**Theoretical Methods for Ensuring the Stability of the Embankment in the Area of the Bridge Interface with the Railway Subgrade**

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**Abstract.** The article presents defects and damages to the elements of the upper structure of the track in the area of the bridge interface with the railway subgrade. Changes in the speed of train movement and oscillations caused by seismic forces on the passage section relative to the upper structure of the track were determined. Based on the values of the determined oscillations, a method for reinforcing the embankment in the passage section with concrete piles was determined, and a pile driving scheme was developed.In addition, a program has been developed that allows you to quickly determine the permissible values of oscillations to ensure the stability of the embankment in the passage section, using the software “Visual Studio 2019, C#”. A graph of the change in the period of natural oscillations of soils on the subgrade depending on the height of the embankment and the presence of a higher level of oscillations in the passage sections from the subgrade to the bridge compared to other sections of the railway has been determined. The choice of the period of oscillation of the embankment depending on the change in the slope of the subgrade is presented graphically.

**Keywords:** Railway, subgrade, soil pressure, pile, stability of passage section, dynamic force, embankment height, slope of subgrade, logarithmic decrement, amplitude

**INTRODUCTION**

Currently, the demand for railway transport is growing. Increasing the speed of trains and ensuring traffic safety is one of the most important issues. Increasing the speed of trains will certainly lead to a significant increase in the demand for railway track structures. For the movement of high-speed trains, it is necessary to modernize railway elements and ensure their high stability.

The railway tracks must operate elastically along their entire length and withstand constant and temporary loads from the train. The elastic operation of railway tracks is associated with the dynamic rigidity of the subgrade soils. To ensure traffic safety on sections with varying dynamic rigidity, it is necessary to reduce the speed of trains. The main reason for reducing speed is the different distribution of pressure from the train. A section with varying rigidity is mainly understood as a passage section from the railway track to the bridge.

Since the rigidity of the railway subgrade is significantly less than the rigidity of the bridge elements, the value of the vertical pressure in the passage section from the bridge to the pavement increases. As a result, deformations of various volumes appear on the subgrade.

As a result of the deformation of the soils in the area of the bridge interface with the railway subgrade, various damages occurs on the elements of the upper structure shown in Figure 1.

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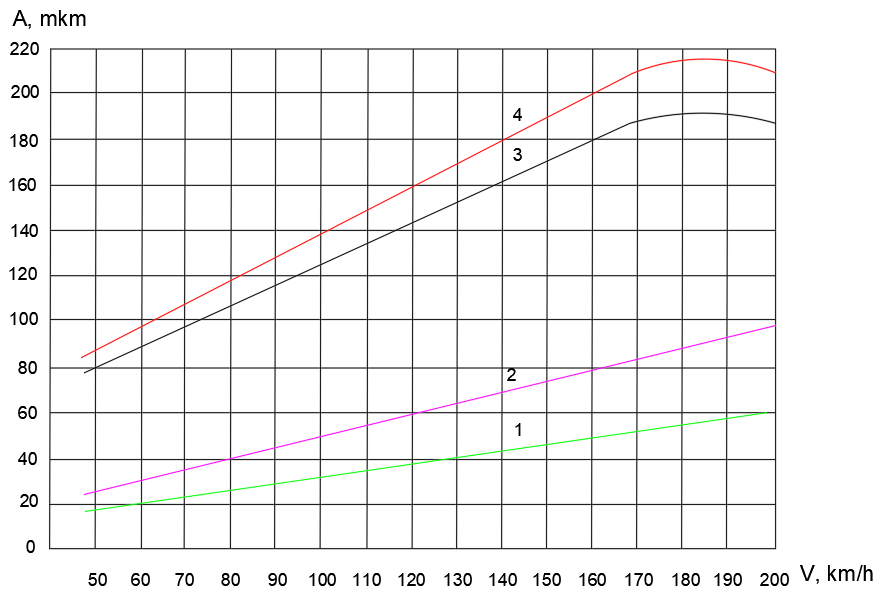
**FIGURE 1.** Damage to the elements of the rail upper structure on the passage sections

The development of modern passage section designs to prevent damage to railway elements on sections with varying dynamic rigidity is becoming increasingly relevant.

**RELATED WORK**

With an increase in the speed of trains in the passage sections from railway track to bridge, various problems arise. As the speed of trains increases, the amplitude of oscillations also increases linearly [1, 2, 3, 4, 5, 6, 7]. The linear increase in the amplitude of oscillations, directly proportional to the speed of the train, was first experimentally determined by V. Prokudin.

