Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2039

Environmental sustainability – strategic geotechnical optimisation & efficiency for the delivery of resilient high-speed rail infrastructure in the UK

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ABSTRACT: Construction is inherently carbon-intensive. For the High Speed 2 (HS2) C23 main civil engineering works, significant emissions were anticipated from the materials required to build the railway infrastructure. The primary sources of these emissions included the transport of imported engineered fill and aggregates for embankment construction, the use of concrete and steel for foundations and earthworks mitigation, and materials such as cement and lime for earthworks improvement. This paper outlines the geotechnical optimisation and efficiency strategy adopted during the detailed design phase of the C23 contract to assess potential carbon emissions and identify sustainable solutions to reduce them. It also presents case studies illustrating how the adopted Routine Life Cycle Assessment (LCA) strategy was implemented by integrating site-specific ground investigation data with detailed modelling to achieve significant reductions in carbon footprint as well as considerable savings in cost and schedule. The strategy was guided by the application of an industry-recognised carbon hierarchy, supported by the adoption of the industry-standard eTool LCA platform to quantify and track reductions in embodied carbon. The results confirmed that the ambitious carbon reduction targets for HS2 C23 earthworks are achievable, establishing a positive sustainability benchmark for future infrastructure projects in the UK and beyond.

KEYWORDS: High-speed, earthworks, sustainability, optimisation, carbon emissions.

1 INTRODUCTION

1.1 *Background*

The High Speed Two (HS2) project is a new high-Speed Railway Line currently under construction in the UK. It is a 230km long new high-speed rail (HSR) that runs between London and Birmingham across the English Midlands. HS2 Ltd. has awarded the C23 Contract for the design and construction of the civil infrastructure works to Eiffage, Kier, Ferrovial Construction and BAM Nuttall (EKFB), a Joint Venture consisting of renowned international civil engineering construction contractors. In turn, EKFB has appointed Arcadis, Setec, and COWI Design Joint Venture (ASC) to provide design services and construction support for the works.

The C23 Contract is an 80km long open route section that connects the Chiltern Tunnel to Long Itchington Wood, located within the Central region between Wendover in Buckinghamshire and Southam in Warwickshire. This section will be constructed using a track slab system with a design speed of 360km/hr. The track will be supported on 30 mainline cuttings, 45 mainline embankments, 15 viaducts and will cross 7km of cut-and-cover green tunnels. Over 30 million m^3 of material is expected to be generated during excavation for formation of cuttings and construction of the tunnels. In addition, significant quantities of engineered fill are required for the construction of mainline embankments, earthworks to transitions and as subgrade.

1.2 *The climate change challenges*

The Infrastructure Carbon Review (ICR), launched in November 2013, was endorsed by key stakeholders across the construction industry, recognising that infrastructure accounts for approximately 50% of the UK's carbon emissions. The ICR outlined a clear set of actions for construction companies to reduce carbon emissions and expected all members of the supply chain to commit to this shared goal by actively seeking and implementing lower-carbon solutions through innovative design, effective management, and strategic optioneering. This marked a pivotal moment for the infrastructure and construction industries, broadening the performance key indicators narrative beyond cost and delivery schedule to include environmental metrics aimed at reducing national carbon emissions and contributing to mitigating the perils of global climate change.

In 2019, the UK became the first major economy to pass laws confirming its committed targets of bringing all greenhouse gas emissions (GHG) to net zero by 2050 (UK Government, 2019). Since then, all new infrastructure projects in the UK are required to adhere to the mandated act. HS2's commitment to "minimising carbon footprint for the new high-speed railway and deliver low carbon long distance journeys supported by low carbon energy" is very much aligned with the Government's commitment to net zero targets. To achieve such commitment, HS2 Ltd. set an industry-leading carbon target of 50% to reduce the whole-life carbon emissions associated with the construction, operations, and maintenance of the main works civil contracts (MWCCs) (HS2, 2017a&b). This constituted a mandatory project requirement, obligating all principal civil works contractors to actively support and contribute to its achievement. Each contractor was, therefore, required to develop and implement an environmental sustainability strategy for their respective route sections, in accordance with the principles and methodologies set out in PAS 2080:2016 - Carbon Management in Infrastructure (BSI, 2011) and HS2 Technical Standards for carbon footprint and life cycle assessment (HS2, 2020a).

