The asset management of railways on soft soils

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Abstract. ProRail is the infrastructure manager of the Dutch railway network. ProRail manages approximately 3000 km of rail embankments, most of which were built before 1920. They were constructed at a time when there were no regulations or standards available and each train company had its own way of constructing railways. These embankments function perfectly every day under intense use, even the ones constructed on soft soils. After publication of the new Dutch standards for existing structures, it was unknown if the network would comply. As ProRail is obliged to keep the safety and availability of the network high, a better understanding of embankment stability is necessary, including the best way to monitor and more efficient improvement measures. This led to the start of Programme Rail Embankment in 2020. This programme consists of four parts which are carried out by different companies and institutions for the past 5 years: National Network Analyses of Embankments (NNAE); Research programme (RESET); Testing ground to gain more and better measures to improve the embankments; Implementation. Now that the first part of the programme is reaching the end, it is time to look back and share some of the (preliminary) results. The NNAE is finished completely and Deltares is starting the final year of the RESET programme, while TU Delft is halfway through the programme. The first pilots have been carried out, and different monitoring techniques were and are still being tested. This paper gives an overview of the Programme Rail Embankment and shares the experience of the programme and its most noteworthy tests.

1 Introduction

Between 1839 and 1935, around 25 different companies constructed an extensive railway network for trains and trams in the Netherlands. As there were no design regulations or standards at the time, each company developed its own construction methods based on location-specific experience. In 1938, these companies merged to form Nederlandse Spoorwegen (Dutch Railways), the predecessor of ProRail, the Dutch rail infrastructure manager. Many track structures in the Netherlands are between 90 and 185 years old. During that time, the superstructure (ballast, sleepers and rails) has been replaced three or four times on average, but the embankment or substructure itself remains unchanged. A lot has changed since the embankments were built. Trains have become heavier and faster and run more frequently.

ProRail now faces a new challenge. Years of use have demonstrated the safety and reliability of the tracks for current usage. However, to facilitate the expected growth in passenger and freight rail transport in the coming decades, the network will need to accommodate more, faster and potentially heavier trains. These changes, together with the expected impact of climate change, mean that an understanding of the technical condition of the Dutch railway infrastructure is required.

For new track structures, it is easy to obtain this insight as design regulations have been in place since 2006, so those comply with the applicable construction standards.

In addition, the site investigation data of the recent earth structures are often included in the BRO (a publicly accessible government portal for underground information, including soil investigation data [1]). However, little or no soil investigation data is available for older railroad structures, and to make the situation more complicated, the construction method is often unknown. Where soil investigation data is available, calculations with the current methodology often show that the railway embankments do not meet the requirements set out in the design regulations.

The Programme Rail Embankment was launched to gain more insight into railway embankments and enable long-term decision-making [2].

2 Programme rail embankment

All assets managed by ProRail must either demonstrably comply with the applicable standards or be demonstrably kept under control. Demonstrable compliance means that an asset meets the current safety requirements based on available data and calculations. If this cannot be shown, the asset — in this case, the railway embankment — must instead be under demonstrable control through monitoring and visual inspections. Monitoring is carried out at least twice a year using a measurement train. This used to take relative height measurements of the heads of the rails. These values are then checked for deviations in height, cant, track twist and track skew. Inspections are carried

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out on a regular basis. Regular inspections are planned, as well as those carried out directly when train drivers report anomalies to train control.

Currently, the track structure is safe for use based on regular visual inspections and monitoring by the measurement train. However, an assessment is required for each new situation, such as for example a change in train traffic or the construction of a noise barrier. To ensure the new situation is also safe, customised solutions may be needed for every new case.

First, better understanding of the condition of the embankments was required. To this end, the entire 3,000 km of railway embankments in the Netherlands has undergone a stability and critical train speed assessment in the National Network Analyses Embankments (NNAE) project. As it was suspected that the NNAE assessment method produced conservative results, further insight into its evaluation process is needed to develop a method that more accurately reflects reality. To this end, the RESET (Research Embankments for Safe Expansion of Traffic) research programme has been set up to conduct applied and scientific research to obtain an improved method to determine the embankment stability.

In addition to the theoretical aspect of the programme, it is important to find solutions that will strengthen the earth structure of the embankment. To this end, a testing ground has been set up where innovative ideas for the Dutch railway embankments can be submitted. This will enable ProRail to expand the number of applicable and affordable solutions.

