NUMERICAL ANALYSIS OF GEOSYNTHETICS AND ENGINEERING FILL IN PERFORMANCE OF RECONDITIONED BALLASTED TRACK

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ABSTRACT

Over the past few decades, geosynthetics have been used extensively during track reconditioning to improve soil stability as it offers many advantages including cost effectiveness, ease of installation and minimal earthworks. Among the wide range of products in the market, geogrid remains the most commonly used geosynthetics for soil reinforcement. The aims of this paper are to investigate the effect of varying subgrade properties on track performance and to examine the effectiveness of geogrids and engineering fill for track reconditioning purpose. In the current study, numerical analyses were conducted using engineering software OptumG2, a finite element program for geotechnical stability and deformation analysis. The results of the parametric study indicated that geogrid inclusion within track substructure have considerable effects on settlement reduction and in particular, increasing the bearing capacity of railway track. The results are also suggested that increase in axial stiffness of geogrids has minimal impact on track deformation. The most effective and practical location for geogrid reinforcement was achieved at interface between ballast and capping layers irrespective of the subgrade strength and stiffness. Sensitivity analyses showed that both total settlement and the bearing capacity of railway track were most affected by the changes in the friction angle of subgrade, compared with cohesion and elastic modulus of subgrade, with or without geogrid reinforcement. The findings concluded that proper design of geogrid reinforcement can eliminate the need or significantly reduce the thickness of engineering fill for the ground improvement purpose.

Keywords: *rail track, geosynthetics, ballast, engineering fill, numerical modelling, track reconditioning*

1 INTRODUCTION

Around the world, ballasted track remains the integral part of many rail networks for transportation of passenger trains and freight trains. For many of the rail operators, ballasted track is unlikely to be replaced by ballastless track due to the cheapness and practical advantages of ballast (Eisenmann 1995). However, one of the major challenges for modern rail operators with ballasted track is to carry out cost effective track reconditioning works in short timeframe over limited amount of track possessions. Unlike track tamping and ballast cleaning, track reconditioning provide an effective mean to remediate the root causes of railway track instabilities, in particular when subgrade improvement is required. Track reconditioning typically involves partial or complete reconstruction of track structure. As demand for transportation capacity on the rise, track reconditioning plays a crucial role in maintaining the reliability of rail networks with ballasted track. Nevertheless, with the cost of track maintenance under increasing scrutiny from train operator and shareholders, better understanding of rail substructure and improved reconditioning techniques are necessary.

Over the past few decades, geosynthetics have been used extensively during track reconditioning to improve soil stability as geosynthetics offers many advantages including cost effectiveness, ease of installation and minimal earthworks. Among the wide range of products available for different applications, geogrid and woven geotextile are the most commonly used geosynthetics for soil reinforcement purpose during track reconditioning.

Geogrid reinforcement improves the stability of supporting materials through interlocking mechanism that limit lateral movement of particles (Indraratna et al. 2014; Brown et al. 2007), which subsequently improve settlement, reduce lateral movement and particle breakage. It also improves load distribution which in turn mobilise more subgrade shear strength and reduce settlement. Due to its ease of installation and economically soundness, its application in track substructure has been widely researched through laboratory testings, field trial and numerical modelling (Hussaini et al. 2015; Indraratna et al. 2006; Oh 2013; Chen et al. 2012; Raymond & Ismail 2003). It was observed that the key parameters that influence the performance of geogrid are stiffness, aperture size, placement location and subgrade type (Indraratna et al. 2013). Generally, higher the geogrid axial stiffness resulting in better overall performance whilst the optimum ratio between aperture size and nominal size of aggregate is within the range of about 1.2 to 1.6 (Brown et al. 2007; Hussaini et al. 2015). Although the optimal geogrid location for ballast reinforcement is within the ballast layer, Indraratna et al. (2009) suggested the placement of geogrid at ballast-capping interface to allow for future maintenance works. Few findings also indicate that the reinforcement effect of geogrid decreases as the stiffness of subgrade increases (Brown et al. 2007; Indraratna et al. 2014).

Woven geotextile is also commonly used to increase the load bearing capacity of rail track as well as offering the function of separation for application in finer grained soil. It does not possess interlocking effect, like geogrid, but relies on its modulus characteristics to provide reinforcement effect. Guidelines provided by Asset Standards Authority (2016) stated the thickness of engineering fill beneath capping for subgrade improvement can be reduced by up to 30 percent after inclusion of geotextile under the engineering fill layer, depending on the subgrade condition.

While the applications of geosynthetics in railway track were widely researched and its advantages were well recognised, most researches have focused on track substructure improvement through strengthening of ballast layer, which predominately based on track formation on competent subgrade. The effects of geosynthetics inclusion for track formation founded on subgrade with different strength and stiffness properties have not been well established. Also, its effectiveness in comparison to conventional approach of using engineering fill has not been explored for track reconditioning practice. In line with the above observations and industrial practices, a parametric study was carried out to investigate the effect of varying subgrade properties to track performance and to examine the effectiveness of geogrid and engineering fill for the track reconditioning purpose.

In the current study, numerical model of ballasted track structure was setup using OptumG2, a finite element program for geotechnical analysis. Instead of performing separate analyses using geogrid and woven geotextile, the parametric study was conducted using geogrid only for 2 reasons. First, geogrid remains the better option for the reinforcement purpose. Second, the software OptumG2 simply considers the axial stiffness and the yield force in the finite element modelling, which essentially make both products indifferent in the modelling for reinforcement purpose. Total settlement and bearing capacity were used as the main indicators for the assessment of track performance.

