Railway embankment behaviour due to increased axle loads - A numerical study

To cite this article: Tan Do et al 2021 IOP Conf. Ser. Earth Environ. Sci. 710 012040

View the article online for updates and enhancements.
Railway embankment behaviour due to increased axle loads - A numerical study

Tan Do, Per Gunnvard, Hans Mattsson, Jan Laue
Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Sweden
tandoh@ltu.se

Abstract. Due to an increase in axle loads, the development of excess pore water pressure and settlement in a railway track foundation of fine-grained subgrade soil can be observed. A thorough understanding of the mechanism of development of excess pore water pressure is essential for understanding the development of settlements and the design of potential ground improvement. In this paper, a three dimensional numerical study is presented, which investigates the effects of an increase in axle loads of trains on both excess pore water pressure and settlement. Special attention is given to a soft soil layer beneath the embankment and the influence of ground improvement (deep soil mixing columns). As a result, an increase in axle loads leads to a considerable increase in both excess pore pressures and settlement in the subgrade layer. This increase is more significant in the case of heavy axle load (32.5 tons) than that of the light axle load (16 tons). In addition, cyclic loading can lead to a considerable increase in both vertical displacements and excess pore water pressure. The use of deep soil mixing columns reduces excess pore water pressures and settlements significantly.

1. Introduction
There is a great demand for increasing the iron ore transportation along the railways in Sweden, due to social and economic reasons. This could lead to an increase of the maximum axle load, which is used as a quantitative value in railway engineering, defined as the allowable load on the railway track per wheel axle. The most common axle load in Sweden is 25 tons. Over the years, the maximum axle load has increased gradually and this value for recent years is 30 tons. In 2019, the Swedish Transport Administration (Trafikverket) started testing one embankment under the maximum axle load up to 32.5 tons on the railway section between Kiruna and Narvik. It should be noted that 32.5 tons of axle load has been so far the highest in Europe [1]. Under this heavy axle load, the railway embankment should remain stable for the safe transportation. Investigations on the railway embankment behaviors should be performed for a better understanding of the load-deformation response and excess pore pressure development subjected to heavy axle loads. There have been a number of studies addressing this subject using various approaches by either experimental studies [1-5] or numerical analysis [4, 6, 7]. From the literature, the excess pore-water pressure or settlement in a railway track foundation has been shown to increase with increasing train speeds or cyclic heavy axle loads. In order to guarantee a required level of performance, reinforcement is potentially needed beneath railway embankments to control settlements and stability under traffic loads [8-10].
In this study, an actual railway embankment (with and without deep soil mixing columns) was simulated in a Finite Element program, Plaxis 3D. Various axle loads (i.e., 16 tons, 20 tons, 25 tons, 30 tons, and 32.5 tons) and loading types (static and cyclic) were adopted in the simulated models. Two important parameters, settlement, and maximum excess pore water pressure, were evaluated based on numerical results.

2. Methodology
A full model with 10-node elements was used to simulate an actual railway embankment. The full model was 49 m wide and 10 m deep, and 8.5 m longitudinal was considered in this work. For the static loading condition, the bottom of the grid was pinned (fully fixed), and its lateral boundaries were supported by rollers (normally fixed). For the cyclic loading condition, the viscous boundary has to be applied in order to absorb waves reaching the boundary (i.e., avoid spurious wave reflections at the far-field boundaries) [11]. In addition, to minimize the distortion wave effect in dynamic analyses, the size of each element must be less than one-tenth of the wavelength [11]. Therefore, a relatively fine mesh (average element size of 1.069 m) was generated. The generated mesh of embankment and soil volumes beneath the embankment were finer (since these areas would be affected by large strains) than far-field areas (Figure 1).