Finally, the implementation strategy of the programme was considered . When changes are made, consideration is given to which measure is most appropriate in each situation. This may involve a physical measure to the railway embankment or, for example, a monitoring system.

The four components of the Programme Rail Embankment are explained in more detail below.

3 NNAE

The NNAE was set up to determine which sections of the 3,000 km railway embankment network in the Netherlands do not comply demonstrably to the standard. To this end, a stochastic subsoil schematisation (SSS) was first carried out, using publicly available data on Dutch geology, soil investigations, groundwater and elevation measurements. The SSS provides several (8 on average) possible scenarios for the soil structure of each 50–200 m railway embankment segment. For each case the probability of occurrence of the subsoil scenario is given.

A stability calculation was performed using the Bishop Method for each scenario (for both slopes of the embankment). All the stability calculations for each segment were then combined to determine whether the segment complies demonstrable to the standard. If all subsoil scenarios have a factor of safety greater or equal to 1,0 the segment is ‘demonstrably compliant’. Fig. 1, shows a section of the national map. In this figure, the demonstrably compliant segments are coloured in dark green. A segment is sufficiently compliant when the occurrence of a subsoil structure with a factor of safety greater than or equal to 1.0 is above 75%. These segments are shown in light green in Fig.1. The remaining railway embankment segments are in grey.

These grey areas, such as the track structures located along the river IJssel, represent areas that are not compliant but in control. However, if changes are made to the frequency, train speed or to the in these ‘grey’ areas, measures will be required to ensure they are demonstrably compliant in the future.

For a detailed description of the NNAE, please refer to the following paper: [3].

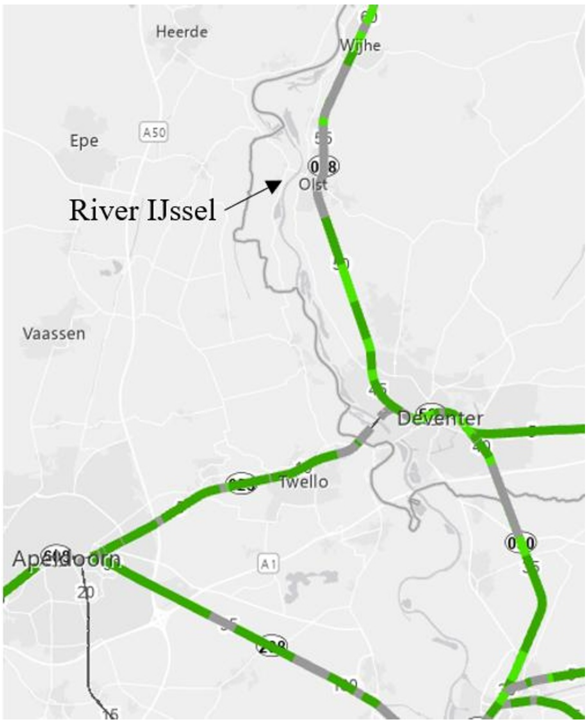

Fig. 1. Section of NNAE on the map.

4 RESET

The Research Programme RESET is assigned to TU Delft and Deltares. In 2020 they proposed a combined research proposal with the goal of increasing the knowledge on the behaviour of rail embankments. In Fig. 2 the framework of the research programme is visualised.

In this research program TU Delft, Deltares and ProRail try to increase knowledge to improve the current assessment as stated in the corporate guideline RLN00414-1-v001 Assessing existing embankments [4]. The basis of the current assessment is the NEN8707:2018 Assessment of an existing structure in case of reconstruction and disapproval – Geotechnical structures. This Dutch Code applies to all geotechnical structures. This means that all construction assessed using this code should be safe for use, when meeting the standard. As a train loaded geotechnical construction is a real specific situation, this guideline is seen as conservative.