1.3 *Scope and objectives*

In 2018, EKFB adopted the ICR and committed to implementing its objectives. Additionally, EKFB and ASC pledged to develop designs and construction specifications that fully comply with the HS2 Environmental Minimum Requirements (EMR) (HS2, 2020b). They continuously sought opportunities along the C23 route to significantly contribute to HS2's goal of reducing its carbon footprint.

This paper presents the geotechnical optimisation and design efficiencies strategy adopted during the detailed design stage. The strategy focused on identifying material "hot spots" and applying an effective carbon management process to explore alternative, optimised solutions that would substantially reduce carbon emissions during construction, operation, and maintenance. Typical case studies, presented as opportunities, are used to illustrate how the strategy was implemented to meet the carbon reduction targets in the identified high-impact areas.

2 ENVIRONMENTAL SUSTAINABILITY GOALS

HS2 Ltd. set a bold ambition to deliver "the most sustainable high-speed railway of its kind in the world," aiming to generate long-term social, environmental, and economic value for communities along the route. To achieve such ambition, HS2 Ltd. set a target of 50% carbon reduction for HS2 MWCCs based on the GHG, determined using the Employer's Reference Design (ERD). In alignment with this vision, EKFB/ASC developed a comprehensive set of sustainability goals for the C23 main civil infrastructure works during the detailed design phase to support HS2's industry-leading carbon reduction targets (HS2, 2017a&b; HS2 2020d) and to embed sustainability into the core of design and engineering decision-making. Key goals included:

- Application of lifecycle assessment (LCA) methodologies to measure and benchmark the environmental impact of design alternatives.
- Systematic analysis to identify carbon-intensive materials, construction activities, and processes with the highest potential for emissions reduction.
- Exploration and implementation of innovative, efficient, and low-carbon engineering solutions, including material substitution, optimised design practices, and strategic construction sequencing.
- Leveraging design efficiencies to achieve both carbon reductions and cost savings, aligning sustainability with commercial performance.
- Development of optimised mass haul strategies to minimise transport emissions, reduce spoil, and enhance resource efficiency across the C23 corridor.

These goals were established to show how sustainability can effectively be operationalised in large-scale infrastructure development projects through data-driven design, collaborative innovation, and performance-based targets.

3 CARBON BASELINE ASSESSMENT AND TARGETS

3.1 *Carbon baseline Life cycle assessment goals*

Upon contract award, EKFB/ASC undertook a whole life cycle assessment (LCA) for the C23 route to:

- Validate HS2 Global Warming Potential (GWP) baseline set out in HS2 Technical standards (HS2, 2017b & HS2, 2018),
- Quantify the environmental baseline over the C23 route,
- Identify hot spots of environmental impact, and
- Agree on the targets to be achieved against the validated whole life cycle assessment carbon baseline.

3.2 *Methodology for developing baseline carbon emissions*

The approach followed to develop the whole LCA baseline is outlined in Figure 1. This was adapted from BS EN 14044. Data and information used in the calculation of the baseline LCA for C23 were primarily obtained from the EDR. The assessment was completed in accordance with BS EN 14040, BS EN 14044, BS EN 15978, and PAS 2080:2016. The assessment considered all main assets to be constructed within the C23 corridor.

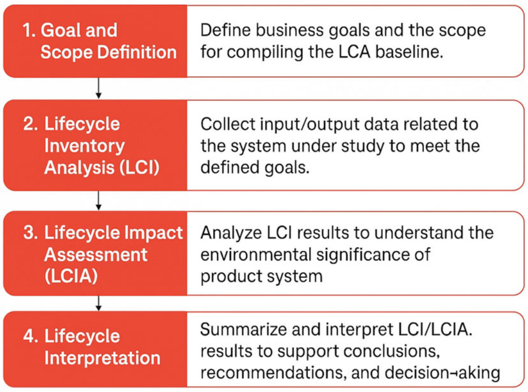

Figure 1. Approach to LCA baseline carbon emissions calculation.

The lifecycle stages and modules included in the GWP assessment are presented in Table 1. These were determined in accordance with HS2 requirements contained in HS2 Technical Standard (HS2, 2020a). The environmental indicators were quantified over a period of 120 years, consistent with the operational design life of the railway infrastructure assets.