![Figure 1. Geometry and generated mesh (Plaxis 3D)](image)

The embankment itself was composed of granular soil (1.5 m high and 9 m wide) with a single layer of geo-grid (i.e., stiffness of 2200 kN/m obtained from the field design). The subsoil consisted of 1.5 m thick peat layer. The phreatic level was located on the original ground surface in the model to reflect the highest risk condition in the field. Under the soft soil layers, a silty till layer (18 m) was considered in this model. The model size was chosen based on two requirements: 1) no elevation of principle stress near the bottom; 2) principle stress near side boundaries is similar to the in-situ stress. The soft soil model was employed for the peat layer (i.e., large deformations would take place in the peat layer rather than in the silty till layer), whereas Mohr-Coulomb was used for the silty till layer. All parameter values of the constitutive models used in the numerical analyses are tabulated in Table 1.

The deep soil mixing (DSM) columns were modeled as volume piles for the proper soil-structure interaction instead of embedded piles. It should be noted that the embedded piles are difficult to capture local arching or stress rotation along with the piles. The procedure for 3D Pile Modelling is presented by Plaxis [12]. The pile locations were arranged to be at an offset of 0.85 m × 1.2 m in the horizontal and longitudinal directions. In addition, the piles were modeled as 10 m in length and 0.3 m in diameter. The stiffness of a DSM column was assumed based on its unconfined compressive strengths (UCS) with respect to soil types and binders from literature reviews [10, 13].

Furthermore, in order to simulate the cyclic axle loading, a simple sinusoidal function \( q(t) = q \cdot \sin(\omega t) \) was used in the model [14, 15]. It should be noted that any traffic cyclic loading depends on the static axle load \( q \) and the speed of that traffic (i.e., represented by \( \omega \)). In this paper,
the number of load cycles (15 cycles) was represented for cyclic simulation as compared to the static cases. The results used in this study were obtained from the data points along the horizontal center-line of the representative cross-section (at the middle of the peat layer). The numerical modelling consisted of six steps: initial geostatic equilibrium, excavation before embankment, embankment construction, consolidation, pile installation (only in the embankment model with DSM columns), and loading (static or cyclic loads).

3. Results and analysis

3.1. Effect of an increase in axle loads

Figure 2a shows the effect of an increase in axle loads (i.e., static loading) on the vertical displacement of the subgrade layer (peat). As a result, a general trend was observed, that is, an increase in axle load led to a considerable increase in vertical displacement (settlement). The increase of axle loads from 16 to 20 tons resulted in a relatively small increase in settlement, while the increase to 32.5 tons was significant. In particular, the maximum displacement of the peat layer under the axle load of 16 tons (light axle load) was only 4.03 mm. This value slightly increased to 5.8 mm as the axle load increased from 16 tons to 20 tons but it significantly raised to 16.4 mm after the heavy axle load (32.5 tons) acting on the embankment. Furthermore, it was found that the displacement of the peat layer took place mostly around the centerline, right beneath the embankment for every axle loading. The heaving areas were also observed at both sides near the toes of the embankment. The maximum heaving displacement was found to be nearly 6 mm (heavy axle load of 32.5 tons). In addition, a good agreement between the development of settlement and excess pore water pressure with respect to the increase of axle loads can be observed from Figure 2b. The maximum excess pore water pressure increased with an increase in axle load. The increase in excess pore pressure was also relatively small as the axle load increased from 16 tons to 20 tons, but noticeable as the axle load increased up to 32.5 tons, expectedly.

### Table 1. Material parameter values used in the numerical analyses [15, 16]

| Parameter                        | Embankment | Silty till | Peat    | Soft soil | Unit    |
|----------------------------------|------------|------------|---------|-----------|---------|
| Material model                   | Mohr-Coulomb | Mohr-Coulomb | Soft soil | -         |
| Soil unit weight above phreatic level | 18         | 18         | 13.5    | kN/m³     |
| Soil unit weight below phreatic level | 20         | 22         | 13.5    | kN/m³     |
| Initial void ratio               | 0.50       | 0.50       | 2.0     |           |
| Young modulus                    | 50000      | 40000      | -       | kN/m²     |
| Poisson's ratio                  | 0.20       | 0.25       | -       |           |
| Modified compression index       | -          | -          | 0.20    |           |
| Modified swelling index          | -          | -          | 0.02    |           |
| Cohesion                         | 0          | 2.0        | 2.0     | kN/m²     |
| Friction angle                   | 45         | 40         | 30      | degree    |
| Dilatancy angle                  | 0          | 0          | 0       | degree    |
| Overconsolidation ratio          | 1.0        | 1.0        | 1.0     |           |
| Pre-overburden pressure          | 0          | 0          | 20      | kN/m²     |
3.2. Effect of loading types

