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RESEARCH ARTICLE

VIBRODYNAMIC RESPONSE OF TRACK SUPERSTRUCTURE ELEMENTS AND SUBGRADE UNDER THE ACTION OF ROLLING STOCK

A. Zhangabylova^{1*} , S. Abdullaev¹ , A. Zamukhovskiy² ,
B. Uskembayeva¹ , M. Kvashnin³ 

¹Satbayev University, 050013, Almaty, Kazakhstan

²Russian University of Transport (RUT (MIIT)), 127994, Moscow, Russian Federation

³ALT University, 050012, Almaty, Kazakhstan

Abstract. *The paper presents the results of a field-based investigation of the vibrodynamic response of railway track superstructure elements and subgrade under the action of rolling stock in real operating conditions. Vertical vibrations were recorded in the shoulder zone of a stable railway embankment during the passage of a VL-80 electric locomotive at different train speeds. To assess the influence of speed on vibration parameters, analyses were performed in both time and frequency domains, including the determination of peak accelerations, root mean square (RMS) values, dominant frequencies, and spectral energy characteristics. The aim of this study is to establish quantitative relationships between train speed and vibration response parameters of the railway subgrade under real operating conditions. Stable relationships between vibration parameters and train speed were identified, reflecting systematic changes in the dynamic state of the “track superstructure–subgrade” system under increasing operational loading. The scientific novelty of the study lies in the in-situ experimental identification of speed-dependent vibration characteristics of the subgrade shoulder and in the integration of time- and frequency-domain parameters for vibration-based condition assessment under real traffic conditions. The obtained experimental data can be applied for vibration-based condition assessment of railway embankments. The proposed approach is aimed at developing practical monitoring methods for early detection of anomalies, improving maintenance planning efficiency, and enhancing the management of railway infrastructure condition.*

Keywords: *track dynamics; subgrade vibration; rolling stock loading; vibration monitoring; field investigation; train speed..*

***Corresponding author**

Aigul Zhangabylova, e-mail: zhangabylova82@gmail.com

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ҒЫЛЫМИ МАҚАЛА

ЖЫЛЖЫМАЛЫ ҚҰРАМНЫҢ ДИНАМИКАЛЫҚ ӘСЕРІ ЖАҒДАЙЫНДА ТЕМІРЖОЛ ЖОЛЫНЫҢ ЖОҒАРҒЫ ҚҰРЫЛЫСЫ ЭЛЕМЕНТТЕРІ МЕН ЖЕР ТӨСЕМІНІҢ ВИБРОДИНАМИКАЛЫҚ ЖҮЙЕСІ

А. Жангабылова^{1*}, С. Абдуллаев¹, А. Замуховский²,
Б. Ускембаева¹, М. Квашнин³

¹Сәтбаев университеті, 050013, Алматы, Қазақстан

²Ресей көлік университеті (РКУ (МИИТ)), Мәскеу қ, 127994, Ресей Федерациясы

³АЛТ университеті, 050012, Алматы, Қазақстан

Аңдатпа. Мақалада нақты пайдалану жағдайында жылжымалы құрам әсерінен теміржол үстіңгі құрылысы элементтері мен жер төсемінің вибродинамикалық жауап беруін далалық зерттеу нәтижелері ұсынылған. Әртүрлі қозғалыс жылдамдықтарында ВЛ-80 электровозы өткен кезде тұрақты теміржол үйіндісінің жиегі бөлігінде тік бағыттағы тербелістер тіркелді. Жылдамдықтың тербеліс параметрлеріне әсерін бағалау үшін уақыттық және жиіліктік аймақтарда талдау жүргізілді, оның ішінде үдеудің шекті мәндері, орташа квадраттық мәндер (ОКМ), басым жиіліктер және спектрлік энергия сипаттамалары анықталды. Зерттеудің мақсаты - нақты пайдалану жағдайында поездың жылдамдығы мен жер төсемінің тербеліс параметрлері арасындағы сандық тәуелділіктерді анықтау. Жүргізілген зерттеулер нәтижесінде тербеліс параметрлері мен қозғалыс жылдамдығы арасындағы тұрақты байланыстар анықталып, жүктеменің артуына байланысты «жолдың үстіңгі құрылысы - жер төсемі» жүйесінің динамикалық күйінің заңды өзгерістері көрсетілді. Зерттеудің ғылыми жаңалығы нақты пайдалану жағдайында жер төсемі үйіндісінің жиегіндегі жылдамдыққа тәуелді тербеліс сипаттамаларын далалық жағдайда эксперименттік анықтауда, сондай-ақ уақыттық және жиіліктік параметрлерді біріктіру арқылы тербеліс негізіндегі жағдайды бағалау тәсілін ұсынуда жатыр. Алынған эксперименттік деректер теміржол үйінділерінің жағдайын тербеліс негізінде бағалауда қолданылуы мүмкін. Ұсынылған тәсіл ақауларды ерте анықтауға арналған мониторинг әдістерін дамытуға, техникалық қызмет көрсетуді жоспарлаудың тиімділігін арттыруға және теміржол инфрақұрылымының жағдайын басқаруды жетілдіруге бағытталған.

Түйінді сөздер: теміржол жолының динамикасы; жер төсемінің тербелістері; жылжымалы құрам әсері; вибрациялық бақылау; натурлық зерттеулер; қозғалыс жылдамдығы.