The effect on the formation of the magnitude of the resultant amplitude of oscillations heading along the path in the passage sections is very small shown in Figure 2.



**FIGURE 2.** The dependence of the amplitudes of oscillation in passing sections on the speed of movement of trains:

1-horizontal constituent along the way; 2-transverse to the way itself; 3-vertical constituent; 4-resultant

At the same time, as in the case of other activities, if they are related to physical exercise and V. Prokudin invited to express his opinion on Formula 1.

when, (1)

where, Paxis - is the load that falls on the central axis, kN.

In the process of oscillations, the type and condition of the way upper structure are important. Changes in way rigidity, i.e. the use of reinforced concrete sleepers, increase oscillations amplitudes by an average of 2.2 times compared to wood sleepers [8, 9, 10].

Oscillatory processes arising from the movement of trains in the passage sections from the subgrade to bridges were studied in works [11, 12]. In the passage sections from embankment to bridge, dynamic forces from trains significantly increase the active pressure in the subgrade. In developed countries, various designs have been developed and are currently used to reduce the impact of soil pressure on the bridge's coastal support.

Oscillations arising from the movement of trains on passage sections occur at different amplitudes. As a result of the amplitude of these oscillations, the active pressure (Ea) increases significantly. In European countries, including Spanish railways, the design of the passage section is formed as a result of joining reinforced concrete slabs and rails shown in Figure 3.

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| **FIGURE 3.** Construction of a passage section made of rails (Spain) [12]. | |

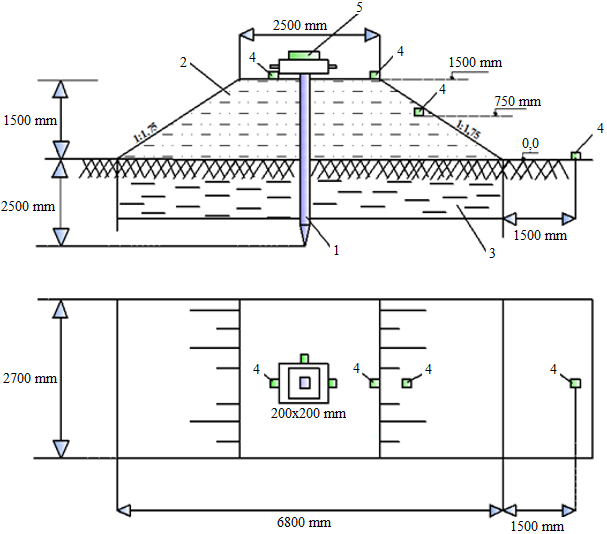
The value of the seismic force increases on account of the high specific weight of the structure of the passage section formed as a result of joining reinforced concrete slabs and rails. As a result, various deformations occur in the passage section [13, 14].

Based on world experience of high-speed railway sections, the development of a design of a passage section with low specific weight and elastic deformation remains a pressing issue.

**MATERIALS AND METHODS**

Testing of reinforced concrete piles for the development of a design of a passage section with low specific weight and elastic deformation was identified as one of the main tasks.

In order to reduce the vibrodynamic forces acting on the subgrade in the passage section, to damping the active pressure acting on the embankment soil, and to quickly damping the period of natural oscillations of the subgrade, a model of the embankment was developed for determining oscillations caused by train movement by driving reinforced concrete piles into the railway track. The general view of the developed model is shown in Figure 4.



**FIGURE 4.** Diagram of the model for determining the oscillatory process on the subgrade embankment:

1 - pile, 2 - subgrade (embankment), 3 - soil of the embankment, 4 - SM-3 sensors receiving results, 5 - vibrator generating oscillatory motion

Experimental work on the model was carried out in 2 seasons. During the experimental periods, the physical and mechanical properties of the model soils were determined under laboratory conditions. The height of the model of the experimental embankment was taken as 1.5 m. The properties of the soil, determined under laboratory conditions, are as follows: soil type - medium sands, specific weight γs=2.65 t/m3, soil porosity coefficient e=0.45, internal soil friction angle φ=400, natural soil moisture W=18%, specific soil clutch c=3 kPa.

