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

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-8


ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

State-of-the-art Report

# High-speed rail earthworks design developments and innovative trials – building Britain's technical legacy

## Travaux de terrassement pour un train à grande vitesse, development de conception et essais innovants - construire l'héritage technique de la Grande-Bretagne

G. Katsigiannis*
*Ferrovial Construction, London, UK*
**georgios.katsigiannis@ekfb.com*

**ABSTRACT**: Selection of appropriate engineering mitigations for Britain's new high speed rail line HS2 earthworks to ensure compliance with track slab performance criteria reflective of the railway's high operating speed represents a major technical challenge which is exacerbated by the challenging ground conditions encountered in the central section (Contract C23) of Phase One. High plasticity over-consolidated clays and extremely weak and weathered mudstones are prone to large magnitude and long duration movements due to loading or unloading. To overcome the technical challenges associated with uncertainty in predicting long-term ground behaviour and ensuring subgrade performance with limited previous case studies on ground formations that had not been extensively studied, the C23 team developed and implemented collaboratively with the Client a number of large-scale innovative Earthworks trials to increase confidence in heave and settlement predictions, pursue significant design efficiencies, validate the geotechnical performance of engineering fill materials and maximise the material re-use of the site won soils. This paper provides an overview of some of these large-scale earthwork trials and the design and construction lessons learnt describing how the C23 team set new standards of practice for the industry while building a strong technical legacy which will be passed on to future infrastructure projects in the UK and abroad.

**RÉSUMÉ**: La sélection des mesures d'atténuation technique appropriées pour les travaux de terrassement de la nouvelle ligne ferroviaire à grande vitesse britannique HS2, afin d'assurer la conformité aux critères de performance de la dalles de la voie ferrée reflétant la grande vitesse operationelle du chemin de fer, représente un défi technique majeur qui est exacerbé par les conditions de sol difficiles rencontrées dans la section centrale (contrat C23) de la première phase. Les argiles sur-consolidées à haute plasticité et les mudstones extrêmement faibles et altérés sont sujets à des mouvements de grande magnitude et de longue durée dus au chargement ou au déchargement. Pour surmonter les difficultés techniques liées à l'incertitude dans la prédiction du comportement du sol à long terme et assurer la performance de la plate-forme avec des études de cas antérieures limitées sur des formations géologiques qui n'avaient pas été étudiées de manière approfondie, l'équipe C23 a développé et mis en œuvre en collaboration avec le client un certain nombre d'essais de terrassement innovants à grande échelle pour accroitre la confiance dans les prédictions de soulèvement et de tassement, poursuivre des efficacités de conception significatives, valider la performance géotechnique des matériaux de remblai d'ingénierie et maximiser la réutilisation des matériaux des sols gagnés sur le site. Cet article donne un aperçu de certains cas de ces essais de terrassement à grande échelle et des leçons tirées de la conception et de la construction, décrivant comment l'équipe C23 a établi de nouvelles normes de pratique pour l'industrie tout en construisant un solide héritage technique qui sera transmis aux futurs projets d'infrastructure au Royaume-Uni et à l'étranger.

**Keywords:** Earthworks; high-speed rail; heave, settlement; materials; lime.

## 1 INTRODUCTION

### 1.1 The HS2 project

In January 2012, the UK Government announced its intention to proceed with a new high-speed railway line (HS2) and published the preferred line of the route from London to the West Midlands as the first phase (Phase 1) of a national high-speed rail network. Phase 1 involves the construction of a new railway line of approximately 230 km in length between London and the West Midlands. For construction purposes, the overall route was subdivided into three Delivery Areas:

- Southern
- Central
- Northern

The delivery areas were further subdivided into seven areas, each representing a main works civils contract (MWCC).

### 1.2 The C23 Project

EKFB, a joint venture that brings together international expertise from four leading civil engineering construction companies: Eiffage, Kier, Ferrovial Construction and BAM Nuttall, have been appointed by HS2 Ltd to deliver Civil Engineering works across an 80km section of the new high speed rail link between the Chiltern Tunnel and Long Itchington Wood. The C23 project represents the biggest single geotechnical contract ever awarded in the UK and the scope includes 45 high-speed rail (mainline) embankments and 30 cuttings, 15 viaducts, over 5 km of green (cut and cover) tunnels, 22km of road diversions and 81 overbridges. The earthworks operations include over 30 million cubic metres of excavation.

The Arcadis, Setec, Cowi Design Joint Venture (ASC) has been appointed by EKFB to provide detailed design services for the civil engineering assets with additional support being provided by TYPSA, ARUP and WSP.

