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Model for determining the elastic moduli of road pavement layers

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Abstract. A mathematical model of dynamic stress-strain state of a multilayer half-space, and a method for constructing and adjusting the design bowl of dynamic deflections under shock loading were developed to solve the problem of determining the elastic moduli of layers of non-rigid road pavement at the stage of its operation. Using this method, the actual dynamic elastic moduli of pavement layer materials were determined for a test section of road. In conclusion, the development prospects of the presented method are discussed as a result of analysis of amplitude-time characteristics of displacements recorded on road pavement surface under shock loading.

1. Introduction

Diagnostics of roads is one of the most technologically advanced and rapidly developing sectors of the road industry. An important task to be solved at the stage of road operation is adoption of rational repair measures to ensure the estimated service life of non-rigid road pavements. To solve this problem, one needs information on the actual state of both the pavement as a whole, and its individual layers.

In-depth experimental studies of stress-strain states of non-rigid road pavements and their temperature and moisture operation modes were carried out in the works of B.B. Teltayev [1, 2]. The results of these works made it possible to directly determine the actual values of stresses and strains at critical points of pavement structure.

In [3–6], the theoretical foundations of backcalculation method for elastic moduli of non-rigid road pavement layers are presented. It combines instrumental measurements for recording elastic deflection bowls on surfaces of road structures and mathematical modeling for construction of design deflection bowls on surfaces of non-rigid roads pavements.

The works [7–11] consider the advantages and disadvantages of mathematical models, which are basis of software systems for construction of deflection bowls. It is noted that for the most part, they all solve the problem of determining the stress-strain state (SSS) in a multilayer half-space under a load uniformly distributed over a circular plate. Solutions for determining the dynamic SSS of road pavements are rarely implemented despite their obvious advantages, in particular, the possibility of taking into account the different time of dynamic load impact and the nature of dynamic impact pulse from various shock loading installations.

In [12–20], the authors analyze software systems for backcalculation of elastic moduli of structural layers of non-rigid road pavements. They consider the Evercalc, Wesdef, Julea software which are universal systems (not associated with specific installations), and Elmod, Primax software, which are specialized systems, i.e. supplied with shock loading systems FWD (falling weight deflectometer) Dynatest and PRIMAX. However, all software systems are mainly based on static models of stress-strain state of the multilayer half-space, which does not correspond to the actual test conditions. Moreover, the shock loading installations are of great diversity, they vary significantly in the impulse time of impact on the pavement,

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and in the parameters of the fall height and the load mass. Another point is perspectivity of the approach, which takes into account the viscoelastic behavior of materials when determining the elastic moduli of the road structure layers. So, development of a method for determining the elastic moduli of layers of non-rigid road pavements, based on application of SSS dynamic model of a multilayer half-space, is of current interest.

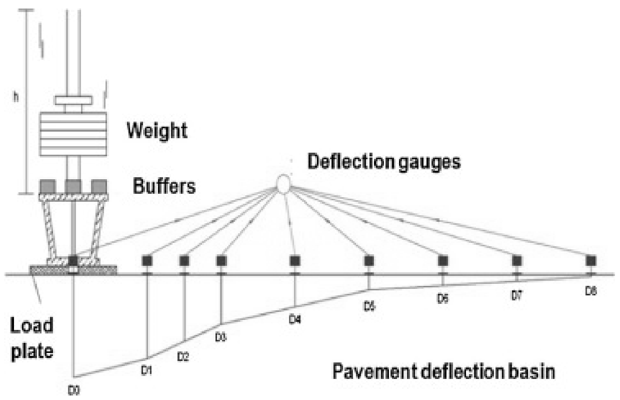
To achieve this goal, it is necessary to solve the following tasks:

- To develop an algorithm for constructing and adjusting the design deflection bowls relative to the experimental ones recorded by shock loading installations in the field conditions;
- To test the proposed method for determining the elastic moduli of layers of non-rigid road pavements for the operated section of road;
- To recommend additional indicators characterizing the structural properties of layers of road pavements.

