

On best practices for trackbed design

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ABSTRACT

This paper reviews the best practices of trackbed design for railway projects. Various existing methods have been studied and recommendations for more economical design are provided. The analytical/empirical methods from various standards such as UIC, AREMA, British Rail, and Australian standards, as well as other commonly used methods such as Raymond and Li-Selig are compared based on a typical track embankment cross section. The outcome was then evaluated against 2D and 3D numerical models. Incorporating numerical methods is shown to render considerable reductions in the required prepared subgrade/structural fill materials and allow for assessment of long-term design issues, such as subgrade shear failure due to excessive plastic deformations.

Keywords: Trackbed Design, 3D Numerical Modelling, Best Practices, Railway Standards

1 INTRODUCTION

With major ongoing and emerging rail projects across the world and in Australia, the rail infrastructure industry seeks innovative solutions to provide sustainable and cost-effective design solutions. Proper engineering design of track-bed and track formations is one of the key components for effective design and operation of railways and minimizing the construction and maintenance costs.

This paper presents a review on various common analytical and empirical methods and standards for track-bed and track formation design. The variations in the design outcomes using these methods are investigated. In addition, the application of innovative solutions including advanced nonlinear finite element method (FEM) analysis and subgrade stabilisation for optimizing the track formation design is discussed.

2 TRACKBED AND TRACK FORMATION

A typical track embankment cross-section is presented in Figure 1. The main function, typical dimensions, and typical material properties for all the required layers are defined in Table 1. Ballast and subballast are normally defined as “trackbed” laying on top of the ‘track formation,” which is the natural subgrade [1].

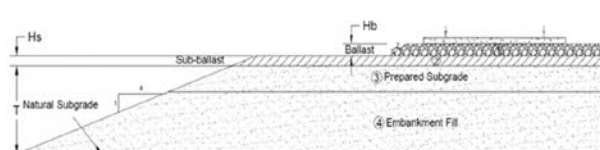


Figure 1. Trackbed and formation typical section

3 ANALYTICAL AND EMPIRICAL DESIGN METHODS AND STANDARDS

3.1 UIC method

UIC [1] requires the following items to be considered in dimensioning the track bed layers:

- Problems of frost protection
- Bearing capacity of subgrade
- Type and spacing of sleepers
- Traffic characteristics

The UIC method of estimating the suggested minimum thickness of the trackbed layers including is depicted in

Figure 2. Table 2 provides the method of determination of subgrade bearing capacity class and required prepared subgrade class and thickness.

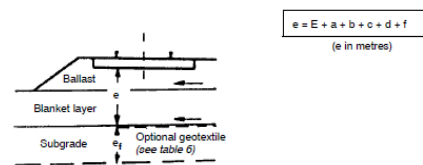


Fig. 15 - Calculation of minimum thickness (e) of track bed

E	= 0,70 m	for soils of bearing capacity class P1 ^a
E	= 0,55 m	for soils of bearing capacity class P2 ^a
E	= 0,45 m	for soils of bearing capacity class P3 ^a
a	= 0	for UIC groups 1-4 ^b
a	= - 0,10 m	for UIC groups 5 and 6 ^b
b	= 0	for wooden sleepers of length 2,80 m
b	= $\frac{2,50-L}{2}$	for concrete sleepers of length L (b in m, L in m; b possibly negative if L > 2,50 m)
c	= 0	for usual dimensions
c	= - 0,10 m	special case for difficult working conditions on existing lines
d	= 0	when the nominal maximum axleload of hauled vehicles does not exceed 200 kN (see UIC Leaflet 700)
d	= + 0,05 m	when the nominal maximum axleload of hauled vehicles does not exceed 225 kN (see UIC Leaflet 700)
d	= + 0,12 m	when the nominal maximum axleload of hauled vehicles does not exceed 250 kN (see UIC Leaflets 700 and 724)
f	= +	the track bed should include a geotextile if the prepared subgrade is formed from soils of quality class QS1 or QS2 ^c
f	= 0	(no geotextile is required) if the prepared subgrade is formed from soils of quality class QS3 ^d

a. The bearing capacity classes are defined in table 6.
b. The UIC groups are defined in UIC Leaflet 714 (edition of 1.1.89) (see Bibliography).
c. See NB in point 2.5 - page 40.
d. The UIC soil quality classes are defined in table 5.

