ADVANCED ANALYSIS OF TRACK FORMATION ON COODE ISLAND SILT

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ABSTRACT

The design of rail formation in Australia is largely dictated by railway standards using a ‘cookbook’ approach. Generally, railway standards define the required thickness of the ‘track formation’ (capping layer and structural fill) based on the soaked California Bearing Ratio (CBR) of the subgrade. In the docklands area of Melbourne, very soft to soft clay deposits of Coode Island Silt (CIS) are present close to the existing ground surface level. This material has a soaked CBR value of less than 1% and therefore falls below the soaked CBR values for which design guidance is provided within the rail standards.

This paper presents the methodology adopted for the design of track formation on subgrade that falls outside conventional railway standards. The advanced Plaxis 2 dimensional (2D) and Plaxis 3 dimensional (3D) analyses demonstrated that the very soft subgrade was not overstressed and the approach was also used to provide an estimate of the ongoing settlement rates in the CIS. Constructability issues considered during the design process due to constructing on very soft clay are also discussed. The design solution developed provided a stable formation on which to construct the tracks. It did not attempt to remove the ongoing issue of creep settlement within the CIS.

This approach could be adopted for designs on similar soft subgrades to demonstrate an acceptable track formation.

1 INTRODUCTION

Track formation design in Australia is typically carried out in accordance with rail standards/specifications (standards) that have been developed by the various rail operators. The rail standards typically use the soaked CBR of the subgrade material in order to determine the thickness of structural fill (if required) between the subgrade and the capping layer. If the soaked CBR of the subgrade is greater than 8%, then no structural fill is required.

The majority of the current Australian rail standards use the criteria presented in Table 1 for determining the thickness of structural fill required between the capping and subgrade.

Table 1 Rail standards typical requirements for structural fill

Subgrade soaked CBR	Thickness of Structural Fill
1 – 3 %	1000 mm
3 – 8%	500 mm

In the docklands area of Melbourne very soft to soft CIS is present near the ground surface level with a soaked CBR<1%. Therefore the conventional rail standards, which would typically be adopted, do not apply and an alternative approach was required. This paper presents the design approach and methodology adopted to develop an alternate track formation from engineering first principles.

2 DESIGN APPROACH

In order to develop a track formation that provides a stable platform on which the track could be constructed, advanced 2D and 3D finite element analyses were carried out. The aim of the analyses was to:

- Develop an alternative to the ‘typical’ track formation in order to minimise the excavation depth to reduce the risk of exposing very soft CIS
- Ensure that a robust track formation design was developed that did not overstress the very soft subgrade
- Provide an estimate of ongoing settlement of the CIS

The following design methodology was adopted:

1. A literature review was undertaken on the parameters of the CIS.
2. Results of the literature review were correlated with project specific site investigations, laboratory testing, insitu testing and seismic information.

3. From the literature review and correlation with project specific information soil parameters were selected for a Soft Soil Creep and a Hardening Soil Small Strain model within the finite element program Plaxis.
4. A 3 dimensional (3D) Plaxis model was carried out to understand the load distribution and static deformations for the defined axle spacings in accordance with AS5100.2 (2004) to ensure appropriate loads were applied in the 2 dimensional (2D) models.
5. 2D static models were calibrated with the 3D model to ensure that the correct loads were being used to capture 3D effects.
6. 2D dynamic analysis was undertaken in Plaxis using both Hardening Soil Small Strain model with cross checks using the Soft Soil Creep model. Cross sections and long sections were modelled.
7. Sensitivity checks were carried out within Plaxis to take account of the existing performance of the tracks (i.e. there are no signs of global instability of the existing tracks) and the parameters refined accordingly.
8. 2D Plaxis models were used to investigate the composition of track formation required as to not overstress the subgrade.
9. Long term settlements of the new track formation determined from Plaxis modelling and empirical formula.
10. Independent Review.

3 GROUND CONDITIONS

The ground conditions in the docklands area of Melbourne are known to be geologically complex. Site specific ground investigations undertaken in the rail corridor at the project site showed that the area is generally underlain by fill, overlying sediments of the Yarra Delta Formation, inturn underlain by the Melbourne Formation. The Yarra Delta Formation consists of CIS, Fishermens Bend Silt (FBS) and Moray Street Gravel (MSG). An extract from the 1:63,360 Melbourne Sheet of the Geological Survey of Victoria is presented in Figure 1.

