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RESEARCH ARTICLE

GEOTECHNICAL INVESTIGATION OF METHODS FOR REDUCING THE IMPACT OF RAILWAY-INDUCED VIBRATIONS ON BUILDINGS

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Abstract. *The aim of this study is to evaluate the propagation of train-induced vibrations in the soil under the geotechnical conditions of the Kyzylorda region and their impact on nearby buildings using PLAXIS 2D numerical modelling, as well as to assess the effectiveness of vibration isolation barriers. The study analyzes the mechanisms of vibration propagation caused by train movement and develops a numerical model corresponding to the engineering and geological conditions of the Kyzylorda region. The vibration velocity and displacement parameters were determined at control points located at different distances from the railway line. In addition, the dynamic response of the building was investigated, and the effectiveness of steel barriers, trench barriers, and rubber-soil composite vibration isolation systems was quantitatively evaluated. The results showed that vibration intensity generally decreases with increasing distance from the railway source; however, a local amplification zone was identified within the 120-130 m interval due to wave reflection and interference effects. The 140-150 m range was assessed as a relatively safe zone.The scientific novelty of the study lies in the fact that, for the first time for the Kyzylorda region, a numerical model of train-induced vibrations based on PLAXIS 2D is proposed, the effectiveness of geotechnical isolation systems is quantitatively assessed, and a residential building model considering vibration effects is developed.*

Keywords: *railway vibration, geotechnical isolation, PLAXIS 2D, soil dynamics, vibration resistance of buildings*

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ШОЛУ МАҚАЛА

ТЕМІРЖОЛ ДІРІЛІНІҢ ҒИМАРАТТАРҒА ӘСЕРІН АЗАЙТУ ӘДІСТЕРІН ГЕОТЕХНИКАЛЫҚ ЗЕРТТЕУ

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Аңдатпа. *Бұл зерттеу жұмысының мақсаты - PLAXIS 2D сандық модельдеу бағдарламасын қолдана отырып, Қызылорда облысының геотехникалық жағдайында пойыз қозғалысынан туындайтын тербелістердің топырақтағы таралу заңдылықтарын және олардың жақын маңдағы ғимараттарға әсерін бағалау, сондай-ақ дірілді оқшаулау кедергілерінің тиімділігін анықтау болып табылады. Зерттеу барысында пойыз қозғалысынан туындайтын дірілдердің таралу механизмдері талданып, Қызылорда өңірінің инженерлік-геологиялық жағдайына сәйкес сандық модель құрылды. Теміржолдан әртүрлі арақашықтықтарда орналасқан бақылау нүктелеріндегі діріл жылдамдығы мен орын ауыстыру параметрлері анықталды. Сонымен қатар, ғимараттың динамикалық жауабы зерттеліп, болат барьер, траншеялық бөгет және резеңке-топырақ қоспасымен толтырылған виброоқшаулағыш жүйелердің тиімділігі сандық түрде бағаланды. Зерттеу нәтижелері бойынша діріл қарқындылығы қашықтық артқан сайын жалпы әлсірейтіні, алайда 120-130м аралығында толқындардың шағылуы мен интерференциясына байланысты локальды күшею аймағы байқалатыны анықталды. 140-150 м аралығы салыстырмалы түрде қауіпсіз аймақ ретінде бағаланды. Зерттеу жұмысының ғылыми жаңалығы Қызылорда өңірі үшін алғаш рет PLAXIS 2D негізінде пойыздардан туындайтын дірілдердің сандық моделі ұсынылып, геотехникалық оқшаулау жүйелерінің тиімділігі бағаланғанында және тұрғын ғимараттың динамикалық моделі қарастырылғанында болып табылады.*

Түйін сөздер: *теміржол дірілі, геотехникалық оқшаулау, PLAXIS 2D, топырақ динамикасы, ғимараттардың дірілге тұрақтылығы*

