Advancements in the detection of embankment instability using measurable track geometry data

AUTHOR:

Matthew Audley

Principal, Phase 1&2 - Data analysis

Matthew is an engineering consultant with ten years of experience in data analytics and its applications in infrastructure asset management, including rail, data centres, oil, gas and water treatment. His focus is on operational data modelling, helping clients make Opex / Capex decisions using their maintenance, inspection and renewal data.

AUTHOR:

Michael Edwards

Principal, Phase 1 & 2 - Client & Technical Direction

Mike is a Principal Engineer in Network Rail's central Technical Authority. His work focusses on portfolio level asset management of c.200k railway earthworks. Recent initiatives Mike has led include the developments of parametric hazard indices, global stability appraisals and rainfall/soil moisture diagnostics. He plays a key role supporting Network Rail's operational business, including policy, standards, competence, assurance, IT and R&D. Mike is a Chartered Engineer and Member of ICE.

AUTHOR:

David Kite

Phase 1&2 - Technical Lead & Project Manager

Dave leads AECOM's Rail Research & Consultancy team and has worked for a range of global clients to develop track renewal strategies, manage track investigations and has led development of digital tools to give rail clients greater insight into their track data. He is a Chartered Member of the ICE and was technical lead for the first phases of development of the embankment instability analysis.

WHY DO WE NEED TO UNDERSTAND EARTHWORKS PERFORMANCE?

The failure of earthworks on the UK rail network is associated with train accident risk, where derailments may occur if support to the track is lost due to embankment failure. Table 1 shows that, whilst earthwork attributed derailments and potentially high-consequence failures were reducing by the end of Control Period 5, total numbers of earthwork failures and earthwork-related temporary speed restrictions remained comparable to a decade earlier. Suppressing underlying failure rates and speed restrictions through effective asset management of earthworks is key to controlling train accident risk to tolerable levels.

This article focuses on the key elements of a programme to build an operational asset management tool for the effective management of earthworks that will help to suppress underlying failure rates and speed restrictions and control train accident risk to tolerable levels.

The condition of rail embankments has been primarily monitored through visual inspections by earthwork examiners using electronic handheld devices since the early 2000s[2]. The last examined state determines both an asset's examination frequency, and whether the asset is promoted for evaluation by Network Rail asset engineers. Evaluation is where all known data related to an asset is scrutinised and a management strategy for the asset determined.

Network Rail typically examines approximately one-third and evaluates approximately one-tenth of its 190,000 earthwork assets annually.

To better understand performance between examinations, and promote deteriorating assets for evaluation where required, Network Rail is seeking to complement earthwork examination data with data captured through other means.

Track geometry data is collected routinely by Network Rail using specialist measurement trains. Previous research has shown that this measurable track geometry data can be used to give an indication of the performance of railway embankments[3].

Furthermore, Network Rail's Earthworks Technical Strategy published in June 2018[1] expresses a desire to better utilise track geometry data for identification of embankment instability, allowing the root cause to be addressed through deep-seated remediation, rather than continuing to deal with symptoms eg tamping track back to line and level.

The research described herein mostly discusses the second phase of a four-phase programme to deliver an operational tool. The phases of the research can be summarised as follows:

PHASE 1 – PROOF OF CONCEPT (2018 – 2019): Analyse the track geometry data of embankments within Network Rail's CP6 work bank with the purpose of identifying indicators of embankment instability. Subsequently use this analysis to develop an algorithm capable of generating a metric that can be used to quantify embankment instability. Further details of this research are summarised in Reference 1.

PHASE 2 – VALIDATION AND REFINEMENT (2020): Analysis of track geometry for a control group of embankment assets from the Anglia Route, not selected based on current performance. This paper will focus on this phase of this research programme.

PHASE 3 – SCALE UP TO WHOLE ROUTE/REGION AND REFINEMENT (DUE TO FINISH 2021): Analysis of track geometry for all embankments within a single Network Rail Route/Region. This study will include the necessary steps required to elevate the proof of concept to a full prototype capable of analysing the substantial volumes of data at Route/Region level.