Table 1. Life Cycle Stages and modules considered in baseline LCA.

Life cycle stage	Life cycle stage module	Included within GWP or LCA calculation
Before use stage	A1-A3 (Product)	Full LCA
	A4 (transport to site)	Only GWP*
	A5 (Construction)	Only GWP*
Use stage	B2 (maintenance)	Only GWP*
	B4 (Replacement)	Full LCA

3.3 *Calculation tool*

The specialist e-Tool software has been adopted by EKFB/ASC to calculate the LCA baseline carbon footprint and the required environmental indicators for environmental performance. The software is an online LCA cloud-based tool which allows the bulk upload of material quantities and matches them to existing environmental product declarations within its database. The software has an invaluable optioneering feature that enables an iterative measurement to be undertaken to assess and compare different scenarios during the low carbon emission option selection process.

The eTool software incorporates a bespoke HS2 database to calculate embodied carbon and deliver LCA outcomes. It operates by combining user-defined inputs with third-party background datasets, which are aggregated as mid-point environmental indicators and stored in internal libraries. These datasets and algorithms work together to quantify environmental impacts, including GWP, across all life cycle stages. Figure 2 illustrates the interaction between user inputs, data sources, and computational algorithms that generate the LCA outputs. Carbon equivalents for the different products are calculated in accordance with BS EN 15978 and PAS 2080, which underpin the methodology represented in Figure 2.

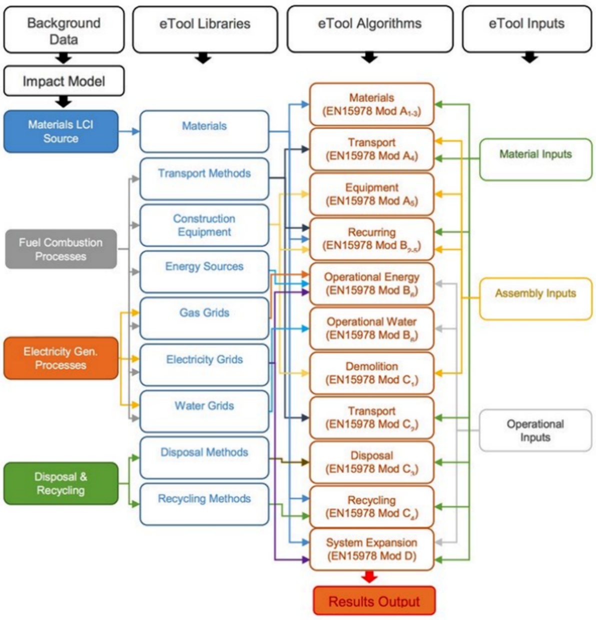

Figure 2. Relationship between e-tool LCI software library, inputs, outputs and algorithms.

3.4 *Whole LCA impact assessment results*

The baseline projected LCA GWP emissions for C23 MWCC were estimated at 2,262,196 tCO2e. These are presented in Figure 3 as percentages for the different quantification stages and modules shown in Table 1.

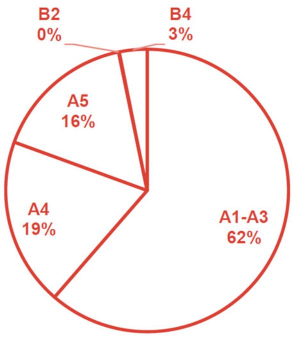

Figure 3. Estimated baseline emissions for the different LCA stages.

The results indicated that the majority of the estimated GWP, representing embodied carbon emissions, is attributed to the Product (A1-A3) lifecycle stage. The estimated projected GWP per asset or group of assets is illustrated as Figure 4.

