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Differential Settlement and Dynamic Load Effects across Lime Treated Rail Transition Zones

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Abstract – Railway transitions from cut to fill are locations across which significant differential settlements may develop. Compounded by similar abrupt changes to subgrade stiffness, accelerated track movement during high speed (HS) train passage may cause track-substructure deterioration and instability. This paper considers a foreseeable scenario in UK rail engineering with transition from unweathered Mercia Mudstone (MMG) to MMG cohesive fill. Separate analysis of (1) differential settlement using one-dimensional oedometer consolidation methods and (2) track bed movements using a three-dimensional Finite Element Analysis (FEA) with moving load were undertaken. This included comparison of untreated and lime treated embankment fill material with parameters for each taken from laboratory and field test data. Results showed a difference in settlement of 26.6mm across the modelled cut to 8metre fill transition giving differential settlement for untreated fill that was too high to meet literature criteria of <20mm over 20m. However, 1.5% lime treatment of the fill causes significant reduction to both consolidation settlement and track movement under dynamic loading to meet the serviceability criteria. Consideration of the full settlement profile across the transition has identified that the Rate of Change (ROC) of settlement is maximum at the start of the fill zone and the ROC in settlement could be a more relevant measure of what a moving train would experience with a sudden unloading/loading action. It is concluded that future work including a coupled FEA analysis, including consolidation and then subsequent stages modelling the resulting amplification of moving loads across the settled profile would give stronger understanding of how differential settlement causes rail level movement from HS traffic. This would help confirm how best to apply differential settlement criteria in geotechnical design of transitions and whether ROC in settlement (e.g. 1mm per 1m) is more informative than a settlement range across a longer fixed distance.

***Keywords*:** cut to fill transitions, differential settlement, railway, settle3, FEA, lime stabilisation

1. Introduction

New high-speed (HS) railways, i.e. >250km/h, are planned in the United Kingdom to meet expected growing demand for rail transport. Although HS rail has many benefits, the loading regime from such fast trains have potential to affect serviceability and maintenance due to increased vibrations in the track bed system [1]. Railway lines require gentle gradients and cut (natural ground) to fill (compacted embankment material) transitions are needed in variable terrain. These transition areas are often associated with abrupt track stiffness variations which can cause significantly increased track sub structure and track geometry deterioration [2].

The loading experienced in railway environments revolves around cyclic loading of the track super and sub structure by moving train loads and is one of the main sources of deterioration. As the train wheel moves towards a reference sleeper the load increases linearly to a maximum when directly above it and then decreases at the same rate as the wheel moves away and outside of the sleeper tributary area. The resultant stresses are distributed into the track bed and subgrade and are influenced by variations in both track stiffness and unloaded track geometry (level). This cyclic loading by trains causes permanent deformations (settlement) in the underlying subgrade soil.

Subgrade settlement of a cohesive soil is characterized by two phases: the initial phase where elastic settlement occurs due to immediate loading and then long-term consolidation settlement under sustained load, the latter includes slow pore water pressure dissipation and particle redistribution [3]. The severity of the settlement depends on the natural or engineered properties of underlying material and the magnitude of load [4]. Thus, embankment fill will undergo settlement due to its own self-weight and from the rail system live loading, with higher embankments having greater overlying mass and more cumulative surface settlement. This presents a differential settlement in the rail level across transitions and the potential for increased track deterioration as the change in displacement excites the train components, leading to a dynamically amplified vertical train-track interaction force [5]. A deteriorating track condition where this influence is excessive would further exaggerate the track displacements and unabated would require costly temporary line speed reductions and further engineering works to remediate. Therefore, to guarantee the operational safety and ride comfort of a HS railway, understanding the long-term settlement behaviour is crucial for establishing acceptable differential settlement profiles across zones transitioning from cut to cohesive fill.

Lime stabilisation is a popular ground improvement method which results in rapid improvement of cohesive fill engineering properties through chemical alterations at the surface of clay particles. Among the reported benefits are increases to stiffness and reduction to the primary consolidation behaviour of the treated material [6] and such improvements could have a significant positive impact to enable use of locally available cohesive fill which may otherwise be too poor to use in HS rail embankments, especially within transition zones.

