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Thermo-mechanical assessment of ballasted railway subgrade deformation under heavy train axle loads and freeze-thaw conditions

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ABSTRACT: The extension of railway networks into cold regions, combined with the adoption of heavier rolling stock, increases the need to understand how temperature variations and mechanical loading together influence track performance. In such environments, subgrade stiffness and strength vary markedly with temperature, leading to settlement, track geometry deterioration, and higher maintenance demands. Elevated axle loads from modern freight and mixed-traffic operations may also exceed the assumptions of current design frameworks. This study investigates the interaction between axle load (20 t, 22.5 t, and 25 t) and temperature-dependent clay subgrades in ballasted track systems, with subgrade temperatures ranging from -15 °C to 0 °C. A three-dimensional finite element model is developed in the commercial FEM package ABAQUS, representing the rail-sleeper-ballast-subgrade system with temperature-dependent material properties. Stiffness and strength parameters for the clay subgrade are obtained from empirical relationships based on previously published laboratory test results at different sub-zero temperatures. The results show that settlement increases sharply as the subgrade approaches the thawing range due to pronounced stiffness loss. From the peak maximum displacement, two key temperature intervals are identified: from -15 °C to -8 °C, displacements increase by 25.45%, indicating gradual weakening; from -8 °C to -0.5 °C, the increase reaches 90.11%, marking a critical phase of subgrade deterioration. These findings highlight the substantial influence of near-thaw temperatures on track performance under heavy axle loading, emphasizing the importance of incorporating temperature-dependent properties in the design and maintenance of cold-region railway infrastructure.

KEYWORDS : Freeze-thaw cycles, Ballasted railway tracks, Finite element modeling (FEM)

1 INTRODUCTION

The structural integrity and long-term performance of railway tracks depend on the interaction between applied loads and the behaviour of the underlying ground. This interaction becomes particularly critical in regions with extreme climates, especially those with prolonged winters where subgrade soils are subjected to repeated freeze-thaw cycles (Selig and Waters, 1994). These thermal cycles alter soil stiffness and strength, leading to deformation, uneven settlement, and long-term deterioration of track geometry. Such changes compromise safety, reduce service reliability, and increase maintenance requirements.

Ballasted track systems, the most widely used track form globally, are especially vulnerable to these climatic effects. While ballast provides drainage and flexibility, it relies on stable and uniform subgrade support for effective load transfer (Li and Selig, 1998). In cold climates, freezing can temporarily stiffen the subgrade through ice bonding, but thawing significantly reduces bearing capacity, often triggering progressive settlement (Shastri et al., 2021). Thawing conditions trigger the most severe deterioration, as unfrozen water content increases rapidly, ice bonds fail, and deformation under train loads accelerates. In this phase, between -15 °C and 0 °C, the subgrade shifts from a fully frozen, high-stiffness state to a weakened, thawed condition (Gao et al., 2025).

Although past studies have investigated frozen-soil behaviour or track response to moving loading, few have examined the combined influence of extreme subgrade conditions and elevated train loads on long-term settlement. This is increasingly important as modern railways face heavier axle loads, high-speed freight, and mixed-use corridors that may exceed the assumptions of existing design standards.

In this study, the deformation of a ballasted railway track is analyzed under sub-zero clay subgrade conditions and varying axle loads. Three load cases 20 t, 22.5 t, and 25 t per axle are considered as per UIC Code 700 to represent current and anticipated future rolling stock. A three-dimensional finite element model is developed with temperature-dependent stiffness and strength parameters, including Young's modulus, Poisson's ratio, cohesion, and friction angle, derived from laboratory-based empirical relationships (Li et al., 2015; Bai et al., 2020). Each wheel load is applied as half the axle load to realistically represent train loading. This framework is used to assess how load magnitude and subgrade temperature interact to influence vertical settlement.

2 METHODOLOGY

2.1 *Numerical Modeling Framework*

A three-dimensional numerical model was developed using the commercial FEM package ABAQUS CAE to examine the settlement behavior of a ballasted railway track under static loading. The model simulated the effect of three axle loads and considered the influence of low temperatures on subgrade response. Figure 1. shows the schematic layout of the track formation, comprising ballast, sub-ballast, and subgrade. For the static loading analysis, a 200 m stretch of track was modelled to evaluate vertical displacements and deformation patterns. Figure 2. presents the axle load configuration under static conditions for locomotive and coach case (Feng, 2011).