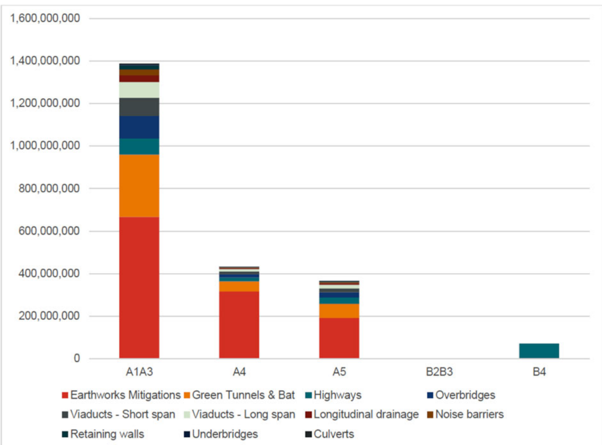

Figure 4. Estimated assets' baseline LCA GWP emissions (kgCO2e).

The hot spots, as identified by assets, are also presented as a percentage contributor to the total projected estimated LCA emissions in Figure 5.

Figure 5. C23 Carbon hot spots.

3.5 *Baseline whole LCA carbon targets*

The validated baseline LCA carbon emissions, along with those estimated by HS2 from the EDR, are summarised in Figure 6. Based on the validated baseline results, HS2 and EKFB/ASC agreed on a target of 50% carbon reduction for the C23 MWCC. Figure 6 also presents HS2's overall carbon reduction targets for MWCCs and the specific target set for C23.

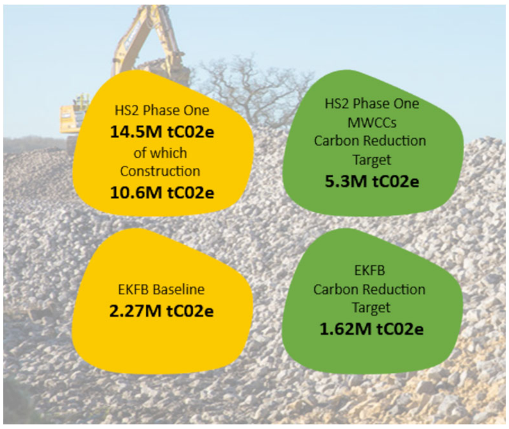

Figure 6. EKFB carbon baseline LCA and agreed targets.

4 GEOTECHNICAL SUSTAINABILITY STRATEGY

4.1 *Geotechnical optimisation and design efficiencies*

Heavy earthworks mitigation measures were identified as contributing approximately 50% of the total GHG in the validated estimated baseline LCA for the C23 section of HS2. Detailed analysis during the baseline quantification stage revealed that the primary sources of these projected emissions included:

- Imported engineered fill and aggregates, used extensively in the construction of embankments and as replacement fill for foundation treatments,
- Concrete and steel, required for structural elements of heavy engineered earthworks mitigation to meet HS2's stringent static and dynamic performance criteria, and
- Binder materials, such as cement and lime, are used to enhance the geotechnical strength properties of soils.

These heavy-engineered earthwork solutions were identified as critical targets for carbon reduction. Consequently, they became the cornerstone of the geotechnical sustainability strategy commitment, focusing on optimisation and design efficiencies to:

- Identify alternative low-carbon, optimised, and efficient design solutions, including the use of site-won materials, soil stabilisation techniques, and digital design tools,
- Achieve cost-saving incentives through integrated carbon and cost analysis, and
- Optimise mass haul baseline plans to reduce haulage distances, minimise spoil, and improve resource efficiency.

This targeted approach to earthworks carbon mitigation was aimed at demonstrating the potential significant environmental and economic benefits that can be achieved when sustainability is embedded early in the design process.

4.2 *Carbon footprint measurement and management*

An industry-recognised carbon reduction hierarchy was adopted to guide targeted geotechnical optimisation and design efficiency initiatives (Figure 7). It is an interrogative LCA optioneering process built around evaluating the following:

- Is there a 'build nothing' solution?
- Can we build less?
- Can we replace high-carbon material with low?

The same life cycle stages and modules used to quantify the baseline carbon emissions (Table 1) were applied to the targeted geotechnical optimisation and design efficiencies assets, with more emphasis on the product stage, as these were the main contributors to overall carbon emissions generated by the heavy earthworks mitigation measures.