### 1.3 Technical challenges

What differentiates HS2 from other earthworks projects in the UK is the tight end product performance criteria for the high-speed rail earthworks assets required to be achieved over the design life of 120 years, reflective of the selection of slab track system and the high operating speed of the rail line. The minimal operational maintenance of the slab track means that it cannot accommodate as much movement as a ballasted track, and therefore any movement of the supporting platform must be kept within specified limits to maintain the safe operation of the railway. Hence, strict post track slab installation heave and settlement performance criteria are imposed by the HS2 Technical Standards - Earthworks to ensure the required geometrical accuracy and stability of the track. Selection of appropriate engineering measures to achieve compliance with the HS2 performance requirements, represents a major technical challenge for the project and has been the key focus area of the geotechnical design teams.

This technical challenge is exacerbated by the particularly challenging, uncertain, and variable ground conditions encountered across the length of the C23 contract. Over-consolidated and high plasticity clays such as the Gault, Ampthill, Kimmeridge and Clay formations and weak mudstones such as the Lias Group Whitby, Dyrham and Charmouth formations are particularly prone to large magnitude and long duration ground movements due to loading or unloading, resulting from variable soil stiffness and low soil permeability.

The severity of impact on the track system combined with the uncertainty presented by the prevailing ground conditions create specific ground risks within the C23 Project area, the key earthworks risks identified by HS2 as the project developed included deep cutting heave, embankment settlement and dynamic amplification.

Overall, the biggest and most pressing challenge for EKFB and ASC has been to identify, specify and build appropriate earthworks design measures to effectively mitigate these technical risks whilst at the same time ensuring that the carbon footprint and the impact on the environment are minimised.

At an early stage in the development of the Scheme Design HS2 and EKFB agreed that investing in a series of earthworks trails during the design stage would enable greater understanding of some of the specific performance characteristics of some of the key strata. This approach reduced uncertainty and enabled efficient solutions to be incorporated into the design. The key to receiving the Client’s support for these early trials was to demonstrate their potential to enable cost efficiencies into the design by reducing uncertainty.

## 2 SETTLEMENT

### 2.1 Predicting settlement

In saturated clay soils of low permeability, the loading due to embankment weight initially results in an immediate settlement and the development of excess pore pressure. This is followed by time dependent consolidation settlement.

The prediction of settlement and comparison against acceptability criteria for the project requires an estimation of both the magnitude of total potential settlement and the time period over which that settlement will occur. Settlement is calculated considering 3 components: immediate (i.e. undrained, elastic or instantaneous), consolidation (i.e. primary, time dependent) and secondary (i.e. creep). Total long-term settlement is the sum of the three components although secondary creep settlement is often assumed to be negligible in over-consolidated clays.

## 2.2 Settlement criteria

The HS2 Technical Standard - Earthworks (HS2, 2019a), defines "earthworks settlement" as *the permanent downward displacement of the earthwork due to static effects (such as consolidation) and any accumulated effects of dynamic loading.* The following sources of settlement were addressed by the design: a) settlements within embankment materials; and b) settlements in natural soils below embankments, including secondary consolidation.

The total settlement limit value to be satisfied by design is 60mm for *long* (i.e. more than 800m long earthwork asset without a discontinuity) high-speed line embankments and 30mm for *short* high-speed line embankments. This further drops to 15mm for the areas within 150m of switches and crossings (S&Cs). The design also needs to satisfy the 1:1000 maximum longitudinal distortion criterion when assessed over less than 15m reducing to 1:2000 when assessed over 120m and 1:1000 maximum transverse distortion to the alignment. The above limit values are to be applied from the time of installation of slab track and for a design life of 120 years.

Several typical mitigations for earthworks settlement are suggested by the HS2 Technical Standards with the ones listed below selected by the C23 JV:

- Excavate and replace (E&R): where the unsuitable material is at shallow depth, and groundwater conditions are favourable to open excavation.
- Consolidation by temporary surcharge: accelerate consolidation of compressible soils.
- Consolidation with band drains: in association with surcharging to reduce time to achieve consolidation.
- Hold period: a duration of time within the MWCC contract where the majority of settlement is allowed to occur prior to track construction. Surcharging and band drains may be used to accelerate settlement and reduce the duration of the hold period.
- Piled foundation with load transfer platform: soft, compressible soil that cannot be improved by other methods, and deep E&R is impractical.

Moreover, for earthworks where the predicted ground movements approach the limits specified in Technical Standards, in-ground instrumentation (e.g. extensometers, piezometers) needs to be installed as appropriate to monitor the ground movements and changes in the porewater pressures during and following construction, in order to verify the predicted magnitude, timescale and rate of ground movement. Where instrumentation is needed to monitor settlement, both internal settlements within newly constructed embankments and settlements of natural ground beneath embankments is monitored.