*Автор-корреспондент

Айгүл Жангабылова, e-mail: zhangabylova82@gmail.com

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НАУЧНАЯ СТАТЬЯ

ВИБРОДИНАМИЧЕСКИЙ ОТКЛИК ЭЛЕМЕНТОВ ВЕРХНЕГО СТРОЕНИЯ ПУТИ И ЗЕМЛЯНОГО ПОЛОТНА ПРИ ВОЗДЕЙСТВИИ ПОДВИЖНОГО СОСТАВА

А. Жангабылова^{1*} , С. Абдуллаев¹ , А. Замуховский² ,
Б. Ускембаева¹ , М. Квашнин³ 

¹Сатбаев университет, Алматы, 050013, Казахстан

²Российский университет транспорта (РУТ (МИИТ)), г. Москва, 127994, Российская Федерация

³АЛТ университет, Алматы, 050012, Казахстан

Аннотация. В статье представлены результаты натурных исследований вибродинамического отклика элементов верхнего строения пути и земляного полотна под воздействием подвижного состава в реальных условиях эксплуатации. При пропуске электровоза ВЛ-80 по железнодорожному пути с различными скоростями движения регистрировались вертикальные колебания грунта в области обочины земляного полотна железнодорожной насыпи. Для оценки влияния скорости на параметры колебаний был проведен анализ во временных и частотных областях, в том числе определены предельные значения ускорения, среднеквадратичные значения (СКЗ), преобладающие частоты и спектральные энергетические характеристики. Целью исследования является определение количественных зависимостей между скоростью поезда и параметрами колебаний земляного полотна в реальных условиях эксплуатации. В результате проведенных исследований были выявлены постоянные связи между параметрами колебаний и скоростью движения, продемонстрированы закономерные изменения динамического состояния системы «верхнее строение пути - земляное полотно» в связи с увеличением эксплуатационной нагрузки. Научная новизна исследования заключается в экспериментальном определении в натурных условиях скоростно-зависимых характеристик колебаний на краю насыпи земляного полотна в реальных условиях эксплуатации, а также в предоставлении способа оценки состояния на основе колебаний путем сочетания временных и частотных параметров. Полученные экспериментальные данные могут быть использованы для вибрационного мониторинга состояния железнодорожных насыпей. Предлагаемый подход направлен на развитие методов мониторинга раннего выявления дефектов, повышение эффективности планирования технического обслуживания и совершенствование управления состоянием железнодорожной инфраструктуры.

Ключевые слова: динамика пути; вибрации земляного полотна; воздействие подвижного состава; вибрационный контроль; натурные исследования; скорость движения поездов.

*Автор-корреспондент

Айгул Жангабылова, e-mail: zhangabylova82@gmail.com

1 INTRODUCTION

Reinforced concrete sleepers and rail fastening systems are key components of ballasted railway tracks, through which dynamic loads from rolling stock are transmitted along the “wheel-rail-fastening-sleeper-ballast” chain, thereby governing the stress–strain state and long-term durability of the track superstructure. In international practice, the assessment of vibration effects on track components is primarily based on the measurement of vibration velocity, as this parameter most adequately reflects the energy characteristics of propagating waves and the level of dynamic impact acting on the structure [1], [2], [3], [4]. Accordingly, methods and instrumentation traditionally used in seismology are widely applied to investigate the vibrodynamic response of railway tracks under moving loads. A number of studies have developed numerical, analytical, and semi-empirical models to analyze the dynamic behavior of railway tracks under moving loads. In particular, so-called “sandwich models” have been proposed, accounting for the coupled interaction of rails, sleepers, and trackbed layers, which has improved the accuracy of describing dynamic processes within the track–foundation system [5], [6]. These approaches enable the evaluation of stresses, displacements, and vibration characteristics of track components over a wide range of operating conditions. However, despite significant progress, the scientific literature emphasizes the need for validation of computational models based on field data and for the expansion of in-situ experimental datasets. Existing models generally do not fully account for real operational factors, such as ballast heterogeneity, seasonal temperature variations, the presence of wheel and rail defects, and variability in the stiffness of rail fastening systems. This can lead to substantial discrepancies between predicted and actual dynamic responses [7], [8]. Recent experimental studies have also demonstrated that the mechanical behavior of ballast is highly sensitive to environmental conditions. In particular, it has been shown that low temperatures can significantly alter the strength and deformation characteristics of the ballast layer, as well as its degradation behavior, thereby directly influencing the vibrodynamic response of ballasted tracks under operational loading [9], [10], [11], [12]. Recent studies have highlighted the importance of experimental investigations and vibration-based assessment methods for railway infrastructure. In particular, vibration characteristics of railway structures and their interaction with the foundation have been investigated in a number of works [13], [14], [15], [16], [17], [18]. These studies demonstrate that vibration parameters can serve as reliable indicators of the technical condition of track structures and subgrade elements under dynamic loading. Thus, the main scientific problem is the insufficient amount of in-situ experimental data describing the vibrodynamic behavior of the “track superstructure–subgrade” system under real train loading conditions. This limits the reliability of calculation models, monitoring criteria, and maintenance decision-making for railway infrastructure. The aim of this study is to analyze the vibrodynamic response of ballasted railway track systems with reinforced concrete sleepers based on in-situ measurements under operational train loading. Particular attention is given to vibration velocity as an informative parameter characterizing the dynamic interaction within the “sleeper–ballast–subgrade” system. The scientific novelty of this study lies in the field-based identification of vibration velocity characteristics of reinforced concrete sleeper–ballast–subgrade interaction under real operating conditions. Unlike studies based mainly on numerical simulations or laboratory tests, this research provides experimental data obtained directly from an operating railway track and establishes relationships between train speed and vibration response parameters. The obtained results can be used to improve vibration-based monitoring methods, support engineering assessment of railway embankments and track structures, and assist in maintenance planning and infrastructure management decisions.