PHASE 4 – SCALE UP TO WHOLE NETWORK AND SUPPORT IMPLEMENTATION (EXPECTED FINISH 2022): Analysis of track geometry for all embankments for Network Rail's entire network. Furthermore, this phase will focus on integrating the analysis technique into Network Rail's systems for use as an operational tool.

This paper is a summary of outcomes from the validation and refinement phase of the research (Phase 2) and is not exhaustive.

INITIAL RESEARCH AND PROOF OF CONCEPT

Over the past six years research has been conducted on the use of measurable track geometry data for detecting embankment instability, primarily by AECOM and Network Rail.

In 2014, a pilot study was carried out by AECOM and Network Rail to assess the feasibility of using measurable track geometry data to detect early stages of embankment failure[3]. In this study, track geometry records between November 2010 and May 2014 were processed for embankments experiencing some degree of instability. It was found that the rate of change of vertical alignment (Top) and lateral alignment, along with a composite parameter referred to as dTop or differential top (equal to Left Rail Top – Right Rail Top) were the best indicators of earthwork movements. This concept is shown graphically in figure 1.

In the Phase 1 study, track geometry data was processed for over 1,800 embankments, which were planned to be renewed, refurbished or maintained as part of Network Rail's Control Period 6 (2019 – 2024). This process involved calculating SD values for the Lateral Alignment and Top parameters of the track geometry using a 20-yard base length, and then trending the data over the relevant time period. Consideration was also given to alternative base-lengths for the SD calculation which showed that the 20-yard base length was most suited to this assessment, providing the best balance between mitigation of alignment errors and sensitivity to localised instability.

The Phase 1 research showed that the Lateral Alignment and dTop parameters could be used to quantify earthwork instability, which resulted in the development of an algorithm which outputs an Embankment Instability Metric (EIM). The EIM value is a measure of the average annual deterioration of the Lateral Alignment and dTop parameters and calculated for each 10-yard section of embankment. The resulting EIM values (units mm/yr.) are calculated for each year for each 10-yard track segment. The study observes a period from 01-May to 30-Apr to calculate an annual measure of the EIM each year, as an assumed 'neutral' point to negate any seasonal variability by taking a full summer-winter season.

A comprehensive summary of the Phase 1 research, along with the criteria for valid track geometry records, can be found in Reference 1.

There have been alternative approaches to the method outlined above, such as an approach developed by Network Rail[5], which uses a 220-yard SD base length for processing the Alignment and Top parameters. The benefit of a 220-yard SD base length over a 20-yard base length is ease of processing, since the 220-yard SD data is already generated by Network Rail for all available track geometry. Thus, for the 220-yard SD method it was not necessary to align and re-process track geometry data for shorter standard deviations such as in this study. Therefore, the speed in which 220-yard SD data can be analysed is an order of magnitude faster. However, it was shown that the use of this longer base-length meant it was not possible to recognise embankment instability due to the lower resolution masking these more localised faults which are typically less than 100 yards in length.

Both methods described above are looking for gradual embankment movements, which are significant enough to move the tracks and therefore manifesting in the measurable track geometry data. The shallower the embankment movement, the less likely it is to manifest in the track geometry data and other types of embankment failure mechanisms (eg highly localised slips or localised animal burrowing) will also not appear at all in the data as these types of failures are unlikely to impact the geometry of the tracks or result in immediate loss of track support.

Control Period	Date Range	Earthwork TSR's (% of all TSRs)	All Earthwork Failures	Potentially high consequence earthwork failures	Earthwork attributable derailments
CP1	1994/95 – 98/99	No data	No data	No data	7
CP2	1999/00 – 03/04	273 (7.3%)	No data	No data	8
CP3	2004/05 – 08/09	135 (3.8%)	477	41	8
CP4	2009/10 – 13/14	441 (4.8%)	528	32	8
CP5*	2014/15 – 18/19	290 (3.4%)	381	18	2
CP6	2019/20 – 23/24				
Trend		relatively stable	relatively stable	reducing	reducing

*Data for 4yr period 14/15 to 17/18 *TSR* = Temporary Speed Restriction *KPI* = Key Performance Indicator

Table 1: Key performance and safety metrics by regulatory control periods (source Network Rail Earthworks Technical Strategy June 2018[1]).