Figure 2. UIC method of calculating the minimum thickness of trackbed layers [1]

3.2 AREMA method

AREMA [2] recommends the Talbot equation for estimating the thickness of the granular trackbed (i.e. ballast + sub-ballast). This method was developed based on field tests conducted in 1910s and 1920s. Subgrade conditions, heavier axle loads, dynamic effects, and granular material quality are factors that have not been considered in this method.

$$H = 0.24 (P_m / P_c)^{0.8}$$

Where,

H is the granular material thickness ($H_a + H_s$),
 P_c is the allowable subgrade stress (138 kPa recommended by AREMA), and P_m is the vertical stress applied on the ballast surface.

Table 1: Trackbed and formation layers

Track layer	Main functions	Typical thickness	Typical material
Ballast	-Transfers and distributes loading from the ties to the underlying subballast or subgrade of the track structure at a tolerable level. -Provides drainage through the support structure and away from the track	300 – 450 mm	Crushed rock/aggregates with maximum size of 63.5 mm (2.5 in)
Subballast/Capping	-Providing a filter/buffer between subballast and subgrade -Drainage	150 mm	Crushed rock/aggregates the maximum grain size of the subballast shall not exceed the maximum grain size of the track ballast and no more than 5% of the subballast shall pass the No. 200 sieve.
Prepared Subgrade/Structural Fill	An additional layer on top of the fill or natural subgrade to further reduce the stress on subgrade and also to provide sufficient overall stiffness	0-500 mm (varies depending on the subgrade strength)	Varies with different standards: well-graded coarse-grained material with low to medium plasticity and maximum 15% to 30% fine-grained
Embankment Fill	Provide the required track level	Depends on the track level design wrt the existing ground	Should be free of unsuitable material: -Materials containing stumps, weeds, leaves, coals, peats, ashes, grasses, and other organic materials. -Contaminated soil -Material with soaked CBR ¹ <2% and swell index ² >3 %
Natural Subgrade	Foundation to the trackbed	NA	Must have a minimum of CBR=2 %; Should be free of unsuitable material as per above

1. 95% Standard compaction – 9 kg Surcharge

2. ASTM D4546 – 14e1 “Standard Test Methods for One-Dimensional Swell or Collapse of Soils”, Test Method A.

Table 2: Determination of subgrade bearing capacity and prepared subgrade thickness

Subgrade/ Fill Soil Quality ¹	Min. CBR ² (%)	Req. Bearing Class for Subgrade ¹	Prep Subgrade Quality Class	Prep Subgrade Min. CBR ³	Min. thickness: “ef” (m)
QS1	2-3	P2 P2 P3	QS2 QS3 QS3	5 10-17 10-17	0.5 0.35 0.50
QS2	5	P3	QS3	10-17	0.35
QS3	10-17	P3	QS3	10-17	NA

1. QS0: “Unsuitable”, QS1/P1: “Poor”, QS2/P2: “Average”, QS3/P3: “Good”. Refer to [1] for details

2. CBR of the in-situ (soaked)

3. CBR of remoulded samples (soaked)

3.3 Raymond Method

Raymond (1985) [3] modified the design method recommended by AREMA. Figure 3 shows the design chart developed by Raymond for vehicles weighing 70-125 tons. The following assumptions have been made in the development of this method:

- Ballast, sub-ballast + subgrade act together as a single homogenous layer
- Uses a single value of axle load disregarding the amount of cumulative tonnage

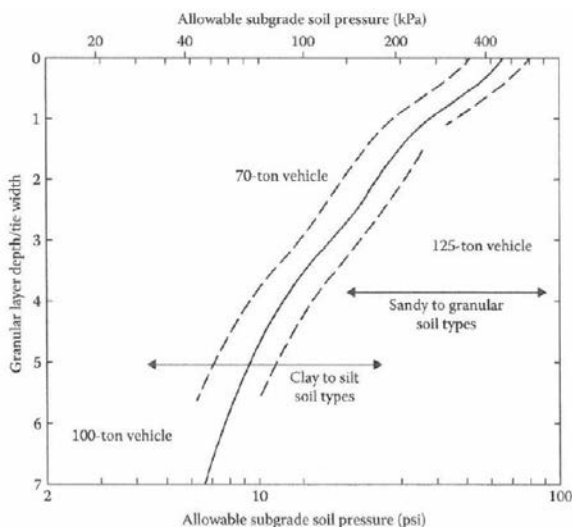


Figure 3. Raymond design chart

3.4 British Rail Method

Heath et al. (1972) [4] developed a threshold stress design method for selecting the granular layer thickness. The threshold stress is the limit stress in the subgrade to protect the subgrade from progressive shear failure (See Figure 4).

