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ЗАЛІЗНИЧНА КОЛІЯ

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FEATURES OF PERCEPTION OF LOADING ELEMENTS OF THE RAILWAY TRACK AT HIGH SPEEDS OF THE MOVEMENT

Purpose. Increase the train speeds movements requires not only the appropriate technical solutions, but also methodological-calculated. Most of the models and methodologies used for solving problems of stress-strain state of the railroad tracks, are based on assumptions and hypotheses adequate only for certain speeds. In the framework of this work will be discussed theoretical background of the changing nature of perceptual load elements of the railway track at high speeds and investigated the numeric parameters of the processes by means of mathematical modeling. As a practical purposes is expected to provide the levels of train speed, the boundaries of which can reasonably exclude the possibility of occurrence of the considered effects. **Methodology**. To achieve these objectives was used principal new model of railway track based on wave propagation theory stresses in the elastic system to study the impact of the movable load, take into account that the deflection in a particular section of the road starts even while the wheels at some distance, and moving the wheels farther from the selected section of the wave front elastic strain continues to spread. According to the results of simulations explores the changing shape of the wave front voltages in time for the foundation under the rail. If the train speeds substantially less than the velocity propagation of elastic waves, the wheel remains in the area implemented deformations. **Findings**. Alternative calculations for various parameters of the railway track (especially for different soil conditions) determined the levels of train speed, the boundaries of which can reasonably exclude the possibility of occurrence of the considered effects. **Originality**. The proposed theoretical study and implementation in the form of mathematical models for processes that occur in the perception of load elements of the railway track at high speeds. **Practical value.** According to simulation results obtained levels of speeds, which define the appearance of the considered dynamic effects in the base under the rail, can be used to justify path construction or establishment of appropriate values of allowable velocities for the implementation of traffic at high speeds.

Keywords: superstructure; high-speed movement; tension of rail; rail deflection; wave model; slab track; ground distortion

Introduction

The steady tendency of transport developments networks demands from railway transport to keep and improve a current state for competitiveness preservation. One of the main indicators of a choice of transport mode traditionally remains the speed of cargo and passengers delivery [9].

The increasing of train speeds service demands not only the appropriate technical means, but also methodological-calculated. Many models and the techniques which are used for the solution of strain-stress state tasks of a railway track based on assumptions and hypotheses adequate only for certain levels of speed movement.

There are elastic deformations and the corresponding tension as a result of reaction to loading from passing rolling stock in a railway track. The bend and compression of layers of a railway track occurs very quickly, but nevertheless not instantly.

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Time for reaction directly depends on speeds of distribution of elastic waves in material of the corresponding element of a track. It is clear that in cases when the loading speed (the movement of the train) of one level with a reaction speed, processes of interaction get significantly others looked in comparison with static loading. Considering that for the majority of materials from which the railway track consists, speeds of distribution of waves considerably exceed opportunities even modern high-speed trains, this question didn't demand attention. But today this thought changes on opposite, especially, as far as concerns railway tracks on soft grounds in which the speed of distribution of waves isn't so great. In some works even the term «soil blow» by analogy to sound blow started appearing [11, 14].

So at the site of the railway that runs along the waterfront Stilton in the UK recorded a sharp change deflection of the rail at speeds of 180 km/h. The explanation was found in the presence of ballast in soft soils such as peat and silty clay [15].

In the Netherlands, the area between Amsterdam and Utrecht conducted tests for measuring the velocity of wave propagation in the soil for the possibility of passing the French TGV train speeds over 160 km / h in areas with mounds, consisting of weak soils [15].

In the south-west Sweden in Gothenburg, Malmö site speed train X2000 was limited to 160 km / h in wave phenomena in the soil [13].

The presence of certain problems of railway track on weak soils is noted on some railroad of Hungary [12].

The issue of delay appearance of rail deflection at high speeds went up in the Austrian authors [3], where, in addition to theoretical considerations, experimental evidence shows the results corresponding effects on test plots near Vienna at speeds over 230 km / h.

