Iran University of Science and Technology

International Journal of

Railway Research

ISSN: 2423-3838

Investigating the effects of polyurethane-reinforced ballasted railway superstructure in reducing the train induced environmental vibrations

Sina Ghahremani[1*], Seyed Ali Mosayebi[2], Fateme Samimi[1], Jabbar-Ali Zakeri[2]

[1] School of Railway Engineering, Iran University of Science and Technology, Tehran, Iran

[2] The Center of Excellence for Railway Transport, Iran University of Science and Technology, Tehran, Iran

ARTICLE INFO

Article history:

Received: 28.06.2025

Accepted: 04.09.2025

Published: 06.12.2025

Keywords:

Railway Ballasted Superstructure

Polyurethane Injection

Environmental Vibrations Caused By Train Passage

Finite Element Method

A B S T R A C T

One of the main challenges in ballasted railway tracks is the vibration induced in the track superstructure and the surrounding environment due to train passage. These vibrations cause significant damage to both the superstructure components and nearby structures. To address this problem, injecting polyurethane into the ballasted superstructure has emerged as a potential solution.

Polyurethane refers to a class of polymers containing urethane bonds, which are formed through an addition reaction between an isocyanate group and an active hydrogen compound, such as a hydroxyl group. Because isocyanate groups are highly reactive, their reactions can progress without requiring elevated temperatures. As a result, polyurethane can be produced in various forms, including foams, films, elastomers, powders, liquids, and emulsions.

This study investigates the effects of injecting an economical and readily available polyurethane into ballasted tracks to reduce environmental vibrations caused by rail vehicle passage, using numerical methods. First, a ballasted railway track was modeled based on the finite element method and validated against existing technical literature. Subsequently, three models were developed: a standard ballasted railway track (without polyurethane), a track with 50% polyurethane injection, and a track with 100% polyurethane injection. The effects of train-induced vibrations were analyzed in terms of the time histories of displacement and vertical acceleration at points surrounding the track.

The results indicate that with 50% polyurethane injection, displacement and vertical acceleration are reduced by 61.87% and 98.6%, respectively, compared to the standard ballasted superstructure. For 100% polyurethane injection, the reductions are 62.15% and 76.93%, respectively.

1. Introduction

The global demand for railway construction has increased significantly due to its capacity to transport large numbers of passengers with greater safety compared to other transportation systems. However, the passage of trains generates considerable vibrations in the track bed and adjacent structures. This problem is particularly critical in station complexes, depots, and sandy regions, where repeated loading can severely damage sleepers, fastening systems, nearby buildings, and sensitive equipment. Moreover, ballast fouling and particle hardening intensify vibration transmission, thereby increasing the risk of damage.

* Corresponding author
Email address: s.ghahremani96@gmail.com

Several studies have been conducted to mitigate vertical acceleration in the railway bed. For instance, Junyun Zhang et al. (2021) investigated the effects of improving the railway bed in sections K329 + 530 and K330 + 990 using rotary jet grouting piles, comparing their accelerations with those of an unreinforced section (K331 + 315). They reported that reinforced beds at a depth of 4.5 meters showed more than 60% surface-level acceleration reduction, while unreinforced subgrades achieved only 50–60% reduction [1]. Similarly, Shan-zhen Li et al. (2021) concluded that replacing ballasted tracks with non-ballasted tracks decreases the range of railway bed acceleration. They attributed the wide range of high frequencies observed in ballasted tracks to short-wavelength irregularities (0.01–0.5 m), which do not significantly affect non-ballasted tracks [2]. Buddhima Indraratna et al. (2019) demonstrated that transient displacements are reduced by 60% after stone blowing, along with a reduction in vertical acceleration [3].

Jing, Guoqing et al. (2018) found that injecting polyurethane into the ballast of transition zones at varying depths and widths improves the vibration characteristics of reinforced ballasted tracks compared to slab tracks, particularly at low frequencies. Their study reported a 16.4 dB reduction in acceleration around 50 Hz [4]. Morteza Esmaili et al. (2014) showed that 62.7% ballast fouling increases maximum transmitted environmental acceleration by approximately 43% [5]. In a related study (2014), they concluded that a V-shaped trench is more effective than a rectangular trench in reducing induced vibrations based on finite element analyses. Considering train speeds of 80 and 120 km/h and optimizing for both minimum trench area and minimum particle acceleration amplitude, the optimal trench dimensions were determined to be w = 2.5 m and d = 5.25 m [6].

Other researchers have investigated polyurethane reinforcement as a promising solution. Woodward et al. (2012) applied polyurethane geocomposites to maintain track geometry in high-speed ballasted railways [7], while Woodward et al. (2014) examined stiffness modification via polyurethane reinforcement [8]. Medero et al. (2013) reported that three-dimensional polyurethane reinforcement significantly reduces settlement [9], and Xiong et al. (2021) evaluated field dynamic performance, demonstrating improvements in vibration control [10]. Collectively, these studies highlight both the benefits and limitations of polyurethane treatment in ballasted tracks.

In this study, polyurethane injection is adopted to reduce the vertical acceleration of the railway bed. Polyurethane is a polymer widely applied in reinforcing ballast in areas such as transition zones, arches, bridges, tunnels, stations, and crossings [11]. A notable advantage of polyurethane is the integrated structure it forms in ballasted tracks, which prevents sand infiltration, ballast fouling, and hardening. Commonly used polyurethane materials for railway reinforcement include RPF (Bayer Material Science), Elastotrack® (BASF), and XiTRACK™ (Dow) [12–14].

The primary purpose of polyurethane injection is to stabilize the ballast skeleton and limit excessive settlement under repeated train loading. Although ballasted tracks inherently exhibit higher damping capacity than slab tracks, this capacity diminishes when ballast particles become fouled, loosened, or degraded. In such cases, polyurethane infiltration binds the particles, prevents excessive deformation, and preserves track geometry. Consequently, polyurethane reinforcement not only ensures long-term ballast stability and settlement control but also modifies vibration transmission—an aspect that forms the focus of the present research.

Despite prior advances, most previous studies have concentrated either on settlement reduction or on vibration control without systematically relating the degree of polyurethane reinforcement to dynamic responses. The present study addresses this gap by developing and validating a finite element model of a ballasted track to compare three cases: untreated ballast, 50% polyurethane infiltration, and 100% infiltration. Specifically, a cost-effective truck air-filter polyurethane—widely used as raw material in heavy-vehicle filters—was selected to assess its potential as an economical alternative for railway track reinforcement. The results provide insights into the mechanisms and practical implications of partial versus full reinforcement.

2. Numerical analysis of train induced environmental vibrations

In this section, the vibrations emitted from railway tracks due to train passage are investigated using the finite element method. As illustrated in Fig. 1, the railway track was modeled under plane strain conditions in ABAQUS finite element software. The study examines the environmental vibrations generated by train passage on the ballasted railway superstructure, both with and without polyurethane reinforcement.

The subsequent subsections provide detailed explanations of the railway model specifications, including the geometry of the numerical model, boundary conditions, material properties of the ballasted superstructure, and the applied loading pattern. It should be noted that the numerical model adopted in this research is based on the framework developed by Esmaili et al. [5].