This paper presents the results of a series of differential settlement calculations and moving load finite element analyses of a transition from an unweathered 'cut' of Mercia Mudstone to an embankment formed from weathered Mercia Mudstone fill. Variations considering untreated and lime stabilised fill are compared and the potential benefits of lime treatment in such transition zones discussed.

2. Methodology

The approach taken was (1) Identify the serviceability criteria relevant to UK rail track systems, (2) Establish a baseline model of a foreseeable cut to fill transition relevant to the UK, and (3) undertake differential settlement and moving load analyses considering how variations in fill material properties (untreated or lime treated) and transition geometry influences results.

2.1. Serviceability criteria

To determine the settlement and track deflection limits and hence success criteria of the modelling, the serviceability requirements of railway lines was reviewed. UK practice has a primary focus on Network Rail guidance which, for tracks with line speeds >201kmh, limit the maximum permissible vertical rate of change (ROC) of the rail to 2mm along a 10m track length during train passage. This expected normal range of oscillation is used for suspension design and areas where track quality is deteriorating outside these limits are typically detected in service by an instrumented measurement train.

As noted in the introduction, differential settlement of the subgrade is one factor that may substantially increase the vertical ROC from a passing train especially at HS. However, Network Rail guidance only limits the total settlement from design level, e.g. 30mm for ballast track and 5mm for slab track (assuming >125mph speed). There is no upfront design means to determine whether a differential settlement profile across a transition is acceptable and instead this would be verified after construction using the measurement train. In the absence of a relevant UK guidance, it is necessary to consider other sources in Table 1 which summarises the stated criteria and includes a comparison to show how much differential settlement this would be across a 1m run (a ROC measurement which will be considered in the later results analysis). Table 1 shows a significant range of 0.625mm to 2mm per m run equivalent and a 1mm limit per m run was considered as a reasonable differential settlement limit for this study focused on HS rail.

Table 1: Differential settlement design standards from literature

Source	Stated Criteria	Max. Differential Settlement per m (mm)
PLK (Polskie Linie Kolejowe) S.A Limits [7]	4mm/year over 30m length	0.13 (per year)
Japanese Standard for non-ballasted railways [8]	12.5mm for a 20m length	0.625
Zhou et al [9] and Chen et al [10]	15mm for a 20m length	0.75
Chinese Suining-Chongqing railway [11]	20mm for a 20m length	1
Cai et al [12]	20mm for 20m length	1
London Underground standards [13]	1:500 along any 10m length	2 (at maximum speeds of 60mph)

2.2. Base Model and Material Properties

The Mercia Mudstone Group (MMG), classified as a red-brown silty mudstone, is a geological formation present across across significant parts of the UK's current and proposed main line rail corridors. Near the surface the MMG is typically heavily weathered to a cohesive soil (weathering grade IV) and with depth grades into an unweathered rock (Grade I) [14]. [14]. Accordingly, the base model of this study considers a foreseeable requirement to transition from a high stiffness/very stiffness/very low compressibility 'cut' area of in situ Grade I MMG, to a lower stiffness/higher compressibility embankment formed of Grade IV MMG placed as a cohesive fill material. Figure 1 shows the typical base model arrangements of the fill embankment at a maximum height of 8m with the transition to the instu Grade 1 MMG at a 4 (vertical) in 15 (horizontal) slopes. Several variables were investigated during modelling and key findings relating to the embankment fill properties (untreated / lime stabilised) and a 1:1 transition gradient (also shown in figure 1) are discussed in the later analysis. Variations in water table location was not a consideration of this study and was set at the bottom of the transition i.e. 8 metres below lower level of the ballast.