2 NUMERICAL ANALYSIS SETUP

2.1 CONSTITUTIVE MODEL, GEOMETRY, MESH AND BOUNDARY CONDITION

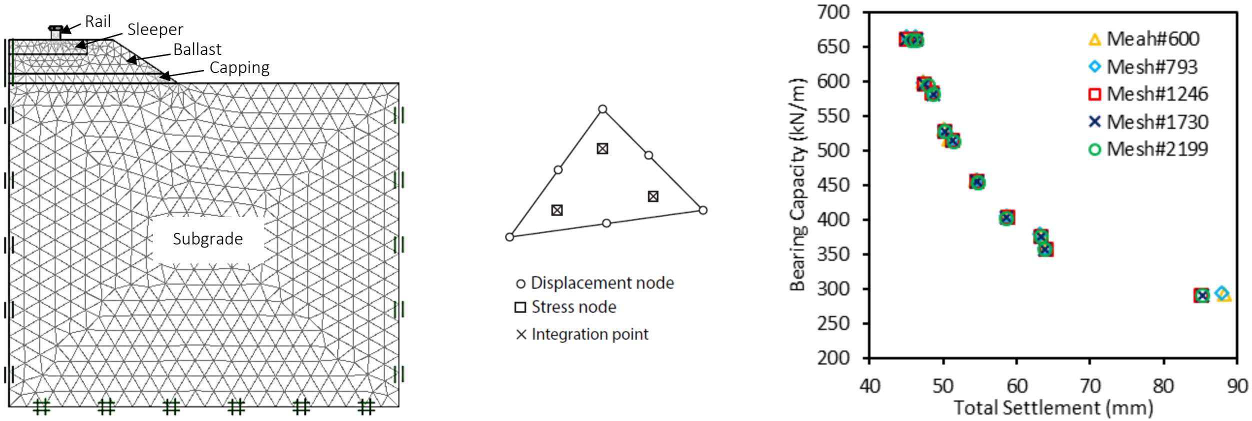
The numerical simulations were conducted using a 2-Dimentional (2D) finite element program, OptumG2, to predict the track performance under loading in plane strain, with or without geogrid reinforcement as well as engineering fill. As OptumG2 is relatively new to the industry compares to other established software such as Plaxis, a replica model in OptumG2 was setup based on a verified Plaxis model presented by Indraratna et al (2012) to evaluate the analytical result. This exercise revealed that both programs predicted comparable results (less than 10% variation) for vertical displacement (settlement) and vertical stress under the sleeper. Therefore, OptumG2 was considered appropriate for the current study.

Standard rail track geometry based on published data provided by Asset Standard Authority of Transport for NSW (TfNSW) was referenced to form the basis of parametric study (Asset Standards Authority 2015, Asset Standards Authority 2016, Railcorp 2012a, Railcorp 2013). The rail environment was set as ‘Mix Passenger Freight Main Line’ (Railcorp 2012b). Based on this context, a baseline model was setup and comprised of 1435mm track gauge, 2400mm heavy-duty concrete sleeper, 300mm thick ballast layer, 400mm wide ballast shoulder, 1.5H:1V ballast shoulder slope and 150mm thick capping layer. Note that the rail track is modelled in half due to symmetry (Figure 1a). Train rail of 60kg rail and sleeper spacing of 600mm were adopted and incorporated into the material properties as well as during the estimation of rail loading.

The numerical analyses were conducted in two stages, including (1) the initial condition and (2) the traffic condition. The initial condition simulates the ground settlement under soil self-weight, whilst the traffic condition simulates track performance under rail loading. Both stages were performed in elastoplastic constitutive model. Limit analysis was carried out to estimate the bearing capacity of track substructure.

All track components, substructure and subgrade layers were modelled using 6-node Gauss elements (Figure 1b), which involves quadratic interpolation of displacements and linear interpolation of stresses (OptumCE 2015). The use of 6-node Gauss element instead of 15-node Gauss element, which is commonly considered as more accurate, was justified by the very close outputs obtained from a series of analyses performed (over 100 different cases) using both element types. The results were mostly within 4-6% but up to 9% variation. Besides, significant saving on computational processing time was achieved using 6-node Gauss element.

Boundary conditions of the models were pin support along the base (fixed in all direction) and smooth vertical contact with fixed horizontal movement for side boundaries. The thickness of subgrade was 5m as the influence of vertical stress was found insignificant beyond this depth. The mesh was also optimised prior to the parametric study. Five different mesh density levels were analysed, i.e. 600, 793, 1246, 1730 and 2199, while all other conditions remain the same. As shown in Figure 1c, the different mesh size does not appear to have significant impact on the estimated bearing capacity (wheel load) and total settlement. Therefore, mesh sizes that corresponds to 1246 elements (medium density) were chosen for this study.



(a) (b) (c)

Figure 1: (a) Finite element mesh of track structure; (b) 6-node Gauss element (OptumCE 2015); (c) Mesh effect

2.2 MATERIAL MODEL AND PROPERTIES

Based on literature reviews and past experiences, the material model and properties are presented in Table 1. The ballast layer was modelled as Hardening soil to reflect the stress dependency and resilient behaviour of ballast (Oh 2013). The properties of ballast and capping layers were obtained from Indraratna et al (2011) as they were the laboratory test results of materials provided by Railcorp. The subgrade material was modelled as Mohr Columb material and its properties in Table 1 were the Normal Operating Point (NOP) for the parametric study.

Table 1: Material model and properties for the numerical model

	Rail	Sleeper	Ballast	Capping	Subgrade (NOP)	Geogrid
Material Model	Elastic	Elastic	Hardening soil	Mohr Columb	Mohr Columb	Elastic
E (MPa)	200000	10000	-	80	15	-
γ (kN/m^3)	78	24	15.6	16.67	18	-
$\boldsymbol{E_{50}^{ref}}$ (Mpa)	-	-	21.34	-	-	-
$\boldsymbol{E_{ur}^{ref}}$ (Mpa)	-	-	64.02	-	-	-
EA (kN/m)	-	-	-	-	-	350
n_p (kN/m)	-	-	-	-	-	20
v	0.15	0.15	-	0.35	0.33	-
v_{ur}	-	-	0.2	-	-	-
c (kN/m^2)	-	-	0	0	4	-
ϕ (degree)	-	-	58.47	35	27	-
Ψ (degree)	-	-	12.95	0	0	-
P_{ref} (kN/m^2)	-	-	50	-	-	-
m	-	-	0.5	-	-	-
$\boldsymbol{K_o^{nc}}$	-	-	0.3	-	-	-

