

DEEP SOIL MIXING GROUND IMPROVEMENT TO MINIMISE DIFFERENTIAL SETTLEMENTS FOR RAIL EMBANKMENT CULVERT APPROACHES FOR THE HEXHAM NEW LOOP PROJECT, NSW

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ABSTRACT

As part of key strategic upgrades programmed and in plan for the North Sydney Freight Corridor (NSFC), improvements to the rail network are close to completion at Hexham. The works at Hexham comprise construction of a new loop approximately 1.7 km in length parallel to the existing up main line to permit more efficient entry of southbound trains into the NSFC. The works are being delivered by an Alliance formed of Australian Rail Track Corporation, Transport Express Joint Venture and AECOM, working with specialist geotechnical contractor Keller Ground Engineering.

The site is located around 130m from the Hunter River in an area underlain by extensive very soft alluvial deposits. The low lying location also means groundwater is at or close to ground level and is subject to tidal influence.

To support the proposed new track and in view of the poor subsoil conditions, the ground improvement method comprising deep soil mixing (DSM) was adopted at the approach embankments and at the proposed culvert location below the rail embankment. The ground improvement is targeted at improving the strength and reducing the compressibility of the soft soils below the culvert to ensure stability of the railway and control differential settlements at the approaches to the culvert. The DSM treatment was considered the most practical, cost effective and suitable ground improvement method amongst the options considered.

This paper discusses the project, the ground conditions and the foundation options considered to meet the project performance criteria. It will present the design of the deep soil mixing technique as applied at this site, including tests results on sacrificial and working DSM columns during construction.

1 INTRODUCTION

The Hexham site is located 15 km northwest of Newcastle CBD. The proposed new loop runs closely parallel to the Pacific Highway and extends between chainage 176+200 km and 177+900 km. An aerial view of the proposed new loop is shown in Figure 1. The Hunter River meanders in a north to south direction to the east of the southern portion of the proposed loop and at its closest is within about 130 m of the proposed extension loop. Rural farming and grazing land is located to the west of the alignment.

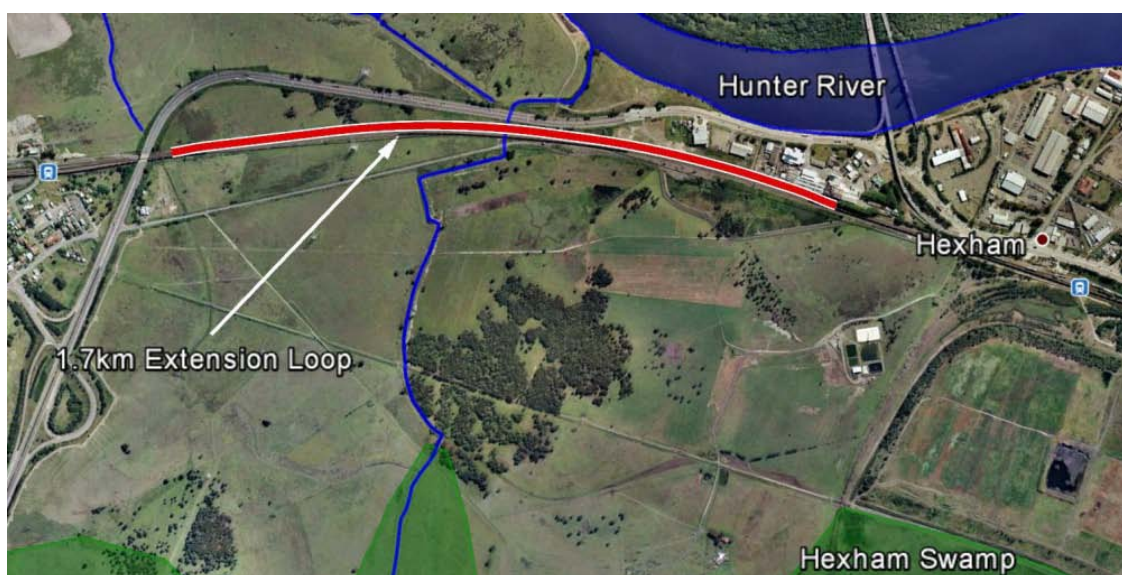


Figure 1: Aerial photo of Hexham proposed extension loop site

There are four existing live rail tracks that operate in the area. These comprise the existing up main, down main, up coal and down coal lines. The existing ground surface is generally flat with the existing tracks built over a shallow 1m high embankment. An existing culvert at chainage 177+060 km runs beneath the railway tracks. A new culvert will be constructed beneath the proposed loop.