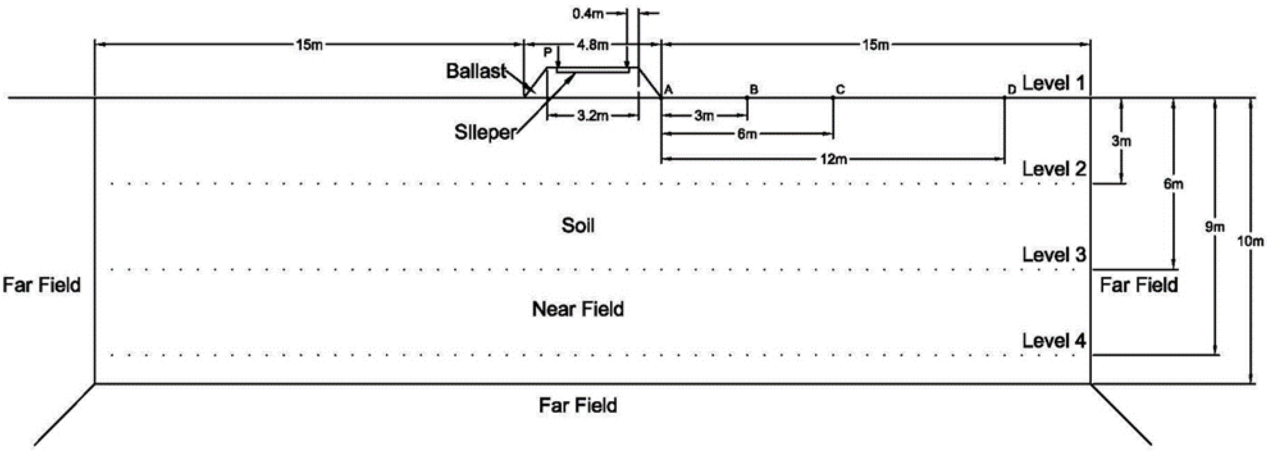


Figure 1. Ballasted railway track model simulated by finite element method

2.1. Geometry of the numerical model and its boundary conditions

To ensure that the numerical model reflects real conditions, appropriate boundary conditions were defined. The outer domain of the model was bounded with springs and dampers to simulate the far field. As shown in Fig. 1, the model consisted of three main parts:

- Track superstructure, including sleepers and ballast / polyurethane-reinforced ballast,
- Track substructure, comprising compacted soil and natural ground (near field),
- Surrounding natural ground, represented by springs and dampers (far field).

All components were discretized in ABAQUS using CPE4R plane-strain elements (4-node bilinear elements with reduced integration). A graded mesh was employed, with finer elements (0.05–0.10 m) in the ballast and sleeper zones, gradually coarsening toward the far field. Mesh-independence was verified by halving the element size in critical regions, resulting in less than 2% variation in peak responses.

To prevent spurious wave reflections, viscous non-reflecting boundaries (Lysmer–Kuhlemeyer dashpots) were applied along the lateral and bottom edges. The dashpot coefficients were calculated from material density and wave velocities. These boundaries realistically simulate radiation damping by absorbing outgoing waves and minimizing artificial reflections in the far field.

The interfaces between different materials were modeled using the Tie option in ABAQUS, ensuring full bonding in regions where polyurethane infiltration created an integrated skeleton. Throughout the analysis, energy balance and hourglass control were monitored to ensure numerical stability.

2.2. Specifications of materials

2.2.1. Ballast

In this study, andesine ballast sourced from the Shahriar Mine was used, with its aggregates graded according to Group 1 of Code 301 (Fig. 2) [15].

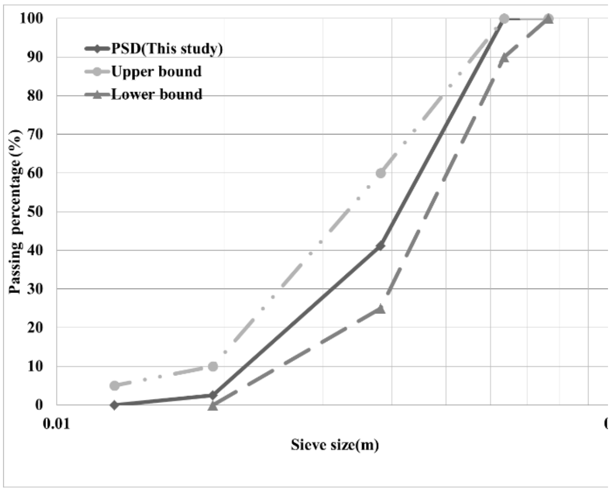


Figure 2. Ballast gradation curve of group 1

Table 1 presents the results of unconfined compressive strength (UCS) tests [16], conducted in accordance with ASTM D3148 [17]. Table 2 summarizes the physical properties of the parent rock from the Shahriar Mine, based on the corresponding experimental results [18–22].

Table 1. UCS tests results of ballast mother rock

	Average dimensions of samples				**The results of the Uniaxial compression test of the ballast samples**		**Elastic modulus and the Poisson ratio of ballast samples**		
Ballast type	Relevant standard	Diameter (m)	Height (m)	Diameter/height	Relevant standard	Uniaxial resistance (MPa)	Relevant standard	Young modulus (MPa)	Poisson ratio
Shahriar	ASTM D4543	0.066	0.145	2.17	ASTM D2938	158.95	ASTM D3148	0.03	0.20

Table 2. Mechanical properties of ballast aggregates

Test name	**Relevant standard**	**Standard limits**	**results of the test**
Test Method for Materials Finer than 75-µm (No. 200)	ASTM C117	≤ 1%	0.34%
Test Method for Clay Lumps and Friable Particles in Aggregates	ASTM C142	≤ 0.5%	0.17%
Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles apparatus	ASTM C535	≤ 30%	27%
Test Method for Relative Density (Specific Gravity)	ASTM C127	≥ 2.6%	2.83%

Test Method for Absorption of Coarse Aggregate	ASTM C127	≤ 1%	0.78%
Test Method for Bulk Density	ASTM C29	-	(kg / m) 1570

2.2.2. Polyurethane

The polyurethane employed in this study was a truck air-filter grade material composed of two components: a polyol (K-FLEX 5534) and an isocyanate (Kabonate-420K) (Table 3).

Table 3. specifications of truck air filter Polyurethane [14]

Polyol Name	K-FLEX 5534
Isocyanate Name	Kabonate-420K
Polyol density (kg /m3)	1012.4
Isocyanate density (kg /m3)	1176
Tank temperature (℃)	20-35
Cream time (S)	20-35
Free rise density (kg /m3)	400000-420000

2.2.3. Specification of superstructure components

In this study, three types of super structure were modeled: untreated ballast, ballast with 50% polyurethane reinforcement, and ballast with 100% reinforcement. The specifications of these cases are summarized in Table 4. The 50% reinforcement case was designed to represent partial infiltration—primarily around the sleeper cribs and shoulders—which is both practical and cost-effective while still allowing standard maintenance operations such as tamping. The 100% reinforcement case represents full-depth treatment, serving as an upper-bound condition that provides maximum stiffness but involves higher costs and reduced maintainability.

The ballast and polyurethane-reinforced ballast were modeled using the Mohr–Coulomb plasticity model, which is widely applied to granular and composite geomaterials. Key parameters, including cohesion, friction angle, and elastic modulus, were taken from Table 4. These composite properties were adopted from the experimental study by Ghahremani et al. (2022) [14], ensuring consistency with published laboratory results on polyurethane-stabilized ballast.

In this modeling framework, material damping was not defined through explicit viscous coefficients. Instead, the main energy dissipation mechanisms were represented by two components:

(1) Plastic deformation energy (plastic work) within the Mohr–Coulomb constitutive model, which simulates the inherent damping of granular materials; and

(2) Radiation damping, accounted for through Lysmer–Kuhlemeyer non-reflecting boundaries that absorb outgoing waves and prevent artificial reflections at the model edges.

This combined approach effectively reproduces the physical energy loss mechanisms in ballasted and polyurethane-reinforced track systems, while avoiding the introduction of arbitrary damping ratios. It also allows the specific influence of the reinforcement percentage on the dynamic response to be isolated and examined objectively.