2 MATERIALS AND METHODS

To evaluate the influence of moving train loads on the dynamic (amplitude–frequency) characteristics of the railway subgrade, an in-situ experimental investigation was conducted on a mainline section of the Almaty railway network operated by JSC “NC KTZ”. The study site was located within the Almaty track maintenance division (UPCh-46) and represents typical operational

conditions of heavily trafficked ballasted railway infrastructure. The vibration sensors were mounted directly on the reinforced concrete sleepers, following installation approaches commonly adopted in previous field studies on railway track dynamics. This configuration allows reliable capture of sleeper vibration responses under operational train loading while ensuring stable mechanical coupling between the sensor and the structural element. (Figure 1).

Installation of a vibration sensor on a reinforced concrete sleeper with a rail mount Vossloh W-14 (Figure 1a). The sensor is attached directly to the surface of the sleeper to record vertical vibrations that occur during the passage of the rolling stock, which makes it possible to assess the dynamic impact on the upper structure of the track.

Installation of a vibration sensor on a reinforced concrete sleeper with a rail mount Zhbr-65-Sh (Figure 1b). This measurement scheme was used to compare the dynamic characteristics of the track when using different types of intermediate rail fasteners and assess their impact on the transmission of vibration loads.

Placement of the vibration sensor on the railway embankment (Figure 1c). This arrangement provides for the recording of vibrations propagating through the ballast layer and the ground cover, which makes it possible to assess the attenuation of vibrations when moving away from the source of impact and determine the features of the propagation of dynamic waves at the bottom of the railway.

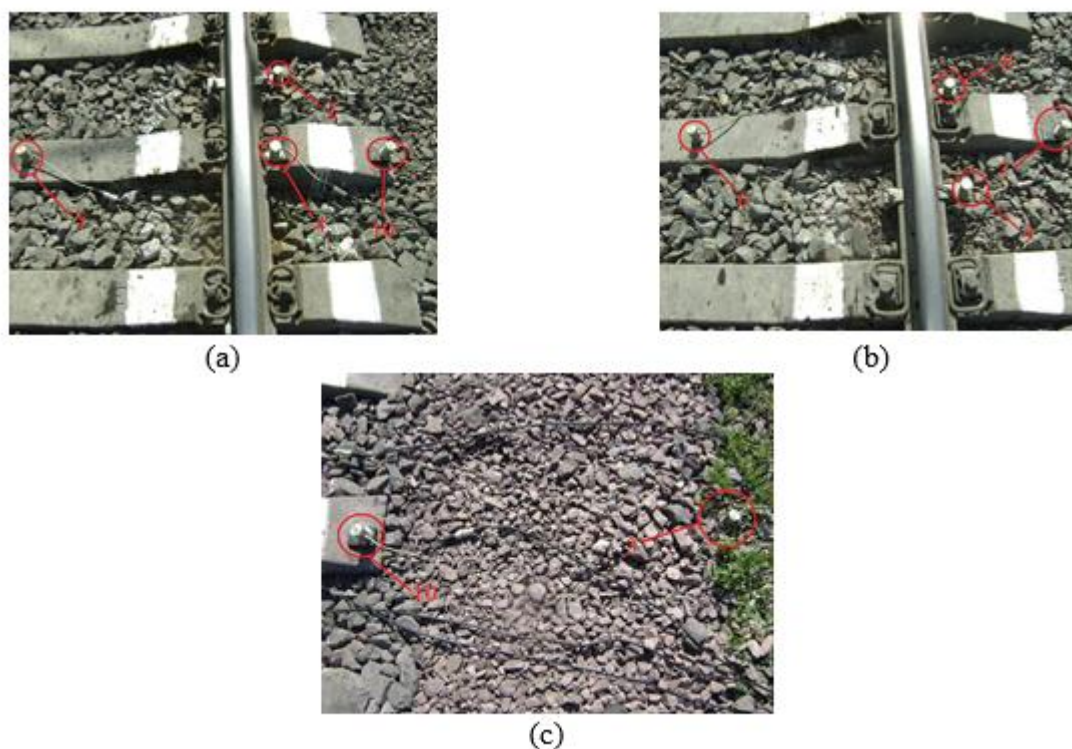


Figure 1 - General view of the experimental setup and locations of vibration sensors: (a) on the sleeper with Vossloh W-14 fastening; (b) on the sleeper with ZhBR-65-Sh fastening; (c) at the shoulder of the railway embankment [Authors' material]

Sensor locations: No. 1–2 – rail head at sleeper mid-span; No. 3 – ballast surface; No. 4 and 8 – fastening clamp bearing region; No. 5–6 – sleeper midsection; No. 7 and 10 – sleeper ends.

Vertical vibration measurements were performed using MB-25D-V vibration sensors. The analog signals from the sensors were converted into digital form using an L-CARD E14-440 analog-to-digital converter (ADC) connected via a USB interface. Data acquisition and measurement control were carried out using a notebook computer, while signal recording and preliminary processing were performed with the LGraph2 software package supplied with the E14-440 module. The measurement system was used in accordance with the manufacturer's specifications. The experimental vibration signals were acquired and visualized using LGraph2 software (Fig. 2) and subsequently processed using a specially developed data-processing routine implemented in Mathcad.