γ = unit weight, E = Elastic stiffness, $\boldsymbol{E_{50}^{ref}}$ = secant stiffness at 50% strength for loading conditions, $\boldsymbol{E_{ur}^{ref}}$ =triaxial unloading/reloading stiffness, EA = axial stiffness, n_p = yield force, v = poisson's ratio for loading conditions, v_{ur} = poisson's ratio for unloading/reloading conditions, c = effective cohesion, ϕ = effective friction angle, Ψ = dilatancy angle, P_{ref} = reference confining pressure, m = stress dependent stiffness factor, $\boldsymbol{K_o^{nc}}$ = coefficient of earth pressure at rest for normal consolidation, The geogrid was modelled as elastic material and permeable layer. There are 3 inputs for geogrid in OptumG2, i.e. axial stiffness (EA), yield force (np) and permeable/impermeable. The axial stiffness and yield force of geogrid were based on industrial product specifications that met the minimal requirements of Asset Standards Authority (2016).

2.3 LOADING

For 'Mix Passenger Freight Main Line', the static axle load of freight train is up to 30 tonnes on 80km/hr speed. However, the static axle load chosen for the current analysis was 20 tonnes (2/3 of maximum capacity) considering the track is mixed used and trains are not always in full capacity. This loading also eliminated subgrade failure during the parametric study. To address the effect of cyclic loading, quasi-static approach was implemented for the estimation of railway loading (Esvel 2001). A simple expression of quasi-static load formula is shown below (Li & Selig, 1998):

$$P_{qs} = \varphi P_S \tag{1}$$

where P_{qs} is the design wheel load (kN) including dynamic factor; φ is the dynamic impact factor (dimensionless, greater than 1), and; P_s is the static wheel load (kN). The dynamic impact factor (φ) was calculated using Eisenmann's formula (Eisenmann 1972) with the following design assumptions:

- Maximum design speed = 80km/hr;
- Track condition = Good;
- Upper confidence limits (UCL) = 97.7%; UCL defines the probability of maximum applied load being exceeded

Based on the dynamic wheel loading, rail properties and track properties, the rail seat load was estimated using Beam On Elastic Foundation (BOEF) method. The BOEF formula is given by:

$$Q_r = 0.5 \times Pd \times S \times \left({}^{k}/_{4EI}\right)^{0.25} \times F1 \tag{2}$$

where Q_r is the rail seat load (kN); *Pd* is the design wheel load (kN); *S* is the sleeper spacing (m); *k* is the track modulus (MPa); *E* is the modulus of rail (MPa)*; I* is the inertia of moment of rail (mm^4), and; *F*1 is factor of safety.

Having determined the rail seat load, the sleeper-ballast contact pressure was then calculated based on the following equation (Clark, 1957):

$$P_a = \left({}^{Q_r}/_{(B \times L)}\right) \times F2 \tag{3}$$

$$L = l - g \tag{4}$$

where P_a is the average contact pressure between the whole sleeper and the ballast (kPa); *B* is the width of sleeper (m); *L* is the effective length of sleeper (m); *l* is the total length of the sleeper (m), *g* is the distance between rail centrelines (m), and; *F2* is the factor of safety.

For the purpose of parametric study, factors of safety in Equations (2) and (3), i.e. F1 and F2, have been taken as 1. The key results from load calculation procedure are summarised in Table 2.

Table 2: Key results from load calculation steps

Dynamic impact factor, φ	1.46
Design (dynamic) wheel load, P_{qs}	143kN
Rail Seat Load, Q_r	45kN
Average Contact Pressure, P_a	203kPa

The effect of different load types and locations were also studied as different approaches were observed from the literature reviews. Three (3) load types and locations, namely line load on top of rail, uniformly distributed load at bottom of sleeper and uniformly distributed load at top of sleeper, were analysed and compared in term of estimated total settlement (Figure 2, Table 3). The results indicated negligible differences in total settlement between all the load cases. Considering the wheel load is directly applied on the rail, it was decided to use line load of 243kN/m for the parametric study.

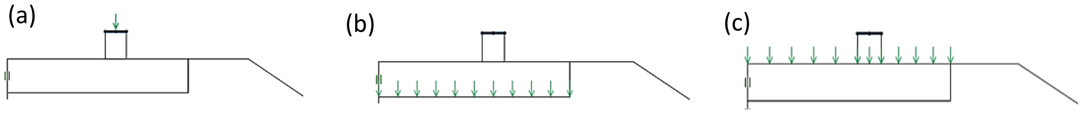


Figure 2: (a) Line load on top of rail; (b) Uniformly distributed load at bottom of sleeper; (c) Uniformly distributed load at top of sleeper

Table 3: Total settlement for different load application methods

Load Types	Total Settlement (mm)
Line load on top of rail	54.7
Uniformly distributed load at bottom of sleeper	54.6
Uniformly distributed load at top of sleeper	54.6

3 PARAMETRIC STUDY

A series of numerical modelling were conducted to determine the effects of subgrade properties, geogrid and engineering fill. During the numerical analyses, total settlements and bearing capacity were observed as the key indicators of track substructure performance and were used for comparison purpose. Note that the bearing capacity in this paper represents the predicted ultimate wheel load (kN/m) that caused formation failure in the numerical model.

3.1 EFFECT OF SUBGRADE PROPERTIES

One of the main triggering factors for track instability that demand for track reconditioning is the presence of weak subgrade resulted in unacceptable differential settlement. It is therefore critical to understand how changes in subgrade condition can affect the overall track performance. In this part of the parametric study, the effect to foundation bearing capacity and compressibility were investigated by varying the cohesion, friction angle and elastic modulus of the subgrade. Note that these parameters were changed individually in separate cases, i.e. no more than one parameter was changed at the same time. All other properties including the Poisson's ratio were kept constant throughout the study.

