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Overcoming design challenges for an urban railway interacting with fragile 19th century infrastructure in London, UK

Surmonter les défis à la conception pour un voie ferrée urbain en interaction avec une infrastructure fragile du 19ème siècle à Londres, Royaume-Uni

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ABSTRACT: The rapid increase in passenger volumes in north London spawned by the successful regeneration of the Elizabeth Olympic Park and Lea Valley hinterland is being alleviated by upgrading a 6.5km section of the existing West Anglia Main Line between Lea Bridge and a new 'Meridian Water' station, through provision of a 3rd track. At Tottenham Hale Station the new track will pass under a 19th century mild steel plate girder on concrete jack arch bridge with limited headroom that carries a trunk road. A 19th century 985mm diameter cast-iron raw water pipe runs near-surface along the centreline of the overbridge and is partially embedded within the shallow foundations of this fragile overbridge. Due to its age and material type, the water pipe is also fragile. Furthermore, the overbridge is underlain by a tunnel of London Underground's Victoria Line, located approximately 12m bgl. In order to meet the current design standard for minimum clearances between the rail and Overhead Line Equipment, the ground level at the overbridge needed to be lowered by approximately 1m. This significantly reduced the ground cover above the water pipe and hence dictated the nature of track support required across the water pipe.
This paper outlines options that were considered and identified a piled slab track as the preferred. The results of finite element modelling that was carried out to more accurately predict the impact on the structural integrity of the underlying tunnel, water pipe and overbridge foundations are also presented.

RÉSUMÉ: L'augmentation rapide du nombre de passagers dans le nord de Londres, due à la régénération du parque Elizabeth Olympic et Lea Valley, est atténuée par la modernisation d'une section de 6,5 km de la ligne principal existante de West Anglia entre les stations Lea Bridge et la nouvelle gare Meridian Water par la construction d'une 3ème voie ferrée. À la gare de Tottenham Hale, la nouvelle voie ferrée passera sous un pont routier du 19ème siècle avec un gabarit restreint. Une conduite principale d'eau d'un diamètre de 985 mm, datant du 19ème siècle, s'étend près de la surface parallèle au pont routier et est partiellement encastrée dans les fondations de ce pont fragile. En raison de son âge et de son matériau, la conduite d'eau est également fragile. De plus, un tunnel du métro de la Victoria Line passe sous le pont routier, situé à 12 m au-dessus du niveau du sol. Afin de respecter les normes pour la conception des équipements à lignes aériennes, le niveau du sol sur le pont routier doit être abaissé d'environ 1 m. Cela réduit considérablement la couverture du sol au-dessus de la conduite d'eau et est déterminant pour la solution pour la voie ferrée adoptée. Ce document décrit les options qui ont été envisagées et a identifié une voie en dale sur pieux comme étant l'option préférée. Les résultats du modèle d'éléments finis qui ont été réalisés pour prédire l'impact sur l'intégrité structurelle du tunnel sous-jacent de la conduite d'eau principale et du pont routier sont également présentés.

Keywords: slab track; piles; 19th century; railway; geotechnical risk; mitigation.

1 INTRODUCTION

The West Anglia Mainline Capacity Improvements Scheme (WAML) involves a project to increase capacity on the West Anglia route from Copper mill Junction (near Lea Bridge Stn) to a new 'Meridian Water' station in north London. The works include provision of a new 3rd track and associated station upgrade works and other lineside infrastructure along the route.

Just south of Tottenham Hale station (Figure 1) is a major arterial road with a 19th century overbridge in poor condition, with limited headroom beneath which the new track will pass.

Figure 1. Road overbridge location in relation to the WAML scheme.

A 19th century 985mm diameter cast-iron raw water pipe runs along the centreline of the overbridge with a cover of 1.25m bgl and is partially embedded within the shallow foundations of the road overbridge. The site is underlain by the southbound tunnel of the London Underground (LU) Victoria Line with its crown at 12m below ground level.

In order to meet the rail soffit clearances required by current Network Rail design standard GL/RT/1210 (Railway Group Standard, 2014) for Overhead Line Equipment (OLE), the existing ground level under the overbridge had to be lowered by approx. 1m. This resulted in a number of technical challenges which needed to be overcome. This significantly reduced the ground cover to the water pipe and hence an underbridge was required to span the water pipe to support the track and maintain a stipulated 75mm air gap between the slab track soffit and the water pipe. The very limited headroom dictated that the underbridge deck be constructed of a 100mm thick steel plate and on consideration of railway operational safety, differential settlements needed to be limited in the transition zone adjacent to this underbridge structure. The length of proposed pile foundations infringed the tunnel exclusion zone specified in the London Underground standard S1050 (Transport for London, 2016).