The underlying soil conditions comprise soft to firm alluvial clay deposits up to 40 m depth with undrained shear strengths generally below 25 kPa, to a maximum of 50 kPa. As such, the underlying soil would not derive sufficient bearing capacity to support the culvert structure and mitigate issues related to stability and long term settlement of the railway embankment and culvert structure. The total settlement was estimated to be 600 mm and the safety factor against slope instability was 0.9. Hence, it was decided between ARTC, TEJV and AECOM that ground improvement or a pile foundation option would be adopted to ensure stability and safe performance of the railway embankment and culvert structure for its intended use.

In determining the most appropriate ground improvement method, a number of options such as stone columns, vacuum pre-consolidation and Deep Soil Mixing (DSM) using both wet and dry methods were considered. Amongst these methods, deep soil mixing (DSM) using the dry method emerged as the preferred option. The option of adopting pile foundations to support the culvert structure was ruled out at the concept design stage as it was considered too costly and not practical given the depth to a competent founding stratum at approximately 55 m. Other methods were ruled out on a combination of cost, program and environmental factors. The dry DSM method has the advantage of providing lateral stability, reduced potential for settlements and a foundation for the culvert structure. The DSM method proposed was adopted after review, which confirmed it would meet the performance and financial requirements of the project.

2 REGIONAL GEOLOGY AND SUBSOIL CONDITIONS

The Geological Survey of New South Wales 1:250,000 Newcastle Map Series Sheet S1 indicates that the site is underlain by Quaternary-aged ‘freshwater and marine gravels, sands, silts and clays’. Permian-aged Tomago Coal Measures underlie the quaternary soils consisting of shale, mudstone, sandstone, tuff and coal.

Geotechnical investigations comprising four Cone Penetration Tests (CPTs) and one borehole were carried out at the culvert locations and both sides of the approach embankments between chainages 177+030 km and 177+080 km. A plot of typical CPT data over the DSM treated area is shown in Figure 2.

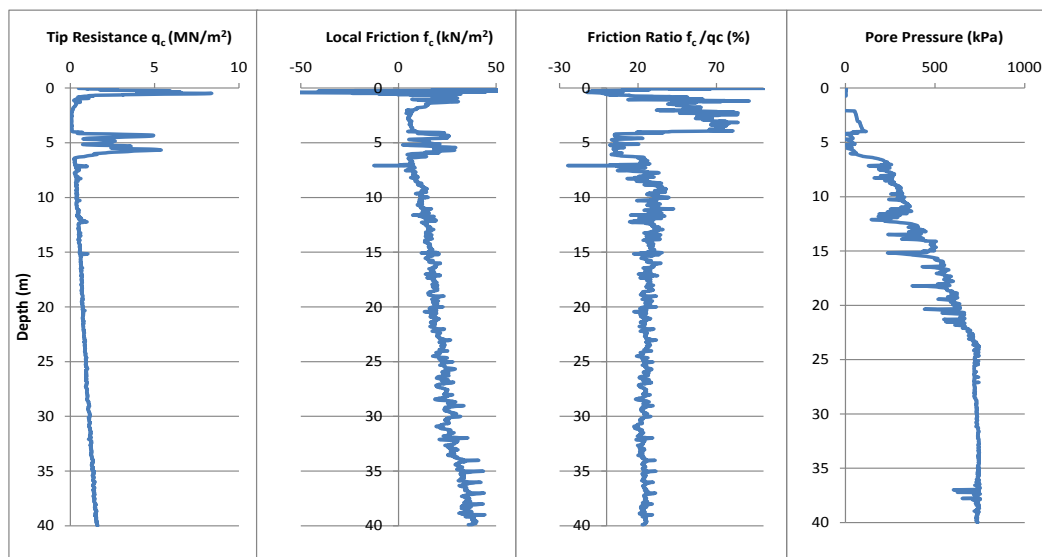


Figure 2: Plot of typical CPT result at culvert location at chainage 177+060 km.

