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DETERMINING VISCOELASTIC CHARACTERISTICS OF THE ELEMENTS OF MULTI-LAYER STRUCTURES BASED ON ENERGY DISSIPATION ANALYSIS

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Abstract

Introduction: The deteriorating operating conditions of roads is one of the most important problems facing specialists in the road industry. It is mainly associated with a reduction in the rigidity of road pavements made as extended multi-layer structures. To identify the causes of rigidity reduction, non-destructive testing is used, which is based on solving the inverse coefficient problem of restoring the elastic constants based on the response on the surface. **Purpose of the study:** We aimed to provide a rationale for a new pavement condition indicator that would take into account the history of deformation and loading from a source on the surface, based on which it would be possible to solve the inverse problem of restoring the elastic and viscous characteristics of pavement layers. **Methods:** To do that, we performed mathematical modeling of the stress-strain state of a multi-layer medium based on the solution of a system of dynamic Lame equations. Viscosity is taken into account by introducing tangents of the angles of wave energy losses in the materials of layers. **Results:** The results obtained in modeling for the first time made it possible to establish the relationship between changes in the modulus of elasticity as well as tangents of the angles of energy losses in pavement layers and the amount of energy dissipation in the structure. **Discussion:** It should be noted that it is possible to switch from the bowl of maximum dynamic deflections as the main pavement condition indicator to the analysis of hysteresis loops on the road structure surface, recorded at different distances from the point of load application and being an analogue of the full bowl of dynamic deflections showing the history of the test object loading.

Keywords

energy dissipation, multi-layer structure, modulus of elasticity, hysteresis loop, falling weight deflectometer.

Introduction

Multi-layer structures are widely used in construction. These are, first of all, roads, where the multi-layer structure is represented by road pavement consisting of the surface course, base course and subgrade perceiving the load from transport and natural factors. The most effective method of non-destructive testing, used to determine the mechanical characteristics of structural layers in road pavement, is the method of determining the modulus of elasticity of the layers, based on solving the inverse problem of restoring the required parameters by maximum vertical displacements (bowl of deflections) recorded experimentally under impact loading. Recent years have witnessed fundamentally new approaches to solving this class of problems: with the use of artificial neural networks (Han et al., 2021; Saltan et al., 2013; Vyas et al., 2021; Wang et al., 2021), genetic algorithms to adjust the theoretical and experimental fields of vertical displacements (Fwa et al., 1997; Le and Phan, 2021; Park et al., 2010; Tsai et al., 2004; Varma et al., 2013; Wang et al., 2019; Zhang et al., 2021), new approaches to dynamic deformation analysis (Bazi and Assi, 2022; Booshehrian and Khazanovich, 2018; Cao et al., 2020; Lee et al., 2018; Zhang et al., 2019; Zhao et al., 2015), consideration for the wave nature of deformation (Al-Adhami and Gucunski, 2021; Chatti et al., 2017; Marchant and Papagiannakis, 2010; Quan et al., 2022; Zaabar et al., 2014).

The wide range of those approaches is due to the high complexity of the problem being solved, mainly related to its optimization part, which requires correspondence between the parameters calculated with the use of mathematical models and the parameters recorded in field experiments. In most cases, experimental equipment for field measurements is represented by falling weight deflectometers (FWD) — a single-axle trailer with an impact loading mechanism mounted on it and equipment in the form of a beam with geophone sensors or accelerometers to record vertical displacements (Vyas et al., 2021). Mathematical models used to solve the direct problem of the theory of elasticity or viscoelasticity, depending on the formulation, may differ significantly. For example, both viscoelastic models of a multi-layer half-space in an analytical formulation (Al-Adhami and Gucunski, 2021; Bazi and Assi, 2022) and finite-element models of multi-layer structures (Chatti et al., 2017; Marchant and Papagiannakis, 2010; Park et al., 2010; Zaabar et al., 2014) can be used. As for methods to solve the optimization problem involving the adjustment of theoretical and experimental parameters, well-known gradient methods, such as the Newton method, which make it possible to minimize the standard deviation between the theoretical and experimental values, as well as methods based on genetic algorithms, are used.

In recent years, the search for a pavement condition indicator that would allow specialists to take into account the history of road structure loading and, therefore, evaluate the viscoelastic properties of the materials of layers as accurately as possible has become the main trend in the development of new methods and models to determine the mechanical parameters of structural layers in road pavements. It is obvious that the bowl of maximum deflections cannot serve as that indicator since it is a discrete characteristic, which does not show dynamic deformation processes occurring within 0.07–0.1 s in dynamic loading during full-scale experiments. Chatti et al. (2017) suggested using the amplitude-time characteristics of deformation as such an indicator. However, in that case, it is quite difficult to derive relationships linking the change in the corresponding rigidity characteristics with the change in the shape of the amplitude-time characteristic for each sensor and time delays between the peaks of the amplitude-time characteristics for each of them. Thus, this problem remains unsolved and extremely relevant since the quality of design solutions developed based on the results obtained during the experiments, and, therefore, the cost and durability of operated roads, depend on accuracy of those results.

We aimed to provide a rationale for a new pavement condition indicator that would take into account the history of deformation and loading from a source on the surface, based on which it would be possible to solve the inverse problem of restoring the elastic and viscous characteristics of pavement layers.

To do that, it is necessary to perform numerical modeling of the influence of elastic and viscoelastic characteristics of pavement layers on the proposed condition indicator and obtain corresponding relationships as well as carry out a trial calculation of elastic and viscous characteristics of pavement layers for an operated road section and assess the correspondence of the results obtained with its operating condition.

Methods

During the study, we used a mathematical model for the dynamic stress-strain state (SSS) of a multi-layer half-space. The SSS is determined based on solving a system of dynamic Lame equations with the use of the Hankel integral transform. Various researchers already considered solutions to this class of problems (Babeshko et al., 1989; Iliopolov et al., 2002; Lyapin et al., 2020; Vorovich et al., 1999).

The mathematical model is based on solving a system of Lame equations in the following form:

$$(\lambda + 2\mu)\, graddiv\mathbf{u} - \mu rotrot\mathbf{u} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2}, \tag{1}$$

where:

λ, μ — the Lame coefficients,

ρ — the material density,

$\mathbf{u}$ — the matrix vector of displacements.

