Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 15.2
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.15.2

Detecting Geotechnical Instability of Railway Embankments Based on Track Measurement Data

W. Meng[1,2] and V. Zania[2]

[1]Technique & Execution, Banedanmark, Copenhagen, Denmark
Department of Environmental and Resource Engineering,
[2]Technical University of Denmark, Kongens Lyngby, Denmark

Abstract

Modern railway maintenance relies heavily on track geometry data to quantify structural health and ensure operational safety. Previous studies have indicated that track measurement data can be used to detect geotechnical instabilities in railway embankments and have suggested different metrics for this purpose. This study aims to evaluate the predictive capabilities of various metrics based on track measurement for three geotechnical failure cases in the Danish railway network. The selected cases are presenting different failure conditions, two slope failures and one time-dependent settlement. The metrics employed for the analysis are the running standard deviation and peak value for the longitudinal and the alignment, the differential standard deviation, and the embankment instability metric. The running standard deviation and amplitude are observed to increase prior to the development of the deeper slope failure. The settlement development can also be identified from the chronological plots. All the standard-stated metrics, however, remain below alert level limits as specified by code provisions. Our study highlights the potential to couple track measurement data with embankment instability, facilitating early detection of embankment failure and improving maintenance strategies.

Keywords: track geometry, railway embankments, geotechnical instability, running standard deviation, slope failure, infrastructure maintenance.

1 Introduction

The sustainability of the modern transportation network relies heavily on the structural integrity and functional longevity of railway infrastructure [1]. As the demand for high-speed rail and heavy-haul freight increases, the degradation of track components accelerates, posing significant challenges to lifecycle management [2]. Consequently, effective maintenance has evolved from a reactive necessity into a strategic pillar for ensuring long-term operational performance [3]. To quantify track health and ensure safe vehicle-track interaction, rigorous geometrical measurements are required. Parameters such as longitudinal level, alignment, gauge, and superelevation serve as the primary indicators of track quality [4]. To ensure interoperability and safety across international borders, these data are interpreted through standardised frameworks [5]. For instance, EN 13848 suggests limit values for track geometric parameters with respect to the wavelength and the track reference speed–alert limit (AL), intervention limit (IL), and immediate action limit (IAL)–to categorise the severity of track defects [6]. Banedanmark, the railway infrastructure manager of Denmark, follows similar principles for the definition of performance metrics [7].

While these standards provide the numerical thresholds for track quality, they do not offer a methodology to identify the factors contributing to the respective limit state. Ballast deterioration [8], rolling contact fatigue [9], fastener corrosion [9], and concrete sleeper fatigue cracking [10] are critical mechanisms contributing to track defects. Beyond the superstructure, the substructure significantly impacts track quality. The stability of railway embankments is instrumental to superstructure performance, as these dynamic geotechnical structures are subjected to cyclic loading, environmental weathering, and pore-pressure fluctuation [11]. Any loss of stability within the earthworks–whether through deep rotational base failure, or long-term creep–manifests directly as track geometry defects that eventually exceed safety limits [2]. Given that geotechnical instabilities can disrupt railway operations, integrating geotechnical monitoring with traditional track recording car data is essential for ensuring infrastructure serviceability. Limited number of studies have investigated the geotechnical instabilities in railway embankments and related them to track measurement data [12,13]. Specifically, an embankment instability metric (EIM) was proposed for Network Rail in the UK [14].

This study aims to investigate the predictive capabilities of railway embankment instability using advanced interpretation of track measurement data. Three unstable railway embankments were back-analysed utilising four metrics: RSD, peak value (Peak), differential running standard deviation (dRSD) and EIM, and the performance of these metrics was analysed. The findings refine the coupling of track geometry and geotechnical stability, identifying the potential of these metrics while highlighting the need for further investigation into rotational indicators and the influence of measurement frequency on detecting shallow failure mechanisms.

2 Methods

The three selected cases represent different geotechnical failure mechanisms in railway embankments. An overview of the geometry, the soil conditions, and the observed failure mode is shown in Figure 1. The sketch represents a simplified demonstration, condensing information from inspection forms and pictures, stability assessment reports and geotechnical site investigations. Cases A and B are characterised by relatively steep slopes (V:H ≈ 1:1.4) on the 10-m-high embankments, while the soil stratigraphy varies in the two cases. The difference in failure mechanisms is probably due to soil conditions and the performance of the old drainage system installed at the foot of the embankment. These two failures necessitated reconstruction with shallower slopes and a modernised drainage system. Case C develops settlements at the base of the embankment in two locations stretching over 100 m and 60 m, associated with the hydrogeological conditions, which are characterised by a high groundwater table and thick peat deposits. Originally deemed unsuitable for expansion in the 1960s, the site experienced acute settlement in 2004. Although part of the embankment was stabilised with sheet piles in 2007, the embankments continue to settle, requiring periodic track adjustments.

