

COST EFFECTIVE DESIGN OF RAIL STRUCTURAL FILL ZONE AND ITS APPLICATION IN SOUTHERN SYDNEY FREIGHT LINE

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ABSTRACT

Rail track structure is a layered system. Between the rail ballast and the subgrade, a subballast layer (comprising a capping layer and a structural zone fill layer) is often required to reduce the induced stress and accumulated strain at the top of the subgrade. Design of the subballast layer, in particular the structural zone fill layer, has normally been carried out based on empirical rules or authority guidelines which have standard, and often exclusive, specification for the material. For example, Railcorp and ARTC Earthworks Standards specify a structural zone fill CBR value of 8% and provide required structural zone thickness based on different subgrade strength/stiffness. The use of higher quality structural zone fill material with CBR values in the order of 20% to 40% may significantly reduce the rail structural fill zone thickness and hence generate cost savings while not compromising the long term performance of the rail structure. However, no design guidelines are available for design. This paper presents the development of a new design method for design of structural zone thickness considering the use of higher quality structural zone fill material, and the application of this design method in Southern Freight Link (SFL).

1 INTRODUCTION

1.1 SOUTHERN FREIGHT LINK (SFL) PROJECT

The Australian Rail Track Corporation (ARTC) is currently undertaking a program of works to improve the efficiency and cost-effectiveness of rail freight services along the North-South Rail Corridor between Melbourne, Sydney and Brisbane. A major bottleneck in the rail freight network currently exists in southern Sydney, where freight trains share existing rail lines with the Sydney metropolitan passenger services operated by RailCorp.



Figure 1: SFL Route.

To alleviate this bottleneck, the ARTC has commenced construction of the Southern Sydney Freight Line (SSFL), which will provide a dedicated non-electrified bi-directional freight line between Macarthur and Sefton in Southern Sydney. The SSFL will provide a third track, specifically for freight services, allowing passenger and freight services to operate independently albeit, within a shared corridor.

ARTC has formed an Alliance with Leighton Contractors to deliver the Southern Freight Link (SFL) Alliance with Aurecon as the detailed designer. The SFL Alliance will complete the construction of a 36 km dedicated freight line

between Macarthur and Leightonfield in southern Sydney. The SFL Alliance will provide the third track in the rail corridor specifically for freight services, allowing passenger and freight services to operate independently. The SFL route is shown in Figure 1.

The regional geology within the rail corridor and along the proposed track route occurs within the Permo-Triassic Sydney Basin. Two major rock associations are encountered within the region: the Wianamatta Group and the Hawkesbury Sandstone. The uppermost unit, the Wianamatta Group, comprises Bringelly Shale, Ashfield Shale and Minchinbury sandstone. Bringelly Shale dominates the northern end from Sefton Station to South of Liverpool Station. Ashfield Shale is present in the south section from south of Liverpool Station and Minchinbury sandstone borders the Ashfield Shale to the south of Liverpool Station. The older rock unit, the Hawkesbury Sandstone comprises mainly quartz sandstone with minor mudstone and siltstone lenses. In addition there are alluvium deposits along the route associated with more recent Quaternary Alluvium and Older Tertiary Alluvium. The expected subgrade material along the route is predominantly residual shale and alluvial materials.

1.2 BALLASTED RAIL TRACK SYSTEM

Ballasted rail track structure is a layered system. The track components of ballasted railway track may be categorised into two groups, as illustrated in Figure 2. The first group is designated as the superstructure, consisting of the rails, the fastening system and the sleepers, whereas the second group is designated as the substructure, consisting of the ballast layer, a sub-ballast layer and the subgrade. The function of the ballast layer is to effectively distribute the trainload and to retain the sleepers in their required position. In the NSW Railcorp Standard (ESC 240, 2011), the ballast depth between a minimum of 100 mm to 350 mm and a maximum of 500 mm in accordance with the existing or proposed track structure class is required for providing sufficient resiliency, strength and energy absorption.