## 2.3 Scheme design

The design of HS2 requires a relatively low alignment but visual and noise mitigation creates a need for large scale landscape bunds associated with many of the mainline embankments. Thus, while the mainline may only be typically 8 to 10m above existing ground level, in some cases the total embankment loading applied by the earthworks may be the result of up to 15m of fill placed over a footprint up to 100m wide.

Stage 1 Scheme design indicated that predicted settlement under these large embankment loadings could be significant with deformation possibly extending to notable depth, particularly within the Charmouth Mudstone formation. This resulted in extensive settlement mitigation measures being proposed under the mainline embankments, in the form of pressure relief drains (PRDs), which accelerate consolidation by providing shorter path for excess pore water pressures to dissipate, and piled load transfer platforms (PLTPs), which reduce settlement by transferring the load to deeper more competent strata. The majority of settlement mitigations were concentrated on viaduct transitions where HS2 longitudinal distortion criteria are particularly onerous when combined with construction programme constraints. The total proposed design mitigations across the 45 mainline embankments included up to 95,000 PRDs and over 4,000 reinforced concrete piles. Requiring over 5,000m$^3$ virgin sand aggregate and 22,000m$^3$ of concrete including 3,250 tonnes of reinforcement, these were costly and carbon intensive settlement mitigation solutions.

## 2.4 Settlement trials

### 2.4.1 Trials scope and objectives

To mitigate uncertainty and assess the actual settlements that will occur with depth (magnitude, depth of influence, consolidation and immediate settlement, duration of settlement), embankment settlement trials were carried out inform detailed design and support the design optimisations. Two trial embankment monitoring sites were identified (see Figure 1) in the northern section of C23. These are referred to as Boddington Settlement Trial 1 and 2. The embankments were formed from material excavated from the adjacent cutting trial and were located within the footprint of future landscape earthworks to minimise double handling. The embankments loading induced settlement of the underlying soils which was monitored using several different techniques.

The purpose of the trials was to provide data on the settlement and corresponding stiffness and consolidation characteristics of the underlying soils. In order to measure this, shape arrays were installed in shallow trenches below the embankments. In addition, further instrumentation, comprising load cells, extensometers, and piezometers, were installed below Settlement Trial 2.

### 2.4.2 Settlement trials location

Settlement trials 1 and 2 are located 7.5 km approximately southeast of Southam and 14 km north of Banbury, on the outskirts of Wormleighton Village, Warwickshire.

*Figure 1. Settlement Trials aerial view.*

### 2.4.3 Ground conditions

The published geological map for the area shows the site located on solid geology of the Charmouth Mudstone Formation of the Lias Group, with no overlying superficial deposits. However, the ground investigation data records show locally Head is present within the footprint of the embankments. The Charmouth Mudstone Formation comprises grey mudstone with sporadic thin bands and nodules of occasionally shelly limestone. The Charmouth Mudstone Formation typically reaches thicknesses of 100 m to 150 m.

Based on the ground investigation information, the Charmouth Mudstone formation is inferred to have a highly weathered thickness of about 10 m. The formation has been distinguished in two facies: CHAM-C Z described as firm to very stiff slightly sandy slightly gravely CLAY; and CHAM-MDST extremely weak becoming weak with depth, thinly laminated/bedded dark grey slightly calcareous to calcareous MUDSTONE. Locally at settlement trial 2 at the sides of the stockpile, HEAD deposits of variable thickness from 0.3 m to 0.85 m, overlies Charmouth Mudstone Formation. This formation comprises generally very soft to stiff slightly sandy slightly gravelly CLAY.

### 2.4.4 Trial embankments construction

Prior to instrumentation installation and embankment construction the site was cleared of ecology and archaeology, temporary drainage was installed and the upper 300 to 400 mm of topsoil and soft subsoil was removed. For Settlement Trial 1, the construction started on 23rd of July 2019 and took about 2 months to reach the full height of the embankment. The geometrical characteristics of the first trial embankment are as follows:

- Embankment width at the base: 70 m
- Crest maximum width: 30 m
- Side slopes: 1V to 2.5H
- Embankment height: 8 m
- Embankment length: 170 m

For Settlement Trial 2, the construction started on 05th of November 2020 and took about 1 month to reach maximum embankment height of 8m. The geometrical characteristics of the second trial embankment are as follows:

- Embankment width at the base: 95 m
- Crest maximum width: 55 m
- Side slopes: 1V to 2.5H
- Embankment height: 8 m
- Embankment length: 150 m

### 2.4.5 Testing, results and analysis

The values measured by the total earth pressure cells installed below the trial were compared to the construction history which allowed an estimate of the bulk density of the fill to be made which was used to estimate the loading imposed on the underlying strata by both embankments.