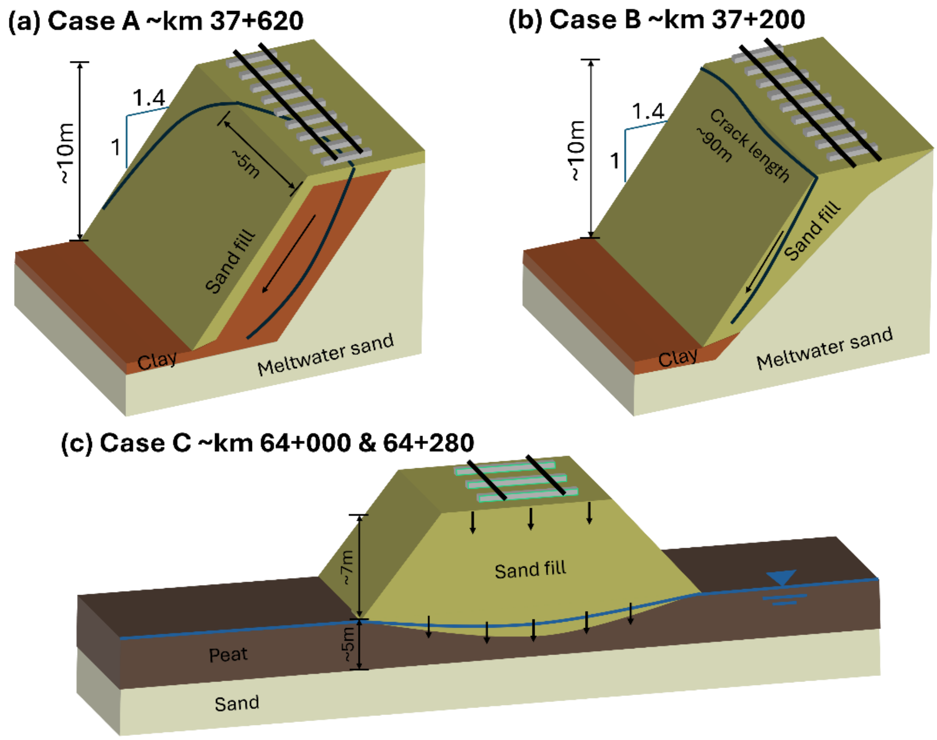

Figure 1: Sketches from the site survey on the instability cases.

Track measurement data is extracted from the International Railway Inspection and Services System (IRISYSS) [15], a maintenance management platform developed in compliance with the EN 13848 series [16]. While the database contains records dating back to 2006, the measurement frequency for the associated railway lines was once per year until 2009; since then, measurements have been conducted biannually in spring and autumn. To correlate track geometry with embankment performance, specific “critical mileages” were identified based on observed geotechnical instability. For Case A and Case B, km 37+200 and km 37+620 were selected, respectively. For Case C, km 64+000 and km 64+280 were selected as the same problem was observed on two embankments. Recognising that track irregularities can also stem from the deterioration of upper track components (such as the rail, fastener, sleeper or ballast) rather than the subgrade, a reference group was established that is deemed unaffected by geotechnical instabilities. Km 37+400 and km 37+750 are chosen for Cases A and B. Km 63+600 and km 63+800 are chosen for Case C. This comparative approach allows for the isolation of irregularities specifically caused by embankment instability.

For this study, the longitudinal level and alignment for wavelengths 20 m (D1) and 70 m (D2) are extracted along with the superelevation. The first metric is the maximum deviation value from the reference line and the filtered longitudinal level and alignment. Based on the operating speeds of two railway lines, the alert limit values for the peak value of the longitudinal level and alignment in D1 are 8 mm and 7 mm, respectively. For D2, the limit value is 12 mm for both wavelength ranges [7]. The second metric is called running standard deviation (RSD). RSD is an empirical method used in Banedanmark and has not been stated in EN 13848 [16] or BN 1-38-7 [7]. It is calculated for both longitudinal level and alignment using Equation (1),

$$\sigma_R = \sqrt{\frac{1}{k-1}\sum_{i=t-k/2+1}^{t+k/2}(x_i-\mu_t)^2} \tag{1}$$

where k is the window size, x_i is the value of data at the point i, μ_t is the moving average, and t is the target track position. The moving window in this study for D1 and D2 is 50 m and 150 m long, which are two times of upper boundaries of D1 and D2. Considering the data resolution of 0.25 m, k is set to 200 and 600 for D1 and D2, respectively.

The third metric is to indicate the track rotation as suggested by [12], which is derived based on RSD by Equation (2) and denoted as “dRSD”

$$\mathrm{dRSD} = \sigma_{R,L} - \sigma_{R,R} \tag{2}$$

where $\sigma_{R,L}$ and $\sigma_{R,R}$ represent the running standard deviations for the left and right rail, respectively.

The next metric is the EIM, following the definition in [14], which combines the deterioration rates of alignment standard deviation and the differential SD (dRSD) between the left and right rails, using wavelength less than 35 m and 18.3 m base length for the calculation. Since IRISSYS already stores the data filtered to D1 and D2, this paper uses data in D1 (~20 m) for the calculations. The same base length is used to calculate the deterioration rates of dRSD and the alignment standard deviation, and EIM is then calculated as the average of the two. The value for each year represents an EIM value for the last deterioration year, e.g., the value at 2025 represents the EIM from Apr. 2024 to Apr. 2025. The results are compared with the thresholds proposed in [14]: “negligible” (<1 mm/yr), “minor” (1~2 mm/yr), “moderate” (2~4 mm/yr), and “failure” (>4 mm/yr).

