INVESTIGATION ON THE STABILITY AND DYNAMIC RESPONSE OF SOIL FOUNDATION UNDER HEAVY HAUL RAILWAY TRACKS

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***Abstract**:* The roadbed is the most deformable and most heterogeneous segment of the railroad track foundation, which states the principal factor deciding the efficiency of the street, and the primary factor behind deterioration of path and its components, leading to the rise in the expense of current maintenance. Notwithstanding the expanding dynamic effect of trains on the railroad framework resulting from heavy haul transportation system, this issue turns out to be especially significant. In this paper, an examination is made of the issue of degradation and giving the strength to the track foundation with an increased axial load on the track, with a strict attention on examination of the excitation mechanisms of cyclic effects and the procedure of their damping by the soil environment. The principal kinds of deformations and defects are portrayed; the mechanisms and explanations behind their occurrence are studied in this paper. Much consideration is paid to the investigation of soil degradation procedures of the roadbed under the dynamic effect of heavy trains. Different components of the roadbed are taken into account, which require support for operation under substantial heavy traffic and huge axial loads. The advanced strategies and structures of strengthening the roadbed are portrayed, the utilization of which permits to build the proficiency of the heavy haul transportation. Taking everything into account, extensive research is carried out to address the issue of ensuring the stability of the roadbed in the association of heavy haul traffic.

1.INTRODUCTION

General:

All over the world, the growth in weight norms of freight trains is one of the priorities to meet the increasing volumes of cargo transportation and improving the efficiency of railways in market conditions. The heavy haul traffic has developed significantly in different countries on all continents: Australia, Brazil, India, Canada, China, Russia, USA, Sweden, South Africa, becoming one of the main indicators of technological progress of railway transportation at the present stage of railway development. The operation of longer and heavier trains provides significant benefits in terms of carrying capacity, operating expenses, and the cost of a rolling stock. At the same time, the introduction of the increased weight and length of freight trains inevitably increases the costs associated with changing the longitudinal dynamics of the train and the emergence of additional loads on the infrastructure. There are large dynamic shock loads having a very high intensity and short duration, depending on the nature of the oscillations of the wheels or rails, and also on the dynamic response of the base. A large cyclic load from trains with heavy axle loads operating at high speeds often causes excessive deformation and degradation of rail track elements. This problem is most acute with regard to the fundamental element of the construction of the railway - the roadbed (foundation), which in many sections of the railways was built according to the technical norms of previous years, not designed for increased axle loads, and which, unlike the top of the railway, operation was not replaced or updated. The loss of stability of the roadbed and, as a consequence of the geometry of the path, inevitably entails a significant increase in the cost of servicing the railway track, estimated in different countries by hundreds of millions of dollars per year.

The railway track formation is a complex of ground objects that function in difficult conditions of the natural and climatic environment and dynamic train loads. Such loads can change the state of the ground environment and affect the level of reliability of the roadbed, especially under conditions of heavy haul traffic, in which the amplitude and frequency of loading cycles are very high.

The degree of displacement of the track under the train load is largely determined by the characteristics of the roadbed soil, which are distinguished by a wide variety, and has a tendency to rapidly change over time. During long-term operation, the railway roadbed is affected by adverse environmental impacts (temperature, water, etc.). As a result, transformations occur in the soils over time. Namely, the physical and mechanical properties, moisture regime, density, and, as a consequence, the stress-strain state of the roadbed as a whole change. For this reason, the roadbed has a huge impact on the operation of the railway and its maintenance. The railway track, which has been stable for a long time, can begin to deteriorate after applying large axial loads typical for heavy haul rolling stock, resulting in a failure to provide the required weights and train speed.

2.OBJECTIVE:

In the current situation of increasing speeds and train loads, special attention should be paid to improving the stability of the track formation. A deeper understanding is required for the mechanisms of dynamic load propagation from heavy haul trains to the track foundation soils and their influence on the mechanical behavior of soils, which in turn depends on the soil type, the water content, the degree of compaction and the type of loading. The further development of existing and creation of new technical solutions for increasing the strength and stability of the roadbed is required. In recent years, great progress has been made in the research aimed at understanding the processes occurring in soils under the vibrodynamic effect of heavy haul trains. A great theoretical and experimental material has been obtained, which requires generalization and systematization. The work mainly focused at increasing the stability of the roadbed under high axle loads, such as the arrangement of protective layers, strengthening of soils, and constructive solutions. Their most characteristic features are analyzed. The section also explains how the use of these methods alters the properties and parameters of the railway track foundation. An attempt is made in the article to reveal current tendencies in the field of inventive activity in the considered direction on the basis of the analysis of patents of the last 10 years.

3.LITERATURE:

3.1 Introduction

So far, several reviews have been published in the field of degradation and stabilization of materials and structural elements of the railway track under the influence of heavy haul trains [2,11–21]. Most often, researchers have focused on the permanent way. Published scientific reviews refer to rails [13–16], sleepers [2,18,20], elastic elements [19]. Several recent reviews have been published with a focus on ballast and transition zones of the variable stiffness transitions between the ballast structure and man-made structures, particularly in **Sol-Sánchez and D’Angelo (2017) [17] and Sanudo et al. (2016)** [21]. At the same time, there are no review articles devoted to the problems of degradation and stability of the soils of the track formation under the dynamic impact of heavy haul trains. Most of the work in this area is diverse and multidirectional. However, in the last few years, there have been quite a lot of changes in this field of research, worthy of attention and discussion.

The purpose of this review is to analyze the degradation and stability of the track foundation under the heavy haul train traffic in the context of the latest scientific research and operational experience, with an emphasis on the features of the mechanisms of excitation and analysis of the consequences of the vibrodynamic impact on the soils of the foundation.

The first section briefly describes the problems of the railway track foundation, which originate in the lower structure of the track and are associated with intensive deformation processes under conditions of increased axle loads from heavy haul trains. The main defects and degradations in the construction of the track foundation due to railway degradation under heavy haul transportation are given.