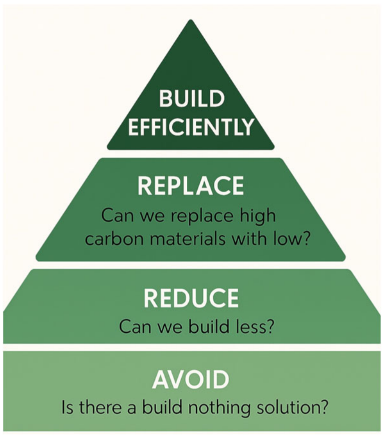

Figure 7. LCA hierarchy used for geotechnical optimisation.

For geotechnical opportunities, a value engineering approach incorporating measurement and tracking was adopted to define low-carbon alternatives, implement designs, quantify carbon, assess impacts, monitor progress, review outcomes, and communicate results for agreement. This process is illustrated in Figure 8.

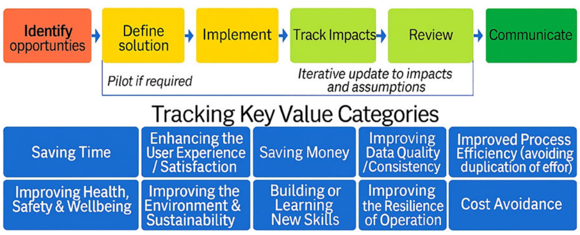

Figure 8. Value engineering measurement approach.

The value engineering measurement approach forms an integral part of the route-wide carbon management plan, developed in alignment with the main components of the carbon management system outlined in PAS 2080 (BSI, 2016). The plan defines the process for identifying opportunities to reduce whole-life carbon, setting targets, measuring, monitoring, tracking, and reporting progress. The route-wide plan is illustrated in Figure 9.

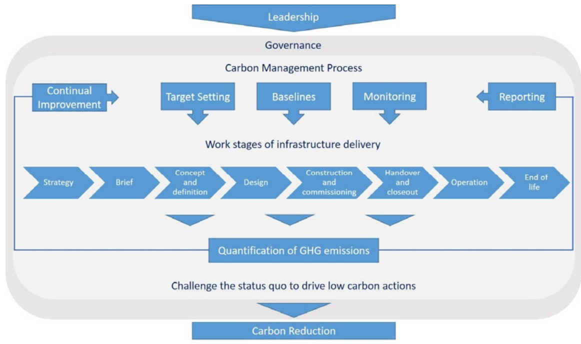

Figure 9. Carbon management plan in line with PAS 2080 (BSI, 2016).

5 GEOTECHNICAL OPTIMISATION AND DESIGN EFFICIENCIES

5.1 *Opportunity no.1 - Mainline Cuttings (Avoid)*

5.1.1 *The issue/risk*

The ground conditions beneath the C23 route include over-consolidated high plasticity clays and Mudrocks. These geological units are known for their unfavourable response to loading/unloading conditions. During scheme design, six (6) deep cuttings were identified as high risk due to predicted long-term heave at their base exceeding the maximum tolerable criteria set by HS2 Technical Standard - earthworks (TS-E) (HS2, 2019). Following preliminary optioneering, a reinforced concrete piled slab was selected as the most suitable mitigation solution to reduce long-term heave.

5.1.2 *Optimisation and design efficiency*

Earthworks mitigation measures were identified as significant carbon hotspots. In the case of the cuttings, the primary sources of carbon emissions were attributed to the concrete and steel required for constructing reinforced piled slabs. Consequently, these high-risk cuttings were prioritised within the geotechnical strategy for optimisation and efficiency.

The design of these cuttings was critically reviewed using new, reliable data from the instrumented and monitored heave field trial (Katsigiannis, 2024) and asset-specific Stage 2 ground investigations. The review confirmed that long-term heave at these locations remained within the tolerable limits defined by HS2 TS-E. This led to the successful removal of all piled-slab heave mitigation measures, thereby avoiding the transportation and use of material, including aggregates, steel reinforcement, and temporary casing (totalling approximately 2.3 km in length and 641 piles).

5.1.3 *Carbon reduction measurement*

Design efficiencies achieved in terms of material embodied carbon and other product stages, calculated using the e-tool LCA software, are summarised in Table 2.

The value management approach integrated into the route-wide carbon management plan was used to report and communicate the above design efficiencies, implement and track impacts and progress.

Table 2. Total estimated embodied carbon reduction resulting from elimination of all reinforced piled slab heave mitigation measures.

