

Fibre Optic Movement Sensing for detecting and monitoring railway track support condition

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ABSTRACT: To maintain a fragile railway including multiple embankments, sub-soil issues and under-track assets, it is required to monitor railway track support condition over several kilometres. Sensing using an optical fibre within an existing telecommunications cable close to the railway track has been evaluated as a large area railway support monitor. In the study, disturbances from passing trains serve as a source for investigating ground movement under and around the track. As such the fibre optic cable acts as a geotechnical sensor. For over 12 months, 7 km of railway between Culemborg and Geldermalsen in the Netherlands has been monitored from the pattern of dynamic strains generated in the fibre by passing trains. Fibre Optic Movement Sensing (FOMS) uses these dynamic strain measurements to evaluate inelastic ground movements produced by passing trains, thereby monitoring railway track support condition continuously and in real time. In addition, data from the BWMS (Branche Wide Monitoring System), satellite data (Asteria), visual inspection data, rainfall measurements (from KNMI), and a geotechnical soil profile (based on Cone Penetration tests (CPT) and borehole data) were gathered and compared to verify and help in interpretation of FOMS data. The FOMS data set shows signals associated with concrete structures, subsidence, re-worked track support and "normal" track. Changes in FOMS data indicate locations of concern beneath the track such as subsidence. Furthermore, locations with a temporary high moisture content can be identified. After several months of monitoring we have built up a good understanding of normal operation and track stability. FOMS is now being used as a reliable tool for monitoring railway track support condition and automatically alerting us to changes or deviations from normal as they happen.

KEYWORDS: Fibre optic, sensor, monitoring, track embankment.

1 INTRODUCTION

Over the last several years continuous track condition monitoring using Distributed Acoustic Sensing (DAS), also known as Fibre Optic Acoustic Sensing (FOAS) has attracted significant interest. Vibrations generated by the wheel-sets of passing trains as they progress on the rails are coupled through rail, ground and cable, ultimately generating tiny vibrations in trackside optical fibres already next to the railway for communications. Data from a FOAS interrogator, tuned to measure these vibrations, can be analysed to separate vibrations originating from rolling stock from those generated by the track. Vibrations related to track can be further analysed to attempt to provide a measure of the track condition.

However, many rail condition issues are associated with track-supporting assets like undertrack crossings or drainage systems, or with the track support stability itself, e.g. subsidence. In this paper we describe results from analysis of track near Culemborg using a new sensing technique called Fibre Optic Movement Sensing (FOMS). FOMS also uses trackside fibres, but unlike FOAS, is tuned to look for inelastic changes in fibre strain from passing trains causing ground movement. This allows FOMS to find and monitor track support issues, even when these are localized to a few meters, tracking small changes over extended periods leading to alerts on potentially dangerous track support issues and allowing preventative condition-based maintenance.

In this paper we will describe the particular challenges associated with the area we selected, the FOMS technique, our processing of FOMS data and experiences from the project.

2 PROBLEM DEFINITION

A large part of the Dutch railway is located on embankments that are over 100 years old, which were built from local materials and designed based on outdated traditional methods. The subsoil also often consists of very soft peats and/or clays. When stability analyses were carried out for these embankments, it was found they do not meet the current standards, although in the field most embankments are performing fine. This, in combination with the wish to increase axle loads of the train, the train frequency and train speed, means that monitoring of displacements in the track embankments is sometimes necessary. Two mechanisms (see Figure 1 and Figure 2) are common, embankment stability and bearing capacity. Because both mechanisms will result in changes in displacement along the embankment as trains pass can be monitored by FOMS.

Both embankment stability and bearing capacity are influenced by the water table in and around the embankment. As we suspect that climate change will result in more extreme rainfall and drought, this may also have a negative impact on the structural safety of the track embankments, further driving need for continuous monitoring.