Purpose

The theoretical prerequisites of emergence of effects of «soil blow» are considered within this work and numerous parameters of process by means of mathematical modeling are investigated. As the practical purpose it is supposed to provide equal train service speeds within which it is possible to exclude possibility of emergence of the specified effects reasonably.

Methodology

Most current models of stress-strain state of railway track, usually based on the principles of static elasticity. It is assumed that the considered system of bodies in a state of equilibrium and elastic deformation under the applied force immediately reach respective values. It isn't enough such approach for tasks in which time between the moment of the appendix of loading and establishment of true balance it is comparable with time of action or change of loading. It doesn't correspond to that on a task and the method of final elements which was widely adopted recently including for modeling of a railway track: it doesn't give the chance to receive full four-dimensional model.

For the solution of these objectives essentially new model of railway track based on the wave theory of tension distribution in system of elastic bodies [1, 2, 8] was used. For creation of such model the railroad is considered as spatial system of objects which are characterized by the geometrical sizes and physical properties determining speeds of distribution of waves and parameters of deformations of elasticity and shift. The emergence and distribution in a body of object of spatial spherical waves is considered as a reaction to action of external forces. Distribution of waves is corrected by the extent of objects and considers changes in parameters of wave process upon transition from one object to another, and also emergence of the reflected waves from borders of contacts. The common decision of the equations describing position of the front of a wave at the moment of time, and the equations defining change of potentials of tension in a body of objects taking into account dynamic deformation of material is result. Such approach gives the chance with a certain temporary in interval to define borders of distribution and value of tension and deformations.

Let's consider the process of forming a deflection of the rail on the example of modeling a sudden application of force to the wheels on the rails. Initially there clutching the rail voltage, but very fast (about 0.03^{rd}-ms) are transmitted to the substrate and then to sleepers. At 0.09^{th} ms and intensity of ties begin to be transferred to the ballast. Almost at the same time (0.1^{st} ms) load transferred from rail begins on the first adjacent sleepers and further along the length of the rails. Deformation substrates lead to a redistribution of stresses in the

doi 10.15802/stp2015/42172

rail and provides the beginning of the bend. At 0.3^{rd} ms and tie is already full contact with the ballast to half its length, given as sole sleepers, and its lateral surface. Ballast begins to contract, making it possible to extend the rail curve. During the transition from the front tension ties to the ballast area of interaction will vary over time (increase from point to the entire surface of the sole sleepers).

From the first moment of this interaction strain will be distributed in the thickness of ballast, but the speed distribution over the surface of the ballast will be significantly less than the growth rate of the area on which the stress transferred from sleepers on ballast. This leads to more complex shapes of the wave front in comparison to the classical description of distribution as two-axial. Depending on the thickness, condition, physical properties of matter ballast, etc., by 1.0…1.8 ms and tensions begin to be transmitted to the roadbed. With the growth and proliferation of elastic contraction in roadbed is at last re-stresses between the layers of sub rail basis and in another passage of some time, depending on the properties of the soil, rake up the final parameters of bending.

Thus, the deflection of a rail is provided with deformation of all layers of which the sub rail basis consists. It must be kept in mind that for a «full» deflection of a rail of deformation of a sub rail basis have to gather the corresponding values not only directly on a vertical shaft of application of force, but also on all length of a lath, it is attracted to a deflection. Depending on the module of elasticity of a sub rail basis length of a notable deflection of a rail makes some meters.

According to the velocity propagation of elastic waves, eventually increasing depth sub rail basis, which is involved in the formation of deflection rails, but on the other hand, the deformation depth decreases rapidly reduce their impact on the overall deflection. Furthermore, even already gained significance in certain strains depth marks do not remain constant over time, and are oscillatory (although aimed at damping) character. All this complicates the criterion for determining such estimated moments when we can assume that the deflection rails gained full implementation.

In the numerical calculations fixed deformation of sub rail bases on several axes adjacent sleepers - the points of coincidence rail deflection and deformation sub rail bases. By bending the rails, as a reference value, determined by the modulus of elasticity sub rail base. If further development deflection changed the modulus of elasticity no more than 5%, it is conventionally recorded acquiring «full» deep.