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НАУЧНАЯ СТАТЬЯ

ГЕОТЕХНИЧЕСКОЕ ИССЛЕДОВАНИЕ МЕТОДОВ СНИЖЕНИЯ ВОЗДЕЙСТВИЯ ЖЕЛЕЗНОДОРОЖНОЙ ВИБРАЦИИ НА ЗДАНИЯ

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Аннотация. *Целью данного исследования является оценка распространения колебаний, возникающих от движения поездов в грунте в геотехнических условиях Кызылординской области, а также их воздействия на близлежащие здания с использованием численного моделирования в PLAXIS 2D, а также определение эффективности виброизоляционных барьеров. В ходе исследования были проанализированы механизмы распространения вибраций, вызванных движением поездов, и построена численная модель, соответствующая инженерно-геологическим условиям региона Кызылорды. Определены параметры скорости вибрации и перемещений в контрольных точках, расположенных на различных расстояниях от железной дороги. Кроме того, была исследована динамическая реакция здания и численно оценена эффективность стального барьера, траншейного барьера и виброизоляционной системы, заполненной резино-грунтовой смесью. Результаты исследования показали, что интенсивность вибрации в целом уменьшается с увеличением расстояния, однако в интервале 120-130 м наблюдается локальная зона усиления, обусловленная отражением и интерференцией волн. Интервал 140-150 м был оценен как относительно безопасная зона. Научная новизна работы заключается в том, что для региона Кызылорды впервые предложена численная модель железнодорожных вибраций на основе PLAXIS 2D, а также выполнена количественная оценка эффективности геотехнических систем виброизоляции с учетом динамической модели жилого здания.*

Ключевые слова: *железнодорожная вибрация, геотехническая изоляция, PLAXIS 2D, динамика грунтов, виброустойчивость зданий*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

In recent years, as a result of the rapid development of urbanization processes, the population in cities has increased significantly, and accordingly, the importance of railway transport as an accessible and efficient means of intercity transportation has grown substantially. The increasing frequency of railway operations, particularly freight and passenger trains, exerts a considerable dynamic impact on the surrounding environment, including the soil mass and nearby buildings. Vibrations generated during train movement originate in the rail-wheel contact zone and propagate through the track structure and soil layers, subsequently transmitting to the foundations and load-bearing elements of buildings. This phenomenon directly affects the technical condition of buildings, their operational reliability, and the comfort level of occupants **(Salem T.N. et al., 2025).**

The design standards currently applied in the Republic of Kazakhstan, including Snip RK 2.03-30-2006**,** as well as similar regulatory documents in CIS countries, are primarily focused on conventional static and seismic loads **(Tuleyev A.T. et al., 2025).** However, these documents do not fully account for long-term repetitive dynamic effects caused by train movement, especially the complex soil-structure interaction in high-rise buildings and complicated geotechnical conditions. In this regard, there is a clear need for specialized engineering analyses that incorporate vibration effects for construction facilities located near railway lines.In Kazakhstan, such studies have mainly been conducted for the city of Almaty, since this region is located in a high seismic hazard zone and is further complicated by metro infrastructure **(Kurabayev A.S. et al., 2020; Kirghizbaeva D. et al., 2025).** In contrast, for the Kyzylorda region, railway-induced vibrations represent the primary source of dynamic impact. The soil conditions and structural characteristics of residential buildings in this area require a detailed investigation of long-term vibration effects. Current design approaches generally consider buildings as systems composed of homogeneous materials resting on an ideal rigid foundation. However, in practice, mixed structural systems are frequently encountered, where the lower part consists of reinforced concrete and the upper part is made of steel. The dynamic response of such systems, particularly under railway-induced vibration loading, has not been sufficiently addressed in existing нормативтік documents **(Seiitkassymuly K. et al., 2025).** One of the most effective engineering solutions for mitigating railway vibrations is the use of geotechnical vibration isolation systems**.** These include open trenches, barriers filled with rubber-mixed soil, sheet pile walls, and wave-blocking systems. Such methods reduce the energy of waves propagating through the soil and decrease the vibration levels reaching buildings **(Tolegenova D.O. et al., 2024).**

Furthermore, an analysis of the international literature indicates that many studies are based on idealized models assuming homogeneous half-space conditions. Real layered soils, regional geotechnical characteristics, and the complete dynamic response of actual buildings have not been sufficiently investigated. This deficiency is particularly evident for the southern regions of Kazakhstan, including the Kyzylorda region.

Accordingly, the scientific gap of the present study can be formulated as follows:

- modern numerical modeling studies on the impact of train-induced vibrations on buildings in the Kyzylorda region are insufficient.
- the effectiveness of geotechnical vibration isolation systems under layered soil conditions has not been adequately investigated.
- modeling studies based on Plaxis 2D considering railway-induced effects are almost absent from domestic scientific literature.

To address this scientific gap, the present study applies a numerical modeling approach based on the Plaxis 2D engineering software package**,** providing a comprehensive analysis of the propagation characteristics of train-induced vibrations in soil layers and the effectiveness of their reduction through geotechnical isolation barriers.

