Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-565

Design and construction carbon reductions for HS2 station road network rail overbridge with polymer geogrid reinforced soil wall abutments and wingwalls on shallow foundations

Réductions de carbone dans la conception et la construction du pont ferroviaire du réseau routier de la station HS2 avec culées de murs en sol renforcé par géogrille polymère et murs en aile sur des fondations peu profondes

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ABSTRACT: Tensar International Limited was subcontracted by Arcadis Setec COWI (ASC) DJV working for Eiffage Kier Ferrovial BAM (EKFB) JV delivering the design and construction of Britain's High Speed Rail Main Works Civils Contract C23, to carry out the design of the load bearing bridge abutments and wing walls that will support an overbridge over Network Rail tracks at Station Road. The original concept design comprised reinforced concrete (RC) bridge abutments and L-Shaped wing walls, all founded on piled foundations. The alternative design replaced the piled RC bridge abutments and wing walls with polymer geogrid reinforced soil bridge abutments and wing walls founded on shallow foundations. Coffey Geotechnics Ltd subsequently partnered with Tensar to undertake a comparative assessment of a reinforced soil wall system against the original piled RC retaining system. This paper presents the technical solution eventually adopted by EKFB and a comparison of the embodied carbon related to the two design options. The carbon emissions compared in this assessment includes the embodied carbon at the factory gate for the main materials and carbon emissions associated with transportation, on-site construction activities and waste disposal. The paper also presents cost savings from adopting the alternative retaining system both in design and construction.

RÉSUMÉ: Tensar International Limited a été sous-traité par Arcadis Setec COWI (ASC) DJV travaillant pour le groupement d'Eiffage Kier Ferrovial BAM (EKFB), pour la conception et la construction du contrat civil C23 des principaux travaux ferroviaires à grande vitesse britanniques, pour réaliser la conception des supports de charge. Les culées du pont et les murs en aile qui soutiendront un pont supérieur au-dessus des voies du Network Rail à Station Road. Le concept original comprenait des culées de pont en béton armé (BA) et des murs d'aile en forme de L fondés sur des fondations sur pieux. La conception alternative a remplacé les culées de pont sur pieux RC et les murs en aile par des culées de pont en sol renforcé de géogrille polymère et des murs en aile fondés sur des fondations peu profondes. Coffey Geotechnics Ltd s'est ensuite associée à Tensar pour entreprendre une évaluation comparative du système de murs en sol renforcé par rapport au système de soutènement RC sur pieux d'origine. Cet article présente la solution technique finalement adoptée par l'EKFB et une comparaison du carbone incorporé lié aux deux options de conception. Les émissions de carbone comparées dans cette évaluation incluent le carbone incorporé à la sortie de l'usine pour les principaux matériaux et les émissions de carbone associées au transport, aux activités de construction sur site et à l'élimination des déchets. Le document présente également les économies de coûts résultant de l'adoption du système de retenue alternatif, tant au niveau de la conception que de la construction.

Keywords: Reinforced soil; sustainability; carbon; bridge abutments; high speed rail.

1 INTRODUCTION AND BACKGROUND

The High Speed Two (HS2) project is a High-Speed Railway Line currently under construction in the UK. Phase 1 of HS2 runs between London and Birmingham across the English Midlands. This scope is part of the HS2 Main Works Civils Contract C23, awarded to Eiffage Keir Ferrovial Bam (EKFB) JV in partnership with the design JV of Arcadis Setec COWI (ASC).

Station Road, which joins the village of Quainton to the A41 in Buckinghamshire is to be realigned to the northwest of its current location. The bridge currently carrying Station Road (Quainton Road Overbridge, MCJ2/184A) over the Marylebone to Claydon Junction (MCJ) is to be replaced to provide access to the Buckinghamshire Railway Centre (BRC) and car park.

Two new overbridges, and associated earthworks, are required to cross over the HS2 supporting earthworks and the existing Aylesbury Link Railway (MCJ) which is being replaced as part of the HS2 works. As the route is used to transport locomotives to the BRC on low-loaders, all new structures must be designed to accommodate SV100 loading. Fiddlers Field Road and Quainton Road will also be realigned.

2 DESIGN PHILOSOPHY AND DEVELOPMENT

The original scheme design of the new Station Road National Rail Overbridge comprised prestressed concrete u-beam deck fully integral with reinforced concrete (RC) abutments and wingwalls, founded on RC piles, in keeping with HS2's design philosophy of minimising maintenance over the structure design life. In order to comply with the highway alignment requirements, the bridge was skewed at 36.8 degrees.