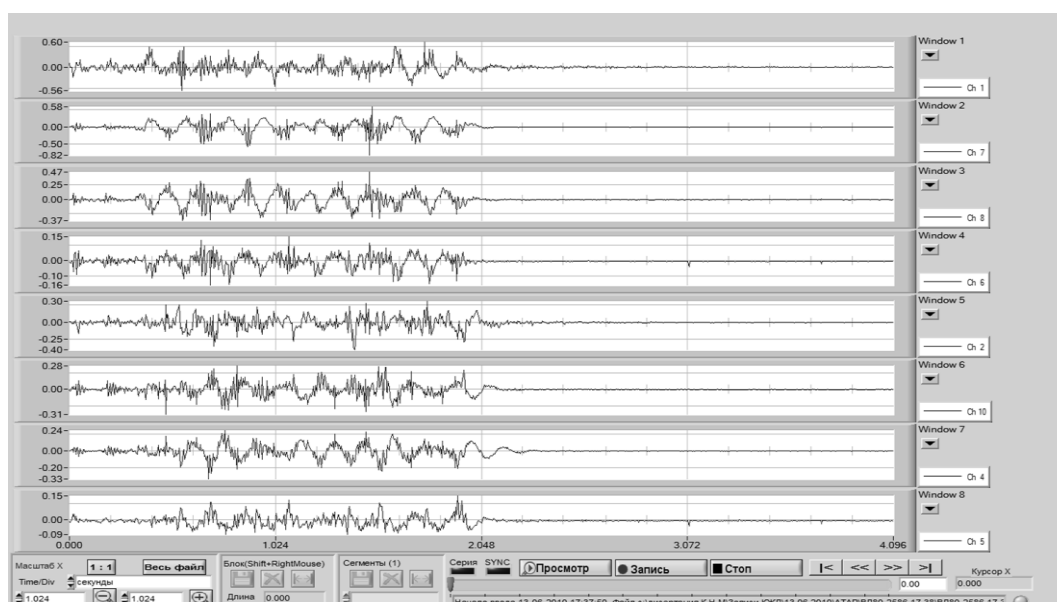


Figure 2 - General view of the "LGraph2" program interface.

The recorded signals were first converted into physical vibration-velocity values using the corresponding calibration parameters of the measurement system. The obtained time histories were then preprocessed to remove the signal offset and low-frequency trend and were filtered within the analyzed frequency range of 0-1000 Hz to reduce unwanted components outside the frequency band of interest. The vibration-velocity signals were analyzed in both the time and frequency domains. The time-domain analysis included the determination of the peak and root-mean-square (RMS) vibration values for the selected portion of each train passage. The frequency-domain characteristics were determined using the Fast Fourier Transform (FFT) applied to the selected vibration-signal segments. This procedure was used to obtain the vibration spectra and identify the dominant frequency components of the track response. In addition, vibration displacement was obtained by numerical integration of the vibration-velocity signal, while vibration acceleration was determined by numerical differentiation. RMS values and frequency spectra were subsequently determined for the derived vibration parameters using the same processing procedure.

Field measurements were performed to capture the vibration response of the subgrade under real operating conditions. To ensure the interpretability and repeatability of the results, the experiments were carried out under known axle load conditions and with a well-defined vibration excitation source. On the investigated section, freight traffic was predominantly hauled by VL-80 electric locomotives; therefore, this locomotive type was selected as the primary excitation source for the vibration analysis. The static wheel load of the VL-80 locomotive is 12 t per wheel, which provided a stable and representative loading scenario for evaluating vibration characteristics induced by moving loads. The recorded vibration signals were subsequently analyzed in the frequency and time domains to identify characteristic response patterns of the railway subgrade under operational train passages. A mobile vibration measurement system equipped with dedicated software packages for data acquisition, processing, and visualization was employed in the field investigations.

During the measurements, the following signal acquisition parameters were adopted: a sampling frequency of 8000 Hz per channel, a recording duration of 65.536 s, an input signal range of ± 10 V, and a trigger synchronization threshold of 0.001 V. These settings were selected to ensure adequate temporal and frequency resolution for capturing vibration responses induced by moving train loads. Field recordings of both freight and passenger train passages were conducted during the summer period over a continuous observation interval of 15 days. Vibration data were collected for all trains passing the test section during daylight operating hours, from 07:00 to 20:00. Over the entire monitoring period, more than 200 individual train passage records were obtained, providing a statistically representative dataset for subsequent analysis (see Table 1). For each locomotive speed,

eight independent measurements were performed. Train speeds were measured using a radar-based speed monitoring device and were further verified through post-processing of the recorded vibration time histories. This combined approach ensured reliable determination of operational loading conditions associated with each recorded train passage.

Table 1 - Distribution of recorded train passages by operating speed of the VL-80 electric locomotive [Authors' material]

Train speed, km/h	Number of records	Train speed, km/h	Number of records	Train speed, km/h	Number of records
45	8	69	8	79	8
50	8	70	8	81	8
53	8	71	8	82	8
59	8	73	8	86	8
61	8	74	8	91	8
63	16	75	8	95	8
66	8	76	8	100	16
67	8	78	8	103	8

3 RESULTS AND DISCUSSION

An analysis of the measured mechanical vibration parameters at the shoulder of the railway subgrade induced by the passage of the VL-80 electric locomotive revealed the following key observations. The dominant frequencies identified in the spectra of vibration displacements $f_{n.s}$, vibration velocities $f_{n.v}$, and vibration accelerations $f_{n.a}$ remained consistent across the entire investigated train speed range from 45 to 103 km/h. For all three vibration parameters, the prevailing spectral frequencies coincided and varied within the range of 29 to 56 Hz, regardless of train speed. As a representative example, Figures 3-5 present the time-domain amplitude histories (Figures 3-5a) and the corresponding frequency-domain spectra (Figures 3-5b) of vibration velocity, vibration displacement, and vibration acceleration recorded at the shoulder of the subgrade during the passage of the VL-80 locomotive at a speed of 71 km/h. These results illustrate the characteristic vibration response of the subgrade under operational train loading conditions.