The change in the wave front of outline stresses in railway track on the simulation results for the soil deformation modulus of 25 MPa is shown on figure 1. The vertical axis on figure coincides with the axis of application of force. The last line shows the time to 26.5 ms after the date of application of the load, for this example corresponds to the condition «full» deflection rails.

For the example figure 2 shows the relationship of the analytical rail deflection by the formula (1) [4, 5] and deflections of sub rail bases axes sleepers on the results of modeling for steady state

$$z = \frac{Pk}{2U} e^{-kx} \left(\cos kx + \sin kx\right), \qquad (1)$$

where P – the vertical force operating on a batten; k – coefficient of relative stiffness; U – elastic modulus of sub rail basics; x – distance along the length of the rails from the point of force application.

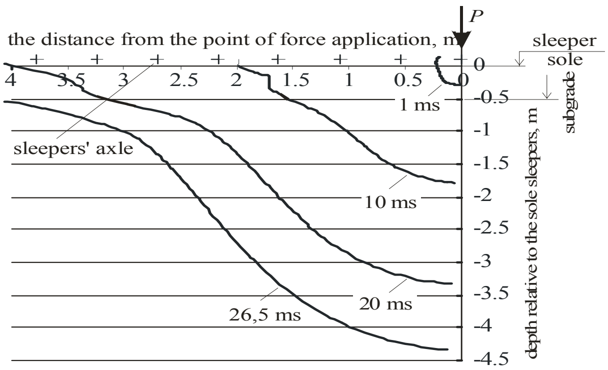

Fig. 1. Outline of the wave front in sub rail space

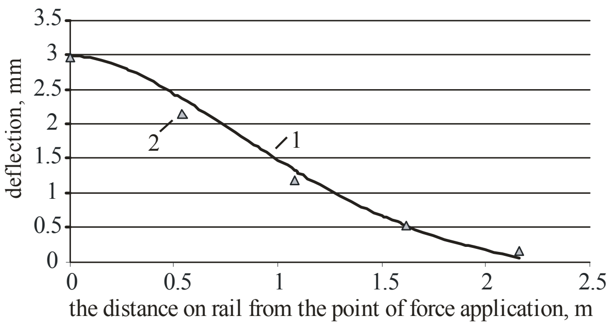

Fig. 2. Change the trough length:
1 − Analytical deflection rails; *2* − deflection of sub rail foundations for re-modeling results

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If to consider conveyances of loading (the movement of a wheel) on a rail, it is incorrect to describe process of a deflection of a lath in section from zero to maximum value, preceding from the assumption what exactly is in this section a wheel all the time of development of a deflection. For probe of a certain section of track, it is necessary to consider that the deflection in it begins in the wheel time spent for some distance. At the movement of a wheel further from the chosen section the front of a wave of elastic deformation continues to extend. In a case when the speed of the movement of the train is significantly less than a speed of distribution of elastic waves, the wheel always remains in a zone of the realized deformations.

If to enter designations: $A(x)$ – set of points of a half-space are limited to the front of a wave sufficient for realization of a «full» deflection $z_п$ in the point x; $B(x,t)$ – set of points of a half-space are limited to the front of a wave after its distribution relatively $A(x)$ on time t, so between running speed, at get on «full» deflection, will be defined by reference

$$z(V) = z_п : A(x+Vdt) \in B(x,dt). \quad (2)$$

The example of calculation by reference (2) for relative exaggerate value dx is shown on fig. 3. At running speed V_1 (line 2) the bending deflection have time to form completely and at speed V_2 (line 4) do not have time.