The last metric is the difference in standard deviation of the longitudinal level, referred to in Banedanmark as DeltaSigmaH. This metric is assessed based on the standard deviation of the longitudinal level over a base length of 200m over a period of three years. For a line speed of 120 km/h, the limit value is 0.31 mm/yr [17].

3 Results

The peak values for the longitudinal level in D1 and D2 are presented for Cases A and B in Table 1 and Case C in Table 2. For Case A, the peak deviation in longitudinal level in D1 is approximately 2.5 mm just after the failure, while for Case B, it is 1.2 mm. These values had remained relatively stable without significant fluctuation prior to the failure in Case A, while in Case B, they even display a slight decrease around the event. Regarding the peak deviation in longitudinal level in D2, an increase of about 5 mm is clearly noted after the failure for Case A, while the values remain unaffected in Case B. Both cases remain within the prescribed limit values for maintenance.

Time	Case A – km 37+620				Case B – km 37+200			
	Longitudinal level-D1 [mm]		Longitudinal level-D2 [mm]		Longitudinal level-D1 [mm]		Longitudinal level-D2 [mm]	
	L-rail	R-rail	L-rail	R-rail	L-rail	R-rail	L-rail	R-rail
2021-11	2.09	1.13	2.55	1.60	1.48	1.06	3.27	2.63
2022-04	2.36	1.11	2.56	1.62	1.74	1.00	3.26	2.78
2022-11	2.19	1.29	2.59	1.22	1.57	1.11	3.31	2.65
2023-05	2.36	1.24	2.41	1.62	1.72	1.20	3.20	3.11
2023-11	**2.44**	**1.24**	**2.52**	**1.82**	1.93	1.12	3.28	3.09
2024-05	**2.86**	**2.36**	**7.26**	**6.98**	2.18	1.29	3.28	3.38
2024-11	2.45	1.97	7.58	6.01	**1.61**	**1.44**	**3.16**	**3.19**
2025-03	2.90	1.97	6.32	5.77	**1.22**	**0.62**	**2.86**	**2.18**
AL-D1	8 mm		12 mm		8 mm		12 mm	

Table 1 Peak values of longitudinal level with alert limit values [7] for slope failures in Case A and Case B. Failure happened between the lines marked with bold.

The peak values in D1 and D2 for Case C, spanning from April 2018 to March 2025, are presented in Table 2. The annual progression of peak deviations varies by location and rail but shows a clear upward trend. At km 64+000, values for the right rail increased from 1.29 mm in 2018 to 2.93 mm by 2025. At km 64+280, the deviation rose more significantly from 1.21 mm to 3.08 mm over the same period. The peak value of the longitudinal level in D2 shows more pronounced degradation than in D1. At km 64+000, the peak value of the right rail increased from 3.40 mm to 5.12 mm. Similarly, at km 64+280, the right rail rose from 1.56 mm to 4.92 mm. The table shows that for D2 at km 64+280, the total increase is 3.36 mm over approximately 7 years, which is approximately 0.5 mm/year. All recorded values remain well below the alert limits.

Time	Case C - km 64+000				Case C - 64+280			
	Longitudinal level-D1 [mm]		Longitudinal level-D2 [mm]		Longitudinal level-D1 [mm]		Longitudinal level-D2 [mm]	
	L-rail	R-rail	L-rail	R-rail	L-rail	R-rail	L-rail	R-rail
2018-04	0.23	1.29	2.19	3.40	0.70	1.21	3.24	1.56
2019-04	0.12	2.42	2.89	3.98	1.02	1.05	1.84	2.15
2020-05	0.32	2.17	2.75	4.12	0.98	0.98	2.33	2.53
2021-06	0.20	2.44	3.25	4.00	1.09	1.29	2.72	2.96
2022-04	0.27	2.64	3.62	3.99	1.73	1.68	3.01	3.24
2023-05	0.28	2.77	3.79	4.16	1.39	1.98	3.44	3.45
2024-05	0.77	2.75	4.18	4.30	1.40	2.44	3.75	4.30
2025-03	0.19	2.93	4.48	5.12	1.46	3.08	4.46	4.92
AL-D1	8 mm		12 mm		8 mm		12 mm	

Table 2 Peak values of longitudinal level with alert limit values [7] for long-term settlement in Case C.

Figures 2 and 3 illustrate the running standard deviation (RSD) for Case A and Case B, derived from the longitudinal level and alignment in D1 and D2. RSD and dRSD are plotted chronologically with the reference group to establish the degradation trend leading up to the failure events. The reference group is also distinguished in the plots using hollow points and dashed lines. Important dates of maintenance and failures are marked in the plots. Following track and ballast renewal undertaken in 2012, track irregularities were initially mitigated.