The equation is solved by decomposing the displacement field into potential and vortex components in the following form:

$$\mathbf{u} = grad\phi + rot\psi. \tag{2}$$

By applying this decomposition and the Fourier integral transform to the system of Lame equations, after a series of transformations we can obtain a system of independent differential equations. The solution to the problem can be found as follows:

$$\mathbf{u}^{(j)}(\mathbf{r}) = \frac{1}{4\pi^2} \iint\limits_{\Gamma_1\Gamma_2} \mathbf{K}(\alpha,\beta,z,\omega) \times$$
$$\times \bar{\mathbf{T}}(\alpha,\beta) \exp\left[-i\alpha x - i\beta y\right] d\alpha d\beta, \tag{3}$$

where:

$\mathbf{K}(\alpha,\beta,z,\omega)$ — the components of the kernel of the integral representation of displacements;

$\bar{\mathbf{T}}(\alpha,\beta)$ — the Fourier transform of load $\boldsymbol{T}(x,y)$;

Γ_j — the integration contour determined by the principle of limiting absorption.

The solution algorithm was earlier described in more detail by Tiraturyan et al. (Tiraturyan, 2017; Tiraturyan et al., 2021; Uglova and Tiraturyan, 2017).

When the mathematical model was being developed, the presence of dissipation in the medium was taken into account by introducing tangents of the angles of wave energy losses in the material $tg\gamma$, considered in this equation when determining reduced vibration frequencies. Therefore, taking into account the principle of correspondence between elastic and viscoelastic problems:

$$\theta_j^2 = \theta^{*2}_j = re\theta_j^2 + i\,\mathrm{Im}\,\theta_j^2 = \theta_j^2(1 + itg\gamma). \tag{4}$$

In terms of the applicability of the SSS modeling results to solving the problem of non-destructive testing of the condition of individual road pavement layers, the main issue is the development of an effective criterion for their condition. The general solution to this problem can be written as follows:

$$\vec{u}(R_i,t) = \mathrm{K}(E_j)P(t); \tag{5}$$

$$\vec{u}(R_i,t) - \mathrm{K}(E_j)P(t) = 0, \tag{6}$$

where:

$\mathrm{K}(E_j)$ — the function that describes the theoretical relationship between the vertical displacements within the bowl of deflections and the modulus of elasticity of the material;

$P(t)$ — the load applied.

$\vec{u}(R_i,t)$ — the bowl of dynamic deflections.

The most effective way is to determine the full bowl of dynamic deflections $\vec{u}\left(P, R_i, t\right)$, where $t \in [0, t_{\max}]$. The characteristic can be constructed by superimposing the amplitude-time characteristics of deflections $\vec{u}\left(R_i, t\right)$ on the loading pulse excited by standard means of dynamic tests P(t). In essence, this characteristic is an analogue of a dynamic hysteresis loop calculated or recorded at characteristic points on the surface of the structure.

On the one hand, the function $\vec{u}\left(P, R_i, t\right)$ fully describes the kinetics of changes in the bowl of deflections on the pavement surface over the entire period of observation over object deformation. On the other hand, it is a hysteresis loop, and it can be uniquely characterized by the shape and area, which is an analogue of the energy spent on pavement deformation, determined as follows:

$$W = \int_0^t P(t)\dot{u}(t)dt. \tag{7}$$

Below, we present the results of studying the patterns of changes in this value depending on the rigidity of the structural road pavement layers and their viscosity.

Results and discussion

By using the developed model, we performed a series of numerical experiments to study the influence of the viscosity characteristics and modulus of elasticity of pavement layers on the area of the dynamic hysteresis loop. The tangent of the angle of energy losses in road pavement layers was used as the main viscosity characteristic. During numerical modeling, the following road pavement structure types were adopted (Table 1):

Figs. 1–6 show the results of calculating the areas of the dynamic hysteresis loops.

When the tangent of the angle of energy losses in asphalt concrete layers changes in the range from 0 to 1, the amount of energy dissipation (according to the sensor installed in the center of load application) varies within 14–20%. Smaller changes are typical for pavement structures with thinner layers, and larger changes are typical for thicker packages of asphalt concrete layers. Another characteristic feature is that the tangent of the angle of energy losses in asphalt concrete layers has the greatest effect in the area closest to the impact point, namely at a distance not exceeding 60 cm. The tangent of the angle of energy losses in subgrade soil has an effect in the range of 2–3% of the amount of energy dissipation, however, it is difficult to assign any area within the bowl of deflections to it since it affects all points in the range from 0 to 2.1 m.

The moduli of elasticity, mainly those with respect to subgrade soil, have a greater influence on changes in energy dissipation. For instance, a 4–6-fold change in the modulus of elasticity of subgrade soil results in a similar 3.7–5.7-fold change in energy dissipation. In terms of the conducted numerical experiments on the variation of the moduli of elasticity, the main finding is that the modulus of elasticity of subgrade soil has the greatest influence on changes in the amount of energy dissipation within the entire bowl of deflections. The moduli of elasticity of the intermediate layers have a significant effect within the entire bowl of deflections, and this effect tends to fade at a distance of about 90 cm. The modulus of elasticity of asphalt concrete has the greatest effect in the area from 20 to 120 cm from the point of load application, and beyond that area, this effect tends to fade.

The results obtained during numerical modeling allow us to conclude that it is possible to solve an optimization equation of the following form:

$$\vec{u}\left(P, R_i, t\right) - \mathrm{K}(E_j, tg\lambda_j)P(t) = 0, \tag{8}$$

where:

Table 1. **Road pavement structures on test sections**

Road pavement structure No. 1	Modulus of elasticity, MPa / (loss angle tangent)	Road pavement structure No. 2	Modulus of elasticity, MPa / (loss angle tangent)	Road pavement structure No. 3	Modulus of elasticity, MPa / (loss angle tangent)
Layer 1: asphalt concrete — 29 cm	500–12,000 MPa (0 - 1)	Layer 1: asphalt concrete — 20 cm	500–12,000 MPa (0 - 1)	Layer 1: asphalt concrete — 19 cm	500–12,000 MPa (0 - 1)
Layer 2: crushed stone / sand mixture reinforced with cement — 20 cm	200–3000 MPa (0 - 1)	Layer 2: crushed stone / sand mixture reinforced with cement — 30 cm	200–3000 MPa (0 - 1)	Layer 2: crushed stone / sand mixture reinforced with cement — 30 cm	200–3000 MPa (0 - 1)
Layer 3: crushed stone / sand mixture — 40 cm	100–900 MPa (0 - 1)	Layer 3: crushed stone / sand mixture — 20 cm	100–900 MPa (0 - 1)	Layer 3: soil	100–900 MPa (0 - 1)
Layer 4: soil	20–120 MPa (0 - 1)	Layer 4: soil	20–120 MPa (0 - 1)		