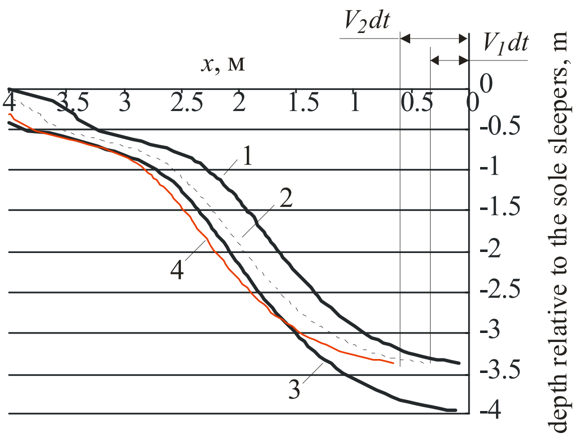

Fig. 3. Outlines of a wave fronts:
1 – $A(0)$; 2 – $A(V_1dt)$; 3 – $B(0,dt)$; 4 – $A(V_2dt)$

Thus, calculations show that the movement with so high speeds can take place; the bending deflection of a rail won't be able to manage to reach the values expected behind static schemes. Perhaps that is said about these processes, for example, in [3]. However, it is still too large such speed, even larger than the transverse velocity of wave propagation in the soil. This is explained by the redistribution quickly load ground work first ties, and ballast. In a number of works ([12, 13, 15]), on the contrary, growth of bending deflections of a rail at the movement with speeds is shown the big just cross wave speed in the soil.

To show an explanation of this process, it is possible on the static circuit. As a rule, the theoretical part of tension calculations and deformations in ballast and a road bed is based on decisions of Bussinsk, Flaman and Mitchell and on their more modern additions. Anyway the half-space, brought to a two-dimensional task which free surface is loaded with constant external force is considered. From loading in the thickness of a half-space there is tension and deformations connected by Hooke's law. The solution of a task consists in clarification of dependence between the external force and internal tension (deformations) [6]. Force is counterbalanced by reactions from deformation of the massif of a half-space. In the Boussinesq's classical formulation the part of half-space conditional section created a half circle of constant radius. Basic Flaman's formulation is considered weightless isotropic plate is limited with only one horizontal side, which has concentrated the external force. The solution, which is proposed by Mitchell in an original form corresponds a cone by the loaded force applied to its top and works in the direction of its axil [10].

Let's consider a task in Boussinesq's classical formulation, but we will separate the settlement array of a half-space biaxial the sphere, answering outlines to distribution of the tension wave at the most enclosed in a point. The analytical model is given in fig. 4.

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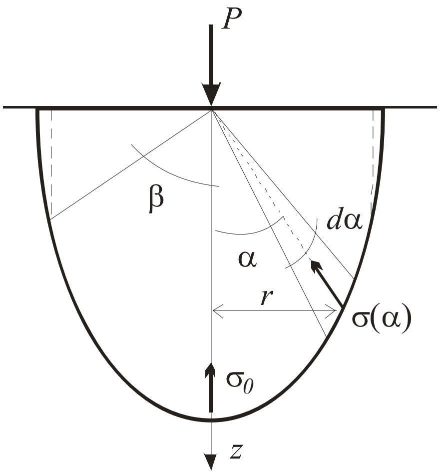

Fig. 4. The analytical model for tension determination in the environment from single unit force

The external load is considered as single unit force P, that applied at the point and acts in the vertical direction (axel « z «). The axes sizes areas determined in accordance longitudinal (C_l) and transverse (C) speed of wave propagation:

$$\left.\begin{aligned} C_l &= \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \\ C\ &= \sqrt{\frac{E}{2\rho(1+\mu)}} \end{aligned}\right\}, \qquad (3)$$

where E – stress-strain modulus; ρ – density of matter; μ – Poisson's ratio.

It is possible to consider that the section surface in space consists of separate rings (fig. 5) which radius increases to a surface

$$r = C_\alpha t \sin\alpha , \qquad (4)$$

where α – angle that determines the position of the point on the section, $\alpha \in [0; \pi/2]$; C_α – wave velocity in the direction α ; t – time indicator.

