28th European Young Geotechnical Engineers Conference – EYGEC 2024

Transpennine Route Upgrade: Geotechnical engineering solutions to replace failed structures caused by peat and dissolution hazards

Jordan Sinnott CEng MICE FGS; Senior Engineer (Geotechnical); (jsinnott@systra.com)

SYSTRA Ltd., Birmingham, United Kingdom

ABSTRACT

For the Transpennine Route Upgrade East (TRUe), SYSTRA and the TRUe Alliance delivered three new flood balancing structures as a replacement to a failed culvert on the Normanton and Colton Junction Line. Geotechnical research into the cause of the culvert failure and geological investigations into this region of North Yorkshire, identified that dissolution of gypsiferous material and the presence of peat deposits had been causing the rail embankment (through which the culvert was constructed) to displace.

Geological evidence indicates that a near-vertical brecciated pipe has formed to the sub-surface, allowing groundwater to rise and saturate peat and alluvial material above. This has resulted in the softening of superficial soils, causing settlement under the embankment weight. This culmination of geological phenomena resulted in the existing culvert to break. New structures had to be installed whilst keeping the line operational, meaning that launch and reception pits were excavated on either side of a Victorian-era embankment to allow for micro-boring. These works were undertaken away from the key geological hazards in order to reduce short and long-term risks to the railway, workers and public. The geotechnical solution of infilling the existing culvert and replacing with three new structures was completed during possession to minimise disruption, resulting in a successful engineering feat that pulled together multiple teams and organisations. This paper will present the scheme, the site's geological occurrences, the engineering proposals and the collaboration involved to safely construct whilst keeping the line operational.

1. NOTATION

ALL	Alluvium: Silt and Clay overlying Gravel
AOD	Above Ordnance Datum
BGS	British Geological Survey
EA	Environment Agency
EPS	Expanded Polystyrene
DTM	Digital terrain model
HEM	Hemingbrough Glaciolacustrine Deposits (Vale of York Lake): Silt, Clay and Sand of Breighton Sands
MASW	Multichannel Analysis of Surface Waves
NOC	Normanton to Colton Junction Line
PPM	Parts per million
TBM	Tunnel Boring Machine
TRU	Transpennine Route Upgrade
TSZ	Track Support Zone

2. INTRODUCTION

The TRU project is the improvement of the railway between York and Manchester in the UK, via Leeds and Huddersfield. Between Leeds and York, this project is referred to as TRUe, and is delivered by the TRUe Alliance. Part of the railway improvement includes electrification of the route, more frequent trains and more reliable journey times. NOC/23 is the name given to a flood alleviation structure, present crossing the NOC Line, South of Ulleskelf, North Yorkshire. This is a brick twin-arch underline structure, estimated to be 179 years in age. The structure services the embankment situated within a floodplain monitored by the Environment Agency, and is located along the local project chainage at 15,190m chains.