The design of the underbridge therefore required impact assessment of third party assets in order to obtain stakeholder buy-in and approval of any proposed solution.

2 TECHNICAL CHALLENGES

2.1 High level challenges

- The congested nature of this particular location with structurally sensitive Victorian-age infrastructure required robust solutions to minimize the risk of damage to the existing structures.
- The limited headroom due to the presence of the road overbridge required lowering of ground levels in order to meet the OLE clearances for the new track. This would in turn result in a reduction of the overburden soil covering the Thames Water pipe, thereby making it vulnerable to ground induced displacements and strains.
- The reduction in ground level adjacent to the shallow foundations of the road overbridge would result in a reduction in bearing capacity and sliding resistance.
- The presence of the LU tunnel would constrain any foundations required to support a bridging structure for the water pipe.
- A bridge structure across the water pipe would require proper consideration for the changes in track stiffness at the bridge approaches, in order to reduce the risk of train derailment.
- Durability and maintenance of any proposed structures would also need to take account of the 120 years design life.

2.2 Technical challenges/Design constraints

The proposed 3rd track will pass beneath a 19th century road overbridge founded on shallow foundations (Figure 2). The overbridge superstructure is overall in poor condition. The proposed 3rd track vertical alignment at this location was mainly driven by the OLE safety clearances required both at the overbridge and the proposed platforms at Tottenham Hale Station as per OLE standard GL/RT/1210 (Railway Group Standard, 2014).

Figure 2. Lateral view of the 19th century road overbridge during ground investigation work

This track alignment resulted in a restricted construction depth over the water pipe which was found insufficient for ballasted track. The existing ground level needs to be lowered by approx. 1m (Figure 3).

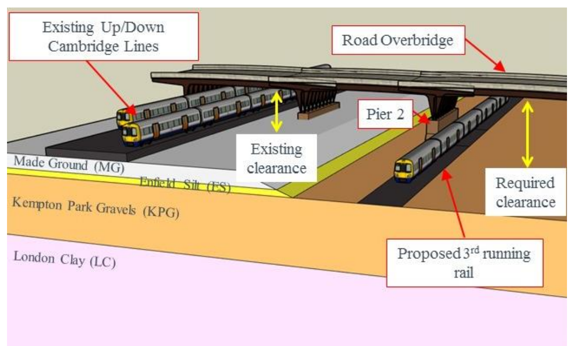

Figure 3. Schematic 3D representation of the clearance.

The horizontal track alignment passes adjacent to pier 2 with passive provision for a future 4th track. The existing pier 2 is a metal trestle founded on a brickwork plinth and mass concrete footing with a formation level only approximately 1200mm below the proposed rail level. Due to its structural configuration, it is very sensitive to differential settlements. The stability of the pier foundations needed to be ensured as a result of this ground lowering.

A 19th century 985mm dia. cast iron raw water pipe owned by Thames Water is located beneath the bridge piers 2 and runs perpendicular to the proposed track. At each overbridge foundation bridge load transfer above the water pipe is achieved via a relieving arch within the shallow foundation (Figure 4).

The pipe is an important asset for Thames Water as it is critical for maintaining water supply to a large residential area. Thames Water had stipulated that a minimum clearance of 75mm would be required above the water pipe to allow for future maintenance. A 1.5m exclusion zone was stipulated by Thames Water to protect the water pipe from possible damage during construction and service. An access for emergency maintenance was also required as Thames Water need to repair major leaks within 4-hours. The structural integrity of this pipe needed to be assured as a result of the new loading regime of the proposed track.

Figure 4. Frontal view of pier 2 with raw water pipe going underneath the arching foundation.

Structural and geotechnical challenges needed to be overcome to ensure that: 1) the structural solution needed to be sufficiently rigid to reduce the deformations for the high rail loads; 2) the Thames Water restriction zone was not violated; 3) the proposed permanent way alignment was followed considering the proximity to the adjacent Tottenham Hale station; 4) the geotechnical solution limited the long-term settlements to guarantee the 75mm gap required for maintenance.

The southbound Victoria Line LU tunnel runs at 12mbgl hence presenting another challenge. As referred above, LU standard S1050 (Railway Group Standard, 2014) provides a piling exclusion zone for bored piles of 6m above the tunnel crown level and 3m on each side of the tunnel.

