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Numerical analyses for the design of helical pile trackbed stabilisation

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ABSTRACT: The presence of compressible soil beneath a rail track can cause recurrent defects and high maintenance costs. This paper describes the numerical analyses carried out for the design of the trackbed stabilisation of a rail embankment over peat through installation of small diameter helical steel piles. A combination of axisymmetric and 2D plane strain finite element analyses were carried out to assess the improvement to the trackbed stiffness offered by the proposed intervention. Trackbed deflection monitoring was also considered for the calibration of the numerical model.

Keywords: Helical piles; trackbed stabilisation; peat; numerical modelling

1 INTRODUCTION

This case history is based on a site in the UK named 'Muston Cottage' which is located on the Hull-Bridlington-Seamer rail line, approximately 3km west of Filey. At this location, the track runs on embankment up to 3m in height and crosses a 40m wide peat deposit. Recurrent track faults were recorded at the site, including top, twist and alignment faults, with deterioration typically 1 to 2mm/yr. Numerous interventions have been required to mitigate against these faults, including tamps and the introduction of temporary speed restrictions.

Figure 1. Site location plan

The proposed remedial option, comprising small diameter helical piles installed within the trackbed, was chosen due to the requirement to work during night-time possessions, without removal of the existing track.

2 BACKGROUD TO TRACKBED PILING

Helical piles have been in use since the 1830s (Clayton, 2005) and have seen recent wider use across the world due to the growing need for foundations with instantaneous load bearing capabilities, rapid installation methods and restricted access sites. This growth has been supported by modern design guidance, for example Clayton (2005), Perko (2009) and Ridgley (2015).

In the rail industry, helical piles are widely used for ancillary structures but trackbed stabilisation applications comprise of only a few recent case histories, therefore the design methods and long-term verification of performance may benefit from further research and documentation of case histories.

Previous case histories include Marlborough Road (Musgrave et al., 2015), Gravel Hole, Severn Tunnel and Brind (Musgrave et al., 2017), Ashton Moss (unpublished), Kintbury (unpublished) and Corracullin Bog (Hedderly, 2020). However, limited data is available about the performance of the piles installed for these case histories, particularly regarding their long term performance.

The proposed helical piles provide stiffening of the soil response to train loading through a mechanism made up of three elements, as shown in Figure 2:

- The track ballast transfers the load from the sleepers to the helical blade at the heads of the piles via soil arching developing between pile heads. Where temporary removal of trackbed is possible, load transfer could be improved further by the introduction of a geogrid or sand filled geocell layer.
- The pile head is loaded, and the stem transfers the load along the pile and through the soft soil deposits.
- The helical blade at the toe of the pile transfers the load to deeper more competent soil.

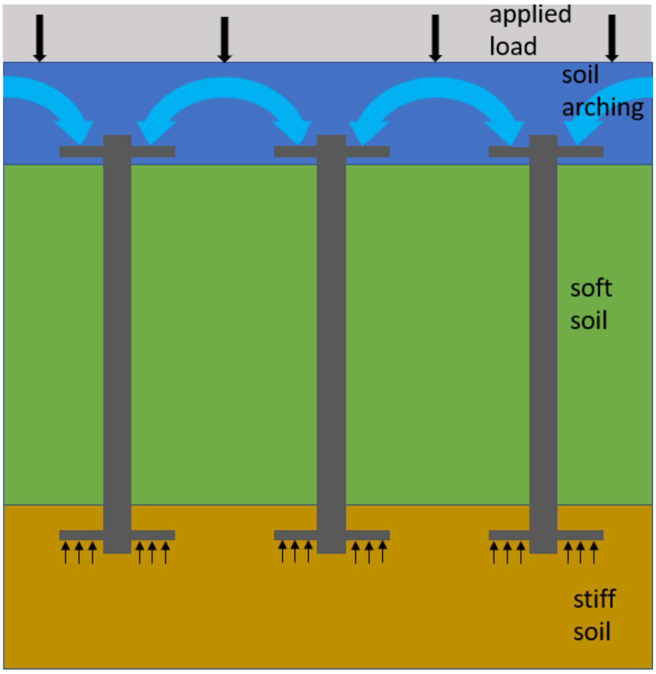

Figure 2. Helical piles kinematics mechanism

Due to the requirement to install the piles without removal of the trackbed, the helix diameter had to be small, approximately 300mm, so that it could be installed in between sleepers.