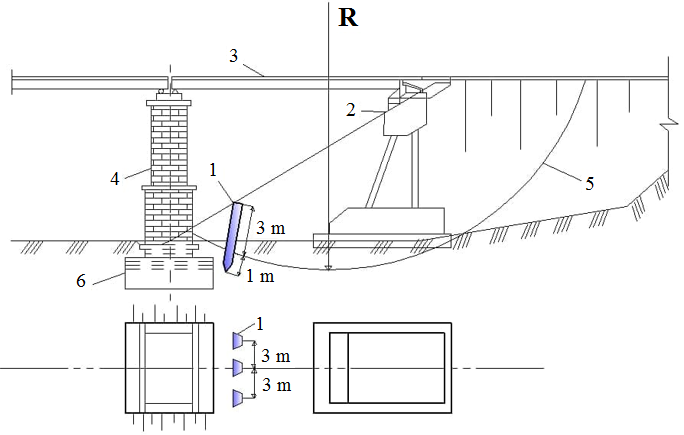
The general view of the model of a special subgrade created for conducting field tests is shown in Figure 5.

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| **FIGURE 5.** Overview of the subgrade model | |

Accurate and correct values reflecting the degree of oscillations occurring on the subgrade’s surface can only be obtained as a result of on-site research.

Based on the tests aimed at determining the amplitude-frequency descriptions arising in the above-mentioned special model of the subgrade, it is advisable to develop a scheme for reinforcing the subgrade of the passage section with reinforced concrete piles.

The calculation of its stability in cases where high rises are adjacent to the coastal base, as well as the anti-slip resistance of the thrust walls at a large depth below the soil, is carried out in approximate methods, assuming that the support, along with the soil, can be pushed along the surface of the slip of a circular. If stability is not provided, the reinforcement of the base shore using additional measures must as shown in Figure 6.



**FIGURE 6.** To protect against the possibility of sliding at great depths, strengthening the coastal base:   
1-pile; 2-shore support; 3-Intermediate device; 4-Intermediate base; 5-sliding surface; 6-Intermediate base foundation

Trapezoidal piles stumble at an angle, and this increases the resistance to displacement at a large depth and ensures stability of the base of soils.

By applying the above method, it is possible to reduce the magnitude of the seismic force acting on railway elements by strengthening the passage section. Reinforcement of the passage section with reinforced concrete piles, the main difference from existing methods (reinforced concrete boxes, slabs) is substantiated by the low specific weight of the applied structure.

**RESULTS AND DISCUSSION**

The values of oscillations in embankment soils increase significantly, mainly in the passage sections from railway bridges to the subgrade or from the subgrade to the bridge. As a result of an increase in the magnitude of oscillations, various deformations appear in the passage sections. The main reason for the varying rigidity of deformation is the different stiffness of the embankment and bridge elements.

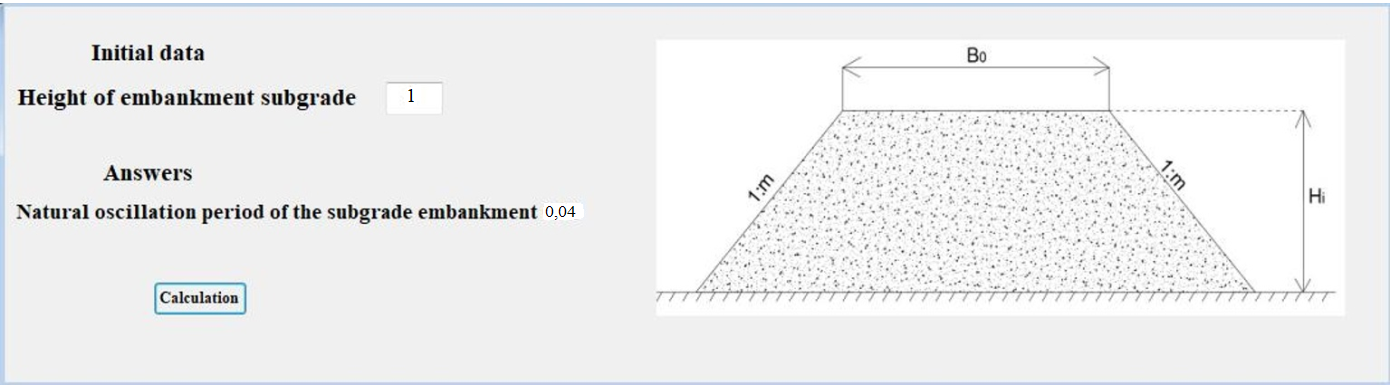
On railways, the magnitude of oscillations arising in the embankment soils in the passage sections of the subgrade and the bridge is determined by the following Formula 2:

*.* (2)

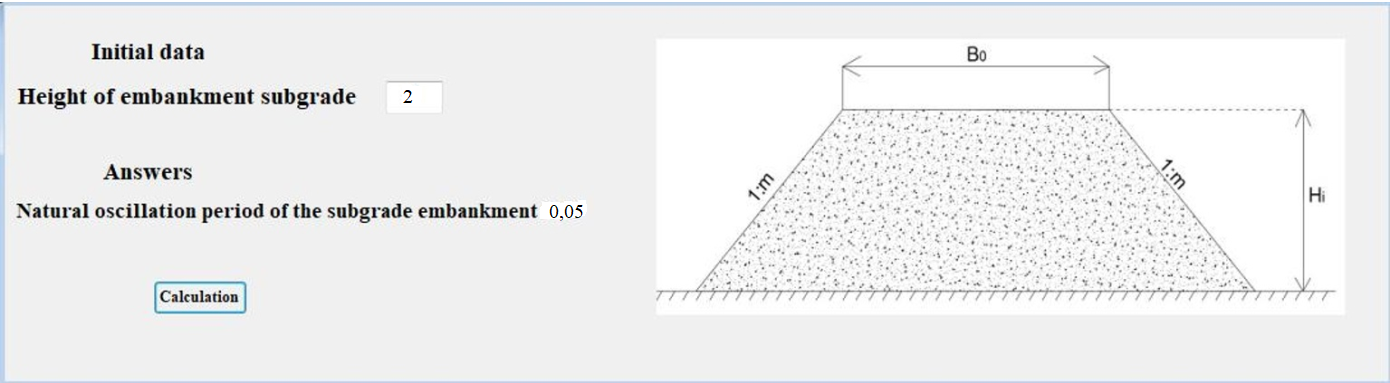
In the formula: Hi - height of the railway track embankment, (m); B0 - width of the main platform, (m); β - coefficient taking into account the properties of the subgrade soil in the passage sections, β=0.06; d - coefficient taking into account the passage sections of the railway embankment to the bridge, d=1.5; z – constructive coefficient accounting for shore support rigidity: z=0.9 for a raked base; z=0.8 for a counterforged raked base; z=0.7 in a pile – reinforced embankment [2].