A value engineering exercise was carried out to reduce cost and programme and improve the sustainability performance of the structure. The piled RC abutments and wingwalls were replaced with polymer geogrid reinforced soil bridge abutments and wing walls parallel to the Network Rail track and supported on shallow foundations. The original RC load bearing bridge abutments replaced with bank seats sat on top of the reinforced earth retaining wall fill.

2.1 Reinforced concrete structure

A piled solution was proposed for the structure to manage the magniture of settlement expected due to the presence of a thick deposit of firm to very stiff clay of the Oxford Clay Formation.

Each abutment was founded on a group of 8no. 1050mm diameter RC piles of 23m length. The pile caps measured 14m in length by 7.2m in width and were 1.5m deep. The abutment walls measured 14m in length by 7.2m in height. The abutment wall thickness was 2.3m

Wingwalls either side of the bridge abutments were also proposed to be founded on two rows of 1050mm diameter piles measuring 20m in length, totalling 39 piles for both sides. The wingwalls varied from 12.8m to 17.7m.in length to suit the approach embankment earthworks, accounting for the skew of the structure. The wingwall pile caps measured 1.5m in depth in 5m in width. The wingwall stem was trapezoidal in shape, with a minimum width of 300mm at the top and a 7degree slope on the back of the wall. The width of the bottom of the stem varied along the length of the structure.

The total volume of concrete required to construct the abutments, wingwalls and piles was 1,885m^3.

2.2 Reinforced soil load bearing bridge abutments and wing walls

Tensar was appointed in April 2020 to carry out the detailed design of the reinforced soil structures proposed to support Station Road Network Rail Overbridge. Reinforced soil retaining walls with near vertical faces were chosen as the preferable to form the bridge abutments and adjoining wingwalls to minimise the bridge span.

The Tensar*tech*® TW3 geogrid reinforced soil retaining wall system was used to create the near vertical face (1° incline). The system comprises four major components, namely the concrete modular face block, the HDPE uniaxial geogrid, the polymeric mechanical block connector and high quality, granularreinforced fill material.

The facing units are produced in an automated factory process in the UK using a semi-dry concrete mix with a minimum crushing strength at 28 days of 40 MPa.

The uniaxially orientated high-density polyethylene (HDPE) geogrids are produced in the UK and are subjected to all internationally recognised standards such as ISO and ASTM. The geogrids carry the European CE registration and the independent HAPAS (ex-British Board of Agrément (BBA)) certification.

The mechanical polymeric connectors are also made of HDPE to provide a high level of load transfer at the grid-block connection whilst allowing the transfer of horizontal shear loads between adjacent blocks. The shape and feature of these connectors is designed specifically for the system, is durable in all conditions and provides high efficiency connection strength.

The shear strength properties for the various soil types used for design are as shown in the table 1 below.

Table 1. Design parameters for reinforced soil wall.

Soil Type	**ϕ' (°)**	**c' (kPa)**	**γ' (kN/m³)**
Reinforced Fill type 6I*[1]	42	0	20
Retained fill 6N	38	0	20
Foundation Treatment Fill Class 1A	38	0	20

*[1] Series 600 of Highways Works Specification in the UK & Maximum particle size not more than 75 mm, Percentage by mass passing 63 micron sieve (0.075 mm) less than 15%, Uniformity Coefficient – higher than 10, pH value of reinforced fill between 4-12

An added advantage of the modular block retaining system was that the individual component parts of the system listed above could be easily transported to the site seperately. In addition, the individual components are all dry laid so no curing time or formwork is necessary, minising construction programme.

2.3 Design Method

Reinforced soil modular block walls have been constructed internationally for more than 35 years. In the UK, reinforced soil structures used in bridge applications are designed in accordance with BS8006-1:2010+A1:2016. Retaining wall structures designed in accordance with this standard, incorporating polymeric geogrids, are classified as 'extensible' reinforcement and utilize a tie-back wedge design method.

Internal stability comprises two fundamental checks: failure against rupture and failure against pull-out of geogrid or adherence check. Internal stability provides the geogrid strengths and spacing that are required for a stable design.

In accordance to BS8006, an additional internal stability check was also carried out to make sure that the geogrids will not strain more than 1% under the sustained working load that they will be subjected to over their 120 year design life.