Generally, materials weaker than Stiff Clay would requires some degrees of ground improvement prior to placement of track structure. Hence, Firm Clay properties were used as the Normal Operating Point (NOP) of the subgrade materials for the current study (Table 1) as it was considered as the mid-range material that requires soil improvement. The range of material parameters used in this study were the typical values for very soft to stiff clayey materials (Table 4). Low-range and high-range material properties were also assigned for comparison purpose.

Table 4**:** Various subgrade properties used in parametric study

Cohesion, c (kPa)	Friction angle, ϕ (degrees)	Elastic stiffness, E (MPa)	Material properties groups
0	25	5	-
2	26	10	Low-range
4	27	15	NOP (Mid-range)
6	28	20	-
8	29	25	High-range
10	30	30	-

Figure 3 shows the effects of cohesion, friction angle and elastic modulus on total settlement and bearing capacity of the track structure. The results indicated that the increase in cohesion and friction angle reduce the total settlement and increase the bearing capacity of track structure. Similarly, an increase in elastic modulus caused reduction in the total settlement, but no impact on the bearing capacity. The results also confirmed friction angle and cohesion of subgrade are the most critical parameters for calculating bearing capacity of subgrade. Although changes in all 3 parameters have impacts on settlement, the elastic stiffness has by far recorded the biggest drop in settlement of 130mm through changing the parameter from 5MPa to 30MPa (Figure 3c).

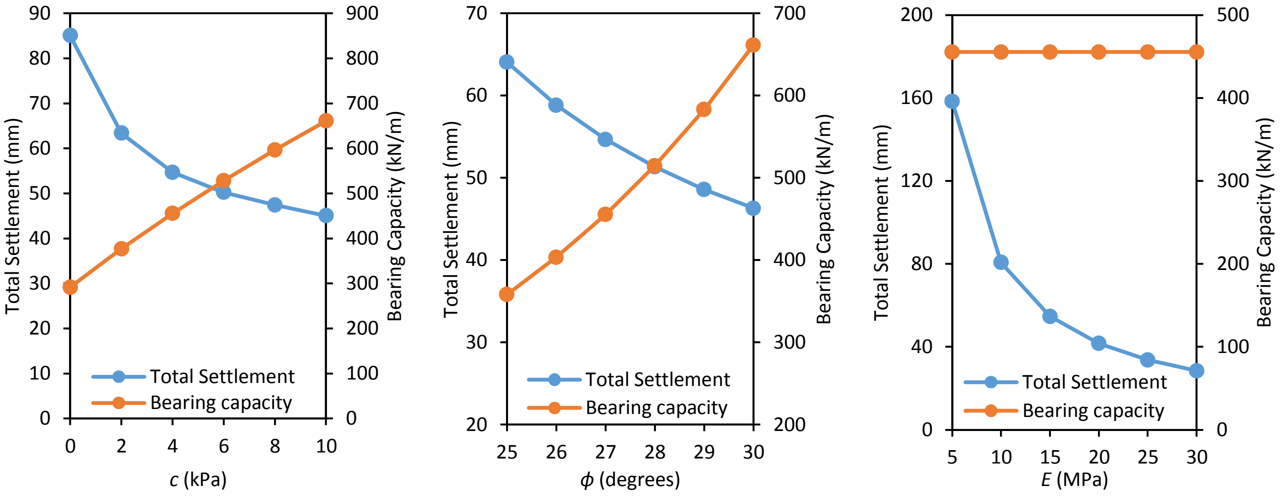
The sensitivity of settlement and bearing capacity to the 3 parameters were also examined using the following formula:

$$Relative\ Sensitivity\ (\%) = \frac{\partial F/_{F}}{\partial \alpha/_{\alpha}} \times 100 \quad (5)$$

where $\partial F/F$ is the percentage of the dependent variable changes; $\partial\alpha/\alpha$ is the percentage of the independent variable changes. In this study, the dependent variables were bearing capacity and settlement whilst the independent variables were cohesion, friction angle and elastic modulus. The sensitivity analyses were conducted for low-range materials properties, NOP (mid-range materials properties) and high-range materials properties, as depicted in Table 4.

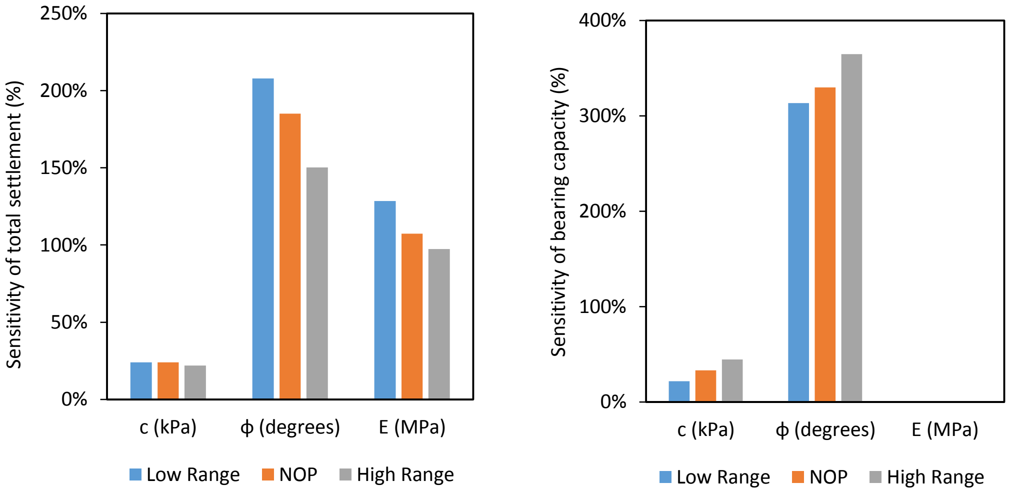
The results shown in Figure 4 indicated that both total settlement and bearing capacity were most sensitive to changes in friction angle of subgrade. The cohesion of subgrade, however, showed much lower influence to the sensitivity of both settlement and bearing capacity. As the subgrade materials became weaker, the data showed increase in sensitivity of total settlement but decrease in sensitivity of bearing capacity.