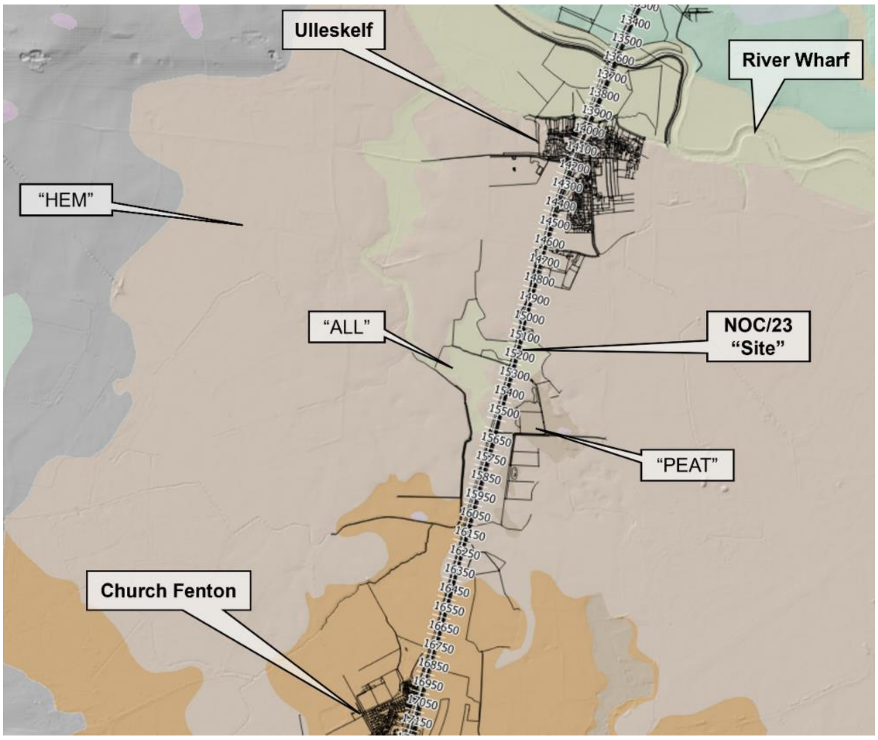

Figure 1: Site Location, with Superficial Geology (as mapped by the BGS 1:50,000 WMS Layer)

Structural examination identified that the base of the culvert barrel on the eastern inlet is at a level of 3.213mAOD, and that the western inlet level is at 4.90mAOD. There is approximately 1.1m of cover from the underside of the sleepers to the top of the culvert on the western (Leeds Lines) side, and 2.2m cover to the underside of the sleepers on the eastern (Normanton Lines) side. The structure no longer performs satisfactorily and is under constant remote monitoring. Significant fractures in the culvert barrel were surveyed and ballast top-up on the track above has been ongoing since the 1940s. This 1.7m difference in inlet level indicates that significant differential movement has occurred across the structure, resulting in its failure.

The scheme remit was to repair or replace the flood alleviation structure in a way to maintain the flood balancing status quo within the region. Several options were considered to repair and/or replace the failed structure, including:

- Option A - Installation of a singular culvert within the existing structure.
- Option B - Installation of two culverts within the existing structure.
- Option C - Installation of two culverts within the existing structure with an additional 1.5m diameter culvert outside of it.
- Option D - Infill the existing structure and install three 1.8m (internal) diameter culverts.

The selection of the most suitable option on the project was driven by the geological conditions present at the site, the requirement to provide minimum disruption to rail activity, and to provide cost efficiencies. The geotechnical input to this scheme was critical to establishing the most suitable option.

3. GROUND CONDITIONS

The existing NOC/23 flood alleviation structure is located within a region of North Yorkshire referred to as Ulleskelf Mires. These mires are an area of elevated flooding risk, with natural grassland and woodland flooding seasonally. The Mires can be identified from aerial imagery and are visible on Figure 1 aligning with the BGS mapped extent of Alluvium and Peat.

Alluvium is mapped underlying NOC/23, suggesting its presence immediately below the railway embankment. Alluvium, comprising clays, silts, sands and gravels, is an unconsolidated detrital material deposited by bodies of water (i.e., by rivers or on their floodplains). The Alluvium is reported to potentially contain layers of peats, tends to be soft and is prone to compressibility. Underlying Alluvium, and present from ground level in the area surrounding Ulleskelf Mires, is the Hemingbrough Glaciolacustrine Deposits. Of Devensian age, these are Vale of York soils deposited from part of the "Glacial Lake Humber" (Ford et al. 2008), appearing as a mainly grey and brown laminated clay with partings of silt and sand. Ground investigation undertaken in the wider North Yorkshire region estimates that this formation is up to 25m in thickness. A public report by the BGS for the Environment Agency (Burke et al. 2017) determines that the zone from Ulleskelf to Church Fenton has the lowest rockhead elevation levels within the region.

Underlying the superficial deposits, the BGS maps the Roxby Formation. The Roxby represents the top of the Zechstein sequence in North Yorkshire, deposited in the Upper Permian. The Zechstein sequence dip gently eastwards, with the Roxby Formation weathered across its top. The formation comprises a calcareous and gypsiferous mudstone, with two significant sequences of gypsum. Within the middle of the formation's sequence is the Sherburn Anhydrite/Gypsum (up to 8m in thickness) and at the base of the sequence is the Billingham Anhydrite/Gypsum (up to 4m in thickness). Based upon this preliminary review, two key geotechnical hazards were identified as potentially present and causing distress in NOC/23. These were the Peats within the Alluvium superficial soils, which have the potential to change volume considerably over time; and dissolution of gypsum within the deeper Roxby Formation resulting in vertical displacement within the subsurface.

