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Ground improvement design for a 12m high and rapidly constructed highway embankment

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1 Introduction

Highway infrastructure constructed on soft ground presents significant challenges due to the potential for excessive settlement, instability during rapid fill placement, and long-term serviceability issues. Embankments founded on alluvial soils are particularly vulnerable, with post-construction deformations often leading to poor ride quality, premature pavement deterioration, and differential movements at critical interfaces with structures. To mitigate these risks, a variety of ground improvement methods are routinely considered, with the final selection depending on ground conditions, programme constraints, and performance criteria.

The proposed A38 junction improvement scheme in central England represents a typical case study illustrating these challenges. The project involves the construction of embankments up to 12 m high overlying soft cohesive alluvium and granular deposits above weathered mudstone as part of turning a roundabout into a grade separated junction. The project also involved extensions to existing structures, including a bridge over an active railway line. The works were further constrained by an accelerated programme, requiring construction rates of up to 2 m/week and a maximum hold period of three months prior to carriageway surfacing. These constraints demanded an optimised ground improvement design that balanced short-term stability with long-term settlement control, particularly at interfaces with bridge structures and reinforced soil walls.

This paper presents the design development and validation of the selected ground improvement solution, including analyses undertaken using Finite Element Analysis (PLAXIS 2D) [1]. The findings highlight the performance of different improvement measures, their impact on settlement behaviour, and the integration of multiple techniques - band drains, lightweight fill, and controlled modulus columns (CMCs) to achieve the required performance within the project's programme constraints. The key challenges included:

- Rapid embankment construction and settlement constraint between new and existing structures.
- Embankment heights with significant differential fill thicknesses.
- Stability of reinforced soil walls and embankments and post-consolidation conditions.
- Minimising differential settlement at the interface with railway infrastructure.

2 Geology and ground conditions

The project site lies within the Derwent Valley, where superficial alluvial deposits overlie the Millstone Grit Group bedrock. Across the site, the ground profile is generally consistent and comprises:

- Made Ground / Embankment Fill: Typically, up to 2 m thick, comprising granular or cohesive fill of variable stiffness.
- Cohesive Alluvium: Firm to soft, occasionally very soft clay, 1 to 4 m thick, locally containing organic laminations. This layer represents the principal compressible stratum controlling settlement.
- Granular Alluvium (Sand and Gravel): Loose to dense sands and gravels underlying the cohesive alluvium, typically 2 to 4 m thick, providing drainage and partial load transfer to the underlying rock.
- Millstone Grit Group: Weathered sandstone (the upper 1 to 2 m is completely weathered), grading with depth to moderately and then unweathered sandstone at around 8 to 10 m depth, providing a competent founding layer.

Ground models for design were developed for each structure and embankment area using recent site investigation data. Groundwater levels were observed close to the base of the existing embankments. Representative characteristic parameters adopted for the design are summarised in Table 1, with moderately conservative values applied in line with Eurocode 7 [2,3] and National Highways [4] guidance. A lower quartile sensitivity analysis was also undertaken to capture variability in permeability and stiffness. The granular alluvium was modelled with drained strength parameters while the weathered Millstone Grit was assigned undrained shear strengths increasing from approximately 80 kPa at the top of the layer to over 200 kPa in the unweathered rock.

Local variations in strata were captured for each sub-area based on borehole data. The cohesive alluvium thickness generally decreases southward, with correspondingly higher rockhead levels. The most compressible conditions were recorded near the railway bridge where the cohesive alluvium reaches up to 4 m in thickness. This geological model formed the basis for numerical and analytical settlement and stability analyses presented in later sections and informed the selection of suitable ground improvement methods to manage variable compressibility and permeability across the junction.

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Table 1. Characteristic parameters adopted for design.