These findings highlighted incorrect estimation of subgrade parameters can lead to significant impact on the design outcome and long term performance of track. For example, a drop of 2 degrees in friction angle from 28 degrees to 26 degrees resulted in total settlement increased by 8mm (approx. 16%) and bearing capacity reduced by more than 110kN/m (approx. 20%). This results signify the need to ensure sufficient geotechnical investigation efforts are put in place to ensure proper estimation of material properties for design of track formation, particularly for friction angle and elastic modulus. The outcomes also demonstrated that all 3 parameters have some degrees of influences on the compressibility of soil, which stressed the benefit of using Mohr-Columb soil model (instead of Linear Elastic soil model) to better estimate the reaction of subgrade material and the overall performance of track structure.



(a) (b) (c)

Figure 3: Estimated total settlement and bearing capacity due to differences in (a) cohesion; (b) friction angle; (c) elastic stiffness



(a) (b)

Figure 4: Sensitivity analysis (a) sensitivity of total settlement; (b) sensitivity of bearing capacity

3.2 EFFECT OF GEOGRID STIFFNESS

One of the key properties of geogrid for soil reinforcement is the elastic axial stiffness. In OptumG2, the input for elastic axial stiffness, EA, is presented in term of force per unit width. Nine (9) levels of EA values were considered in this assessment. Note that a single layer of geogrid was positioned at the interface between capping layer and subgrade throughout this evaluation process. As shown in Figure 5, the results confirmed the increased EA continuously improved the total settlement but delivered no impact on the bearing capacity of the rail track. The effect of increasing EA also marginally lessens from around 300-350kN/m upward, which happens to be the minimum requirement of standard specification for typical track reconditioning practice in New South Wales. Nevertheless, the overall effect of varying EA has minimal impact on track performance as changes from 200kN/m to 600kN/m has only reduced the total settlement by less than 1mm (less than 2% improvement). In other words, use of higher geogrid stiffness to improve soil reinforcement does not necessarily provide the economic benefits and desired outcomes in practice.

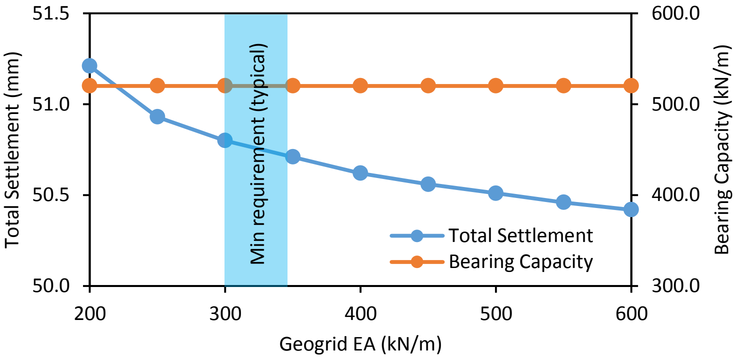
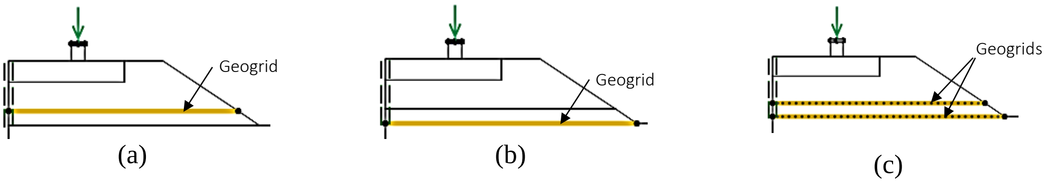


Figure 5: Effect of geogrid stiffness

3.3 EFFECT OF GEOGRID LOCATIONS AND LAYERING

The influences of geogrid locations and layering on track performance were evaluated. Three (3) geogrid configurations were assessed, i.e. geogrid at ballast/capping interface, geogrid at capping/subgrade interface, and geogrids at ballast/capping and capping/subgrade interfaces (Figure 6). All configurations were applied on the same range of subgrade parameters in Table 4. Note that the effect of geogrid reinforcement within ballast layer was not investigated as it was considered impractical for future maintenance of track formation.



(a) (b) (c)

Figure 6: Various configurations of geogrids (a) Config 1: Geogrid at ballast/capping interface; (b) Config 2: Geogrid at capping/subgrade interface; (c) Config 3: Geogrids at ballast/capping interface and capping/subgrade interface

The effectiveness of geogrid reinforcement was calculated by taking the percent in difference (improvement) given in the following equation.

$$Percent\ in\ difference\ (\%) = \frac{R_r - R_u}{R_u} \times 100 \qquad (6)$$

where R_r is the result of case with geogrid reinforced; R_u is the result of case with no geogrid reinforcement. The results of current study are shown in Figure 7.

The results showed greater improvement was achieved with geogrid at ballast/capping interface (Config 1) compares to geogrid at capping/subgrade interface (Config 2), irrespective of subgrade strength and stiffness. This effect was likely due to the change in interface materials and stress levels. As anticipated, configuration with geogrids installed at both top and bottom of capping layer (Config 3) has provided the largest improvement in track performance. At NOP, Config 3 achieved 16% improvement in total settlement and 31% improvement in bearing capacity. This was compared to 12% improvement in total settlement and 17% improvement in bearing capacity for Config 1 as well as 7% improvement in total settlement and 14% improvement in bearing capacity for Config 2.