3.1. Previous Research – North Yorkshire Gypsum

Gypsum (hydrated calcium sulphate) has the potential to dissolve resulting in the loss of volume in rock and in situ weathering of materials that it was originally held within. The dissolution of gypsum is dependent on the presence of groundwater and groundwater flow, with dissolved chemicals within the water having a bearing on the rate of dissolution.

Cooper (2019) reports that the Sherburn Gypsum varies in thickness based upon public and commercial borehole records, with the variation in thickness being attributed to dissolution. It is suspected that cavities in the ground as a result of the dissolution is caused by jointing in rock, resulting in water supplied from underlying aquifers accessing the deposits. Caves are reported to have formed in relatively thin gypsum bands in the North of England, such as at the Vale of Eden (Ryder and Cooper, 1993). The Billingham Gypsum is not as well covered by boreholes, with evidence available to identify variation in thickness of gypsum being more sparse.

As the key cause of underground dissolution is the passage of groundwater through deeper aquifers, an upward flow of water would be expected. This may be exhibited at the surface and observed as springs and boggy ground (i.e., Ullekself Mires). Historic BGS boreholes within the region demonstrate evidence of subartesian and artesian conditions, indicating a mechanism for the development of dissolution features.

A further line of evidence that indicated the likelihood of dissolution occurring at depth within the region of NOC/23 was the presence of an elevated sulphate content within groundwater in historical boreholes. It is considered likely that any sulphate saturation would have resulted from the dissolution of Gypsum and rising upwards with groundwater flow. Research into this, by Cooper (2019) reviewed available borehole records surrounding NOC/23, identifying the following:

- BGS borehole SE53NW3 (at Church Fenton) reports historical records from Prof Kendall's notebook, page 107, that encounters artesian water that is "… safe perhaps, but evidentally charged with sulphates".
- BGS borehole SE53NW2 (at Church Fenton) noted spring water within the vicinity. Analysis of the spring water identified an elevation in calcium sulphate (1570ppm).
- BGS borehole SE53NW7 (1km southwest of NOC/23) yielded artesian water.
- BGS borehole SE53NW82 in Ulleskelf drilled to 320ft (approximately 97.5m) identified gypsum and poor-quality water. The borehole notes that due to the quantity of chlorides, nitrates and total solids, that this water was unfit for domestic use.
- BGS borehole SE53NW1B yielded water within 3700ppm solids, of which 1845ppm were sulphate and calcium carbonate. This borehole also penetrated gypsum and anhydrite.
- BGS borehole SE53W92 (1km to the west of the Site) yielded artesian water, containing 1500mg/l of sulphate and 592mg/l of calcium.

Based upon the above, dissolution of the Sherburn Gypsum is considered to be widespread, however is likely concealed (Cooper 1986) as a result of infilling of cavities and pipes with superficial soils. It was therefore considered a critical risk to the NOC/23 site and a potential cause of the failure of the structure. Given that the existing structure is located within Ulleskelf Mires, a particularly boggy region, the upward rising of groundwater was considered likely to be occurring at the Site.