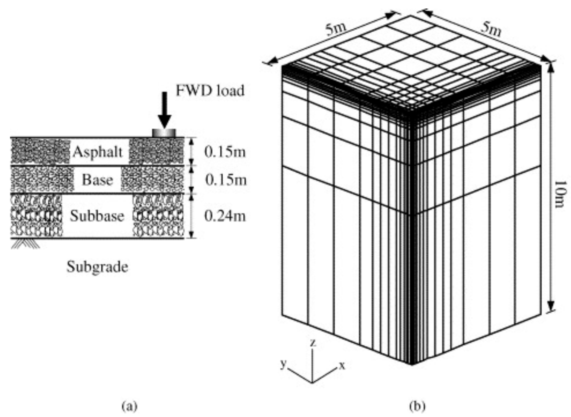
2. *Methods*

The methods considered in this work are solutions and algorithms obtained by the authors and embedded in the AEM software package. The process of determining the elastic moduli of structural layers of non-rigid road pavements can be represented in the form of a diagram (Fig. 1). The FWD shock loading unit used at the first stage is a semi-trailer with a shock loading mechanism mounted on it with 5–10 geophone sensors, as a rule. The geophones placement scheme has various configurations. The most common scheme is when geophone sensors are spaced at intervals of 30 cm at a distance from the shock loading point. Under the shock impact at the FWD unit, the impact of the calculated load from the vehicle wheel on the pavement surface is simulated. At the same time the deflection bowl on the pavement surface is recorded by geophone sensors.

Stage I – Experimental registration of dynamic deflection bowl of a road structure



Stage II – Calculation of dynamic deflection bowl of a road structure



Stage III – Determination of elastic moduli of layers of road structure at the current operation stage

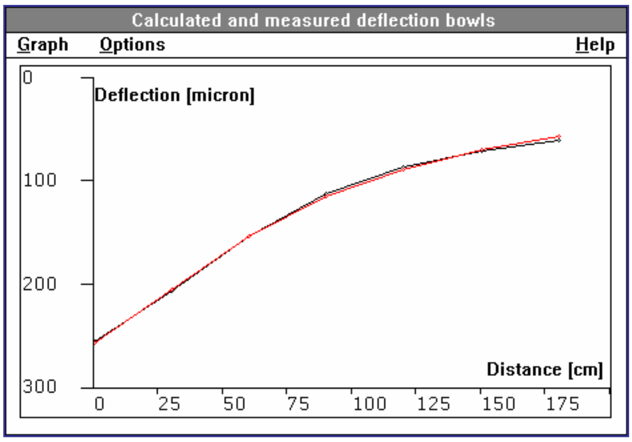


Figure 1. Method for calculation the elastic moduli of structural layers of non-rigid road pavements at the operational stage.

The mathematical model is based on the solution of problem of determining the dynamic SSS of a multilayer half-space under a shock load. The proposed algorithm for solving this problem is based on the works of I.I. Vorovich, V.A. Babeshko, A.N. Belokon, E.V. Glushkov, M.G. Seleznev, S.K. Iliopolov, H. Grundmann, J. Prozzi, M. Schanz et al. [21–27]. The statement of the problem is written as follows.

Road pavements is a N-layer elastic half-space $D = D_1 \cup D_2 \cup ... \cup D_N$, described in cylindrical coordinate system (R, θ, z) as (Fig. 2):

$$D_1 = \left\{R \in \left(0, +\infty\right), \theta \in \left(0, 2\pi\right), z < 0\right\}$$

is a half-space; $D_j = \left\{R \in \left(0, +\infty\right), \theta \in \left(0, 2\pi\right), z \in (z_{j-1}, z_j)\right\}$, $z_j = \sum_{i=1}^{j} h_i$; $(h_1 = 0)$ is the j-th layer (j = 2,...,N).

The elastic properties of media in $D_j,\ j = 0,1,...,N$ are determined by density ρ_j elastic modulus E_j Poisson's ratio ν_j expressed in terms of Lame parameters λ_j, μ_j.