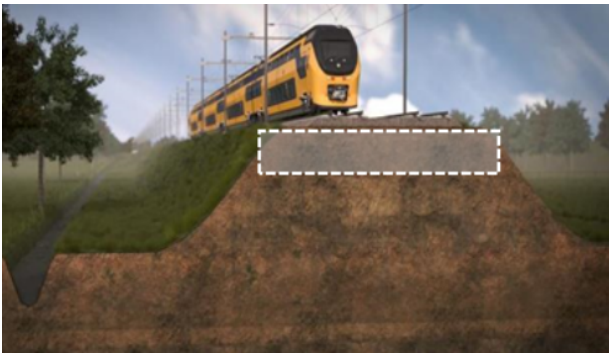


Figure 1. Location of reduced bearing capacity under the track



Figure 2. Example of sliding plain in the track embankment

These risks have been inventoried for the entire Dutch railway network in the National Network Analyses for Embankments. From these analyses we can state that the track can be used safely, but when changes in or around the track are made, measures must be taken to preserve safety. Along the track in Culemborg the train speed had to be raised from 100 km/h to 140 km/h. Because of critical train speed problems, a ‘Planum Schütz Schicht’ (subgrade protection) layer (also known as Pile-Slab-Supporte, PSS layer) was installed under the track. This solved the problem for most of the track, but the track on the west side still has some problems to do with drainage.

The PSS- layered zone is under increased supervision, with the track section being regularly inspected and maintained. Additionally, a speed limit has been set over a length of 1 kilometer, resulting in an increased travel time between Utrecht and Den Bosch. Due to stability issues with the track bed, there are higher maintenance costs against lower transport performance.

In this project we have investigated whether track-support stability and subsoil monitoring can be established with FOMS using existing fiber optic cables that are already present along the track section. We had the following goals:

- Digitisation and automation of the inspection
- Generating alarms if maintenance is needed, in order to prevent damage to the track by timely maintenance
- Detecting local hotspots of instability, so that speed restrictions can potentially be shortened.

3 TEST SITE CULEMBORG

3.1 Location

The research site is located in the middle of the Netherlands, alongside the railway track between Culemborg and Geldermalsen, see Figure 3. The fibre optic cable, which is a

spare within an existing cable normally used for communication purposes, is buried in the top of the embankment on which the railway is situated.

A single-mode (SM), non-dispersion-shifted (NDS) fibre that conforms to ITU-T G.652.D was available for the measurements along the west side of the track between Culemborg and Geldermalsen. This fibre is approximately 8 km long and has been patched twice. The fibre is installed in a HDPE tube with a diameter of either 32 mm or 40 mm.



Figure 3. Location of test site in the Netherlands

3.2 Background Embankment

The track embankment is made up of two parts. In 1868, the western section was built for a single track. This section consisted of a clay embankment with a thin layer of sand on top. As the railway proved successful, work began on doubling the track on the eastern side as early as 1885. This section of the track was built alongside the existing section and was made of sand.

A track renewal was carried out in the summer of 2023 due to the high number of deformations in the track when trains passed at speeds of approximately 140 km/h. A PSS layer (a highly compacted, almost waterproof sand layer, 30 cm thick) was installed under the tracks to enable speeds of up to 140 km/h. However, this layer did not solve the problem sufficiently. Therefore, a temporary speed restriction for trains and monitoring of the track via FOMS was introduced. Figure 4 shows the cross section of the rail environment.

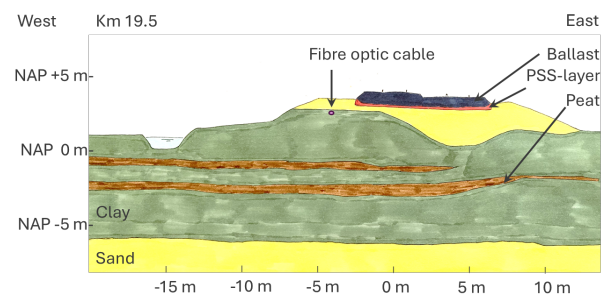


Figure 4. Cross section of the rail topology

3.3 Geological background

The ground under the embankment is diverse due to the presence of various river deposits. During the early and middle Pleistocene periods, the Meuse and Rhine rivers deposited large

quantities of fluvial sand and gravel in this area. During the late Pleistocene, specifically the Saale glacial period, the area between Culemborg and Geldermalsen was located just south of the glaciers and glacial moraines that covered the northern Netherlands. The riverbeds, which were mainly dry, carried meltwater.

During the subsequent Weichselian ice age, the Netherlands was a vast polar desert. During this period, a thick layer of aeolian sand (the Boxtel Formation) was deposited. This sand is used to build pile foundations 10 to 15 metres deep in the western part of the Netherlands and can be found on the surface in the east. In the area between Culemborg and Geldermalsen, this layer is present sporadically; because, it has eroded in many places, revealing a river sand deposit (Kreftenheye Formation) instead.