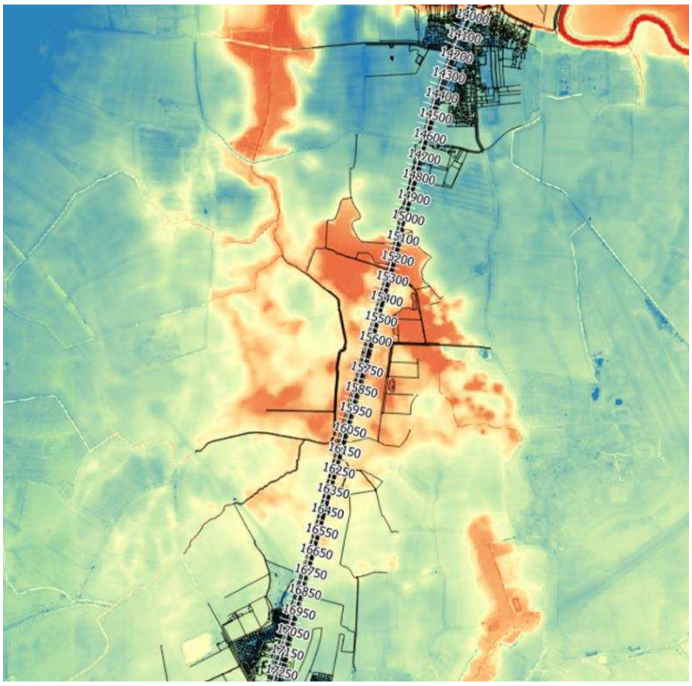

Figure 2: 1m LiDAR DTM dataset of Ulleskelf Mires, North Yorkshire (reproduced from the EA dataset, UK GOV)

The revised 1:10,000 Scale BGS map SE53NW, compiled by Cooper (2000) shows large areas of Alluvium and Peats (see Figure 1) that are likely gypsum subsidence features. The Department of the Environment gypsum subsidence study (Thompson et al. 1996) maps subsidence features from air photographs, illustrating sinkholes in the area north of Church Fenton. Based upon the Environment Agency Open-Source LiDAR datasets, mapping provided at Figure 2 shows the region of NOC/23 to be generally flat, however shows a depression, likely attributed to subsidence (orange), at NOC/23 and Ulleskelf Mires. Cooper (1986) identifies a similar pattern of hollows in subsidence surface patterns as a result of confirmed dissolution locations at Ripon. They are interpreted as amalgamated hollows, whereby subsidence occurs as a result of the first hollow collapsing the underlying cave, resulting in water flow to adjacent gypsum veins, allowing the subsidence area to grow.

3.2. Ground Investigation

A combination of multiple methods of ground investigation were undertaken within the vicinity of the Site, and along the majority of the Transpennine railway route as part of wider TRUe delivery works. Specific to NOC/23, ground investigation was undertaken on and off track by both intrusive and non-intrusive methods.

Seismic surveys were undertaken by P Wave and Shear Wave, and individually plotted (see Figures 3 and 4). The P Wave tomographic model indicates that from approximately chainage 15,160m, a gradually deepening zone of lower P Wave velocity, compared with the subsurface profile to the north (down chainage). A similar, but clearer trend is shown in Figure 4, whereby S Wave velocity is considerably lower in a conical shape around the location of NOC/23 (labelled as an underbridge on Figures 3 and 4).

The conical shape of the structure identified within both P Wave and S Wave plots align with the shape of an expected brecciated pipe that would occur as a result of dissolution of Gypsum within the Roxby Formation. These surveys supplemented research to provide evidence that the site is the location of a dissolution hazard. Based upon the above, gypsum is thought to have dissolved at depth, below -10mAOD, and has been infilled by overlying superficial stratum. This superficial stratum is thought likely to be softened further by subartesian water flow, responsible for the lower velocity of seismic waves. It would appear, based upon the seismic profiles that the northern boundary of the brecciated pipe is between 15,140m and 15,180m, with the southern boundary not established by the survey.

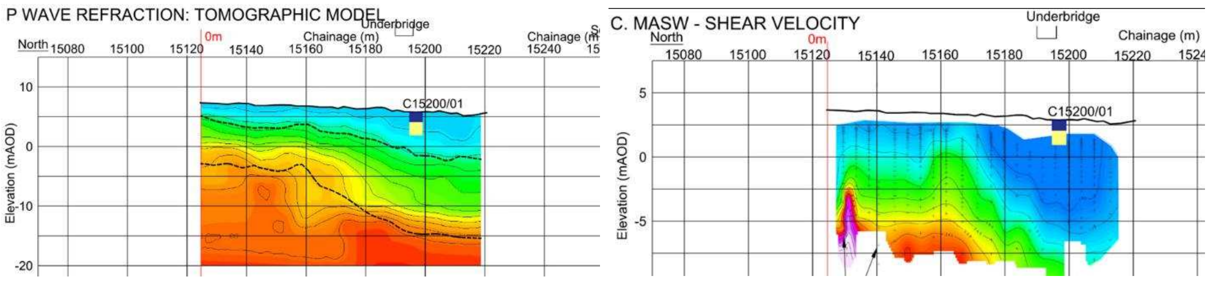

Figure 3: P Wave Refraction Tomographic Model (Left) and S Wave Velocity Model (Right), reproduced from integrated results of geophysical survey for TRU East of Leeds