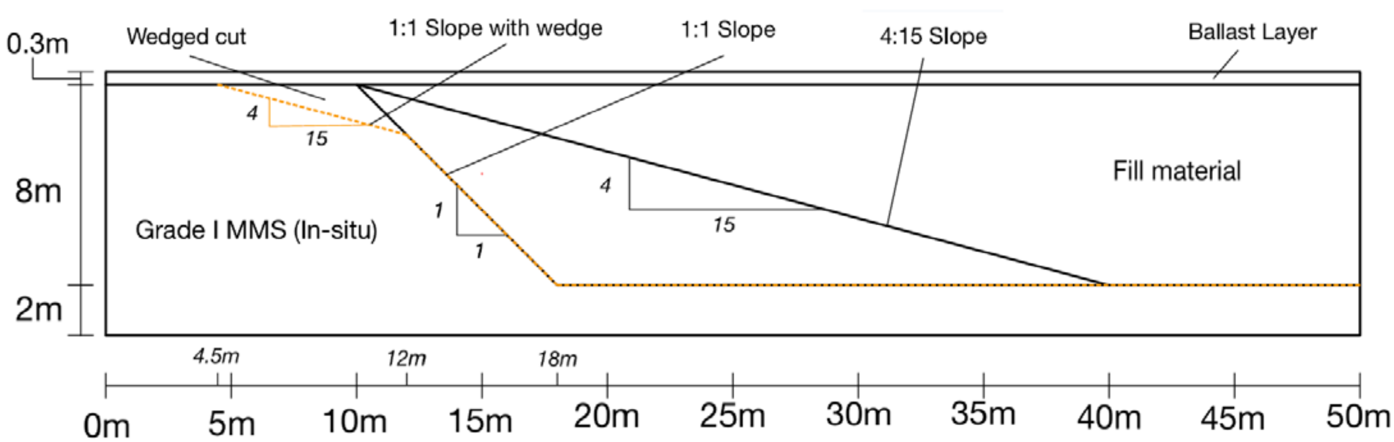

Figure 1: Longitudinal section showing the base model transition slope (4:15) and a steeper (1:1) transition used in variations

As part of a large ongoing research programme (as yet unpublished) into the use of lime treated grade IV MMG as embankment fill, delivered in collaboration with Balfour Beatty Vinci, the authors had access to extensive commercial lab results on 100mm diameter triaxial test specimens (Permeability and Consolidated Undrained tests) alongside field trial test data. This dataset was used to derive most of the parameters for the untreated and lime treated fill material, supplemented by literature references for the insitu Grade I MMG as summarised in Table 2. The 0.75% and 1.5% lime treated parameters are from specimens cured for 90 days at 20°C. Compaction of all fill specimens used standard (2.5kg) proctor compactive effort at a moisture content between 1.05 to 1.1 times the Optimum Moisture Content (a moisture condition deemed generally suitable for placement of such fill by the separate ongoing study).

Table 2 suggests that lime treatment will promote significant benefit to the modelling with the highest lime addition (1.5%) having a co-efficient of compressibility (Mv) value less than half that of the untreated and a Shear Modulus (G_0) around 4 times higher.

2.3 Settlement under static load

Rocscience Settle3D software was used to quantify expected settlements across the transition zone using the base model (Figure 1) with different material properties for untreated and lime treated fill and some variations to the transition gradient. Boussinesq method was chosen in these analyses as it is compatible with this soil profile including fill placement [15], making it suitable for the relative sensitivities of HS railway.

The train load area was simulated assuming the SW/2 axle loading detailed in Eurocode 1 part 2 [16] where loading for global effects should be uniformly distributed over a width of 3.00m at a level of 0.7m below the running surface of the track. This produced an area load of 52kN/m² and required no dynamic factor or enhancement needs to be applied to the uniformly distributed load [16].

Table 2: Material parameters. For most Grade IV material values were derived from laboratory test data either directly or by a published method as indicated by the asterisks (*) in the table footnote. All Grade I parameters were taken from [14].

Soil Parameter		Material				
		Grade I MM (Insitu)	Grade IV MM (0% Lime)	Grade IV MM (0.75% Lime)	Grade IV MM (1.5% Lime)	Ballast
Name	Unit	Value	Value	Value	Value	Value
Unit Weight	MN/m³	0.0248	0.0213	0.0207	0.204	0.186
Youngs modulus E	MPa	250	11.6	47.6	138	200
Compressibility Mv *[1]	m²/MN	0.004	0.076	0.064	0.036	-
Permeability K*[2]	m/yr	0.01	0.01	0.01	0.01	-
Consolidation Cv *[3]	MN/m²	N/A	0.2	0.238	0.422	-
Shear Modulus G_0 *[4]	MPa	5000	91	-	378	77
Poisson's ratio v	-	0.2	0.3	-	0.3	0.3

Note:

*[1] Derived using clause 6.3.5 of BS1377-8

*[2] Measured by triaxial permeability. A typical very low permeability value from all tests was used as no clear difference across lime addition rates. It is likely the clodded nature of the fill dictates permeability in this cohesive fill material and hence the insensitivity to lime content.