During the warmer Holocene period that followed, the groundwater level rose and the rivers Lek, Waal (which together form the Rhine) and Maas flowed again, depositing sediment (the Echteld Formation) on the research site. The town of Culemborg and the village of Geldermalsen are located on former levees, and the area between them consists of bowl grounds. These bowl grounds consist mainly of weak clay (mostly humus-rich) interspersed with sandier stream belts. See figure 5, geotechnical profile.

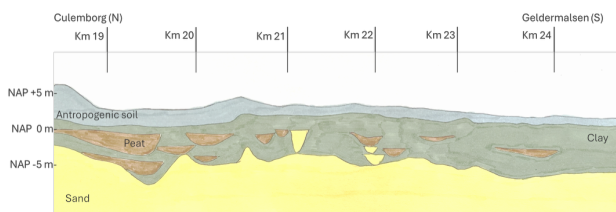


Figure 5. Culemborg to Geldermalsen geotechnical profile.

4 FIBER OPTIC MOVEMENT SENSING (FOMS)

4.1 Installation

After ProRail's Asset Management department choose the test site the following installation procedure was followed.

First a fibre-optic was allocated to the project. Then records were examined to find a rail-bound building with space and power suitable for placing the Indus. Once the building was chosen, its availability for the relevant period was established with the manager and the maintenance team. When a fibre does not run all the way over an entire test site but terminates within intermediate rail-bound buildings. In that case, the fibre optic cable must be patched so that one optical circuit that runs from the start to end of the zone to be monitored. An Optical Time-Domain Reflectometer (OTDR) measurement was carried out to determine whether the fibre route required re-work.

A passive terminator was installed at the distal end of the test zone to remove the adverse effects on measurements from Fresnel reflections. The Indus interrogator was then activated and setup. Subsequent data was processed using the Indus platform, which combines edge and cloud processing to achieve real-time continuous measurements. The test zone was then georeferenced using signals from passing trains and occasional local stimuli like hammer blows so that every meter of the fibre was mapped to a physical location. Fibre inside rail-bound buildings was tagged as unsuitable for measurements.

4.2 Measurements

Focus Sensors developed Fibre Optic Movement Sensing (FOMS) to provide continuous monitoring of track stability. FOMS uses Indus measurements to isolate inelastic changes in fibre strain imposed by ground movements from passing trains. Normal train passages cause tiny inelastic (permanent or semi-permanent) movements in the ground supporting the track. These movements cause minute strain changes within optical fibres which run alongside the track. In this way we can compute a separate FOMS measurement for every metre of track, normally updated every day. A stable track moves differently to an unstable track when a train passes over it. Instabilities can be a result of subsidence, under-track features and water saturation of the ground, and it is the variation in these movements which allow track issue diagnosis. Additionally, because FOMS uses measurements captured just before, during and after passing trains, FOMS is not directly sensitive to slow changes, such as temperature. Focus Sensors use their purpose-designed distributed dynamic strain interrogator Indus to monitor the fibre. For this project the Indus was set to monitor the 7km test fibre with a channel spacing of 10ns (approx. 1m) and pulse repetition frequency of 10kHz. Note, Brillouin based distributed absolute strain sensors are not suitable for FOMS, as their update rate of seconds or minutes is too slow to capture passing trains, and the strain changes imposed (which are of order 100nε), are too small to be measured with these systems. Data from the Indus interrogator was processed by the Indus Platform to provide FOMS measurements over the entire test fibre.

FOMS has been used effectively in the UK and Europe for monitoring a variety of issues; embankment slips, switch and crossing sub-components, drainage system health, undertrack assets, and mine workings have all been identified and monitored using FOMS.

4.3 Methodology

Raw FOMS data is often displayed as a Geopanel, a heat map displaying FOMS history related to several hundred metres of track. Stable areas will experience the effects of passing trains but will typically return to the same state as before the train arrived, giving a low strain change and low FOMS value. A Geopanel can quickly highlight stability changes over time. Focus systems automatically identify areas where track stability varies compared with the rest of the track, called Areas of Interest (AOIs). If the FOMS system detects a rapid or unexpected change in an AOI, then an alarm is raised, alerting the customer. An example Geopanel is shown in Figure 6, where eleven months of FOMS data is displayed for an 800m section between Culemborg and Geldermalsen. Two areas of interest (AOIs) are shown in this area (A1 and A7) indicating worsening track stability four months into the deployment.