Interpretation of the CPT and borehole results indicated that the location of the proposed culvert and approach embankments consists generally of 1.5 m depth of fill overlying normally consolidated alluvial clays up to depth of 40 m with a sand layer of approximately 1.5 m thick at depth of 4 m. Interbedded sand and clay layers were encountered between depths of 45 m and 55 m. Beneath the sand and clay layers, sand and silty sand with possible gravel lenses were encountered to CPT refusal at depth of 62.5 m. The vane shear tests carried out in the borehole indicated shear strength ranging between 15 kPa and 25 kPa between the depths of 2.8 m to 12.6 m and 40 kPa to 65 kPa between the depths of 15.2 m to 15.6 m. The liquid limit of the alluvial soils ranges between 58% and 65% and moisture content ranges between 55% and 65%. The one dimensional consolidation tests results indicated the coefficient of vertical consolidation (c_v) generally between $0.2\text{m}^2/\text{yr}$ and $0.4\text{m}^2/\text{yr}$.

3 CULVERT INFORMATION

In undertaking the detailed design, AECOM adhered to the ARTC’s Hunter 200+ Infrastructure Guidelines for Track, Civil and Structures. Section 5.1.1 of the Guidelines stipulates that large box culverts are to be designed for 350 LA (35 tonne axle load) rail loading.

The proposed concrete box culvert is approximately 6 m in length, 5.6 m in width and 1.2 m in depth. The culvert supports a 1.0 m high embankment including 0.5 m thick railway ballast above. The total serviceability load imposed on the culvert structure is 110 kPa (live load of 80 kPa and dead load of 30 kPa). A typical section of the railway track formation detail is shown in Figure 3.

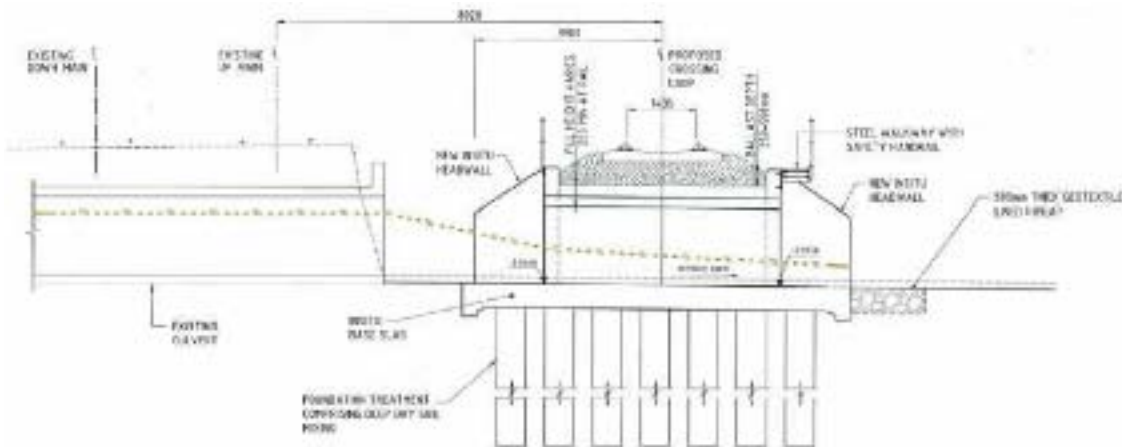


Figure 3: Typical section of railway track formation at culvert location

4 BASIS OF DESIGN AND INTERPRETED SOIL PARAMETERS ADOPTED

The basis of design proposed by ARTC for differential settlement of the railway track formation is 1 in 500 for any one year and 1 in 100 in the longitudinal direction over the 100 year design life of the structure. A minimum safety factor of 1.5 is required in design for the long term stability for cut and fill batters.