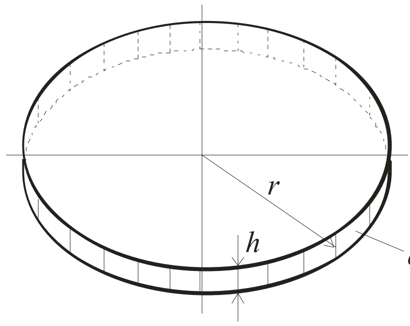

Fig. 5. Space of the action ring tension of identical value

The area of the ring will be determined by the formulation

$$dF(\alpha) = 2\pi r h , \qquad (5)$$

where h – conventional thick rings, $h = C_\alpha t d\alpha$; or in a final form

$$dF(\alpha) = 2\pi C_\alpha^2 t^2 \sin\alpha d\alpha . \qquad (6)$$

On the surface calculation section will apply tension and strain occurs as a reaction to external force. Different issues can be considered normal and tangential components of the stress acting on the ground tangent to the surface and cross section perpendicular to the direction of the force, etc. If in a general view to tell about full of tension σ_α, forces directed to a point of application, that, considering that the surface of section is formed by the sphere, the following dependence is offered

$$\sigma_\alpha = \sigma_0 \frac{C_l^2}{C_\alpha^2} \cos^2\alpha , \qquad (7)$$

where σ_0 – stress acting along the axis of application of force P .

For the system which is in an equilibrium state (the static task is considered), the equation has to be carried out

$$P = \int_0^{\frac{\pi}{2}} \sigma_\alpha \cos\alpha dF(\alpha) , \qquad (8)$$

or, considering the previous formulas

$$P = 2\pi C_l^2 t^2 \sigma_0 \int_0^{\frac{\pi}{2}} \cos^2\alpha \sin\alpha d\alpha . \qquad (9)$$

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Equation (9) can be reduced to Boussinesq's formulation definition of stress at a given depth z

$$\sigma_0 = \frac{3P}{2\pi z^2}. \quad (10)$$

The hypothesis is that at a movement speed $V > C$, the sphere (see Fig. 4) doesn't manage to be created. In that case external loading will be counterbalanced by a smaller surface

$$P = 2\pi C_l^2 t^2 \sigma_0 \int_0^\beta \cos^2\alpha \sin\alpha d\alpha, \quad (11)$$

where β – angle, that determines the level of implementation areas,

$$\sin^2\beta = \frac{\varphi^2}{1-\varphi^2}\left(\frac{C_l^2}{V^2} - 1\right), \quad (12)$$

where $\varphi = \sqrt{\frac{1-2\mu}{2(1-\mu)}}$.

The level of increase in vertical tension, and respectively and deformations, it is possible to express through coefficient which shows the reaction attitude from the full sphere (9) reactions from the limited sphere (11)

$$k = \frac{\frac{1}{3}}{\int_0^\beta \cos^2\alpha \sin\alpha d\alpha}. \quad (13)$$

Given the above dependence and taking Poisson's ratio equal to 0.3, the rate of increasing in vertical stress and strain can be obtained in the form

$$k = \frac{1}{1 - \left[1.4 - \frac{1.4C^2}{V^2}\right]^{\frac{3}{2}}}. \quad (14)$$

More detailed calculations require taking into consideration that the bending deflection of rail consists not only of ground deformation that shape the wave front in the soil, being transferred from ballast different from the correct biaxial field [7], and so on. In a certain degree it is possible to reach applying the mode of modeling stated above [8].

As an example, in fig. 6 the dependence of a bending deflection of rail a wheel from movement speed for the soil with the module of deformation of 10 MPa received by results of modeling taking into account the stated hypothesis is shown.

Considered the characteristic of the soil there corresponds the cross speed of a wave 185 km/h. In fig. 6 significant growth in a rail deflection at the movement with speeds is observed, it is more than specified. Results are shown correspond to the experimental data given in work [15].

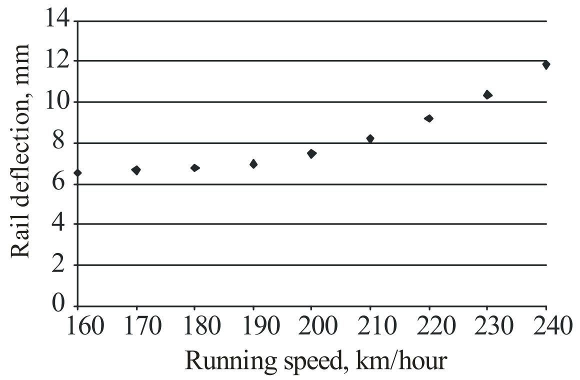

Fig. 6. The dependence of the rails deflection from the speed of the ground with E =10 MPa

Findings

Using the wave model of stress-strain state lines was determined speed, which upon reaching deflection rail does not have time to acquire the «full» value. The calculations were performed according to the conditions described above (see. Fig. 3). The various options of basic data are considered. Selectively results of calculations are given in tab. 1. Thus the design of a track was presented by ferroconcrete cross ties with distance of 0,54 m between shafts and a crushed-stone ballast 0,5 m thick under a cross tie.