A significant limitation of micro piling through the trackbed without removal of the track is the lack of pile head restraint. This may be problematic where there are high lateral loads such as centrifugal force on bends, nosing load, actions arising from slope instability, soil squeezing, asymmetric loading or confinement of the piles. A Network Rail (NR) Engineering Advice Note on Helical piles 'CDE B&C EAN04' was published in July 2020 which reports on details of maintenance issues and included the need to add a raked pile to increase the lateral load resistance of a vertical helical pile which had deflected significantly.

3 SITE INVESTIGATIONS

A range of investigations were carried out to understand the origin of the track faults, inform the design process and to provide monitoring of ground and track movement before, during and after the works.

3.1 Desk Study

Historical maps show that a stream was culverted beneath the track in a NE-SW direction in 1885 and the deposit of peat encountered follows the line of the historical channel. Between 1888 and 1913 the water course was realigned to cross under the track in the short perpendicular direction at the west end of the alluvial channel. This provides an abrupt end to the peat deposit at the west end of the site with a gradual thinning of the peat towards the east. In 1983 a pond formed to the north of the railway embankment, indicating changes in the groundwater regime of the area. Defects to the culvert indicative of ground settlement were noted in 2006 and rapid deteriorations in track quality were recorded between 2011 and 2013. Minor repair works were carried out to the culvert and embankment between 2016 and 2019, but the track quality continued to deteriorate with severe Top Left and Twist faults for a 40 yard distance east of the culvert (Figure 3).

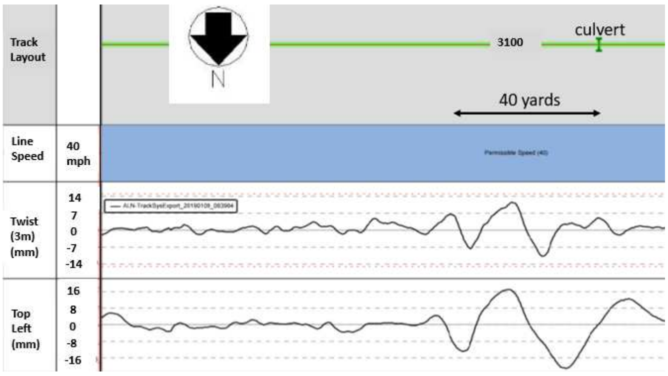

Figure 3. LADS track system export 29.01.2020

3.2 Ground Investigation & Instrumentation

Historical Ground Investigation was carried out in 2014. This was supplemented by a further Ground Investigation carried out in 2020 (see Figure 4).

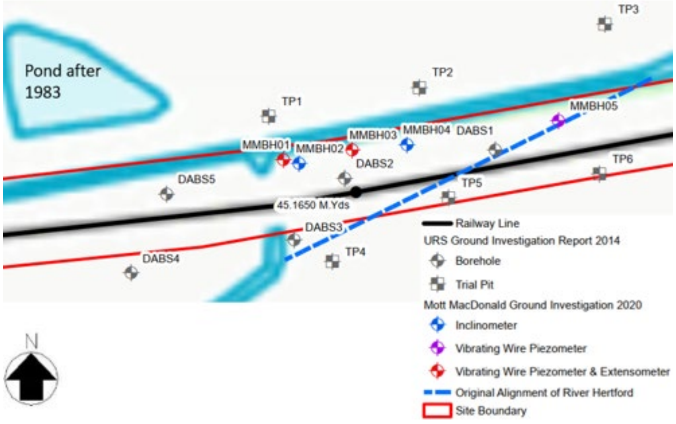

Figure 4. Geotechnical investigation plan

3.3 Design Ground Model

The ground model and main soil properties adopted for the analyses are summarised in Table 1.

Table 1. Design ground model

Layer	Top level [m AOD]	γ [kN/m³]	Φ [°]	E' [kPa]
Ballast	31.00	18	35	50,000
Made Ground	30.67	18	30	10,000
Peat	29.32	8	25	2,400
Glacio-lacustrine deposits	26.8-27.7	19	35	50,000

4 DESIGN CRITERIA

The main purpose of the works was to reduce the maintenance requirements of the section of rail line considered. No set design criteria were defined in advance of the works, however it was acknowledged that Musgrave et al. (2017) provides a rule of thumb that deflection for a good railway should be circa 2mm, depending on line speed and traffic type. In order to have a quantifiable way to measure the improvement resulting from the proposed works, it was decided that the effects of the proposed piles could be assessed through estimate and measurement of the magnitude of reduction of track settlement under a passing train achieved after pile installation.