The interpreted soil parameters adopted in design are summarised in Table 1 below:

Table 1: Interpreted soil parameters adopted in design

Depth (m)	Soil Description	Unit weight (kN/m ²)	Undrained cohesion, c_u (kN/m ²)	Drained cohesion, c' (kN/m ²)	Friction angle, Φ' (deg)	Elastic modulus (MPa)
0 – 1.5	Existing fill	17.0	33.5	10	30	4.0
1.5 – 4.0	Alluvial clay	16.0	10.0	0	24	1.0
4.0 – 5.5	Alluvial sand	18.0	-	0	35.0	-
5.5 – 10.0	Alluvial clay	16.0	20.0	0	26	2.0
10.0 – 15.0	Alluvial clay	16.0	30.0	2	26	4.5
15.0 – 20.0	Alluvial clay	17.0	40.0	0	28	6.0
20.0 – 25.0	Alluvial clay	17.0	50.0	0	28	7.5
25.0 – 30.0	Alluvial clay	17.0	60.0	2	28	12.0

The parameters outlined in Table 1 above have been utilised in undertaking the slope stability analyses for the embankment to determine the minimum factor of safety in the short and long term and also in calculating the composite shear strengths of the improved block in the undrained and drained condition.

For the area treated with DSM columns, the composite shear strength calculated for the undrained condition is 42kPa. For the drained condition, the composite shear strength calculated is 31 kPa for cohesion and 30 degrees for friction angle. The composite modulus calculated is 11 MPa.

5 DEEP SOIL MIXING

5.1 BACKGROUND AND INSTALLATION PROCEDURE

The worldwide use of soil mixing has increased rapidly over the last 10 years. Soil mixing is a widely used name and the applications, installation methods and design issues have major differences. The differences and applications were reviewed by Massarsch and Topolnicki (2005). The process used on this project was the Scandinavian dry Deep Mixing (DSM) Method, also known as LCM (Lime Cement Mix) Columns.

The Scandinavian method was originally developed in Sweden in the late sixties and early seventies by Prof. B. Broms and engineer K. Pause [Bredenberg *et al.* (1999)]. The technique was first used in Australia in 2005 on the Sandgate Rail Separation Project, some 5 km from the Hexham Loop Extension Project. The dry DSM method is intended for improving very soft and soft silt and clay soils, the benefit of the method being that the high moisture content typically associated with these soils provides sufficient moisture to hydrate the dry cementitious or lime binder introduced into the soil. Experience in Australia has been principally with cement based binders due to the high relative cost of lime and logistical issues.

The mixing rig for the installation of columns is equipped with multi-bladed mixing tool at the end of a hollow Kelly bar. Column construction commences with a controlled insertion of the mixing tool to the required depth of treatment, with the high rotation speed of the tool breaking down the soil matrix during penetration. Upon reaching the target depth a cementitious binder is pneumatically conveyed through the hollow Kelly bar exiting at the mixing tool. During column construction the binder dosage, depth, extraction and rotation speeds are some of the parameters monitored and recorded for quality assurance.