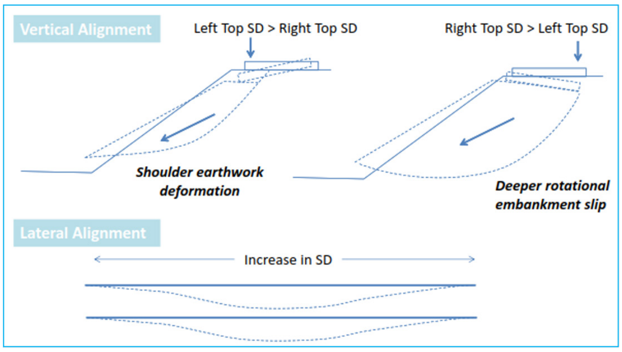

Figure 1: Effect of typical rotational slip on track geometry.

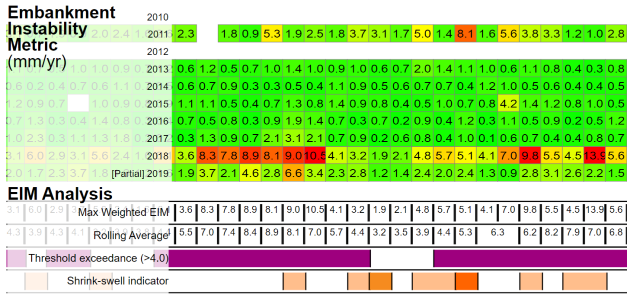

Figure 2: Extract of Embankment Instability Metric (EIM) heatmap and EIM aggregation and shrink swell identification modules, where each block represents a 10-yard segment.

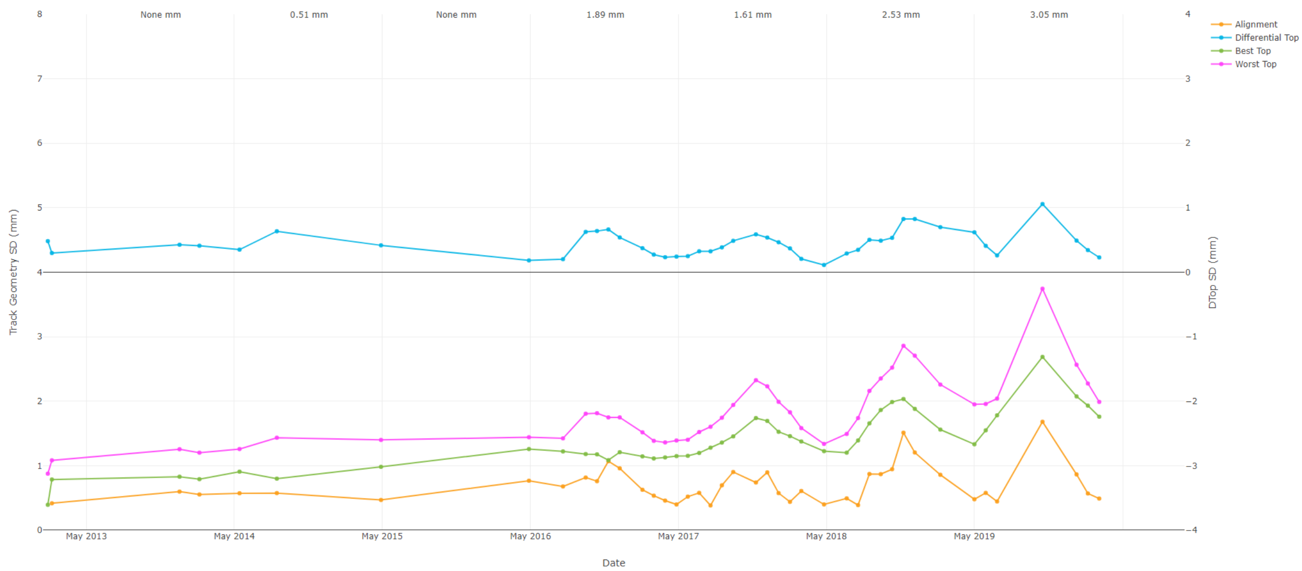

Figure 3: Time series plot showing seasonal shrink-swell behaviour, with annual EIM values at the top of the plot.