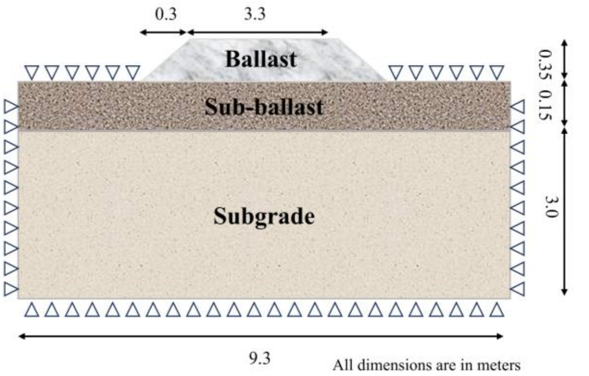

Figure 1. Schematic diagram of the railway track section, after (Feng, 2011)

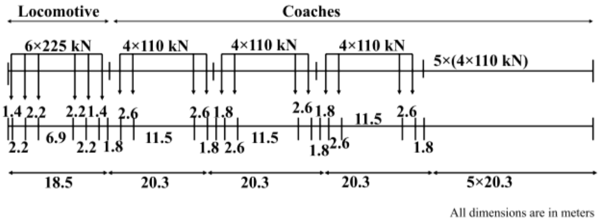

Figure 2. Train axle load configuration, after (Feng, 2011)

The geometric model was optimized for computational efficiency following (Khan and Dasaka, 2020), using plane symmetry along the track centreline Figure 3. illustrates the assembly of the substructure layers and materials used in the model. The simulation adopted the international UIC 60 rail profile, with rail dimensions conforming closely to the standard and represented by an approximate I-shaped cross-section. Reinforced concrete sleepers were modelled with dimensions of 2.6 m (length) × 0.265 m (width) × 0.205 m (thickness), in line with typical specifications. The sleepers were placed at a centre-to-centre spacing of 600 mm, consistent with European standards for standard gauge railways (European Committee for Standardization, 2009). The ballast and sub-ballast layers were assigned thicknesses of 300 mm and 150 mm, respectively, supported by a homogeneous subgrade layer of 3.0 m thickness. The 3D track model comprised the main structural components subgrade, sub-ballast, ballast, sleepers, and rails each assigned material properties as detailed in Table 1. Boundary conditions were applied to simulate realistic track support: a fixed (ENCASTRE) condition was assigned to the bottom surface of the subgrade, motion normal to the lateral surfaces was restrained (U1 = U3 = UR2 = 0), and displacement in the x-direction was restricted on the symmetric surface (U1 = UR2 = UR3 = 0). Loading was applied as concentrated forces at nodes, as shown in Figure 2. For better numerical accuracy, the mesh was refined in the ballast and sub-ballast near the load application zone, using mesh biasing to create finer elements in stress concentration areas and at material interfaces, and coarser elements elsewhere. This ensured accurate static loading results while keeping computational demands reasonable.

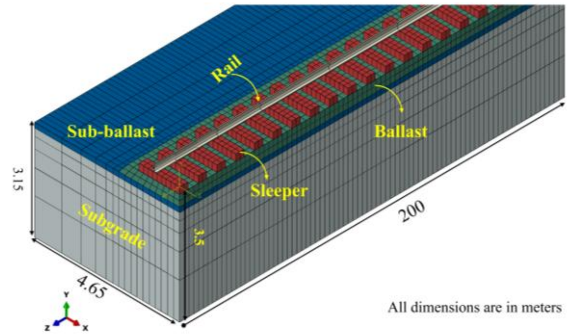

Figure 3. Three-dimensional FEM model of ballasted railway track section

2.2 *Validation Study of 3D Finite Element Models*

To ensure the reliability and accuracy of the proposed model, a stepwise validation approach was adopted. The modelling framework is based on the elastic rail-track model developed by (Feng, 2011), which was originally validated against field data from (Kjörling, 1995). In this analysis, both the track superstructure components (rail and concrete sleeper) and the substructure geomaterials (ballast, sub-ballast, and subgrade) are modelled as linear-elastic materials. The material properties used in the simulation are taken from (Feng, 2011) and are listed in Table 1.