According to the table it is possible to determine movement speed (C), at which the observed increase in rail deflections, and speed (V_z), in which will not have time to realize «full» deflection rails. Speeds are specified on a major factor - the module of deformation of a soil. The module of elasticity of a sub rail basis was defined results of modeling of a deflection as the additional characteristic.

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Originality and practical value

The latest similar of the intense deformed condition of a railway track which allowed solving problems for which time for emergence of reactions in a railway track from a rolling stock plays an essential role are applied.

The offered theoretical justifications of processes which take place at perception of loading elements of a railway track at high speeds of the movement.

According to the simulation results obtained significance level speeds that determine the appearance of the considered dynamic effects in sub rail basis. The obtained data can be used to justify the construction or installation gauge the relative values of allowable velocity for the implementation of high-speed traffic.

Table 1

Determinants level speeds

Stress-strain modulus, MPa		Modules of sub rail basis (U), MPa	running speed, km/hour	
ballast ($E_б$)	ground ($E_{гр}$)		Which exceeding the speed transverse waves in ground (C), km/hour	at which the deflection isn't completely realized (V_z), km/hour
100	7	11	160	215
	10	15	185	250
	15	20	230	315
	20	26	265	360
	25	31	300	395
200		38		405
	30	44	325	440
	40	53	375	485
	50	64	420	530
	75	86	520	640

Conclusions

At the movement of the train on a railway track with a speed more cross speed of distribution of waves in a soil nature of perception of loading in sub rail to a basis changes that gives to notable (to two times) to increase in rails deflections.

In the presence of soft grounds, the rate limit of the movement, corresponding to emergence of the specified phenomenon, decreases. So, for soils with the module of deformation of 7 MPa, the cross speed of waves distribution makes only 160 km/h.

Even at such speeds time to ensure soil elastic deformation to form a trough rails. This is because the load is distributed on a ground layer of ballast that provides quick involvement ground interaction.

With further increasing the speed of the sub rail basis may not have time to implement the entire length of the deformation formation deflection rails. This would result in effect when the rail will not have time to fully bend. Even in soils with little deformation modules (7…10 MPa) for the speed of the appearance of this effect has 215…250 km / h respectively. The level of speed, in addition to the characteristics of the soil (although they are crucial), also affect the properties of the layers of ground.

By drawing up a road bed of the ground which has the deformation module sufficient for providing the general module of elasticity of a sub rail basis at the level of 40…50 MPa and more (that is put in the majority of track calculations on strength) are investigated effects can appear at rather big on today's levels movement speed − 350…400 km/h and above.

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ОСОБЕННОСТИ ВОСПРИЯТИЯ НАГРУЗКИ ЭЛЕМЕНТАМИ ЖЕЛЕЗНОДОРОЖНОГО ПУТИ ПРИ ВЫСОКИХ СКОРОСТЯХ ДВИЖЕНИЯ

Цель. Увеличение скоростей движения поездов требует не только соответствующих технических а и методико-расчетных решений. Большинство моделей и методик, которые используются для решения задач напряженно-деформированного состояния железнодорожного пути, базируются на допущениях и гипотезах адекватных только для определенных скоростей движения. В рамках данной работы будут рассмотрены теоретические предпосылки изменения характера восприятия нагрузки элементами железнодорожного пути при высоких скоростях движения и исследованы числовые параметры процессов при помощи математического моделирования. В качестве практической цели предполагается предоставить уровни скоростей движения поездов, в границах которых можно обосновано исключить возможность появления рас-