5 NUMERICAL ANALYSES

There is limited published guidance for the design of trackbed stabilisation with helical piles. The guidance that does exist recommends finite element modelling is carried out (Musgrave et al., 2017). This guidance also offers a simplified specification approach based on the thickness of the underlying soft stratum, thickness of track formation, and a subgrade stiffness design chart. Further development of design methods and monitoring would be beneficial, given the limited case-histories and lack of historical data, to allow understanding of the long-term performance of the system.

The methodology described herein is intended to provide a practical design approach that can be employed by the practicing design engineer. It is based on the design of rigid inclusions, which is a more widespread geotechnical system and has a well-established analysis procedure (Thomas et al., 2017, Lődör&Móczár, 2018, Wong&Muttuvel, 2011 and Salhi et al., 2013). The finite element package Plaxis 2D is employed to carry out both axisymmetric and plane strain analyses using a linear elastic, perfectly plastic Mohr-Coulomb constitutive model.

5.1 Axisymmetric Analysis

Initially, a set of axisymmetric analyses were carried out. The scope of these analyses was to:

- Assess the behaviour of a single pile under characteristic (unfactored) vertical loading.
- Assess the effect of varying pile spacing on the pile performance and the soil arching effect achieved above the pile head.
- Assess the impact of varying pile length and blade geometry on the pile performance.

The piles, consisting of 114.3 x 10.0mm CHS steel shafts with 300mm diameter blades at the head and toe, were modelled as a single 10mm thick volume element representing the CHS shaft and horizontal blades, and assigned appropriate linear elastic material properties, as shown in Figure 5.

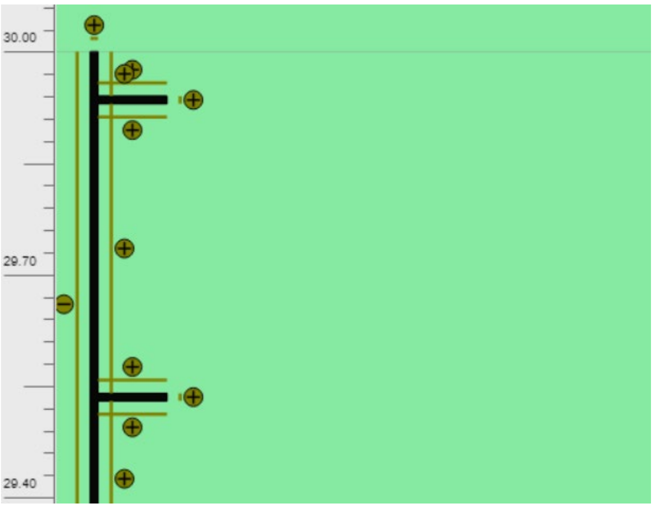

Figure 5. Detail of pile shaft and double helix pile head modelled in Plaxis as volume element with interfaces

The following phases were analysed:
i) Pre-existing conditions, prior to train loading;
ii) Train load applied as pseudo-static load without piles installed (to establish baseline deflections prior to the installation of the proposed piles);
iii) Pile installation with displacements reset and;
iv) Train load applied as pseudo-static load with piles.

In order to assess the optimal pile layout, three different pile spacings were tested in the axisymmetric model by varying the distance between centreline of the pile and vertical boundary of the model. The tested pile spacings were 2.150m, 1.075m and 0.717m to represent 2no, 3no, and 4no. piles respectively, installed laterally across a sleeper crib. Longitudinal spacing (along the rail) was designed to closely match the transverse spacing. Due to the great number of sensitivity checks required, mesh sizing was optimised for fast run of batch analyses without affecting accuracy of the results.

The directions of principal stresses above the pile heads were examined, see Figure 6.