Mitigation Type	A1A3 Material embodied (tCO2e)	A4 Transportation (tCO2e)	A5 Construction (tCO2e)
Heave piled slabs	62552	1480	243

5.2 *Opportunity no. 2 – Embankments (Build less)*

5.2.1 *The issue/risk*

Similar to the risk associated with long-term heave for cuttings, preliminary design of embankments under track loading found that the long-term ground movements of the majority of mainline embankments supported on high plasticity clays exceeded the maximum tolerable total and differential settlement criteria specified in HS2 TS-E (HS2, 2019). Following preliminary optioneering, the pressure relief drains (PRDs) option was selected as the preferred mitigation measure to accelerate long-term settlements. For example, for Stoke Mandeville embankment, the proposed mitigation comprised excavate and replace of 4m of soil for treatment of foundation and the installation of about 15,000 PRDS, which accounted at the time for nearly 35% of the total PRDs proposed along the C23 route.

5.2.2 *Optimisation and design efficiency*

The design of this embankment was critically reviewed using new reliable information from the long-term instrumented settlement field trials (Katsigiannis, 2024) and the asset-specific Stage 2 ground investigation. The review findings revealed the geotechnical strength parameters and stiffness of the in-situ plasticity clays, derived from the asset-specific ground investigation, to be better than previously assumed. Additionally, the long-term settlement magnitude obtained using the improved strength properties in conjunction with reliable information from the settlement field trials was much less than the maximum tolerable limiting criteria specified in HS2 TS-E. The revised settlement results obtained from the optimisation and design efficiency efforts are presented as Figure 10.

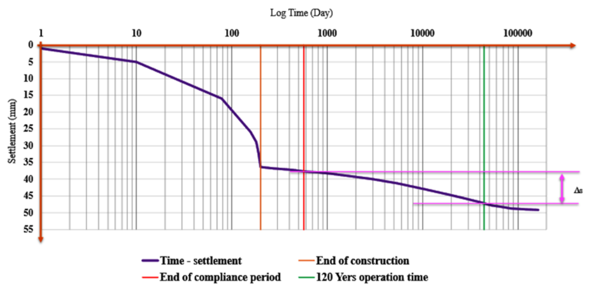

Figure 10. Optimised design – Settlement vs log time.

This efficient design resulted in the complete elimination of all PRDs for Stoke Mandeville embankment, significantly reducing the volumes of imported aggregates to site. The same optimisation and design efficiency approach was followed for other mainline embankments identified as hot spots, resulting in the elimination of over 80,000 PRDs along the C23 route.

5.2.3 *Carbon reduction measurement*

Design efficiencies achieved in terms of material embodied carbon and other product stage impacts, calculated using the e-Tool LCA, are summarised in Table 3. Similar to other opportunities, the value engineering measurement approach was used to report and communicate the above design efficiencies and track impacts and progress.

Table 3. Total estimated carbon reduction from optimised settlement mitigation.

Mitigation Type	A1A3 Material embodied (tCO2e)	A4 Transportation (tCO2e)	A5 Construction (tCO2e)
Pressure relief drains (PRDs)	13663	2416	1209

5.3 *Opportunity no. 3 - re-use of site won material (replace)*

5.3.1 *The issue/risk*

A significant challenge identified during the early stage of the project was the shortage of high-quality site-won granular fill material along the C23 route. This meant that significant volumes of engineered granular fill would need to be obtained from off-site and transported to site for construction of mainline embankments and as replacement fill for foundation's treatment. Such requirements and associated activities were identified during the baseline LCA carbon emission assessment as an intensive carbon hotspot.

5.3.2 *Optimisation and design efficiency*

Consideration of using site won material to compensate for the shortage of suitable granular fill formed an important part of the geotechnical strategic environmental sustainability targets. Efforts were therefore focused on ascertaining the feasibility of treating the unsuitable site fills with the aim of rendering them suitable for reuse as engineered fill for mainline embankments, earthwork transitions to structures, and for foundations treatment. Several material field trials were performed to assess the suitability of using unstabilised and stabilised fill materials as high-speed rail (HSR) embankment fills (Boumendjel-Game et al. 2024, Boumendjel-Game et al. 2025). The trial results confirmed the suitability of these materials for re-use as HSR fills and provided the minimum compaction performance requirements to be targeted during construction to ensure that the end product will achieve the static and dynamic performance requirements specified in HS2 TS-E (HS2, 2019). Figure 11 shows a typical example of material field trial embankment.