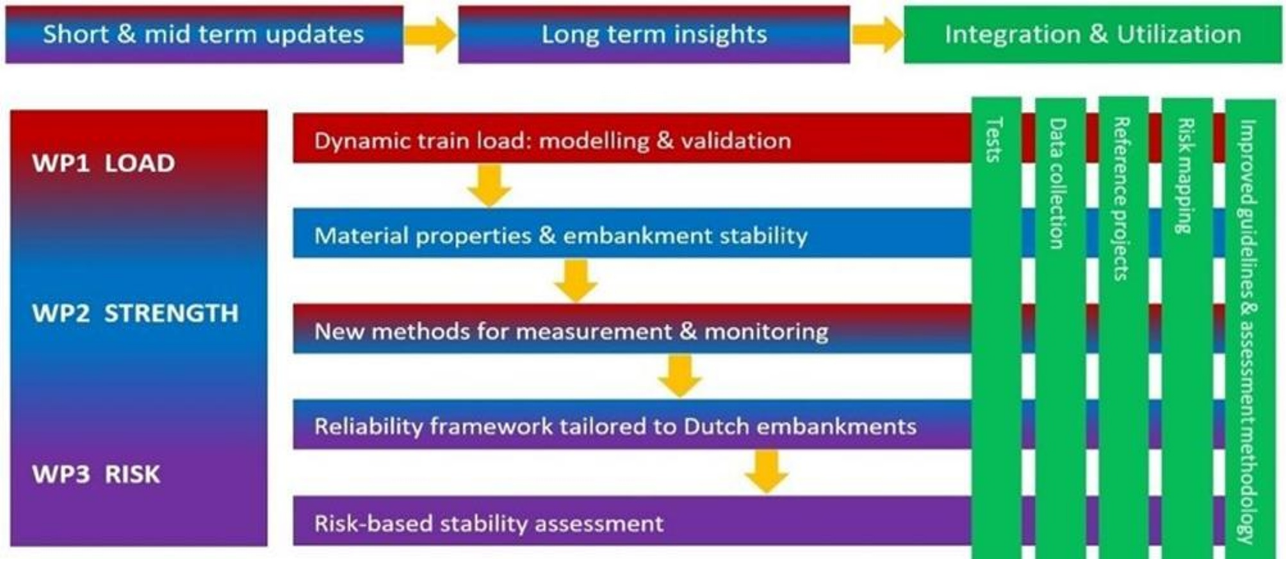

Fig 2. Framework of the research programme RESET.

Therefore, the framework of the research programme RESET is set up to get better understanding of the influence of the train on the embankment stability, within the three main themes:

- Load
- Strength
- Risk

4.1 Framework RESET

4.1.1 Load

One of the aspects is the load side of the assessment. For the last 20 years a monitoring system known as Quo Vadis is tracking the axle loads. Additional information is available from measurement train and inspection data. This means, that a lot of information is available. It is also clear that the current state of the embankments is sufficient for carrying these loads, even if the assessment tells otherwise.

However, the impact of the load from moving and stationary trains on the Dutch track structure and the influence of the superstructure need to be investigated further. One of the objectives is to improve our understanding of how train loads are distributed across the track structure, the embankment and the soft subsoil beneath it.

4.1.2 Strength

An in-depth analysis of soil properties is carried out. In the current testing method, soil layers are assigned a low characteristic value based on geology for use in the parameter set behind the NNAE.

Spatial heterogeneity was investigated in a test field (Sec. 4.2.1), using the classic approach of comparing local data and global data. The local-to-total variance ratio used was 0.75, based on engineering experience. To prove that this engineering value should be higher the test field data was used to determine higher strength parameters. Unfortunately, this could not be proven and so it did not lead to new insights.

On the other hand, an investigation into porewater pressures revealed some interesting insights. To assess excess pore pressure development under a moving train load on top of the embankment, the classical approach used in the regulations was that any increase in pressure should cause an equal increase in the pore water pressure, given the low hydraulic conductivity of the soft cohesive soils under the embankment. However, due to regular loading (passing trains) and geometrical influences the pore water pressures are lower than those based on this classical approach. The percentage to use in the regulations instead has not yet been determined, but we can state that pore pressures caused by a moving train are lower than the theoretical value imposed by the current regulations. Once a percentage of pore pressure has been determined following further research the results will be implemented in the cohesive soil layers identified within the NNAE to locate the weakest spots in the rail network.

4.1.3 Risk

Additionally, an investigation is carried out on whether the risk changes when the use changes, for example when a new type of rolling stock is deployed. The follow-up question is then how this changing use negatively affects the situation, and how ProRail, as the railway infrastructure manager, can mitigate it with additional measures.