Between the rail ballast and the subgrade, a subballast layer (comprising a capping layer and a structural zone fill layer of different material characteristics) is often required to reduce the induced stress and accumulated strain at the top of the subgrade. The application of the structural zone fill layer, depends on the strength and stiffness conditions of the subgrade below which is represented by a natural ground formation or a placed soil fill.

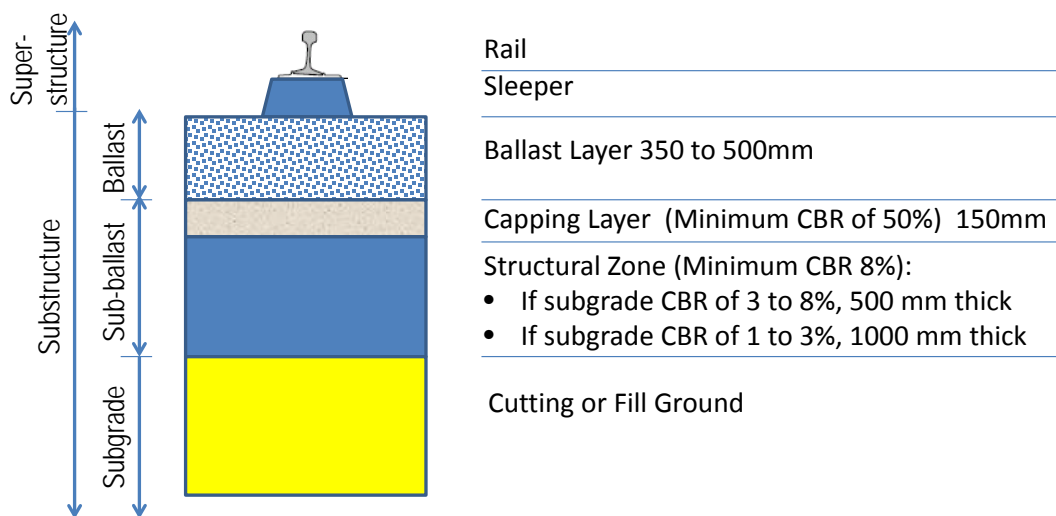


Figure 2: Components of Rail Structure and Railcorp/ARTC Design Guidelines.

1.3 PURPOSE OF THE CURRENT STUDY

Design of the subballast layer, in particular the Structural Zone fill layer, has normally been carried out in Australia based on empirical rules or authority guidelines which have standard, and often exclusive, specification for the material properties. The current Railcorp design guidelines (ESC 410, 2010) stipulates a 4-day soaked California Bearing Ratio (CBR) of 8% for the structural zone fill material, and requires a structural zone fill thickness of 500 mm or 1000 mm based on different subgrade CBR values, as also illustrated in Figure 2. Similar design guidelines have also been adopted by ARTC.

However in practice, higher quality Structural Zone fill materials, satisfying the requirements of Particle Size Distribution, Atterberg Limits and Dry Density stipulated in the Railcorp Specification, but with CBR values in the order of 20% to 40% can often be available at a competitive price to the standard Structural Zone fill with a CBR of 8%. Hence there is a potential for use of higher quality Structural Zone fill material with CBR of 20% to 40% to reduce

the rail Structural Zone fill thickness and hence generate cost savings while not compromising the long term performance of the rail structure. Given that no existing guidelines are available for design, extensive studies have therefore been carried out as part of the SFL design and a design method for design of Structural Zone thickness has been developed considering the use of higher quality structural zone fill material.

2 DEVELOPMENT OF THE DESIGN METHOD

2.1 REVIEW OF INTERNATIONAL PRACTICE

The key design objective for rail substructure design is that the combined ballast/subballast layer thickness must be sufficient to prevent progressive shear subgrade failure, and excessive settlement through plastic strain accumulation in the subgrade. The bearing capacity for rail track has to consider not just a single load application but also repeated loading. Allowable stress under repeated loading is much less than that under static loading (Selig and Waters, 1994). This design principle is incorporated in the design methods adopted in various countries with the induced vertical stress with depth being determined using a single layer elastic theory, however in different forms.