Installation and performance of the magnetic extensometers was largely successful. When plotted, the extensometer results suggested, as might be expected, that the elastic settlement ceased shortly after the completion of the embankment. For Settlement Trial 1, the settlement at the end of construction was 55mm, compared to the observed settlement below Settlement Trial 2 of 40mm at the same point in time.

The Asaoka (Asaoka, 1978) method was used to interpret and extrapolate settlement observations for both Settlement Trials. The observed settlement during Settlement Trial 1 was plotted using four different time intervals, Δt (10, 25, 50 and 100 days) and the total settlement was estimated to be around 85mm.

It was concluded that the drainage paths are shorter than might be assumed from the ground investigation infromation, possibly suggesting that the discontinuities within the weathered and unweathered Charmouth Mudstone act as drains. If the ground model is forced to fit the initial drainage scenario, with longer drainage paths, then the values of the coefficient of consolidation (cv) needed to provide a match to the settlement data are significantly larger than the values measured from oedometer tests. Based on the above, the drainage path length was assumed to be 4.8m which would give a height of the assumed compressible layer of 4.8m for one way drainage and 9.6m for two-way drainage. Using these lengths, the cv was estimated to be 1.3m$^2$ per year for one-way drainage and 1.8m$^2$ per year for two-way drainage.

The observed settlement during Settlement Trial 2 was plotted using the same time intervals (10, 25, 50 and 100 days) and the total settlement was estimated to be around 96mm. Drainage path lengths of 3.1 and 6.2m or one and two-way drainage were adopted while two way drainage into the underlying limestone was also checked. Using these lengths, the cv was estimated to be 1.0m$^2$ per year for one-way drainage and 1.3m$^2$ per year for two-way drainage.

While consolidation was still ongoing at slower rate when the embankments were decommisioned to allow for construction of the permanent works to proceed, the extensometers showed that 65% of the settlement occurs in the weaker soils between ground level and 2.5m. These soils will likely be dug out and replaced (E&R mitigation) during the HS2 permanent embankments construction. In addition, only 4% of the total movement was measured in extensometers installed below 15m which enabled the designers to succefully establish the zone of influence of the embankment loading.

Several vibrating wire piezometers were installed to monitor pore water pressure at different depths below Settlement Trial 2. The smoothed data from these plots allowed the excess pore water pressures to be calculated and plotted with time. Upper piezometers, installed from 10 to 20m depth, showed, as expected, that the excess pore water pressures increased at the end of loading and decreased through the monitoring period.

### 2.5 Settlement design efficiencies

Based on the observations from both Settlement Trials, the settlement analyses were refined in the detailed design, supported also by information from the targeted ground investigation and laboratory soil testing results within the high-risk areas of the C23 embankments and transitions zones to viaducts. The horizontal permeability was assumed to be greater than the vertical permeability due to conditions such as particle orientation, fissures and jointing in the rock due to geological processes and the possible presence of silt partings while a moderate increase in soil stiffness values for Charmouth Mudstone was also confirmed. The implementation of the findings in the detailed design of the permanent embankments eventually resulted in the elimination of 3,070 load transfer platform piles (59km total piling length) and removal of over 80,000 PRDs (640km total vertical drain length) as part of the settlement mitigations. This contributed to approximately 20,000 tC02 emissions savings including material embodied carbon and emissions related to transportation and construction works.

## 3 HEAVE

### 3.1 Predicting heave

The HS2 Phase 1 alignment creates the requirement for several deep (up to 30m) cuttings within the C23 area which will be underlain by high plasticity over consolidated clay and mudstone deposits. Since the early stages of the scheme design, there has been an appreciation of the level of risk associated with heave occurring at the base of such excavations with magnitudes and time to completion which could cause unacceptable deformations in the sensitive HS2 track slab.

During the excavation of a cutting, many tonnes of soil are removed and the ground below the formation level experiences a reduction in vertical stress which causes the ground to relax or rebound; this upward expansive movement is defined as heave (Butler et al., 2020).

Heave has been observed in over-consolidated high plasticity clay soils across the UK and is expected to occur in deep cuttings excavated in Gault, West Walton, and Oxford Clay formations and in mudstone and clay geological formations of the Lias Group of Jurassic age. The heave movement is anticipated to comprise of two main components:

- Immediate heave due to vertical unloading (elastic confining stress relaxation)
- Plastic and time dependent heave which is assumed to be the inverse of a consolidation settlement mechanism.