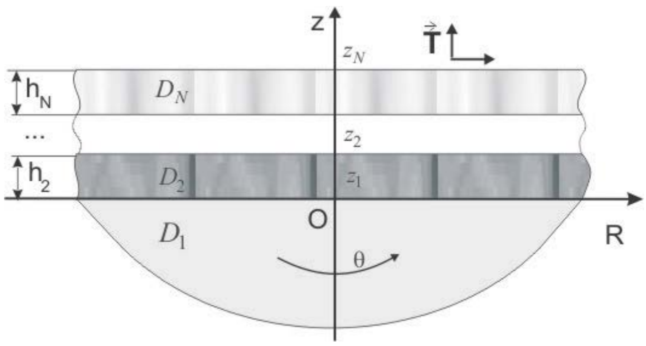


Figure 2. Multilayer half-space in a cylindrical coordinate system.

The displacement of medium under the action of an impact load is described by dynamic Lame equations. The viscous properties of layers are taken into account by introducing the tangents of loss angles of longitudinal and transverse waves, when determining the reduced vibration frequencies.

$$\nabla\nabla \cdot \mathbf{u}^{(j)}(\mathbf{r}) - \frac{\theta_{j1}^2}{\theta_{j2}^2} \nabla \times \nabla \times \mathbf{u}^{(j)}(\mathbf{r}) + \theta_{j1}^2 \mathbf{u}^{(j)}(\mathbf{r}) = 0, \quad (1)$$

$\theta_{j1}^2 = \omega^2 / V_{Pj}^2, \theta_{j2}^2 = \omega^2 / V_{Sj}^2$ are the reduced vibration frequencies, $V_{Pj} = \sqrt{\left(\lambda_j + 2\mu_j\right)/\rho_j}$, $V_{Sj} = \sqrt{\mu_j/\rho_j}$ are the velocities of longitudinal and transverse waves propagations in the j-th medium.

The solution to this system of equations is the Hankel integral transformation in the form:

$$\mathbf{U}^{(j,N)}(\mathbf{R}, \omega) = \int_{\Gamma_+} J_k(uR) \sum_{n=1}^{2} \mathbf{P}^{(j,n)}(u,z) \cdot \overline{\mathbf{X}}^{(j,n)}(u) u du \quad (2)$$

where J_k is Bessel function;

$\mathbf{P}^{(j,n)}$ is the core of the integral representation for a multilayer half-space;

$\overline{\mathbf{X}}^{(j,n)}$ are the Hankel transforms for voltage at the boundaries of layers (n = 1,2), determined from the boundary conditions.

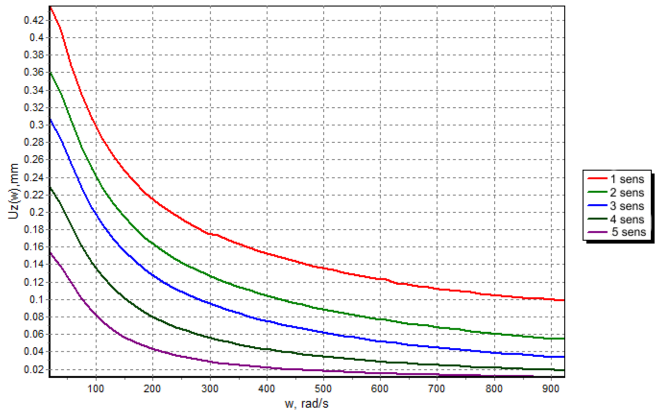


Figure 3. Frequency response of displacement of surface points of a road structure.

A solution is constructed for each characteristic frequency ω_k (Fig. 3) calculated as:

$$\omega_k = k\pi / (T + \tau) \tag{3}$$

where T is the time of observation over the deformation of the road structure surface under shock loading, selected from the damping conditions of the previous pulse, s.

τ is the duration of the loading pulse, s;

k is the amount of decomposition harmonics, determined from conditions of accuracy for shock loading pulse approximation $P(t)$.

The multiple layers of medium are taken into account via the superposition principle. It implies the replacement of variables for a homogeneous half-space by variables of the j-th layer in the equation, and the components of displacement vectors at the boundaries of the road pavement layers are set equal.