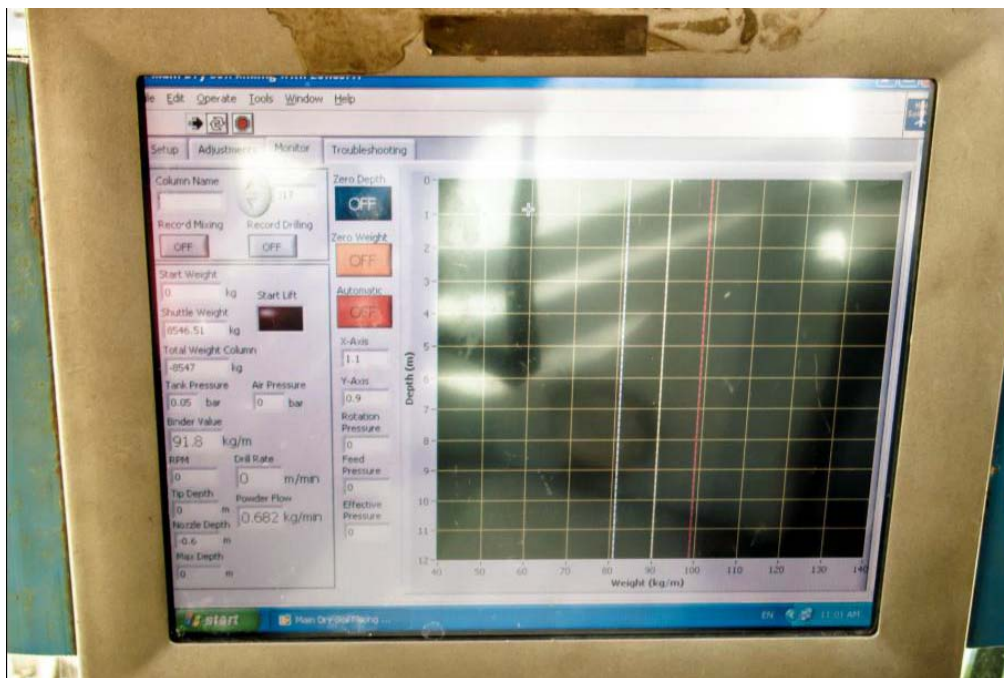


Figure 4: Monitoring and column construction data acquisition display in mixing rig cab

Typical column diameters formed through the mixing process typical range between 0.6 m to 0.8 m with a depth of treatment of up to 25 m.

The dry DSM columns installed for this site are typically 0.6 m in diameter and extend to a maximum depth of 15 m below the culvert structure. Figure 5 shows a photo of the DSM columns being installed from the working platform level. The flags mark the surveyed locations of the DSM columns yet to be installed.



Figure 5: DSM columns construction

5.2 DESIGN METHODOLOGY

The design concept for dry DSM treatment is to produce a stabilised soil mass that mechanically interacts with the surrounding natural soil. The design approach and technical development for the dry DSM to evaluate improved deformation and shear strength parameters are derived from the method described by Broms (1999) and the Swedish Geotechnical Society (SGS, 1997).

The improvement of the ground with deep soil mixed columns is achieved by the interaction between the treated columns and the surrounding untreated soils. The composite soil parameters are calculated which are primarily a function of the area ratio of the soil treatment, defined as the area of the columns as a ratio of the total area treated. In the case of columns spaced on a square grid of "s" metres, this is defined as:

$$\text{Area ratio, } a = (A_{\text{col}})/A_{\text{grid}}$$

where $A_{\text{col}} = \text{area of column} = \pi/4 \times \text{dia}^2$,
 $\text{dia} = \text{diameter of column} = 0.6 \text{ m}$
 $A_{\text{grid}} = \text{area of grid or unit cell} = s^2$

When the area ratio is determined, composite parameters for the shear strength and elastic modulus are then calculated based on the following formula:

$$c_{\text{ucom}} = a \cdot c_{\text{ucol}} + (1-a) \cdot c_{\text{uclay}}$$

where $c_{\text{ucom}} = \text{Composite shear strength of improved block}$
 $c_{\text{ucol}} = \text{Shear strength of DSM column}$
 $c_{\text{uclay}} = \text{Shear strength of natural soil}$

and $E_{\text{com}} = a \cdot E_{\text{col}} + (1-a) \cdot E_{\text{clay}}$

where $E_{\text{com}} = \text{Composite modulus of improved block}$
 $E_{\text{col}} = \text{Modulus of DSM column}$
 $E_{\text{clay}} = \text{Modulus of natural soil}$

The composite shear strength calculated for the undrained and drained condition is then used as input in the stability analyses to assess the factor of safety of the treated ground against slope failure and also used in the assessment of the bearing capacity of the culvert in accordance with conventional bearing capacity calculation.

Through this design process, a minimum factor of safety of 1.6 was achieved against slope failure in the short term and 2.0 in the long term. The slope stability analyses was analysed using the Morgenstern and Price method. The ultimate bearing capacity calculated for the improved ground beneath the culvert structure is estimated to be 220 kPa.