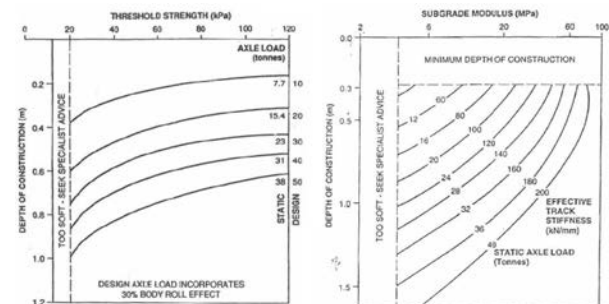


Figure 4. Subgrade threshold stress for selecting granular layer thickness [4]

3.5 Li-Selig Method

The Li-Selig Method (1998) [5,6] can be used based on the allowable stress at the subgrade surface (allowable cumulative plastic strain), as well as the allowable subgrade deformation. Figure 5 provides examples of design charts. In these charts, H is granular material thickness. I_ϵ and I_p are referred to as the strain influence factor and the deformation influence factor, respectively:

$$I_\epsilon = \frac{\sigma_{da}A}{P_d}$$

$$I_p = \frac{\rho_a/L}{a(P_d/\sigma_s A)^m N^b} \times 100$$

Where, σ_{da} is the allowable deviator stress at the subgrade surface, ρ_d is the allowable total subgrade plastic deformation for the design period, N is the total equivalent number of load repetitions during the design period, P_d is the design dynamic wheel load, σ_s is the soil compressive strength, a , m , and b are the material parameters dependent on soil type, A is the area factor selected to make deformation influence factor dimensionless, (0.64m², 1000in²), and L is a factor to make charts dimensionless (6in, 0.152m).

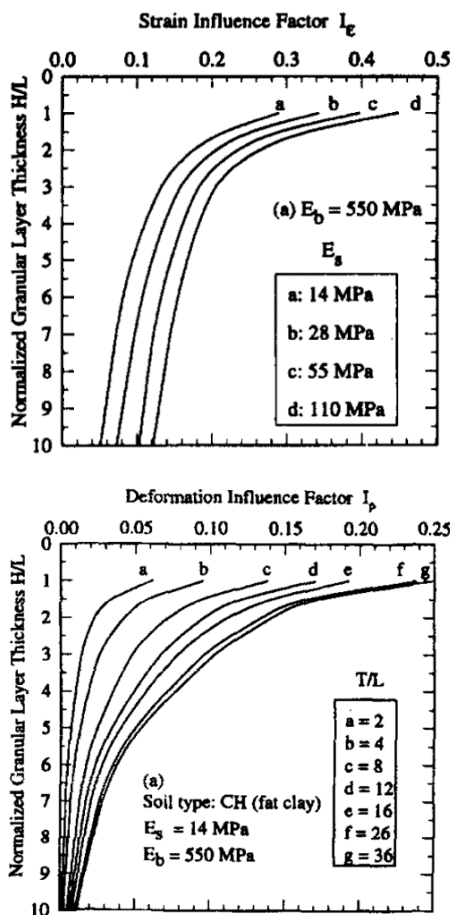


Figure 5. Li-Selig example design charts [5]

Two main failure mechanisms were considered for the development of this approach:

- 1) Subgrade progressive shear failure (Figure 6): This has been reported by the European railways and in the United States for track under heavy axle loads especially on fine-grained soils without sufficient

granular layer thickness. This normally causes a heave at trackside which can block the proper drainage. Water coming from the granular layer can be trapped in the subgrade depression areas which can aggravate the failure.

- 2) Excessive Plastic Deformation due to Repeated Loading: This can cause ballast pockets under the track (Figure 7) and happens predominantly in soft soil subgrades.

Other types of failure include mud pumping, excessive consolidation settlement, and slope stability failure. The granular layer thickness does not influence these [5].

