The paper was published in the proceedings of the 17th African Regional Conference on Soil Mechanics and Geotechnical Engineering and was edited by Prof. Sw Jacobsz. The conference was held in Cape Town, South Africa, on October 07-09 2019.

Design and Construction of Railway Tracks over Compressible Foundations

Theva Muttuvel
Principal engineer Geotechnics & Tunnels, SMEC Australia Pty Ltd, Australia

Ashok Peiris
Technical Director, GHD Australia Pty Ltd, Australia

Firman Siahaan
Senior Geotechnical Engineer, Coffey Services Australia Pty ltd, Australia

ABSTRACT: In recent years, construction of rail tracks over compressible foundations such as soft ground and landfill has become inevitable. Placement of rail tracks over a compressible foundation leads to (a) significant settlement of tracks with time and (b) subgrade failure under train loadings if the compressible foundation is not treated. Such treatment can pose issues such as significant capital cost, increased construction time and environmental impacts. Therefore, an effective design and maintenance approach should be developed to eliminate the need for expensive ground treatment while achieving the performance specification required by railway operators. In this paper, development and application of an effective design and maintenance approach on two major railway projects associated with soft ground and landfill in Australia are discussed. Vertical alignment has been designed incorporating predicted long-term settlement to ensure that rideability of trains is not compromised by ongoing settlement. This design approach has been complemented by tamping at targeted locations as agreed by railway operators. In addition, consideration should be given to reducing the risk of subgrade failure under repeated loadings, leading to significant track deflection and failure during operation. To reduce the risk of subgrade failure, soft subgrade may need to be improved using expensive ground treatment.

1 INTRODUCTION

The design and construction of railway tracks over compressible foundations should address various challenges including performance requirements and capital and maintenance cost. Tracks placed on compressible foundations without any ground treatment could lead to a) significant long-term settlement and b) failure of weaker subgrade under repeated loadings with an increased likelihood of unsafe train operation. Ground treatment to reduce long term settlement involves significant capital cost. Therefore, the design should find a balance between capital and maintenance cost while meeting the performance requirements.

This paper discusses how an innovative design approach can be implemented to reduce the capital cost with an optimised maintenance cost while achieving the performance requirements including rideability. This was only possible with cooperation from the railway operators. For presentation purposes of this paper, two projects namely Project 1 and Project 2 have been selected. Project 1 involves construction of rail tracks over soft ground. This project has been completed and in operation for the last five years. Project 2 involves construction of rail tracks over landfill. In this case, most of construction works including earthworks associated with this project have been completed.

Project 1 involves the construction of five railway tracks located next to the existing up and down coal tracks on the east coast of Australia. The tracks are intended to accommodate trains generally comprising two or three locomotives and up to 91 wagons requiring a minimum standing room of 1.67 km. The tracks will support heavy coal trains with axle loads of 30 to 35 Tonne. The proposed tracks are located on a floodplain consisting of soft soils with the potential for significant post construction settlement if not improved. In addition, a portion of the footprint of the proposed tracks has already been preloaded by coal washery fill (i.e. existing fill) placed 25 to 50 years ago. In these areas fill had to be removed while elsewhere filling was required to meet vertical alignment requirements. In addition, a protection structure supported by piles for a gas main crossing the track alignment had to be constructed. This structure forms a hard spot for the tracks. Placement of variable fill thickness, varying stress history of the soft clay layers and the hard spot create the potential for differential settlement along the alignment after construction. The magnitude of this differential settlement will dictate the number of interventions and maintenance cost during the design life of the project. Provision of an adequate formation over soft subgrade is also important to reduce the risk of subgrade failure and to meet the dynamic deflection requirements of the tracks during operation. Hence, the assessment of adequate formation and prediction of the post construction settlements were critical elements in the design of this railway embankment over soft ground.

Project 2 involves the construction of two railway tracks on the east coast of Australia to link an existing line to a freight terminal. A portion (about 270 m long) of the proposed railway tracks was to be built on an embankment constructed over buried landfill cells. The age of these cells measured from the completion of waste dumping varies from about 15 years to just over 30 years. Based on the geotechnical investigation (Siahaan et al. 2017), the waste materials comprise Municipal Solid Waste (MSW) with highly heterogeneous content and a putrescible organic content in the range of 10% to 12% by weight. The thickness of landfill varies by up to 15 m in the transverse and longitudinal directions along the proposed railway alignment. The heterogenous nature of void distribution and compressibility of the MSW as well as its variation in thicknesses is likely to cause excessive differential settlements on the proposed railway tracks including settlements due to void collapse at random locations. Such risk of excessive differential settlements would potentially impact the design track super elevation and induce other track geometrical defects. These can consequently influence the rideability of trains leading to unsafe train operation. Figure 1 below illustrates how a sudden void collapse can impact the train operation. Therefore, such issues need to be addressed to reduce the risk of derailment during the operation.