The aim is to determine the risk distribution across all components of the embankment and soil structure. One approach is to redefine the partial factors that are specific to this situation. The aim is to enable simple calculations to be performed on many cross-sections directly (like is done in the NNAE). This eliminates the need for a probabilistic analysis of each cross-section. So only for special situations more advanced models will be used.

Although the current models seem to be very conservative in the assessment of the current situation, the models do provide insight into the different mechanisms that occur and their impact on calculated safety. So, both simple models and advanced models are used as input for the Risk Assessment according to ProRail Safety Governance.

4.2 Noteworthy tests

Various large- and small-scale tests and models were conducted to substantiate some of the hypotheses. To determine whether more local soil investigations would result into higher strength parameters a test field was introduced.

A heavy test train experiment was carried out to investigate the strength of the embankment. The assumption is that the embankment strength in the operational life is higher than that used in the assessment models.

Additional tests such as centrifuge tests and V-track have been and will be conducted to provide experimental insights and validate the stability assessments developed within the research programme RESET. As these four tests are the most noteworthy, they are presented briefly below.

4.2.1 Test field

The railway line between Delft and Schiedam was built around 1900. As the number of trains per hour needed to be significantly increased and this is an old railway embankment, an intense soil investigation was carried out. This section of track is equipped with three measuring locations, each characterised with CPT data. In each measuring location, an extensometer measures vertical deformations, and inclinometers measure horizontal deformations. Pore water pressures are measured at three depths below the track bed. All these measurements are continuous over time.

In addition, CPTs were carried out at 100-metre intervals along the track section between Delft and Schiedam. In addition to the CPTs, Ground Penetration Radar was performed on both tracks.
The amount of available site investigation data is one of the reasons why this section was chosen as a test section for the RESET.

Beside the investigation on the embankment, a test field (Fig. 3) has been set up next to this railway line. To gain a better understanding of the heterogeneity of the soft soil layers and to collect sufficient soil samples for element testing by TU Delft and Deltares, a total number of 45 CPTs, 22 boreholes and 8 seismic CPTs were carried out. A fibre optic cable was also installed for seismic purposes.

4.2.2 Test train

The most visible part of the ongoing research has been the loading of the embankment between Delft and Rotterdam in November 2025. A specially assembled train (Fig. 4) ran multiple times during normal executed timetable on a Friday. In a train free period on a Saturday, slow runs and standing still tests were performed (Fig. 5).

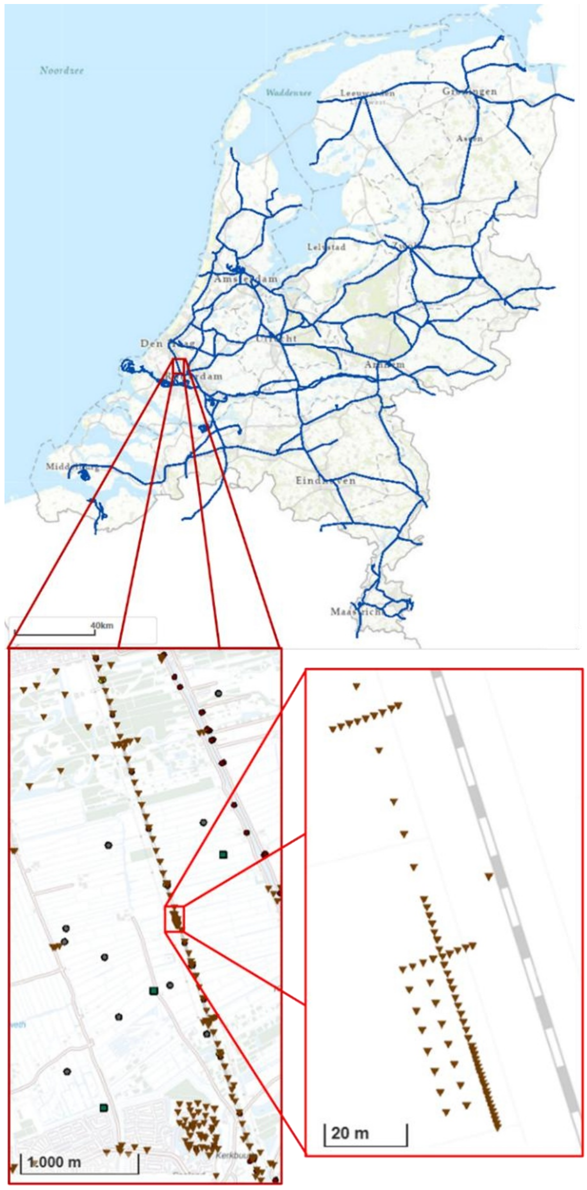

Fig. 3. Site location and location of CPTs in the test field along the Delft-Schiedam trajectory [5, 1].