Strata	γ' (kN/m^3)	φ' (°)	Cu (kPa)	UCS (MPa)
Cohesive Alluvium	18	22	36	-
Alluvium – Sand & Gravel (medium to dense)	18	36	-	-
Weathered Millstone Grit Group (GG)	22	25	80	-
Moderately Weathered Millstone (GG)	22	26	-	0.75
Un-weathered Millstone (GG)	22	28	-	1.25

3 Ground improvement design

The ground improvement design for the site was validated through a combination of numerical and analytical analyses to assess settlement and stability during construction and in the long term. Analyses were undertaken using commercial Finite Element software (PLAXIS 2D - plain strain) and Rocscience Settle3, providing complementary assessments of embankment performance, soil-structure interaction, and retaining wall stability. The methodology focused on:

- Settlement Control: Immediate, primary, and long-term consolidation settlements.
- Stability Checks: Ensuring reinforced soil walls and embankment slopes remained stable during and after construction.
- Soil-Structure Interaction: Assessing load transfer between new embankments and existing infrastructure.

Where predicted settlements exceeded allowable limits, design interventions such as CMCs [5], band drains, excavation and replacement were applied. Sensitivity analyses were carried out to capture variability in compressible alluvial layers.

4 Design implementation

The design considered construction practicality, including installation rates, embankment sequencing, and the interface with reinforced soil walls. Embankments up to 6 to 8 m in height were constructed rapidly, with short hold periods to allow consolidation whilst reinforced soil walls were adopted as wing walls to enable the grade separation of the junction. The implementation of the design is discussed subsequently.

4.1 Embankment widening – Western arm

The widening of the embankment on the south side of the western arm of the roundabout, where the flood arch and railway bridge structures were to be extended, required careful management of settlement across the carriageway. New fill was benched into the existing embankment flank, and the upper layer of cohesive alluvium was excavated beneath the fill footprint and replaced with compacted granular material. Where the underlying alluvium remained, conservative stiffness and permeability values were adopted to capture potential variability. Maximum total settlements were predicted to remain below 100 mm, higher settlements were expected under areas of the existing embankment where no improvement was applied, highlighting the importance of localised ground treatment.

For the extension to the flood arch structure, lightweight fill was adopted to reduce loads on the soft soil and to protect existing masonry wing walls. The construction sequence involved the partial excavation of the embankment, replacement with compacted granular fill under the wing walls, and placement of lightweight aggregate to final levels. This method reduced the risk of differential settlements between the existing structure and the new embankment. Post-construction settlements were limited to less than 40 mm overall, with differential settlement between new and existing structures kept below 5 mm. Temporary construction-induced heave was minimal and quickly reduced as the fill load increased.

Cohesive alluvium behind the railway bridge abutments was partially excavated and replaced as part of the extension of this structure, with band drains installed in zones where full-depth replacement was not possible. This allowed staged consolidation, maintaining differential settlement between the new embankment and existing abutments within 5 mm. Excavation widths were optimised to reduce temporary works volume while providing adequate support. The approach ensured stable embankment slopes and minimal post-construction settlement, allowing for the 100-day hold period prior to carriageway surfacing.

4.2 Western approach to roundabout

The railway bridge is located on the western approach to the roundabout where the carriageway reaches approximately 10 m above the surrounding ground. The north side of the carriageway is constructed over the existing embankment, gradually reducing in height from approximately 8 m near the railway to 5 m at the roundabout, while the south side and southern slip road are built on full-height new embankments. The cohesive alluvium thickness varies from 1.5 to 1.8 m near the railway bridge, increasing to 2.5 m toward the roundabout.

Ground improvement was essential to limit post-construction settlement both behind the bridge abutments and across the carriageway due to the significant difference in embankment height. Controlled Modulus Columns (CMCs) were specified within approximately 25 m of the bridge to stiffen the cohesive alluvium. These bespoke short vibro-concrete columns, 360 mm in diameter and spaced at 1.3 to1.6 m, transfer load from the soft soil through direct head loading, negative skin friction, and end-bearing into the underlying granular layer. Columns are overlain by a 600 mm thick unreinforced granular load distribution mattress, with basal reinforcement providing additional lateral stability.