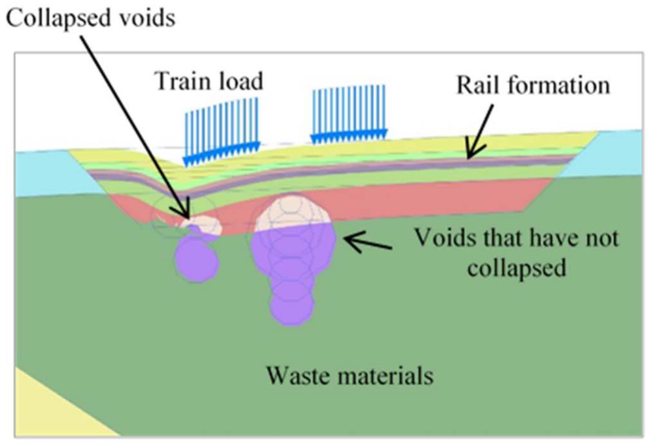


Figure 1. Illustration of impact of sudden void collapse on train operation

2 DESIGN APPROACH

The design requirements for the encountered ground conditions are not covered by any of the available design standards developed by Australian railway authorities. Therefore, design of the tracks over these difficult ground conditions becomes a non-standard design. A brief description of design adopted in each project is summarised below.

Project 1:

As discussed previously, the project corridor has been used before as a stockpiling area for coal washery material. As such there is some fill material overlying the soft ground. During the design development, a cost-effective option of placing rail formation on top of the existing ground, utilising the existing fill material as part of formation, was considered (i.e. minimum cut option). Due to the placement of this fill material during the period between 1960 and 1990, the existing ground is at a higher elevation than the existing up coal track. It was advised by railway operator that the level difference between the existing up coal track and the adjacent proposed new track should be 1.2 m or less for the future maintenance purposes. The level difference between the existing up coal track and the proposed track with the “minimum cut” option would be more than 1.2 m over most of the alignment and hence, this option was not considered further.

After eliminating the “minimum cut” option, a number of subgrade modification methods were explored with the intention to develop a cost-effective formation design as well as reduce the post construction settlement. Risks and opportunities of each subgrade modification method were carefully weighed in the process of selecting an appropriate subgrade modification method. A summary of the subgrade modification methods considered during the design process and the pros and cons of each method is given in Table 1.

In the selection of an appropriate subgrade modification method, the following factors were considered:

(a) Relative cost benefits of each method (i.e. capital and maintenance cost);
(b) Risks associated with the installation of columnar inclusions due to obstructions within the existing fill, vibration impact on adjacent operating tracks and potential delays in construction;
(c) The impact on the construction period of the rigorous testing regime and trial requirements associated with ground inclusions and cement mixing panels; and
(d) It was also noted columnar inclusions and cement stabilised panels still required some cut of existing ground to meet level difference between the proposed new track and the existing up coal track as well as material double handling.

Considering the above factors and the risks and opportunities outlined in Table 1, it was decided by the project team to proceed with the "remove and replace" option for the formation design. A typical arrangement of components of the adopted rail track is presented in Figure 2 to show the definition of "formation".

Table 1. Risks and opportunities of various subgrade modification methods (Muttuvel and Neville, 2017)