The amplitude-time characteristics (ATC) of displacements (Fig. 4) at given points on the pavement surface are calculated using the formula

$$\mathbf{U}^{(N)}(\mathbf{R},t) = \sum_{k=1}^{M} p_k \left\{ -\cos\eta_k \operatorname{Im}\left[\mathbf{U}^N(\mathbf{R},\omega_k)\exp(-i\omega_k t)\right] + \sin\eta_k \operatorname{Re}\left[\mathbf{U}^N(\mathbf{R},\omega_k)\exp(-i\omega_k t)\right] \right\} \tag{4}$$

for all observation points on the surface of a multilayer half-space. Here p_k are the coefficients of the shock loading pulse $P(t)$ expansion into the Fourier series, calculated by the formula:

$$p_k = \int_0^{\tau} \sin(\omega_k t + \eta_k) P(t)\, dt \tag{5}$$

$$\eta_k = 0.5 \cdot k \cdot \pi \cdot T / (T + \tau), \tag{6}$$

and $\operatorname{Re}(\mathbf{U}^{(N)}(\mathbf{R},\omega_k))$, $\operatorname{Im}(\mathbf{U}^{(N)}(\mathbf{R},\omega_k))$ are the real and imaginary parts of the vertical displacement vector at given frequencies ω_k .

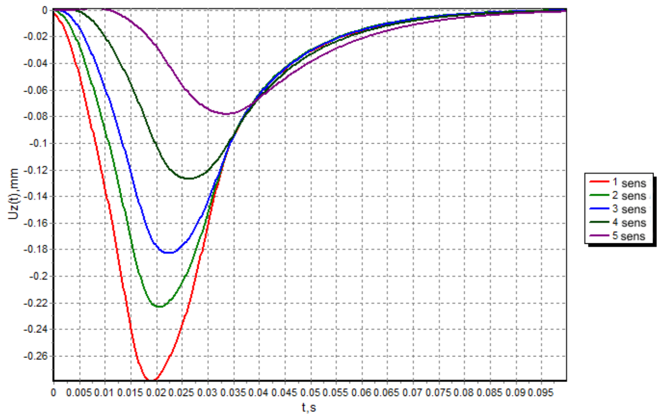


Figure 4. The amplitude-time characteristics of displacements.

The final stage of construction the calculated bowl of maximum dynamic deflections is to select the maximum amplitudes of vertical displacements of the medium surface points $\max_t \left| U_z^{(N)}(R,t) \right|$. It is selected within the studied time interval for each of the observation points set on the road structure surface. Further these values are put on the final plot of dynamic deflection bowl (Fig. 5).

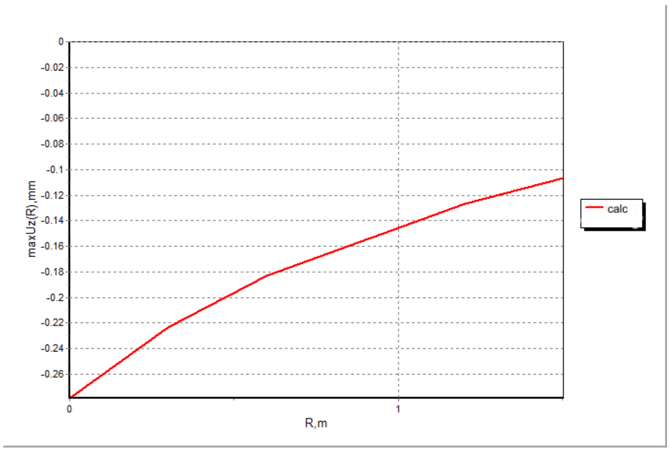


Figure 5. The calculated bowl of dynamic deflections of road pavement.

The resulting calculated bowl of maximum dynamic deflections is constructed for the design values of the elastic moduli of the structural layers of the road pavement. Further it is corrected taking into account the experimental bowl of dynamic deflections recorded in field conditions. The inflection points on the graph show the locations of geophone sensors, in accordance with the setup configuration selected for testing.

To integrate the software package with FWD impact loading installations, a batch mode was developed. It allows exporting data on the actual deflection bowls recorded during impact loading from the output file of the installation software in *.fwd format.

The method of adjusting the calculated deflection bowl relatively to the experimental one is implemented in the form of a first-order method for an iterative process that includes the following sequence of actions:

1. One numerically finds $\dfrac{\partial U_y\left(x_k^{(0)}, E_1^{(0)}, E_2^{(0)}, E_3^{(0)}\right)}{\partial E_j}$, $j = 1,2,3$, according to the calculated bowl of maximum dynamic deflections for the design values $E_j = E_j^{(0)}$.