In the second section, the mechanisms of generation and propagation of vibration are analyzed in the interaction of heavy haul rolling stock and engineering infrastructure. The estimation of the vibrational modes of the permanent way structure and the frequency ranges of its elements is given, as well as the nature of their influence on the track formation. The frequency patterns of the track formation geostructure under vibration influence are established.

The effect of parameters of ground media is analyzed including water saturation and external pressure on its mechanical characteristics (shear modulus and damping coefficient) in the region of small and medium shear stresses.

The last section discusses the main directions for increasing the stability of the roadbed under high axle loads, such as the arrangement of protective layers, strengthening of soils, and constructive solutions. Their most characteristic features are analyzed. The section also explains how the use of these methods alters the properties and parameters of the railway track foundation. An attempt is made in the article to reveal current tendencies in the field of inventive activity in the considered direction on the basis of the analysis of patents of the last 10 years.

4.EXPERIMENTAL SURVEY

4.1 Deterioration of Railway Track Foundation on Heavy Haul Lines

4.1.1 Description of The Problem

The traditional railway track is not capable of providing reliability under the influence of increased axle loads and train speeds. The rapid growth of axle loads leads to a more intensive wear and tear of the permanent way and track formation. Additional risks arise in terms of traffic safety, as well as the cost of the railway track maintaining. Accelerated degradation and deterioration of the railway track is the main problem for the heavy haul transport and requires constant maintenance costs. Separate works are devoted to important problems of rail surface wear and fatigue phenomena in the elements of the permanent way, which can lead to deteriorations and train derailments.

4.1.2 Deterioration Processes in Railway Track Foundation

The railway track is a complex engineering structure that can be divided into two main components: the upper track structure (permanent way) and the track substructure (track foundation). The cross section of a railway track showing its structure is given in Fig. 1.

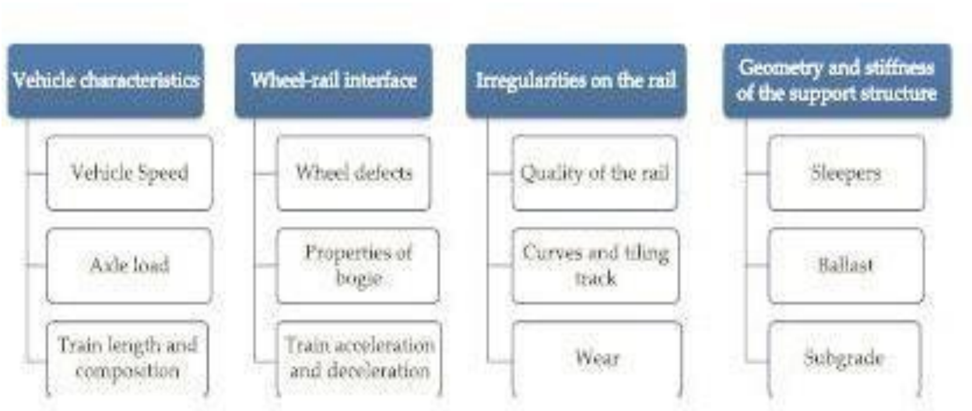
The condition of both the track structure and substructure plays an important role for the safety and comfort of any kind of transportation. Effective and stable operation of the railway under the heavy haul trains is possible when its track structure is able to bear the periodic force impacts of high axle loads from heavy haul trains. The upper structure of the railway track consists from rails, sleepers, fastenings, and other elements. Dynamic processes and deteriorations in the permanent are of great interest and widely discussed in the literature. Among The typical deteriorations of the permanent way are usually related to the rail head wear, accumulation of residual deformations and material fatigue in rail joints, track geometry degradation. These problems become more frequent in the conditions of heavy haul transportation and may lead to the speed limitations or even train derailment. Rail track substructure is the most essential component of the railway system in view of track stability. It includes ballast and sub-ballast layers (granular layers), blanket and a subgrade. Granular layers of the railway track are packed with angular rock particles (usually 20–60 mm). The ballast is the key load-bearing layer that provides structural support against dynamic stresses caused by moving trains. It performs a number of functions:

regulates the distribution of the loads intensity from the sleepers transferred to the roadbed.
reduces the pressure from sleepers on the underlying structural layers preventing settlement of the upper structure of the track.
providing resistance to the movement of sleepers under the influence of forces (for example, in curved sections).
provides the necessary drainage and trapping of surface water.
accumulates fine particles within the voids.

The stability and condition of the ballast is directly related to the proper functioning of the sub-ballast layer. The dynamic loads from the heavy haul trains creates stresses in the subgrade to 5 m and above. A stable foundation can begin to destruct rapidly after a noticeable increase in the axial load under heavy haul traffic. The stability of the railway track is also affected by the karstic soils (karst caves, sinkholes). Karst occurs in areas with soluble rocks (carbonates, gypsum, chlorides and other) and efficient underground drainage. The development of karst in the railway subgrade leads to railway track settlements.

4.2. Dynamic Interaction Between Heavy-Haul Train and Soil Subgrade Bed Vibration Induced by Heavy Haul Trains

Vibrations are a consequence of the movement of heavy-haul train and the contact interaction of wheels, rails and subgrade. Their impact on a track foundation increases along with the increasing maximum axle load from 7 to 40 tons. There are many parameters that affect the level and characteristics of the induced heavy haul train vibration, including, in particular vehicle characteristics, wheel-rail interface, irregularities on the rail, geometry and stiffness of the support structure.



One of the main mechanisms for excitation of ground vibrations from a moving heavy- haul train, is the quasi-static pressure created by the wheel axle on the rail track. Such pressure extends into the track foundation through the sleepers. The length of the train speed and the spacing between sleepers determine the mechanism of vibrodynamic impact characterized by temporal delay between the forces and their location in space, represented as a superposition of elastic waves transmitted into the ground. Examples of loads on the railway track with resulting accelerations and pressures on the roadbed are shown in Table 2.