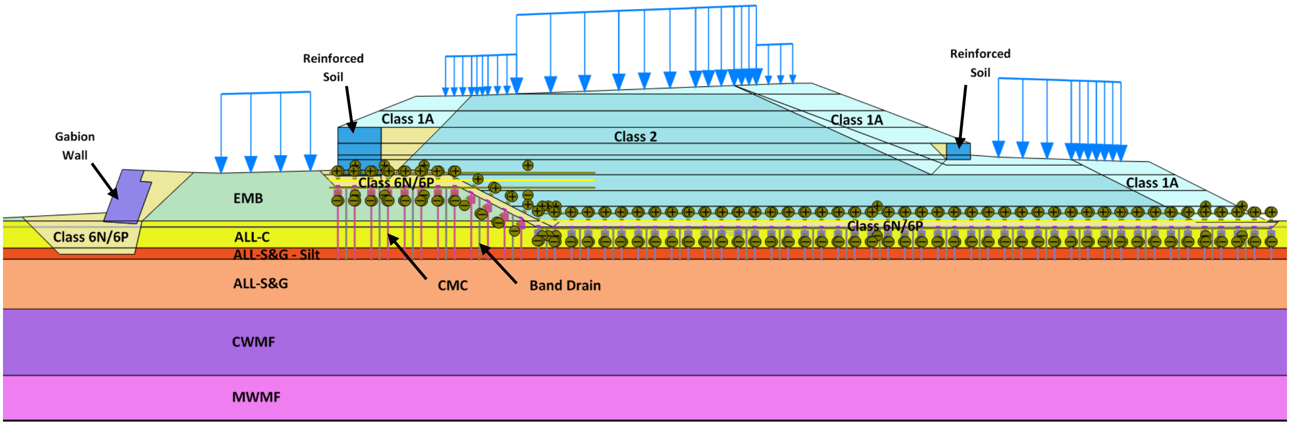

Figure 1. Existing and proposed embankment section.

Cross-section analysed in PLAXIS 2D is shown in Figure 1. The CMCs were modelled as embedded beam elements with a spacing of 1500 mm, and a diameter of 360 mm. The columns extended through the cohesive alluvium and existing embankment fill to 500 mm into the underlying granular layer. The overlying 600 mm granular mattress and basal reinforcement were included. Lower-bound values of compressibility and permeability were applied for the cohesive alluvium to capture potential variability. The analysis confirmed that the CMC layout, combined with basal reinforcement and optional temporary surcharging, effectively controlled post-construction settlement, maintained serviceable carriageway gradients, and mitigated differential movement across the embankment.

4.3 Central roundabout

The 10 m high embankment between the bridges required consistent support across reinforced soil walls to avoid differential settlement. Controlled Modulus Columns (CMCs) were installed to penetrate compressible alluvial layers into denser granular soil below. Band drains were placed in transition zones to accelerate consolidation, and basal reinforcement was used beneath the embankment to reduce lateral soil pressures and enhance slope stability during rapid construction. Post-construction settlements were limited to less than 25 mm near critical structures, while settlement gradients across the carriageway remained within acceptable limits. Localised excavation removed very soft or organic clays beneath wall foundations to prevent bearing failure.

4.4 Roundabout eastern arm

For the roundabout's eastern arm, the north side of the carriageway was constructed over the existing embankment, while the south side involved full-height new embankments. CMCs were installed near bridge abutments, with band drains deployed in less critical zones to accelerate consolidation. Embankment heights varied from 6 to 12 m, and the cohesive alluvium thickness ranged from 3 to 4 m. Selective excavation of very soft layers ensured a uniform foundation, maintaining post-construction settlement under 25 to 30 mm. Figure 2 shows an example cross carriageway post construction settlement profile from the analysis for different potential hold periods (no hold period up to a six month hold period). The peak occurs at the interface between the existing and proposed embankment. Transition zones between CMC-reinforced areas and band-drained zones were carefully designed to avoid abrupt differential settlement, with basal reinforcement providing additional lateral stability.

Further from the roundabout, the embankment lay partly on existing embankment and partly on new fill, with heights gradually reducing from 12 m to 6 m. Ground treatment objectives included controlling cross-carriageway settlement, limiting differential movement at transitions between the existing and new embankment, and maintaining stability during rapid construction. Settlement analyses indicated that allowing a 100-day hold period after embankment filling reduced post-construction settlement from approximately 50 mm to 33 to 39 mm, ensuring gradients remained within design limits.