2. These values are compared with those obtained from processing of experimental data. Based on this comparison, one identifies the points $x = x_k^{(0)}$ at which their maximum divergence takes place. The number of points should coincide with the number of defined parameters (in this case $k = 1,2,3$).

3. The main terms of expansion of the left side of equation (1) – the calculated bowl of maximum dynamic deflections – are determined in increments of unknown parameters.

$$U_y\left(x, E_1^{(0)} E_2^{(0)} E_3^{(0)}\right) + \sum_{j=1}^{3} \frac{\partial U_y\left(x, E_1^{(0)}, E_2^{(0)}, E_3^{(0)}\right)}{\partial E_j^{(0)}} \Delta E_j \tag{7}$$

This expression in nodes $x = x_k$ must be equal to the experimentally obtained maximum dynamic deflections in the corresponding points. As a result one gets the following system of linear algebraic equations for ΔE_j determination.

$$\sum_{j=1}^{3} \frac{\partial U_y\left(x_k^{(0)}, E_1^{(0)}, E_2^{(0)}, E_3^{(0)}\right)}{\partial E_j^{(0)}} \Delta E_j = \varphi(x) - U_y\left(x_k^{(0)}, E_1^{(0)}, E_2^{(0)}, E_3^{(0)}\right), \quad k = 1,2,3. \tag{8}$$

Using values ΔE_j obtained as a result of solving the system, one obtains the first approximation of the desired elasticity models

$$E_j^{(1)} = E_j^{(0)} + \Delta E_j, \tag{9}$$

4. The bowl of maximum dynamic deflections is calculated for the obtained values of $E_j^{(1)}$, and the procedures 1-3 are repeated until the required accuracy is achieved.

To compare the results obtained by the presented mathematical model using the software package that implements it, we used the engineering approach presented in the draft of the Belarusian normative document TKP 140 “Roads. Diagnostic procedure”. This document makes it possible to calculate the elastic moduli of layers of road pavements based on deflection bowls recorded in the field conditions. The elastic modulus of the asphalt-concrete (a-c) layer is defined as:

$$E_{a-c} = \frac{D(E_{total} - E_{base})}{0.3h}, \tag{9}$$

where h is the thickness of an assembly of asphalt-concrete layers, cm;

E_{total} is the total elastic modulus of the surface of road pavements, MPa;

E_{base} is the total elastic modulus of the base layer surface, MPa;

D is the diameter of the calculated wheel print, cm.

The elastic modulus of the base layer surface is:

$$E_{base} = K \cdot E_{total}, \tag{10}$$

K is the coefficient considering the thickness of asphalt-concrete layers and the ratio of deflections under geophones 2-4.

The elastic modulus of subgrade soil is calculated using deflections recorded by the sensors 4-9 of the shock loading installation

$$E_{s.s.(4-9)} = \frac{p \cdot D^2 \cdot (1-\mu^2)}{4 \cdot r \cdot l_{\mathrm{st(4\text{-}9)}}}, \tag{11}$$

$l_{st(4\text{-}9)}$ are the static deflections recorded by the sensors 4-9;

D-diameter of load circle;

r is the distance from the center of load application to geophones 4-9,

P is the pressure on the surface, kPa.

3. Results and Discussion

To assess the adequacy of results obtained by this method, the elastic moduli of road pavement layers calculated using the AEM software package were compared with that calculated by the Belarusian technique described in Belarusian normative document TKP 140 “Roads. Diagnostic procedure”. The comparison was carried out for a section of the 3rd category road in the Rostov region. This road section was completed by major repairs in 2017. The construction of road pavements on this site includes two layers of asphalt-concrete with a total thickness of 12 cm, and an incoherent base layer with a thickness of 35 cm. The surface temperature during testing was 8 °C. The FWD PRIMAX 1500 impact loading apparatus was used to register experimental elastic deflection bowls [20].

The determined actual elastic moduli using both methods are presented in Fig. 6.