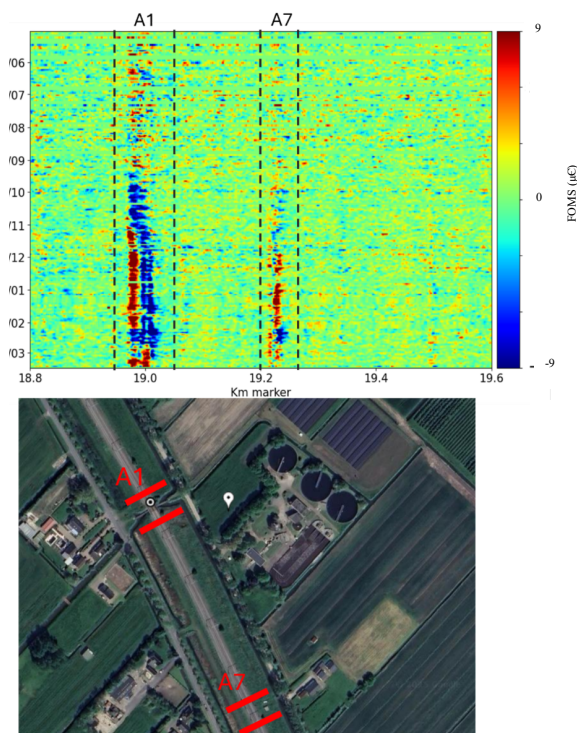


Figure 6. (a) Example of FOMS history showing signals from areas of interest (AOIs) A1 and A7, (b) The locations of the areas of interest A1 and A7 on aerial photograph.

FOMS data related to areas of interest are processed to produce a summary metric, a unitless derived quantity which describes the evolving status of each AOI. Sometimes a ‘subtracted metric’, emphasizing performance at the AOI relative to nearby stable track is used. Over time, the system learns ‘normal’ behaviour for each AOI, such that alarms can be sent via email whenever abnormal changes occur indicating significant degeneration. An example metric timeseries is shown in Figure 7 for AOI A7. The system checks for extreme gradients and divergence away from a rolling standard deviation (Bollinger bands) which provide the conditions for an alarm trigger. Here a combined anomaly (all three conditions) is represented by a red point. The system currently checks for combined anomalies daily and creates an alert email in the case of triggers.

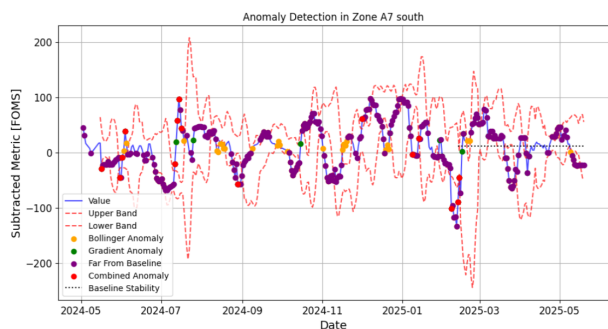


Figure 7. FOMS metric (AU) for AOI A7, showing degradation around November 2024, this change corresponded with rough ride reports in this area.

5 RESULTS

5.1 Areas of interest (AOI)

Following installation in April 2024 and a short calibration period, FOMS data was analyzed to identify AOI. In total 14 AOI have been identified and monitored. Area A2, A6, A7 and A8 were identified by measurement train (which measures relative height) or by the inspector visually. The others were identified using FOMS data only. Table 1 a gives summary of the locations and the associated issues. All of the locations were confirmed as areas of track movement or track degradation, with zero false negatives and false positives. In the following sections we will consider area A1 in more detail.

Table 1. Areas of interest found with FOMS along the track

Aera	Issue
A1	<i>Subsidence</i>
A2	<i>PSS-supported area on continuous monitoring</i>
A3	<i>30m elevated movement section</i>
A4	<i>Level crossing around midpoint</i>
A5	<i>Concrete underpass under monitor</i>
A6	<i>Area of track movement leading to rough rides</i>
A7	<i>Area of track movement leading to rough rides</i>
A8	<i>Area of track movement leading to rough rides</i>
A9	<i>Area identified by classification algorithm</i>
A10	<i>Area identified by classification algorithm</i>
A11	<i>Area identified by classification algorithm near bridge</i>
A12	<i>Area identified by classification algorithm near bridge</i>
A13	<i>Area identified by classification algorithm near bridge</i>
A14	<i>Area identified by classification algorithm at a turnout</i>