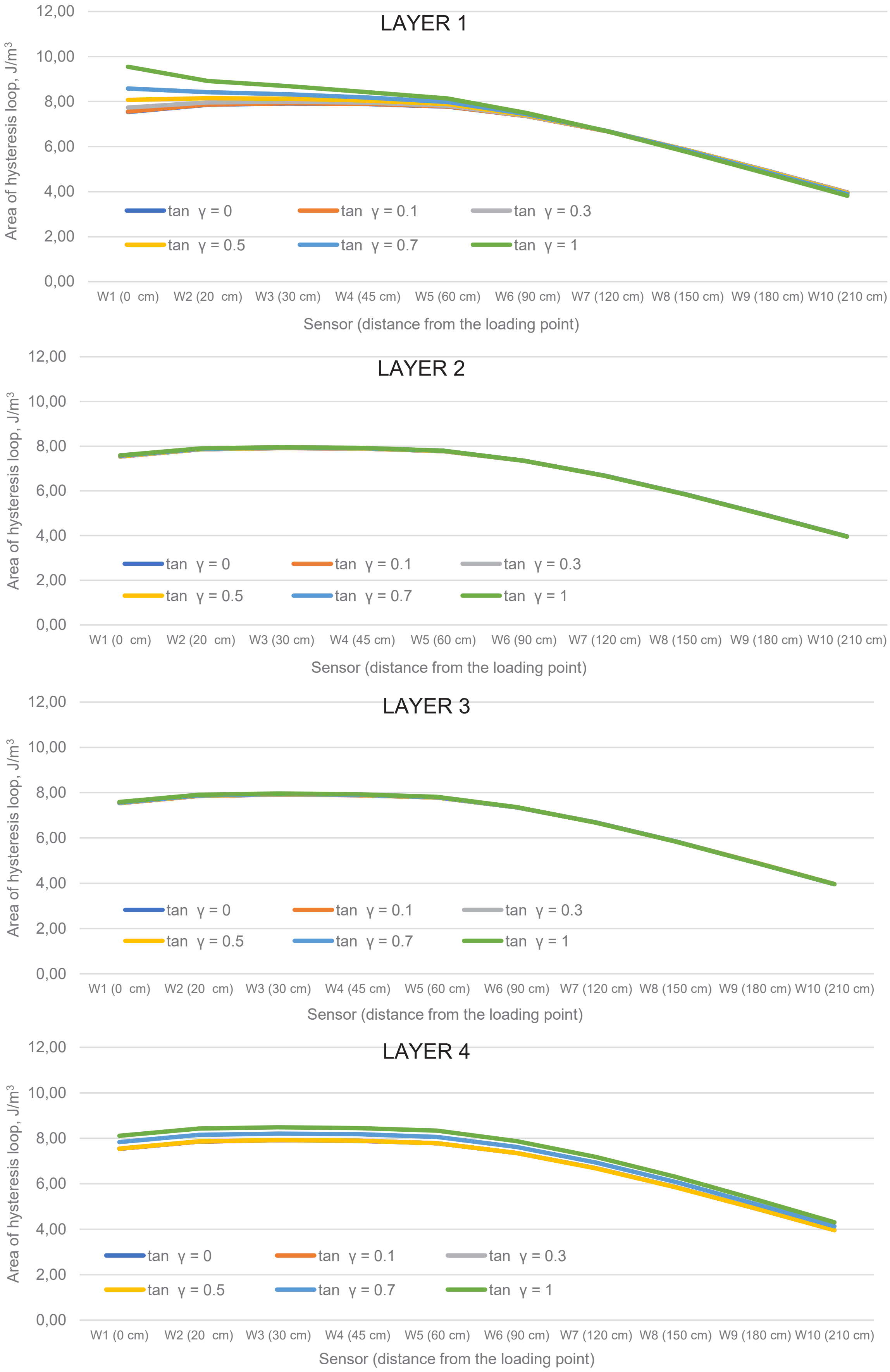

Fig. 1. Modeling the influence of the tangents of the angles of energy losses in pavement layers on the dissipation of impact energy for structure No. 1