Steel and concrete components—including rails, sleepers, and the base slab—were modeled as linear elastic materials, reflecting their comparatively high stiffness relative to ballast. Where polyurethane infiltration created a bonded skeleton within the ballast, inter-particle and inter-layer interfaces were modeled using Tie constraints to simulate full bonding. Other contacts within the composite zones were also tied at the continuum scale to represent effective composite behavior.

Table 4. General Characteristics of different superstructure layer types

	Density (kg/m)	**Elastic modulus (MPa)**	**Poisson's ratio**	**Internal friction angle (Degree)**	**Coefficient of adhesion (MPa)**	**Dilation angle (Degree)**
Ballast **[14]**	۱٥٧۰	۰,۰٣	0.2	41.97	۰,۰٦٤	۱۱,٤٤
٪٥۰polyurethane	1658	۰,۰٤۱	۰,٣٥	٤٣,۹٧	۰,۱۱٦	٨,٤۱٥
٪۱۰۰ polyurethane[۱۴]	1747	۰,۰٥٢	0.5	45.97	۰,۱٦٨	٥,٣۹

2.3. Loading pattern

In this model, the dynamic load from the train was applied at the rail level in the form of a moving step load. The loading pattern corresponds to the passage of a freight train traveling at 60 km/h with a bogie axle spacing of 9 m (Fig. 3) [23–25]. Each wheel load was represented by a force of 93 kN, applied sequentially according to the train speed and axle configuration. The loading history was simulated over a total duration of 2.0 s with a time increment of 0.002 s, ensuring sufficient resolution to accurately capture the vibration response.

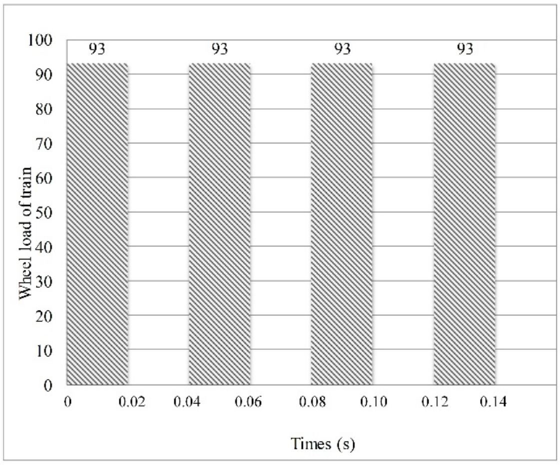


Figure 3. Step loading pattern [25]

3. Validation of the model

For validation of the ballasted railway track model, the study by Esmaili et al. (2012) was adopted as a reference [5]. The maximum displacements of the two models were compared. The present model yielded a maximum settlement of 0.000427 m, while the reference model reported 0.000413 m (Fig. 4), corresponding to a difference of only 3.4%. This close agreement confirms the accuracy of the numerical model.

Beyond peak values, the displacement response pattern obtained in this study was consistent with the trend reported by Esmaili et al. (2012), further supporting the reliability of the model. Since the primary focus of this research is vibration analysis, the vertical acceleration response of untreated ballast (6.7 m/s²) was also evaluated against the range reported in the literature, showing good agreement.

In addition to the above, the displacement and acceleration time histories obtained from the present model were extracted and compared with those reported by Esmaili et al. (2014). As shown in Figures ٥ and ٦, the overall response patterns in both studies are consistent: the increase in track stiffness due to ballast fouling results in a reduction in displacement and an increase in acceleration. Although some differences in amplitude were observed, the temporal variations of the responses are in good agreement, demonstrating that the developed numerical model is reliable not only in terms of peak values but also in reproducing the dynamic behavior and vibration time-history patterns of the ballasted track system.

On the basis of this validation, the polyurethane-reinforced ballast simulations presented in the following sections are considered credible and representative.

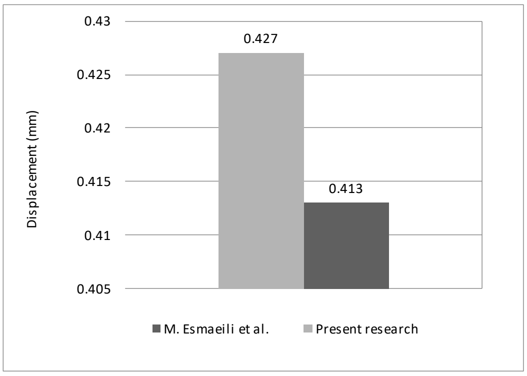


Figure 4. Comparison of the maximum displacement of the present research model and Esmaeili et al. (2012)

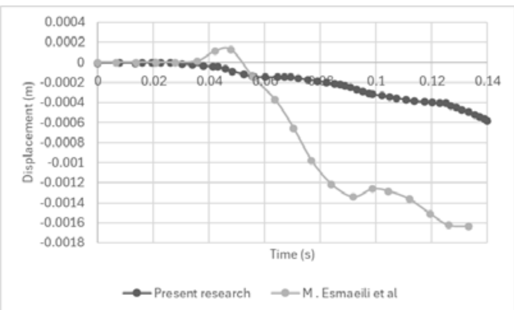


Figure ٥. Comparison of displacement time histories between the present model and the results reported by Esmaili et al. (2014).

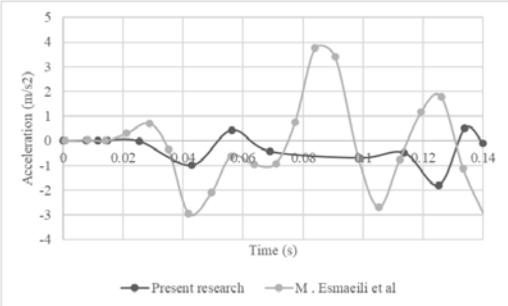


Figure ٦. Comparison of acceleration time histories between the present model and the results reported by Esmaili et al. (2014).

4. Investigating the effects of ballasted superstructure with and without polyurethane on environmental vibrations caused by train passage

This section presents and interprets the numerical results, focusing on displacement and vertical acceleration in twelve different cases. The responses were evaluated at points A, B, C, and D, located at horizontal distances of 0, 3, 6, 9, and 12 meters, as well as at four elevation levels of 0, 3, 6, and 9 meters (Fig. 1).

4.1. The results of the environmental vibrations around the railway track due to polyurethane injection into the ballast

The numerical modeling results at the specified intervals are shown in Figs. ٧ and ٨. Overall, the analyses indicate that polyurethane injection reduces both environmental vibration displacement and vertical acceleration compared with untreated ballast. As expected, displacement and acceleration decrease with increasing distance from the vibration source.

As shown in Fig. ٧, the lowest displacement was observed in the case with 50% polyurethane reinforcement. For example, at level 0 in case A, displacement was reduced by 61.8% compared with untreated ballast. This difference became more pronounced at greater distances from the vibration source. In general, displacement decreased with elevation, although the reduction was less significant in the vertical direction than along the longitudinal axis.