Furthermore, the research thus far has generally looked at embankments with known instability issues, however the following section describes the second phase of this research project which examined a control group of embankments.

RECENT METHODOLOGY IMPROVEMENTS

This section details the approach carried out for Phase 2 of this research which largely adopts the methodology described in the initial phase[1]. The objectives of this phase of research were to further validate and to improve the accuracy of the methodology, thus, several improvements were made to the calculation of the EIM, described in the following sections.

NORMALISATION OF EIM VALUES BASED ON THE MEASUREMENT FREQUENCY

During the first phase of this research it was shown that higher measurement frequencies resulted in calculation of higher EIM values, since EIM values are a function of track geometry, which can change rapidly but is measured infrequently. Since the relationship between measurement frequency and the resulting EIM value was observed, it follows that normalisation to correct for the disparity in the measurement frequency should be a consideration.

A simulation was therefore completed in Phase 2 to establish the relationship between measurement frequency and calculated EIM value. This simulation used five years of data from 340 10-yard embankment segments from different parts of the network. Commencing with the original 10 records per year, the simulation performed a systematic removal of an increasing quantity of geometry records, followed by a recalculation of the EIM value.

The resulting calculated EIM values were plotted against the simulated recording frequency. This showed a very strong linear relationship for segments with lower EIM values, with the relationship becoming less linear and weaker with higher EIM values.

The consistency of this relationship allowed for a normalisation correction factor to be calculated and applied to the EIM values, depending on the frequency of available data for the track segment and year for which it is calculated.

Track Rotation Metric (SD, mm)																						
2010																						
2011	0.3		0.3	-0.8	-1.3	-0.9	-0.7	-0.9	-1.5	0.5	-0.1	-0.1	-0.2	1.8	0.0	0.9	0.2	-0.8	0.4	-0.1	-1.6	
2012																						
2013	0.3	-0.6	0.2	-0.5	-0.5	-0.7	-0.2	-0.7	-0.5	-0.1	-0.7	-0.2	-0.5	0.1	0.3	0.3	0.3	-0.4	0.3	0.4	-0.8	-0.4
2014	0.7	0.8	0.6	0.4	0.4	0.3	0.1	0.7	0.6	0.0	-0.2	-0.3	-0.2	0.2	0.8	0.8	0.3	-0.1	0.5	0.4	0.6	0.3
2015	0.7	0.7	0.5	0.3	1.3	1.0	0.9	1.4	1.2	0.5	-0.1	0.0	-0.2	0.4	0.7	0.8	0.0	0.1	0.7	0.6	0.9	0.9
2016	0.2	0.1	0.9	0.4	1.4	1.6	1.1	0.3	0.0	0.3	-0.2	0.7	0.5	0.8	0.3	0.3	0.6	-0.2	0.3	0.6	0.2	0.4
2017	0.4	0.7	0.9	0.7	2.5	3.5	1.9	-0.4	0.3	0.3	-0.6	0.2	-0.1	0.3	0.2	0.5	0.2	-0.7	0.8	1.0	-0.6	0.1
2018	1.8	3.0	4.4	1.1	2.5	6.7	6.4	-1.2	1.4	1.3	-1.0	1.6	2.7	2.9	1.5	3.0	-1.5	-3.9	4.2	3.8	-1.0	2.6
[Partial] 2019	0.5	2.2	1.8	-0.4	1.9	1.2	2.5	-0.7	-0.5	0.2	-0.4	-1.2	-0.7	1.4	0.1	0.4	0.7	0.1	1.4	1.5	-0.9	-1.2