The determined actual elastic moduli of road pavement layers

in forward direction **in backward direction**

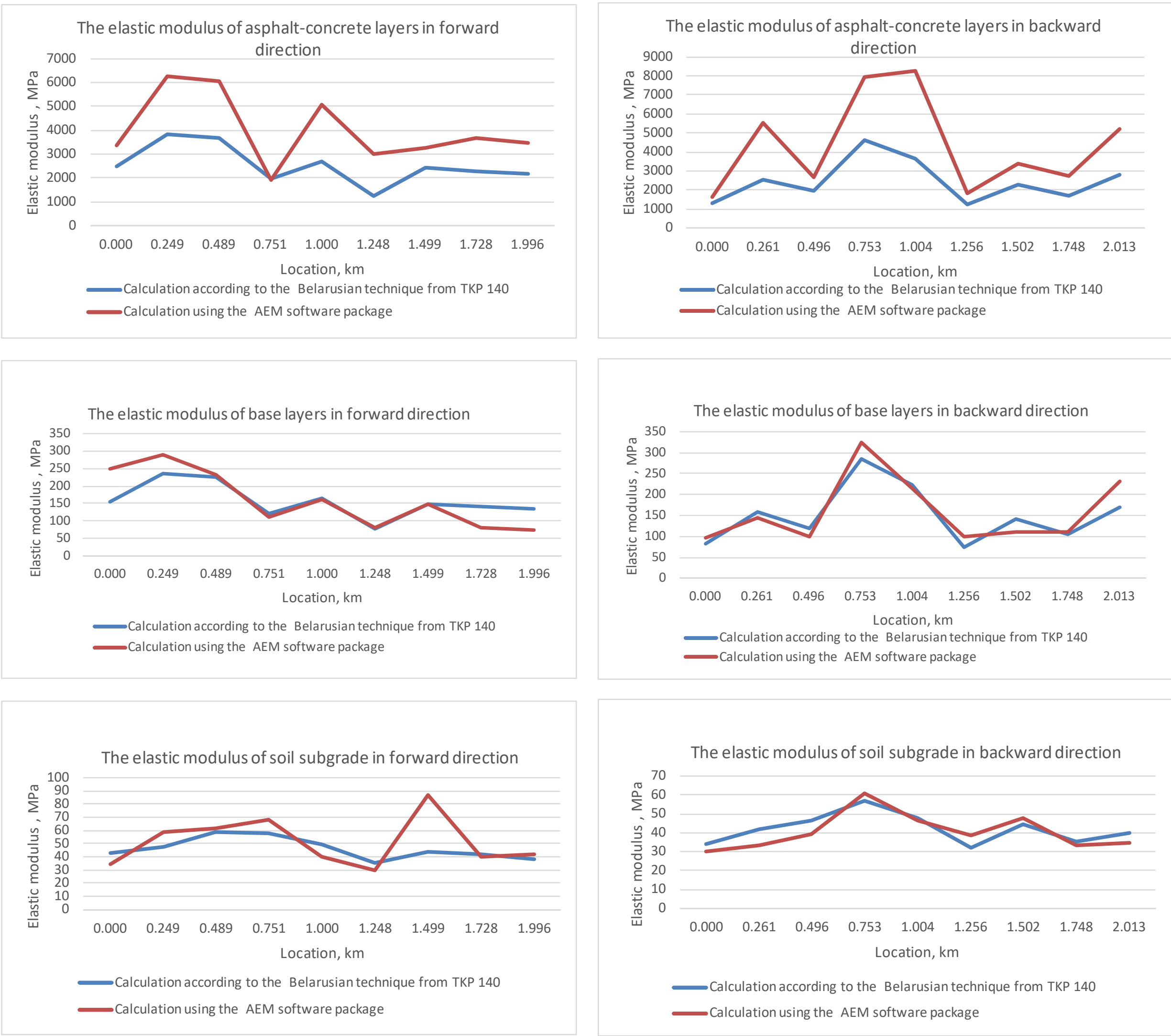


Figure 6. The actual elastic moduli of road pavement layers calculated using the AEM software package and according to the TKP-140 technique.

The plots show that elastic moduli of road pavement layers calculated using the AEM software package and using the technique described in TKP 140, are generally described by a common pattern of changes along the length of the examined section of road. We believe it confirms the adequacy of the used bowl processing algorithms.