The time-dependent component is the main concern as it has the potential to extend well into the operational phase of HS2. It was recognised at an early stage that there were limited case studies of the heave phenomenon in the strata present in the C23 project area and that this created significant uncertainty in predicting long-term ground behaviour. The predicted heave behaviour largely depends on the soil stiffness; stress history and locked in horizontal stresses; and the soil permeability which are parameters notoriously hard to confidently measure even with advanced laboratory or in-situ soil tests.

Initial analysis undertaken at concept stage suggested that cuttings greater than 12m depth in the high plasticity clay strata likely to be encountered by the HS2 could exhibit significant long-term heave and thus present a risk of long-term deformation.

### 3.2 Heave criteria

The HS2 Technical Standard for Earthworks (HS2, 2019a), defines "earthworks heave" as *the permanent upward displacement of the earthwork due to static effects, including hydraulic uplift.*

The total heave limit value to be satisfied by design is 60mm for *long* high-speed line cuttings and 15mm for *short* cuttings. This further drops to 10mm for the areas within 150m of S&Cs. The design also needs to satisfy the 1:1000 maximum longitudinal distortion criterion when assessed over less than 15m reducing to 1:2000 when assessed over 120m and 1:1000 maximum transverse distortion to the alignment. The above limit values are to be applied from the time of installation of slab track and for a design life of 120 years.

### 3.3 Scheme design

During scheme design, heave was assessed by ASC DJV, and numerical analyses were undertaken. Based on these studies, 6 deep mainline cuttings were identified as high-risk where the predicted long-term heave movements exceeded the HS2 Technical Standards limits and hence provision for robust heavily engineered mitigation was considered necessary. Following optioneering studies, a piled supported 1m thick reinforced concrete slab was selected as the most appropriate heave mitigation. Within the 6 identified cuttings of concern the total proposed mitigation slabs encompassed over 2.3km of the route and incorporated over 640 tension piles. Requiring a total of 37,800m3 concrete and 5,700 tonnes of reinforcement, this was a costly and carbon intensive heave mitigation solution.

### 3.4 Heave trial

#### 3.4.1 Trial scope and objectives

Due to uncertainty in predicting long-term ground behaviour, particularly estimating magnitude, and duration of deep cutting heave below formation level during 120 years of operation, it was proposed to undertake a heavily monitored trial cutting to inform the understanding of the heave. The aim of the heave trial cutting was to provide an increased level of certainty in the estimation of heave that could be incoperated into the detailed design of the earthworks to enable the optimisations of mitigation measures for the potentially heaving cuttings.

A combination of in-ground magnetic extensometers and inclinometers, and surface topographical targets were specified to record ground movements. Vibrating wire piezometers were specified to record changes in pore pressures. Generally, the design of the extensometers and piezometers considered the depth of influence of anticipated ground movement due to stress relief while the inclinometers were installed in lower and mid-upper slope. Moreover, a weather station was installed to allow seasonal trends to be investigated.

#### 3.4.2 Trial location

The site selected for the trial was located 7.5 km approximately southeast of Southam and 14 km north of Banbury, on the outskirts of Wormleighton Village, Warwickshire. The topography of the site is characterised by the rolling hills of the area and was constructed on the HS2 line of route and will ultimately form the northern-most 300m of the approximatley 2 km long Boddington Cutting.

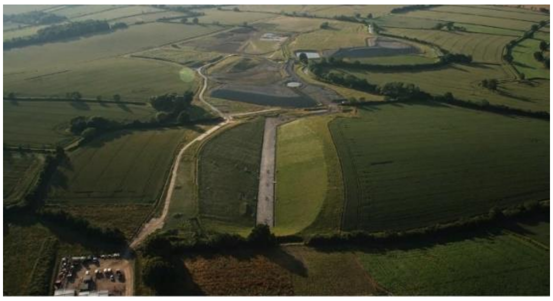

*Figure 2. Heave Trial aerial view.*

#### 3.4.3 Ground conditions

The site is underlain by the Charmouth Mudstone formation of varying weathering grades with minor head deposit in the vicinity of the transition to the Oxford Canal South Embankment. The formation typically comprises grey mudstone with sporadic thin bands and nodules of occasionally shelly limestone. A potentially continuous limestone band was identified in the ground investigation that had the potential to impact the observed response to excavation.