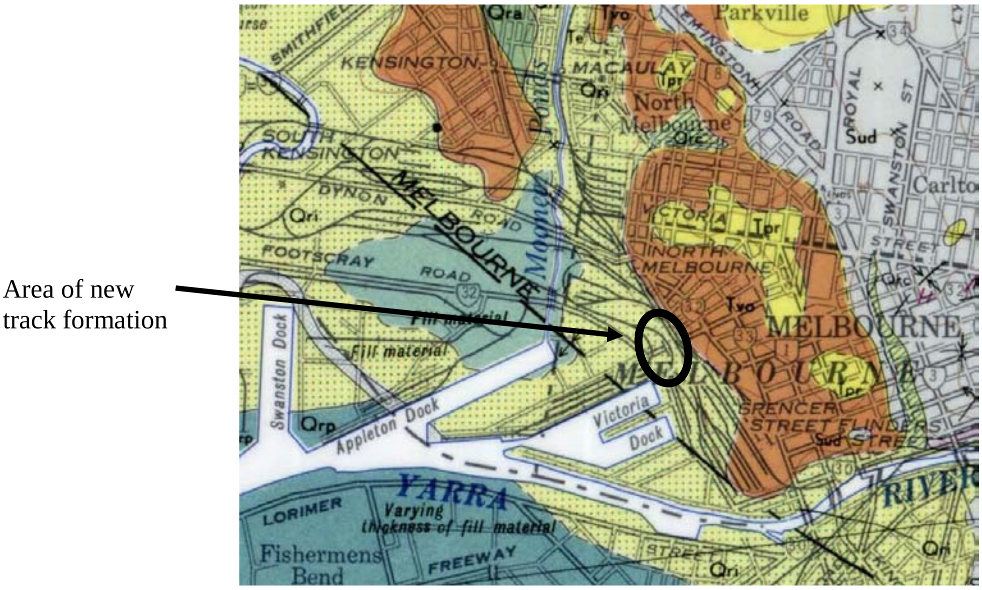

Figure 1: Extract from 1:63,360 Melbourne Sheet of the Geological Survey of Victoria

CIS is renowned for being a very soft to soft sediment that is highly compressible and susceptible to secondary compression (creep) under low loads. Properties of CIS are presented by Ervin (1992) and Srithar (2010).

Site investigations carried out indicated that varying depths of fill (ranging from 1 m to greater than 8 m) were found to be underlain by fill derived CIS or natural CIS. Further investigations including a seismic survey and seismic Cone Penetrometer Testing (CPT) were carried out to assist with the track formation design. The seismic survey comprised seismic refraction and Multi-channel Analysis of Surface Waves (MASW). From the seismic survey and the seismic CPT's, the shear modulus (G_o) of the CIS was derived.

4 DESIGN INPUT PARAMETERS

The following sections present the key design input parameters adopted for the geotechnical analysis.

4.1 TRAIN LOADING

The following design axle load and design speeds were used for the track formation design:

- 23 tonne axle load (static) with axle spacings in accordance with AS5100.2 (2004)
- Design speed of 65km/hr
- Wheel diameter 0.9m

To account for the dynamic nature of the loading, a corresponding dynamic wheel load (P_{di}) was calculated using the methodology presented by Li and Selig (1998b):

$$P_{di} = \left(1 + \frac{0.0052V}{D}\right)P_{si}$$

where P_{di} is the dynamic wheel load, V is train speed, D is wheel diameter and P_{si} is static wheel load. Using the above formula, a dynamic wheel load of approximately 320 kN was calculated.

4.2 TRACK CONFIGURATION

In accordance with the project requirements, the following track configuration was used during design:

- 2.6 m long sleeper, 0.25 m wide x 0.15 m deep
- 1.6 m between tracks
- centre line to centre line sleeper spacing of 0.685 m
- 300 mm ballast below the underside of sleeper and bearer
- 150 mm capping layer

4.3 PAST TRAIN LOADING

In the area that the tracks were to be constructed, there had historically been rail tracks. The past loading of the soil due to the train loading was taken into account during modelling. This was done by preloading the soil in increments emulating the increase in locomotive size over the years. The following increments and loads were assumed in the analysis:

- 13t axle load for a period of 20 years (statically loaded)
- 15t axle load for a period of 20 years (statically loaded)
- 18t axle load for a period of 5 years (statically loaded)

If the past train loadings were not taken into account during the modelling, excessive deformations were found to occur. Therefore the past use of the area as train yards had a significant effect on the modelling results.