Track Rotation Metric (SD, mm)																					
2010																					
2011	-0.8	-1.4	-0.2	0.9	1.1	1.3	0.7	0.2		-0.4	-0.2	0.0	-0.3		0.1	0.8	0.0	-0.3	-0.9	-0.2	-1.2
2012																					
2013	-0.3	-0.8	1.0	1.0	0.8	0.7	0.7	0.3	-0.4	-0.6	-0.4	-0.2	-0.7	0.5	0.1	0.5	0.3	-0.3	-0.3	0.3	-1.3
2014	0.4	-0.2	0.7	0.4	1.0	1.1	0.6	0.4	-0.5	-0.4	-0.3	-0.7	-0.7	-0.4	1.0	1.1	0.0	-0.1	-0.1	0.3	-0.3
2015	1.2		-0.6	0.5	0.8	0.7	0.3	0.3	-0.5	-0.5	-0.5	-0.4	-0.8	-0.5	1.3	0.9	0.4	0.3	0.0	0.5	-0.9
2016	0.4	-0.8	-0.6	0.4	1.4	0.8	0.5	0.6	-0.1	-0.6	-0.4	-0.2	-0.9	-1.2	0.2	0.3	0.9	0.4	-0.7	-0.2	-1.1
2017	0.9	-1.1	0.4	1.7	1.4	2.0	1.3	1.3	-1.4	-0.5	-0.6	-2.1	-1.2	0.1	-1.1	0.2	2.3	0.9	-0.8	-0.5	-1.2
2018	3.3	-2.3	0.2	4.7	3.1	1.7	1.3	0.7	-1.7	-0.9	-1.2	-1.1	0.0	1.1	-1.3	-1.3	0.7	-0.6	-1.8	-0.8	-2.0
[Partial] 2019	-0.2	-1.8	1.1	1.2	1.8	1.6	2.0	2.3	-1.3	-1.1	-1.6	0.2	-0.1	2.0	0.7	0.4	0.2	0.3	-0.5	-1.1	-0.2

Figure 4: Extract of track rotation metric data.

In order to minimise the amount of adjustment of the EIM values from their original calculated results, the normalisation was carried out to the equivalent of six records per year. This frequency was selected as this is the average number of track geometry records which meet the criteria for calculation of an EIM value.

TEMPORAL AND SPATIAL AGGREGATION OF EIM VALUES

Aggregation is necessary to reduce the quantity of data for user consideration to a manageable level, and aggregation of all the annual EIM values to a single 10-yard segment EIM value is the first step in this process. In order to provide a single result for each segment, the maximum calculated EIM over the analysed period or following any significant earthwork intervention has been proposed, with a weighting to reduce the influence of older data.

Using the maximum EIM value maintains the variance of the dataset and the preservation of the metric units. This approach also places significance on the calculated EIM during a particular year, regardless of the observed instability during other years. An additional reason for use of the maximum EIM method, is due to the difficulty in accurately measuring the deterioration rate and the tendency to underestimate the true rate of geometry deterioration, as discussed in the previous section.

In conjunction with using the maximum EIM value a historic data weighting is also proposed to compensate for the relative importance of more recent instability. This method weights calculated EIM values from the past three years with a factor of 1.0, with this factor dropping by 0.1 for each year. Further research related to historic data weighting is required and should be carried out as part of any future phases of this research.

One drawback however, of using a single maximum weighted EIM value, is the extent to which erroneous data can influence these Segment EIM results. This is partly addressed through spatial aggregation, which is now discussed.

For Phase 2 of this research 26,889 EIM values, split across 5,591 track segments and covering 595 embankment assets were calculated. For an earthworks engineer, using a tool to assess the performance of their embankment portfolio, this may seem overwhelming. Thus, spatial aggregation of multiple track segments is necessary to allow a rapid first-pass filter, removing the need for the engineer to review every 10-yard segment of data. There were two main objectives in performing spatial aggregation. Firstly, to accentuate spatially clustered high EIM values and reduce the effect of isolated high EIM values, since it has been recognised that isolated values are more likely to be erroneous track geometry data or resulting from misaligned data.

Figure 5: Drone footage of failure site from 2019/20.

The second objective is to support grouping of segments into larger sections of track which can be reported for further action.

After consideration, a method using a 50-yard rolling average was deployed to smooth and group the segment EIM results, with the chosen base-length seen as a good approximation for an average length of track which might be affected by an earthwork related instability.