Research Objective: The objective of this study is to evaluate the propagation of train-induced vibrations in soil under the geotechnical conditions of the Kyzylorda region and assess their impact on nearby buildings using Plaxis 2D numerical modeling, as well as to evaluate the effectiveness of vibration isolation barriers.

The tasks of the study include:

- analyzing the mechanisms of vibration propagation caused by train movement.
- developing a numerical model corresponding to the soil conditions of the Kyzylorda region.
- determining the dynamic response of buildings considering vibration effects.
- evaluating the effectiveness of vibration isolation barriers.
- identifying a safe distance from the railway line.

Scientific Novelty of the Study: For the first time for the Kyzylorda region, a Plaxis 2D-based model of train-induced vibrations is proposed, the effectiveness of geotechnical isolation systems is quantitatively evaluated, and a residential building model considering vibration effects is investigated.

The issue of vibrations induced by railway traffic is widely recognized by researchers worldwide as one of the most pressing engineering challenges, especially in the context of the rapid development of high-speed railways and urban rail transit systems. Most authors agree that the primary source of vibration is the wheel-rail contact zone, from which dynamic waves propagate through the track superstructure, embankment, and surrounding soil before reaching nearby buildings and engineering structures. For example, **(Aires Colaço et al. 2025)** focus primarily on the mechanism of vibration propagation through multilayer soil media and emphasize the risks of structural damage to nearby buildings. Their study provides a detailed description of wave transmission paths but pays limited attention to the effectiveness of practical mitigation measures under different geotechnical conditions. In contrast, **(David et al. 2016)** eexaminesthe problem from the perspective of urban environmental impact, highlighting not only structural effects but also issues related to human comfort, serviceability of sensitive equipment, and long-term durability of buildings. Thus, while both studies address the same physical phenomenon, their methodological emphasis differs: the former concentrates on the transmission mechanism, whereas the latter focuses on engineering consequences for urban infrastructure.

A comparative analysis of the existing literature shows that vibration mitigation measures are commonly classified into three levels: source reduction, wave-path isolation, and receiver protection. Among these, geotechnical vibration isolation, which modifies the propagation path of waves through the soil, has attracted particular attention due to its ability to protect multiple structures simultaneously. The review studies **(Slimane Ouakka et al. 2021; 2022)** provide a comprehensive comparison of various mitigation systems, including open trenches, in-filled trenches, sheet pile walls, and wave impeding blocks. These authors conclude that open trenches generally demonstrate higher vibration attenuation efficiency, particularly against Rayleigh waves. However, their application in dense urban areas is often limited by stability requirements, groundwater conditions, and interference with underground utilities. Conversely, soft-filled trenches and geofoam-based barriers offer more practical engineering solutions, although their effectiveness strongly depends on soil stratification, excitation frequency, and barrier geometry. Similarly, **(Ashref Alzawi et al. 2011)** demonstrate through full-scale experiments that geofoam-filled trenches can significantly reduce transmitted vibration energy and, in some cases, provide more stable long-term performance than open trenches. However, compared with the theoretical studies of Ouakka and others, these work-places greater emphasis on experimental validation, which strengthens the reliability of the proposed solutions.

Despite the substantial body of research, several important limitations remain. First, many studies rely on idealized homogeneous half-space models, whereas actual urban soils are typically layered, heterogeneous, and anisotropic. Second, most published works are based predominantly on numerical simulations, while full-scale field validation remains limited. Third, previous studies often evaluate mitigation efficiency only at selected points in the soil mass, without sufficiently considering the full dynamic response of adjacent buildings and foundations. Finally, the majority of available studies have been conducted for European, Chinese, and metropolitan subway systems, whereas similar investigations under the engineering-geological conditions of Kazakhstan have not been sufficiently developed.

Therefore, the scientific gap addressed by the present study lies in the lack of modern numerical investigations of railway-induced ground vibrations under local soil conditions and their impact on nearby buildings in Kazakhstan. In particular, there is insufficient research based on advanced geotechnical numerical tools such as PLAXIS 2D, capable of simulating layered soil behavior and assessing vibration attenuation over practical distances from the railway line. The present study aims to fill this gap by analyzing the propagation of train-induced vibrations and evaluating their attenuation characteristics in the 100-150 m zone under realistic local geotechnical conditions.

2 MATERIALS AND METHODS

The train-induced vibration was modeled as a transient cyclic dynamic load applied at the rail-soil interaction zone. The loading scheme considered: axle load, train speed, loading frequency, pulse duration, repeated cyclic action. The dynamic load simulates the wheel-rail interaction and subsequent wave propagation into the soil massif.