4.4 GROUND PROFILE

The following design stratigraphy was modelled in Plaxis for the formation design:

- Fill 0-1.2 m
- CIS 1.2-8.0 m
- FBS >8.0 m

From the site investigation carried out in the area this stratigraphy was considered to be the ‘worst case’ ground profile. When the thicknesses of the sleepers, ballast and capping layer were accounted for, the CIS was approximately 0.5 m below the underside of the capping. Groundwater was assumed to be 1.0m below the existing ground surface level.

4.5 GEOTECHNICAL PARAMETERS

The geotechnical parameters presented in Table 2 were adopted for the track formation design. These parameters were derived from reference documents, site specific site investigations, laboratory testing results, seismic survey results, seismic cone penetrometer results and site observations.

Table 2 Geotechnical Parameters

Material	c' (kPa)	ϕ' (degs)	Hardening Soil Small Strain Parameters					Soft Soil Creep Parameters		
			E_{50} (kPa)	E_{oed} (kPa)	E_{ur} (kPa)	$\gamma_{0.7}$	G_o (kPa)	λ*	κ*	μ*
Ballast	10	40	76,100	91,300	274,000	0.0001	400,000	-	-	-
Capping	5	35	34,170	41,000	123,000	0.0001	160,000	-	-	-
Fill	5	32	20,000	20,000	80,000	0.0005	80,000	-	-	-
CIS	3	24	5,000	5,000	50,000	0.001	50,000	0.025	0.0026	0.0075
FBS	5	28	-	-	80,000	-	-	-	-	-

5 DESIGN METHODOLOGY

Plaxis 2D was used as the main design tool for the track formation design. However, 3D analysis was first undertaken to understand the load distribution from the tracks, to the sleepers, ballast and capping layer and therefore provide a realistic effective line load for the 2D modelling.

5.1 3D PLAXIS ANALYSIS

A 3D Plaxis model was created to understand the load distribution and static deformations of the axle spacings in accordance with AS5100.2 (2004). The track configuration present in Section 4.1 and the geotechnical parameters presented in Section 4.4 were used in the analysis and past loading of the subgrade was accounted for at the intervals and loads presented in Section 4.3. In the 3D analysis hardening soil small strain parameters were adopted.

From the 3D model, the pressure being exerted due to the train loading at the capping layer/subgrade interface was determined. This was then used to calibrate the 2D model as further discussed in Section 5.2. The 3D model provides an accurate load distribution from the rails to the sleepers, through the ballast and capping layer. A typical geometry and output from the 3D Plaxis analysis is presented in Figure 2.

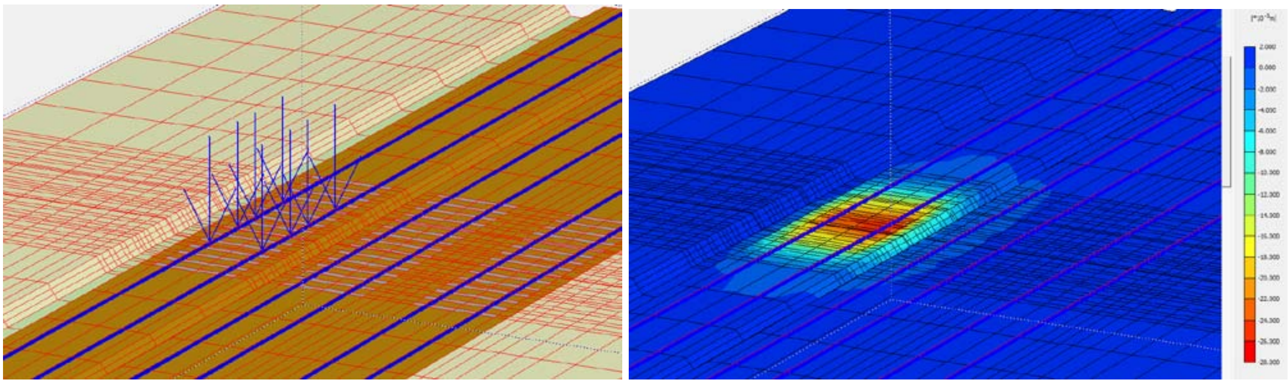

Figure 2: Typical geometry and output from 3D Plaxis.

5.2 2D PLAXIS ANALYSIS

A 2D Plaxis model was set up with the same parameters, configuration and staged construction sequence as the 3D model. For the 2D analysis, initially a cross sectional model of the tracks was created. The line loads applied in the model to simulate the wheel axles were modified in order to replicate the pressure predicted by the 3D Plaxis model at the top of the capping material. The line loads were reduced progressively, until the pressure calculated at the capping layer/subgrade interface was comparable to the 3D analysis. The line load used in the cross section model was 135 kN/m.