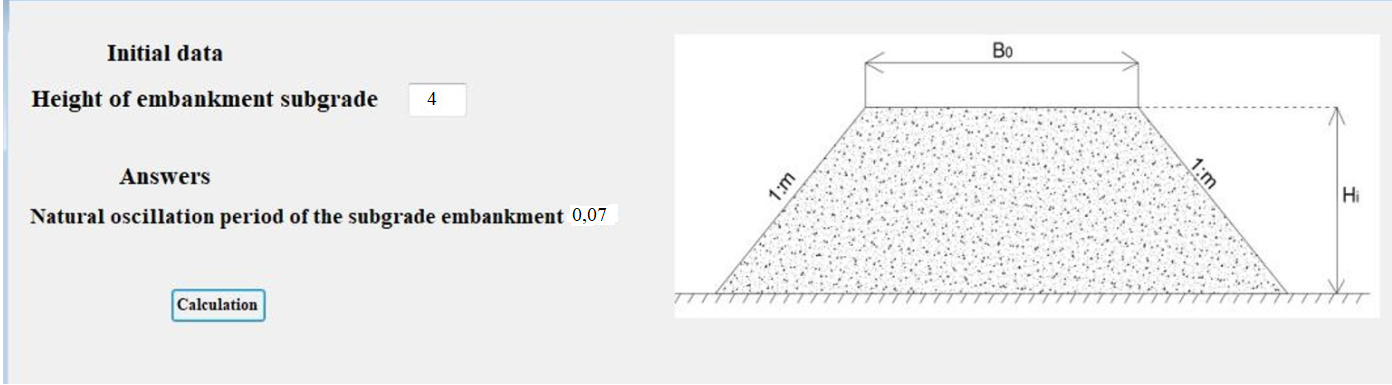
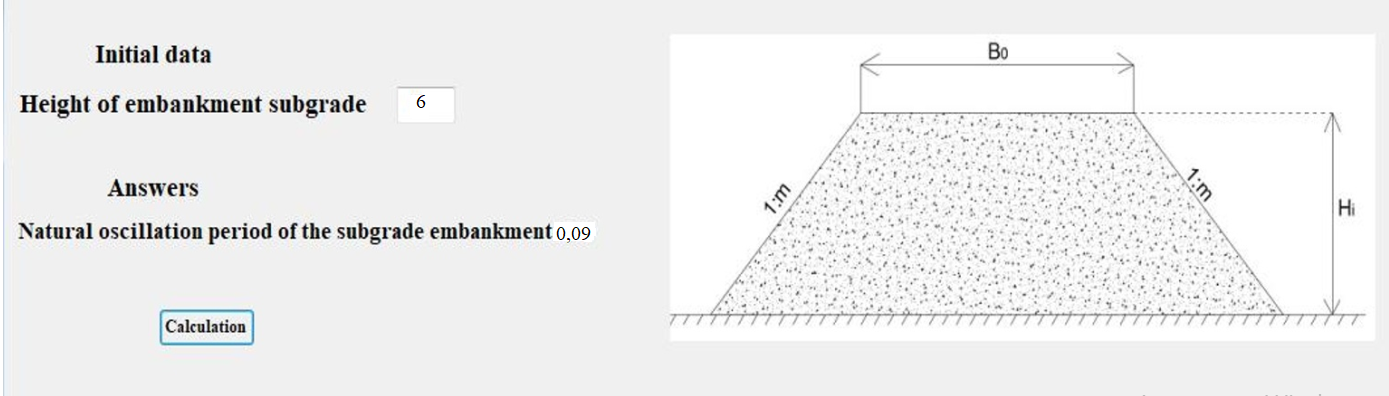
Based on the above formula 2, it was possible to determine the period of oscillation of the railway embankment, taking into account various parameters in the passage sections. One of the terms of the above formula, “d,” was determined experimentally in the model and added to the formula.

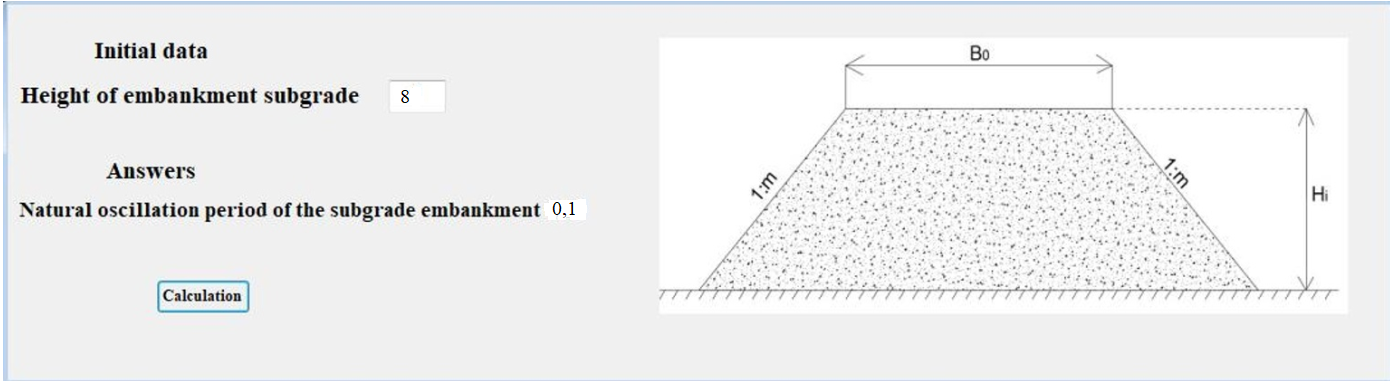
Using the “Visual Studio 2019, C#” programming language, a program was developed that allows for the detection of vibrations in railway embankments in passage sections, and with the help of this program, the period of natural oscillations generated by moving trains on embankments of different heights was determined as shown in Figure 7, 8, 9, 10, 11, 12.