5.3 DESIGN SPECIFICS

The soil improvement was selected as a foundation solution for the culvert to ensure the short and long term stability of the culvert at the required elevation whilst allowing effective drainage and water flow through the culvert. While the treatment ensures the limiting of settlement of the culvert, the untreated portion of the railway loop founded on untreated soft clays will undergo inevitable significant long-term settlements. To mitigate differential settlement the final design included a length of transition zone on either side of the culvert with a phased reduction in area ratio and depth to provide a smooth transition between the rigidly supported culvert foundation and the unimproved new rail embankment. Two alternative solutions were proposed incorporating either a 17 m or 34 m long transition zone. Both options were discussed with TEJV and ARTC. The 17 m transition option was ultimately adopted by ARTC for their asset, as a more cost effective compromise, acknowledging that it is likely to result in greater deformations that will require additional tamping and maintenance. There was no benefit in adopting the more expensive 34 m transition option as both options could not comply with ARTC’s design criteria for differential settlement and tamping will be required in the long term.

The transition zone design used interlocking 0.6 m diameter dry DSM columns, installed in panels orientated perpendicular to the railway track in the location of the approach embankments and as isolated individual columns below the proposed new culvert structure. The presence of existing services as well as unexpected obstruction necessitated changes to the final column layout. Figure 6 shows the as-built layout plan of the DSM columns proposed at the culvert location and under the approach embankments. Using SGS design principles, a target design shear strength of the improved columns of 150 kPa was determined. C_v value of $1 \text{ m}^2/\text{yr}$ was adopted to estimate the time rate of consolidation settlement.

Columns in green were installed to 5 m below ground level (bgl), orange to 10 m bgl and blue to 15 m bgl.

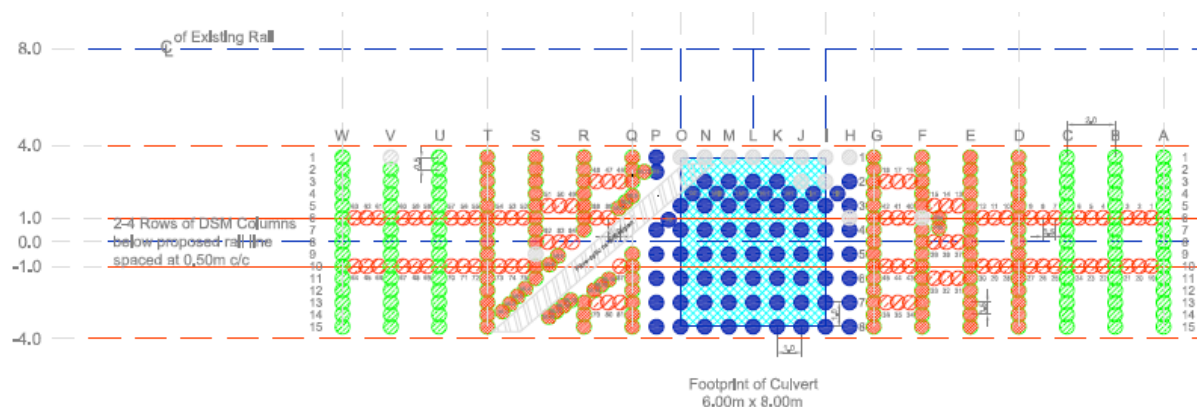


Figure 6: As Built layout plan of dry DSM columns.

5.4 FIELD TESTING / QUALITY ASSURANCE

Field testing and quality assurance is a critical aspect of any ground improvement project. The project adopted the common procedure whereby prior to commencement laboratory testing was performed on field samples to determine the target cement dosage to reach the column design shear strength. It was intended to validate the work on site onsite using seven Push In Resistance Tests (PIRT) to prove the column strengths. The site conditions presented challenges to the testing method as the near surface layers of more sandy clay resulted in significantly higher column strengths than anticipated, which could not be penetrated with the standard PIRT test apparatus. In order to validate the design column strengths cores of the soil mixed columns were taken for visual inspection and subjected to laboratory Unconfined Compressive Strength (UCS) testing.