Table 1. Material Properties assigned in the railway track model after Feng (2011).

Parameter	Density, ρ (kg/m^3)	Young's Modulus, E (MPa)	Poisson's Ratio, ν
Rail	7850	207000	0.28
Sleeper	2400	70000	0.3
Ballast	1600	150	0.35
Sub-ballast	1900	50	0.35
Subgrade	2000	10	0.4

The loads were modelled as locomotive and coach sections, with axle loads of 22.5 t and 11 t, respectively. Due to symmetry, each wheel load was applied as half the axle load.

Figure 4. compares the vertical displacement (δ_v) from the present study with the results of (Feng 2011) under static loading. In both cases, δ_v was measured at a depth of 0.35 m below the sleeper level to maintain consistency and ensure accurate capture of the deformation zone beneath the sleepers. For the locomotive axle load of 22.5 tonnes, (Feng, 2011) reported a maximum vertical displacement (δ_v) of 4.18 mm, while the present analysis obtained 4.68 mm. Under the coach axle load of 11 tonnes, smaller δ_v values were observed, but the variation along the track length (L) followed the same trend in both studies. Across the 200 m track section, the displacement profiles exhibit a consistent pattern, demonstrating the reliability of the present numerical model in capturing the static response of a ballasted railway track.

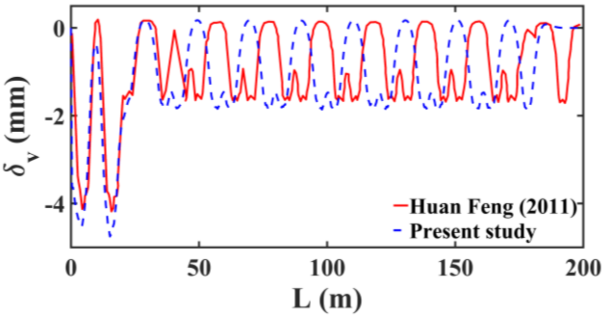

Figure 4. Validation of vertical track displacement response

3 RESULTS

Following the validation of the numerical model against (Feng, 2011), the results from a series of parametric analyses conducted under railway loading conditions are presented in this section. The objective was to evaluate how variations in wheel loads and subgrade stiffness, particularly under low-temperature conditions, influenced the vertical deformation behaviour of a ballasted railway track system. Three loading combinations were analyzed: locomotive axle loads of 22 t, 22.5 t, and 25 t, as specified in UIC Code 700. Although these values exceeded conventional limits for high-speed passenger trains, they were selected to represent potential future scenarios such as high-speed freight operations, shared corridors with heavy locomotives, or extreme axle loading events. This approach enabled an assessment of track substructure deformation under increased axle loads.

In addition to varying the axle loads, the subgrade layer properties were modified to reflect temperature-dependent stiffness and strength behaviour through an elastoplastic constitutive model. The temperature dependence of Young's modulus, Poisson's ratio, cohesion, and friction angle was calculated using the empirical equations reported by (Li et al., 2015; Bai et al., 2020), as given in Table 2. While the original studies applied these equations for temperatures between -0.5 °Cand -8 °C, in the present work they were extended to cover the full range from 0 °C to -15 °C to represent a broader spectrum of frozen subgrade conditions. For analyzing the effect of railway loading on a subgrade subjected to different sub-zero temperatures, all other material parameters, including the rail, sleeper, ballast, and sub-ballast, remained consistent as linear elastic as described in Table 1, except for the subgrade material, which was modelled with elastoplastic behaviour Figure 5. presents the vertical displacement profiles of the ballasted railway track under three-wheel loads (100 kN, 112.5 kN, and 125 kN) for subgrade temperatures of -15 °C, -10 °C, -8 °C, and -5 °C. These four temperatures were selected to represent key points within the examined range from 0 °C to -15 °C, with -15 °C corresponding to the extreme frozen condition considered in this study. The intermediate values illustrate the progressive change in subgrade stiffness and resulting deformation as temperature increases. The horizontal axis (L) represents the distance along the track length in metres, and the vertical axis (δ_v) represents the vertical displacement in millimetres. Across all wheel loads, displacement values increased as the subgrade temperature rose, indicating a reduction in stiffness with warming.