In order to derive a suitable subgrade performance criterion in terms of the allowable stress and strain that may be induced by rail loads on the subgrade, for development of the new design charts, a review of the international practice is carried out and summarised in below:

- The American Railway Engineering Association (AREA) Engineering Manual specifies a 12 in. (305 mm) minimum ballast thickness and a 6 in. (150 mm) minimum subballast thickness. This results in a minimum granular layer thickness of 18 in. (460 mm). AREA has also specified various equations to determine the induced subgrade stress, which then compares with the subgrade bearing capacity, for which, the AREA Manual recommends a universal 140 kPa limit, however typically 35 kPa maximum for alluvial soils, 55 to 70 kPa for soft clay or wet/loose sand, and 108 to 137 kPa for dry gravelly soils (AREA, 1991).
- British Rail developed a “threshold stress” ($\sigma_1' - \sigma_3'$) design method, limiting the stress on subgrade soils to protect against subgrade failure by excessive plastic deformation. The threshold stress was determined from repeated load tests on soil samples of London Clay. Concept design charts have been developed by British Rail for selecting granular layer thickness for various threshold stress and axle loads, making it possible to determine the ballast depth required for a particular axle load induced threshold value, as shown in Figure 3 below (Heath, 1972).
- German Railway specifies that the permissible compressive stress, σ_z on the formation related to number of loading cycles is given by $\sigma_z = \frac{0.006E}{1+0.7\log n}$ (where E is the elastic modulus from the second load step and n is the number of load cycles) (Selig and Waters, 1994).

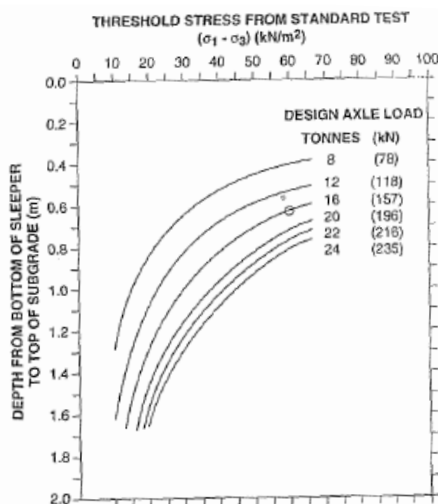


Figure 3: British Rail Design Charts.

Selig and Waters (1994) concluded that in most ballasted track, ballast is the main source of settlement between surfacing (re-ballasting) operations, and subgrade related long term settlement, usually accumulating very slowly, can be adjusted by surfacing operations. This is probably why the design concept of limiting strain at the subgrade level, usually adopted for design of flexible or lightly trafficked pavements (e.g.

Austrroads, 2010) is not adopted in any of the ballasted rail design standards discussed above. However, clayey subgrade shear deformation associated with pore water pressure development under repeated rail loads is related to progressive shear failure. Hence for rail structure on subgrade of clayey materials, it may be prudent to design to limit the strain at the subgrade level. The limiting strain depends on the anticipated number of axle loading cycles over its working life. Empirical equations for limiting strain have been developed for use in road pavement design which may provide some guidance to the rail formation design. For example, Austrroads (2010) specifies that the limiting micro-strain may be estimated by $\frac{9300}{\sqrt[3]{n}}$.

The allowable stress and strain at the subgrade level, implied in above-mentioned international design guidelines, are interpreted in Table 1 below:

Table 1: Allowable Subgrade Stress and Strain Implied in Various International Practices

Authority	Allowable Stress (kPa)	Limiting Strain on Subgrade	Remarks
AREA	13 CBR	N/A	Described by Selig & Waters as non-conservative
British Rail	12 to 15 CBR	N/A	Assessed from the concept design curve
German Rail	8.4 CBR	N/A	Based 2.24×10^7 load cycles in a 100 year life
Austrroads	N/A	830 micro-strain	Based 2.24×10^7 load cycles in a 100 year life

2.2 ASSUMPTIONS AND ANALYTICAL MODEL

2.2.1 Rail Load Transfer to Subgrade

For the purpose of the development of the design method for use in SFL, only one type of rail load, 300LA, has been considered. The axle load and spacing for 300LA from AS5100.2 are reproduced in Figure 4.