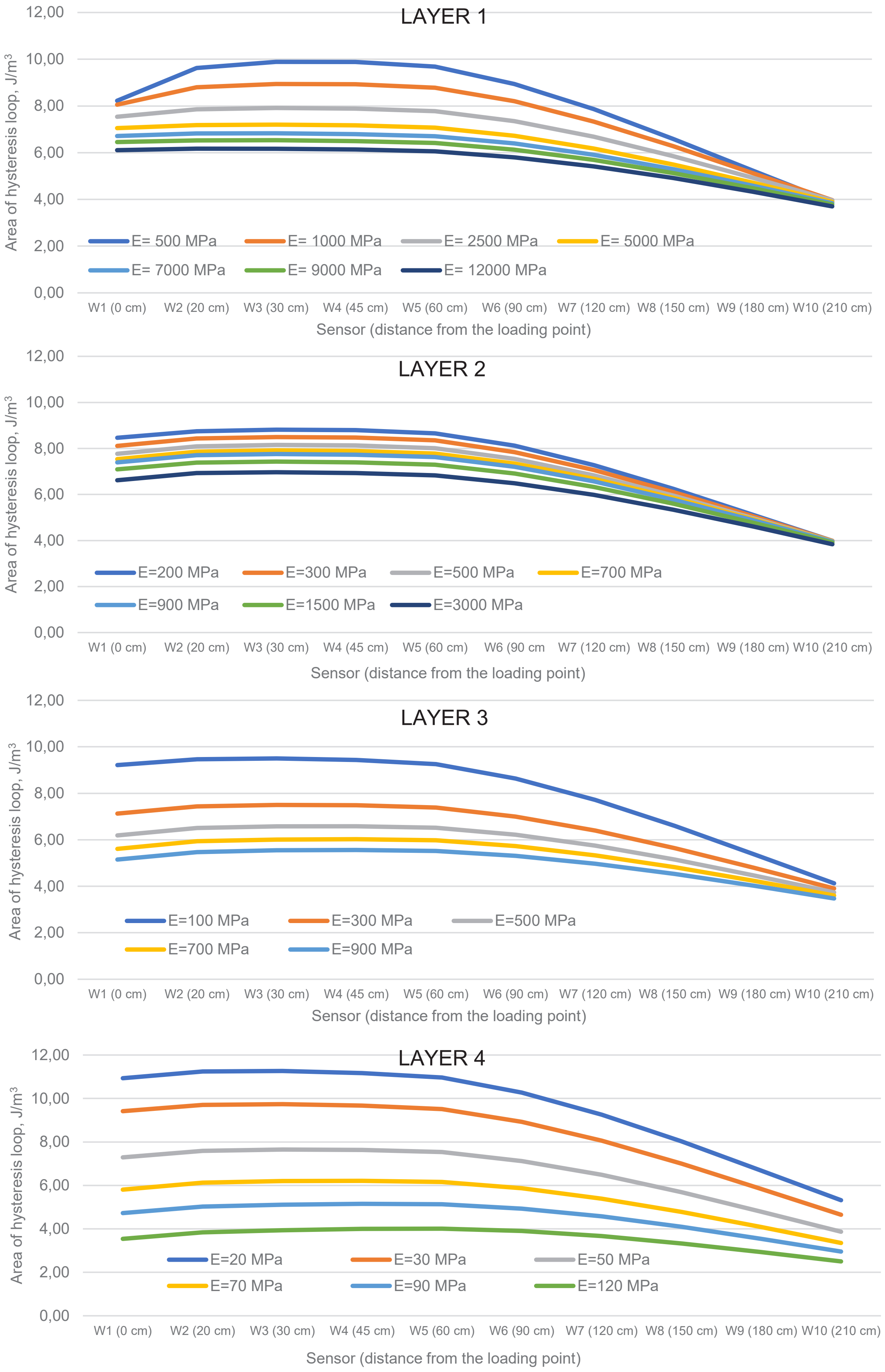

Fig. 2. Modeling the influence of the moduli of elasticity on the dissipation of impact energy for structure No. 1

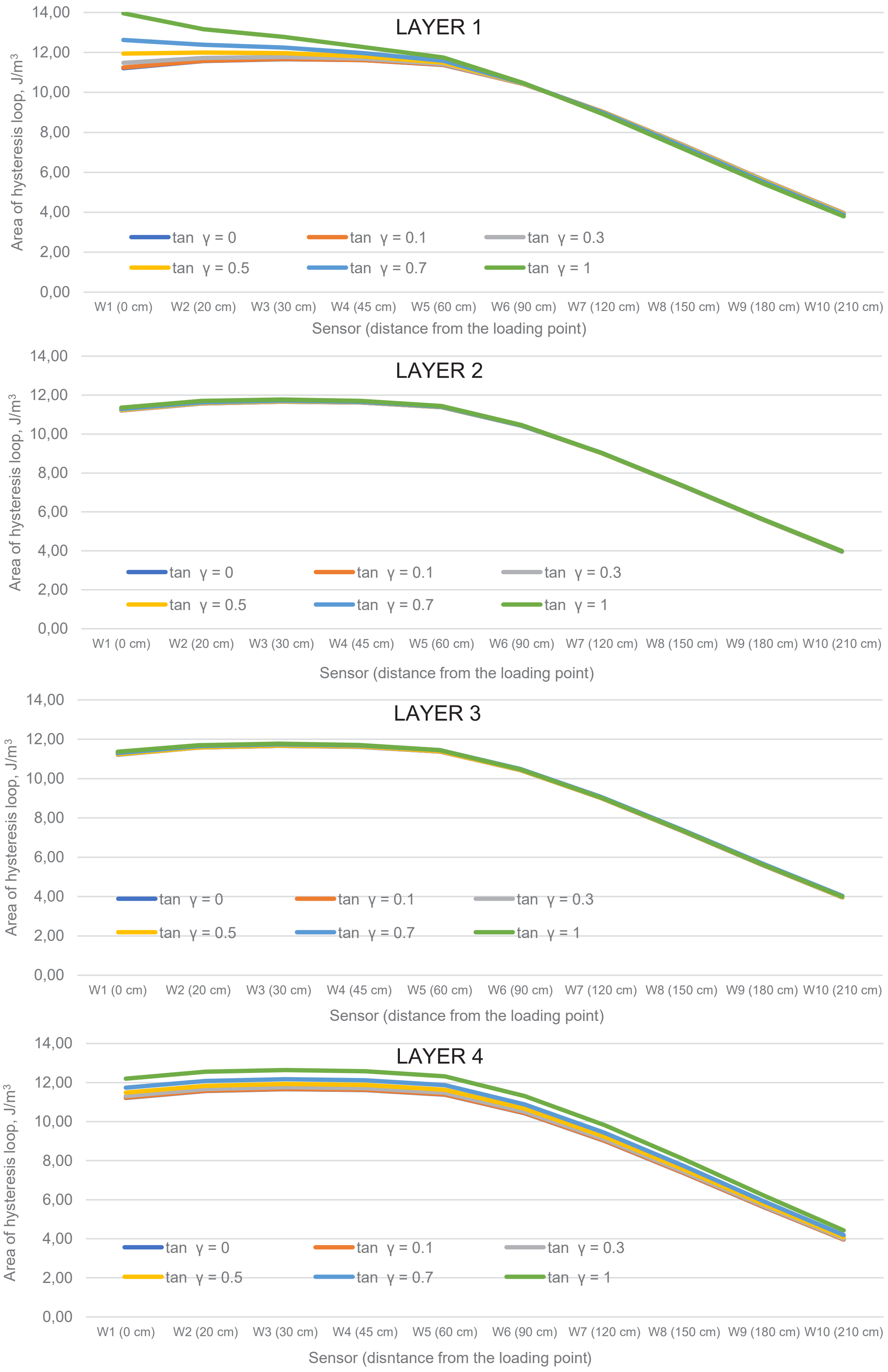

Fig. 3. Modeling the influence of the tangents of the angles of energy losses in pavement layers on the dissipation of impact energy for structure No. 2