The considerable effects of loading types (static and cyclic) on the vertical displacement as well as the maximum excess pore water pressure of the subgrade layer are illustrated in Figure 3. As shown, a negative effect of cyclic loading was discovered. The cyclic loading can lead to a considerable increase in vertical displacement due to the cyclic load-induced accumulated settlement. The maximum displacements in the case of static loading was 4.03 mm (light axle load of 16 tons) and 16.4 mm (heavy axle load of 32.5 tons). However, in the case of cyclic loading, these values increased more than 2 times (8.65 mm) and 3 times (59.7 mm) for the light axle load and heavy axle load, respectively. A similar finding was observed in the maximum excess pore water pressure of the peat layer (Figure 3b). The increase in the excess pore water pressure due to cyclic loading was more significant (approximately 4 times) for the heavy axle load (32.5 tons) than that of the light axle load (16 tons).
3.3. **Effect of ground improvement (deep soil mixing columns)**

Figure 4 presents the effect of ground improvement with deep soil mixing (DSM) columns on vertical displacement and maximum excess pore water pressure of the subgrade layer (peat). It should be noted that the stiffness of the modelled DSM column was derived from unconfined compressive strength (UCS) of 1 MPa from literature reviews [10, 13]. Representative axle loads (16 tons, 25 tons, and 32.5 tons) were prepared for both case studies of without and with ground improvement by DSM. It is worth noting that a significant decrease in both vertical displacement (Figure 4a) and maximum excess pore water pressure (Figure 4b) was observed with the addition of DSM columns in the models. While vertical displacements and excess pore water pressures of the models without DSM sharply increased with respect to axle loads, those with DSM showed little growths, even in case of the heavy axle load (32.5 tons). In other words, there was a noticeable improvement when using DSM columns. In addition, no heave was observed at the toes of the embankment with DSM, whereas the heaving displacements of the embankment toe without DSM were very pronounced, as evidenced in Figure 5. It can be concluded that the DSM columns can be used to effectively improve the stability (compressibility) of the railway track foundation. The vertical displacements (settlement and heave) and excess pore water pressures improved from having very large to relatively low values after using DSM columns.

**Figure 4.** Effect of ground improvement (DSM) on (a) vertical displacement and (b) maximum excess pore water pressure of the subgrade layer (peat)

**Figure 5.** Effect of ground improvement with DSM on vertical displacement of the subgrade layer (peat) under (a) the static light axle load and (b) static heavy axle load
Finally, the effects of unconfined compressive strengths (UCS) of DSM columns on the vertical displacement as well as the maximum excess pore water pressure of the soft soil layer are presented in Figure 6a. As shown, the values of vertical displacement and maximum excess pore water pressure decreased with a corresponding increase in the UCS of DSM columns. This tendency is primarily due to the increase in the maximum $\sigma_1$ in DSM columns as seen in Figure 6b. In this sense, the higher the strength of DSM columns are, the more stress is transferred to DSM columns. This made the less stress transferred to soft soil layer (peat), and eventually the vertical displacement and maximum excess pore water pressure in the soft soil were reduced.

4. Conclusions
In this study, a numerical analysis was conducted to investigate the effects of an increase in axle loads of trains on both excess pore water pressure and settlement. An actual railway embankment (with and without DSM columns) was modelled in a Finite Element program, Plaxis 3D. The following conclusions can be drawn:

1. Vertical displacements and excess pore water pressure increased with an increase in axle loads. These increases were more significant in the case of heavy axle load (32.5 tons) than those in the case of the light axle load (16 tons).