#### 3.4.4 Heave trial construction

The cutting slopes were designed at an angle of 1V:4H with a platform width of approximately 17m and a maximum depth of about 15m to closely resemble the geometry of the permanent works. The total projected volume to be excavated, based on the trial cutting geometry, was 271,000 m$^3$. It was intended to undertake the excavation in one phase but due to adverse weather conditions and flooding events, the construction programme was carried out in 3 phases. After the clearing of ecology and archaeology, the construction of access routes and drainage, and the installation and baselining of instrumentation bulk earthworks commenced in August 2019, but the works were hampered by inclement weather throughout October culminating in a significant rainfall event at the end of the month. At the beginning of December 2019, EKFB were able to drain and recommence works on the site and the final excavation level was reached on the northern part of the cutting with approximately 2.50m of excavation remained on the southern part (volume excavated up to end of December 2019 was 257,500 m3 with 13,500 m3 left to excavate). Continuing restrictions due to weather and then the Covid-19 pandemic resulted in the final excavation works only re-starting in June 2020 with the final level of excavation reached at the end of July 2020.

*Figure 3. Heave Trial at formation level.*

### 3.4.5 Testing, results and analysis

Monitoring periods have been defined to ensure the ground response was recorded over the relevant periods.

- Monitoring Period 1 (pre-excavation): the period prior to the excavation, after installation of the in-ground monitoring instruments. This period was used to establish stable readings and set a baseline for each instrument.
- Monitoring Period 2 (excavation): the period from start of the excavations works, until the bottom of the excavation profile (formation level of the cutting) is reached. This period was originally specified to last 3 months in the design but actually lasted for approximately 1 year between August 2019 and July 2020 and has been sub-divided into 3 phases.
- Monitoring Period 3 (post excavation): the period from reaching final excavation profile to the decommissioning of the trial and commencement of the main works for the Boddington Cutting and Oxford Canal South Embankment. Monitoring over this period was critical, as the response of the trial cutting to unloading was expected to occur mainly on this period, and results from this monitoring would allow to confirm design assumptions and so possibly impact the specified heave mitigations for the permanent works. This period lasted for approximately 2.5-3 years from summer 2020 until early 2023.

The results from the Heave Trial indicated that the mechanism of heave movement in the base of the excavation is a distributed movement over a significant depth which can be attributed to swelling due to stress relief due to the excavation of the cutting. This occurred as both immediate (during excavation) and long-term swelling with a maximum value being recorded at the deepest part of the cutting.

The conclusion was that a maximum movement of 30-50mm occurred in the deepest parts of the cutting. The immediate heave was estimated at approximately 30% of the total observed movement (i.e. 10-15mm) which is distributed over a shallower depth than the longer term swelling. The magnitude of ground movement reduces with depth, with the proportion of immediate to long-term reducing as well. Negligible movement was considered to be occurring 35m below the base of the cutting. The swelling in the upper 2.5m was estimated to have reached 95% of the predicted total at after 2.5 to 3 years. The period to reach 95% of the predicted movement reduces with depth, reaching 1-1.5 years 25 m below the base of the cutting. A forward projection was undertaken for the surface monitoring points and upper most magnets located along the centreline of the cutting which indicated that there was a further 5-15mm of movement still to occur albeit at a very slow rate. This residual movement (which was below the HS2 Technical Standards total heave limit) was expected to be concentrated over the upper 2.5m located directly below the base of the cutting.

The trial also provided valuable lessons in relation to the installation and commissioning of the instruments and subsequent monitoring phases. The most prominent issue was the result of the flooding of the excavation during the works and the subsequent build-up of debris in several of the magnet extensometer monitoring ducts. The flooding also caused delays in the construction programme, resulting in 3 phases of excavation instead of the single, continuous phase of excavation specified as part of the design. There were also lessons learnt associated with the survey control and impact to the measurements due the casing reductions required during excavation.

In additon to heave, a second mechanism of ground movement occurred during the trial. This was a downslope ratcheting mechanism attributed to the seasonal drying and wetting in the near surface (1-2m bgl). A seasonal fluctuation of up to 10mm was recorded in the vertical inclinometers installed in the upper clay slope with approximately 50% being irrecoverable. This movement was comparable with observations in other cut slopes and is indicative of the "Vadose Zone" effects that are identifed as risks in the HS2 Technical Standard for Earthworks (2019a).

### 3.5 Heave design efficiencies

The Heave Trial observations indicated that the total measured heave was about half the original cautious prediction, and the rate of the movement was faster than the initially estimated rate. This greater certainty in the heave mechanism reduced the uncertainty and enabled a reduction in conservatism to be fed into the detailed design of the earthworks. The soil stiffness and anisotropic permeability values were refined supplemented also by information from the targeted ground investigation and laboratory soil testing results within the high-risk areas of the C23 deep cuttings.