- The subgrade showed the highest stiffness at -15 °C, with displacements of 0.76 mm, 0.85 mm, and 0.95 mm for the 100 kN, 112.5 kN, and 125 kN wheel loads, respectively.
- A reduction in stiffness at -10 °C resulted in displacements of 0.88 mm, 0.99 mm, and 1.10 mm under the same loading conditions.
- Further softening at -8 °C increased displacements to 0.95 mm, 1.07 mm, and 1.19 mm.
- The lowest stiffness occurred at -5 °C, producing displacements of 1.10 mm, 1.24 mm, and 1.38 mm.

Overall, the displacement behaviour under each wheel load clearly showed that as temperature increased, the subgrade weakened, causing greater vertical deformation. This trend highlights the critical role of thermal effects on track performance in cold-region operations, leading to greater settlements beneath the applied wheel loads.

Table 2. Mechanical properties of frozen clay, referred from (Li et al., 2015; Bai et al., 2020)

Parameter	Equation
Young's modulus E (MPa)	$E = 22.5 + 11.3(-T)^{0.6}$
Poisson's ratio ν (-)	$\nu = 0.28 - 0.007\ (-T)$
Cohesion c (kPa)	$c = 20 + 6(-T)^{1.24}$
Friction angle ϕ (∘)	$\phi = 20 + 3.4(-T)^{0.38}$

The empirical equations mentioned in Table 2. has been extended to the temperatures in the range of -15 °C≤ T ≤ 0 °C after (Li et al., 2015; Bai et al., 2020)

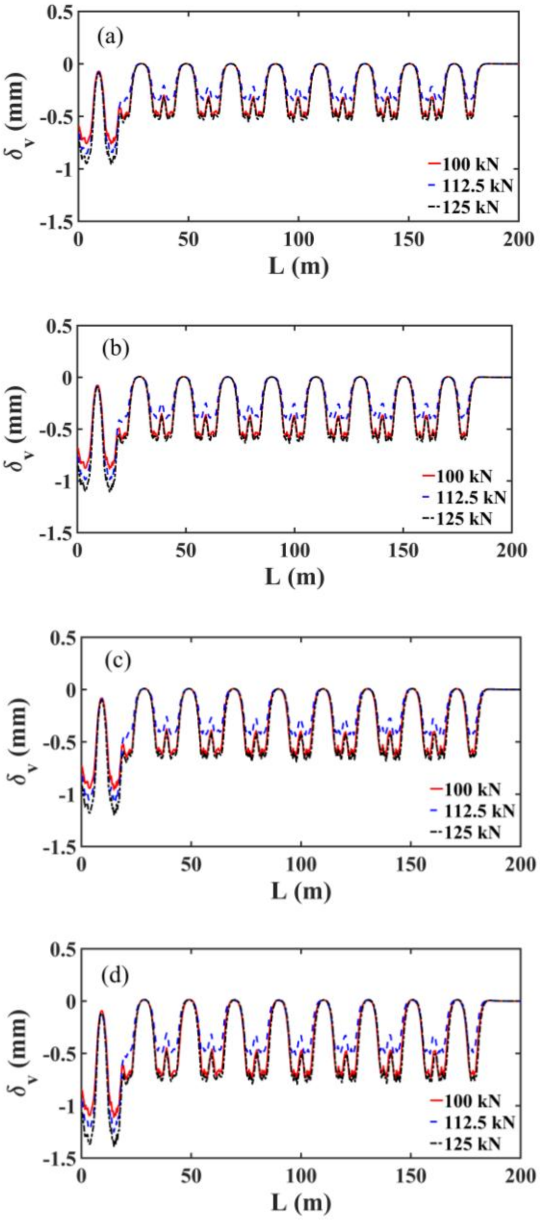

Figure 5. Vertical displacements in the subgrade under railway loading at sub-zero temperatures of (a) -15°C, (b) -10°C, (c) -8 °C, and (d) -5 °C

4 DISCUSSION

Figure 6. illustrates the variation in peak vertical displacement ($\delta_{v,\text{ peak}}$) with increased sub-zero subgrade temperature (T ˚C), showing a clear and progressive reduction in the stiffness of the track foundation as it warms. At low temperatures (around -15 ˚C), the subgrade remains in a fully frozen state, exhibiting high rigidity and resulting in minimal deformation under all railway wheel loads. As temperature increases, the stiffness of the soil decreases, and the vertical displacement correspondingly increases.