2. The effects of loading types on the vertical displacement as well as the maximum excess pore water pressure of the subgrade layer were found to be significant. The model response under cyclic loading can lead to a considerable increase in both vertical displacements and excess pore water pressure (up to 3 times larger than in static loading).

3. Vertical displacements and excess pore water pressures of the models without deep soil mixing (DSM) columns significantly increased with respect to axle loads. However, those of with DSM columns showed little growths, even in case of the heavy axle load (32.5 tons). In other words, DSM columns can be used to improve the stability of the railway track foundation. Eventually, it was found that the higher the strength of DSM columns is, the less vertical displacement and maximum excess pore water can be observed (i.e., due to the less stress transferred to the soft soil layer).
Acknowledgements
This work has been supported by the Swedish transport administration (Trafikverket), the Swedish joint research program for road and railway geotechnology Bransch-samverkan i grunden (BIG), and Luleå University of Technology

References
[1] Trafikverket 2019 https://www.trafikverket.se/nara-dig/ Norrbotten/projekt- i-norrbottens-lan/Malmbanan/stax-325-ton-pa-malmbanan/
[2] Wong RC, Thomson PR, Choi ES 2006 In Situ Pore Pressure Responses of Native Peat and Soil under Train Load: A Case Study Journal of Geotechnical and Geoenvironmental Engineering 132(10) 1360-1369.
[3] Hendry MT, Martin CD, Barbour SL 2013 Measurement of cyclic response of railway embankments and underlying soft peat foundations to heavy axle loads Canadian Geotechnical Journal 50(5) 467-480.
[4] Gräbe H, Vorster J 2013 The effect of axle load on track and foundation resilient deformation under heavy haul conditions International Heavy Haul Association Conference.
[5] Gräbe H, Shaw F, Clayton C 2005 Deformation measurement on a heavy haul track formation 8th International Heavy Haul Conference.
[6] Fortunato E, Resende JR 2006 Mechanical behaviour of railway track structure and foundation – three dimensional numerical modelling International Conference on Railway Track Foundations.
[7] Xu F, Yang Q, Liu W, Leng W, Nie RS, Mei H 2018 Dynamic Stress of Subgrade Bed Layers Subjected to Train Vehicles with Large Axle Loads Shock and Vibration 1-12.
[8] Esmaeili M, Khajehei H 2016 Mechanical behavior of embankments overlying on loose subgrade stabilized by deep mixed columns Journal of Rock Mechanics and Geotechnical Engineering 8(5) 651-659.
[9] Wijewickreme D, Atukorala UD 2015 Ground Improvement for Mitigating Liquefaction-Induced Geotechnical Hazards Ground Improvement Case Histories, Butterworth-Heinemann, San Diego, pp. 3-50.
[10] Holm G, Andréasson B, Bengtsson PE, Bodare A, Eriksson H, Djupstabiliser S 2002 Mitigation of Track and Ground Vibrations by High Speed Trains at Ledsgård, Sweden.
[11] Messioud S, Okyay US, Sbartai B, Dias D 2016 Dynamic Response of Pile Reinforced Soils and Piled Foundations Geotechnical and Geological Engineering 34(3) 789-805.
[12] Plaxis 2018 How to volume pile – A brief step-by-step guide.
[13] Topolnicki M 2013 In situ soil mixing Ground improvement 377-378.
[14] Indraratna B, Rujikiatkamjorn C, Ewers B, Adams M 2010 Prediction of the Behavior of Soft Estuarine Soil Foundation Stabilized by Short Vertical Drains beneath a Rail Track Journal of Geotechnical and Geoenvironmental Engineering 136(5) 686-696.
[15] Trafikverket 2014 TK Geo 14: Trafikverkets tekniska krav för geokonstruktioner.
[16] Al-Zubaidi I 2017 Numerisk simulering av sättningar och portryck för en provbank på sulfidjord p. 75 (In Swedish).