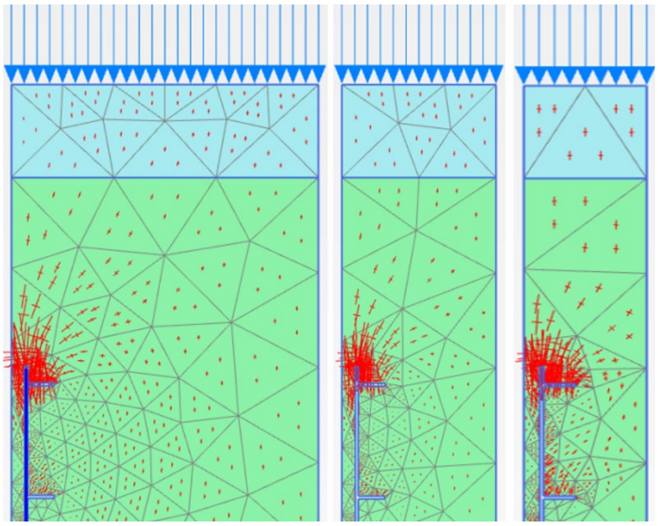

Figure 6. Directions of principal stress above pile head for piles at 2.150m (left), 1.075m (centre) and 0.717m (right) spacing

The direction of principal effective stress was considered as a visual indication of the degree of soil arching achieved between pile heads and therefore, the degree of load transferred to deeper layers offered by the piles.

Full soil arching was achieved at the lesser, 0.717m spacing whereas poor soil arching was achieved at the wider 2.150m spacing. The 1.075m spacing, equivalent to installing 3no. piles in alternate sleeper cribs, achieved partial soil arching and was deemed the best balance between support and cost and therefore was the proposed layout.

5.2 2D Plane Strain Analysis

Following axisymmetric analyses to define the optimum pile layout, 2D plane strain analyses were carried out to assess the overall performance of the proposed solution under combined horizontal and vertical loading. This would also assess the geometrical asymmetry of the problem due to different slope angles on the up and down line sides of the embankment and inclination of soil layer boundaries, as shown in Figure 7. A slight rake was introduced in the outside piles, to better resist some of the lateral forces generated by the nosing load.

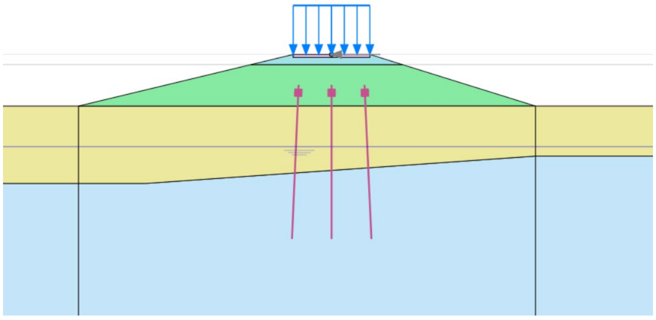

Figure 7. Plane strain model of the embankment and piles

Within the plane strain model, the piles were modelled as Embedded Beam Row (EBR) elements. Shaft and base resistances for the axial capacity of the piles were calculated using established methods (Clayton, 2005, Stanier et al., 2014 and Türedi&Örnek, 2020) and directly assigned to the EBR elements.

Again, a baseline phase was run without the pile elements activated, to allow the comparison between trackbed performance before and after the proposed piling works.

SLS loading was applied to assess the deflection reduction and ULS loading was considered to check the geotechnical and structural capacity of piles.

As expected, the plane strain analyses indicated that the small diameter, free-headed piles were very susceptible to lateral movements under load, limiting their performance in reducing vertical deflections at track level compared to the axisymmetric model results.

Figure 8 and Figure 9 show the deformed mesh and total displacement at track level and above pile heads when train vertical load only is applied.

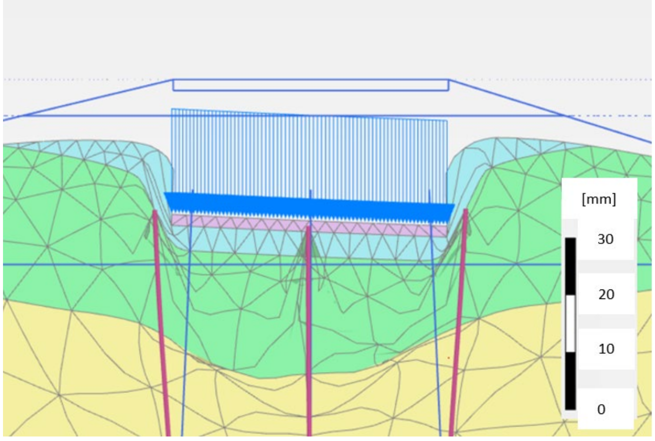

Figure 8. Deformed mesh beneath the track following application of train vertical load only