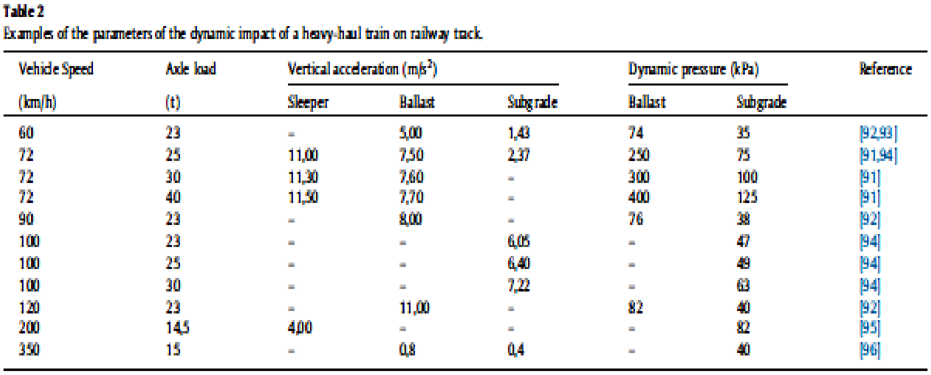


Table 2
Examples of the parameters of the dynamic impact of a heavy-haul train on railway track.

Vehicle Speed	Axle load	Vertical acceleration (m/s^2)			Dynamic pressure (kPa)		Reference
(km/h)	(t)	Sleeper	Ballast	Subgrade	Ballast	Subgrade	
60	23	-	5,00	1,43	74	35	[92,93]
72	25	11,00	7,50	2,37	250	75	[91,94]
72	30	11,30	7,60	-	300	100	[91]
72	40	11,50	7,70	-	400	125	[91]
90	23	-	8,00	-	76	38	[92]
100	23	-	-	6,05	-	47	[94]
100	25	-	-	6,40	-	49	[94]
100	30	-	-	7,22	-	63	[94]
120	23	-	11,00	-	82	40	[92]
200	14,5	4,00	-	-	-	82	[95]
350	15	-	0,8	0,4	-	40	[96]

Studies of the dynamic load and vehicle designs in solving the problem of the impact of heavy haul train on the transport infrastructure have shown that the rolling stock, rail track, ballast and subgrade play different roles in the generation of propagating vibrations. Vibrational modes of the railway track are determined by the resonant frequencies of the elements of the track infrastructure, which can include in-phase and out-of-phase vibrations and can be divided into low- (0–40 Hz), medium- (40– 400 Hz) and high (400–1500 Hz) frequency ranges affecting the track foundation and permanent way. The vibration frequencies resulting from the described above mechanisms depend on the speed of the train. Table 3 presents the characteristic frequencies for each of the key elements generated by the dynamic impact on the roadbed.

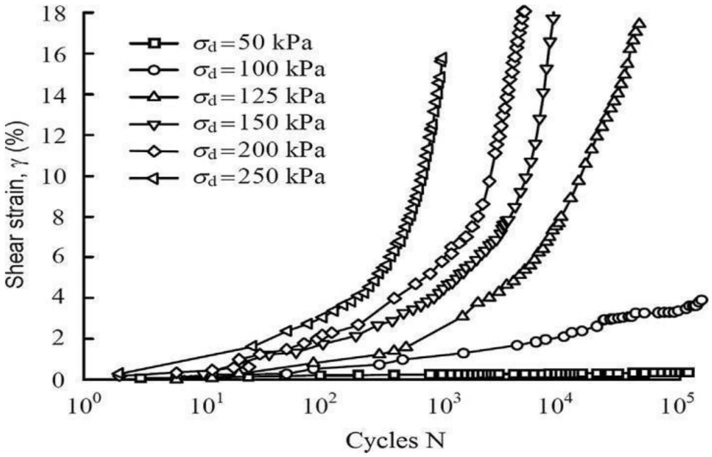
The vibration created by the railway movement is transmitted through the upper structure of the railway track to the ground. The soil is not a homogeneous medium and has significant differences between the layers, which determine the specific features of the process of the elastic wave's propagation. Therefore, a correct understanding of the degradation processes arising in the ground environment is an actual transport task and is of great importance.

4.2.2 Degradation of Subgrade Soil Under Loading:

Dynamic stability of soils is the basis for solving the problem of reducing the rigidity and strength of soils under dynamic loads from heavy haul trains. The mechanism of stability degradation of the roadbed is due to the ability of soils to absorb the energy of dynamic impacts, growing under development of heavy haul transport. The soils composing the track foundation can be divided into Cohesive soil and Cohesionless soil. The most important factors determining the dynamic properties of track foundation are shear modulus and damping ratio. Both depend on the number of cycles and the frequency of the vibrodynamic effect.

4.2.3 Cohesionless Soil

The vibrational processes that occur during cyclic loads in highly compressible disperse soils are accompanied by a redistribution of ground particles and an increase in its density, leading to a decrease in the sensitivity of non-cohesive soil to dynamic loads, reaching the existing critical values of density and porosity coefficient. Fig. 10 shows the characteristic behavior of non-cohesive soils with the increase of cyclic dynamic impacts from heavy haul train. The accumulation of shear deformations leads to settlement of the ground mass, demonstrated in the mutual displacement of particles, accompanied by their repackaging and can be prolonged. Increasing the train axle load accelerates the process of settlement of cohesionless soil. The consolidation of particles of disconnected soils is maximum in the dry and water-saturated state but decreases noticeably with increasing humidity. Hyperbolic dependence between the coefficient of porosity of sand and acceleration (or power) of vibrations from heavy- haul train in the region of vibration acceleration to _10 m/s2 is determined by linear dependence.



Cumulative deformations in cohesionless soil under heavy-haul train loading.

Rapid growth of pore pressure in conditions of increasing moisture content and dynamic impacts can provoke the processes of its liquefaction and the loss of its bearing capacity, caused by the loss of direct contact between the grains of the ground environment. Continuing dynamic impact leads to the removal of water and soil compaction, increasing the resistance to subsequent vibrodynamic effects. For dynamically stable cohesive soils, negative pore pressure is characteristic, accompanied by an increase in the cohesion of soil medium particles. In conditions of continuous low-amplitude cyclic loads, mobility under dynamic loads and without inversion of the stress sign does not allow dense water-saturated cohesionless soils to provide considerable shear resistance, which can lead to their sudden liquefaction (within the more friable zones that are formed in this case). The degree of sign inversion of the tangential stresses in each load cycle has an immense influence on the nature of development and the consequences of cyclic mobility, since the deformation of the soil is thereby greatly facilitated.