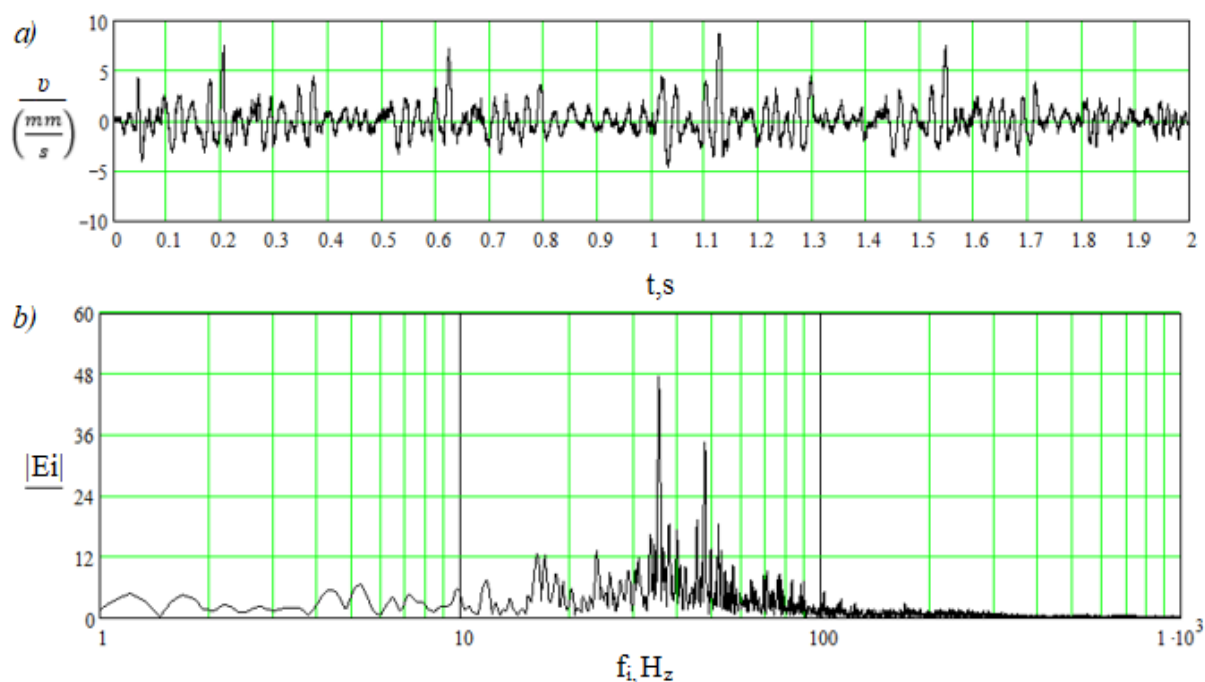


Figure 3 - (a) Vertical vibration time history measured by Sensor No. 3 located on the ballast surface during the passage of the VL-80 locomotive at a speed of 71 km/h; (b) corresponding frequency spectrum (maximum spectral peak at 35.8 Hz) [Authors' material]

The relationships between the peak and root-mean-square (RMS) values of vibration velocity

and vibration acceleration and the train speed at the railway subgrade formation exhibit low coefficients of determination, indicating poor approximation quality. Consequently, these relationships are not suitable for use as generalized evaluation criteria.

At the shoulder of the subgrade formation, the dependence of the peak vibration displacement on the operating speed of the VL-80 electric locomotive is well described by a parabolic function, whereas the RMS vibration displacement shows a linear relationship with train speed

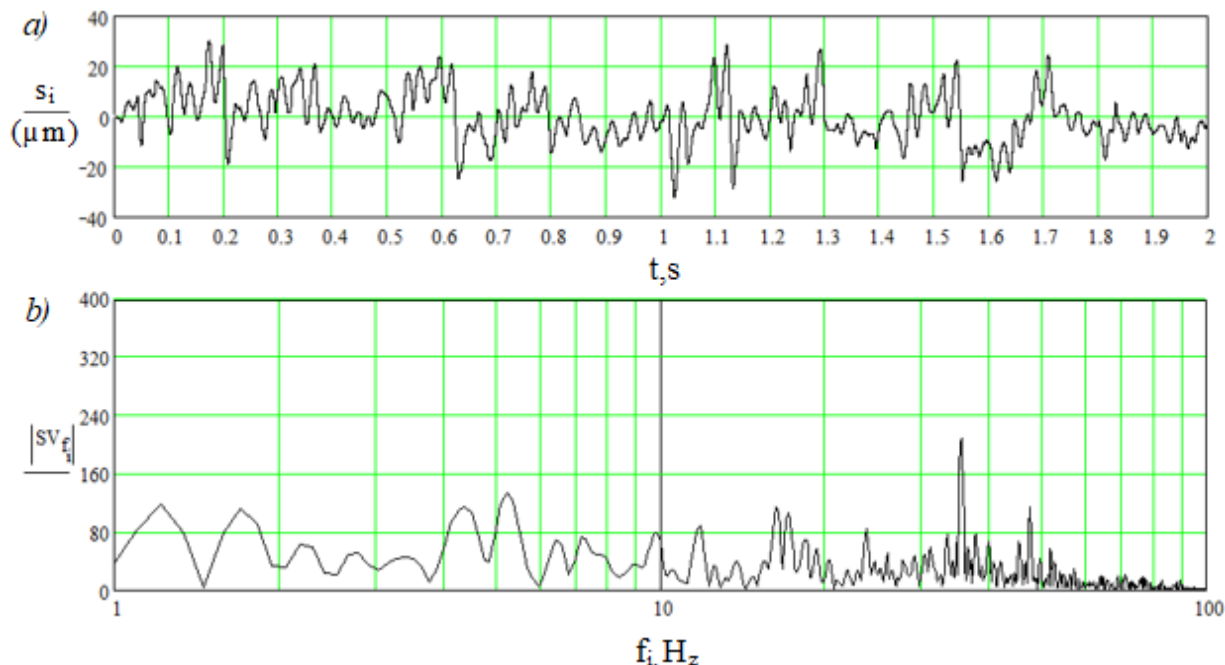


Figure 4 - (a) Oscillogram of the vertical vibration response recorded by Sensor No. 3, installed on the ballast surface adjacent to the reinforced concrete sleeper, during the passage of the VL-80 electric locomotive at a speed of 71 km/h; (b) corresponding frequency spectrum (maximum spectral peak at 35.8 Hz) [Authors' material]