2.4 External Stability & Shallow Foundation Design

Tensar, in collaboration with Geofem Limited, developed the foundational designs of the reinforced soil abutment and wing walls for Station Road National Rail Overbridge. A two-dimensional (2D) plane strain finite element analysis (FEA) was performed using Plaxis 2D Version 22, capitalizing on the uniform geometry of the abutment and wing walls. This approach facilitated the simultaneous evaluation of potential failure modes and prediction of foundation settlement.

The modelling work aligns with the protocols set out in published papers (Lees, 2016), ensuring the adopted methods adhere to recognised industry standards.

A division of the Oxford Clay at 74.7mAOD introduced varied strength and stiffness characteristics. Boundary constraints minimized boundary effects, and groundwater levels were set at the formation level. Initial findings pointed to potential sliding, bearing failures under undrained conditions, and bearing failures in drained conditions without ground modifications. For an optimal safety margin, we implemented the following measures:

- Foundation soil replacement with Class 1A $\varphi'=38°$ and $\gamma=20kN/m^3$ material, 3.7m in depth.
- Geogrid Reinforcement length of 10m and 7.8m for the abutment and wing walls, respectively.

Fill materials adhered to the standardised Linear Elastic Perfectly Plastic (Mohr-Coulomb) constitutive models. The FEA model integrated Geogrid specifications from Tensar, accounting for the material's long-term resilience. Load assessments incorporated the fill material's self-weight density and mechanical properties FEA modelling unfolded over several phases, each contemplating diverse loading and soil scenarios for a thorough evaluation. Adjustments in soil and fill strengths were predicated on foundation soil drainage conditions, with strategies ranging from stepwise reduction to equilibrium attainment without discernible failure routes. Drained ULS (with partial factors applied only on the loads in the drained case) assessments for both structures yielded a safety factor (via shear strength reduction) exceeding 1.25 (Figure 1). Figure 2 depicts the wing wall's slip surface. For undrained ULS, partial factors modified the soil parameters, with the model converging smoothly (safety factor > 1.0). Post-construction predictions include a wall displacement of approximately 12mm, a bankseat shift close to 13mm, horizontally, vertically of ~28mm shown in Figure 3, and a peak geogrid tensile axial force of around 20kN/m in any SLS analysis. Notably, an average additional post-construction tensile strain of 0.12% is anticipated in the lowermost geogrid layer due to prolonged foundation consolidation, remaining within accepted boundaries.

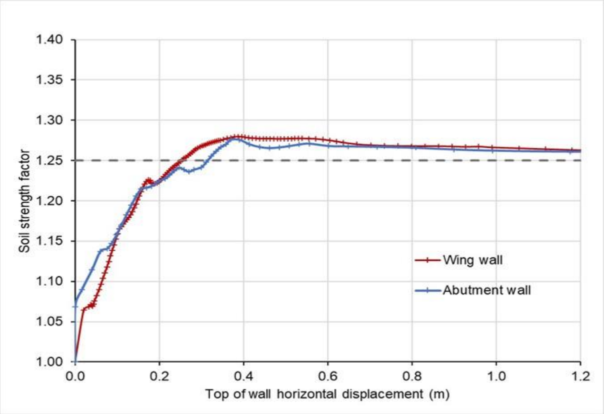

Figure 1. Drained ULS Safety Analysis.

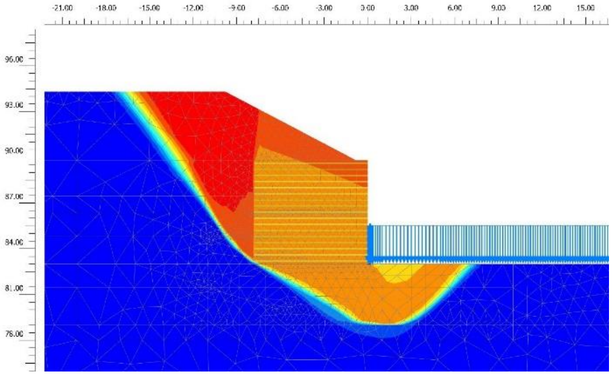

Figure 2. Slip Surface at the Wing Wall.