As shown in Figure 2a, both Case A and Case B exhibit a general increasing trend of 0.1 mm/year in the longitudinal level compared to the reference group. Frequent variation is observed. Prior to the maintenance, it appears that all four locations follow the same trend in variation of the RSD, but with small variations in magnitude; the maximum offset is 1mm. The RSD for track alignment presented in Figure 2b shows no discernible trend, however, the measurements on Cases A and B are overlying the reference locations.

Regarding the chronological development of RSD in D2 it appears to be set to 0.5 mm for both longitudinal (Figure 3a) and alignment (Figure 3b) after the maintenance event. However, after 2018, a continuous development is observed for both measurements and all observation points. Although official documentation is not available, it is hypothesised that this may correlate with regional seismic activity. A significant escalation in RSD for the longitudinal level in D2 is observed in Case A (Figure 3a), with an increase of 2.8 mm between the measurements immediately preceding and following the failure event. In contrast, Case B exhibits no significant change in RSD around the event. Notably for Case A, RSD remained after the failure rather than recovering, even though embankment reconstruction was carried out right after the failure. Figure 3b indicates no significant development in alignment compared to the reference group. A substantial increase of 1.5 mm is specifically observed for Case B. Following the failure event, a reduction in RSD of alignment is noted for both cases, as well as at the reference point (km 37+750).

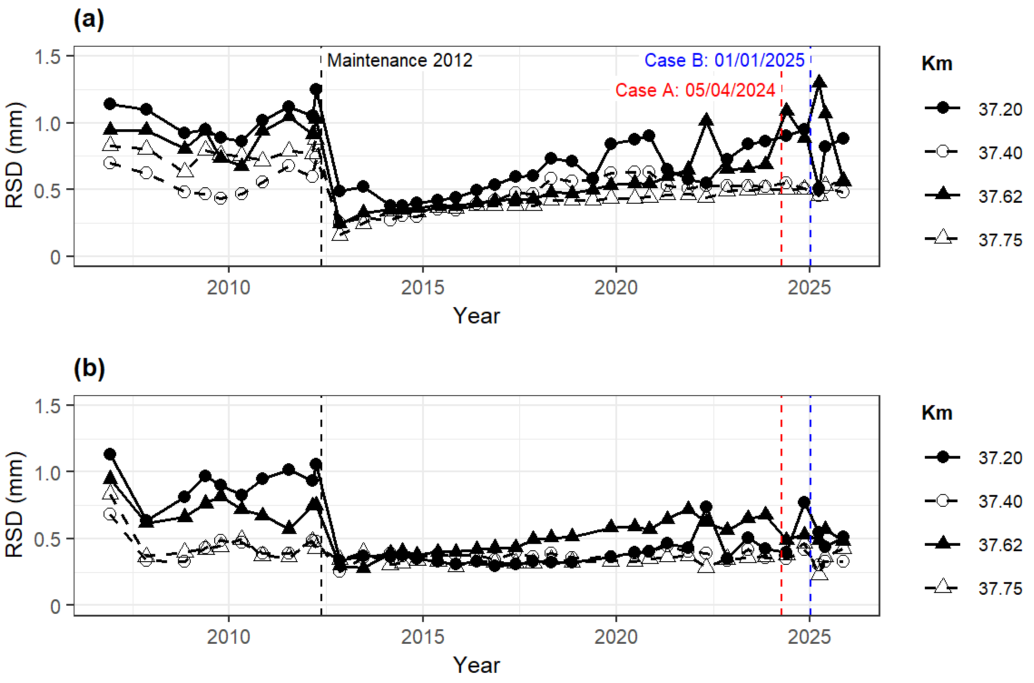

Figure 2 Running standard deviation (D1) for Case A (km 37+620) and B (km 37+200). (a) Longitudinal level at centre of track; (b) Alignment at centre of track.