Figure 1 shows the experimental arrangement of a steel vibration barrier installed in the soil mass in order to reduce the propagation of dynamic vibration waves. The barrier consists of steel elements vertically embedded into the ground in a single linear row and is intended to attenuate the elastic waves generated by the vibration source before they reach the building foundation. This geotechnical isolation element primarily creates a mechanical obstacle to the propagation of Rayleigh surface waves, as well as longitudinal and transverse waves. The steel barrier reflects part of the wave energy, scatters another part, and partially absorbs it, thereby reducing the vibration intensity within the soil mass. As can be seen in **Figure 1**, the barrier elements are arranged along a straight line with a certain spacing between them. Such an arrangement makes it possible to disrupt the direct propagation trajectory of waves within the soil and reduce the oscillation amplitude in the protected area. This method is one of the geotechnical vibration isolation techniques used to protect buildings located near railway lines, metro systems, and high-speed railways.

Figure 1 - Experimental installation of a steel vibration barrier for limiting wave propagation in the soil mass (author's material)

Figure 2 shows the field view of a vibration-isolation trench barrier installed to reduce the propagation of vibration waves within the soil mass. The main structure of the barrier consists of vertically installed steel screen elements and a trench filled with a rubber-soil composite mixture arranged along their length. This system is considered one of the effective types of geotechnical vibration isolation methods, since the rubber component possesses high damping properties. This material absorbs a portion of the vibration energy, thereby reducing the amplitude of the waves. At the same time, the soil mixture ensures the structural stability of the system and creates an additional mechanical obstacle along the wave propagation path. As can be clearly seen from the figure, the trench is uniformly filled with a dark-colored rubber-soil mixture along its entire length. Such a solution is particularly effective in attenuating Rayleigh surface waves, reducing their transmission to the building foundation, and limiting the zone of dynamic impact propagation. This method is widely regarded as one of the geotechnical vibration isolation technologies used for protecting buildings located near railway lines, metro systems, and high-speed railways.

Figure 2 - Field installation view of a vibration-isolation trench barrier filled with a rubber-soil composite mixture(author's material)

Figure 3 illustrates the construction stage of the trench barrier installation designed to attenuate railway-induced vibrations. This stage represents an essential part of the section and reflects the field implementation procedure of the geotechnical vibration isolation system. As shown in the figure, a longitudinal trench was excavated in the soil mass using specialized earthmoving equipment. The trench was positioned along the vibration propagation path in order to create an artificial geotechnical barrier that limits the transmission of dynamic waves toward the protected building zone. Subsequently, the trench was prepared for filling with a damping material, such as a rubber-soil composite mixture, or for the installation of steel screen elements. This configuration is intended to reduce the amplitude of Rayleigh surface waves as well as longitudinal and transverse waves propagating through the soil mass. The construction stage shown in Figure 3 is methodologically important, since the trench geometry, depth, width, and relative position with respect to the railway line directly affect the accuracy and reliability of the subsequent numerical modelling results.

Figure 3 - Construction stage of the installation of a trench barrier designed to attenuate railway-induced Vibrations (author's material)

Figure 4 illustrates the mechanized excavation process of a trench intended to limit the propagation of vibration waves in the soil mass. As shown in the figure, a narrow and deep trench is excavated using specialized mechanical equipment, ensuring uniform geometric dimensions along its length. Such a trench is subsequently used either for the installation of steel screen elements or for filling with damping materials such as rubber-soil composite mixtures, crushed stone, or geosynthetic fillers. The trench depth and width directly influence the attenuation characteristics of vibration waves, particularly Rayleigh surface waves. Therefore, maintaining precise geometric parameters during excavation is essential for ensuring the reliability of the subsequent numerical modelling and comparative analysis. This mechanized excavation method is widely used in field investigations related to railway-induced vibration mitigation and the protection of nearby building foundations.

Figure 4 - Mechanized excavation process of a trench designed to limit the propagation of vibration waves (author's material)

This study is devoted to the geotechnical investigation of methods for reducing the impact of railway-induced vibrations on buildings and structures located in the railway influence zone.
The numerical analysis was carried out using the PLAXIS 2D finite element software package, which allows simulation of dynamic wave propagation in the soil mass and assessment of the effectiveness of vibration mitigation measures. The objective of the modelling was to determine the attenuation characteristics of railway vibrations in the soil and to evaluate the efficiency of geotechnical vibration isolation methods in reducing the dynamic impact on nearby buildings.1.