IDENTIFICATION OF SEASONAL SHRINK-SWELL BEHAVIOUR

A fundamental assumption for trending of track geometry data is that the geometry does not typically improve substantially without maintenance intervention. However, the initial phase of this research identified examples of seasonal cycles showing large but gradual improvements in track geometry, followed by gradual deterioration.

After consideration, this seasonal cycle was attributed to the shrink-swell behaviour of expansive soils in the embankment core material, since the gradual nature of improvements contrasted to the rapid improvement in geometry typically seen with maintenance events. An example of the related worsening and gradual improvement in track geometry is shown in figure 3.

This effect can be clearly seen in figure 3, between 2016 and 2019, most notable in the dTop, Alignment and Worst Top parameters.

Since the deterioration in dTop and Alignment parameters associated with shrink-swell behaviour can appear like the development of a rotational failure, it was recognised that it is important to distinguish this effect, programmatically if possible. Therefore, an algorithm capable of identifying segments of track which exhibit this seasonal shrink-swell behaviour was developed and has been used to analyse all track segments within this phase of study.

The shrink-swell algorithm analyses elements of the dataset, including the length of time between, and the month during which peaks and troughs in the data appear, as well as how gradually the geometry improves and the relative size of the peak-trough amplitude. These factors are required to be satisfied by two out of three parameters analysed, for any three years, for a segment to be identified as exhibiting a seasonal shrink-swell behaviour.

It is acknowledged that this analysis still requires refinement, since the total identified segments is thought to be lower than the prevalence of the behaviour. However, it is recognised that seasonal shrink-swell behaviour will vary with differing climatic conditions and the presence of high-water demand trees.

IDENTIFYING THE MAGNITUDE AND DIRECTION OF ROTATIONAL INSTABILITY

Since the primary failure modes identified through this analysis of track geometry are shallow and deep rotational movements, it follows that analysing the magnitude and direction of rotation programmatically could assist with identifying potential failure modes for segments. The compound parameter referred to as differential Top is calculated, with a larger value of SD Top assumed to indicate downward settlement related to that rail. Therefore, a positive value of dTop implies the vertical alignment of the left (cess) rail is worse than the right (6ft) rail, more likely to indicate a shallow rotational movement (anti-clockwise looking in direction of travel). A negative value of dTop is therefore more indicative of a deep rotational movement. Figure 1 gives a visual representation of how the movement of the rails is indicative of the movement of the earthwork.

An algorithm was developed to calculate the magnitude and sign of the change in dTop on an annual basis, reporting a sum of the change in dTop in mm SD for each segment-year.

The resulting values are reported along with the EIM values to support interpretation of areas of identified instability by providing an annual measure of the direction and magnitude of measured rotational movement. The track rotation metrics are presented in a similar heatmap to the EIM values with (shallow slip) positive values shaded progressively darker orange and (deep seated) negative values shaded progressively darker magenta. Figure 4 shows an example of the track rotation metric heatmap, with values reported on a per 10-yard per deterioration year basis. Such data can aid, for example, identification of embankments where rotational failure can be seen to be propagating along the track, or where data shows shallow rotation leading to a deep-seated rotational movement, suggesting the slip plane is moving beyond the track centreline.