*[3] Derived from equation 52 for linear material in section 4.4 of the Settle3D Theory Manual

*[4] Derived from field Continuous Surface Wave testing and [14].

2.4. Dynamic analysis (Elastic displacement under Train moving load)

The primary purpose of the dynamic analysis in this study was to evaluate temporary track surface movement under HS train passage. The dynamic track movement due to the elastic response of the ground has been successfully estimated using FEA in previous studies [17].

Track displacement is excited by shallow surface waves (e.g. Rayleigh waves) alongside the elastic loading of the trackbed system from repeated very short term, but significant magnitude axle loading from the HS train. This modelling considers only the movement caused by the Rayleigh waves and fundamentally it is expected that stiffer subgrade will permit surface waves to move faster through the ground, to cause less wave resonance and therefore less rail level movements [18].

With Midas GTS NX software, a three-dimensional FEA version of the 4:15 base model (figure 1) was constructed using a linear elastic constitutive model whereby the model algorithm calculates Rayleigh wave velocities through the materials using small strain G_0 values (Table 2). The moving load was applied to the surface of the ballast layer (sleepers/rail omitted to simplify the model) and simulating a passenger train with axle load of 170 kN and train speed of 186 mph (see [19] and [20] for more detail). Various interim steps were followed before finalising the model set up e.g. boundaries and element size, to correctly determine the dynamic response from the load into the ground and propagation of the Rayleigh waves at track surface. For brevity these modelling step details are omitted but the interested party is referred to [19], [20], [21] and [22].

3. Key Findings and discussion

3.1. Settlement under static load

Results from untreated fill on the baseline 4:15 transient gradient are shown in figure 2 and 3. Figure 2 shows the development of the settlement profile of this base model, identifying most of the settlement occurs within 0.5 years with ongoing consolidation over time to accumulate a maximum difference of 26.6mm across the 30m long transition after a 120 year design life. Most literature limits in table 1 specify a maximum settlement across a stated distance and for example the 20mm over 20m limits ([10] and [11]) would be breached after around 10 years. Figure 2 also highlights that the greatest differential settlement occurs across the start of the transition (around chainage 10) and the potential impact of this is pronounced in figure 3, which represents the same data but in terms of the rate of change (ROC) of mm per m. The ROC is potentially more relevant as a measure of what a moving train would experience on ballasted track with a sudden unloading or loading action (see section 2.1). Considering the ROC may also be relevant to slab track systems to identify points where potential excess stress/wear may be applied to the reinforced concrete components. When considering the 1m the untreated fill would exceed the 1mm/m limit (as noted from literature in section 2.1) between chainages 10m to 20m for all time intervals modelled and with this measure would clearly present a failing transition design.