The main parameters of the soil:

- density, ρ=1800 kg/m^3;
- modulus of elasticity, E=25MPa;
- Poisson's coefficient, ν=0.30;
- Internal friction angle, φ=28 ^{0C}:
- Clutch ratio, c=15 kPA

As boundary conditions, the lower boundary of the model was fully fixed, and at the lateral boundaries, viscous boundaries were used to reduce wave reflection. The train load was introduced as a time-dependent harmonic load applied to the rail axis as a dynamic effect in motion.

The interval of 100-150 m was selected to evaluate the attenuation of train-induced vibrations in soil and their influence on nearby structures. This range allows the assessment of the dynamic response of the soil mass and the determination of a relatively safe distance for adjacent buildings.
The vertical vibration velocity was determined according to the classical kinematic relationship:

$$\upsilon_y = \frac{\partial u_y}{\partial \mathrm{t}} \tag{1}$$

where:

–υ_y - vertical vibration velocity, m/s.

–u_y - vertical displacement, m.

–t - time, s.

The vertical acceleration was determined as the first derivative of velocity and the second derivative of displacement with respect to time:

$$a_y = \frac{du_y}{\mathrm{dt}} = \frac{d^2u_y}{dt^2} \tag{2}$$

where:

– a_y - vertical acceleration, m/s².

To evaluate the efficiency of vibration mitigation measures, the following expression proposed by the authors was used:

$$\eta = \frac{\upsilon_{y,initial} - \upsilon_{y,protected}}{\upsilon_{y,initial}} * 100\% \quad (3)$$

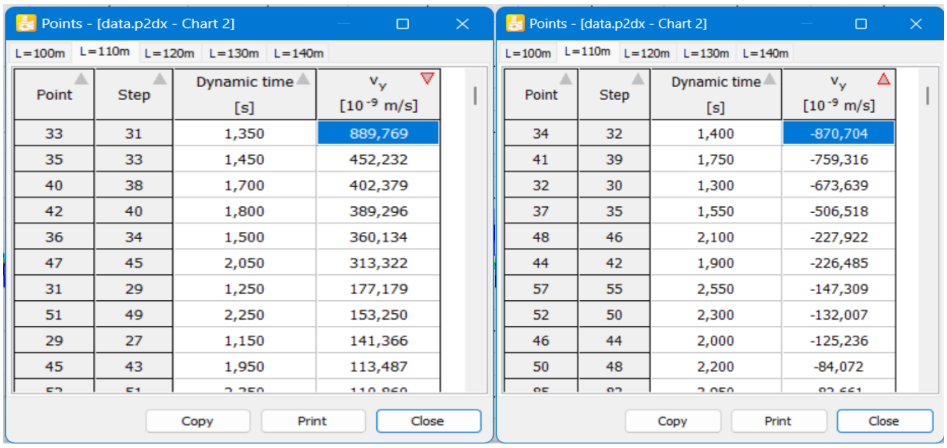
where:

– η - mitigation efficiency, %;

– $v_{y,initial}$ - initial vibration velocity, m/s;

– $v_{y,protected}$ - vibration velocity after the application of the protective barrier, m/s.

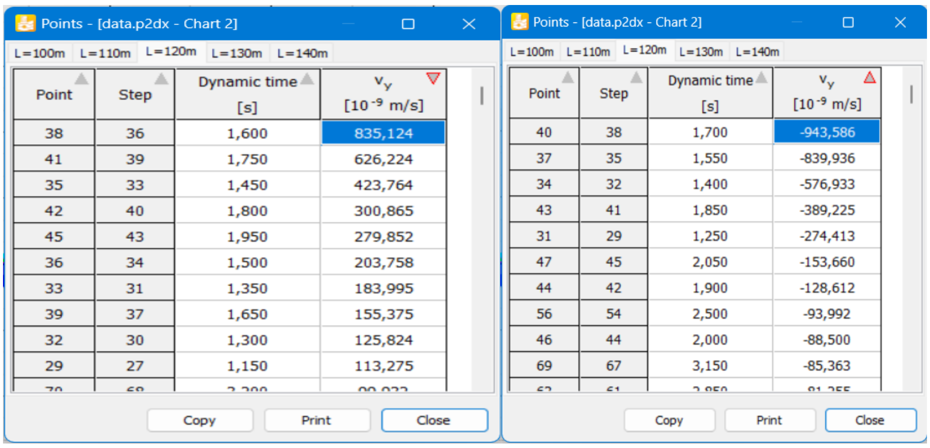
Figures 5-7 present the maximum and minimum vibration response values obtained from the PLAXIS 2D dynamic analysis module at control distances of 110 m, 120 m, and 150 m from the railway line. According to the adopted methodology, control points were placed at specified distances from the vibration source in order to evaluate the attenuation characteristics of railway-induced dynamic effects within the soil mass. For each control point, the software output included: calculation step, dynamic time, vertical vibration parameter. The extreme values (maximum and minimum) were extracted and subsequently used for comparative analysis of vibration attenuation with increasing distance from the railway. This methodological approach made it possible to assess the effectiveness of geotechnical vibration mitigation measures and determine the relatively safer zone for nearby buildings.