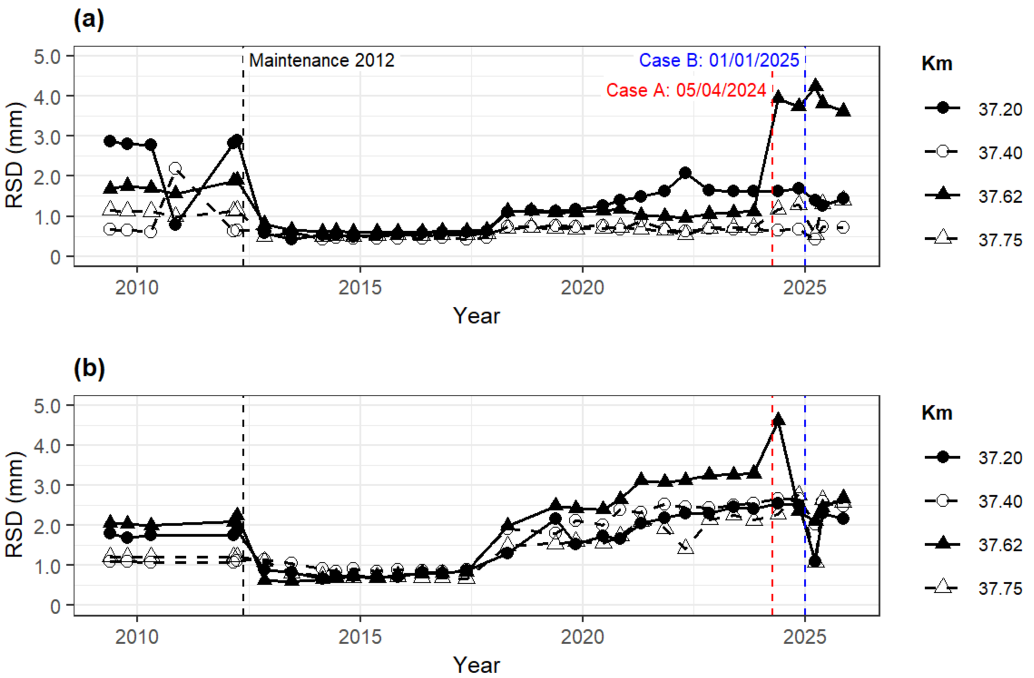

Figure 3 Running standard deviation (D2) for Case A (km 37+620) and B (km 37+200). (a) Longitudinal level at centre of track; (b) Alignment at centre of track.

Figures 4 and 5 present RSD in D1 and D2, respectively, for Case C in both locations. The results show progressive track geometry degradation, particularly following the 2018 interventions. Analysis of the longitudinal level reveals a consistent, approximately linear degradation over time. The RSD in D1 shows a steady increase with a growth rate of approximately 0.1 mm/year (Figure 4a). A more pronounced linear development is observed, with the RSD in D2 increasing at a rate of approximately 0.2 mm/year (Figure 5a).

The RSD of alignment in D1 suggests distinct periods of instability, specifically around 2022 and 2023 (Figure 4b). For D2, following the track adjustment in 2018, the RSD exhibits a further linear degradation. This trend is characterised by a rate of approximately 0.4 mm/year, indicating a higher sensitivity in the D2 wavelength range compared to D1.

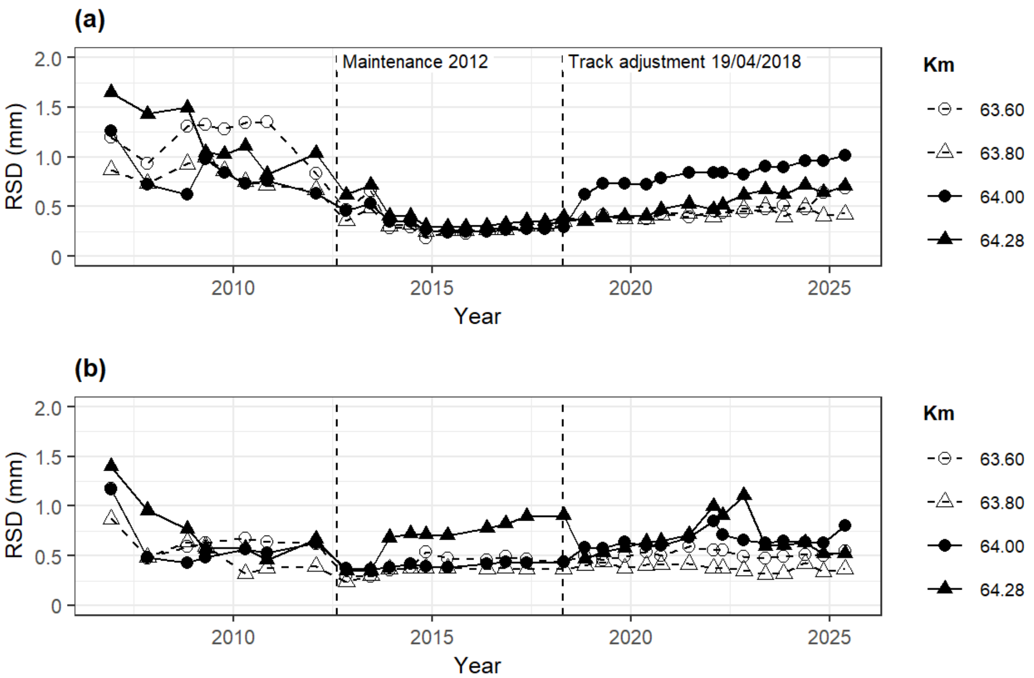

Figure 4 Running standard deviation (D1) for Case C. (a) Longitudinal level at centre of track; (b) Alignment at centre of track.