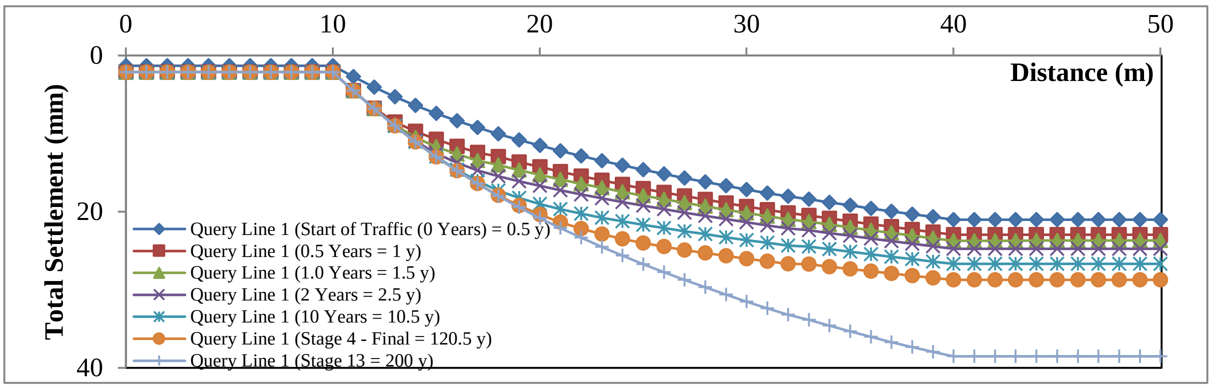

Figure 2: 4/15 Base Model - Distance vs. Total Settlement

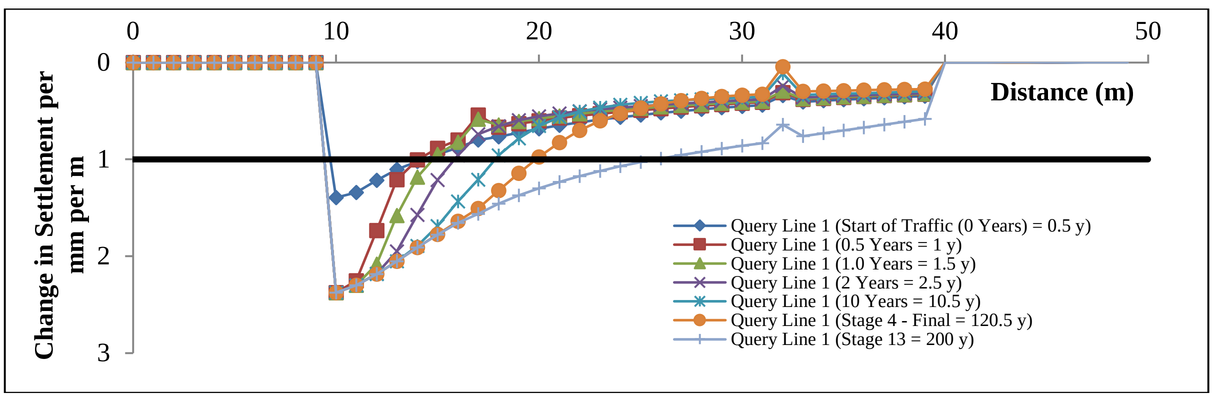

Figure 3: 4 in 15 transition ROC settlement over the years modelled. (Horizontal line indicates suggested threshold settlement of 1mm per metre from literature)

Figure 4 shows the effects of 0.75% and 1.5% lime addition in reducing the ROC in settlement across the transition after 120 years. This reduction in ROC corresponds with the reduced magnitude of total settlement caused by the reduced Mv and increased E. With just 0.75% lime addition, there is a significant improvement in differential settlement with only the first 5 metres of transition falling outside the literature ROC limit. With 1.5% lime addition this improvement is well below the 1mm per m criteria.

The potential relevance of considering the ROC rather than averaging the effects across a prescribed distance such as 20m is further shown when a steeper transition slope of 1:1 is modelled (Figure 4). The differential settlement across the transition is now concentrated over an 8m length and this causes a substantial increase to the 120-year ROC which is well in excess of the 1mm/1m run criteria between chainages 10m to 18m, with up to 9mm/m for the untreated fill and 2.5 mm/m for the 1.5% lime treated fill.

The influence of transition geometry was further investigated by modifying the 1:1 transition slope to include a zone (or shallow wedge) between chainages 4.5m and 12m where the top of the transition gradient was reduced to 4:15 as shown in figure 1 by the orange dashed line. This provided a further benefit by effectively smoothing out the sudden ROC in settlement (figure 4), although even with the combined benefit of 1.5% and the shallow wedge there was still a 2m section between 13m and 15m chainage just outside the limit. Notwithstanding, this highlights how the design focus may wish to prioritise a localised detail where the ROC is a concern rather than altering the full transition gradient which may not be necessary.