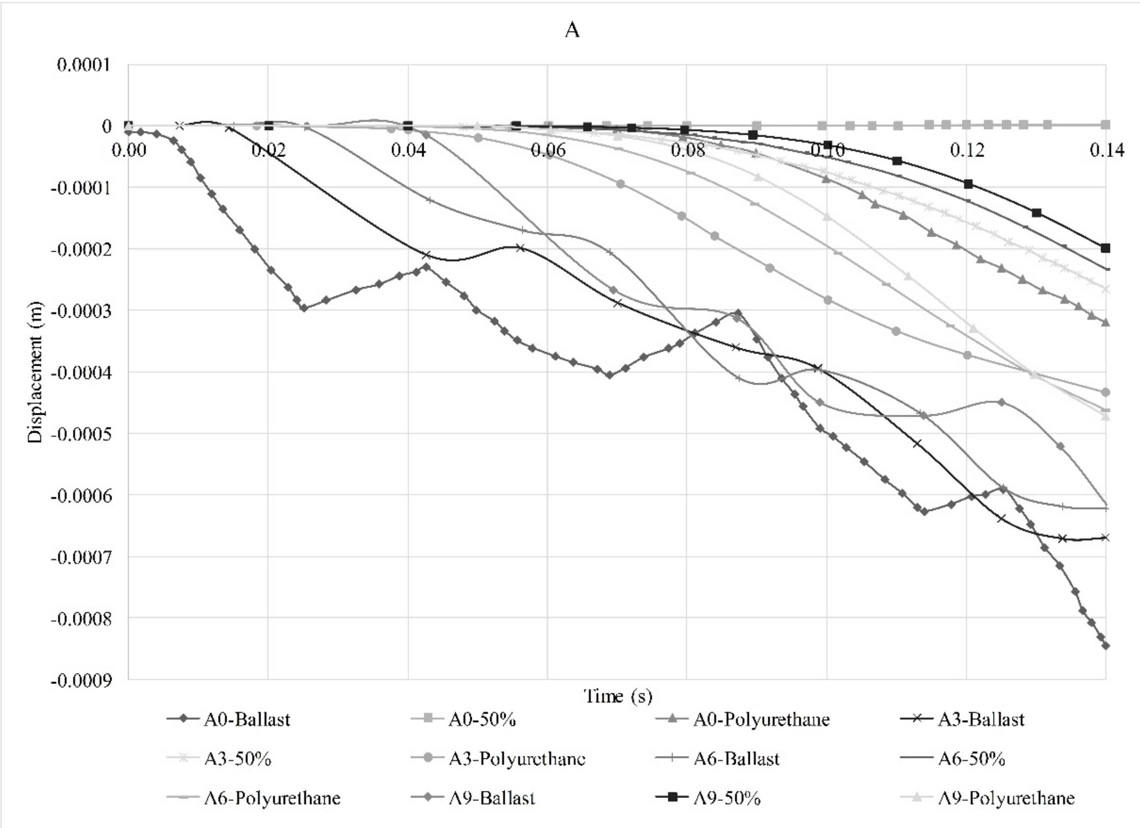
Similarly, Fig. ٨ shows that the 50% polyurethane case produced the lowest vertical acceleration. At point A, the maximum acceleration of untreated ballast was 5.62 m/s², whereas the 50% polyurethane sample recorded only 0.08 m/s², corresponding to a 98.6% reduction.

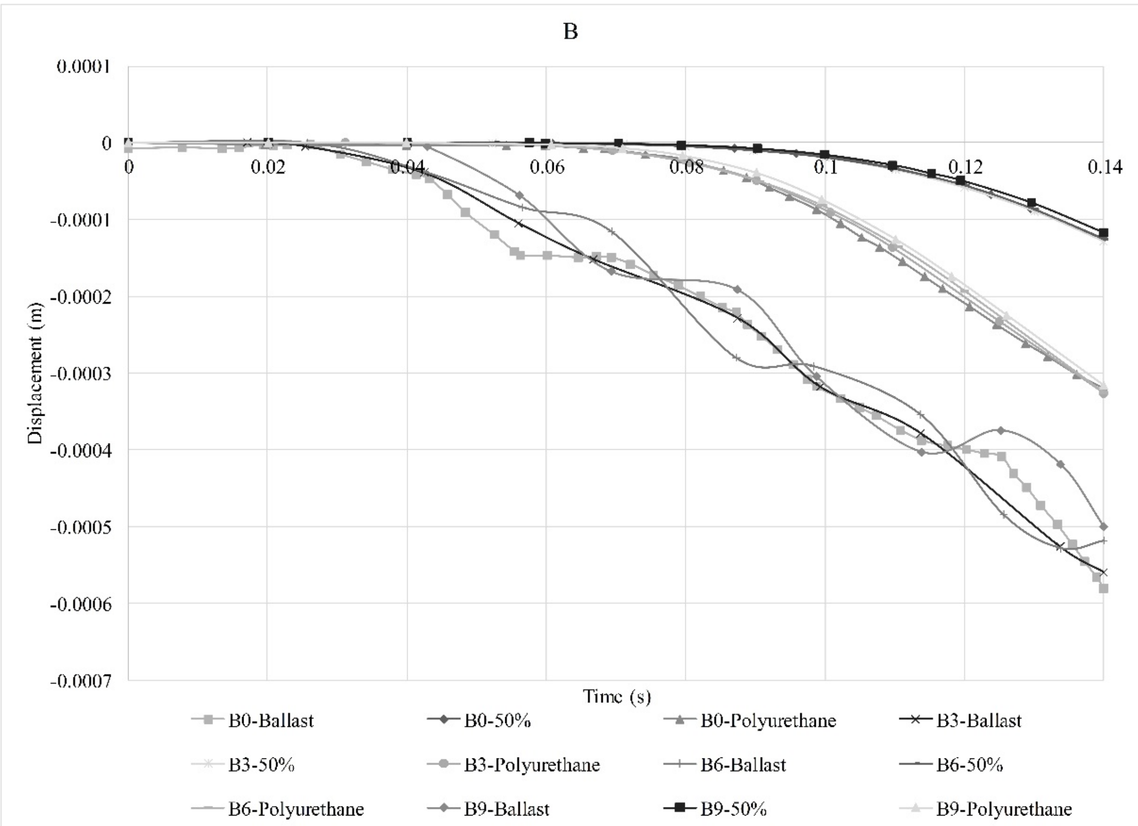
Key findings from the displacement and acceleration ratios (point A to point D) are summarized below:

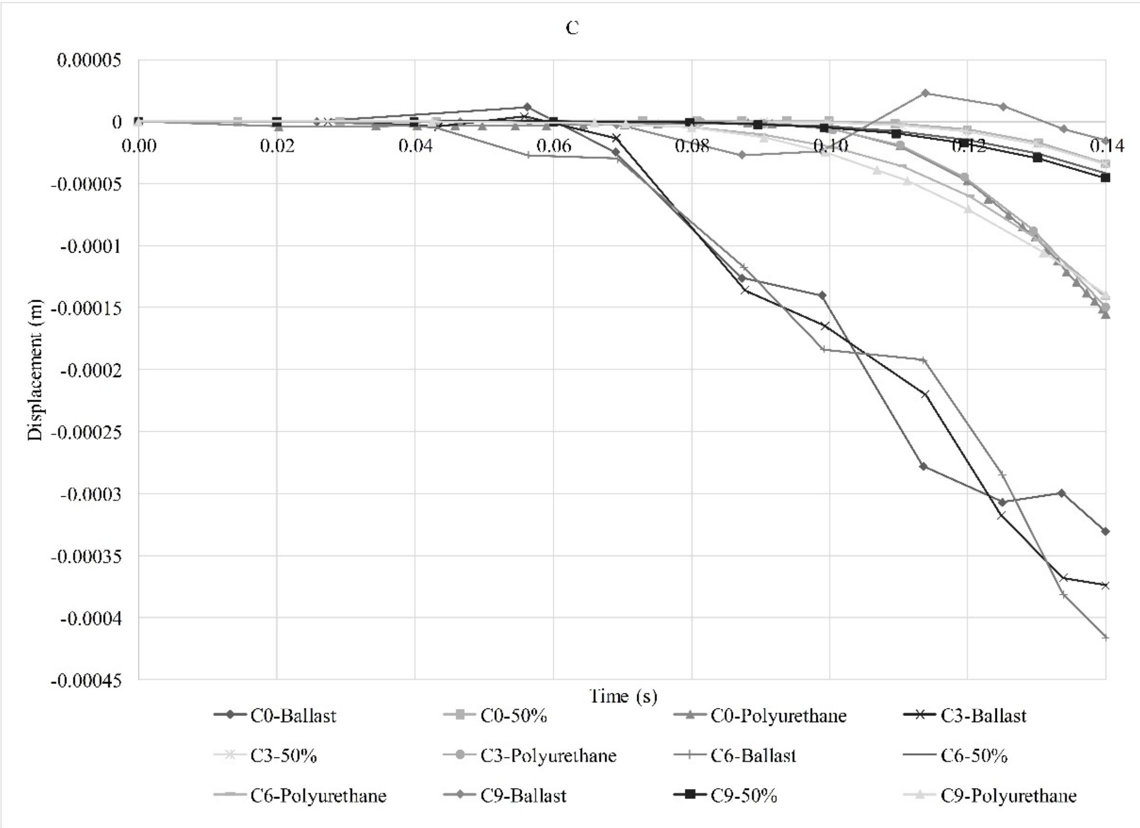
- Level 1: Displacement ratios were 14.38 (ballast), 1.00 (50% PU), and 72.23 (100% PU). Acceleration ratios were 12.30, 158.78, and 11.49, respectively.
- Level 2: Displacement ratios were 9.61, 104.24, and 42.55, while acceleration ratios were 7.95, 102.36, and 10.53, respectively.
- Level 3: Displacement ratios were 13.95, 490.53, and 95.85, while acceleration ratios were 4.92, 490.11, and 5.76, respectively.
- Level 4: Both displacement and acceleration reductions were significant across reinforced cases.