Intrusive surveys identified an increase in embankment thickness around NOC/23. Holes drilled through the embankment around NOC/23 identified Made Ground at up to 8m thick in several places. This is considered to likely be due to embankment subsidence, resulting in ballast level top ups and embankment renewals to maintain rail level over its life. Boreholes undertaken in the vicinity of the extent of the brecciated pipe (as mapped on Figure 3 S Wave Velocity Model) identified organic clays and peats. In-situ SPT testing determined this material to be very soft, with majority of values ranging between 0 and 3. Looking spatially, to develop a 3D understanding of the extent of the peat deposits and potential shape of the brecciated pipe across track, peat levels significantly deepen towards the east side of the railway. This thickening of peats on the east side of NOC/23 provides a mechanism for the differential failure of the structure, as this side has the lower inlet level of 3.213mAOD, compared to 4.90mAOD on the west.

Off the brecciated pipe, and at depth, especially at Ch. 15,100m, the Vale of York deposits were recovered principally as the Hemingbrough Glaciolacustrine Clay. These laminated clays often included sand lenses and showed a clear trend of increasing strength with depth upon review of in-situ testing. Several boreholes encountered groundwater during drilling. Shallow water strikes did not rise and appear to be perched within sand lenses earlier identified. Two exploratory holes, C15180/05 and C15200/01, undertaken in the centre of the brecciated pipe, struck water between 13 and 14mAOD. Water rose in these holes after 20 minutes by approximately 12m, indicating deeper water tables exhibiting subartesian conditions.

4. CONSTRUCTION CONSIDERATIONS

4.1. Optioneering and Constraints

The research and geotechnical investigation undertaken provided strong evidence for the cause of the serious distress occurring within NOC/23. It is thought that the presence of a brecciated pipe, formed as a result of dissolution of gypsum within the Sherburn Gypsum of the Roxby Formation, has resulted in an upward propagation of groundwater flow and subsidence of overlying superficial soils into the pipe. It is likely that this process is ongoing, and as a result, vertical displacement of the entire rail embankment network is occurring. This is exacerbated by the presence of peats, generated by the brecciated pipe, which vary in thickness, and are likely the cause of differential displacement of the existing structure.

Reconstruction of NOC/23 was ruled out by the TRUe Alliance based upon the geotechnical hazards identified at the site. It was considered that due to the widespread nature of the brecciated pipe, that reconstruction would likely result in similar failures occurring, and that ground improvement would be extensive and expensive. Moreover, this hazard is impacting the wider rail infrastructure, not just NOC/23, and any effort to stabilise a reconstructed flood alleviation structure (by piling to mitigate some of the vertical displacement) would still result in differential movement of the track. This may cause an effective “hard-spot” whereby track deflections would require continual monitoring to avoid potential derailments.

Geotechnical effort in the research of the hazards and cause of the structure failure was fundamental in driving a preferred option of constructing off of Ulleskelf Mires. Construction of the new flood balancing structures (replacement culverts) needed to consider impacts to the rail infrastructure. The first option considered was top-down approach, whereby the embankment would be stripped back, culvert sections installed, and the embankment and railway reinstated. This would require closing the rail route by blockade. Possession of the railway would only potentially be available during the public holidays of Christmas and Easter, however, would likely require further possession times. Possession outside of these time periods were estimated to cost an additional £1 million, with added disruption to passengers, freight and the local economy.

The three culverts were proposed to be constructed as precast concrete pipes, installed by trenchless methods.