Point	Step	Dynamic time [s]	v_y [10^{-9} m/s]
33	31	1,350	889,769
35	33	1,450	452,232
40	38	1,700	402,379
42	40	1,800	389,296
36	34	1,500	360,134
47	45	2,050	313,322
31	29	1,250	177,179
51	49	2,250	153,250
29	27	1,150	141,366
45	43	1,950	113,487

Point	Step	Dynamic time [s]	v_y [10^{-9} m/s]
34	32	1,400	-870,704
41	39	1,750	-759,316
32	30	1,300	-673,639
37	35	1,550	-506,518
48	46	2,100	-227,922
44	42	1,900	-226,485
57	55	2,550	-147,309
52	50	2,300	-132,007
46	44	2,000	-125,236
50	48	2,200	-84,072

Figure 5 - Maximum and minimum vibration response levels at a distance of 110 m from the railway (author's material)



Point	Step	Dynamic time [s]	v_y [10^{-9} m/s]
38	36	1,600	835,124
41	39	1,750	626,224
35	33	1,450	423,764
42	40	1,800	300,865
45	43	1,950	279,852
36	34	1,500	203,758
33	31	1,350	183,995
39	37	1,650	155,375
32	30	1,300	125,824
29	27	1,150	113,275

Point	Step	Dynamic time [s]	v_y [10^{-9} m/s]
40	38	1,700	-943,586
37	35	1,550	-839,936
34	32	1,400	-576,933
43	41	1,850	-389,225
31	29	1,250	-274,413
47	45	2,050	-153,660
44	42	1,900	-128,612
56	54	2,500	-93,992
46	44	2,000	-88,500
69	67	3,150	-85,363

Figure 6 - Maximum and minimum vibration response levels at a distance of 120 m from the railway (author's material)

Extreme values

L=100m L=150m

Dynamic time [s]	v_y [10^{-9} m/s]
2,000	256,422
2,050	-154,514

Figure 7 - Maximum and minimum vibration response levels at a distance of 150 m from the railway (author's material)

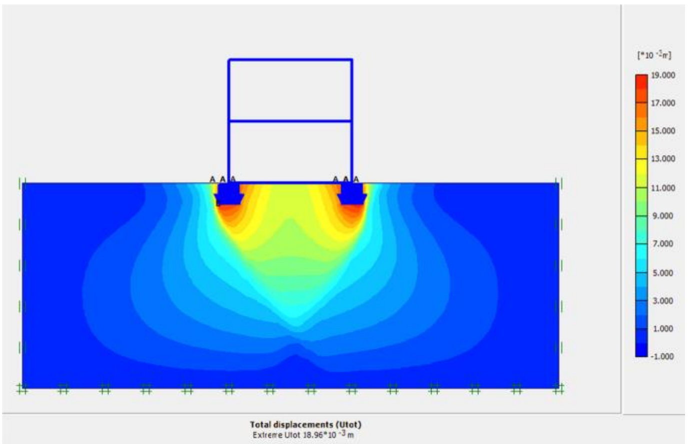


Figure 8 - Contour distribution of total displacements in the soil mass and foundation zone under railway-induced dynamic loading y (author's material)