These results demonstrate that 50% polyurethane reinforcement consistently outperforms the 100% case. This outcome can be explained by the material behavior: partial polyurethane infiltration enhances stiffness and damping by creating a spring-like composite structure. However, when all voids between ballast particles are filled (100% case), stiffness increases excessively while damping efficiency decreases, reducing overall vibration mitigation.

It is also important to note that the apparent lack of damping in untreated ballast (Figs. ۷–۸) does not indicate numerical instability but rather reflects the inherently low energy dissipation of granular ballast. In contrast, polyurethane-reinforced ballast exhibited clearly damped responses. Numerical stability was further confirmed through mesh-independence checks, energy balance monitoring, and the implementation of non-reflecting boundary conditions.


A
0.0001
0
-0.0001
-0.0002
-0.0003
-0.0004
-0.0005
-0.0006
-0.0007
-0.0008
-0.0009
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Displacement (m)
Time (s)
A0-Ballast
A0-50%
A0-Polyurethane
A3-Ballast
A3-50%
A3-Polyurethane
A6-Ballast
A6-50%
A6-Polyurethane
A9-Ballast
A9-50%
A9-Polyurethane


B
0.0001
0
-0.0001
-0.0002
-0.0003
-0.0004
-0.0005
-0.0006
-0.0007
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Displacement (m)
Time (s)
B0-Ballast
B0-50%
B0-Polyurethane
B3-Ballast
B3-50%
B3-Polyurethane
B6-Ballast
B6-50%
B6-Polyurethane
B9-Ballast
B9-50%
B9-Polyurethane