To give the train sufficient weight and length, it consisted of 12 locomotives, only two of which were in service at the front and rear. Four carriages were also included between the locomotives, and measurements were taken by Delft University of Technology (Fig. 4 and Fig. 5).

Additionally, measurements were taken along the track at one of the three existing measurement locations. These were supplemented by geophone measurements, displacement measurements using a high-speed-camera, and pressure mats under the ballast.

The collected data will be used by TU Delft and Deltares to determine the response of the embankment under the different types of loading.

Fig. 4. Measurement train at test location. The yellow car is the CTO measurement car of TU Delft.

Fig. 5. Test train wheel at measurement location, camara on left hand side measuring speckle pattern on outer rail at test location Delft Schiedam.

4.2.3 Centrifuge tests

Deltares carried out eight centrifuge tests within the RESET programme to bridge the gap between laboratory (cyclic) tests, field tests and models development. In the tests a sand embankment was placed on top of a soft clay layer. Variations were made in loading rate, geometry and stiffness of the clay. [6] In Fig. 6 an example of the test result is given, showing the sand embankment on top of the clay foundation brought to failure.

Four additional centrifuge tests were carried out by University Gustave Eiffel within the Programme Rail Embankment, inside the EU transnational access GEOLAB, to investigate the influence of frequent train traffic and a reduction in follow-up time. The setup was similar to the previous one [7]. The advantage of centrifuge testing is that a railway embankment can be brought to failure in a scaled test under realistic stress conditions, which is not practically achievable at full scale in the field where trains have to run. To bridge this gap, cyclic tests were carried out at the geotechnical laboratory at the TU Delft.

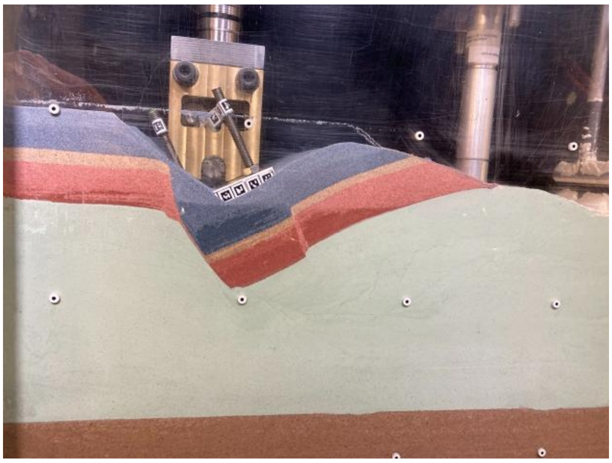

Fig. 6. The sand embankment on top of a clay foundation, was brought to failure in the centrifuge.

4.2.4 CYC-DoSS

The research includes testing of soil samples from the Delft Schiedam railway line with an innovative multidirectional compression-shear testing equipment developed in the geotechnical engineering laboratory at TU Delft. The apparatus is capable of independent multi-axial control and enable accurate force measurement at frequencies up to at least 15 Hz and validated on samples from the Leendert de Boerspolder [8]. The testing programme includes repeated loading cycles at different frequencies and amplitudes with intermediate consolidation periods, to replicate the increase in the number of train passages foreseen in the field. The main scope of the test is to better understand pore water pressure generation and dissipation under repeated train passage and enlighten the dependence of soil strength on cyclic pre-shearing.

4.2.5 V-Track

At TU Delft a scaled 5 m diameter circular track model is available, the V-Track, to study wheel–rail–track–soil interaction under controlled cyclic loading. This model has a concrete foundation. To get a better understanding of the influence the track has on a sand embankment and the soil beneath, the concrete foundation will be partly replaced by a foundation made out of sand and soft soil and instrumented with pore pressure sensors and accelerometers. This research is still in the design and testing phase.