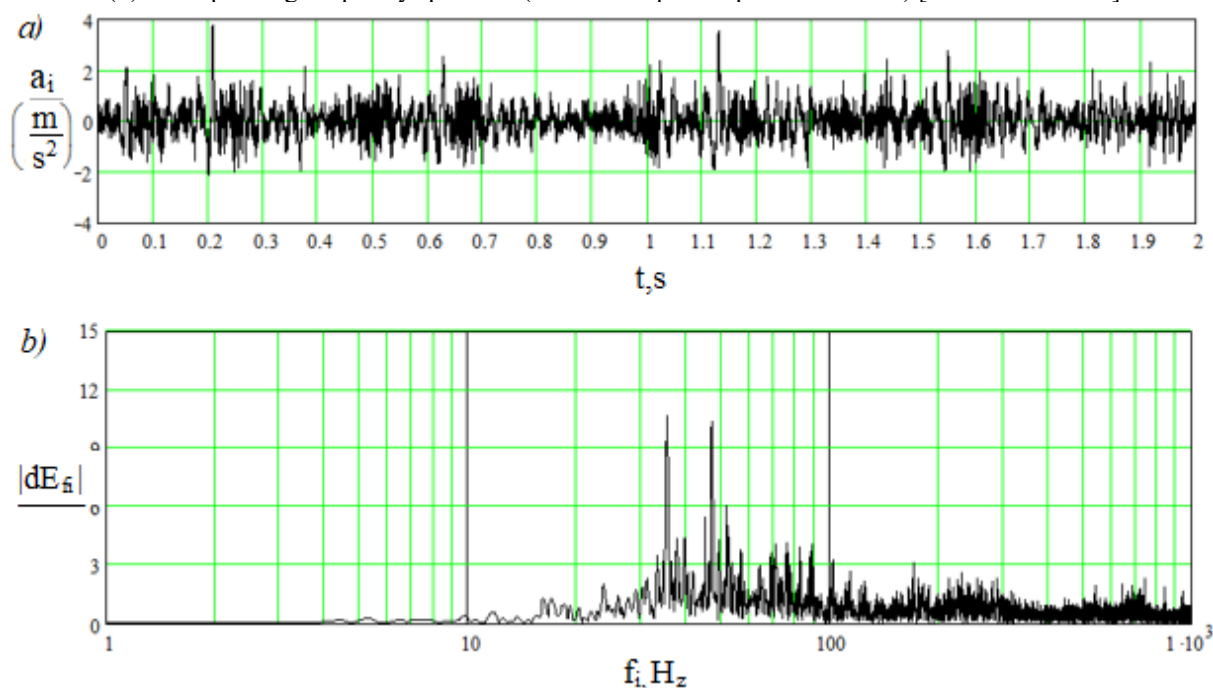


Figure 5- (a) Accelerogram of vertical vibration recorded by Sensor No. 3 installed on the ballast surface during the passage of the VL-80 electric locomotive at a speed of 71 km/h; (b) corresponding frequency spectrum (maximum spectral peak at 35.8 Hz) [Authors' material]

The minimum measured peak vibration displacement ($19\ \mu\text{m}$) was recorded at a locomotive speed of $45\ \text{km/h}$, whereas the maximum value reached $40\ \mu\text{m}$ at $103\ \text{km/h}$. Figure 6 shows the dependence of the peak vibration displacement at the railway subgrade formation on the operating speed of the VL-80 electric locomotive. The obtained relationship is well approximated by a second-degree polynomial,

$$S_p = 0.0025V^2 - 0.1066V + 20.759 \quad (1)$$

with a coefficient of determination of $R^2 = 0.8428$. The intercept at zero speed corresponds to the elastic quasi-static displacement (deflection) of the subgrade shoulder for the case of a stationary locomotive located near the investigated cross-section under conventional wheel-load pressure distribution, yielding $S_{st} = 20.759\ \mu\text{m}$.

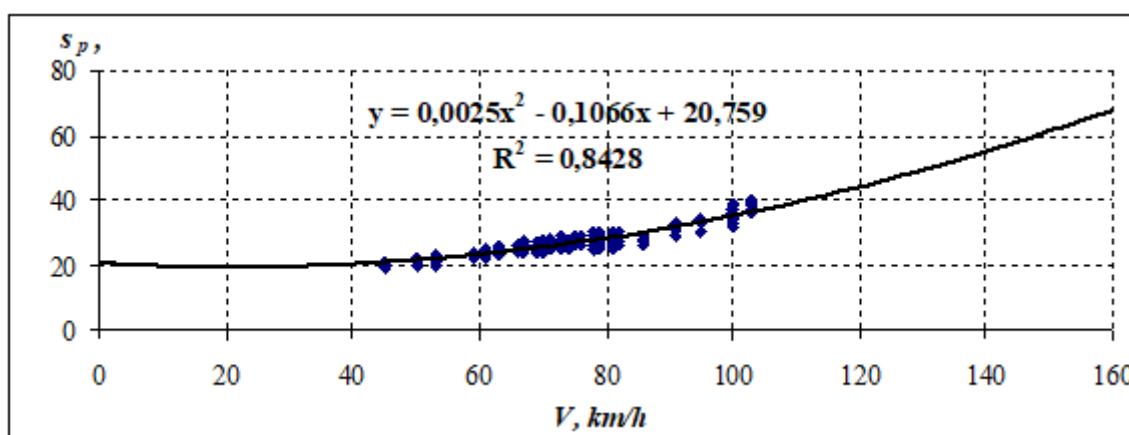


Figure 6 - Relationship between the peak vertical vibration displacement recorded by Sensor No. 3 installed on the ballast surface and the operating speed of the VL-80 electric locomotive [Authors' material]