5.2 Area of Interest (AOI) A1

In this section we describe FOMS measurements from area of interest A1. Area A1 was identified shortly after installation in April 2024. Elevated FOMS values were detected compared with nearby track as shown in Figure 6 a). AOI A1 FOMS metric is shown in Figure 8. The metric shows a period of elevated but stable FOMS up to October 2024. In October 2024, the metric rose to 100 units (12.9 microstrain per train), leading to an automatic alarm. At that time, the track was inspected but no visible issue was found. Later in December 2024 the metric had risen further to 200 units (about 24.7 microstrain per train). Over the next period we saw significant changes in the FOMS, leading to a further alarm in March 2025. Further track inspection revealed subsidence and significant track shear. Emergency lifting and realignment of the track was required.

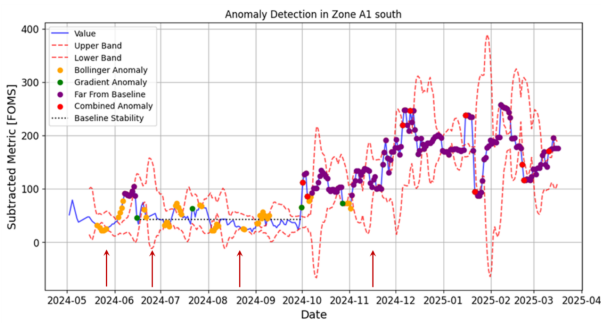


Figure 8. Calculated FOMS metric (AU) AOI A1. A1 was identified in April 2024 as an area of elevated FOMS. Greater instability was observed starting around October 2024. The dates of measurement train visits to the area are shown as red vertical arrows.

Figure 9 shows a FOMS Geopanel zoomed around A1. The figure shows several changes in the sign of the FOMS signal. At km 18.99 FOMS goes from positive (red, ground expanding with each train) to negative (blue, ground contracting with each train) then back to positive again. Whereas a few hundred meters away we see negative (blue) signals switch to positive (red). The ground is contracting in the area near the bridge (km 18.99) and expanding out after the bridge (km 19.0 +). This movement is indicative of subsidence because it shows ground has moved away from km18.98 leading to blue contraction areas and associated expansion (red expansion zones).

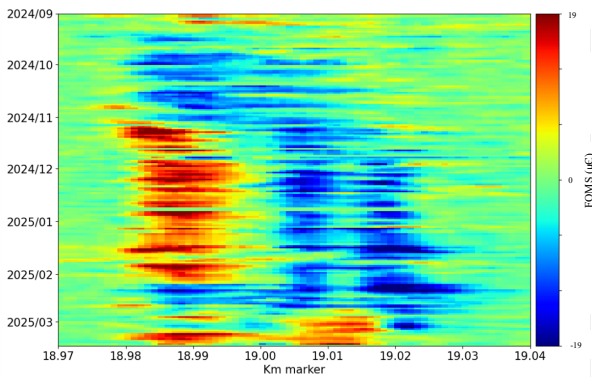


Figure 9. AOI A1 geopanel zoomed, showing evidence of subsidence.

Visits from the measurement train to area A1 are shown as red vertical arrows in Figure 8. We see the first two visits from the measurement train in June and July 2024 corresponded with periods of relative stability, so the track instability detected by FOMS was not reflected in measurement train data. The data collected by the measurement train in August 2024 and November 2024, was requested by ProRail from the BWMS (Branche Wide Monitoring System). When the combined track parameter (which is a ProRail proprietary measure used to indicate issues with the displacement of the track) and the vehicle effect are compared from the August measurement run and the one from November, an increase (dark green parts) in both parameters is seen, which means a degradation in track geometry, as detected by FOMS. See figure 10.

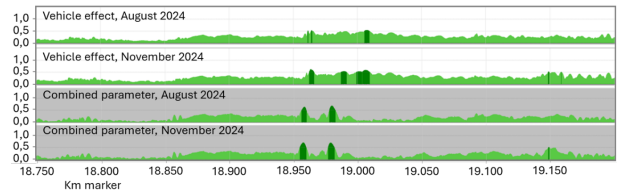


Figure 10. Measurement train data at AOI A1

5.3 Relation to rainfall and displacements

From daily practice ProRail knows that most of the displacements during operations will occur in the transition zones between concrete structures such as bridges or level crossings and the soil embankment. This is also evident in the FOMS results.