Following the calibration of the 2D model, the cross sectional model was used to investigate the make up of the track formation required to provide a 'stable' formation on which to construct the tracks. The track formations investigated included:

- Use of geotextiles
- Use of varying thicknesses of structural fill (soaked CBR 8%)
- Use of an 'improved' structural fill material

A limit of 4% strain was adopted as the maximum strain level that could be sustained by the subgrade. This limit is based on the level of strain that can be withstood by the CIS subgrade before excessive deformation occurs that would result in compromising the integrity of the formation.

Once a potential track formation was identified, a longitudinal section 2D Plaxis model was developed. This model enabled the strains in the subgrade to be checked perpendicular to the sleepers and allowed dynamic analysis to be carried out so that the dynamic effect on the strain levels could be investigated.

In the 2D analysis, the CIS was modelled using both hardening soil small strain and soft soil creep soil models. Using the two soil model types ensured that the secondary compression of the CIS and the small strain behaviour were accounted for during the design. Example outputs from the cross section and long section 2D Plaxis analysis are presented in Figure 3.

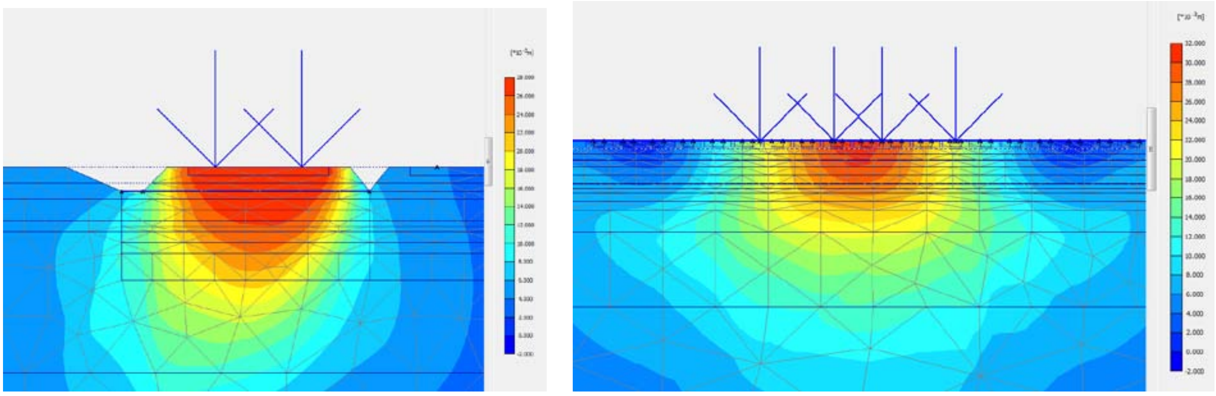

Figure 3: Cross Section and Long Section deflection output from 2D Plaxis

5.3 ESTIMATION OF LONG TERM SETTLEMENT

The design intent was to provide the rail operators with an estimate of the ongoing settlement rather than negate all settlement. The rail operators could then take into account the estimated settlement as part of their track maintenance schedule.

The settlement of the tracks was estimated by combining the settlement calculated using two methods:

- 2D Plaxis analysis results
- Empirical formula for cyclic long term settlement

The estimation of immediate and creep settlement from the 2D Plaxis analysis was calculated by repeatedly applying the train loading over a specified time period. Using the empirical method the cyclic long term settlement was calculated using details provided in the project documents regarding the number of train movements per day. The formula developed by Selig and Waters (1994) was used to calculate the cyclic long term settlement:

$$\frac{\varepsilon_n}{\varepsilon_i} = 1 + c \log N$$

where ε_n is the permanent strain after N loading cycles, ε_i is the initial strain, c is the soil material constant (0.2 or 0.4) and N is the number of repeated loading cycles.

6 RESULTS AND DISCUSSION

The following section presents the results of the analyses and discusses the composition of the track formation that was developed as part of the design.

6.1 PLAXIS ANALYSIS

Using the methodology presented in this paper, several different track formations were investigated using the 2D Plaxis models. These included using geotextiles, use of structural fill and using an ‘improved’ structural fill layer.