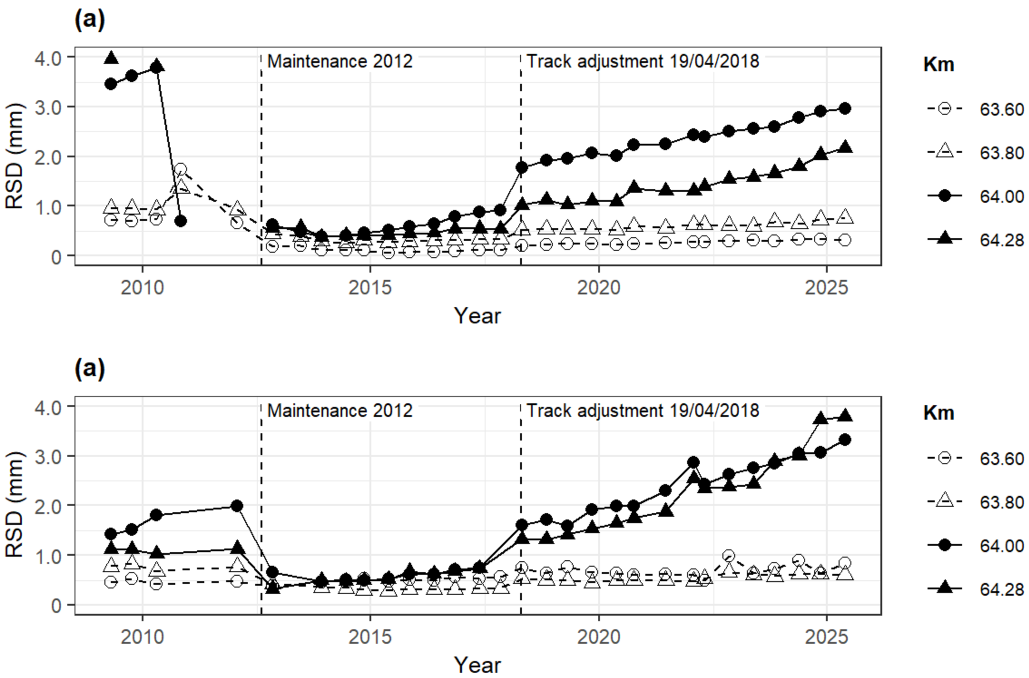

Figure 5 Running standard deviation (D2) for Case C. (a) Longitudinal level at centre of track; (b) Alignment at centre of track.

Figure 6 illustrates the differential running standard deviation (dRSD) across the selected track positions, providing insight into the relative degradation between the left and right rails. Following 2018, the dRSD for both Case A and Case B decreased at a rate of approximately 0.2 mm/year. This trend indicates that the RSD of the left rail became progressively lower relative to the right rail during this period. Immediately following the failure event, a divergence is noted: dRSD increased for Case A while decreasing to nominal values for Case B. These shifts are likely attributable to the localised repair of the embankment and track bed.

Aside from an erratic spike recorded in 2018, the dRSD for Case C exhibits a sustained increase at a rate of approximately 0.1mm/year. While superelevation was also analysed as part of this study, the data did not yield any discernible or statistically significant changes. The calculated embankment instability metric (EIM) for Case A (km 37+200), Case B (km 37+620), and Case C (km 64+000 and 64+280) is summarised in Figure 7. Across all recorded measurements between 2013 and 2025, EIM values remained consistently below the “negligible” threshold. Most sections exhibited very low activity until approximately 2020, after which a slight upward trend is observed. The peak EIM was recorded in Case B around 2022, reaching approximately 0.48mm/year.

The recent DeltaSigmaH is recorded at 0.02 mm/yr for Case A and approximately 0.08 mm/yr for Case B. Higher rates are observed at Case C, with values of approximately 0.13 mm/year at km 64+000 and 0.18 mm/year at km 64+280. All recorded values are smaller than the threshold level.

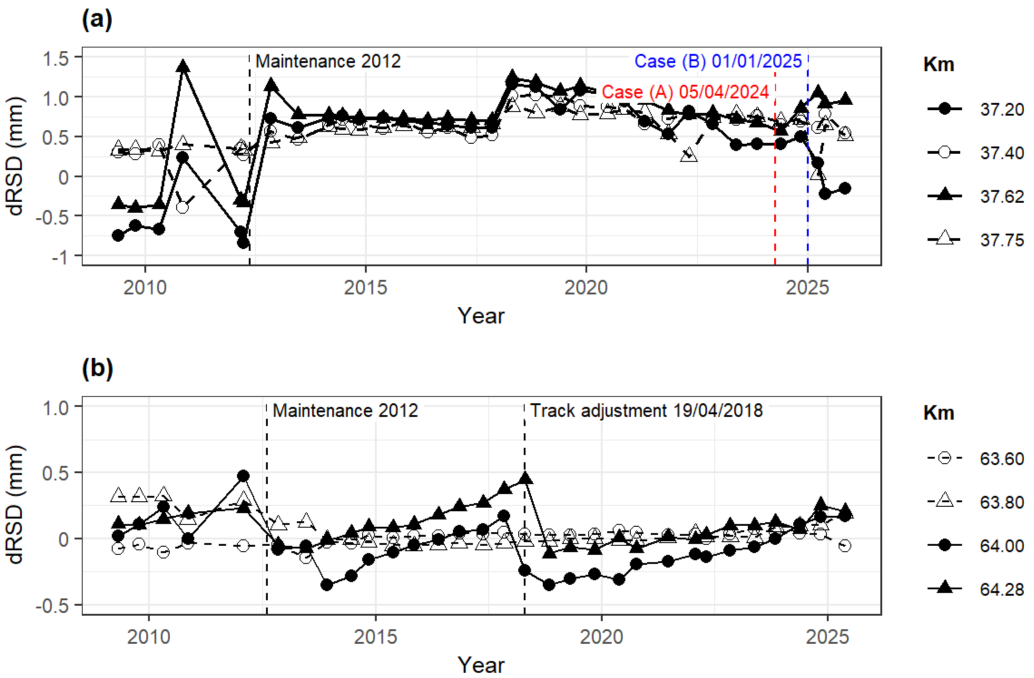

Figure 6 Differential running standard deviation (D2). (a) Case A and B; (b) Case C.