Method	Risks	Opportunities
1: Remove and Replace with rock fill	• Disposal of removed material	• Straight-forward construction. • No standard capping layer required. • Reduce the post construction settlement due to removal of material. • Cheaper than other methods
2: Partially penetrated Concrete Injected Columns (CIC)	• Load transfer platform with structural geofabric (LTP) required. • Working platform to be cleaned after installation to build formation with spoil management. • Installation difficulties due to boulders within existing fill.	• Lesser formation thickness and post construction settlement than Method 1. • Installation is quicker than Methods 3 and 4. • Strength and stiffness parameters achieved with reasonable control. • Dynamic deflection lower than all other methods.
3: Partially penetrated Stone Columns (SC)	• (LTP) required. • Working platform to be cleaned after installation to build formation with spoil management. • Additional granular material required with increase in column diameter due to expansion of soft clay caused by vibro-compaction. • Installation is slower compared to CIC.	• Lesser formation thickness and post construction settlement than Method 1. • Required strength and stiffness parameters can be achieved with reasonable control. • Dynamic deflection lower than Method 1.
4: Partially penetrated Cement mixing panels	• Laboratory and field testing required: Cost and Time • (LTP) required. • Working platform to be cleaned after installation to build formation with spoil management. • Slower installation rate than CIC.	• Lesser formation thickness and post construction settlement than Method 1. • Dynamic deflection will be lower than Method 1.

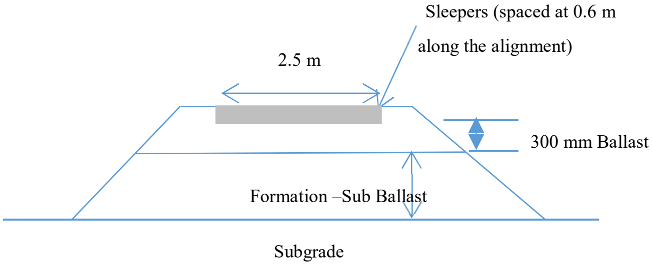


Figure 2. Components of a Rail Track

The available design standard proposes various thickness of formation fill depending on the California Bearing Ratio (CBR) of the subgrade. The exposed subgrade mostly had a CBR value of 1 or less, particularly within the low-lying areas for the "remove and replace" option. As the standard did not cover the case of a subgrade with a CBR of 1 or lower, the railway operator had concerns on how tracks would perform over soft ground under repeated loadings and requested for various design solutions during design phase. As part of the non-standard formation design, requirements for formation had been developed to ensure that subgrade will not fail under repeated loadings while meeting operational requirements (i.e. dynamic deflection of tracks), within allowable limits. The formation design procedure adopted is presented elsewhere (Muttuvel and Neville, 2017).

The predicted settlement over 40 years is in the order of several hundred millimetres. The various ground treatment discussed in Table 1 and surcharge with wick drains was also considered to reduce post construction settlement. Subsequent to various discussions with railway operators and their evaluation of the maintenance cost required to cope with the assessed total and differential settlement together with the capital cost of ground improvement, it was agreed to proceed without any specific ground treatment. The railway operator agreed to maintain tracks through tamping as part of regular maintenance program.

Project 2:

The proposed railway infrastructure is being built to satisfy a project-specific criterion of 0.25% change in grade for the vertical alignment. Further criteria relating to track geometry defects were also taken into account including the vertical alignment and a limit of 15mm on the change in super-elevation. Excessive and unexpected changes in the super-elevation due to settlement or sudden void collapse can result in a higher risk of unsafe train operation.

Various ground treatment options including surcharging, dynamic compaction and application of rigid or semi-rigid inclusions were considered. The dynamic compaction was initially favoured due to its effectiveness in collapsing critical voids. However, the surcharge treatment was then adopted in lieu of dynamic compaction to minimise any impact on existing landfill features including the leachate circulation system and liners.

Additionally, surcharge treatment was considered a cheaper and more practical solution due to availability of materials on the project site. The dynamic compaction and rigid/semi-rigid inclusions were deemed to be more expensive. Furthermore, dynamic compaction would require extensive in-situ testing and some waiting period for settlement measurements to validate the effectiveness of the compaction. As a result, the application of dynamic compaction would not necessarily result in optimising construction time.

In order to induce a similar void collapse to that which would have been achieved by dynamic compaction, the fill surcharge was extended up to 9 m above the design embankment height to obtain sufficient weight to collapse the voids by breaking the microstructures supporting the larger voids.

The surcharge design along with waiting period were employed with the following objectives in mind:

- Achieve general void reduction required to complete the primary settlements
- Induce strain levels required for the improvement of creep strain rate (Siddiqui et al. 2013)
- Sufficient surcharge weight and time to induce collapse of larger critical voids

It was initially found that the magnitude of long-term settlement was relatively high in the order 500 mm over 40 years despite the application of ground treatment. Following a consultation with railway operator, higher long-term settlement magnitude was accepted for this project based on the performance of Project 1 where similar a scenario has been successfully managed.