The observed speed-dependent increase in peak displacement is consistent with prior field observations and validated studies indicating that train-induced vibration/displacement levels may rise with operating speed, and can become significantly amplified when the train speed approaches characteristic wave velocities of the track-ground system. The observed increase in peak vibration displacement with operating speed is consistent with previous field investigations and validated modeling studies, which have shown that train-induced vibration may intensify with increasing speed, particularly as the train speed approaches the characteristic wave velocities of the track-ground system (Federal Railroad Administration (FRA), 2018). Figure 7 presents the dominant vibration frequencies, defined as the frequencies corresponding to the maximum spectral peaks, as a function of locomotive operating speed.

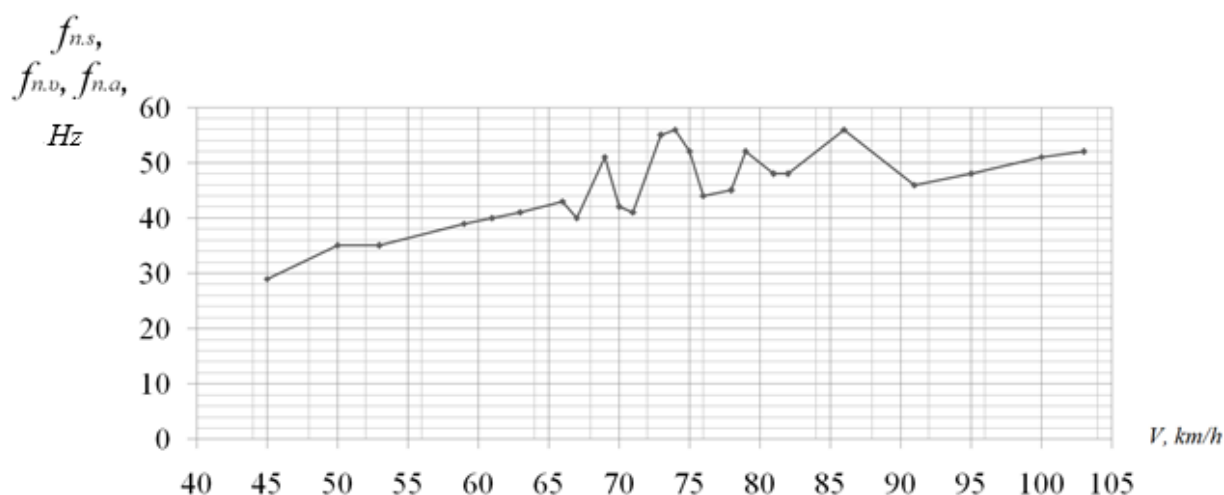


Figure 7 - Relationship between the dominant vibration frequencies recorded by Sensor No. 3 installed on the ballast surface and the operating speed of the VL-80 electric locomotive [Authors' material]

Within the speed range of 66-86 km/h, the dominant frequencies were approximately 43-56 Hz. These conditions may be considered potentially critical because vibration within this frequency range may promote thixotropic effects in susceptible soils, potentially reducing their strength and deformation characteristics. Figure 8 presents the relationship between the root-mean-square (RMS) vibration displacement at the railway subgrade formation and the operating speed of the VL-80 electric locomotive. The RMS vibration displacement was calculated from the recorded time-history signals using the standard RMS equation, while the frequency spectra were obtained by applying the Fast Fourier Transform (FFT) to the measured vibration signals. The dependence is well described by a linear function, [$s_e=0.1255V$], with a coefficient of determination of $R^2 = 0.875$ (Fig.8). At a locomotive speed of 40 km/h, the RMS vibration displacement reaches approximately 5 μm . Increasing the speed from 40 to 80 km/h results in an approximately twofold increase in RMS displacement to 10 μm . A further increase in speed from 80 to 120 km/h leads to an RMS vibration displacement approximately three times higher than that observed at 40 km/h. The experimental measurements were conducted within the locomotive speed range of 45-103 km/h. The values presented at 40 and 120 km/h were not obtained experimentally but were estimated by extrapolation of the regression model beyond the measured speed range. Therefore, these extrapolated values should be interpreted with caution and are provided only to illustrate the general trend predicted by the regression model. The primary conclusions of this study are based on the experimentally investigated speed range of 45-103 km/h. Further field measurements are required to validate the predicted response outside this range.

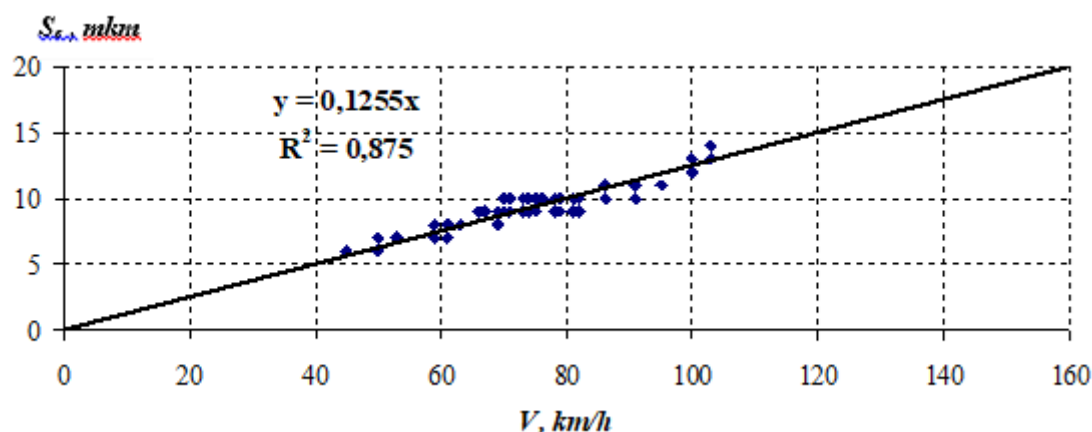


Figure 8 - Relationship between the root-mean-square (RMS) vertical vibration displacement recorded by Sensor No. 3 installed on the ballast surface and the operating speed of the VL-80 electric locomotive [Authors' material]