Figure 11. Typical example of an embankment field trial site.

Equipped with this invaluable information, the designs of the priority mainline embankments and earthworks to transitions, identified opportunities for optimisation, were revised by replacing the requirement of class 1A1 granular fill with suitable site won fill. This design efficiency approach enabled the development of sustainable solutions that have not only minimised the need for imported engineered granular fill but also reduced costs, shortened the construction schedule, and, most importantly, significantly lowered the carbon footprint associated with earthworks materials and construction. The design efficiency resulted in the re-use of about 3 million m^3 of site won materials as embankment fills, thereby avoiding the import of an equivalent volume of engineered granular fill.

5.3.3 *Carbon reduction measurement*

Design efficiencies achieved in terms of embodied carbon and material transportation, calculated using the e-tool LCA, are summarised in Table 4.

Table 4. Total estimated carbon reduction from optimising re-use of site won fill materials.

Mitigation Type	A1A3 Material embodied (tCO2e)	A4 Transportation (tCO2e)	A5 Construction (tCO2e)
Site won fill materials	73,012	95, 109	420

A notable outcome of this optimisation and design efficiency, compared to Opportunities 1 and 2, was the significant carbon reduction achieved by minimising the transportation of imported granular fill and replacing it with suitable site-won material.

An additional benefit of the embankment material field trials was the relaxation of the HS2 specification for binder content, reducing the minimum requirement from 2.5% to 1.5% (HS2, 2022). Although seemingly minor, this adjustment eliminated approximately 30,000 tonnes of lime and 4,500 tonnes of cement, resulting in a carbon emissions saving of over 60,000 tCO_2e.

5.4 *Summary*

From the outset, EKFB/ASC has been committed to supporting HS2 Ltd. in delivering its net-zero plan and achieving the 50% carbon reduction target set for the MWCCs. The case studies presented highlight exemplary opportunities that demonstrate the effectiveness of the geotechnical optimisation and design efficiency strategy developed to reduce the carbon footprint during the detailed design phase and contribute to the agreed baseline carbon reduction target for C23 main civil works. Combined with baseline emission assessments using the eTool LCA software, this strategy enabled the identification and development of alternative low-carbon, sustainable, and optimised solutions for key mainline earthwork structures identified as carbon-intensive hotspots.

It is important to note that this campaign is ongoing. Therefore, the carbon reduction values quoted in this paper reflect achievements during the detailed design stage and should be considered indicative of the potential reductions achieved at that time. Since then, further optimisation opportunities have been explored, along with enhancements to the eTool LCA software. These developments may yield different or improved carbon reduction outcomes, which are expected to increase as more opportunities are identified and more accurate measurement tools are employed.

6 CONCLUSIONS

It was understood from the outset that the defining features of the HS2 project included HS2 Ltd. key requirements to:

- Deliver a rail infrastructure with a 120-year design life,
- Ensure resilience to future climate change impacts, and
- Achieve a 50% reduction in embodied carbon for the MWCCs, as part of its net-zero strategy.

EKFB/ASC committed early to support HS2 Ltd. achieve its net-zero ambitions by aligning its own carbon reduction targets through the agreed carbon reduction baseline for C23 Contract. A major contribution was achieved by developing a route-wide whole-life carbon assessment (LCA) methodology, enabling robust measurement and management of carbon emissions. This was further strengthened by a targeted geotechnical optimisation and design efficiency strategy, focused on earthworks carbon mitigation and delivering significant reductions, as demonstrated by the exemplary opportunities highlighted in this paper. Together, these initiatives illustrate how embedding sustainability principles from the earliest design stage and integrating them into the culture and mindset of the delivery teams across the supply chain can generate substantial environmental and economic benefits. The geotechnical strategy emphasises the critical role of technical innovation in achieving meaningful carbon reductions and supporting HS2's long-term net-zero objectives.

7 ACKNOWLEDGEMENTS

The authors would like to thank HS2 Ltd. for their support in the preparation of this paper and Dr Georgios Katsigiannis for his key role in developing the strategy.

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