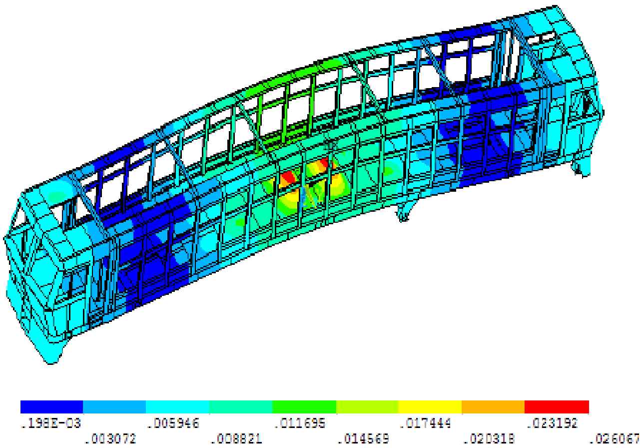


Figure 9 - Numerical contour distribution of displacements and deformation in the railway carriage frame under dynamic loading y (author's material)

Figures 8 and 9 present the numerical models used in the Materials and Methods section to evaluate the dynamic impact of railway-induced vibrations. **Figure 8** shows the contour distribution of total displacements in the soil mass and foundation zone obtained from the PLAXIS 2D finite element analysis, which was used to assess the propagation of dynamic loading through the soil. **Figure 9** illustrates the numerical deformation model of the railway carriage frame, adopted as the initial source of dynamic excitation for determining the vibration loading parameters transmitted to the soil and nearby structures.

The results obtained according to tabular data when values are assigned to the program are shown in **Table 1**.

Table 1
Results of the research work

№	Distance (m)	$v_y$max (×10⁻⁶ m/s)	$v_y$min (×10⁻⁶ m/s)
1	100	1.378	1.309
2	110	0.890	0.871
3	120	0.835	0.944
4	130	0.991	0.625
5	140	0.454	0.414
6	150	0.256	0.155

The graph was constructed on the basis of the numerical results obtained from the PLAXIS 2D dynamic analysis at the selected observation points. The values of vy,max $v_y$max and vy,min $u_y$min were extracted for each control section in order to evaluate the attenuation pattern of railway-induced vibrations within the soil mass. Overall, the methodological framework combines numerical modelling, field-based geotechnical barrier concepts, and comparative analysis of vibration parameters, allowing a comprehensive assessment of methods for reducing the impact of railway-induced vibrations on nearby buildings.

3 RESULTS AND DISCUSSION

The numerical simulation results demonstrated a general decrease in railway-induced vibration intensity with increasing distance between the vibration source and the observation points.

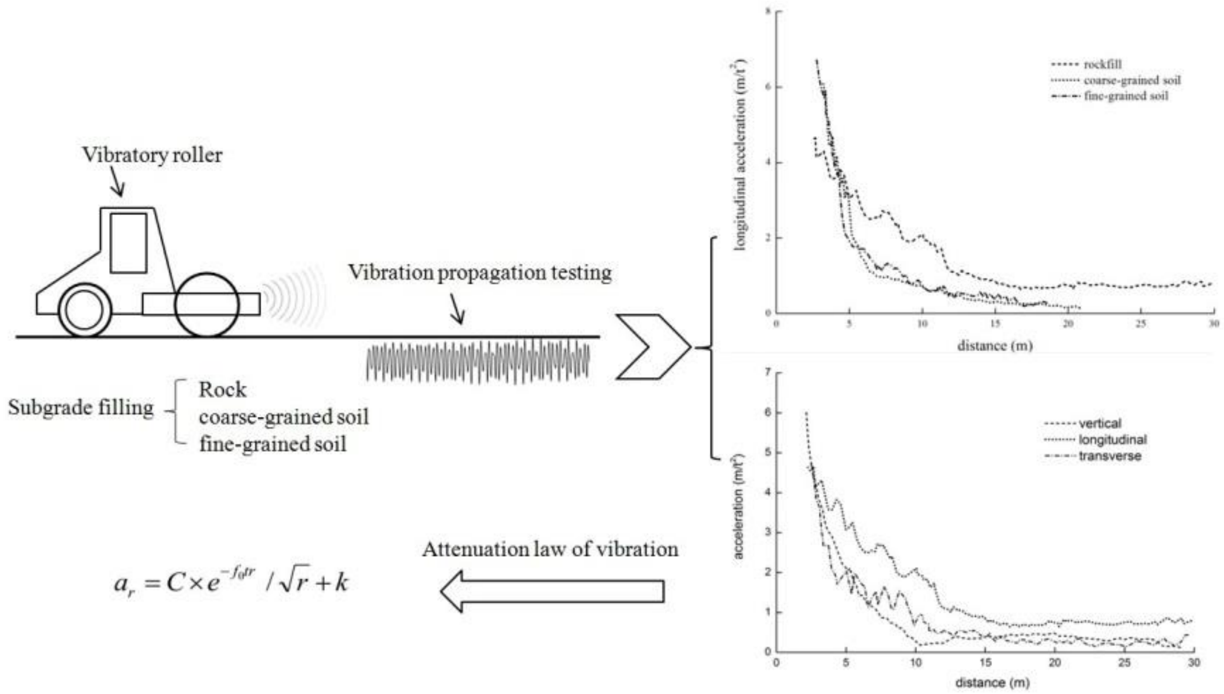


Figure 10 – Schematic illustration of vibration propagation testing in layered soil and attenuation characteristics with distance (author's material)