The concentration of the observed residual movements over the upper 2.5m below the base of the trial cutting provided the sufficient evidence to the designers so that the heave of the permanent deep cuttings to be mitigated with a combination of 2-3m E&R with well graded Class 1 material (which in many cases were also required to satisfy the static and dynamic subgrade performance requirements) and a Hold Period ranging from 9 months to 22 months. This represented a more cost-efficient response to the remaining residual heave risk and resulted in the removal of all 6 areas of pile slabs in the detailed design eliminating the need for 37,000 $m^3$ of concrete and 5,700 tonnes of steel reinforcement and contributing to approximately 70,000 tC02 emissions savings including material embodied carbon and emissions related to transportation and construction works.

## 4 PERFORMANCE OF EARTHWORK MATERIALS

### 4.1 Earthworks scale

C23 is the single largest earthworks contract ever awarded in the UK requiring about 30,000,000 $m^3$ engineering fill materials for high-speed line (mainline) embankments, highway earthworks and landscape (environmental) bunds. This large volume of material is being sourced from the C23 cutting and green tunnel excavations and needs to be properly handled and transported in line with the EKFB's complex and sophisticated mass haul plan representing a significant planning and operations challenge.

### 4.2 Embankment requirements

HS2 mainline Upper Embankment Fill (UEF) and Lower Embankment Fill (LEF) consist of either structured chalk, stabilised chalk, stabilised glacial till or granular fill e.g., Class 1A1, 1B1, 1C1, 9G, 9J or 9K (HS2 SCEW 600, 2019b). Cohesive soils (Class 2) with high sulphate contents are not suitable for reuse as mainline or highway embankment fill due to risk of swelling while low to intermediate plasticity cohesive soils (LL <50%) with low sulphate content are suitable for reuse as mainline embankment fill after stabilisation. High plasticity cohesive soils (LL>65% and PI>40%) are Class 4 (HS2 SCEW 600, 2019b).

In addition to the material and compaction requirements of the mainline fill, there are static and dynamic stiffness performance criteria required for the constructed earth structure i.e. Modulus of Deformation based on EV2 measurement and dynamic performance based on Raleigh Wave Velocity criteria.

In order to secure the C23 mass haul plan baseline and introduce further carbon and cost efficiencies by maximising site won material re-use, EKFB in collaboration with ASC and HS2, planned and executed a number of large-scale earthwork material trials utilising materials and construction techniques proposed for the main works. The aim of these trials was particularly to confirm the suitability of a number of earthworks materials for high-speed rail UEF, LEF and E&R (i.e. foundation treatment).

#### 4.2.1 Trial scope and objectives

The earthwork material trials were planned based on the availability of an area of land, the published geology, the underlying ground conditions, and the likely nature of locally available fill. The objectives of the trials included the review of suitable improvement options (e.g. stabilisation) for re-use of any excavated materials for embankment fill; determination of in situ Modulus of Deformation (EV2) and dynamic performance parameters; verification of the foundation conditions; earthworks control and verification to validate performance of earthworks during construction; and review of SCEW 600 contract specific Tables 6/1 and Table 1/5 requirements.

As mentioned before, many of the C23 embankments are built with Glacial Till stabilised with lime to increase its strength, density, stiffness, and shear wave velocity. A 3m height embankment trial was carried out in Newton Purcell area with lime stabilised locally sourced Glacial Till, obtained from a borrow pit excavated adjacent to the trial embankment.

The Glacial Till was encountered below the glaciofluvial deposits and was described to comprise firm, becoming stiff, grey to dark grey, slightly gravelly to gravelly clay. The gravel comprised limestone, flint, and mudstone, suggesting that the till is derived from local and distant rocks.

The design geometry of the embankment, which was governed by the surface geophysics testing requirements, comprised of target height of 3.5m, including 16 layers of 200-250 mm compacted thickness; and total length of 60m and width 20m including 2 testing areas 30m x 20m. For the construction of the embankment, the material was improved using binder contents of 1%, 1.5%, 2%, and 2.5% and produced the stiff to very stiff material generally seen throughout the trial. After adding lime, the Glacial Till classifies as 9J lime stabilised cohesive material.

### 4.2.2 Testing results

Strength/stiffness tests (UCS, triaxial, CBR, shear box) and the classification tests (particle density, pulverisation, calcium carbonate content, PSD) were conducted and samples were tested for optimum moisture content using modified (4.5kg hammer) and standard (2.5kg hammer) proctor tests and also for the natural moisture content tests.