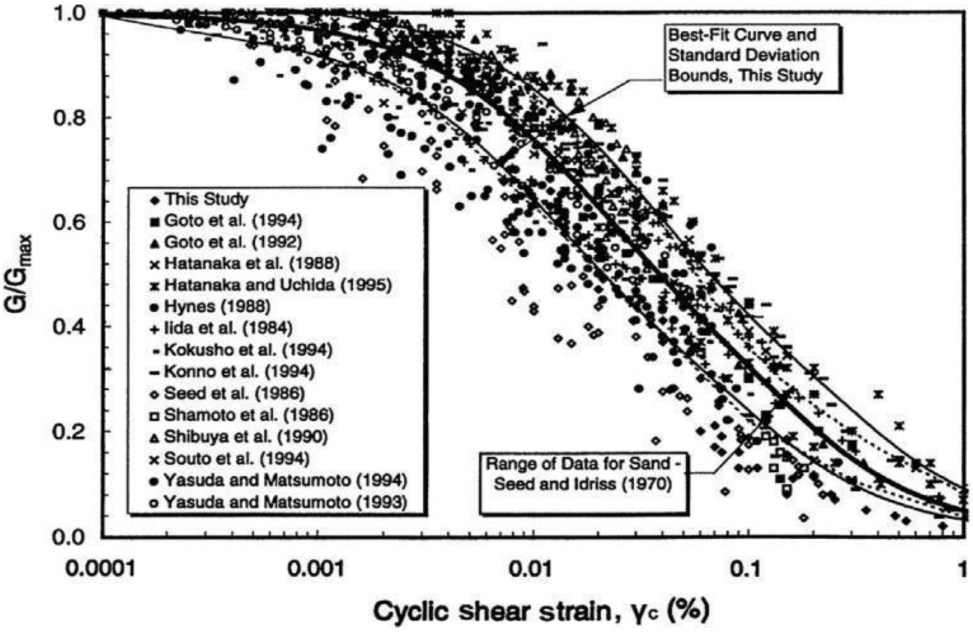
Analysis of a wide class of samples of non-cohesive soils studied in was completely

generalized in, which summarized data is given in Fig. 11. Their approximations allow determining the dependence for the normalized shear modulus G/Gmax on shear strain (c) as a slowly varying hyperbolic function. The empirical relationship between shear modulus (G) and shear strain (c), determined in, is described by the following equation:

$G/Gmax = 1/(a+by(1+10^{-cy}))$

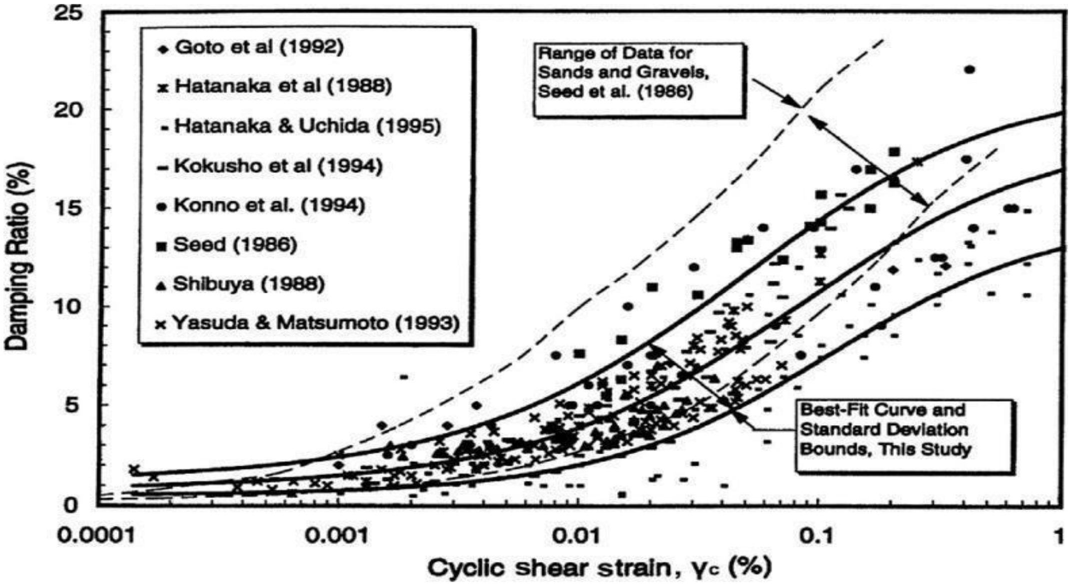
where a, b, c are the parameters that depend on the selected non cohesive soil, which are selected considering the deviation of the experimental data and the curve values for the selected c is minimal. When calculating the optimal values of the parameters (a, b, c) for the regression function G (c), the least squares method can be used to achieve a minimum discrepancy with experimental data. For approximation by the averaged data from, the parameters correspond to the values: a = 1.2; b = 16; c = 20 and were determined with an accuracy of ± one standard deviation. These parameters give a curve passing near the center of the data range represented in Fig. 11. A similar result was obtained earlier in for sands.

It was found that the regularity parameters vary depending on the granulometric composition of the cohesionless soil. The relative decrease in the deformation modulus usually occurs faster in soils of a larger fraction. At the same time, the curve topology describes well the experimental data, wherein their accuracy can level the existing variation. During each dynamic load cycle, a certain amount of vibrodynamical energy is damped. With a small deformation (c h1 0 _5), the damping ratio (D) is rather low (2–4%) for cohesionless soil, changing significantly less than shear modulus (G) for small deformations, see Fig. 12. With an increase in the shear strain, the effect of the plasticity index Ip on shear modulus (G) becomes more pronounced. At a shear strain level of 10-3, the damping coefficient is about 10–15% in low-plastic (granular) soils, whereas attenuation in cohesive soils is much less – the order of 3–8%. The average value of the data for sand and gravel presented by Seed et al. is in good agreement with the data obtained by Vucetic and Dobry.