Further, the sleepers are considered to be 2.44 m long x 0.23 m wide at 600 mm spacing based on ESC 230 (Railcorp, 2011). Although it is expected that the pressure in the middle of the sleeper may be smaller than the pressure under each rail-seat, as observed in a PLAXIS 3D analysis, it is assumed that the pressure exerted by the sleeper on the ballast is uniform along the sleeper in order to simplify the analyses. Based on the above dimensions, the uniformly distributed load applied on each sleeper can be assessed. For the 300LA, a static load of 214 kPa has been assessed. It is common practice to assess the rail system behaviour for a static load, taking into account the dynamic effects of the running speed on load by a Dynamic Amplification Factor based on the Eisenmann formula (Esveld, 2001). For the assessment of subgrade performance, a Dynamic Amplification Factor of 1.3 to 1.45 may be taken considering the condition of the track.

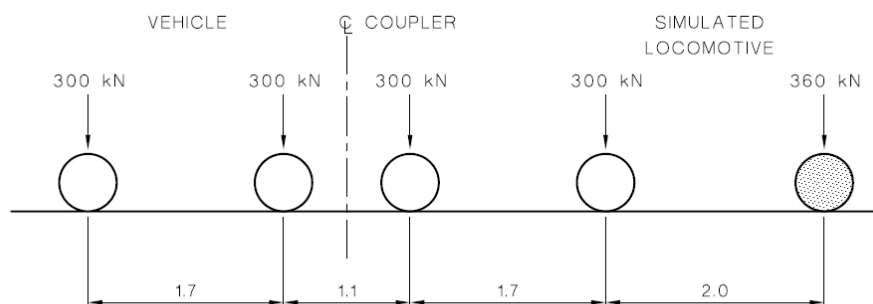


Figure 4: 300 LA Railway Traffic Loads – Axle Loads (AS5100.2).

2.2.2 Subgrade Performance Criteria

From a review of the international practice on rail formation design, a conservative subgrade performance criterion has been adopted for the development of the new design method for SFL.

- Allowable stress induced on subgrade shall be less than $7.5 \times \text{CBR}$ (kPa);
- Limiting strain on the subgrade surface shall be less than 650 micro-strain.

To verify the appropriateness of the design criteria, an assessment has been carried out for the existing Railcorp/ARTC design using the structural fill CBR of 8%.

Table 2: Comparison of adopted design criteria and current Railcorp/ARTC Standard Design

Item	Adopted design criteria	Railcorp Standard Design for Subgrade CBR 1 to 3	Railcorp Standard Design for Subgrade CBR 3 to 8
Allowable Stress on Subgrade	7.5 CBR (kPa)	4.7 to 8.1 CBR	4 to 7.6 CBR
Limiting Strain on subgrade	650 Micro strain	425 to 695	348 to 670

The comparison confirms that the adopted design criteria is appropriately within the intent of the original Railcorp Standard Design.

2.2.3 Analytical Method and Key Parameters

The stress and strain developed at the subgrade level under rail load has been firstly investigated using commercially available software PLAXIS 3D assuming the rail load is a line load along the rail beam, for some typical cases. Extensive parametric studies have then been carried out using another commercially available computer program FLEA (Finite Layer Elastic Analysis) which was developed by Sydney University and can calculate the stresses and displacements within a multi-layered soil deposit of finite thickness generated by multiple uniform surface loadings.

The adopted parameters are given in Table 3 below.

Table 3: Analytical Model and Soil Parameters

Layer	Description	Unit Weight (kN/m ³)	Cohesion (kPa)	Friction Angle, ϕ (°)	Modulus (MPa)	Layer thickness (mm)
1	Ballast	17	0	42	350	350
2	Capping	20	20	33	300	150
3	Structural zone material	20	10	30	8 x CBR	Various
4	Subgrade	19	3	26	10 x CBR	Infinite

2.2.4 Parametric Study

A comprehensive parametric study has been carried out considering:

- Structural Zone fill CBR values between 8% to 40%;
- Subgrade CBR values between 1% to 7%.