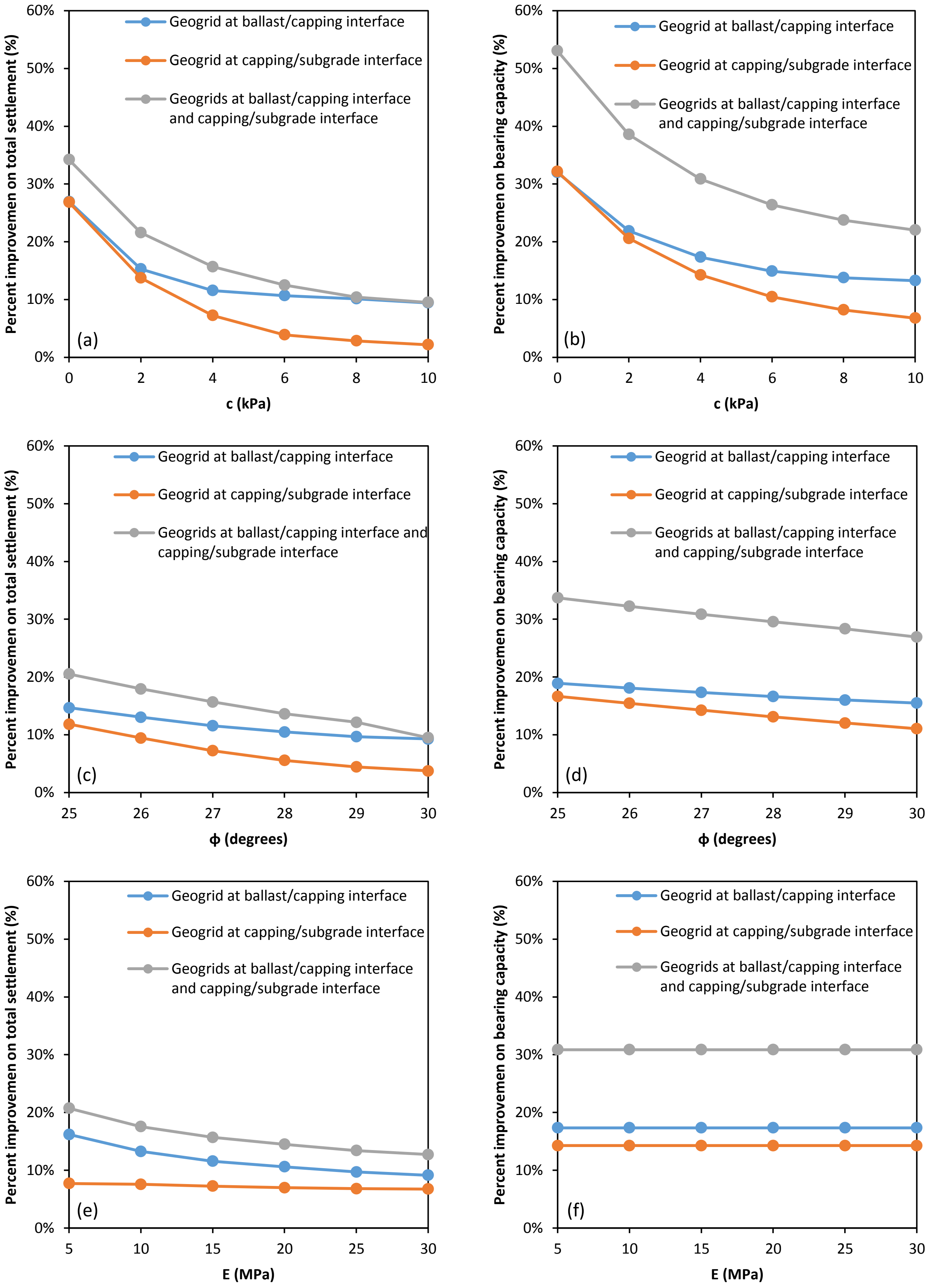


Figure 7 Percent improvement on total settlement (TS) and bearing capacity (BC) due to different types of geogrid configuration under influence of varying subgrade conditions: (a) TS vs. cohesion, (b) BC vs. cohesion, (c) TS vs. friction angle, (d) BC vs. friction angle, (e) TS vs. elastic modulus, and (f) BC vs. elastic modulus.

The effects of geogrid reinforcement were observed, in general, greater when the subgrade materials become weaker as more geogrid strength was mobilised with higher strain. Also, the track responses to geogrid reinforcement appeared vary between subgrade parameters, i.e. cohesion, friction angle and elastic modulus, with highest response (percent improvement) recorded when cohesion of subgrade equalled to 0.

The results in Figure 7 also indicated geogrid reinforcement have higher impact on bearing capacity than total settlement, i.e. higher percent improvement gained in bearing capacity than total settlement. The relative impact between bearing capacity and total settlement was also appeared to widen as subgrade materials became stiffer. In some cases, the percent improvement gained in bearing capacity was up to 3-4 times higher than percent improvement grained in total settlement.

Sensitivity analysis of total settlement and bearing capacity on soil parameters were also carried out for cases with and without geogrid using Equation 5. As shown in Figure 8, geogrid reinforcement of track formation reduces the sensitivity of both performance indicators towards the individual soil parameters. Though, friction angle remains the most influential soil properties followed by elastic modulus and cohesion.

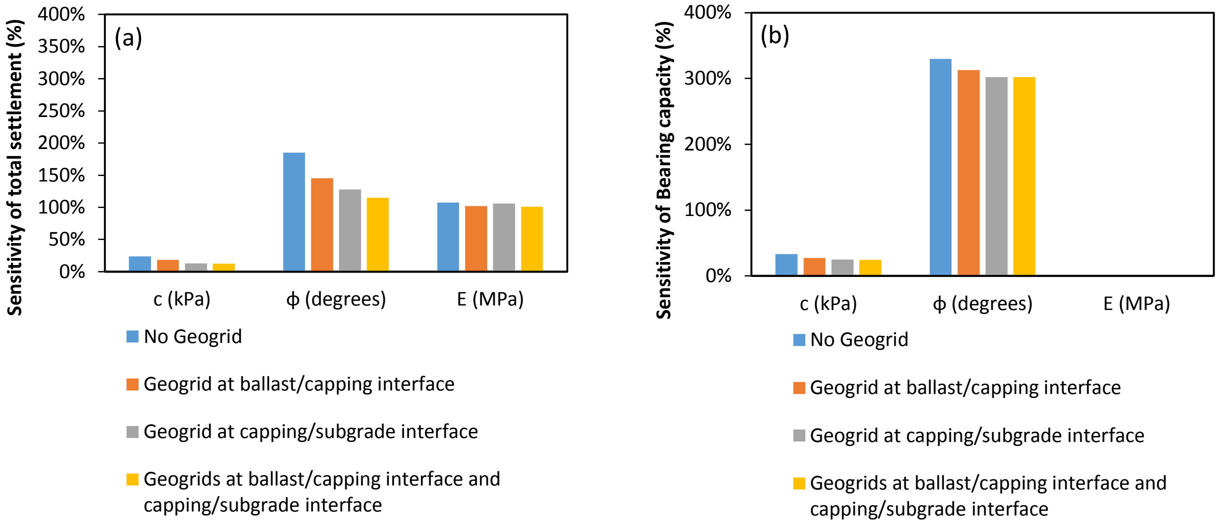


Figure 8: (a) Sensitivity of total settlement at the normal operating point (NOP with and without geogrid reinforcement; (b) Sensitivity of bearing capacity at NOP with and without geogrid reinforcement