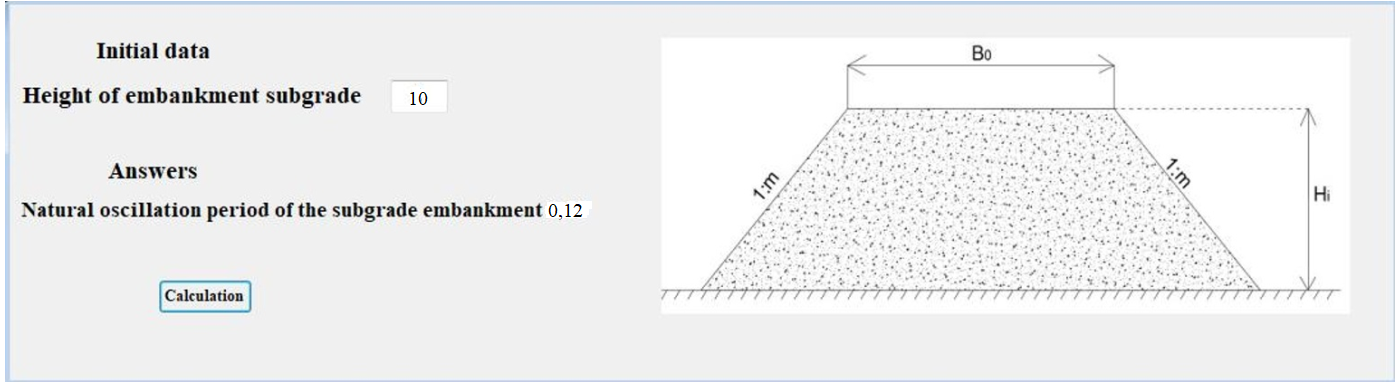


**FIGURE 7.** When the height of the railway track in the passage section is 1 meter, the period of oscillations caused by train movement is 0.04 seconds

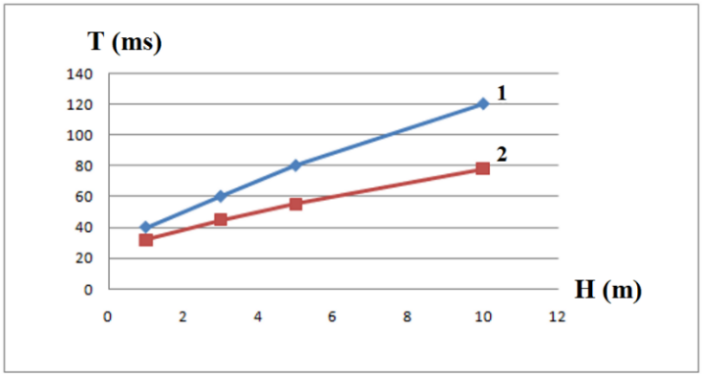
**FIGURE 8.** When the height of the railway track in the passage section is 2 meter, the period of oscillations caused by train movement is 0.05 seconds

**FIGURE 9.** When the height of the railway track in the passage section is 4 meter, the period of oscillations caused by train movement is 0.07 seconds**FIGURE 10.** When the height of the railway track in the passage section is 6 meter, the period of oscillations caused by train movement is 0.09 seconds

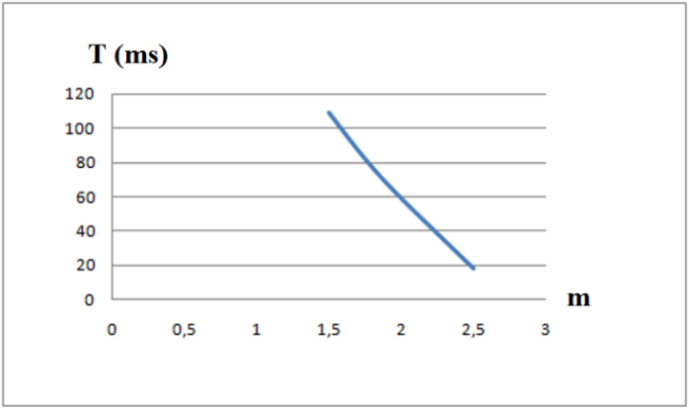
**FIGURE 11.** When the height of the railway track in the passage section is 8 meter, the period of oscillations caused by train movement is 0.1 seconds

**FIGURE 12.** When the height of the railway track in the passage section is 10 meter, the period of oscillations caused by train movement is 0.12 seconds

Using the above program, we obtain a graph of the period of oscillations of the railway track in the passage sections during the movement of high-speed trains depending on the height and slope of the track is shown in Figure 13, 14.