2.3 MODELLING OF SUBGRADE PERFORMANCE

Modelling of the subgrade performance under rail loads has been carried out using PLAXIS 3D. Figure 5 shows the case where Structural Zone fill is 525mm thick with a CBR of 20% and the subgrade modulus is 2%. The predicted vertical displacement from PLAXIS3D under the sleeper is 2.3mm, and the induced vertical stress on the subgrade has been assessed to be between 10.1kPa to 16.5kPa. The results appear to be in good agreement of the FLEA assessments where the predicted displacement is 1.5mm and the vertical stress on subgrade is 15kPa.

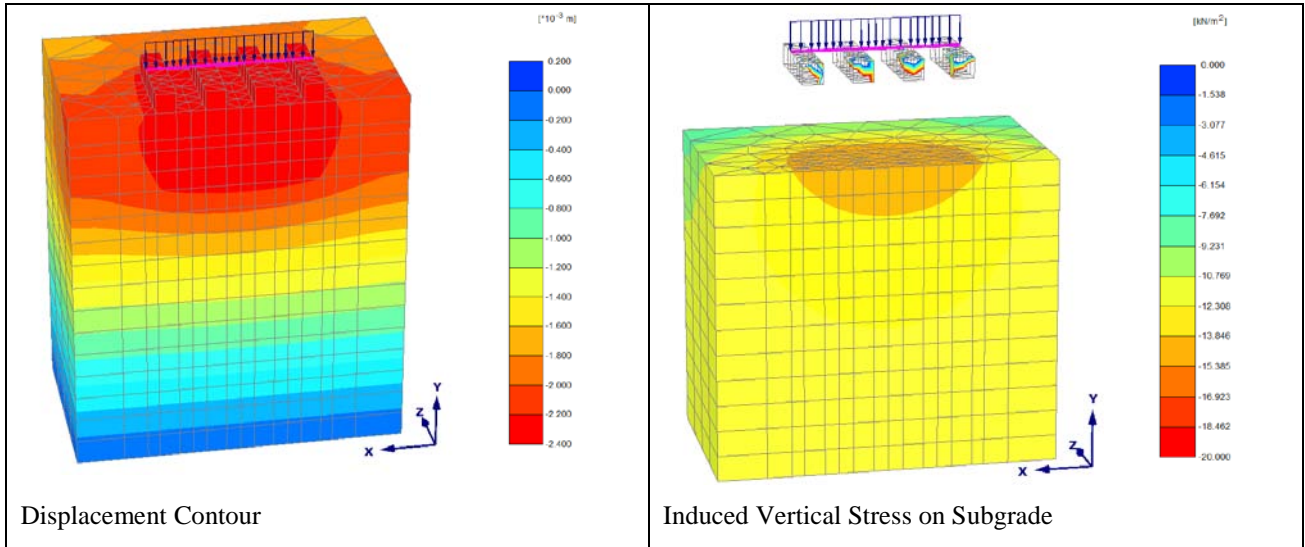


Figure 5: PLAXIS 3D Modelling of a Typical Case.

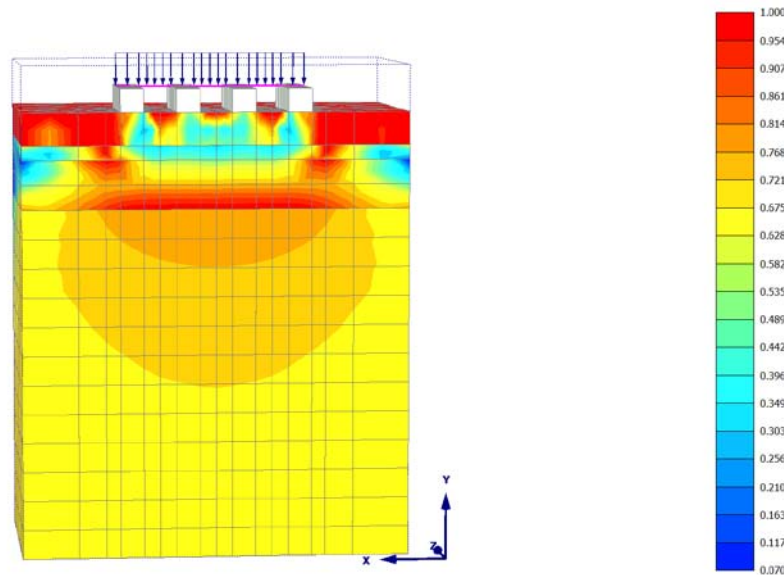


Figure 6: Plot of Relative Shear Stress.