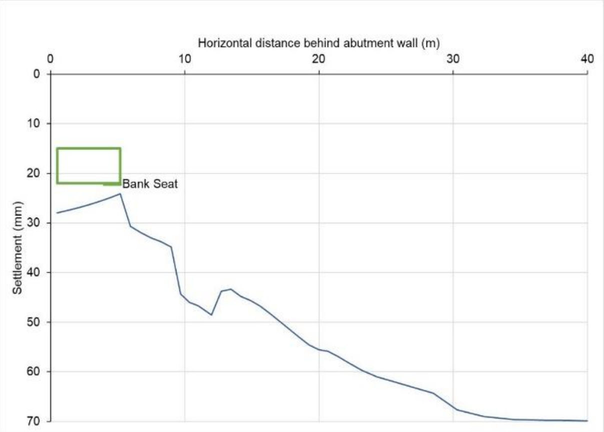

Figure 3. Deformation behind the Wall and underneath the Bank Seat.

3 CARBON CALCULATIONS

3.1 Background

The Climate Change Act 2008 committed the UK to an 80% reduction in carbon emissions by 2050, compared to 1990 levels and in 2019 this was updated to 100% reduction (Institute for Government, 2020). This made the UK the first major economy to set legally binding carbon budgets which require emissions, including those from transport, to be Net Zero by 2050. This commitment is supported by HS2's Environmental Sustainability Vision and Net Zero Carbon Plan and EKFB's target to reduce carbon emissions by 50%.

The call to measure and reduce carbon dioxide emissions comes from two directions: regulatory and commercial. Regulatory pressures arise from government drives to reduce greenhouse gas emissions in the UK and commercial pressures arise from increased client demand for information to demonstrate steps taken to limit carbon emissions.

Following the change in the design of Station Road Network Rail Overbridge, a comparison of the carbon emissions arising from the construction of RC bridge abutments and wing walls supported on piled foundations against polymer geogrid reinforced soil bridge abutments and wing walls founded on shallow foundations, was undertaken.

For the purpose of this paper, only the carbon emissions of the major elements of the wall construction have been considered, it does not take into account other things that may be included in a life cycle assessment such as storage, on site movements, removals and land use change.

3.2 System Boundaries

It is important when communicating carbon dioxide emissions that the boundaries of the calculation are known. Comparison of carbon dioxide emissions for different products can only be made if they are based within a similar set of boundaries.

This approach is in line with EKFB's Carbon Management Plan and based on PAS 2050:2011 (BSI, 2011) and BS EN 17472:2022 (BSI, 2022) and considers cradle to end of construction. The boundaries cover 'Product' module stages: 'Raw Material Supply' (A1); 'Transport'; (A2) and 'Manufacturing' (A3). It also considers 'Construction Process' module stages: 'Transport' (A4); and 'Construction Installation' (A5). The 'Use' and 'End of Life' module stages have not been considered in the calculations. Emissions have been calculated separately for the 'Product' stages (A1 to A3), 'Transport' stage (A4), and 'Construction Installation' stage (A5), and are then combined for assessment and comparison.

3.3 Process

Process maps were derived for each structural option detailing the requirements of each stage in the process. For the 'Product' modules this included manufacturing/production of the wall components including, geogrids, modular blocks and connectors, concrete, reinforcing steel and aggregate. The 'Construction Process' modules included transport of all the components (by a variety of vehicles either by train or road) and the construction elements included, but were not limited to, boring of piles, excavation of foundation, pouring of concrete for the piles, pile cap, walls, levelling pad and bankseat and placement and compaction of aggregate for the different fill types (i.e. Class 1A, 6I1 and 6N).

3.4 Collecting Data

A combination of primary and secondary data sources was used in the calculations, with primary data sources such as design drawings, details of specific transport vehicles and Environmental Product Declarations (EPDs) from manufacturers being the preferred option. Emission factors that convert activity data into carbon emissions were typically from secondary sources including the Inventory of Carbon and Energy database (Circular Ecology, 2019) and UK Government GHG Conversion Factors 2023.

3.5 Calculating the Emissions

Total CO_2 equivalent emissions to the end of construction were calculated for both bridge supports. The RC wall option was not considered at detailed design, therefore, assumptions have been made on the material quantities based on reasonable engineering judgement and typical construction practices. The concrete bankseat has been included in the Reinforced Soil wall calculations to ensure a comparable design up to the level of the bridge bearings. It is assumed that the deck construction and its ancillaries would be the same in both cases, therefore this has been omitted from the carbon emission calculation.

3.6 Results

The potential reductions in carbon dioxide equivalent emissions available by constructing a Reinforced Soil wall in comparison to a RC wall have been calculated and are shown in Figure 4.

The total calculated carbon emissions for the Reinforced Soil wall are 663 tCO2e of which 58% is in the 'Products', 35% in the 'Transport' and 7% in the 'Construction Installation'. For the RC wall there is 2,002 tCO2e of which 91% is the embodied carbon in the 'Products', 6% in the 'Transport' and 3% in the 'Construction Installation'.