**FIGURE 13.** T=f(H), H1=1 m, H2=3 m, H3=5 m, H4=10 m link graph:  
1 - one – track subgrade; 2-two-track subgrade

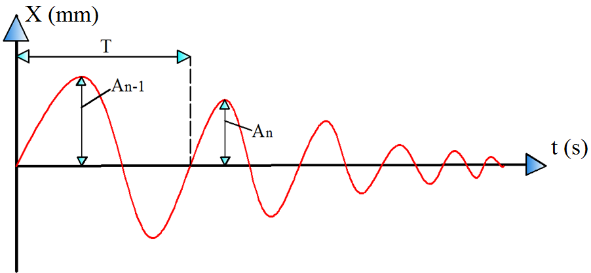


**FIGURE 14.** T=f(m), m1=1.5, m2=1.75, m3=2, m4=2.5 link graph

Based on the graphs, it can be said that with an increase in the height of the railway track, the magnitude of oscillations arising from the movement of trains also increases. The second line on the T=f (H) graph substantiates the possibility of achieving damping of oscillatory motion as a result of strengthening the passage sections by driving a reinforced concrete pile.

The active pressure that the soil exerts on the bridge shore support is greatly increased by the movement of the high-speed train as well as by the seismicity of the area through which the way track passes. As the dynamic rigidity of the subgrade soils decreases as it approaches the coastal base, the amplitude of oscillations increases, which can be reduced by tripping piles into the subgrade.

By processing the values obtained as a result of the experiment performed on the railway track model, we obtain a graph of damped oscillations is shown in Figure 15.



**FIGURE 15.** Graph of girder oscillations in front of the girder support

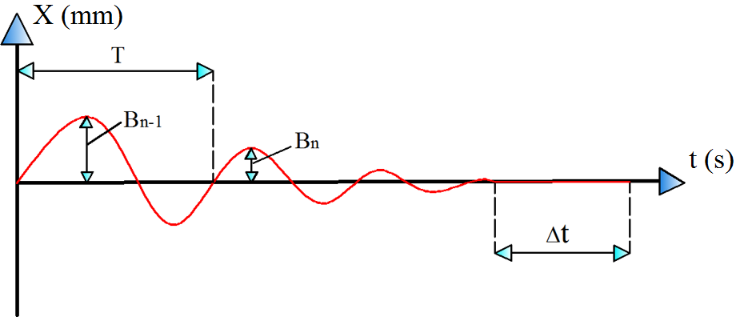
Ap is the n-amplitude of oscillations; A(n-1) is the n-1st amplitude of oscillations; T - is the period of oscillation.

The oscillations will continue to fade until the dynamic rigidity of the embankment becomes larger by the following Formula 3.

(3)

It is observed that the value of the logarithmic decrement, determined by formula 3, increases without reinforcement with piles, the main reason for which is an increase in the amplitude of oscillations during oscillatory motion.

In order to increase the dynamic rigidity of the embankment in front of the coastal base, we will drive the piles and look at the graph of the oscillations obtained using the SM-3 seismograph is shown in Figure 16.



**FIGURE 16.** Graph of embankment oscillations obtained near the shore base after the piles driving: Bn is the   
n-amplitude of oscillations; B(n-1) is the n–1-amplitude of oscillations; T - is the period of oscillation; ∆t is the early fading time of oscillatory motion

At the expense of increasing the lift rigidity with the help of piles, the logarithmic decrement of oscillations in the soils of subgrade decreases, that is, the time of oscillations is reduced by ∆t, as shown in Formula 4.

(4)

A decrease in the value of the logarithmic decrement, determined by formula 4, is observed for the case of reinforcement with piles, the main reason for which is a decrease in the amplitude value of oscillations during oscillatory motion. The finite and infinite element method also allows determining the value of the logarithmic decrement.

Seismograms recorded in test works aimed at determining the amplitude-frequency descriptions arising in a special model of the subgrade are presented in Figure 17.

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| а) |  |
| b) |  |

**FIGURE 17.** Seismograms of oscillations formed on the embankment in the passage sections from the railway track to the bridge: a) seismogram of oscillations on a pile with a SM-3 sensor installed, b) seismogram of oscillations on a railway track with a SM-3 sensor installed

The resultant value of the amplitudes in the seismograms of oscillations arising in the soils of the embankments in the passage sections from the railway track to the bridge embankment support is determined by Formula 5.