4.2. Proposed Structure Solution

The three new culverts of 1.8m diameter internal width had a proposed invert level of 4.9mAOD. New structures were assigned the names NOC/22C, NOC/22D and NOC/22E, and were located at local project chainages 15,111m, 15,121m and 15,131m respectively. This would site them off of the identified brecciated pipe, and off of recovered peat soils. Cover to new pipes varied across the embankment width, with the lowest amount of cover at NOC/22E below the Up Normanton Line (eastern most lone) of 1.634m. Each culvert would be 23.45m in length, a distance selected to ensure minimum tunnelling distance and time, whilst ensuring track support zones were stabilised both before and after jacking.

To facilitate pipe jacking, the launch pit was proposed on the east (Normanton) side of the embankment, with a 7.0m wide pit proposed. The reception pit on the opposite side to the track would be 4.0m in width. Each pit would be constructed by sheet piles in the temporary cases, with the concrete channel cast against this for the permanent case to allow for conversion to a drainage ditch to allow for flow of water to the south where ground level lowers.

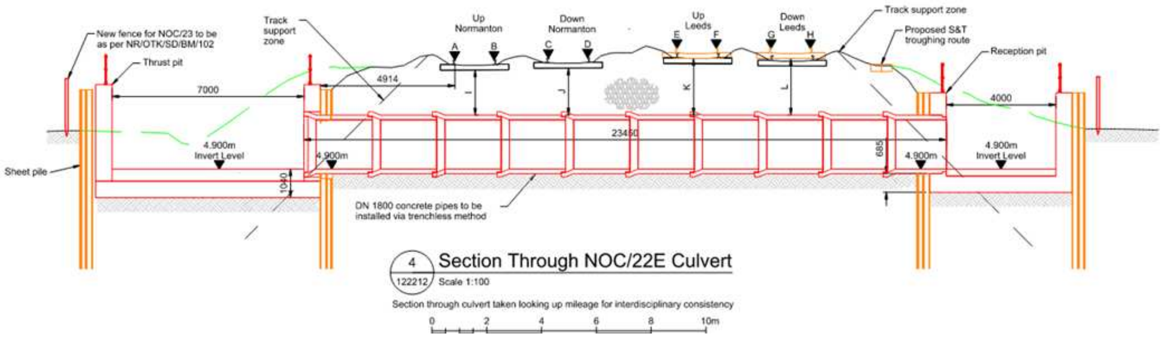

Figure 4: Extract of cross section, showing one of the proposed culverts (NOC/22E), against natural ground levels and existing embankment setting

With a proposed invert level of 4.9mAOD, proposed drainage channels/pits on either side of the embankment would require excavation from natural ground levels by approximately 3.5m. As the embankment was wider than the proposed culvert length of 23.45m, excavation of channels and pits would result in dig out of the toe of the embankments on both sides. It was noted that, when accounting for overdig in the worst-case, this would mean that sheet piles in the temporary case would need to retain 5m of railway embankment and underlying natural ground. In the temporary case, propping was required to support excavations during tunnel installation and channel formation.

As the existing rail embankments are of Victorian Era age and are life expired, global stability checks in the permanent and temporary cases were required to determine that change in use would not have a detrimental impact. Findings of the stability assessment advised that not only was propping necessary in both the permanent and temporary cases to keep pits and channels open, but also that sheet piles would need to be of necessary length to prevent failure planes generating as a result of unloading of slope toes whilst excavating channels.

4.3. Existing Structure Solution

With the proposed replacement structures to the north, NOC/23 can be abandoned. However, there is a risk that abandoning without remediation may eventually result in catastrophic and ultimate failure of the structure, which poses a serious risk to track stability. Any intervention may inadvertently result in accelerated vertical displacement by settlement however, which again would also result in in track deflections. The proposal made by the geotechnical team was to infill the structure with a lightweight fill (i.e., a polystyrene). Design checks were required to inform differential settlements between the structure and the surrounding embankment, as well as an assessment of the long-term structural integrity of the culvert.

EPS blocks selected for use have a lower density than alternative infill materials, such as foamed concrete, making it the preferable option to reduce magnitudes of settlement. The settlement calculation undertaken was to provide guidance of likely displacement as a result of infilling to advise Network Rail in their monitoring efforts of the line. With the addition of an EPS, consolidation was estimated to be 10mm on both sides of the existing structure, compared to surrounding embankment movement.