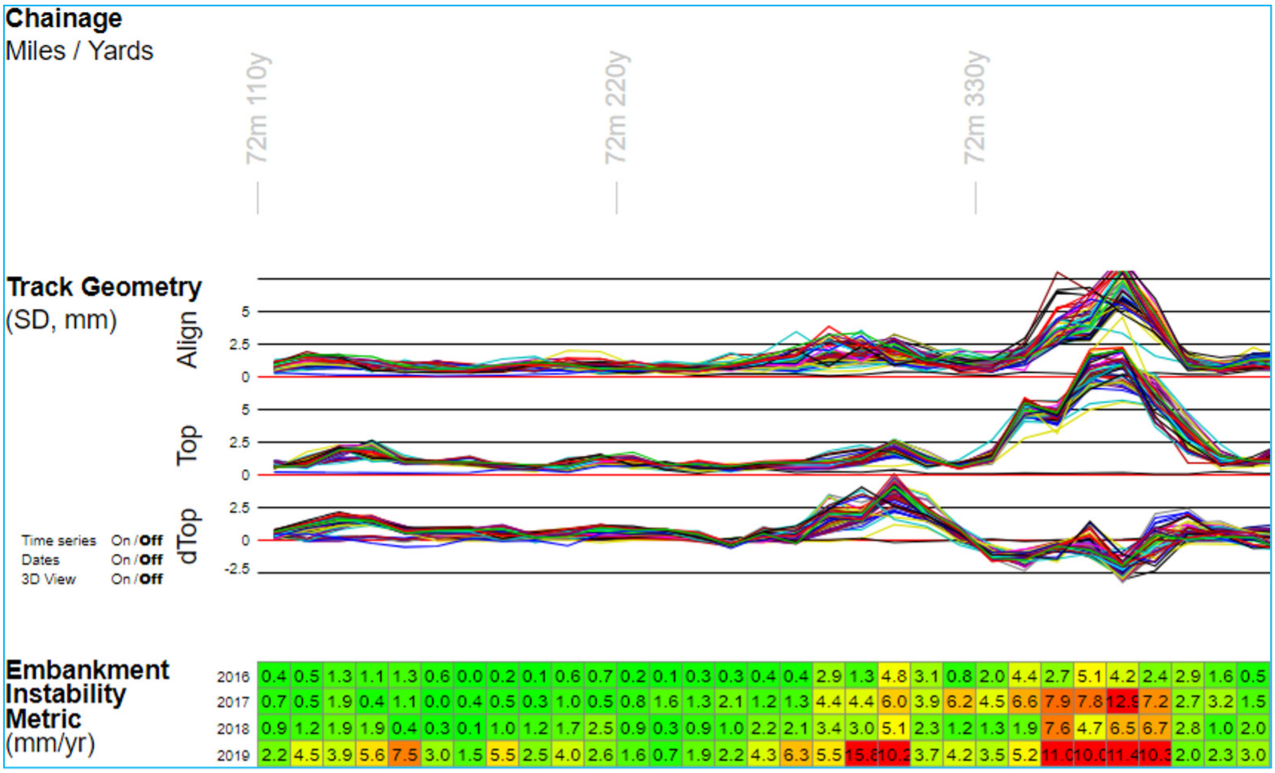

Figure 6: Longitudinal track geometry data plot with EIM heatmap superimposed.

Research around the track rotation metric is still in its infancy. Thus, the next step will be to validate this analysis with some selected sites known by the client, and additionally to program the algorithm to recognise these sites automatically from the data.

VALIDATION OF THE METHODOLOGY

Following recent improvements to the methodology listed above, the updated algorithm was used to calculate a total of 26,889 EIM values, split across 5,591 track segments and covering 595 Embankment Assets. The average EIM value in Phase 2 of this research was calculated as 1.24 mm/year.

In order to assess the validity of the calculated EIM values and segment level values, Network Rail provided the following sub-sample datasets for correlation: assets with a known desiccation issue, assets with visual signs of distress and assets with a known failure. Average EIM values for these embankment assets averaged 2.06mm/yr., 4.41mm/yr. and 4.41mm/yr. respectively, all significantly higher than the average EIM for all assets (1.24mm/yr.).

An additional dataset provided included the assumed embankment fill type, which originates from a study commissioned by Network Rail to provide an analysis of the fill material used during the original construction of embankments. This assumed fill type was available for 82.9% of the embankments analysed in Phase 2 of this study. Embankments consisting of high potential cohesive soil had an average EIM value of 1.31mm/yr., which was the highest out of all the different fill types. This was expected as embankments consisting of high potential cohesive soil are more susceptible to embankment instability issues than other fill types.

A full breakdown of results will be provided in further publications of this research.

FAILURE ANALYSIS

During the initial phase of research, 35 failure sites were analysed to provide understanding of the accuracy of this methodology and insight into the feasibility of using this technique for early failure identification. An additional four failure sites (from winter-2019/20) were considered during the most recent phase of the study and figure 5 shows drone footage from one of these failure sites.

The failure analysis carried out in the most recent phase of this work successfully highlighted embankment instability issues in three of the four failure sites analysed, where the reported failure locations coincided with the highest amounts of geometry deterioration in and around the area, data also showed instability throughout most of the years of available data.