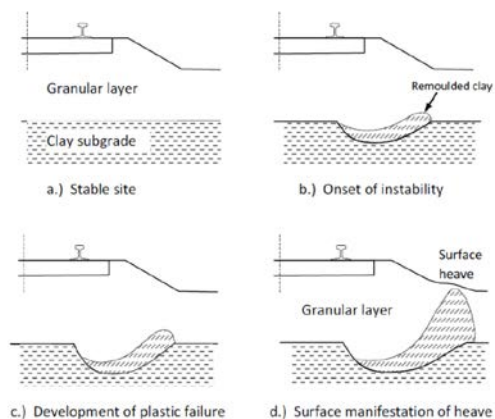


Figure 6. Subgrade progressive shear failure

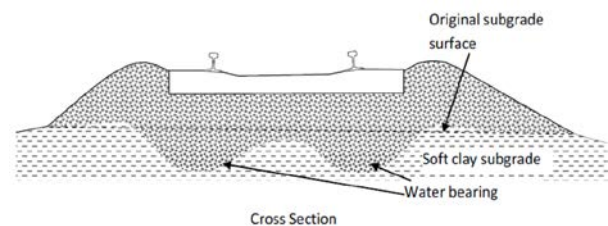


Figure 7. Excessive plastic deformation due to repeated loading [5]

3.6 Australian Standards

ARTC and ASA [7,8], VLine [9] and MTM [10] standards provide relatively similar guidelines for trackbed design. A minimum of 0.3m ballast and 0.15m subballast or capping is recommended (total granular layer thickness of 0.45m). Typical thickness/depth for the prepared subgrade/structural fill layer is provided based on the CBR of the natural subgrade as presented in Table 3.

Table 3: Structural Fill/Prepared Subgrade Depth (m) per Australian Standards

Subgrade/Fill Material Soaked CBR (%)	ARTC/MTM ¹	VLine
1-2	1	NA ²
2-3	1	1
3-5	0.5	0.5
5-7	0.5	0.3
≥8	0.5	0/0.2

1. Minimum subgrade CBR is 3% by MTM, 2% by VLine, 1% by ARTC
2. Minimum fill CBR is 2% by VLine
3. 0mm for subgrade, 200mm for fill

3.7 Comparison of Methods

An example is worked based on the discussed methods in this section to compare the required thickness of the granular layer ($H=H_b+H_s$) from different methods. The example is based on an axle load of 160 kN. It is assumed that granular layer will lay on an underlying layer with QS2 soil quality with CBR~5% (~150kPa). Table 4 provides the estimated required thickness ranging between 0.4m to 0.5m.

Table 4: Granular layer thickness from various methods/standards

Method	Ballast+Sub-ballast Thickness (m)
UIC	0.5
AREMA	0.4
Raymond	0.4
British Rail	0.45
Li-Selig	0.45
Australian Standards	0.45

The required prepared subgrade thickness is 0.35m based on UIC specifications. Based on Australian standards a thickness of 0.5m is required.

4 FINITE ELEMENTS METHOD

4.1 Finite Element Method

In the previous sections, it was shown how various methods and standards can result in different thickness values for trackbed layers.

With the current computational capabilities, 3D finite element methods (FEM) can help engineers with more economic and more reliable design. Following sections provides the result of a 3D train embankment model using LS-Dyna in comparison with a 2D Plaxis model. The impacts of cyclic degradation in subgrade has not been considered.

4.2 Geometry

Figure 8 presents the isometric and cross section view the 3D model for a track embankment cross section from a project in Victoria. The length of the model is about 25m equal to the length of a train car. The trackbed includes a 0.3m ballast, underlain by a 0.15m subballast/capping layer over a prepared subgrade/structural fill. The natural subgrade is assumed to have a CBR=3.

As shown in the analytical example above, this condition renders a structural fill of 0.5m according to Australian standards. However, in this case, a 0.3m of prepared subgrade from stabilised subgrade material with CBR=15 has been proposed to replace the structural fill to save on cost. Using a Ls-Dyna model, the proposed design is being validated by checking the stress and strain developed in the subgrade and by checking for bearing failure.

The train loading assumes a 23 tons axle load (two bogies, four axles per car), resulting in 450kN/m linear load for each wheel applied on top of the rail track over the length of a sleeper (0.25m) (see Figure 9).