5. CONSTRUCTION, MONITORING AND CHALLENGES

The construction of the new structures took place during the summer months of 2023. Construction commenced with both the launch and reception pits. 10.0m long sheet piles were installed to a toe level of -0.90mAOD comprising L605 grade (PU22-1/GU21N) sheets. Two frames were specified for the opening of pits, MP150 struts were installed in both pits.

Figure 5: Launch Pit, during operation of railway

Once culvert openings were cut through sheet piles and headwalls cast, the three mini TBMs, Nicola, Kathryn and Emma, were lowered into the launch pit. During Week 21, the three culverts were jacked simultaneously beneath the railway, the first time that this feat had been achieved in the United Kingdom. Tunnel designers considered there to be a significant risk of works inducing settlement to the overlying track. There was less than 1.7m cover below the railway tracks, and the risk was deemed very high. Extensive remedial works were required to maintain track geometry, which was monitored and rectified during the possessions. Contingencies were put in place within construction possession to action remediation and reinstatement based on hazards identified.

Pre-possession, the first two culvert sections were installed at each location (NOC/22C, NOC/22D and NOC/22E) from the launch pit side. These segments were installed up to the TSZ for the Up Normanton Line, which remained open until 01:00am on Saturday 19th August 2023. For the next 23 and ½ hours, the two Normanton Lines were blocked to all rail traffic (with all traffic sent down the Leeds Lines), allowing for the progression of the TBMs through the Normanton TSZ to install the next three culvert segments at each location. On Sunday 20th August 2023, both the Leeds Lines and the Normanton Lines were blocked from 00:30am and the TBMs were progressed through the overlapping TSZ's of both lines. There was a 7 hour and 15-minute window to install two culvert segments within this section. From 07:45am, the Normanton Lines were re-opened to all rail traffic. With TBMs outside of the Normanton TSZ, there was a 21 hour and 15-minute blockade on the Leeds Lines to install remaining culvert sections. By Monday 21st August, at 05:00am, the Leeds Lines were repaired of any misalignments and all lines were fully re-opened to traffic.

The construction of the three tunnels was only possible due to the extensive contingency plans put in place. The two northern most culverts were progressed solely by TBM cutting faces, however the southern encountered clayey sandy soil, within the variable embankment make-up. This material was not conducive to being removed by the cutter head, and handheld breakers facilitated the removal of material which the cutter face could not dig. The contingency was acted upon and completed within the possession timeframes.

6. CONCLUSIONS

The distress and failure of the NOC/23 flood alleviation structure highlighted the impact of geological hazards present in North Yorkshire on the existing rail network. Preliminary geological assessments identified that the hazards of dissolution and peats are mechanisms for the vertical displacement of assets within the region.

Historical research in the wider region reported on the known presence of gypsum within the bedrock geology of the Roxby Formation. Evidence collated identified:

- Vertical displacement evidence in LiDAR imagery and topographical surveys, resulting in mappable sunken features at the surface,
- Historical borehole records encountering the Sherburn Gypsum, especially within the region of between Church Fenton and Ulleskelf,
- The elevation of sulphate particles within groundwater recovered from boreholes and wells within the wider site vicinity, and
- The mechanism of subartesian and artesian groundwater conditions rising up through dissolution features to saturate overlying superficial soils, often resulting in bogging and peat formation within near-surface soils.

Ground investigation tailored to identify these hazards dovetailed research findings, providing strong evidence to confirm the presence of a brecciated pipe below NOC/23 resulting in embankment displacement, along with the presence of thick layers of highly compressible peat.

Effective collaboration between multiple disciplines, and design and construction teams allowed for the proposal of an effective remedy, with geotechnical input critical in optioneering replacement structures off of the dissolution feature. Multidisciplinary interface developed a solution that saw the first simultaneous triple pipe jack beneath the railway in the UK. The solution allowed for construction without full closure of the line, minimising disruption to the public, freight traffic and the economy. This approach reduced carbon output and waste when compared to a potential cut/fill approach. The project also had a net biodiversity gain, with a 10% increase in trees planted as a result of site planning. All works undertaken were delivered within agreed possession arrangements, lines were fully reopened without delays and all core works were completed within agreed budgets.

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