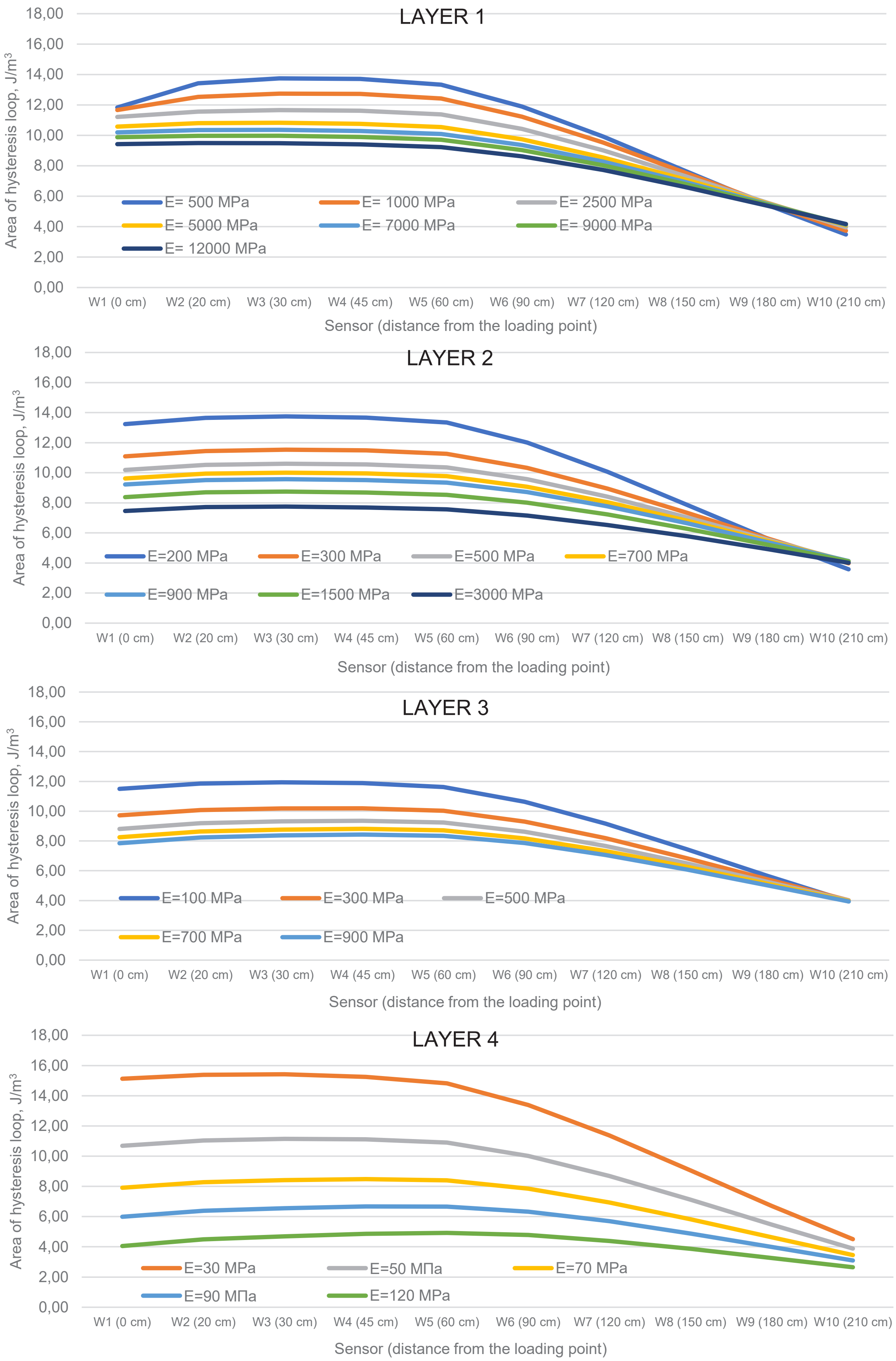

Fig. 4. Modeling the influence of the moduli of elasticity of pavement layers on the dissipation of impact energy for structure No. 2