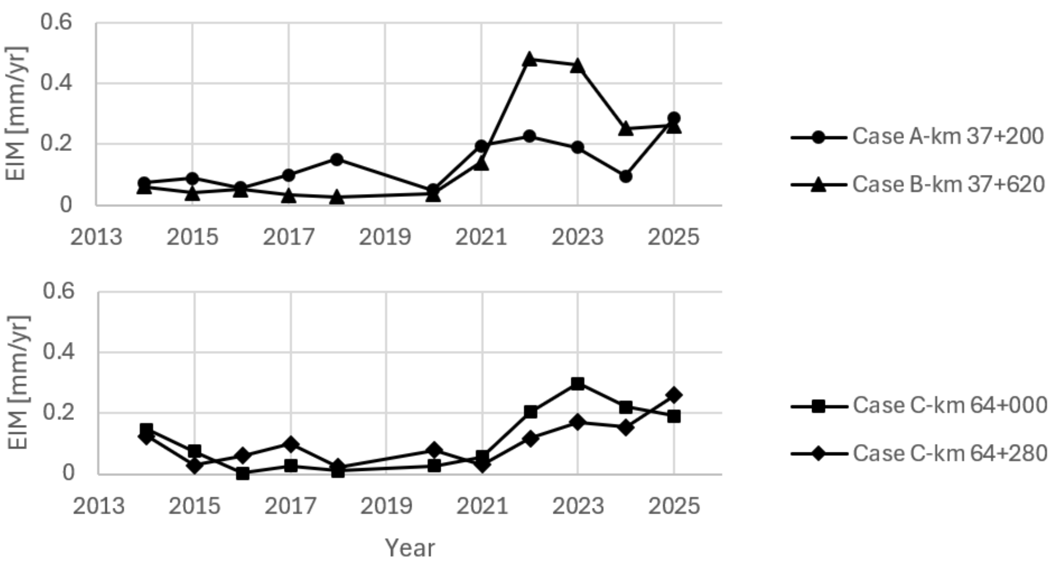

Figure 7 EIM values for the three cases.

4 Discussion

This paper presented preliminary results and evaluated the performance of relevant metrics by utilising track geometry data to analyse three specific geotechnical failure cases of railway embankments. For the slope failure characterised by a slip surface originating from the track centre (Case A), evident track geometry changes were observed. Conversely, for the shallow slope failure where the slip surface had not reached the track structure (Case B), only a minor trend in D1 wavelength was identified. However, whether this subtle trend in D1 is directly correlated with the progression of instability remains to be investigated. For the time-dependent settlement (Case C), the RSD, Peak, and dRSD metrics indicate a clear trajectory of track deformation.

The positive dRSD observed prior to the failure in Cases A and B implies that the left rail (slope side) exhibited a larger RSD than the right rail. While existing literature [13] suggests such changes may relate to deeper rotational embankment failures, both instances here were identified as shallow failures. Furthermore, it is unexpected that the superelevation does not indicate track rotation, suggesting that these rotational metrics require more rigorous investigation and discussion.

Regarding the long-term settlement at Case C, the trend is discernible but minor. A comparison of RSD in D1 and D2 reveals that D2 shows a more pronounced development for both longitudinal level and alignment. While the settlements at km 64+000 and km 64+280 are generally aligned, certain deviations remain. This may be attributed to the spatial variability of the subsoil and embankment conditions, a factor that requires further elaboration in future work.

An evaluation of EIM values against established thresholds [14] indicates “negligible” deterioration rate (<1 mm/yr) across the three cases. Given the scale and mechanisms of the instability, there appears to be a deficiency in utilising this metric to analyse these specific cases. This discrepancy likely stems from differences in superstructure stiffness and filtering methods between the Danish network and Network Rail in the UK [18], for which EIM was originally proposed.

A primary limitation of this study is the low measurement frequency: the track was measured only twice per year, hindering the detection of early warning signals for slope failures, such as those in Cases A and B. This frequency also obscures potential seasonal effects [13] on track deterioration. Further research will expand this study by incorporating additional cases from Banedanmark’s archives, covering various failure types. Given the significant variance in embankment and track stiffness, establishing a robust link between track geometry fluctuations and actual embankment performance remains a key objective.