The variation in vertical displacement with subgrade temperature reveals a clear and progressive reduction in the stiffness of the track foundation as it warms. At low temperatures (around -15 °C), the subgrade remains in a fully frozen state, exhibiting high rigidity and resulting in minimal deformation under all axle loads. As the temperature increases, the stiffness of the soil gradually decreases, and the vertical displacement correspondingly increases.

The most pronounced change is observed in the range of -5 °C to 0 °C. In this interval, the displacement curves for all three axle loads steepen markedly, indicating the onset of advanced thawing. The breakdown of ice bonds within the soil matrix during this stage substantially reduces the load-bearing capacity, producing a sharp rise in deformation. Outside this critical thawing range, the influence of temperature on displacement is comparatively modest.

A notable feature in Figure 6. is the nearly constant separation between the displacement curves for the different axle loads across all temperatures. This consistency indicates that temperature variations primarily affect the stiffness of the subgrade material, without significantly altering the relative influence of axle load. For instance, while the displacement for a 100 kN load at -15 °C is considerably lower than that at -5 °C, the difference between 100 kN and 125 kN remains approximately the same at both temperatures.

Based on these observations, three distinct stages of subgrade behaviour can be identified: (i) a stable frozen state below -10 °C, characterised by minimal stiffness loss; (ii) a gradual softening phase between -10 °C and -5 °C, reflecting the onset of thawing; and (iii) a critical thawing phase between -5 °C and 0 °C, during which stiffness degradation accelerates significantly. The latter stage is of particular concern for track performance in cold regions subject to seasonal freeze-thaw cycles, as relatively small increases in temperature within this range can cause disproportionately large deformations.

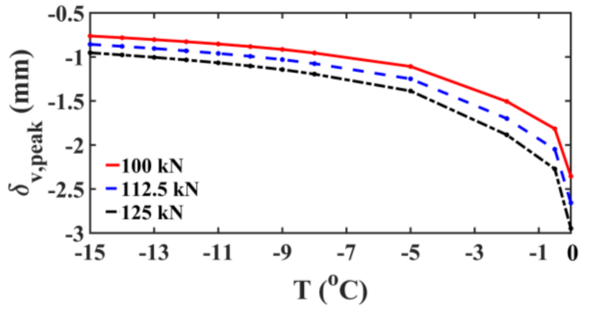

Figure 6. Variation in the peak vertical displacements in the track under various train wheel loads at subgrade temperatures from -15 °C to 0 °C

5 CONCLUSIONS

The influence of locomotive wheel loads and subgrade temperature variations on the vertical deformation behaviour of a ballasted railway track was investigated using a three-dimensional finite element model developed in ABAQUS. The analysis considered railway loading across a frozen soil temperature range of -15 °C to 0 °C, with subgrade properties varying according to temperature-dependent empirical relationships derived from previously published laboratory test results.

- For the three simulated train wheel loads of 100 kN, 112.5 kN, and 125 kN, subgrade displacements considerably increased with load magnitude, signifying the critical sensitivity of frozen railway subgrades to temperature changes under heavy freight loading conditions.
- An increase in subgrade temperature, representing thawing, led to higher vertical displacements due to reduced stiffness of frozen soils.
- From the peak maximum displacement, two key temperature intervals were identified: from -15 °C to -8 °C, displacements increased by 25.45%, indicating gradual weakening; from -8 °C to -0.5 °C, the increase reached 90.11%, marking a critical phase of subgrade deterioration.

The results demonstrate that temperatures approaching the thawing point cause the most severe deterioration in subgrade performance under railway loading, emphasizing the importance of incorporating temperature-dependent soil properties in the design and maintenance of cold-region railway infrastructure. Future studies may address a few limitations of the present work, including considering full thermo-hydro-mechanical coupled behaviour and a four-phase soil system, in which ice and unfrozen water are treated as distinct phases. Dynamic railway loading conditions can also be simulated, incorporating the effects of soil plasticity and damage accumulation under repeated load cycles. These considerations can provide a more accurate representation of track substructure behaviour in cold climates.

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