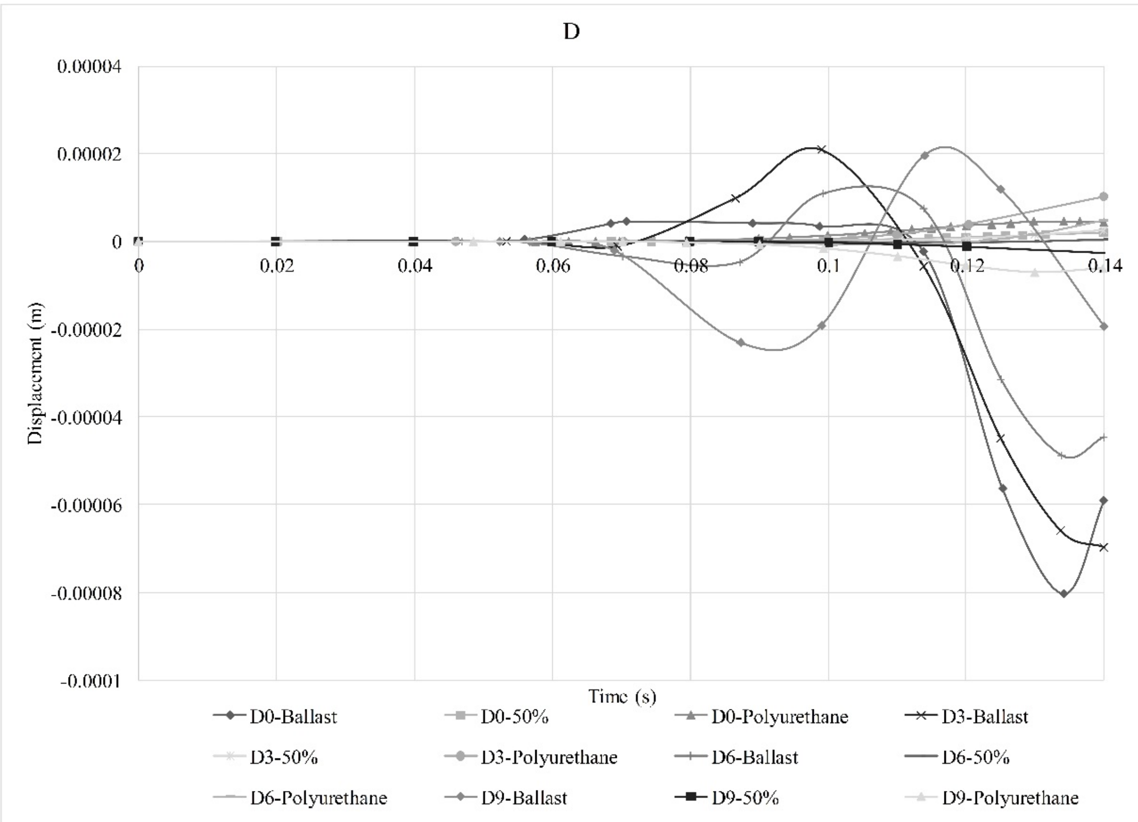
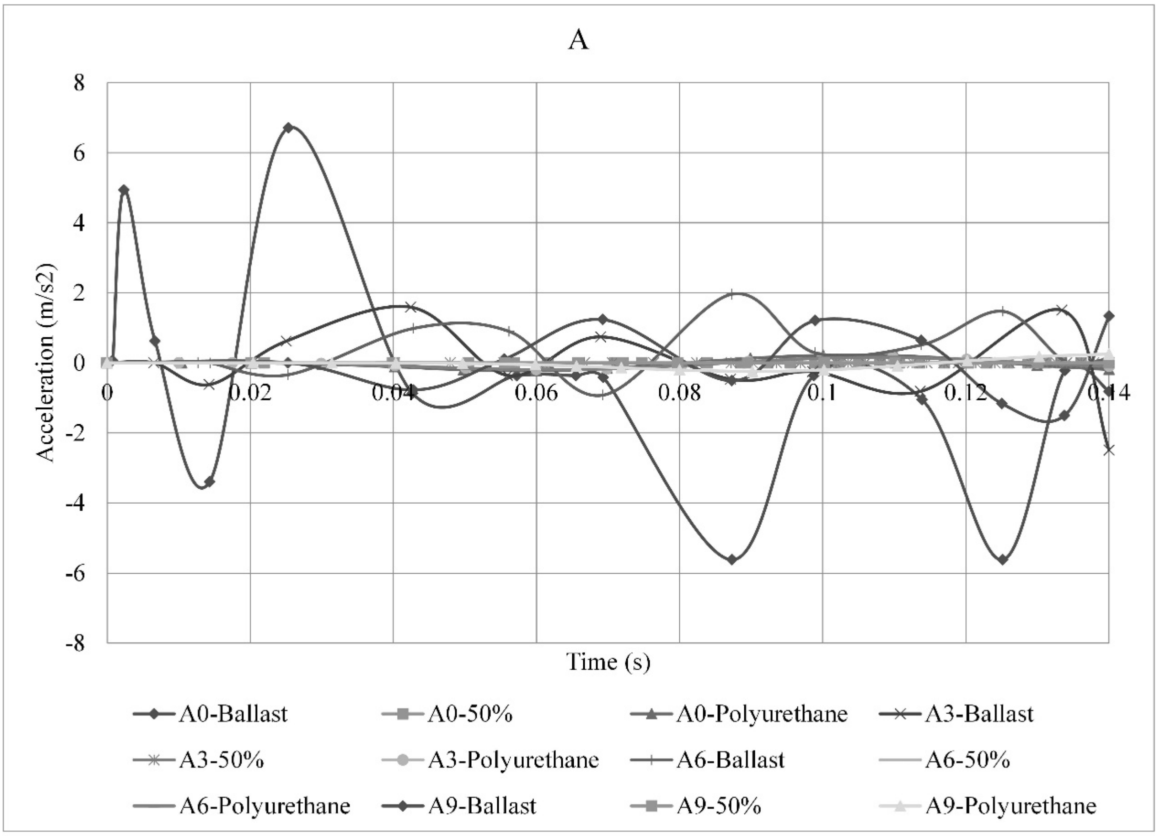
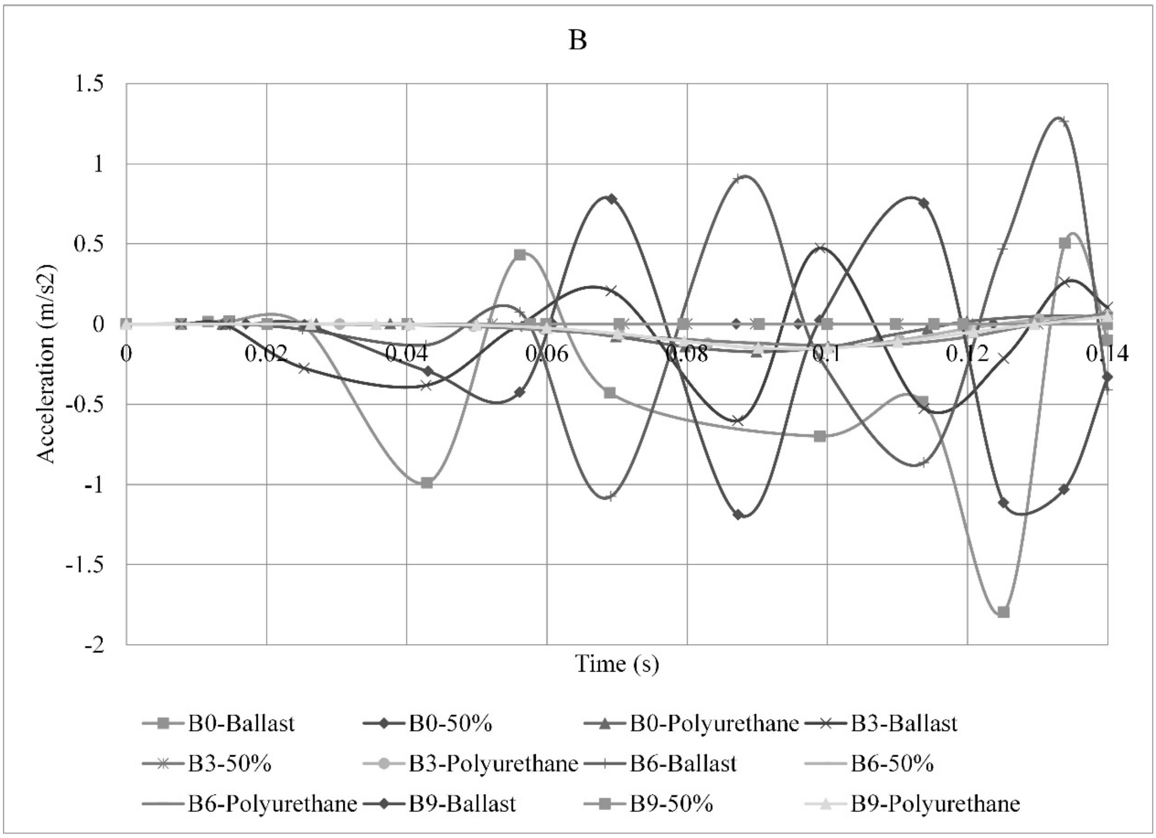
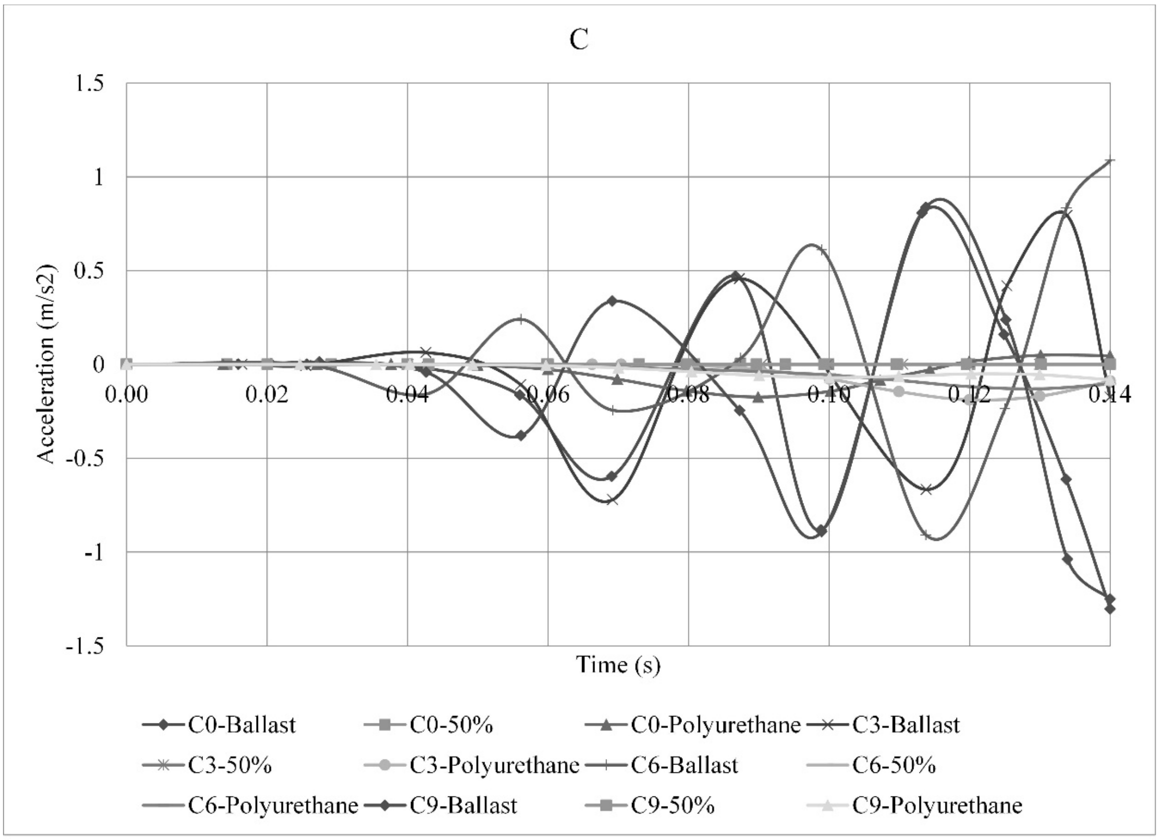


Figure ٧. Vertical displacement of different points of the railway track.