Figure 5 shows a schematic representation of the main design constraints related to the construction of the 3rd running rail under the road overbridge.

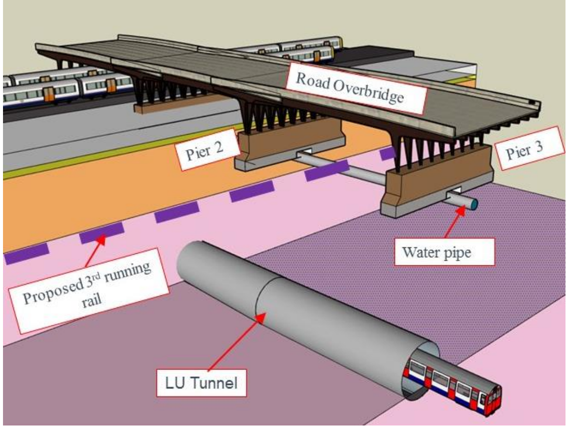

Figure 5. 3D schematic representation of the design constraints at the road overbridge location.

Furthermore, the buildability of the proposed solution was also constrained by the limited access for construction plant and environmental constraints of noise and vibration.

3 GROUND CONDITIONS

A site-specific ground investigation was carried out involving cable percussion boreholes with associated laboratory testing and ground water monitoring. The stratigraphy is summarised in Table 1. Ground water level is generally high since the site lies only approximately 200m from a tributary of the Lea River, and the presence of the granular superficial deposits readily provides hydraulic continuity with the site. Ground water was a key consideration in some of the options that were considered.

The highest ground water level recorded on site was 630mm below the proposed rail level. Therefore, any options requiring dewatering were unsuitable as high volumes of water requiring pumping were likely to be involved, which would in-turn potentially compromise the structural integrity of the sensitive raw water pipe and existing overbridge foundations, due to settlement.

Table 1. Adopted ground model.

Strata	Top of strata (mAOD)	Bulk Density, γ (kN/m3)	Peak Internal Friction Angle, ϕ'_{pk} (deg.)	Effective cohesion, c' (kPa)	Undrained shear strength, Cu (kPa)	Vertical Stiffness, E_v (kPa)	
						Euv	E'v
Made-Ground	108.0	18	28	0	-	-	4 500
Enfield Silt	107.0	18	32	0	-	-	4 500
Kempton Park Gravel	106.5	19	34	0	-	-	40 000
London Clay	102.0	20	24	0	$60+8z^1$	750Cu	600Cu
Note 1: z measured from the top of stratum							

4 OPTIONEERING

The main challenges were to develop options for spanning over the existing water pipe without adversely affecting the structural integrity of the Thames Water pipe, LU tunnel and road overbridge. Table 2 presents the merits and demerits of options that were considered.

Table 2. Advantages and Disadvantages of main options considered.

Option	Advantages	Disadvantages
Ballasted track only	• Simple, quick and inexpensive • Suitable for high groundwater conditions	• Construction depth required for ballasted track ranging between 500 and 700mm. This was greater than the available construction depth • Protection required for the cast iron water pipe to prevent damage from train loading / tamping • Excessive OLE clearances to the overbridge required for ballasted track
Ballasted track approaches and foundationless rails spanning over water pipe	• Quick and inexpensive • Reduced impact to the water pipe as the load would be transferred deeper than the water pipe level	• Minimum rail of 2.6m span required, which is much higher than the maximum allowable rail span of 1.0m to avoid lateral torsional buckling and fatigue • Higher OLE clearances to the overbridge required for ballasted track
Ground bearing slab track spanning over the water pipe	• Quick solution • Reduced OLE clearances to the overbridge	• Possible damage to overbridge due to potential settlement of the main pier foundation • Unfeasible thin reinforced concrete track slab for the available construction depth - highly congested reinforcement arrangement