Proposed G/Gmax for cohesionless soil based on the experimental results of several researchers.

Proposed D curves for cohesionless soil based on the experimental results of several researchers.

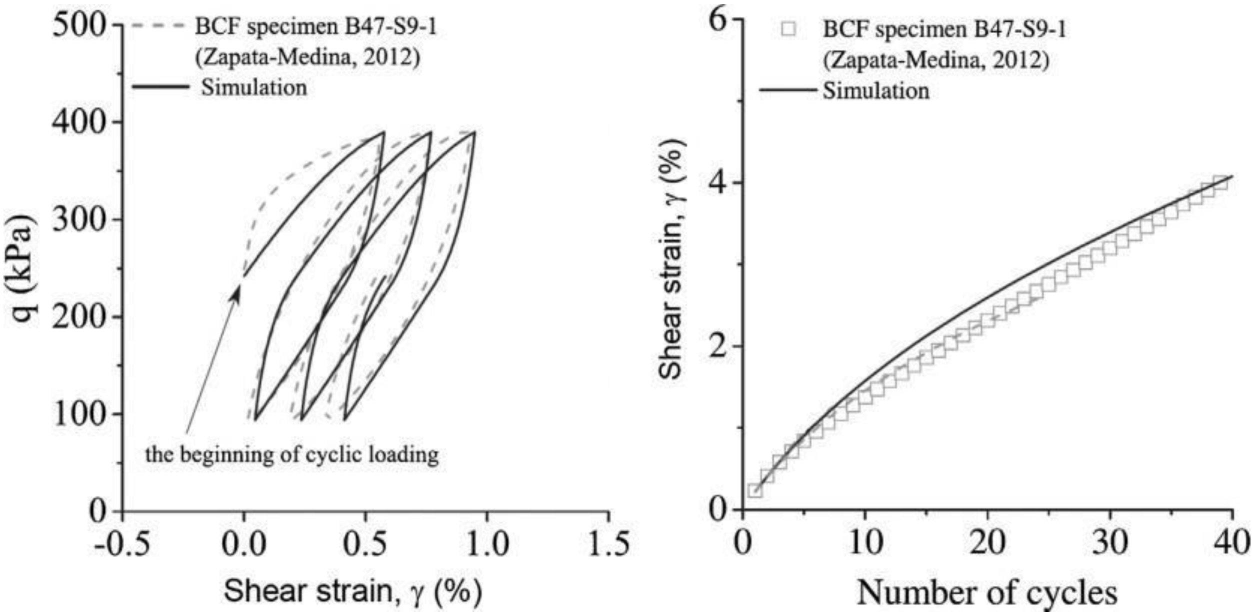


4.2.4 Cohesive Soil

Dynamic instability of cohesive soils manifests itself in the form of partial or complete (until liquefaction) loss of strength under dynamic action, which leads to large uneven settlements of engineering structures, landslide formation and other negative consequences. After vibration stop, these soils are capable of thixotropic restoration of strength, due to the complete or partial destruction of structural bonds of the soil under the action of an external load and their subsequent spontaneous restoring in rest with constant temperature, porosity and moisture. However, the ultimate strength of natural cohesive soils after the completion of the restoration, as a rule, does not reach the initial level, which is due to their quasi- thixotropic. Restoration can be partial or almost complete, when the soil is liquefied, although it is quite rare in comparison with cohesionless and weak soils. In this case, the strength changes only through adhesion, and the angle of internal friction of the soil does not change. The effect of cyclic loads leads to the accumulation of deformation by cohesive quasi- isotropic soils (Fig. 13). For small deformations (c h1 0 _5), the changes in the shear modulus coefficient occur according to a quasilinear law. Gmax is constant and does not depend on the magnitude of the shear strain. The main factors affecting Gmax are the porosity coefficient and the acting voltage. The minimum value of the damping coefficient Dmin is also independent of c in the region of small deformations and is determined by the pore fluid and load frequency in the interval up to 10 Hz.

Impact of cyclic loads on cohesive soils based on the experimental results of several researchers.

The growth of cyclic deformations leads to the appearance of a hysteresis effect. In this case, the possible increase in pore pressure and a decrease in the bearing capacity leads to an increase in plastic deformation. An increase in the cyclic loading time can lead to an increase in the rate of deformation, as well as when a critical number of cycles is reached, to loss of ductility of cohesive soils. Based on the results of the analysis of cyclic loads on cohesive soils in the conventional and consolidated state, it was established in that the main factor affecting the normalized shear modulus G/Gmax and the damping coefficient D is plasticity index (PI), see Fig. 14. The observed regularity is due to a change in the deformation mechanism from the viscous to the hysteresis mechanism.



Curve G/Gmax (a) and D (b) for cohesive soil based on the experimental results of several researchers.

At the time of the termination of the vibration action, a hardening having a thixotropic nature occurs. Three effects are based on this hardening:

An increase in the interaction energy of particles in the secondary potential well due to the approach to the optimum

An increase in the number of structural bonds per unit volume of soil due to the destruction of microaggregates; and

The formation of a new bond more homogeneous in strength structure.