To reduce risk of unsafe operation and poor rideability, the design was carried out to meet the criteria pertaining to differential settlement, vertical alignment and other track geometry defects. To achieve these, provision was made for about 8 or 9 tamping events during the design life of 40 years where elevation of the rail tracks will be readjusted and ballast retamped. These events can be conducted as part of the routine track maintenance works.

For the consideration of the overall track geometry, the rail readjustment was designed to limit the settled track level to be between the design track level and lowest compliant track level (refer Figure 3).

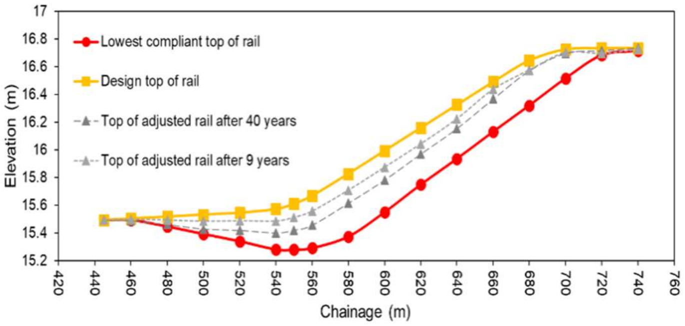
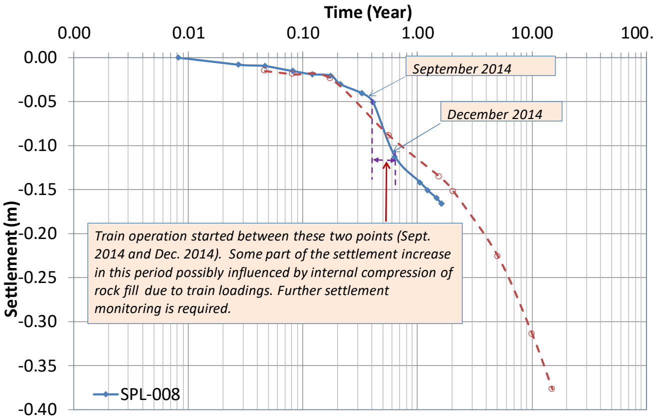


Figure 3. Design track levels, lowest compliant levels and adjusted tracks at two selected readjustment events

3 CONSTRUCTION AND PERFORMANCE MONITORING

Project 1 has been completed and in operation for five years. As discussed previously, no specific ground treatment has been implemented to reduce the post construction settlement. The soft clay is lightly to normally consolidated at depth and has a low permeability. As such, the primary consolidation settlement has been a part of post construction settlement. The settlement monitored using settlement plates after construction over a year have been reviewed against the prediction at selected locations (refer Figure 4). Figure 4 indicates that the predicted settlement is about 25 mm less than the observed settlement to date of back analysis. Considering limited data available at the time of back analyses and the prediction is only about 15% lower than the observed settlement, no attempt has been made to revise forward prediction and to revise tamping. However, no significant concerns have been raised so far in terms of track performance to authors' knowledge.



Train operation started between these two points (Sept. 2014 and Dec. 2014). Some part of the settlement increase in this period possibly influenced by internal compression of rock fill due to train loadings. Further settlement monitoring is required.

Figure 4. Observed settlement and predicted settlement (Muttuvel and Neville, 2017)

Pile Driving Monitor (PDM) survey techniques have been used to record the dynamic deflection of operating tracks. This was required to assess whether the performance of track formation is consistent with the predicted dynamic deflection. The detailed description of the use of the PDM and details associated with back analysis have been published elsewhere

(Muttuvel and Sasiharan, 2015 and Muttuvel and Neville, 2017). An example of the observed dynamic deflection of the track is presented in Figure 5. For the initial review of dynamic deflection data against the design prediction, back analysis has been carried out for a selected location using PLAXIS 2D. The original geotechnical design parameters adopted for the formation rockfill and soft subgrade were adopted unchanged for the back-analysis purposes. The assessed track vertical movement (i.e. dynamic deflection) for a train on a track with fully loaded wagons is 5.3 mm. This is comparable to the observed dynamic deflection using PDM presented in Figure 5.