4.3 Material Model

An Elasto-Plastic, Mohr-Coulomb constitutive model was implemented, adopting material parameters as per Table 5. The water table was not considered within the model, assuming a dry subgrade (zero pore water pressure).

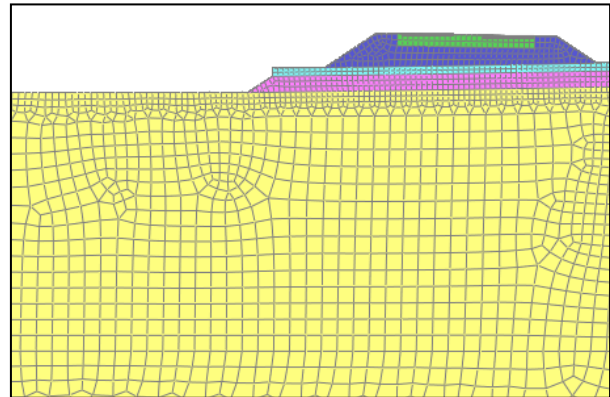


Figure 8. Isometric and cross section view of the track formation

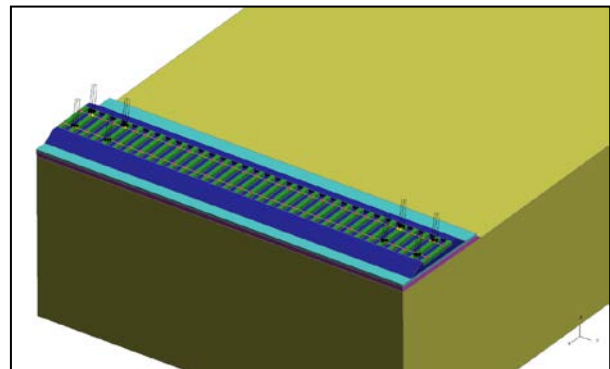


Figure 9. Train loads

4.4 Results

A summary of model outputs, including stress and strain distribution, as well as deformations and plastic strains are provided below (see Figures 10 to 14). The shear stress within the subgrade is below 15 kPa and the vertical stress is below 50 kPa, the subgrade allowable stress, hence no plastic stain is observed. The deformation at the sleeper level shows to be less than 5 mm, which is below the common acceptable criteria of 10 mm (1/2 in). This validates the proposed design of 0.3m prepared subgrade with higher CBR, instead of the 0.5m structural fill with CBR=8 required by Australian standards.

Results of LS-Dyna model was then compared with an equivalent Plaxis 2D model of the longitudinal cross section. As shown in Figure 15 and 16, the 2D model shows a maximum stress of 140 kPa in ballast, about 20% lower stress as compared with 3D LS-Dyna. Similarly, looking at the shear stress distribution, from Ls-Dyna the

maximum shear stress is around 15 kPa in the subgrade and around 27 kPa in the prepared subgrade layer, whereas Plaxis shows maximum of 12 kPa in subgrade and 40kPa in the prepared subgrade. The 2D model underestimated the maximum stress, hence the deformations, in the trackbed layers.

Table 5: Track formation material properties

Layer	Friction Angle	Cohesion	Undrained Shear Strength	Unit Weight	Young's Modulus	Poisson's Ratio
	Deg	kPa	kPa	kN ³ /m	MPa	
Ballast	40	0	0	23	280	0.3
Sub-ballast	35	0	0	23	150	0.3
Prepared Subgrade (CBR=15)	0	0	250	20	200	0.3
Natural Subgrade (CBR=3)	0	0	50	19	30	0.3