At a distance of 100 m, the highest vibration level was recorded. At this point, the maximum vertical vibration velocity was

v_y,max=1.378×10^{-6} m/s

v_y,max=1.378

v_y,max=1.378×10^{-6} m/s and the minimum value was

v_y,min=1.309×10^{-6} m/s

The relatively small difference between the maximum and minimum values indicates a comparatively stable oscillation pattern. At this distance, the dissipation of vibration energy in the soil mass remains limited, and therefore the influence of railway-induced dynamic loading is most pronounced.

Within the 110-120 m interval, a noticeable decrease in vibration intensity was observed. At 110 m, the maximum value decreased to v_y,max=0.890×10^{-6} m/s. Which corresponds to an approximately 35-40% reduction compared to the 100 m reference point. However, at 120 m, the minimum value increased to v_y,min=0.944×10^{-6} m/s. This local increase may be attributed to wave reflection, interference phenomena within the soil layers, or the influence of local ground conditions.

At 130 m, the maximum vibration value increased again to v_y,max=0.991×10^{-6} m/s indicating the presence of a local amplification zone. At the same distance, the minimum value sharply decreased to v_y,min=0.625×10^{-6} m/s. This increase in amplitude suggests possible resonance effects or wave superposition within the sandy soil layer. A significant attenuation of vibration intensity was observed within the 140-150 m interval. At 140 m, v_y,max=0.454×10^{-6} m/s while at 150 m v_y,max=0.256×10^{-6} m/s. The minimum value at 150 m decreased further to v_y,min=0.155×10^{-6} m/s.

Compared with the 100 m point, the maximum value decreased by approximately five times, while the minimum value decreased by more than eight times. Therefore, the 140-150 m zone can be considered a vibration attenuation zone with relatively reduced dynamic impact on nearby structures.

4 CONCLUSIONS

The present study provided a geotechnical investigation of methods for reducing the impact of railway-induced vibrations on nearby buildings and structures by combining field-based barrier concepts and numerical simulation in PLAXIS 2D. The results obtained allow the following scientifically significant conclusions to be drawn:

1. A general attenuation trend of railway-induced vibration waves in sandy soil was established within the 100-150 m distance range. The maximum vertical vibration velocity decreased from 1.378×10^{-6} m/s at 100 m to 0.256×10^{-6} m/s at 150 m, confirming the high energy dissipation capacity of sandy soils.

2. The study revealed that vibration attenuation is non-monotonic. A local amplification zone was identified within 120-130 m, where the vibration intensity temporarily increased despite the overall attenuation trend. This effect is attributed to wave reflection, interference phenomena, Rayleigh surface wave amplification, and the presence of a sandy layer at an approximate depth of 12 m.

3. The identification of this local vibration amplification zone constitutes one of the main new scientific results of the study, since it demonstrates that simplified assumptions of continuous vibration decay may not be sufficient for engineering design in railway-adjacent areas.

4. The numerical and field-based geotechnical analysis confirmed the effectiveness of vibration isolation measures, including steel barriers, trench barriers, and rubber-soil composite damping systems, in reducing the transmission of dynamic loading through the soil mass.

5. Based on the obtained numerical results, the 140-150 m interval can be considered a relatively safe zone for the placement of buildings under geological conditions like those investigated in this study.

The scientific significance of the work lies in improving the understanding of railway vibration propagation mechanisms in sandy soils and in providing a methodological basis for the design of geotechnical vibration mitigation systems intended to protect buildings and urban infrastructure.

The practical significance of the study is associated with the possibility of applying the obtained results in urban planning, railway-adjacent construction design, and the development of engineering vibration isolation solutions. The principal scientific novelty of this work lies in demonstrating that railway-induced vibration attenuation in sandy soil is not strictly monotonic and includes a local amplification zone caused by wave interaction effects. This finding is essential for improving geotechnical vibration protection strategies for buildings located near railway lines.

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