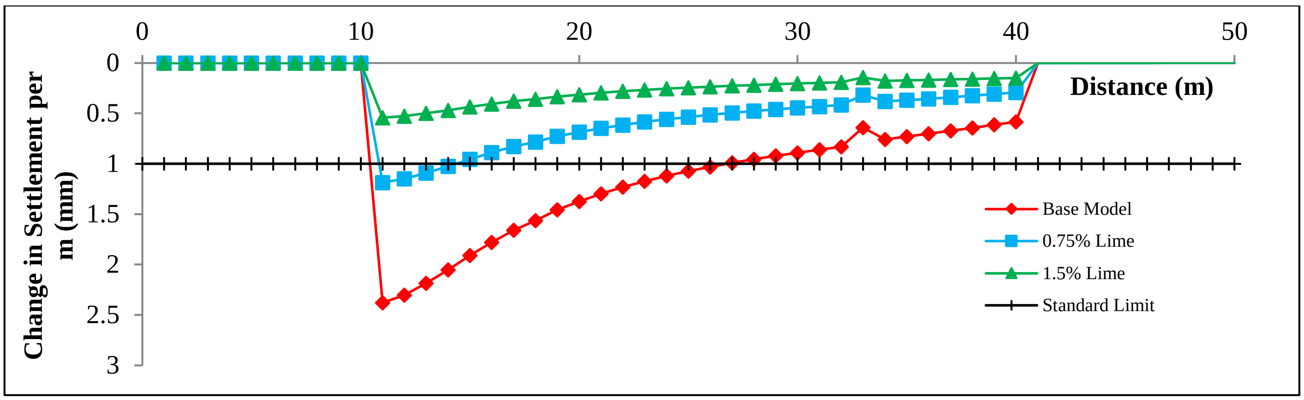

Figure 4: 4 in 15 transition ROC settlement after 120 years for untreated and lime treated fills

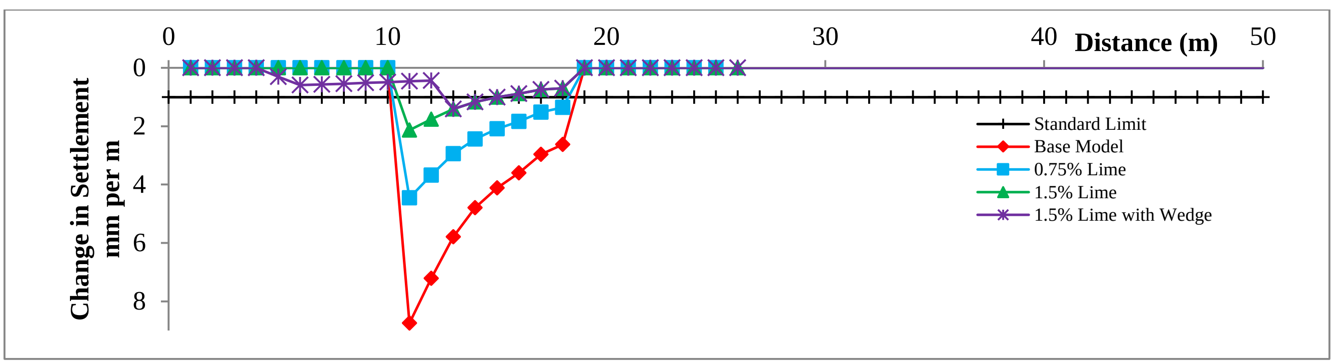

Figure 5: 1 in 1 transition ROC settlement after 120 years for untreated and lime treated fills

3.2. FE models (Dynamic loading)

Figure 6 shows a long section of the maximum vertical displacement determined across the transition in response to the moving load, with comparison between the untreated and 1.5% lime treated fill material. While it is apparent that the lime treated fill realises less differential movement (0.05mm difference across the 30m zone) than the untreated (0.19mm difference across the 30m zone) in comparison the Network Rail guidance which allows a track vertical movement of 2mm over 10m (see section 2.1), there appears to be no concern with either fill due to moving load effects across the transition.

However, the limitation of the dynamic modelling needs to be understood in context with the prior discussed differential settlement profile across the transition. In this study, the modelling of the static and dynamic loading were undertaken separately whereas in reality ongoing differential settlement across the transition would change the surface along which the moving load applies. Banhimahd et al [5], discuss this effect would causes rail traffic to experience a large vertical acceleration at points of significant differential settlement. To model this effect in a more relevant manner for these transitions it would be necessary to undertake a form of coupled analysis to first allow the FE model to consolidate the surface profile to that identified by the static analysis. Thereafter, a series of models to simulate how this modified running surface would change the dynamically applied forces to quantify both the Elastic response of the track bed system and Rayleigh wave propagation to quantify this combined effect on surface movements.