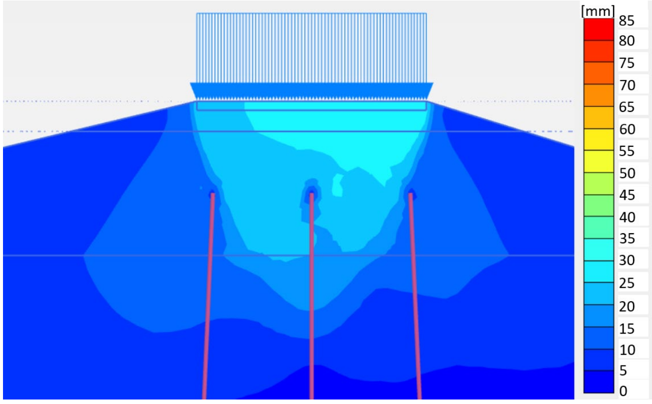

Figure 9. Total displacement following application of train vertical load only

Figure 10 and Figure 11 show the deformed mesh and total displacement at track level and above pile heads when horizontal nosing load is applied in combination with train vertical load. The vertical displacement generated is twice as much as noted with vertical load only and a lateral deflection almost equal to the vertical settlement is noted.

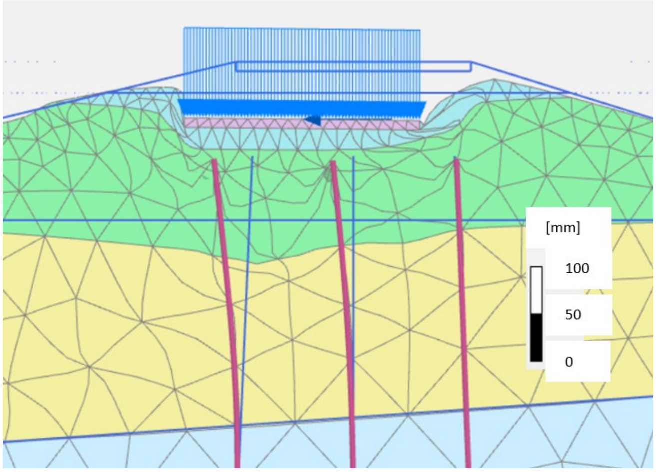

Figure 10. Deformed mesh following application of train vertical load and nosing load

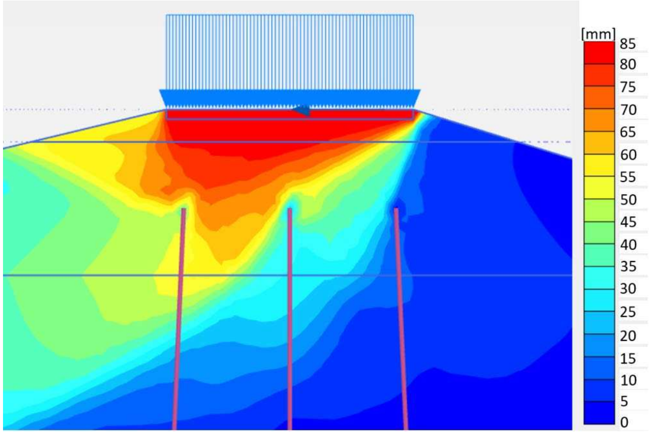

Figure 11. Total displacement following application of train vertical load and nosing load

This could be an issue for the long term performance of the system, since the repeated lateral loads could potentially result in a degradation of performance with time. The structural capacity of the piles must also account for the bending induced from this mechanism.

However, the nosing load is the biggest contributing factor to lateral loading of the piles and is defined in BS EN 199-2:2003 as a 100kN force spread over 2m length of rail, with no consideration of the train weight or speed or the geometry of the track alignment. Therefore, in this project, where the alignment has a small curvature and the line speed is low, the nosing load applied will be lower than what considered.

Sensitivity analyses were carried out to assess the effect of varying the pile embedment into competent soil. These analyses, with piles with two blades at the pile toe, show negligible benefit by having more embedment into competent ground (Table 2)

Table 2. Assessment of effect of pile length on system performance

Pile length	% Settlement reduction (vertical load only)	% Settlement reduction (vertical load + nosing)
6m	34%	23%
5m	34%	28%

Additional sensitivity analyses were carried out to assess the impact of having a single blade or two blades at the pile toe, with piles 5m long (Table 3).

Table 3. Assessment of effect of number of blades at pile toe on system performance

Number of blades at pile toe	% Settlement reduction (vertical load only)	% Settlement reduction (vertical load + nosing)
2 blades	34%	28%
1 blade	34%	26%

Increasing the number of blades at pile toe level provided negligible improvement in the performance of the system, hence one single blade was specified in the final design.