Further the plot of relative shear stress, shown in Figure 6, appears to suggest that the behaviour of the subgrade is well within the elastic range. This provides good confidence on the design criteria that have been adopted.

2.4 DEVELOPMENT OF DESIGN METHOD

Through extensive parametric study, it is concluded that the design thickness of the structural zone fill for a typical Railcorp/ARTC rail formation, i.e. with a minimum ballast zone of 350mm and a capping layer of 150mm, may be taken as:

$$t = 1600 + (135 \times \ln CBR_{subgrade} - 265) \times \ln CBR_{structural\ fill} - 810 \times \ln(CBR_{subgrade}) \quad (1)$$

Where t is the thickness of structural fill that may be required in mm. $CBR_{structural\ fill}$ shall be between 8 to 40, and $CBR_{subgrade}$ shall be between 1 to 7.

The comparison of proposed design line and the analysed cases is shown in Figure 7.

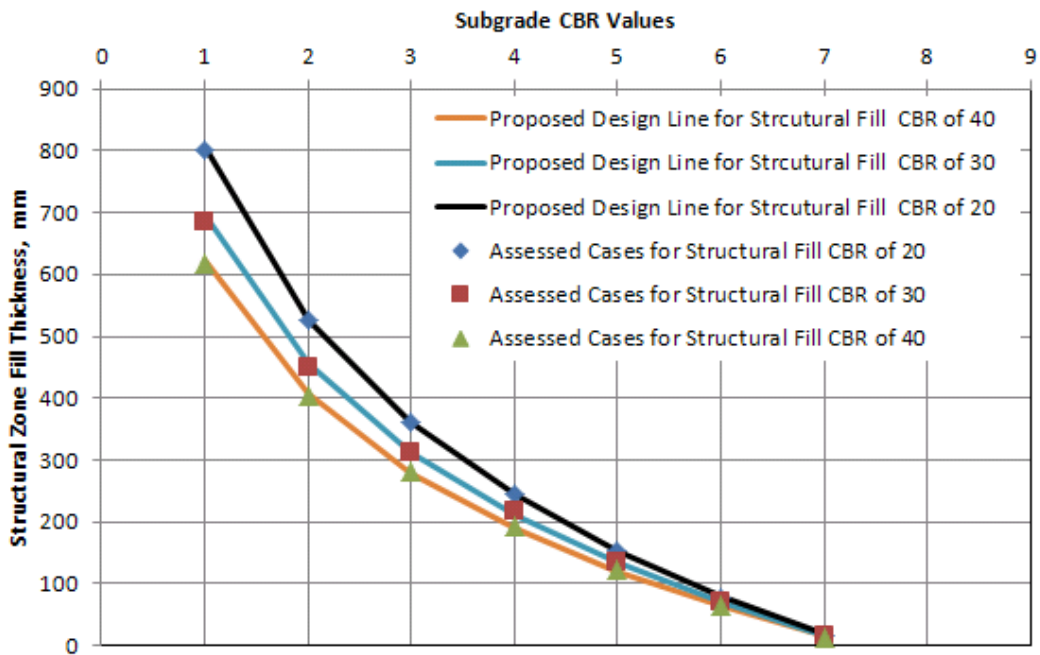


Figure 7: Proposed Design Lines and Assessed Cases.

3 APPLICATION IN SOUTHERN SYDNEY FREIGHT LINK

The developed method has been implemented in SFL. A typical design is shown in Figure 8. A minimum structural fill CBR of 20% was specified in SFL and the structural zone fill thickness has been adopted as:

- For Subgrade CBR of 1% to 3% 600 mm
- For Subgrade CBR of 3% to 7% 300 mm
- For Subgrade CBR greater than 7% No structural fill zone is required

The use of higher standard structural zone fill has generated a saving of approx. 65,000 m³ structural fill material.