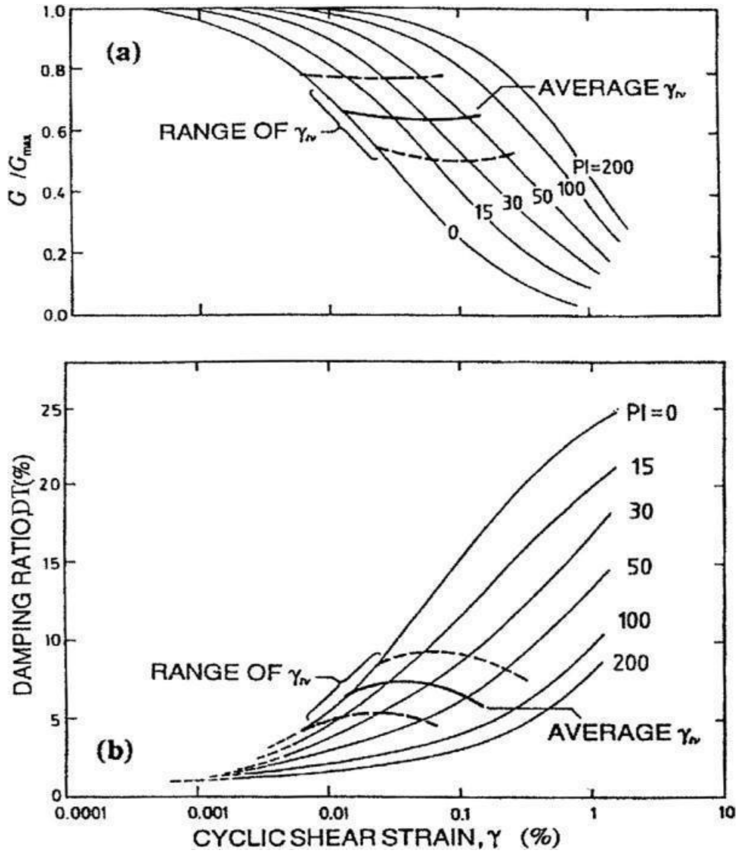
In studies with compacted cohesive soils, an increase in the value of Dmax to _10% was found in comparison with the natural state of bound soils. A similar tendency is observed in, where an increased damping factor Dmax is reported for naturally cemented cohesive soils. An increase in the creep rate during vibration, leading to degradation of the soil strength (lowering the creep threshold) and accelerating its destruction or accumulation of deformations occurs in conditions of prolonged vibrational loads. The moisture increase accelerates the degradation of strength under dynamic influence, and the dependence of the value of the softening coefficient on moisture passes through a maximum, usually near the yield point. This is explained by the weakening of structural bonds and the increase in the mobility of particles as their hydrate shells thicken when the moisture rises to a critical level, above which the initial strength of the soil already in the fluidly or even stealthy consistency decreases sharply, leading to a decrease in the relative softening.

The moisture content of the maximum softening is practically independent of the dynamic load parameters and is determined by the physico-chemical activity of the soil. Here, the optimum moisture content occupies a special place, at which the shear modulus (G) and the damping ratio (D) of the samples increase. In [200], an additional study was made of the influence of the water saturation of the cohesive soil on the normalized young’s modulus E/Emax, which showed its linear dependence on the moisture content in the sample. The increase in pressure leads to the fact that Gmax ceases to depend on the water content in the sample, and the damping coefficient Dmax taking values in the range 6.5–8.5%.

The factors of maximum reduction in the strength of cohesive soil under dynamic impact are the time or number of impact cycles. For relatively high frequency (5–40 Hz) tests on a shaker, this time interval does not exceed 5 min for clay soils of plastic consistency and is reduced to 1–3 min when testing specimens of fluid or secretive consistency. Thus, the number of loading cycles necessary for the most complete degradation of soil strength or the accumulation of critical deformations can be very great under certain conditions but depends on the power characteristics-the amplitudes of the acting stresses and vibration acceleration. With their increase, the energy of the dynamic effect on the soil increases, causing an increase in its softening, which, however, is damped: when a certain critical level of power is reached, most structural bonds that determine the strength of the soil are destroyed? Therefore, a further increase in the amplitude of the stresses and in the acceleration of the oscillations cans no longer lead to any noticeable additional softening. The greatest decrease in strength, as a rule, is observed with vibroacceleration up to 0.7 g.

The influence of frequency on the dynamic properties of cohesive soils is determined, first of all, by the duration of the action of the maximum stresses in each cycle. In addition, in one way or another, the influence of the frequency of impact on the dynamic reaction of cohesive soils determines: 1) the rate of pore pressure dissipation, 2) the growth of the energy of the action with frequency, 3) resonant phenomena, 4) creep and 5) thixotropic restoration. In the region of vibrational frequencies (above 5 Hz) with increasing frequency of loading at constant amplitude, the energy of impact on the ground increases, causing a progressive decrease in strength. However, this increase in softening is not a monotonous function of the frequency and is complicated by resonance effects. Most often, the resonant strengthening of softening for different clay soils is recorded in the range of 11–25 Hz, and for quasiisotropic soils one sufficiently flat resonance maximum of the strength degradation is observed.

The accumulation of deformations and soil weakening can be slowed down by a decrease in frequency due to partial thixotropic soil restoration between load phases. And thixotropic restoration begins to appear not immediately, but after a certain level of destruction of structural bonds of soil - in this case, when the specimen is axially deformed, about 3% (after about 50–60 cycles).



5.RESULTS & DISCUSSIONS:

5.1 CURRENT SOLUTIONS FOR STABILITY IMPROVEMENT OF SOIL FOUNDATION IN HEAVY HAUL RAILWAY TRACKS

The reliability of the railway track is determined by the quality of the construction of the roadbed during its building. Various techniques and approaches have been used for the track foundation reinforcement providing its stability and load-bearing capacity. They are intended to increase the efficiency of the heavy-haul traffic.

One of the main reasons of the roadbed reinforcement under increasing freight traffic and dynamic loads from heavy haul trains is its insufficient bearing capacity, which is primarily caused by defects and deformations of the track foundation and the decrease in the stability of embankments slopes and cut sections. In general, the reliability of the railway track is determined by the quality of the construction of the roadbed during its building. Implementation of any changes in the roadbed on the operating railway section is rather difficult. This tightens the compliance requirements for construction and building technologies. During the maintenance of the operated section of the railway, the most simple and economical way to keep it in proper condition is to provide internal or external drainage to drain unwanted water from the inside and outside the track. In some cases, to lower the stresses in the ground to a level sufficient for reducing the progressive shear and plastic deformation, it may be enough only to increase the thickness of the ballast and sub-ballast layers. However, this does not exclude the need for repair or modification of the roadbed construction. The main features of the reinforcement of the existing railway track foundation are that the maintenance must be carried without interrupting train traffic in a short time on a limited and small working area. In this regard, many reinforcement techniques that can be used during the new roadbed building, in these conditions are not applicable. Usually, the implementation of these activities for existing railway section is carried out with overhaul works or reconstruction of the track. Today, various techniques and approaches have been used for the track foundation reinforcement providing its stability and the load-bearing capacity. The current techniques for improving the operational characteristics of the roadbed are given in Fig. 15. They are intended to increase the efficiency of the heavy-haul traffic. These techniques can be divided into three groups: (1) protective layers, (2) soil improvement, (3) structural solutions (Fig. 15). A wider classification of soil improvement methods, covering not only railway, but also civil engineering, can be found in the special literature.