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смотренных эффектов. **Методика.** Для решения поставленных задач была использована принципиально новая модель железнодорожного пути, основанная на волновой теории распространения напряжений в системе упругих тел. Для исследования воздействия от подвижной нагрузки учитывалось, что прогиб в определенном сечении пути начинается еще во время нахождения колеса на некотором расстоянии, а при движении колеса дальше от выбранного сечения фронт волны упругой деформации продолжает распространяться. По результатам моделирования исследуется изменение очертания фронта волны напряжений во времени для подрельсового основания. Если скорость движения поезда существенно меньше скорости распространения упругих волн, колесо остается в зоне реализованных деформаций. **Результаты.** По вариантным расчетам для различных параметров железнодорожного пути (прежде всего, для разных характеристик грунта) определены уровни скоростей движения поездов, в границах которых можно обоснованно исключать возможность появления рассмотренных эффектов. **Научная новизна.** Предложены теоретические обоснования и реализация в виде математической модели для процессов, которые возникают при восприятии нагрузки элементами железнодорожного пути при высоких скоростях движения. **Практическая значимость.** По результатам моделирования получены уровни скоростей движения, которые определяют появление рассмотренных динамических эффектов в подрельсовом основании. Они могут быть использованы для обоснования конструкции пути или установления соответствующих значений допустимых скоростей для внедрения движения с высокими скоростями.

Ключевые слова: верхнее строение пути; скоростное движение; напряжение в пути; прогиб рельса; волновая модель; подрельсовое основание; деформация грунта

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ОСОБЛИВОСТІ СПРИЙНЯТТЯ НАВАНТАЖЕННЯ ЕЛЕМЕНТАМИ ЗАЛІЗНИЧНОЇ КОЛІЇ ПРИ ВИСОКИХ ШВИДКОСТЯХ РУХУ

Мета. Збільшення швидкостей руху поїздів вимагає не тільки відповідних технічних, а й методично-розрахункових засобів. Багато моделей та методик, що використовуються для вирішення задач напружено-деформованого стану залізничної колії, базуються на допущеннях та гіпотезах, адекватних тільки для певних рівнів швидкості руху. В рамках даної роботи будуть розглянуті теоретичні передумови зміни характеру сприйняття навантаження елементами залізничної колії при високих швидкостях руху та досліджені чисельні параметри процесів за допомогою математичного моделювання. В якості практичної мети передбачається надати рівні швидкостей руху поїздів, в межах яких можна обґрунтовано виключати можливість появи розглянутих ефектів. **Методика.** Для рішення поставлених завдань була використана принципово нова модель залізничної колії, заснована на хвильовій теорії розповсюдження напружень у системі пружних тіл. Для дослідження дії від рухомого навантаження враховувалось, що прогин у певному перерізі колії починається ще під час знаходження колеса на деякій відстані, а при зрушенні колеса далі від вибраного перерізу фронт хвилі пружної деформації продовжує поширюватись. За результатами моделювання досліджується зміна обрису фронту хвилі напружень у часі для підрейкової основи. Якщо швидкість руху поїзда суттєво менше за швидкість розповсюдження пружних хвиль, колесо залишається в зоні реалізованих деформацій. **Результати.** За варіантними розрахунками для різних параметрів залізничної колії (перш за все, для різних характеристик ґрунту) визначено рівні швидкостей руху поїздів, в межах яких можна обґрунтовано виключати можливість появи розглянутих ефектів. **Наукова новизна.** Запропоновано теоретичні обґрунтування та реалізацію у вигляді математичної моделі для процесів, що мають місце під час сприйняття навантаження елементами залізничної колії при високих швидкостях руху. **Практична значимість.** За результатами моделювання отримано рівні швидкостей руху, що визначають появу розглянутих динамічних ефектів у підрейковій основі. Вони можуть бути використані для обґрунтування конструкції колії або встановлення відповідних значень допустимих швидкостей для впровадження руху з високими швидкостями.

Ключові слова: верхня будова колії; швидкісний рух; напруження в колії; прогин рейки; хвильова модель; підрейкова основа; деформація ґрунту

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