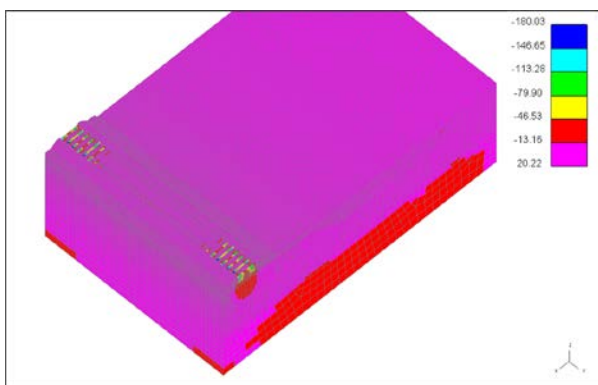


Figure 10. Stress under the sleepers

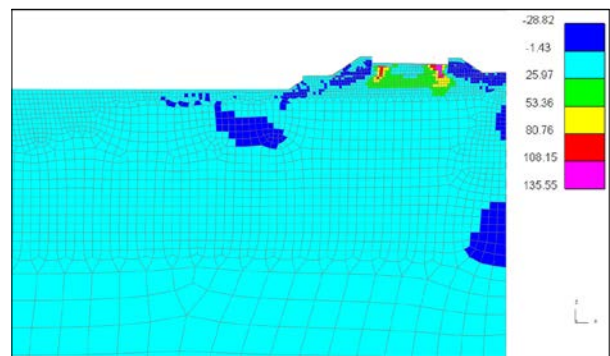


Figure 13. Von-Mises stress (=2 × shear stress)

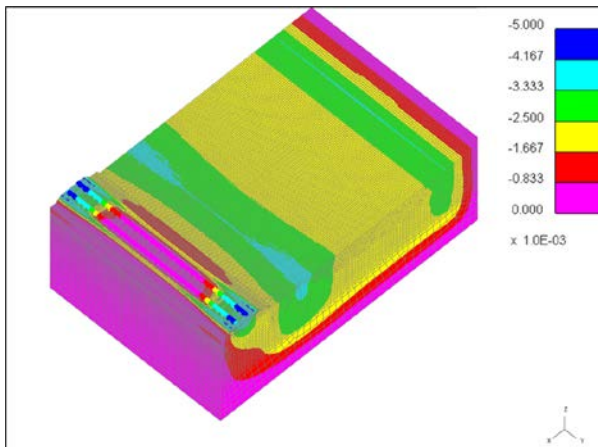


Figure 11. Vertical deformations

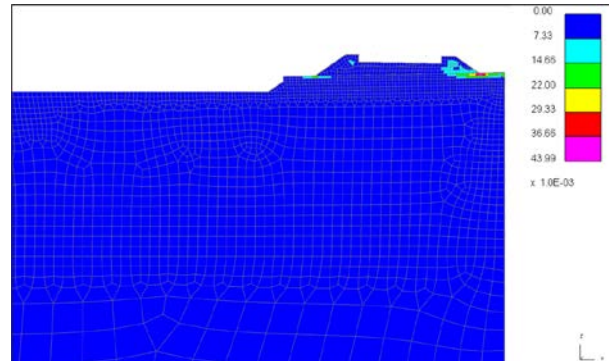


Figure 14. Plastic strains

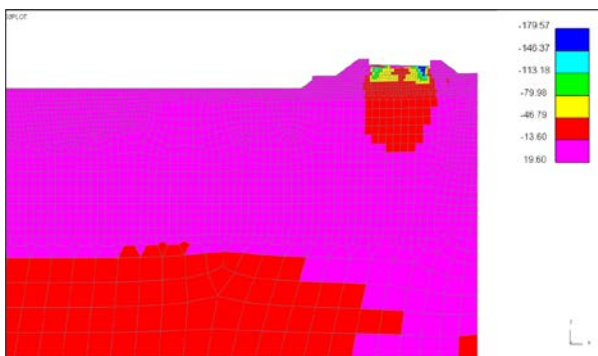


Figure 12. Vertical stress

5 CONCLUSIONS

Among the discussed analytical design methods, Li-Selig is the only method that considers both allowable stress and deformation at subgrade with respect to the train loading cycles, providing a more reliable trackbed design. Incorporating 3D numerical

simulations, can further improve the design, by providing a more accurate assessment of stress distribution and deformations in the subgrade, resulting in potential reduction of the required depth for the structural fill/prepared subgrade layer on soft natural subgrades.