The direct comparison between these two equivalent structures demonstrates that the Reinforced Soil design contributes a 66% carbon saving in comparison to the RC design.

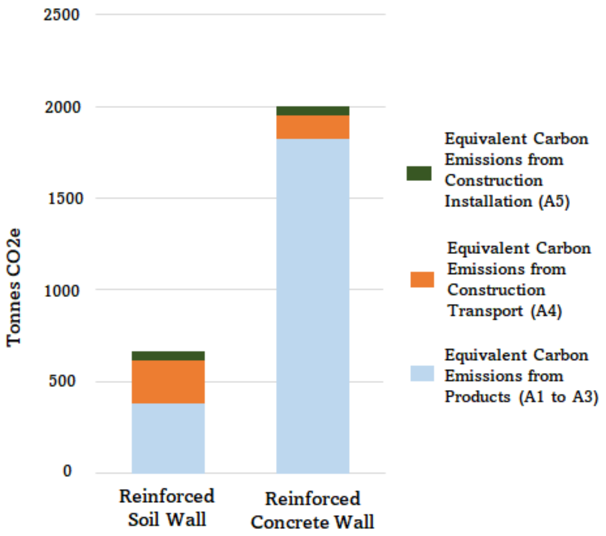

Figure 4. A comparison of the equivalent carbon emissions in both the Reinforced Soil Wall and Reinforced Concrete Wall.

3.7 Discussion

The majority of the embodied carbon in the RC wall comes from the concrete (842 tCO2e) and steel (898 tCO2e) making up 95% of the 'Product' emissions with only 5% coming from the structural fill element (85 tCO2e). Both concrete and steel production are very carbon-intensive with steel being the largest industrial source of CO_2 emissions in the UK (E&T, 2021) and cement being the largest single industrial emitter of CO_2 emissions globally (Ellis et al, 2019). These high value CO_2 emissions for concrete and steel also contribute to the Reinforced Soil wall results with the concrete reinforced bankseat comprising 36% of the embodied carbon within the 'Products' for a component which makes up only 2% of the overall volume. The remaining CO_2 emissions attributed to the embodied carbon in the 'Products' for the Reinforced Soil wall include 21% in the Reinforced Fill, 20% in the Class 1A foundation, 2% in the Class 6N behind the bankseat and 21% combined from the geogrid, modular blocks and connectors.

The CO_2 emissions calculated for 'Transport' were higher for the Reinforced Soil wall (230 tCO2e) due to the movement of a larger amount of aggregate required for the construction of the 3.7m deep foundation. Material is to be sourced from UK quarries up to 295km away from site.

The CO2 emissions for ‘Construction Installation’ were similar for both wall options with the Reinforced Soil wall being slightly higher at 49 tCO2e compared to 48 tCO2e for the RC wall. For the RC wall the majority of the emissions relating to construction came from the boring of 1,148 linear metres of 1050mm diameter piles. This equated to 95% of the carbon emissions in the ‘Construction Installation’.

For the Reinforced Soil wall, the majority of the emissions relating to construction came from the disposal of the excavated soils for the foundation. This equated to 93% of the carbon emissions in the ‘Construction Installation’. In both cases the carbon emissions generated by construction activities are small in comparison to the carbon in the ‘Products’ and ‘Transport’.

4 COST COMPARISON

The direct comparison between the two equivalent structures demonstrates that the Reinforced Soil bridge abutment option resulted in savings of the order of 35% in comparison with the Reinforced Concrete bridge abutment supported on piled foundation.

5 CONCLUSIONS

Within the last 40+ years, polymeric geogrid reinforced structures have become established as reliable alternatives to conventional reinforced concrete structures and have been successfully used in high-risk applications like bridge abutments. This paper, through a direct comparison between two equivalent structures, has proven that a Reinforced Soil design contributes up to 66% savings in carbon in comparison with a Reinforced Concrete design, when assessing emissions from cradle to end of construction, and savings in cost of the order of 35%. Additionally, significant extra savings will be achieved in programme, personnel and plant movements.

In conclusion, in this project, by replacing the traditional RC bridge abutment construction solution with polymer geogrid-reinforced soil wall alternative, a robust, cost and carbon effective solution was provided, while championing HS2's legacy as one of the world's most sustainable high speed rail network.

ACKNOWLEDGEMENTS

The authors are grateful to High Speed 2 Ltd. for allowing us to publish this case study.

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