As is the norm with small diameter testing of DSM samples the UCS test results recorded high variability in shear strength with an average UCS of 500 kPa achieved.

6 INSTRUMENTATION AND MONITORING

Upon completion of construction of the railway track, instrumentation and monitoring drawings were provided to ARTC, setting out a plan to monitor and respond to ongoing settlements. The basis of the monitoring is an array of survey pins to allow assessment of the total and differential settlement of the track. A reducing monitoring interval over an initial period of 10 years is proposed. The survey pins would be installed on the sleepers of the railway track at the culvert location and on both sides of the approach embankments over a distance of approximately 40 m. The predicted primary settlement profile over 5, 10, 20 and 40 years are presented in Figure 7.

Given the magnitude of the predicted primary settlements, a higher frequency of monitoring has been proposed for the initial operating period of the track. Upon completion of construction, monitoring was recommended to be carried out at a weekly to fortnightly frequency over the initial 6 months and then reducing to a monthly to quarterly frequency between 6 months and 3 years. Between 3 and 10 years, monitoring frequency was recommended at half yearly intervals. Beyond 10 years, monitoring was recommended at the discretion of ARTC based on their scheduled regular maintenance program. The performance of the railway track will be monitored over time by ARTC and a comparison with the made of predicted and actual settlements to provide a guide to longer term performance.

On the basis of the predicted settlements using parameters adopted from investigation and published work, a ballast tamping frequency over a period of 10 years has been proposed. The tamping frequency serves as a guide and actual frequency of tamping will be decided based on the monitoring results.

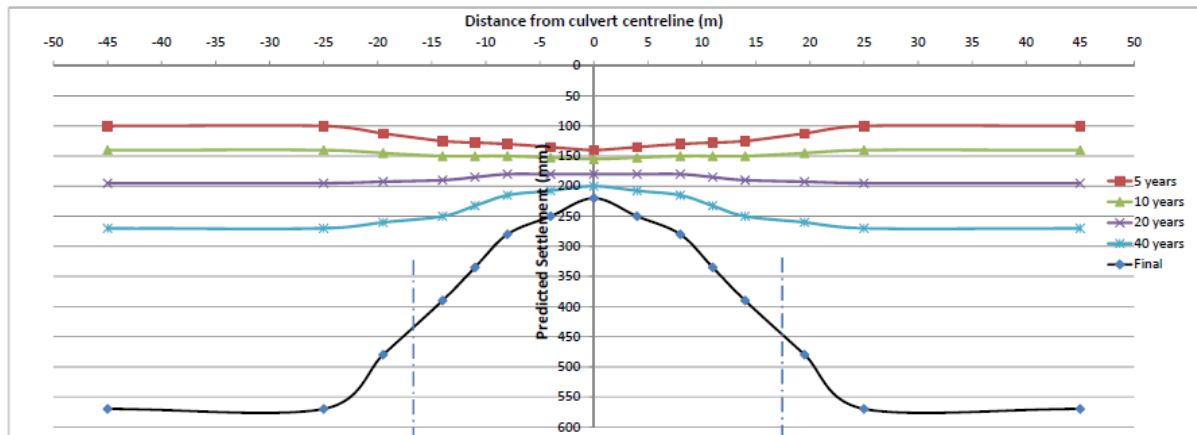


Figure 7: Predicted Primary Settlement Profile with time across culvert.

At this stage, construction of the railway track has just been completed and monitoring data is not available. Further assessment of the performance of the structure is ongoing.

7 CONCLUSION

Dry DSM method has been used to improve soft and compressible ground beneath a major culvert on the Hexham New Loop project. The improvement includes a graded transition zone to manage ongoing differential settlement and consolidation of the adjacent unimproved natural alluvial clays. The DSM treatment is an effective way to improve the strength of very soft to soft deep clay deposits. However, some consolidation of the adjacent natural ground is to be expected and it is therefore crucial that survey monitoring is carried out and track movements assessed to instigate engineering maintenance. Based on the monitoring results, tamping is to be carried out as part of the railway maintenance program to mitigate any possible risk that may affect the track.

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