5.3 Calibration of the numerical model using track deflection survey

Prior to, and following trackbed stabilisation, surveys were carried out to measure the magnitude of vertical track deflection caused by running trains.

The method employed was based on published literature (Musgrave et al., 2015 and Vorster et al., 2010). A high resolution camera was positioned at a suitable perpendicular offset from the running rail such that passing trains would not affect the stability of the recorded image. Monitoring targets were fixed to the running rail along the study area and recorded as trains passed. Still images extracted from the video recordings could then be processed to obtain a measurement of vertical track deflection, as shown in Figure 12.

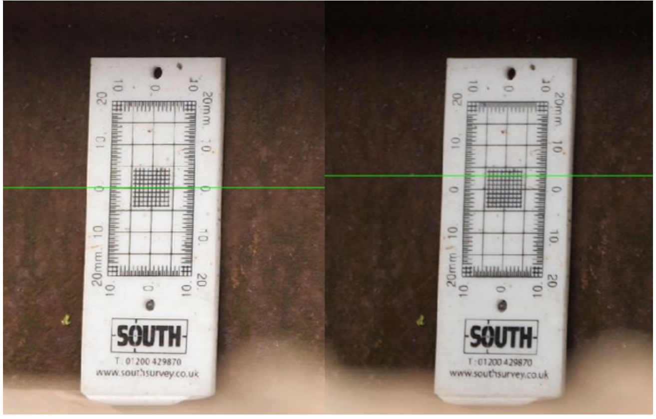

Figure 12. Example of a track deflection survey result – baseline reading (left) and maximum vertical movement of 3mm as a train axel passes over the study area (right)

Void meters affixed to the rails at the target locations confirmed that the recorded deflections represented a mass movement of the track formation and not movement of the track-only.

The train class was recorded for each pass so that the appropriate loads could be applied to calibrate models. Maximum deflections of 4.0mm were recorded for Class 170/4 passenger trainsets and 5.5mm for a freight train pulled by a Class 37/4 locomotive. The recorded images confirmed that deflections were elastic, with the rail level returning to baseline after each pass.

Due to time constraints, most of the design work was carried out in advance of performing the camera track deflection surveys. Following the survey, it was possible to calibrate the original 2D plane strain model to obtain baseline movements comparable to the monitoring results. The elastic moduli of the soil layers were modified to match the settlement recorded in the monitoring campaign. The analysis was then re-run to assess the performance of the system with calibrated properties.

It was found that following installation of the piles, the anticipated settlements of the trackbed, would have been reduced from 4.0mm to 2.6mm, hence a 35% settlement reduction, comparable to that estimated using uncalibrated parameters. These findings were comparable to case history experience at Brind and Gravel Hole (Musgrave et al, 2017).

6 PILES INSTALLATION

The piles were successfully installed during night time possession of the track within the agreed times.

The design required a working load of 30kN compression per pile which was to be verified as a ULS action of at least 72kN. 5 no. The results of CAPWAP pile tests ranged from a total pile resistance of 120 to 305kN. Installation torque for the test piles varied from 6 to 10kNm. An increase in torque readings was observed when each pile passed below the peat and a correlation between dynamic compressive ground resistance and torque and rotation rate was established to verify that the other 184no. piles would provide the required vertical capacity at lengths of 5.4m.

Track monitoring did highlight piling induced heave of the track at the eastern end of the works slightly beyond the permitted construction tolerance, associated with the baseline track design. The monitoring data indicates that soft soil displaced laterally whereas more competent soil at the eastern area heaved. Careful attention is recommended for transition zones beyond the edge of soft soils.

7 CONCLUSIONS

This paper presents the numerical analyses carried out to design a trackbed stabilisation intervention using small diameter helical piles. A relatively simple method consisting of a combination of axisymmetric and 2D plane strain analyses were used to assess the reduction of settlement under a passing train resulting from the installation of the piles and therefore define the most cost-effective pile layout, length and geometry.

Track deflection surveys were used to calibrate the soil parameters and therefore obtain realistic settlement values from the numerical analyses.

The analyses showed that bending induced by lateral pile deflection is a key consideration when designing micropiles in this context.

Future monitoring of the performance of the system will allow further validation of the proposed design method and assess the long-term performance of the proposed solution.

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