5.2 Protective Layers

One of the most effective techniques for the railway subgrade reinforcement is installing the protective layers under the ballast to perform the following basic functions:

Reinforcement –uniform distribution of the train load on the soils of the subgrade, reducing vertical stresses in order to provide the load bearing capacity.

Waterproofing – protection of the subgrade from atmospheric water.

Separation – preventing mixing the particles of the ballast material and the subgrade soils.

Frost protection – protection against freezing of the underlying frost-susceptible soils of the subgrade.

Vibration protection – providing effective mitigation of impact and vibration damping from trains.

The standard material for the construction of protective layers of the subgrade is artificially selected sand and gravel mixtures. Their main disadvantages in reinforcing the existing subgrade are insufficient mechanical characteristics and the need for deep cutting the soil, which becomes expensive under the conditions of the operating railroad section and does not fit into traditional repair techniques.

5.3 Soil Improvement

The second group of track reinforcement techniques under consideration is soil improvement methods, which are currently widely used in civil engineering. Complete replacement of substandard soils in the track foundation is the most effective way to restore its performance. However, such a technique is feasible only when the trains are completely stopped for a long period of time and only in those regions where the network of railways and highways is well developed and it is possible to redistribute traffic to other roads for the period of repairs. The way out of this situation seems to be the application of methods to increase the stability of the operating sections of the railway roadbed, based on the transformation of the initial physico- mechanical properties of soils. The essence of these methods lies in the use of various soil treatment technologies, along with partial or complete artificial transformation of their structure. These include thermal fixing of ground with hot air and combustible fuel, electroosmosis, lowering of groundwater level, sealing by loading, vibration, use of various fibrous materials, silicification, use of enzymes, resin treatment, jet cementation bitumization, etc. However, with regard to rail transport, the economic feasibility of the above methods is ambiguous and requires careful analysis in each specific case (on the one hand, rather cheap solutions, on the other - expensive equipment and labor-intensive strengthening works).

The most reasonable and tested in the conditions of heavy haul traffic to date are techniques of reinforcing the roadbed, providing the treatment of soils with cementitious binder materials. Depending on the work technology and the treatment area, these methods are divided into two types:

in-depth - hardening of soils is carried out without a disturbance of its natural formation. Surface - hardening of soils is carried out with a disturbance of its natural formation by mixing it with the hardening solutions.

Generally, the purpose of treating the soils of the railway track formation with cementitious binders is to increase their strength and waterproofness. Shang et al (2017) used cement to stabilize the swelling soils of the subgrade of the heavy haul section of the Menghua, Haolebaoji-Ji'an, China railway. Using the dynamic triaxial test method, the authors studied the regularities of the dynamic characteristics of a cement-stabilized swelling soil in a wide range of vibrodynamic loads. The results of their studies show that, in comparison with the initial unstabilized swelling soil, the dynamic shear strength and modulus of elasticity of stabilized cement soil increases by 2–3 times, while its critical dynamic stress - by 5–6 times. The expediency of using cement binders to stabilize swelling soils was also evaluated in, confirming the effectiveness of this approach. One of the in-situ methods of the roadbed stabilization is the jet grouting technique, based on the simultaneous destruction and mixing the soil with a high-pressure jet of a cementing material. This technique allows strengthen a wide range of soils - from gravel deposits to finely dispersed clays and silts. An important feature of this technology for the stabilization of a railway roadbed is the high speed of construction of soil–cement piles. Thus, it allows to perform construction and repair works during the limited time windows, in cramped and difficult conditions - on slopes, tunnels, approaches to the bridges. At the same time, an inaccurate determination of the technological parameters of jet grouting under given geotechnical conditions significantly increases the production time and cost of construction.

Therefore, the economic feasibility of using this technology requires at the preparatory stage a very thorough assessment of the quantitative parameters characterizing the effectiveness of the soil treatment process for various working conditions and areas of technology application. Furthermore, one of the main limitations of jet grouting technology is the difficulty of reliably predicting the geometry of the final ground-cement body, which is strongly dependent on the parameters of the medium injection and the properties of the soil to be strengthened.

Deep Soil Mixing (DSM) technology is known as one of the most effective ways to stabilize weak soils under road and railway embankments to improve their stability. The technology of deep soil mixing is the production of soil-cement piles using special drilling- mixing equipment. Deep mixing is performed by feeding the binder (cement, lime, gypsum, slag) under pressure into a weak soil with simultaneous stirring. As a result of the application of the technology, a substantial increase in the strength and deformation characteristics of the weak soil is achieved.

In the study by Esmaeili and Khajehei (2016), laboratory tests were carried out on the deep mixed columns when strengthening the embankment on sandy grounds using cement. Based on the laboratory experiments carried out on the physical models of embankments, the authors showed the possibility of increasing the bearing capacity of the embankment using deep mixed columns by _63%.

In the work of Lambert et al. (2012), static load testing of two 600 mm diameter columns on silty ground is discussed (Fig. 22). The results of these tests showed a strong mechanical response of the columns providing an increase in the bearing capacity of the base. At the same time, laboratory tests of excavated columns showed heterogeneity of the ground-cement material, which affects the uneven distribution of compressive strength and modulus of elasticity along the length of the column

5.4 Structural solutions

The third group under consideration is constructive solutions for increasing the stability of the track foundation soils. Table 6 presents some well-known examples of the implementation of the methods of this group with respect to the problem of strengthening the railway track under heavy haul traffic.