Plate Load Tests were performed for measuring the EV2 of the material and Light Weight Deflectometer (LWD) for measuring the bearing capacity (deflection) of the subgrade/subsoils. The HS2 Technical Standard (2019a) requires minimum EV2 values of 45MPa – 60MPa and a maximum EV2 value of 500 MPa to be measured. For the measurement of EV2, the French standard procedure was specified which uses a 600 mm diameter plate and has an approximate depth of influence of 1.2m. The results showed that EV2 values remain mainly within the same range of 60-200 MPa and very small increases were observed as the embankment height was ascending. No significant differences were observed between the two test areas for each layer.

There was also an opportunity for the Continuous compaction control (CCC) to be tested in Newton Purcell trial. CCC is a roller integrated compaction measurement method for dynamically excited rollers, which allows for the compaction success to be continuously measured online. During the trial, the optimum number of compaction passes were assessed in line with the specification for the fill material and an optimized compaction rate was applied in the remainder of the embankment construction after the assessment.

Upon assessment of the trial results and considering the compaction and static performance requirements, an 1.5% minimum lime content was recommended by the DJV for HS2 permanent embankment fill. Minimum dry density of 94% and Maximum Air Voids of 5% were proposed as appropriate acceptance criteria for the 1.5% lime stabilised material.

Moreover, surface wave geophysical tests, namely MASW and CSW, were undertaken while rotary open hole boreholes were drilled through the completed trial embankment to a depth of 15m below formation level, to undertake downhole and crosshole seismic testing through the embankment fill and foundation strata to validate the inverted values of shear wave velocity from MASW/CSW surveys. The results from both the surface wave and intrusive geophysical methods succesfully confirmed exceedance of the shear wave velocity design assumption of 250m/s for the stabilised fill material for all minimum binder contents tested as part of this trial.

### 4.2.3 Material efficiencies

Overall, the earthworks materials trials successfully enabled the re-use of site won materials as engineering fill for mainline embankments and E&R. They also successfuly demonstrated the potential to reduce the minimum (lime) binder content from 2.5% to 1.5% while also satisfying the materials performance criteria, EKFB were able to eliminate up to 30,000 tonnes of lime for C23 permanent works, securing significant cost savings and over 50,000 tC02e reduction.

## 5 CONCLUSIONS

The planning and execution of the settlement and heave earthwork trials in advance of detailed design enabled the C23 teams to refine design parameters and incoperate significant cost efficiencies into the design by reducing or eliminating heavily engineered heave and settlement mitigations. The greater certainty as a result of these trials also enabled a reduction in the risk provision reduired for the project as it moved into construction. Ongoing construction stage monitoring installed in the permanent HS2 earthwork assets will further validate the information gathered from the field trials, in relation to settlement and heave in these challenging ground conditions and should enable further risk reduction and potential efficency in terms of the active managment of hold periods within the construction programme.

The C23 heave and settlement trials are amongst very few large-scale, instrumented earthwork trials carried out in the UK and will provide valuable information for the design of similar earthworks in the future.

Moreover, a large number of site won materials trials succesfully confirmed the improved performance through stabilisation and the suitability as engineering fill for permament works securing EKFB's mass haul plan but also introducing efficiencies by reducing the total volume of lime binder required in C23 embankments by 40%.

*Figure 4. Lime Stabilised Glacial Till Trial in Newton Purcell,*

Further earthworks design and material re-use efficiency opportunities have already been mapped out and are being pursued at the late stages of the detailed design, with particular focus on the remaining carbon hot spots.

EKFB technical teams working collaborativelly with the DJV and the Client are delivering technical excellence while building a lasting technical and sustainability legacy that will be passed on to future earthworks projects in the UK and abroad.

## ACKNOWLEDGEMENTS

The author would like to thank his colleagues from HS2 Ltd, EKFB JV and ASC DJV involved in the planning and design of the earthworks trials, the execution of works and the interpretation of the results and implementation of the findings in the detailed design of the C23 permanent earthworks. An acknowledgement is also due to the HS2 and EKFB Project and Risk Management teams that recongnised the value that the early implementation of those proposed trials represented.

## REFERENCES

Asaoka, A. (1978). Observational procedure of settlement prediction. Soils and Foundations, Journal of the Soils and Foundations Engineering, 18(4), 87-101.

Butler, S., Hope, A., Madinier, B., & Zilles, A, (2021). Ground Heave in Deep Cuttings: Evolution from Generic to Specific Models to Enable Refinement of a Risk Management Strategy. ICE Publication High Speed Two (HS2): Infrastructure Design and Construction (Volume1), 2021. https://doi.org/10.1680/hs2.65765.371.

HS2 (2019a). Technical Standard – Earthworks.

HS2 (2019b). Specification for Civil Engineering Works (SCEW) 600 series - Earthworks.