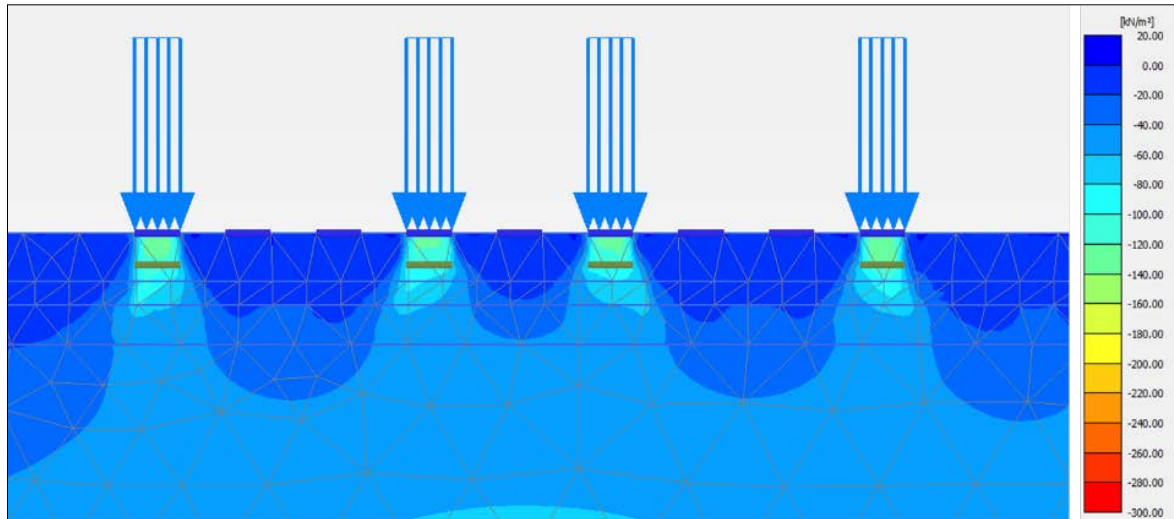


Figure 15. Vertical stress – Plaxis 2D

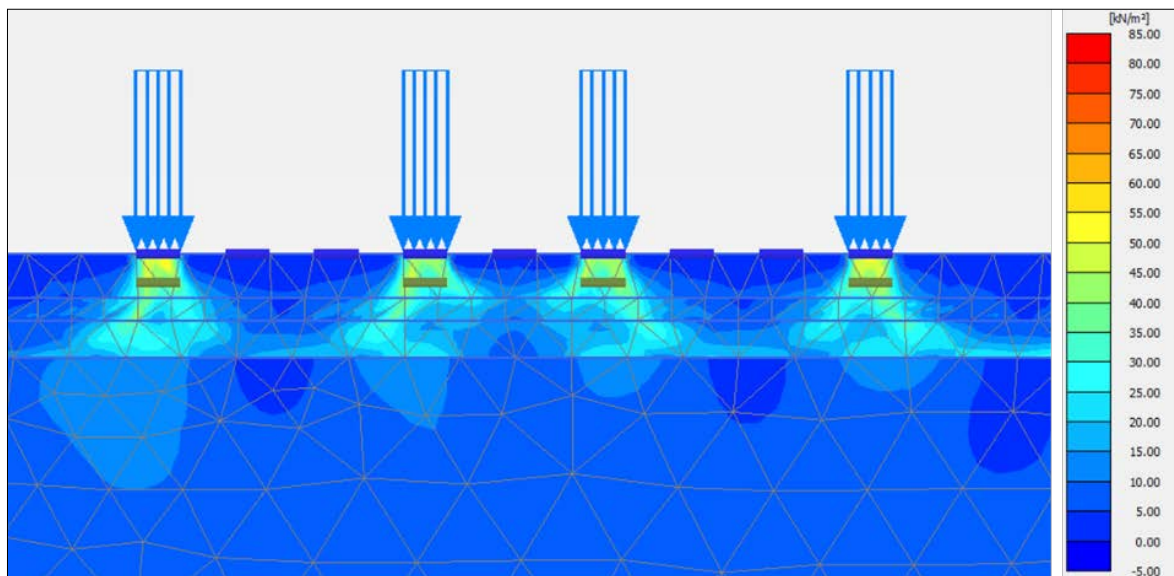


Figure 16. Shear stress – Plaxis 2D

These methods also allow for identifying potential long-term issues with bearing failure or excessive plastic strain due to cyclic loading. Although it is common for clients to demand compliance with standards, there is often provisions for applying more rigorous design methods beyond the standards by getting client approvals for derogations in early phases of a project.

6 ACKNOWLEDGEMENTS

This study was sponsored by Arup University.

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