Overall, the obtained results demonstrate a clear and systematic relationship between train operating speed and the vibration response of the railway subgrade formation. The identified trends in dominant frequencies and vibration displacement parameters provide experimentally grounded evidence of speed-dependent dynamic effects under real operating conditions. From a practical perspective, the established relationships between vibration characteristics and locomotive speed may be employed as evaluation criteria for the development of railway embankment monitoring systems. In particular, the identified speed ranges and corresponding vibration parameters can support the definition of threshold indicators for condition assessment and early detection of unfavorable subgrade behavior. The presented findings therefore contribute to the integration of field-measured dynamic response parameters into system-level monitoring and infrastructure management frameworks. Based on the discussed results, the main conclusions of the study and their implications for railway track monitoring and management are summarized in the following section

4 CONCLUSIONS

This study presents an in-situ experimental assessment of the vibration-induced response of the railway subgrade shoulder under operational train loading, using a VL-80 electric locomotive as a controlled excitation source. The scientific novelty of the study lies in the experimentally established quantitative relationships between train speed and the vibration displacement characteristics of the railway subgrade shoulder under the investigated track and operating conditions. Based on the experimental results, the following conclusions can be drawn:

1. The root-mean-square (RMS) vibration displacement, representing the vibration intensity of the subgrade shoulder, showed a strong dependence on train speed and was reliably approximated by a linear relationship within the investigated speed range of 45-103 km/h. This experimentally established relationship provides a quantitative characterization of the speed-dependent vibration response of the subgrade shoulder.
2. The peak vibration displacement, representing the maximum measured dynamic response, exhibited a nonlinear dependence on train speed and was adequately described by a second-degree polynomial relationship within the investigated speed range. The polynomial model is considered applicable only within 45-103 km/h; its intercept at zero speed represents an extrapolation and is therefore not assigned a physical interpretation.
3. The combined analysis of RMS and peak vibration displacement provides complementary information on the vibration response of the railway subgrade shoulder: RMS characterizes the overall vibration intensity, whereas the peak value reflects the maximum dynamic response. Their joint consideration provides a more comprehensive assessment of the vibration behavior of the subgrade under operational train loading.
4. The experimental results indicate changes in the vibration response within the 66–86 km/h speed range. However, the present measurements do not provide direct evidence linking this behavior to thixotropic effects or vibration-induced strength reduction in the soil. Such an interpretation requires additional investigation of soil composition, moisture content, and physical and mechanical properties.
5. The experimentally established speed-dependent relationships provide a basis for further development and validation of vibration-based assessment approaches for railway subgrade structures. Further in-situ investigations under different soil, track, and loading conditions are required to evaluate the broader applicability of the identified relationships and to support the development of engineering criteria for railway subgrade design and maintenance.

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

ARTIFICIAL INTELLIGENCE STATEMENT

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.

AUTHOR CONTRIBUTIONS

Aigul Zhangabylova – conceptualization of the study, conducting experimental measurements, processing and analysis of vibration data, interpretation of results, and preparation of the original manuscript draft.

Seydulla Abdullaev – scientific supervision of the research, methodology development, analysis and interpretation of results, critical review, and editing of the manuscript.

Alexander Zamukhovsky – experimental investigations, contribution to the research methodology, consultation on structural mechanics and structural dynamics, analysis of results, and manuscript review.

Bagdat Uskembayeva – literature review, validation of research results, and participation in manuscript preparation and editing.

Michael Kvashnin – data collection, visualization of results, and technical editing of the manuscript.

INFORMATION ABOUT THE AUTHORS

- Aigul Zhangabylova
- Candidate of Technical Sciences, PhD Student, Department of Transport Engineering
- Satbayev University
- Almaty, Kazakhstan
- E-mail address: zhangabylova82@gmail.com
- ORCID ID: <https://orcid.org/0000-0001-9305-3803>

- Seydulla Abdullaev
- Doctor of Technical Sciences, Professor, Head of the M. Tynyshpayev School of Transport Engineering and Logistics
- Satbayev University
- Almaty, Kazakhstan
- E-mail address: s.abdullayev@satbayev.university
- ORCID ID: <https://orcid.org/0000-0001-5028-8143>

- Alexander Zamukhovsky
- Candidate of Technical Sciences, docent
- Russian University of Transport (RUT (MIIT))
- Moscow, Russian Federation.
- E-mail address: miit.ppx@inbox.ru
- ORCID ID: <https://orcid.org/0009-0008-9303-7537>

- Bagdat Uskembayeva
- Candidate of Technical Sciences, Associate Professor, Institute of Architecture and Construction, Department of Construction and Building Materials
- Satbayev University
- Almaty, Kazakhstan
- E-mail address: b.uskembayeva@satbayev.university
- ORCID ID: <https://orcid.org/0000-0003-4189-9772>

- Michael Kvashnin
- Candidate of Technical Sciences, Associate Professor, HAC Associate Professor in the specialty "Construction"
- M. Tynyshpayev ALT University
- Almaty, Kazakhstan
- E-mail address: kvashnin_mj55@mail.ru
- ORCID ID: <https://orcid.org/0000-0002-3969-9299>

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