During the design process it was found that geotextiles were not effective in spreading the train loading as only a limited width was available due to the proximity of existing tracks and the site boundary. Varying the thickness of the structural fill (CBR 8%) was also found not to be a viable solution, as even with a 1.0 m thick layer of structural fill, the strain in the subgrade was found be greater than 4%. In addition, the structural fill layer would have been likely to penetrate into the CIS which would not have met the design intent. Therefore an ‘improved’ structural fill material was the preferred solution and was used directly below the capping layer. This layer was termed ‘sub-capping fill’ and was developed using the same properties as the capping layer defined by the rail standards. This approach was adopted, such that an alternate specification was not required for the material, whilst still having properties that were required to meet the design intent.

Through the Plaxis analysis, numerous iterations were performed to develop a ‘stable’ track formation. Using the methodology presented in this paper, the alternate track formation presented in Figure 4 was developed:

- Ballast – 300 mm below sleeper
- Capping -150 m Thick layer
- Sub-Capping Fill – 200 mm thick layer
- Self Compacting Fill – 300 mm thick layer
- Geotextile – Bidim A34 or similar

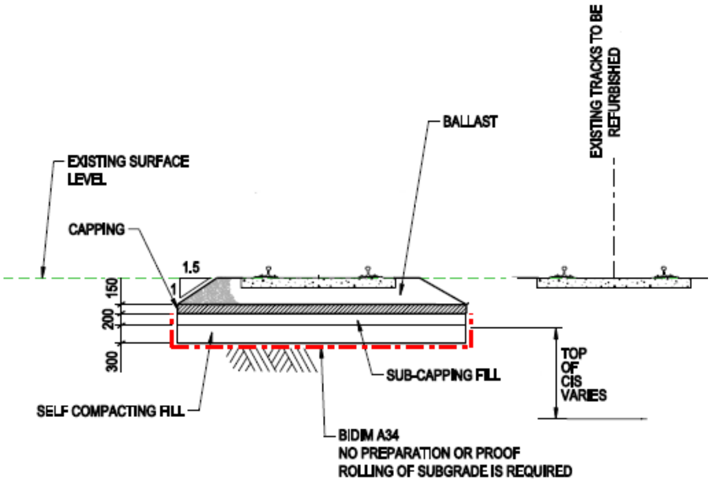

Figure 4: Alternate Track Formation on CIS

The thickness of the ballast and capping layers were not altered from the rails standards. The material termed ‘self compacting fill’ was developed such that the use of compaction equipment directly on top of the CIS was mitigated. The geotechnical properties of this self compacting fill were broadly similar to the sub-capping fill. Placing heavy compaction equipment directly on the very soft to soft CIS could result in large ground movement under the machinery. The grading of the self compacting fill was selected, so that the material self compacts upon placement. In order to achieve this, the material was detailed so that the material is well graded. To assist with placement of the self-compacting fill onsite, a non woven geotextile was placed below the layer to provide separation between the subgrade and new fill.

In addition checks were carried out on the compatibility of the materials used in the track formation to ensure that fines would not migrate between the layers, which could compromise the integrity of the formation. This was done using the method presented by Lambe and Whitman (1968).

6.2 ESTIMATED LONG TERM SETTLEMENT

The settlement of the new track formation constructed over CIS was determined from the 2D Plaxis modelling and using empirical formula. The estimated settlements were provided for time intervals of 0 to 6 months, 2 to 24 months and 2 to 20 years so that the rail operators could make allowances for track maintenance required to keep the vertical alignment within the required tolerances. The settlements estimated using the design approach and methodology presented in this paper are provided in Table 3.

Table 3: Estimated track formation settlement

Immediate Settlement (mm)	**Cumulative Creep Settlement (mm)**			**Cumulative Cyclic Degradation (mm)**			**Total Settlement in 20 yrs (mm)**
	0-6mths	**6-24mths**	**2-20 yrs**	**0-6mths**	**6-24 mths**	**2-20 yrs**	

30	5	10	40	5	20	110	180

The values presented in Table 3 are considered to be upper bound estimates of settlement, as the geotechnical parameters used in the analysis are lower bound and some of the settlement is expected to occur during construction.

7 CONCLUSION

The design approach and methodology outlined in this paper were used to develop an alternate track formation to the rail standards normally used in Australia. The alternate approach was required as the rail standards do not provide a design solution when the soaked CBR of the subgrade falls below 1%. The design approach used a combination of 3D and 2D finite element analysis to demonstrate that the very soft subgrade was not overstressed due to the train loading. In addition it used a combination of 2D finite element analysis and empirical formula to provide an estimate of the track formation settlement over a period of up to 20 years.

The design approach presented could be adopted for designs on similar soft subgrades to demonstrate an acceptable track formation.

8 REFERENCES

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