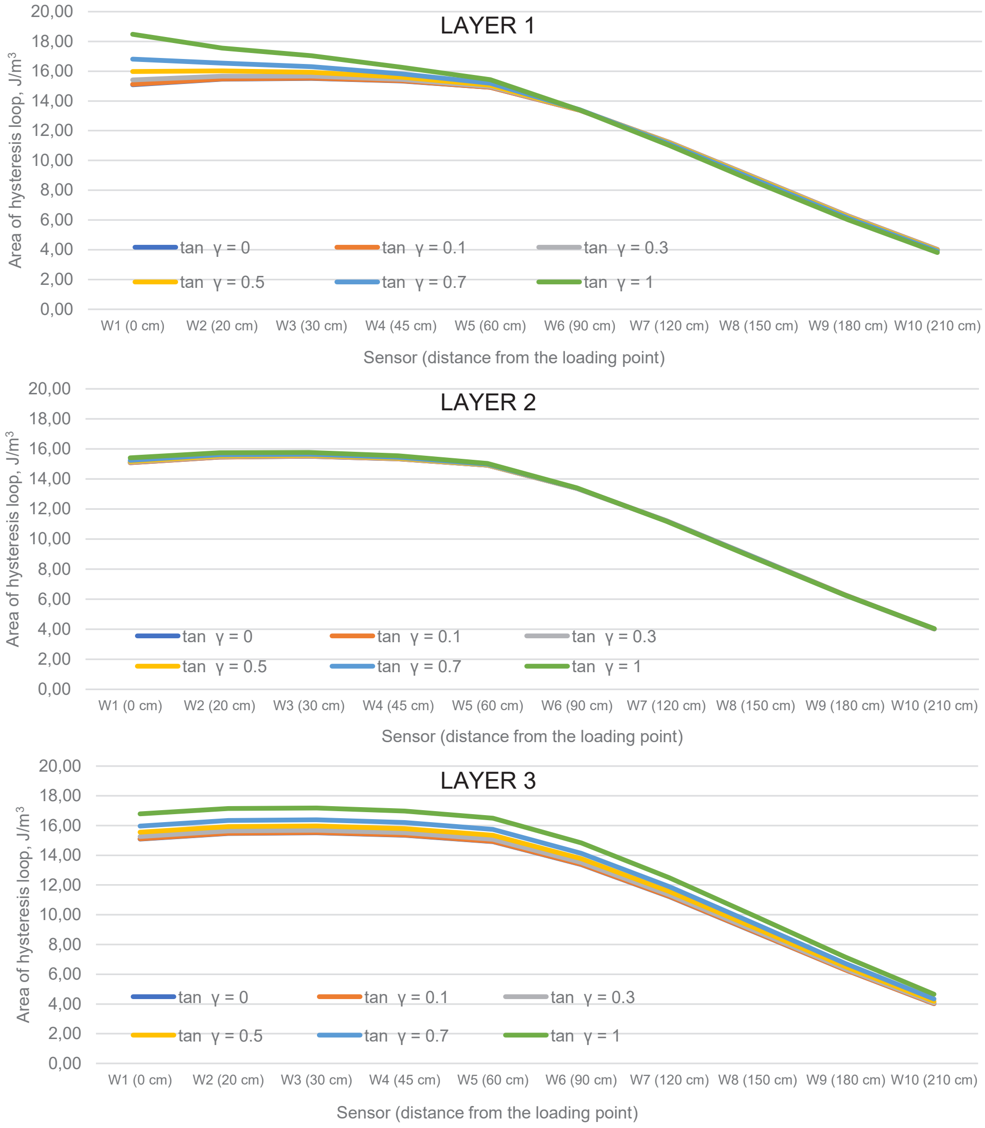

Fig. 5. Modeling the influence of the tangents of the angles of energy losses in pavement layers on the dissipation of impact energy for structure No. 3

$\vec{u}(P,R_i,t)$ — the complete experimental diagram of deformation on the pavement surface upon impact loading;

$K(E_j,tg\lambda_j)P(t)$ — the complete assumption diagram of deformation on the pavement surface, presented as the product of the function $K(E_j,\lambda_j)$ and the estimated pulse $P(t)$.

To test the proposed approach, we performed tests and then adjusted the obtained hysteresis loops on a section of a road with the following pavement structure (Table 2).

The hysteresis loops were experimentally recorded using an FWD PRIMAX 1500 equipped with a set of geophone sensors to record bowls of elastic deflections[1]. It should be noted that in the examined area with two pavement layers recently replaced, rutting and plastic deformations were observed near the pavement edges.

Fig. 7 shows the hysteresis loops recorded experimentally. In a similar manner, with the use of a mathematical model, we constructed estimated hysteresis loops for the design values of the modulus of elasticity of pavement layers (Fig. 8) and then adjusted them manually using the relationships obtained during the numerical experiment (Fig. 9). Figs. 7 and 9 show that the actual experimental and estimated bowls of deflections are characterized by sufficiently close loading and unloading trajectories. To quantify the correspondence between the estimated and experimental hysteresis loops, we present the calculated areas of the obtained hysteresis loops in the table 3.

Table 4 shows the final values of the adjusted moduli of elasticity and tangents of the angles of energy losses in the structural layers.

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[1] Distance from the deflectometer sensor location to the point of load application: 0–0.20–0.30–0.45–0.60–0.90–1.20–1.50–1.80–2.10 m

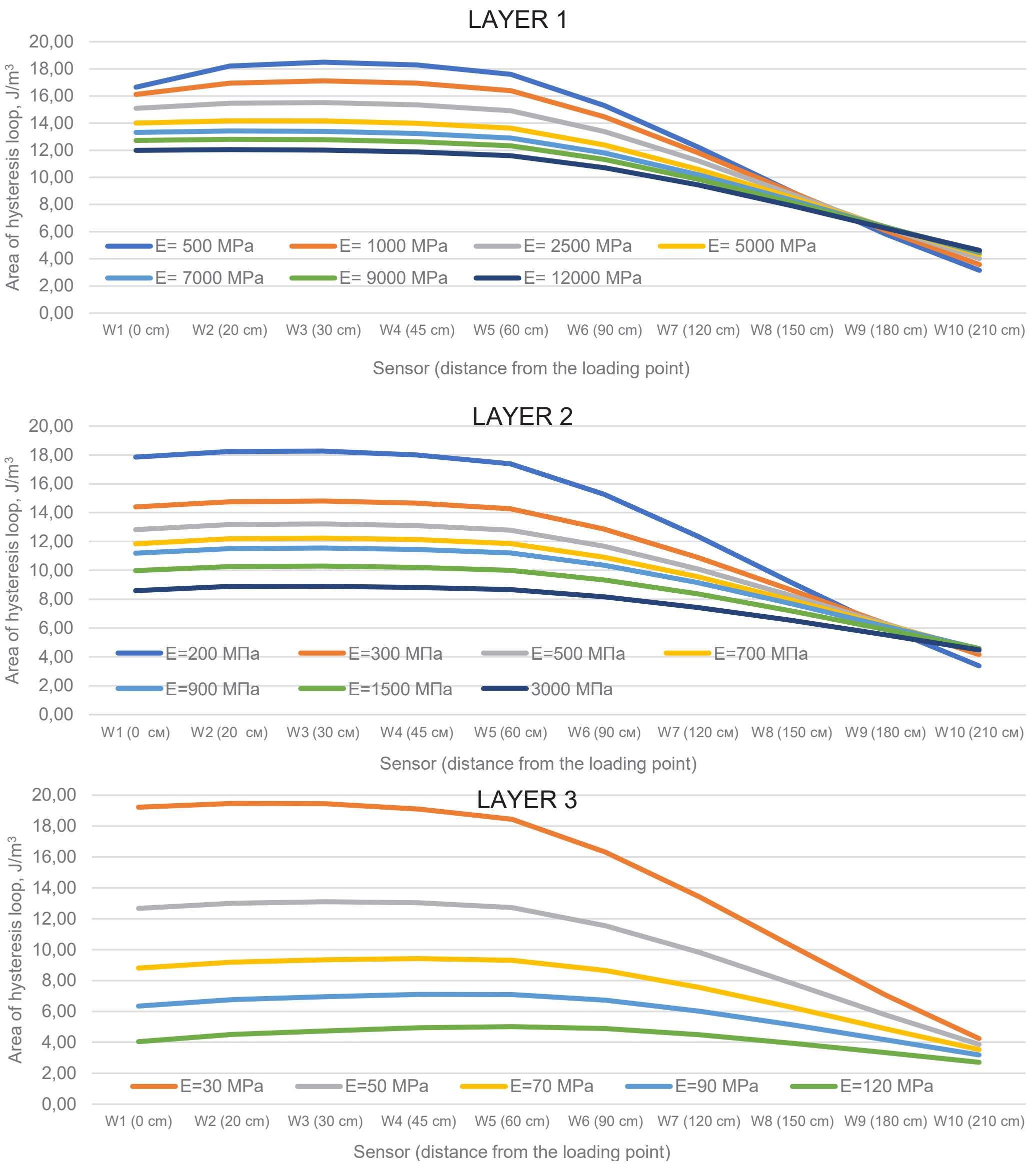

Fig. 6. Modeling the influence of the moduli of elasticity of pavement layers on the dissipation of impact energy for structure No. 3