A
Acceleration (m/s2)
Time (s)
A0-Ballast
A0-50%
A0-Polyurethane
A3-Ballast
A3-50%
A3-Polyurethane
A6-Ballast
A6-50%
A6-Polyurethane
A9-Ballast
A9-50%
A9-Polyurethane


B
Acceleration (m/s2)
Time (s)
B0-Ballast
B0-50%
B0-Polyurethane
B3-Ballast
B3-50%
B3-Polyurethane
B6-Ballast
B6-50%
B6-Polyurethane
B9-Ballast
B9-50%
B9-Polyurethane



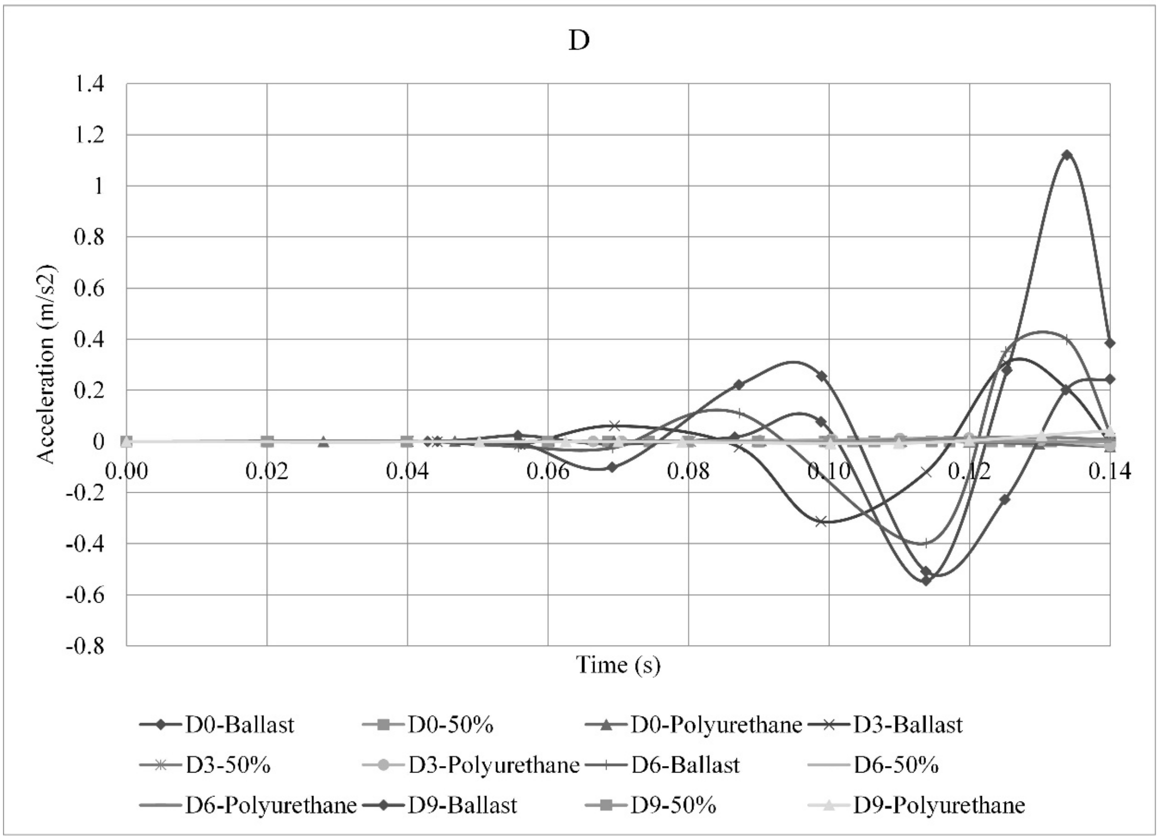


Figure ٨. Vertical acceleration applied on the railway track

4.2 Mathematical relationship between polyurethane percentage with displacement and maximum acceleration

Fig. ٩ illustrates the variation of maximum displacement and acceleration with different percentages of polyurethane infiltration. The results clearly show that 50% reinforcement provides the optimum performance. At this level, vertical displacement decreases to 0.000322 m (a reduction of about 62% compared with untreated ballast), while acceleration is minimized to 0.088 m/s² (a 98.6% reduction).

When infiltration is increased to 100%, the displacement remains nearly the same as in the 50% case; however, the acceleration rises to 0.226 m/s². This behavior can be explained by the interaction between stiffness and damping: partial reinforcement strengthens the ballast skeleton while still permitting controlled micro-sliding at particle contacts, which enhances energy dissipation. By contrast, full-depth reinforcement makes the ballast excessively stiff, reducing damping efficiency and thereby increasing accelerations.

The following regression equations were derived to mathematically describe these relationships (with $R^2 \approx 0.99$ in both cases, confirming their reliability for engineering applications and forecasting):

- The relationship between the vertical displacement and the percentage of polyurethane

$$Y = 2 \times 10^{-7} X^2 - 3 \times 10^{-5} X + 0.0009 \quad (١)$$

- The relationship between the vertical acceleration and the percentage of polyurethane

$$Z = 13 \times 10^{-4} X^2 - 19.89 \times 10^{-2} X + 6.7074 \quad (٢)$$

where Y is the maximum vertical displacement (m), Z is the maximum vertical acceleration (m/s²), and X is the percentage of polyurethane.

This non-monotonic trend is consistent with the physical mechanism and earlier observations in Figs. ٧–٨, highlighting that partial reinforcement (50%) is more effective than full reinforcement (100%) in mitigating train-induced vibrations. The findings confirm that an optimum reinforcement level exists between untreated and fully reinforced ballast.

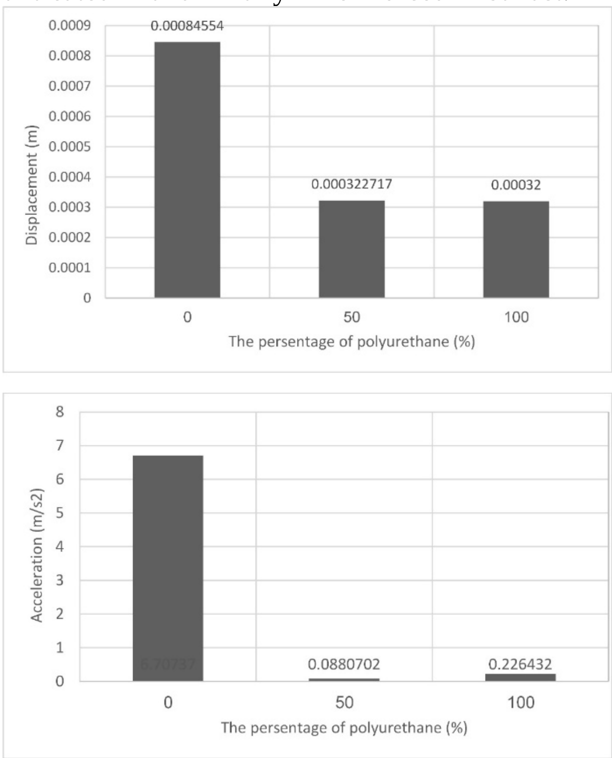


Figure ٩. The relationship between polyurethane percentage with (a) maximum displacement and (b) acceleration

5. Conclusions

The passage of trains on ballasted superstructures generates high levels of vibration that affect both the track bed and adjacent structures, leading to damage in the railway superstructure and nearby buildings. This research investigated the effects of polyurethane injection into the ballasted superstructure as a method for reducing train-induced environmental vibrations. Polyurethane, a polymer with excellent bonding and stabilizing properties, integrates the ballast structure, prevents fouling and track hardening, and thereby limits vibration amplification.