However, during wet periods when a lot of rainwater has to run off the embankment to the parallel ditches. Some of this rainfall will inevitably infiltrate the track bed and have an influence on the bearing capacity of the sand at the top of the embankment. To gain an initial understanding of the moisture content of the soil in the investigated embankment, Asterra satellite data was used. As can be seen in figure 11 at location A3 the moisture content at the AOI is clearly higher (more orange and red) than in the surrounding embankment.



Figure 11. Asterra satellite data: (A), AOI A1 where subsidence near a bridge was discovered. (B) AOI A3, a 30m section with regular displacement.

In addition to the Asterra data, the regional moisture content data from the open Meteo API was used to compare the FOMS results and the moisture content. It can be seen that there is a correlation between moisture content (25 cm under surface level) and FOMS as some of the peaks align well. However, the correlation is not very strong highlighting the presence of other influences, see figure 12.

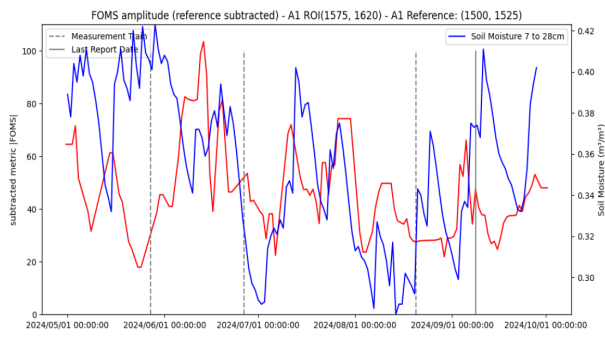


Figure 12. Soil moisture content correlated with FOMS (AU)

To supplement the moisture content analyses, further data was gathered. The groundwater head was measured around, and in the surrounding area of the track. As can be seen on the left-hand side of figure 13, when the groundwater head (light blue) decreases in spring and summer (let us assume that the embankment begins to dry out from the top) the FOMS signal remains fairly stable. Later at the end of September a period of rain begins and the temperature drops by a few degrees, the embankment soil becomes wet and it is around this time that we see displacements.

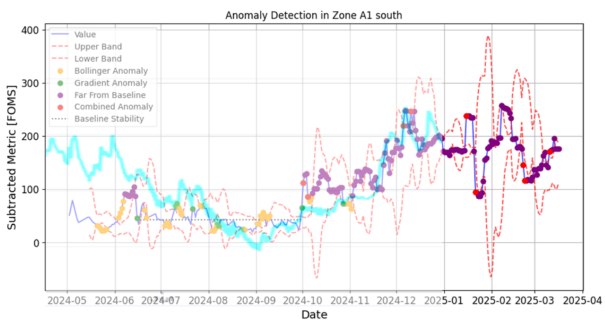


Figure 13. FOMS (AU) metric with ground water overlay

6 CONCLUSION

Track is traditionally monitored on a periodic basis by patrolling (track walks), manual measurements, and geometry measurement trains. These are time-consuming, expensive and result in disruptions to the train service. Continuous monitoring using FOMS gives the opportunity for gradual changes to be monitored in real time and provide a more representative understanding of the state of AOIs, along with identifying any emerging issues. Through a combination of FOMS data analysis and track inspection, several track issues were identified, including subsidence, corrugation, sheer and presence of ballast voids.

Our main conclusions from the study were that FOMS can find subsidence, monitor undertrack features and monitor drainage condition changes using existing trackside fibre and normal train movements. It was also noted that periodic monitoring can give a false impression as periods of instability could be missed. At area A1, measurement train movements happened at areas of stability, masking a growing issue that was identified and monitored by FOMS.

FOMS can provide near-instant alarms when things change, allowing rapid rectification of issues.

Over our monitoring period every track issue identified by FOMS was verified by other means (zero false positives) and no track issues that should have been detected were not seen by FOMS (zero false negatives).

7 RECOMMENDATIONS

To get a better understanding of the relationship between weather conditions, groundwater levels and the FOMS-metric, further research is required. It is advised that a weather station, a freatic groundwater head measurement and soil moisture measurements at different depth are installed at the location of the embankment to get a better understanding.

8 ACKNOWLEDGEMENTS

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