat but not constant. In our case, not two of the tiltmeters were consistent in their direction of tilt over the full time period examined. A denser network (a tiltmeter every 10 - 50 m) could provide more clear results and allow for conclusions but this would also mean a higher cost in terms of resources. In retrospect, for research purposes, collocated tiltmeters or another independent technology could provide some security on this. At the location of Tilt 2, we have also installed a seismic node and a soil moisture probe. We plan to use these data to independently verify and further analyse the recordings of Tilt 2.

The sampling rate we chose to use was 10 minutes. For further analysis, such a high sampling rate will introduce unnecessary noise and variation in the tilt values that a lower sampling rate could have otherwise avoided. We had limited information as to what to expect when this project started and decided to choose a higher sampling rate. Unknowingly at the time, this also allowed us to observe a varying time-lag over time between the tiltmeter temperature and the calculated tilt values. We plan to use this to further characterise the relationship between the two signals aiming to remove the effect of temperature-induced drift.

Interpretation of tiltmeter data for areas where no significant movement is expected is very difficult. If the tiltmeters are not deployed beneath the ground surface (which for the cases where a large number of tiltmeters is deployed, burying them can be very time consuming and costly), temperature variations can deem the recorded tilts unusable. Temperature drift needs to be taken into account but correcting for it is not straightforward because the temperature drift does not always manifest itself as the immediate response of tiltmeter to the temperature variations. We showed this non-linearity through the use of Wavelet Coherency Transforms.

The choice of the type of tiltmeters used in this study was based on the type commonly used in construction projects in the UK by various organisations including contractors working on projects commissioned by the Environment Agency, Network Rail and Scottish Water and the deployment followed common deployment practice as it will be those professionals who will provide such services to the owners of any industrial geobattery project in the future. The challenges the authors faced in this study, are challenges faced by professionals on construction sites.

Most of the time, what does not work is not reported. And as such, mistakes and errors are repeated. This study aspires to contribute towards improving our knowledge in applying tiltmeter technology in practice through a 'lessons learned' approach.

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