The key findings of this study can be summarized as follows:

- The minimum vertical displacement (2.65×10^{-6} m) was observed in the sample containing 50% polyurethane. At level 0, point A, displacement decreased by 61.8% compared with untreated ballast.

- The minimum vertical acceleration (0.08 m/s²) also corresponded to the 50% polyurethane case, representing a 98.6% reduction relative to untreated ballast.
- Numerical results indicate that displacement and acceleration decrease with polyurethane reinforcement up to an optimum percentage, after which values begin to increase again.
- In all evaluated cases, 50% polyurethane reinforcement consistently yielded the best results for vibration reduction.
- Regression analysis confirmed that displacement and acceleration trends can be represented by quadratic equations with very high accuracy ($R^2 \approx 0.99$).
- While this study focused on 50% and 100% infiltration as representative cases of partial and full treatment, the results suggest that intermediate levels of reinforcement (e.g., 25–40%) may also provide significant benefits at lower cost. Future studies should validate these cases under field conditions.

From a practical perspective, 50% polyurethane reinforcement emerges as the most effective and feasible solution for railway applications. It delivers substantial vibration reduction while remaining cost-effective and compatible with maintenance operations such as tamping, making it particularly suitable for transition zones, stations, and other sensitive locations. Conversely, 100% reinforcement should be reserved for critical sections with severe settlement or very weak subgrades, as it provides maximum stiffness but at the expense of higher costs and reduced maintainability.

References

[1] Zhang, J., He, Z., Chen, S., Zhang, L. "Vibration Response Characteristics and Application of Existing Railway Subgrade. Shock and Vibration, 2021, pp. 1-10, 2021.

https://doi.org/10.1155/2021/9926980

[2] Li, S-z., Ling, X-z., Tian, S., Ye, Y-s., Tang, L., Cai, D-g., Wang, K. "In-situ test and analysis of subgrade vibration with ballasted track in deep seasonally frozen regions", Transportation Geotechnics, 31, pp. 10065, 2021.

https://doi.org/10.1016/j.trgeo.2021.100658

[3] Indraratna, B., Sajjad, M., Ngo, T., Correia, A., Kelly, R. "Improved performance of ballasted tracks at transition zones: A review of experimental and modelling approaches", Transportation Geotechnics, 21, pp. 100260, 2019.

https://doi.org/10.1016/j.trgeo.2019.100260

[4] Guoqing, J., Luchao, Q., Valeri, J., wenli, J. "Polyurethane reinforced ballasted track: review, innovation and challenge", Construction and Building Materials, 208, pp. 734-748, 2018.

10.1016/j.conbuildmat.2019.03.031

[5] Esmaeili, M., Zakeri, J-A., Mosayebi, S-A. "Effect of sand-fouled ballast on train-induced vibration", International Journal of Pavement Engineering, 15(7), pp. 635-64, 2014.

https://doi.org/10.1080/10298436.2013.818146

[6] Esmaeili, M., Zakeri, J-A., Mosayebi, S-A. "Investigating the optimized open V-shaped trench performance in reduction of train-induced ground vibrations", International Journal of Geomechanics, 14(3), p p. 0401400, 2014.

https://doi.org/10.1061/(ASCE)GM.1943-5622.0000331

[7] Woodward, P.K., El-Kacimi, A., Laghrouche, O., Medero, G., Banimahd, M. "Application of polyurethane geocomposites to help maintain track geometry for ballasted high-speed railway tracks". Journal of Zhejiang University SCIENCE A (Applied Physics & Engineering), 13(11), pp. 836–849, 2012.

https://doi.org/10.1631/jzus.A12ISGT3

[8] Woodward, P.K., Kennedy, J., Laghrouche, O., Connolly, D.P., Medero, G.M. "Study of railway track stiffness modification by polyurethane reinforcement of the ballast".

Transportation Geotechnics, 1(4), pp. 214–224, 2014.

https://doi.org/10.1016/j.trgeo.2014.06.005

[9] Kennedy, J., Woodward, P., Medero, G., Banimahd, M. "Reducing railway track settlement using three-dimensional polyurethane polymer reinforcement of the ballast". Construction and Building Materials, 44, pp. 615–625, 2013.

https://doi.org/10.1016/j.conbuildmat.2013.03.032

[10] Xiong, Z., Liu, J., Wang, P., Liu, G., Xiao, J., Yu, S. "Field dynamic performance testing and analysis of polyurethane track and ballasted track in a high-speed railway". Journal of Civil Structural Health Monitoring, 11, pp. 867–877, 2021.

https://doi.org/10.1007/s13349-021-00489-6

[11] Jing, G., Qie, L., Markine, V., Jia, W. "Polyurethane reinforced ballasted track: Review, innovation and challenge". Construction and Building Materials, 208, pp. 734-74, 2019.

https://doi.org/10.1016/j.conbuildmat.2019.03.031

[12] Keene, A., Edil, T., Tinjum, J. "Mitigating ballast fouling and enhancing rail freight capacity", National Center for Freight and Infrastructure Research and Education (US), CFIRE 04-07, 2012. [online] Available at: https://rosap.ntl.bts.gov/view/dot/26171

[13] BASF "BASF the chemical company", [online] Available at: http://www.basf.com/group/ corporate/en/. [Accessed:2012]. [10] Dow, T.D.c.c., in http://www.dow.com/. 2012.

[14] Ghahremani, S., Zakeri, J-A., Samimi, F., Movahedi, M., Esfandiari, R., Esmaeili, M., Astaraki, F. "Ballast Stabilization with Polyurethane for Use in Desert Areas", Periodica Polytechnica Civil Engineering, 66(3), pp. 853-865, 2022.

https://doi.org/10.3311/PPci.19968

[15] Management and Planning Organization "Standard No. 301, Organization, General technical specifications of railway pavement", I.R.o. and M.a.P, Iran, 2006.

[16] Esmaeili, M., Shamohammadi, A., Farsi, S. "Effect of deconstructed tire under sleeper pad on railway ballast degradation under cyclic loading", Soil Dynamics and Earthquake Engineering, 136, pp. 106265, 2020.

https://doi.org/10.1016/j.soildyn.2020.106265

[17] ASTM "D3148, Standard Test Method for Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression", Annual Book of ASTM Standards, USA, 2010.

[18] ASTM "C, Standard test method for bulk density ("unit weight") and voids in aggregate", Annual Book of American Society for Testing and Materials, USA, 2009.

[19] ASTM "C127, Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate", Annual Book of American Society for Testing and Materials, USA, 2012.

[20] ASTM "C535, Standard test method for resistance to degradation of large-size coarse aggregate by abrasion and impact in the Los Angeles machine", ASTM West Conshohocken, USA, 2012.

[21] ASTM "C117, Standard test method for materials finer than 75-µm (No. 200) sieve in mineral aggregates by washing", Annual Book of American Society for Testing and Materials, USA, 2013.

[22] ASTM " C142, Standard Test Method for Clay Lumps and Friable Particles in Aggregates", Annual Book of American Society for Testing and Materials, USA, 1997.

[23] Adam, M., Estorff, O. "Reduction of train-induced building vibrations by using open and filled trenches", Computers & Structures, 83(1), pp. 1124, 2005.

https://doi.org/10.1016/j.compstruc.2004.08.010

[24] Di Mino, G., Giunta, M., Di Liberto, C-M. "Assessing the open trenches in screening railway ground-borne vibrations by means of artificial neural network", Advances in Acoustics and Vibration, 2009, 2009.

https://doi:10.1155/2009/942787

[25] Esmaeili, M., Zakeri, J-A., Mosayebi, S-A., Abbasi, R. "Effects of vibration in desert area caused by moving trains", Journal of Modern Transportation, 20, pp. 16-23, 2012.

https://doi.org/10.1007/BF03325772