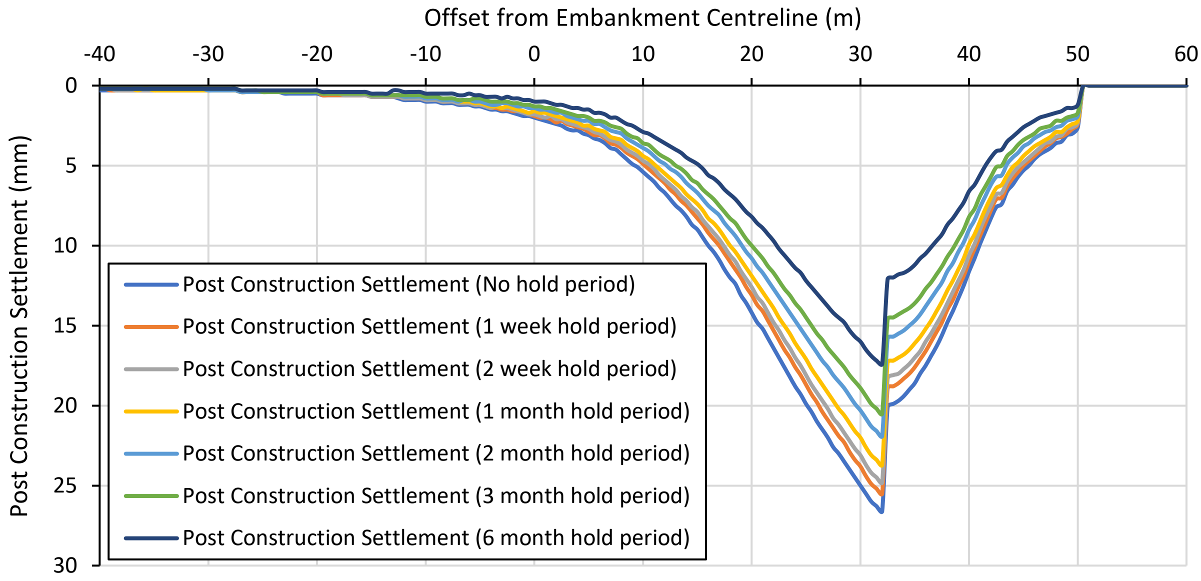

Figure 2. Example cross carriageway post construction settlement profiles for increasing hold periods.

In areas where embankment heights exceeded 6 m, band drains were recommended to supplement the CMCs, ensuring sufficient consolidation before surfacing. Transition zones between CMC-reinforced ground and band-drained areas were designed to smooth settlement profiles, with maximum post-construction differential settlements kept below 15 mm. Basal reinforcement beneath the embankment and retaining walls ensured lateral stability and helped distribute loads, while selective removal of very soft clays under critical sections maintained bearing capacity and prevented localised failures. This phased approach allowed rapid embankment construction at rates of up to 2 m/week while ensuring that post-construction settlements and gradients remained within serviceability limits. Continuous monitoring was recommended to verify consolidation progress and adjust surfacing schedules accordingly.

5 Conclusions

The ground improvement strategy successfully balanced rapid construction, large embankment heights, and soft, compressible ground conditions. The combination of CMCs, band drains, lightweight fill, and selective excavation and replacement effectively controlled total and differential settlement, ensuring long-term embankment stability and interfaces with structures. Post-construction settlements across carriageways remained within acceptable limits, even with up to 12 m of fill overlying soft soils.

Tailoring ground improvement techniques to specific sub-area conditions proved essential. Lightweight fill in critical locations reduced the differential settlement risk, CMCs provided uniform support, and band drains accelerated consolidation in partial replacement zones, allowing short hold periods without compromising performance. Careful sequencing and integration of complementary techniques achieved both construction efficiency and long-term serviceability.

Overall, the project demonstrates that integrated ground improvement solutions are critical for highway embankments over soft soils, particularly where rapid construction and high-performance requirements coincide. Lessons learned can guide future projects in selecting appropriate methods, designing transition zones, and managing settlement risks to maintain safe, durable, and serviceable infrastructure.

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