The results obtained indicate a decrease in the modulus of elasticity of the base course made of the crushed stone / sand mixture. The moduli of elasticity of asphalt concrete and subgrade soil comply with the regulatory requirements. This confirms the fact that the weak intermediate base course, with a periodically replaced asphalt concrete layer, resulted in rutting. Thus, when planning repair, it is necessary to include works on stabilizing the non-cohesive subgrade. The main advantage of the road pavement condition indicator proposed in this study is the possibility of restoring both elastic and viscous characteristics of the materials of structural layers in road pavements as well as ensuring correspondence between the estimated and experimental characteristics of response over the entire period of instrumental measurements.

Table 2. **Road pavement structures on test sections**

Road pavement structure with a non-stabilized road bed	**Layer thickness, cm**	**Design modulus of elasticity, MPa**
Asphalt concrete	34	2500
Crushed stone / sand mixture	35	200
Soil – clay	–	47

Conclusions

- In this paper, we provided a rationale for the possibility of using hysteresis loops recorded at different distances from the point of load application as an effective road pavement condition indicator. Hysteresis loops serve as an analogue of the full

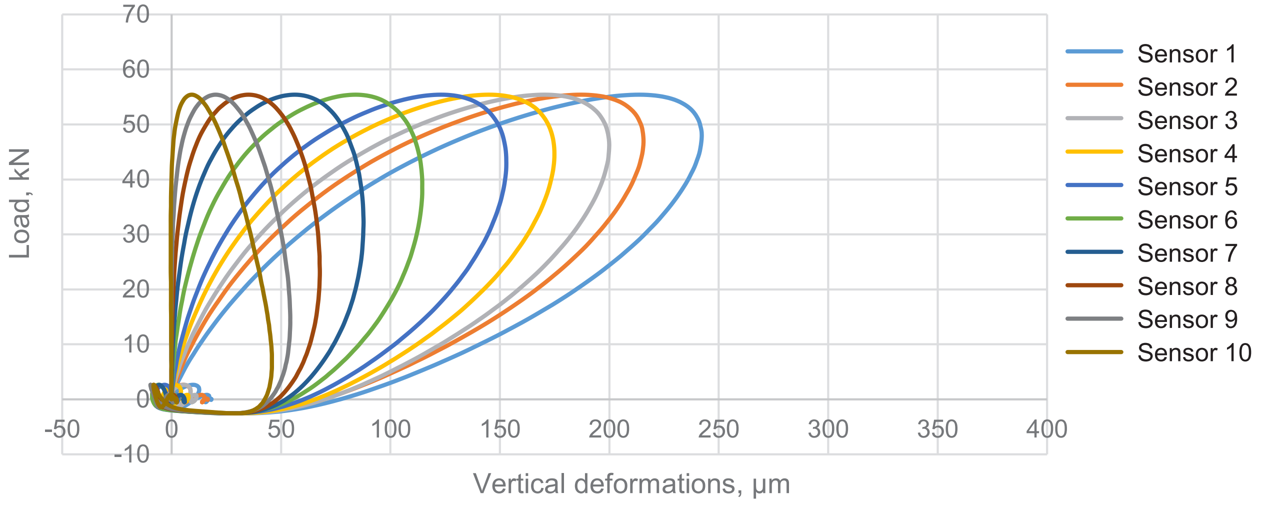

Fig. 7. Experimental dynamic hysteresis loops recorded on the test road section

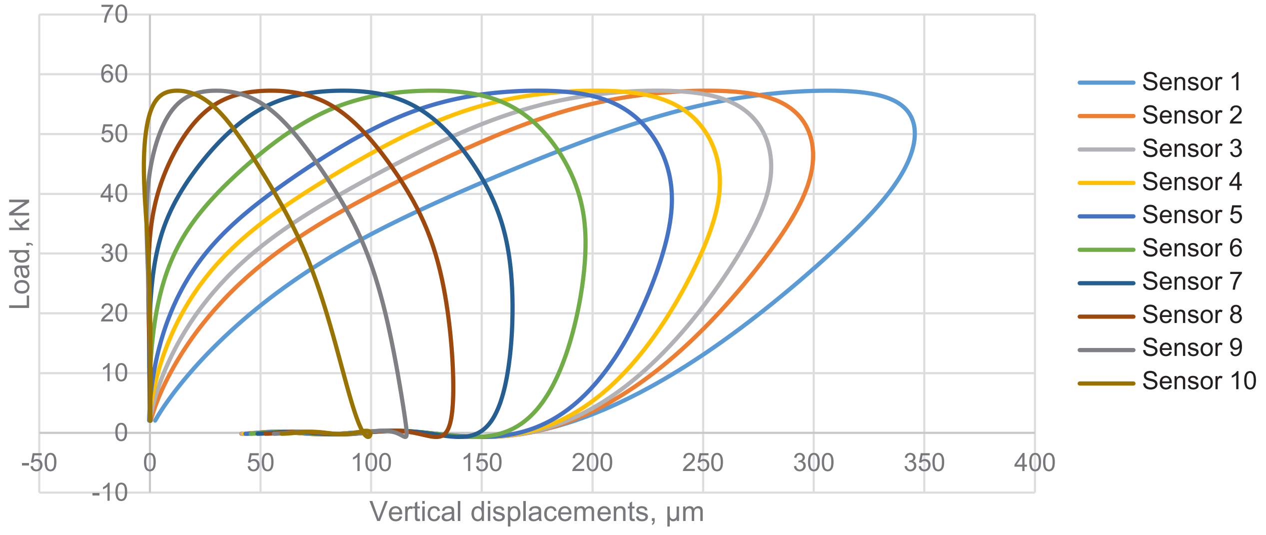

Fig. 8. Estimated dynamic hysteresis loops for the test road section before adjustment