Option	Advantages	Disadvantages
Slab track spanning over the water pipe founded on ground improvement [Note 1]	• Quick and inexpensive • Reduces amount of final settlement • Increases ultimate bearing capacity of the soil	• Possible long-term damage to water pipe due to vibrations and potential settlement • Possible damage to road overbridge due to potential settlement of the main pier foundation • Equipment required is generally large and would struggle to operate under overbridge • Would require onsite monitoring of existing tracks and overbridge foundations during installation
Steel slab spanning over water pipe, supported on piles and ground bearing approach slab tracks	• Guarantees air gap of 75mm above water pipe as required • Higher control of differential settlements • Transfers load to load bearing strata below	• Large diameter piles require larger plant and vibration, including a temporary bridge over water pipe • Depth of pile cap (for transfer of bending moments) increases depth of excavation • Ground bearing approach slabs also require piles to limit differential settlement
Lift/jack existing deck to achieve required OLE clearance	• Simple trackbed construction achievable as space would be available	• Involves major civils works ie. structural, geometrical & highways alignment challenges • Involves temporary shut-down of an arterial road

Note 1: Ground improvement options considered: vibro-compaction, stone columns, dynamic compaction, grouting, groundwater lowering

5 SELECTED OPTION & MODELLING

In order to satisfy Thames Water requirements as well as meet the clearance for the OLE, the proposed solution comprises a track support structure with direct rail fixings bridging over the water pipe. The proposed track support structure above the water pipe consists of a steel slab deck with 100mm thick steel slab strengthened by 4No. strengthening strips welded to the base founded on a robust foundation system.

On each side of the water pipe, the steel deck is supported on piled foundations comprising 8 No. 300mm dia. rotary bored piles. The span was optimised to provide a reasonable clearance to the water pipe to mitigate risks from piling and also to minimise pile lengths. The location of the proposed piles complies with the exclusion zone established by Thames Water.

A similar solution was implemented on both sides of the steel deck involving 2No. reinforced concrete approach slabs supported on 300mm dia. reinforced concrete piles, to minimise track /OLE tolerances beneath the road overbridge and to mitigate against excessive settlements of the adjacent bridge pier and water pipe. This also reduced the differential settlement between the adjoining track support structures.

The piles were founded in the underlying London Clay and thus extended into the LU restriction zone for the tunnel to limit settlement and to comply against the ultimate limit state for axial capacity according to BS EN 1997-1 (British Standards, 2013) as shown on Figure 6.

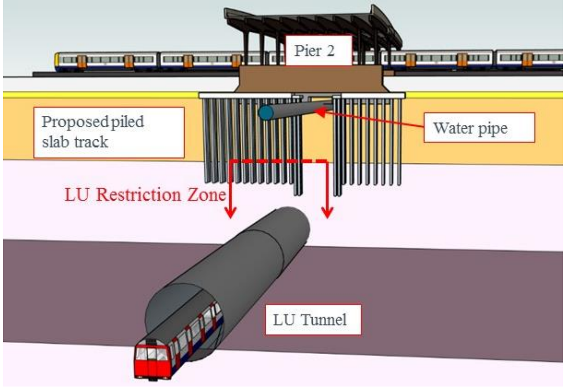

Figure 6. Schematic representation of the proposed solution.

Piling within the exclusion zone is subject to detailed consultation with LU including a potential damage assessment and tunnel monitoring. The potential damage assessment (PDA) was required to demonstrate that the proposed track bed solution could maintain adequate clearance above the water pipe during the design service life (120 years), whilst not compromising the integrity of the London Underground tunnel, Thames Water pipe, or the existing bridge foundations.

The complexity of the soil-structure-interactions required finite element modelling: London Underground's Southbound tunnel of the Victoria Line, Thames Water pipe, and Network Rail's road overbridge.

The objectives of the potential damage assessment were to:

- Predict LU tunnel displacements due to the proposed works, both in terms of the tunnel cross-section (ovality) and the longitudinal tunnel profile;
- Verify the structural adequacy of the LU precast segmental tunnel lining after the proposed works;
- Estimate the change in the flexural strains, rotation and pull-out at joint locations of the water pipe due to the proposed works;
- Assess the rotations and settlements of the foundations of the existing overbridge adjacent to the proposed works.

Two plane strain 2D Plaxis models were undertaken. The finite element modelling simulated the construction history of existing structures to capture the stress condition, followed by impact due to the installation of the proposed new track support structure. The existing condition of the tunnel assessment assumed 1% volume loss during construction and with reduced lining stiffness to account for radial joints.

The Hardening Soil constitutive model in 2D Plaxis was used for the London Clay whilst other soils were modelled with the Mohr-Coulomb constitutive soil model.

Two load cases were considered based on the position of the LM71 point loads (British Standards, 2010), in order to maximise the effects either on the water pipe or on the LUL tunnel.

6 FEM RESULTS

Figure 7 shows the estimated deformed shape of the tunnel lining at the current stage and after the installation of the proposed slab track.