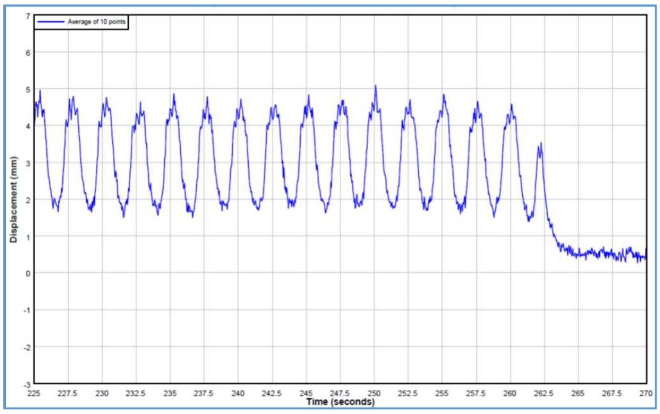


Figure 5. Observed dynamic deflection of track

The construction settlements in Project 2 were measured by means of a series of Settlement Plates and Hydrostatic Profiling Gauges. The settlements measured during the surcharge waiting period are shown in Figure 6 below for a comparison against the settlements predicted during the design stage.

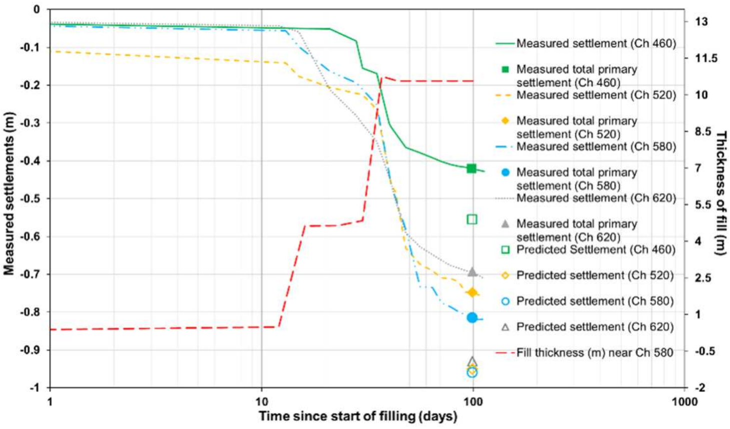


Figure 6. Plots of predicted settlements and measured settlements with time for representative chainages

The plots in Figure 6 indicate the measured settlements were generally within 25% below the predicted settlements. In addition, the introduction of surcharge with about 4 to 8 times of design height was deemed to have reduced the risk of any future sudden void collapse under the relatively low design embankment.

The monitoring data presented in Figure 6 indicates a reasonable outcome where predicted values were not too conservative, but on the safe side despite high uncertainty and heterogeneity associated with MSW materials. Although, the monitoring data during rail operation for project 2 has not yet become available, it can be inferred from the observed primary settlement that the predicted post construction settlements comprising secondary settlements are likely be within the prediction. This implies that the number of readjustment or tamping events is likely be consistent with or better than the number of events provided for in the design.

4 REFERENCES

Bareither, C. A., Benson, C. H. and Edil, T. B. 2012. Compression Behavior of Municipal Solid Waste: Immediate Compression, *ASCE Journal of Geotechnical and Geoenvironmental Engineering, 138 (9): 1047 – 1062*.

Muttuvel, T and Sasiharan, N. 2015. Back analysis to estimate resilient modulus of soft clay, *International Conference on Geotechnical Engineering, ICGE 2015, 113-116.*

Muttuvel, T and Neville, T. (2017). Design of Railway Embankment over Soft Ground, *Australian Geomechanics Society Symposium Sydney Chapter, 72-81*

Siahaan, F., Muttuvel, T. and Peiris, A. 2017. Characterization of Municipal Solid Waste Materials for the purpose of engineering design in transport infrastructure project. *Aust. Geomech. Jnl., 52 (3): 67 – 75.*

Siddiqui, A. A., Powrie, W. and Richards, D. J. 2013. Settlement characteristics of mechanically biologically treated wastes, *ASCE Journal of Geotechnical and Geoenvironmental Engineering, 139 (10): 1676 – 1689.*

Sharma, H. D. and De, A. 2007. Municipal Solid Waste landfill settlement: Postclosure Perspectives, *ASCE Journal of Geotechnical and Geoenvironmental Engineering, 133 (6): 619 – 629.*

Van Impe, W. F. and Bouazza, A. 1996. Densification of domestic waste fills by Dynamic Compaction, *Canadian Geotechnical Journal, 33: 879 – 887.*