, (5)

where Bmin – is the smallest value of the amplitude in the seismogram (mm), Bmax is the largest value of the amplitude in the seismogram (mm).

Decreasing the logarithmic decrement greatly reduces acceleration shown in Formula 6, while increasing the seismic wave velocity as shown in Formula 7.

(6)

(7)

where, ω is the cyclic frequency of oscillations (1/s); π=3.14; T – oscillation period (s).

Using the above expressions 6 and 7, the maximum speed and acceleration of oscillations generated by train speeds in the embankment soils at the crossings from the subgrade to the bridges are determined.

Proposed method for reducing oscillations in the passage sections from railway track to bridge, it is possible to transfer part of the vertical forces from the train directly to the foundation compared to the use of existing structures, reduce the amplitude of oscillations, prevent residual deformation, and save material and labor costs for current and overhead repairs of the railway.

**CONCLUSION**

1. In order to prevent vertical dives of the railway track, it was proposed to strengthen the embankment with reinforced concrete piles, taking into account the increase in dynamic rigidity at the passage sections of the soils of subgrade with the bridge and the reduction of vibrodynamic oscillations.
2. Taking into account the reduction of the period of natural oscillations of subgrade soils under the influence of seismic force, work was carried out on the calculation of the period of natural oscillations of the soil of embankment under the ECM program “Visual Studio 2019, C#”.
3. A graph has been developed for determining the oscillations arising during train movement in the passage sections of the railway track and the bridge, according to which it has been established that by driving reinforced concrete piles into the embankment, the duration of the soil oscillations of the track decreases by Δt.
4. A method has been developed for reinforcing the slopes of the embankment with reinforced concrete piles to ensure elastic operation, reducing the specific weight and amplitude of oscillations of the subgrade in the zones of connection of the railway embankment with the bridge's coastal support.

**FUTURE SCOPE**

Advanced Numerical Modeling: The research in the future can be done with the advancement of numerical modeling of the subgrade reinforced with concrete piles under different loads and seismic activities (such as Finite Element Method, Finite Difference Method). Predictive tools based on AI can also enhance the accuracy of the modeling integrating them.

Optimisation of Pile layout and Pile geometry: Additional research work can optimise the geometry (length, diameter) and layout (spacing, arrangement) of reinforced concrete piles under various soil conditions and load. It will guarantee efficiency with minimum cost on material.

Multi-Axial Vibrations: What is the detailed soil-structure interaction (SSI) in multi-directional seismic and moving train-induced dynamic loading in order to understand how reinforced concrete piles reduce oscillations?

Smart Monitoring Systems: Real-time monitoring systems could be developed based on using IoT-based sensors (accelerometers, strain gauges) placed inside the embankment and piles to provide monitoring on vibrations and detect the failure early, as well as to provide long-term structural health.

Scaled Models Experimental validation: The theoretical and numerical solutions can be experimentally validated by making laboratory-scale physical models and full-scale field modeling experiments. This will assist in enhancing reliability and practicability of the reinforcement methods.

Greener Eco-friendly Reinforcement Materials: Research on basket (Bristol) or bamboo will be undertaken into alternatives to conventional reinforcement materials in piles, and earlier work on geopolymer concrete or fiber-reinforced composite may provide more sustainable, less-corrosive and less-environmentally-damaging piles.

Influence on High-Speed Railways: Further investigations can involve behaviour of embankment-bridge transition points that are reinforced with concrete piles designed and used specifically with high-speed trains where the dynamic force and the vibration are very strong.

Combination with Earthquake-Resistant Design Guidelines: Investigate how the role of pile-reinforced embankments can be specified and made standard across countries and continents, included in national and international earthquake resistant design guidelines concerning railway infrastructure.

Long Term Settlement and Fatigue Assessment: Study the long-term settlements of the reinforced embankments, fatigue of the reinforcements to repeated load and material degradation particularly in high ground water areas.

AI-Based Predictive Maintenance: Data on the path of the new road and monitoring parameters can be used by integrating AI/ML in algorithms and predict outcomes such as possible failures, maintenance requirements, or recommend an ideal course of action in building reinforcement in the same terrain and similar soil structure.

Cost-Benefit Analysis of Mass-Scale Deployment: Deployment of pile-reinforced embankments in the entire railway networks of a large number of countries would present an overall cost-benefit analysis based on lifecycle cost comparison, operational advantage, better safety, and reduced downtimes.

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