Testing Ground

To identify weaker locations in the track bed resolve them when necessary, measures that increase stability and critical train speed are required. Currently, engineering firms quickly recommend a support berm or an underground sheet piling wall. However, support berms cannot always be constructed due to a lack of space, and sheet pile walls are extremely expensive due to the large amount of steel required. Furthermore, neither solution is able to mitigate the problems related to the critical train speed.

To investigate a wider range of possible solutions, a testing ground has been set up for market parties to register for. The testing ground was divided into two sections: the first for concepts not yet ready for field testing, and the second for existing solutions that had not yet been tested under the railway.

The search for new measures focused on cost-effectiveness versus the required duration of train-free periods on the track, as well as the extent to which the stability of the embankment would be increased. Ultimately, a wide range of possible solutions was proposed. After the first round, 12 were selected for further design development. The following four solutions were selected for testing 'on track' or in the laboratory in the second round:

- Gravel columns with sleeves under the track to reinforce the soft soil layers beneath the embankment. (Haskoning, Swietelsky and Boskalis)
- 'Geo-anchors', which involve nailing through the track bed (Witteveen + Bos)
- Mixed in Place: In-situ soil mixed with cement columns inside and outside the track bed (Civil 7)
- BISI (Bio Inspired Soil Improvement): bacteria that strengthen the soil (Groundwater Technology)

The first testing ground with BISI has now been completed [9]. The second testing ground, involving the gravel columns, is almost completed. The columns have been installed under the track/embankment (Fig. 7), which is currently being monitored [10]. The two remaining methods have not been implemented yet.

Fig. 7. Installation of gravel columns under embankment and track.

5 Implementation

All the results of the programme will be implemented in the Asset Management Plan of the Embankments. This will consist of three categories, namely the decision rules on increasing use of the system, the vision on how to keep the network available and safe under changing conditions including climate change and, lastly, an update of the corporate guidelines, which might be complemented by new ones on improving existing embankments.

The authors would like to express their sincere gratitude to the Ministry of Infrastructure and Water Management and ProRail for their financial support of the Programme Rail Embankment on railway embankment stability. Many thanks to our partners TU Delft, Deltares, Sweco, Arcadis, Witteveen+Bos, Haskoning, and Ricardo Rail. Without their contributions it would not be possible to carry out the Programme Rail Embankment.

References

1. TNO, BRO-loket, 2025 https://www.broloket.nl/ondergrondgegevens
2. A. van Uitert, S. van Eeten, D. Verbruggen, The Geotechnical state of the railway embankments in the

 https://doi.org/10.1051/e3sconf/202673005004

Netherlands / De Geotechnische staat van de spoorbaan in Nederland, ISSMGE Geotechniekdag2023-4 (2023)

3. A. van Uitert, E.P. Grünewald, E.L. Jorissen, K. Koster, E.P. van Onselen, A.A.M. Venmans, E.A.V. van der Putte, I.M. Hergarden, J.R. de Baat, J. Bonnes, I.E. van Berkom, Engineering geology and the asset management of 3000 km of track embankment, IAEG 2026 (submitted)
4. ProRail, RLN00414 (2016)
5. ProRail, Spoordata, RailMaps, 2026, https://www.spoordata.nl/informatieproducten/railmaps
6. C. Cengiz, C. Zwanenburg, T. Schweckendiek, A. van Uitert, Understanding Soft Soil Stability Challenges in Dutch Railways through Centrifuge Modelling, ICPMG 2026
7. B. van Dijk, W. Ovalle-Villamil, C. Cengiz, A. van Uitert, E. Vink, Geotechnical Centrifuge Modelling of Railway Embankments on Soft Clay Foundations, ICSMGE 2026 Proceedings paper (2026)
8. K. Chatzis , S. Muraro, C. Jommi, Numerical guidance to multi-direction cyclic testing of soft organic clay with the CYC-DoSS device for railway embankments, This Volume, (2026)
9. Y. Venis, E. Vlijm, A. van Uitert, E. Kavazanjian,L. van Paassen, C. van de Steenoven, P. de Groot, Improving Railway embankment stability through Bio Inspired Soil Improvement. In: ICBBG 2025 Proceedings Paper (2025)
10. P. Dijk, Grindkolommen voor stabieler spoor, De Ingenieur (2025)