Figure 6 displays the track geometry data along with an EIM heatmap covering the area of an embankment showing signs of instability. The data shows rapid deterioration of the differential Top, with negative values indicating deep rotational failure centred at 72m 375y with EIM values consistently above high risk threshold (4mm/yr.) between 72m 259y and 289y. The analysis demonstrates that there have been instability issues with this embankment for at least the last four years which this methodology would flag up for further investigation.

SUMMARY AND CONCLUSIONS

An initial study (Phase 1) developed the proof of concept technique and analysed approximately 1800 embankment assets identified for maintenance intervention between 2019 and 2024. Further analysis (Phase 2) has now been completed for a control group of 595 embankment assets in the Anglia Region, consisting of 26,889 EIM values being processed over 5,591 10-yard track segments. These EIM results have been successfully correlated with client provided datasets: sites with desiccation issues, failure sites, assumed embankment fill material and movement indicator data, confirming the validity of the methodology. This control group has also been compared with Anglia embankment assets planned for renewal and refurbishment, showing higher EIM values resulting from analysis of the track geometry for these embankments.

Further developments to the methodology have been completed during this recent phase of work, including: spatial and temporal aggregation of EIM values to aid reviewing of results, normalisation of EIM values to account for varying track geometry measurement frequency, automatic identification of shrink-swell behaviour and development of a metric to indicate the direction and magnitude of rotational movement.

Validation performed on the EIM value has clearly demonstrated that this method of analysis offers the potential to recognise instability of embankments using track geometry data, providing an invaluable quantitative tool to geotechnical engineers giving insight on the timing, rate and location of detected movement. Where rotational movement is taking place, the direction of rotation can be established and propagation along the embankment analysed.

The main remaining challenges in the deployment of this technique are:

- Ensuring sufficient track geometry data coverage and measurement frequency.
- Identifying and allowing for errors in track geometry data measurements.
- Refining the algorithms used in the processing of the longitudinal alignment of the track geometry data.

Future phases of this research plan to address these challenges, conducting further algorithm developments, such as using a variable minimum data measurement frequency and automated detection of track geometry data errors. Additionally, the AECOM team are working on fully automating the alignment of track geometry data to improve the consistency and accuracy of data alignment, allowing this technique to be more easily scaled up to a network level tool. Additionally, it is planned that this technique is trialled using data from in-service revenue vehicles (known as UGMS data by Network Rail) as this dataset offers far greater measurement frequency than the track geometry records. This dataset is however only being gathered for a small fraction of the network currently, and the measurement history is limited at present, however it is envisaged this will change and UGMS will become an increasingly useful dataset for future analysis of embankment stability.

REFERENCES

1. Networkrail.co.uk. 2018. Earthworks Technical Strategy June 2018. [online] Available at: https://www.networkrail.co.uk/wp-content/uploads/2018/07/Earthworks-Technical-Strategy.pdf

2. Power, C., Mian, J., Spink, T., Abbott, S. and Edwards, M., 2016. Development of an evidence-based geotechnical asset management policy for Network Rail, Great Britain. Procedia engineering, 143, pp.726-733.

3. Sharpe, P.; Hutchinson, D. Prediction of Earthwork Failures Using Track Recording Car Data. In Proceedings of the Railway Engineering Conference, Edinburgh, UK, 30 June–1 July 2015.

4. Kite, D., Siino, G. and Audley, M., 2020. Detecting Embankment Instability Using Measurable Track Geometry Data. Infrastructures, 5(3), p.29.

5. Nogy, L. Railway Earthworks Instability Diagnosis Using Track Geometry Measurement Data-CCQ and Top 35m; Permanent Way Institution: Warley, Brentwood, 2016.

TECHNICAL ARTICLE

AS PUBLISHED IN

The PWI Journal

July 2021

VOLUME 139 PART 3

#thepwi

W thepwi.org

PermanentWayInstitution

@PermWayInstit

Permanent Way Institution

@the_pwi

If you would like to reproduce this article, please contact:

Kerrie Illsley
CREATIVE MANAGER
Permanent Way Institution
kerrie.illsley@thepwi.org