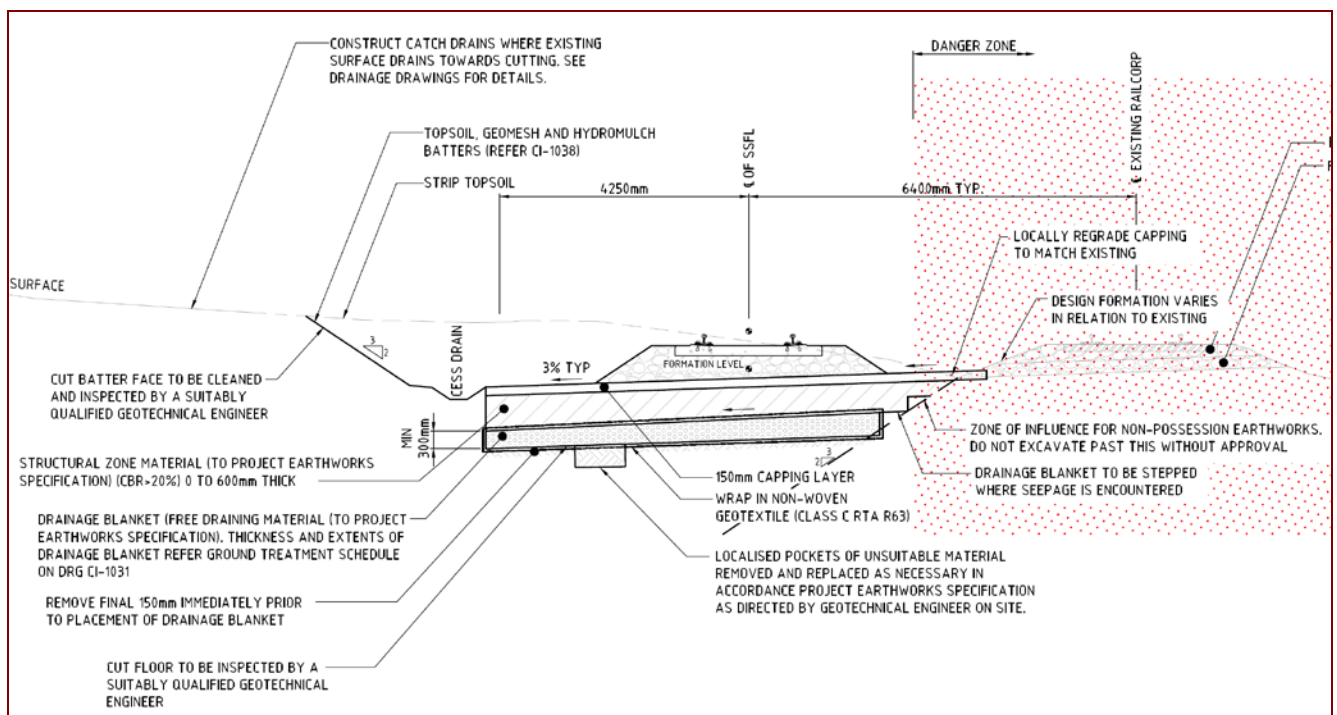


Figure 8: SFL Cut Floor Typical Design.

4 CONCLUSIONS AND RECOMMENDATIONS

This paper presents the development of a new design method for design of structural zone fill thickness considering the use of higher quality structural zone fill material with a CBR value of 20% to 40% instead of the CBR of 8% specified in the standard Railcorp/ARTC Specification, and the application of this design method in Southern Freight Link (SFL). In conjunction with the development of this design method, a subgrade performance criterion has been specified based on a study on international practice on rail formation design. The developed design method may lead to significant reduction of the use of Structural Zone fill material while not compromising the long term performance of the rail structure.

Although the current design method has only considered the 300LA rail traffic load, it can be easily extended to other types of rail traffic loads including 200LA, 350LA and Railcorp Passenger Main Line. However this is beyond the scope of this paper.

5 ACKNOWLEDGEMENT

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