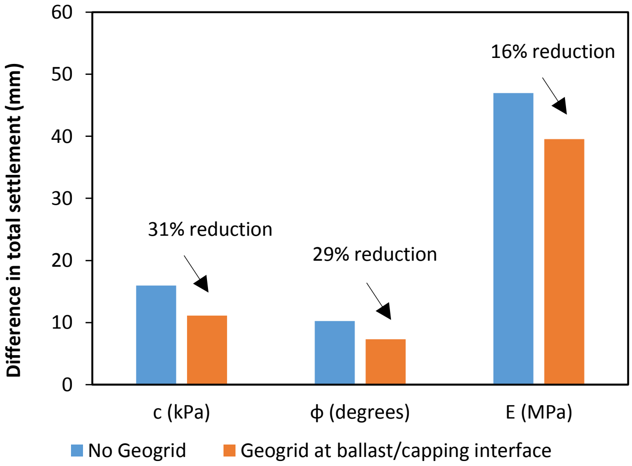


Figure 9: Difference in total settlement between low-range material and high-range material with and without geogrid reinforcement

The difference in total settlement between low-range subgrade material and high-range subgrade material were also investigated. This part of study was to simulate situation where localised soft subgrade surrounded by relatively stiffer subgrade, which may be missed during geotechnical investigation. Note that this was not differential settlement as the distance between the reference points were not known. The analyses were conducted for track formation with and without geogrid reinforcement. The results showed notable reduction of difference in total settlement (up to 31%) after geogrid inclusion at ballast/capping interface (Figure 9). Hence, inclusion of geogrid can also be particularly beneficial to reduce the effect of localised soft zone during track reconditioning.

3.4 EFFECT OF ENGINEERING FILL THICKNESS

In accordance to Asset Standards Authority (2016), engineering (structural) fill can be used to improve substandard subgrade during track reconditioning. It stated that subgrade with CBR value (California Bearing Ratio) of 3-8% can be remediated with 500mm of engineering fill whilst subgrade with CBR value of 1-3% can be remediated with 1000mm of engineering fill. It further suggested that the engineering fill thickness for subgrade with 3-8% CBR can be reduced from 500mm to 350mm (30% reduction) if geotextile is laid at the base of engineering fill. Similarly, engineering fill thickness for subgrade with 1-3% CBR can be reduced from 1000mm to 500mm (50% reduction) if geogrid is laid at the base of engineering fill. On this basis, the influences of engineering fill thickness on track performance were evaluated in conjunction with geogrid reinforcement.

Due to practical reason, capping quality materials are commonly used as the engineering fill during track reconditioning works. For this reason, material properties of capping layer in Table 1 were used as the properties of engineering fill in this study. All analyses in this section were carried out using the same subgrade condition, i.e. NOP, with engineering fill placed beneath capping layer. The results of current study are shown in Figure 10. In consideration of practicality and guidelines provided by Asset Standards Authority (2016), the thickness of engineering fill used in this assessment was capped at 1000mm.

As shown in Figure 10, the improvement gained on total settlement and bearing capacity increases as the thickness of engineering fill increases. However, unlike geogrid reinforcement, the percent improvement gained for both total settlement and bearing capacity were relatively similar for subgrade improvement using engineering fill. The results also indicated that geogrid placement at the base of engineering fill can have considerable effects on settlement and, in particular, bearing capacity of track structure. The additional percent improvements gained due to geogrid inclusion were 11-14% on bearing capacity and 2-6% on total settlement. The effect of geogrid reinforcement was observed reducing as its location becomes deeper with thicker engineering fill.