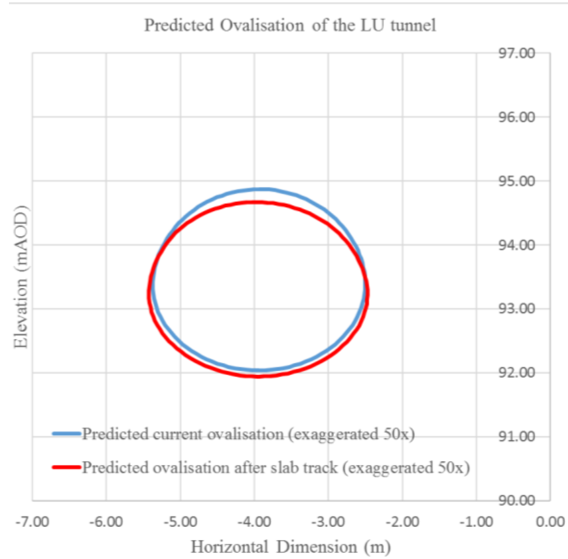

Figure 7. Predicted ovalisation of the LU tunnel.

The predicted long-term movements of the LU tunnel represented a maximum increase in ovality from 0.60% to 0.65%, which is less than the maximum 1% defined in LU S1055 (Transport for London, 2017). The dimensional survey was compared with the predicted LU tunnel deformed shape in Plaxis, showing good agreement.

The ultimate moment thrust envelope (M-N) for the unreinforced concrete section is shown in Figure 8. The design N-M actions are plotted for different construction stages. The increase in long-term stresses was found to be within the structural capacity of the unreinforced concrete section of the tunnel as per BS EN 1992-1-1 (British Standard, 2014). Overall the predictions suggested the works had slight beneficial effects for the LU tunnel longitudinal curvature as they reduce the amount of hogging currently on the tunnel.

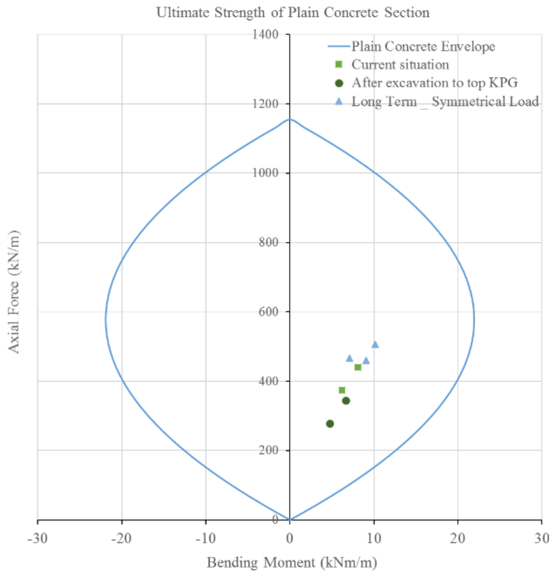

Figure 8. Ultimate moment thrust envelope for the LU tunnel lining against N-M design forces.

The predicted pull-out of the water pipe after the installation of the slab track was predicted to be less than 3mm and rotation and strains were also within allowable limits as shown in Table 3.

Table 3. Summary of the assessment criteria of the Thames Water pipe.

Criterion	**Current Situation**	**Slab track**	**Check**
Max. rotation (deg.)	<0.1	<0.1	<0.1
Pull-put (mm)	<1.5	<3	<3
Tensile strains (με)	248	330	Difference <100

A bearing capacity and sliding check for Pier 2 foundation indicated adequate capacity once the ground level was lowered as part of the works. The analyses predicted Pier 2 to settle by up to 7mm and to rotate by less than 0.1 degrees (equivalent to +/- 2mm at the foundation edges).

7 CONCLUSION/SUMMARY

The use of finite element modelling allowed for realistic soil stiffness parameters and models to be used thus enabling realistic soil behaviour to be closely mimicked. This enabled realistic predictions to be made of stresses and movements to inform the design and long-term performance.

Based on the results, appropriate mitigation measures were mooted and developed which were assured by stakeholders and overall more cost-effective than would have otherwise been invoked if more simplistic methodologies had been adopted. It is recommended that the structures be monitored during and following construction with trigger levels and associated mitigation measures agreed with stakeholders.

The solution was implemented in 2018.

8 ACKNOWLEDGEMENTS

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