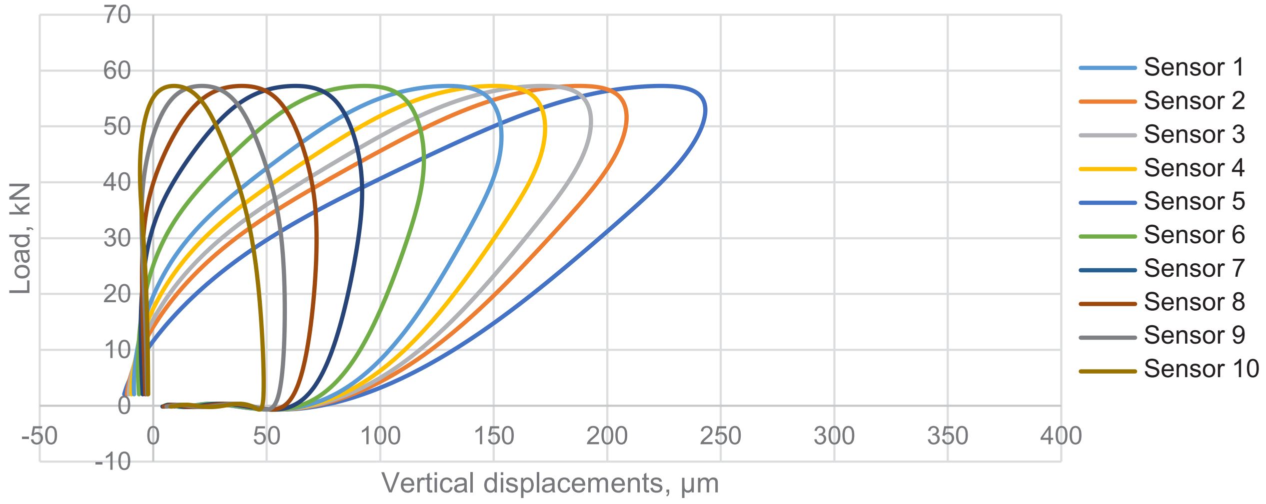

Fig. 9. Estimated dynamic hysteresis loops for the test road section after adjustment

Table 3. **Results of comparing the resulting areas of the estimated and experimental hysteresis loops**

Structure 1. Energy dissipation according to sensor, J/m^3										
Sensor	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Experiment	7.28	6.78	6.60	6.09	5.60	4.70	3.95	3.23	2.59	2.02
Estimated values	7.05	6.68	6.48	6.19	5.87	5.00	4.01	3.31	2.81	2.20
Deviation	0.03	0.01	0.02	–0.02	–0.05	–0.06	–0.02	–0.02	–0.08	–0.09

Table 4. **Final results of calculating the moduli of elasticity and loss angle tangents with account for the adjustment of the estimated bowls of deflections and hysteresis loops**

Road pavement structure with a non-stabilized road bed	**Modulus of elasticity, MPa**	**Loss angle tangent**
Asphalt concrete	3860	0.7
Crushed stone / sand mixture	60	0.5
Soil – clay	152	1

bowl of deflections, combining the history of road pavement deformation and loading from a source on the surface.

- During numerical modeling, we established the following: the modulus of elasticity of subgrade soil has the greatest influence on the amount of deformation energy dissipation within the entire bowl of deflections; the viscous properties of asphalt concrete have the greatest effect on the amount of energy dissipation in the area closest to the impact point; and changes in the rigidity and viscous characteristics of the intermediate layers have the greatest influence on changes in energy dissipation in the middle zone of the bowl of deflections.

- In the test case, we showed the possibility of determining elastic and viscoelastic characteristics when using hysteresis loops recorded at different distances from the point of load application as the main road pavement condition indicator. The deviation of the estimated hysteresis loops from the experimental ones, obtained by varying the moduli of elasticity and tangents of the angles of energy losses in pavement layers, did not exceed 10%. Based on the calculations obtained, we determined the cause of defect formation on the test road section — the non-cohesive subgrade with the actual modulus of elasticity of 60 MPa against the design value of 200 MPa.

- The practical significance of the obtained research results is in improving the accuracy and reliability of the results of non-destructive testing of road pavement condition, which is manifested in the restoration of both elastic and viscous characteristics of the materials of road pavement layers. The results obtained can be used to assess the residual life of the road pavement as well its strength during operation.

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ОПРЕДЕЛЕНИЕ ВЯЗКОУПРУГИХ ХАРАКТЕРИСТИК ЭЛЕМЕНТОВ МНОГОСЛОЙНЫХ КОНСТРУКЦИЙ НА ОСНОВЕ АНАЛИЗА ДИССИПАЦИИ ЭНЕРГИИ

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Аннотация
Введение: Ухудшение эксплуатационного состояния автомобильных дорог является одной из важнейших проблем, стоящих перед специалистами дорожной отрасли. В первую очередь его связывают со снижением жесткости дорожных одежд, представляющих собой многослойные протяженные конструкции. Для выявления причин снижения жесткости применяют неразрушающие методы контроля, в основе которых лежит решение обратной коэффициентной задачи восстановления упругих постоянных по замеренному на поверхности отклику. **Целью работы** является обоснование нового индикатора состояния дорожной одежды, учитывающего историю деформирования и нагружения поверхностным источником, на основе которого возможно решение обратной задачи восстановления упругих и вязких характеристик слоев дорожной одежды. Для достижения цели **использован метод** математического моделирования напряженно-деформированного состояния многослойной среды, базирующийся на решении системы динамических уравнений Ламе. Вязкость учитывается путем введения тангенсов углов потерь энергии волн в материалах слоев. **Результаты**, полученные в ходе моделирования, позволили впервые установить зависимости между изменением модулей упругости и тангенсов углов потерь энергии в слоях дорожной одежды и величиной диссипации энергии в ее структуре. При обсуждении полученных результатов отмечена возможность перехода от чаши максимальных динамических прогибов, как основного индикатора состояния дорожной одежд к анализу петель гистерезиса на поверхности дорожной конструкции, регистрируемых на различном удалении от точки приложения нагрузки и являющихся аналогом полной чаши динамических прогибов отражающей историю нагружения испытываемого объекта.

Ключевые слова: диссипация энергии, многослойная конструкция, модуль упругости, петля гистерезиса, установка ударного нагружения.