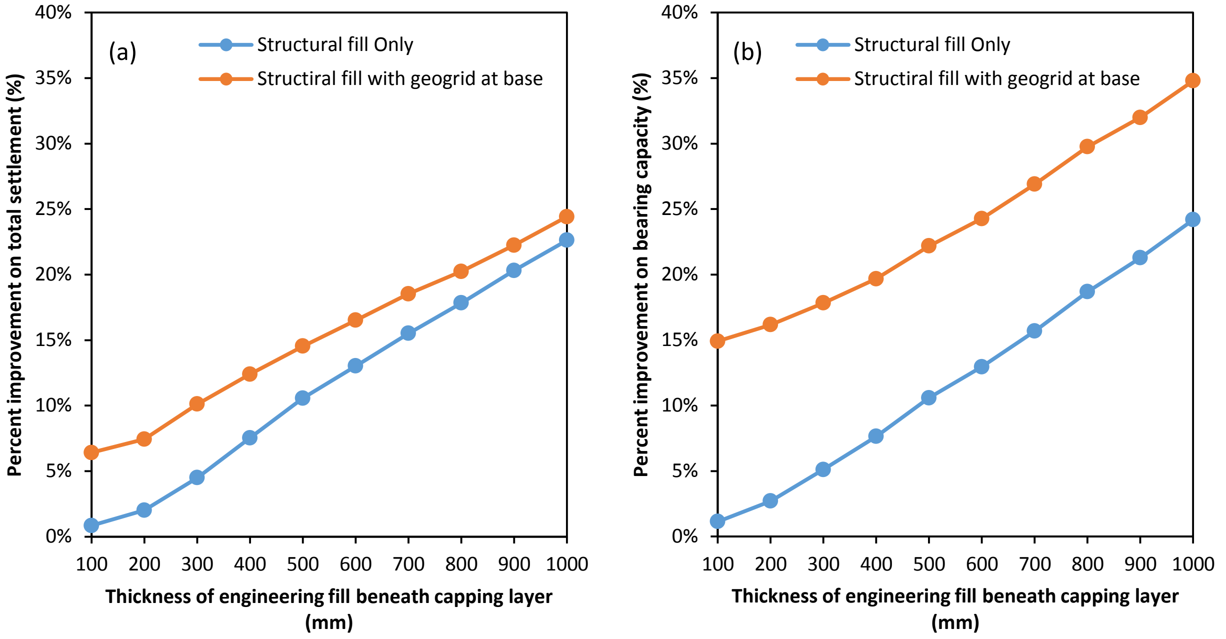


Figure 10: Effect of engineering fill thickness with and without geogrid at base (a) total settlement (b) bearing capacity

In reference to Figure 10a, engineering fill thickness could be reduced by 36% from 500mm to 320mm if geogrid is placed at the base of fill. Yet, the fill thickness could only be reduced by 8% from 1000mm to 920mm as the depth of geogrid increased. These findings were compared to the guidelines provided by Asset Standards Authority (2016), which were discussed earlier in this chapter. While the recommended thickness reduction was comparable for 500mm engineering fill (at 30% compares to 36%), the 50% thickness reduction for 1000mm engineering fill appeared to be unachievable compared with the current analytical result (at 8%). Nonetheless, it is to be understood that the ASA Guidelines considered different subgrade strength/stiffness and geosynthetics (geotextile and geogrid). Further experimental investigation and numerical analysis are needed to draw conclusion on this matter.

The percent improvement gained from geogrid reinforcement (Figure 7a) were compared to the results in Figure 10. This exercise revealed that a layer of geogrid at ballast/capping interface (Config 1) has comparable improvement gained of 500mm thick engineering fill whilst 2 layers of geogrids at both top and bottom of capping layer (Config 2) has similar improvement gained of 700 mm thick engineering fill. Furthermore, an additional analysis was carried out and found that the thickness of 1000mm engineering fill could be reduced to 500mm by using 3 layers of geogrid (Figure 11). While it should be noted that these findings were based on one subgrade strength/stiffness (i.e. NOP), the results in Table 5 indicated that proper design of geogrid reinforcement can eliminate or significantly reduce the thickness of engineering fill for ground improvement purpose.

Table 5: Comparable percent improvement of using geogrid reinforcement and engineering fill

Geogrid Configuration	Thickness of engineering fill that achieved comparable percent improvement in total settlement (using Figure 10a)
1 layer of geogrid (at ballast/capping interface)	500mm
2 layers of geogrid (at ballast/capping interface and capping/subgrade interface)	700mm
3 layers of geogrid (at ballast/capping interface, capping/subgrade interface and base of 500mm engineering fill)	1000mm

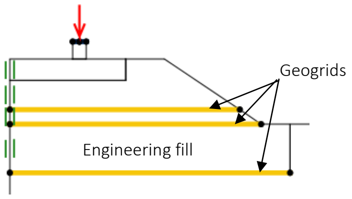


Figure 11: Geogrids at ballast/capping interface, capping/subgrade interface and base of engineering fill

4 CONCLUSIONS

In this study, a series of numerical analyses were conducted to determine the response of ballasted track on different subgrade conditions, with or without geogrid reinforcement as well as with or without an engineering fill. Conclusions made from this study include:

- A FEM software OptumG2 was used to analyse the track structure based on appropriate material properties.
- Different methods of rail loads, such as line load on top of rail and uniformly distributed load at bottom of sleepers, were applied. The results indicated negligible differences in the total settlement of track.
- The numerical analysis results confirmed that all 3 subgrade variables used in this study, including the friction angle, the cohesion and the elastic modulus, have great influence on the compressibility of soil. The results also confirmed that the friction angle and the cohesion of subgrade are the most critical parameters for calculating the bearing capacity of subgrade. The parametric studies on subgrade material properties have clearly demonstrated the consequences of incorrect estimation of subgrade parameters in the overall performance of track structure.
- Results indicates the geogrids inclusion within track substructure has considerable effects on the settlement and the bearing capacity of railway track. The most effective and practical location for geogrid reinforcement was achieved at interface between ballast and capping layers irrespective of the subgrade strength and stiffness. Inclusion of geogrids can also be particularly beneficial to reduce the effect of localised soft zone during track reconditioning. The effects of geogrid reinforcement were also observed greater when weaker subgrade materials prevailed. The results also indicated that increasing axial stiffness of geogrids has minimal impact on further improvement of track deformation, especially if the product already meets the minimum requirement of standard specifications for the typical track reconditioning practice in New South Wales.

- The sensitivity analyses showed that both the total settlement and the bearing capacity were most affected by the changes in friction angle of subgrade, compared to cohesion and elastic modulus of subgrade, with or without geogrid reinforcement. The sensitivity of both performance indicators, in general, was also found to be reduced with the geogrid reinforcement.
- Implementing an engineering fill on natural subgrade improved both total settlement and bearing capacity of the railway track. The improvement gained on the total settlement and the bearing capacity increased as the thickness of engineering fill increased as expected. The results also indicated that geogrid placement at the base of engineering fill can have significant positive effects on the performance of the track structure, but its effectiveness continued to reduce as its location becomes deeper with a thicker engineering fill.

Overall, based on the results it can be concluded that proper design of geogrid reinforcement can eliminate the need or significantly reduce the thickness of engineering fill for ground improvement purpose. It is considered that the current parametric study has provided a useful basis for further research leading to better understanding on effect of subgrade variables and ground improvement techniques using geosynthetics and engineering fill. More accurate modelling technique, such as discrete element methods (DEM), 3-dimentional (3D) model or true cyclic loading, may be considered for future study, together with further experimental investigation to verify the analytical results.

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