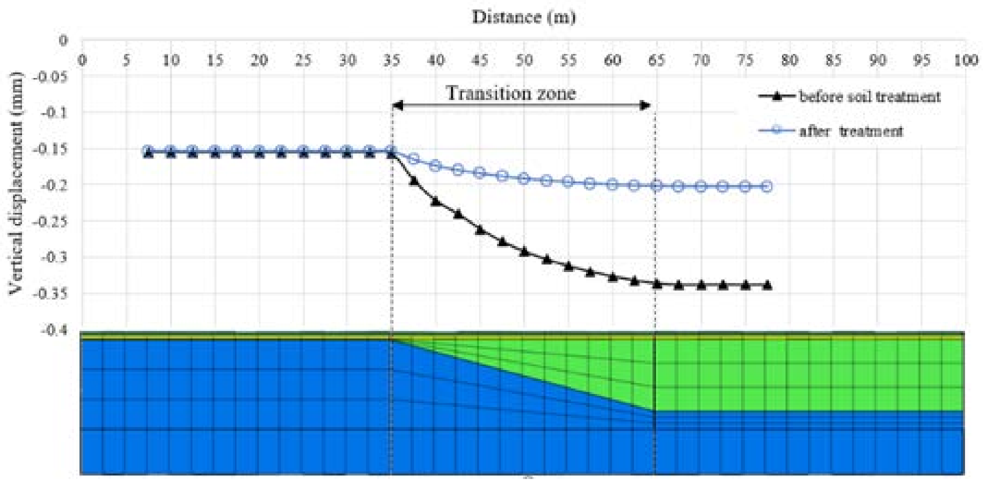

Figure 6: Vertical displacement on the top surface of ballast along the embankment with and without fill treatment

4. Conclusions and recommendations for further work

This study has investigated a reasonably foreseeable scenario for HS rail in the UK of a transition from a cut in Grade I (unweathered) MMG to an 8m embankment fill of Cohesive Grade IV MMG. Static loading (consolidation settlement) and dynamic loading (3D FE) analysis using parameters derived from laboratory, field test and literature considerations allow conclusions that:

- There is no direct limit on differential settlement in design guidance from Network Rail (the UK rail network operator) which makes it difficult for geotechnical designers to understand the upfront suitability of transition designs, although other literature sets criteria for consideration e.g. 20mm over 20m.
- The ROC in settlement over a metre is suggested as a relevant measure to consider of either; what a moving train would experience in ballasted track with a sudden unloading or loading action (this aligns more closely with how Network Rail identify excessive vertical movements experienced by a measurement train); or in slab track systems points where potential excess stress/wear may be applied to the reinforced concrete components.
- 1.5% lime treatment substantially reduces the consolidation settlement permitting a transition gradient of 4 in 15 to meet literature differential settlement criteria and a ROC indicator of 1mm in 1m which untreated fill would otherwise fail.
- Consolidation settlement analysis shows that the ROC of settlement is greatest where transition from cut to fill commences. Models with a steep (1 in 1) transition gradient identified localised increases in the ROC in settlement of up to 9mm per m in untreated and 2.5mm per m in 1.5% lime treated fill and both were considered likely to fail in service serviceability measurements.

- To make steeper and therefore cheaper transitions, a combination of localised reduction in the transition gradient alongside use of lime treated fill may be used to average out otherwise unacceptably large increases to the ROC in settlement. In all transition scenarios efforts to identify locations of sudden increase to the ROC and then adapt the design to average these out would add benefits to train operation and/or reduced track system degradation.
- Lime treatment also provides benefits in reducing vertical displacements from moving loads, however, the dynamic modelling in this study was too limited to determine how the settled profile would change surface movement. A coupled FE analysis (consolidation followed by moving load stages) and including track superstructure, ideally with different ballast depths and slab track comparisons, is recommended to make this link and help confirm how best to apply differential settlement criteria in geotechnical design of transitions. In particular it would be interesting to investigate whether a ROC in settlement indicator is a more appropriate design focus than a settlement range across a fixed larger distance (e.g. 20mm in 20m) approach.

While the findings of this study are based on results from lab and field tests and provide a useful comparison of the differences between lime and untreated fills in a transition, a sensitivity analysis on the derivation of design parameters using different test methods and different stress ranges was not performed. Such a comparison would be necessary outside of this academic exercise to understand the value range of the key parameters of Mv, Cv and G_0 appropriate to the design. The work could also be expanded to consider how these parameters change over longer cures, with higher binder additions and with different binder types e.g. cement. Creep settlement was not considered in this study and is an aspect of further interest when considering long term differential settlement of lime treated fills. Due to the high stiffness of the treated fill, the constitutive model used in FE analysis was linear elastic, however, alternative soil constitutive models should be considered in future models.

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