Study of Esmaeili and Arbabi (2015) was devoted to an experimental and theoretical study of the separated tied back-to back system (STBBS), which is a rod with support plates at the ends, and designed to stabilize high rail embankments (Fig. 24). The results of laboratory tests indicate that STBBS can increase the load capacity of the track foundation to 35%. The results of numerical finite element analysis showed that with the construction of a single row of STBBS, the calculated safety factors of 10, 15 and 20 m embankments under a load of 25 tons per axle increase by 12.5%, 19.5% and 24% respectively. The use of the second row of STBBS can provide for 15 and 20 m embankments an increase in the safety factor by 27% and 40.4%, respectively. In the subsequent works of Esmaeili and Arbabi (2017) it was shown that the increased effect of the application of the tied back-to-back system can be achieved by grouting, the use of which increases the failure load of railway embankment by up to 37% compared to the tied back-to-back without grouting.

Another study of Sabermahani et al. (2018) considers the possibility of stabilizing existing embankments using the integrated tied back-to-back system (ITBBS), in which, unlike the previously proposed STBBS, separated ties are attached to each other through continuous end bearing plates. This decision, in addition to increasing the side-slope of the mound, allowed increasing its bearing capacity by up to _50%. The possibility of using the methods of horizontal reinforcement to improve the stability of the roadbed under the impact of heavy haul trains is also considered by Hu and Luo (2018), using the example of a mechanically stabilized earth (MSE) wall, which is a block of soil reinforced externally by a facing wall, and inside by a reinforcing element (metal nets, geotextiles, geonets, etc.).

Strengthening of the foundation soils of heavy haul lines can also be carried out with use of piles. For this purpose, different types of piles are used. Pile reinforcement is one of the technologically simple methods and allows to save materials in comparison with the complete excavation of weak soils and replacement of them with stronger ones. Depending on the construction method and types, piles can play the role of bearing elements that receive loads from the structure or can be used to compact and improve the properties of weak water-saturated soils.

Micro piles, which include piles with a diameter of less than 300 mm, can increase the bearing capacity of the roadbed and reduce the development of sediment. Vertical and inclined grill ageless micropiles can be used for the formation of the reinforced soil array to increase the stability of the bases and the embankment slopes. In particular, based on the results of physical and FEM simulations, it was shown in Esmaeili et al. (2013), that using at the embankment toe with 2 vertical and 2 inclined at 45_ micropiles provides an increase in loadbearing capacity of 65%, while the settlement of the embankment crest decreases by about 35% and uplift movements of the bed sides are reduced by more than 65%.

A method for reinforcing a railway track is known, based on a device for vertical drainage wells (Prefabricated Vertical Drains, PVD), which functions to disperse the excess pore pressure that occurs when consolidating the soils of a weak base. PVD are used to accelerate the consolidation of weak cohesive soil substrates under embankments.

6.Conclusions:

This article comprised a state-of-the-art review of dynamic behavior and stability of soil foundation in heavy haul railway tracks. From this review, the following concluding remarks can be drawn:

The track foundation is the most important element of the railway track construction. It is subject to intensive dynamic impact under the development of heavy haul transport. The operation of heavy trains with increased axle load results in rapid occurrence of deformations and defects in the track foundation, which increases the cost of track maintenance and the requirements for its construction.

Typical failures in the track foundation are mostly associated with ballast degradation and insufficient load-bearing capacity under heavy haul traffic conditions. In particular, high axle loads contribute to the uneven settlements of the ballast layer (ballast pockets); fooling the ballast material, causing drainage deterioration and consequently over moistening the track foundation. As a result, the track foundation degrades and its load bearing capacity decreases.

The main factors that determine the dynamics of soil behavior of the roadbed under cyclic loads from heavy haul trains are its magnitude and duration. In the case of cohesionless soils, an increase in the number of loading cycles leads to hyperbolic dependence on its deformation, and the steepness of this curve is determined by the amount of loading accelerating the process of shrinkage of soil with increasing accumulation of shear deformations. Stabilization of shrinkage of cohesionless soil of the track foundation reaches a maximum in the state of optimum moisture and significantly decreases with the growth of water saturation and long cyclic loads without inversion of the stress sign, leading the ground

environment to liquefaction. The shear modulus in the region of small deformations is determined by the hyperbolic dependence, which rate of decrease rises with increasing fraction of the soil. The growth of the damping properties
of cohesionless soils is low (_2–4%), for small deformations substantially increases (_20%) with prolonged cyclic loads during compaction.

The basis for increasing the load-bearing capacity of cohesive soils under cyclic loads from a heavy haul train is a taxotrophic effect that ensures the complete or partial restoration of the broken structural bonds of the soil. The factors of maximum reduction in the strength of cohesive soil under dynamic impact is the time or number of cycles of impact. The influence of the frequency of cyclic impacts on the dynamic properties of cohesive soils is determined, first of all, by the duration of the action of the maximum stresses in each cycle. The balance between the accumulation of deformation and the destruction of structural bonds of ground is dense, determined by the period of cyclic loads. The complete degradation of the strength of the ground or the accumulation of critical deformations is determined by the amplitude of the acting stresses and by the acceleration, reaching _0.7 g. The mechanical properties of cohesive soils in the region of small deformations, which depend only on the porosity coefficient and the acting stress with increasing strain, are determined significantly by the Plasticity index (PI), which is due to the change in the deformation mechanism from viscous to hysteresis.

The use of geosynthetics, asphalt mixtures, concrete and piles are currently the most common ways of stabilizing the railway track foundation when organizing heavy train traffic. The choice of a technical solution should be based on an integrated assessment of soil, hydrological, climatic conditions, the type of construction (embankment height, depth of excavation, steepness of slopes), based on a technical and economic comparison of options. At the same time, the wide introduction of the methods of reinforcing the roadbed in question requires the methodically correct observation of the construction and operation of experimental structures and the generalization of the results of these observations.

A possible direction to increase the stability of the roadbed in order to minimize uneven subsidence of the foundation is the use of impurities to existing soils to improve the mechanical properties of the subgrade soils, and to ensure quality control of soil compaction at the construction stage in order to achieve its maximum and uniform density. Conflict of interest There is no conflict of interest. Acknowledgments This work
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