5 Conclusions

This study evaluates the efficacy of Peak, RSD, dRSD, and EIM metrics in predicting geotechnical instability, using three case studies from Denmark as a basis for analysis. The preliminary findings demonstrate that RSD and Peak metrics can identify time-dependent instabilities. However, limitations were observed in the assessment of instantaneous and shallow failures, likely due to insufficient measurement frequency and varying sensitivity of these metrics to the scale and specific type of geotechnical failure. Furthermore, the inherent stiffness of the track superstructure may affect the reliability of these geometry-based indicators, as all standard-stated metrics were significantly below the corresponding alert limits.

Future research will focus on quantifying these influencing factors, with a specific emphasis on higher-frequency data acquisition and the development of a more robust framework for distinguishing between superficial and deep-seated embankment failures. This will facilitate a more proactive approach to infrastructure maintenance and the early detection of embankment instability.

Acknowledgements

The authors express their gratitude to colleagues within the Track Department and Geotechnics Department of Banedanmark for their invaluable technical guidance and support during the case study and data collection.

References

[1] C. Esveld, "Modern Railway Track", MRT-Productions, Zaltbommel, The Netherlands, Chapter 1, 1-15, 2001.

[2] B. Lichtberger, "Track Compendium", Eurorailpress, Hamburg, Germany, 2011.

[3] D.F. Cannon, K.-O. Edel, S.L. Grassie, K. Sawley, "Rail defects: an overview", in Youshi Hong, (Editor-in-Chief), Richard W. Neu, Takashi Nakamura, Thierry Palin-Luc and Andrea Spagnoli, (Editors), "Fatigue & Fracture of Engineering Materials & Structures", Blackwell Publishing Ltd, Oxford, Cannada, Volume 26, Issue 10, 865-886, 2003, Doi: 10.1046/j.1460-2695.2003.00693.x

[4] Danish Standards Association, "Railway applications – Track – Track geometry quality – Part 1: Characterization of track geometry", Copenhagen, Denmark, DS/EN 13848-1:2019, Section 6, 8-15, 2019.

[5] R. Lewis, U. Olofsson, "Wheel-rail interface handbook", CRC Press, Cambridge, United Kingdom, 2006.

[6] Danish Standards Association, "Railway applications – Track – Track geometry quality – Part 5: Geometric quality levels – Plain line, switches and crossings", Copenhagen, Denmark, DS/EN 13848-5:2017, 2017.

[7] Banedanmark, "Sporbeliggenhedskontrol og sporkvalitetsnormer", Copenhagen, Denmark, BN1-38-7, 2024.

[8] U. Ehrhart, D. Knabl, S. Marschnig, "Track Deterioration Model-State of the Art and Research Potentials", “Infrastructures”, MDPI, Basel, Switzerland, Volume 9, Issue 5, Article 86, 2024, Doi: 10.3390/infrastructures9050086

[9] Y. Zhao, Z. Liu, D. Yi, X. Yu, X. Sha, L. Li, H. Sun, Z. Zhan, & W. J. Li, " A Review on Rail Defect Detection Systems Based on Wireless Sensors", “Sensors”, MDPI, Basel, Switzerland, Volume 22, Issue 17, Article 6409, 2022, Doi: 10.3390/s22176409

[10] J.C. Bastos, J.R. Edwards, M.S. Dersch, B.O. Andrawes, " Laboratory analysis of track gauge restraining capacity of center-cracked railway concrete sleepers with various support conditions", “Engineering Failure Analysis”, Elsevier Ltd, England, Volume 94, 354-363, 2018, Doi: 10.1016/j.engfailanal.2018.08.018

[11] D. Li, E.T. Selig, “Resilient Modulus for Fine-Grained Subgrade Soil”, “Journal of Geotechnical Engineering”, American Society of Civil Engineers, New York, the United States, Volume 120, Issue 6, 939-957, 1994, Doi: 10.1061/(ASCE)0733-9410(1994)120:6(939)

[12] P. Sharpe, D. Hutchinson, "Prediction of Earthwork Failures Using Track Recording Car Data", Railway Engineering 2015, Edinburgh, United Kingdom, 2015.
[13] L. Nogy, "Railway Earthworks Instability Diagnosis Using Track Geometry Measurement Data – CCQ and Top 35m", Permanent Way Institution, Warley, Brentwood, United Kingdom, 2016.
[14] D. Kite, G. Siino, M. Audley, "Detecting Embankment Instability Using Measurable Track Geometry Data", "Infrastructures", MDPI, Basel, Switzerland, Volume 5, Issue 3, Article 29, 2020, Doi: 10.3390/infrastructures5030029
[15] Erdmann-Softwaregesellschaft mbH, "IRISSYS® User Manual: International Railway Inspection and Services System.", Görlitz, Germany, 2012.
[16] Danish Standards Association, "Railway applications – Track – Track geometry quality", Copenhagen, Denmark, DS/EN 13848, 2017-2025.
[17] Banedanmark, "Ballastlaget, vedligeholdelse og fornyelse", Copenhagen, Denmark, BN2-4-3, 2024.
[18] M. Wehbi, P. Musgrave, "Optimisation of track stiffness on the UK railways", "Permanent Way Institution Journal", Permanent Way Institution, UK, Volume 135, Part 3, Page 24-31, 2017.