At the same time, differences in the absolute values of actual elastic moduli of individual layers of road pavements are obvious. The dynamic elastic moduli of the asphalt-concrete layer calculated in the software package significantly exceed that obtained using the TKP 140 method [28]. The latter is based on reduction of the calculated elastic moduli of pavement layers to static values at the design temperature of 10 °C. The character of this phenomenon is known and is associated with the fact that the modulus of elasticity of asphalt concrete depends on temperature and frequency, which was noted in many works [29, 30]. The elastic moduli of layers of the unreinforced base and subgrade soil, determined both by the TKP-140 methodology and calculated using the AEM software package, are quite close to each other. Nevertheless, it should be emphasized that layers of non-cohesive materials operate in conditions of all-side compression, and the layer elastic modulus is essentially non-linear along their depth. Currently, there exist methods for taking into account the nonlinearity of elastic modulus of a granular material. However, they all imply the division of one layer of a non-cohesive material into a number of sublayers, and the elastic modulus is calculated within each of them taking into account octahedral stresses. This problem is relatively easy to solve at the stage of designing road pavement, but it is quite complex in terms of configuration of these sublayers at the stage of pavement operation. Now the authors are working to improve the proposed algorithm.

The field results should be refined from the standpoint of assessing the structural properties of individual layers of road pavements. It can be made based on analysis of the amplitude-time characteristics (ATC) of displacements recorded under shock loading. To confirm this conclusion, we examined the ATC displacements on the surface of road pavements. As test systems we used a new section of road without defects, and a road section with critical defects on the asphalt-concrete pavement, which has been in operation for 6 years (Fig. 7, 8).

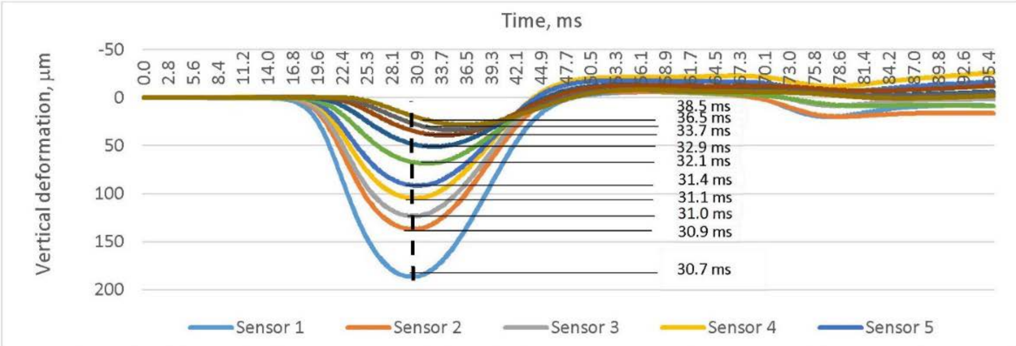


Figure 7. The amplitude-time characteristic of displacements recorded under a shock impact on the pavement surface without defects.

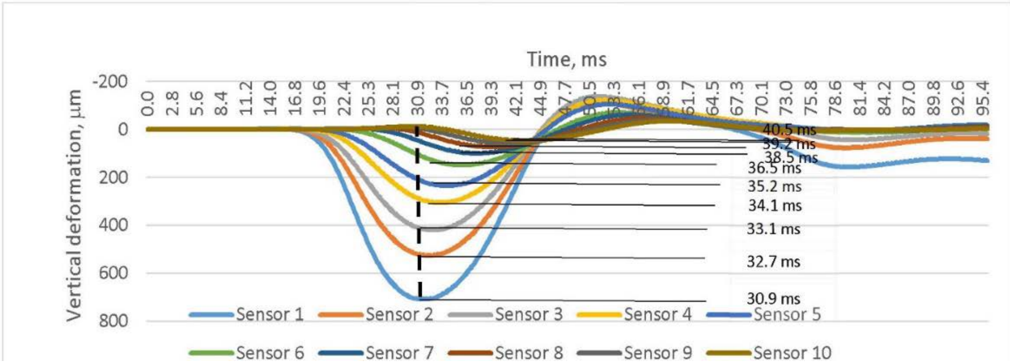


Figure 8. The amplitude-time characteristic of displacements recorded under a shock impact on the pavement surface with defects.

As it can be seen from the plots, the time delay between the extrema of amplitude-time characteristics of displacements on a road section with defects significantly exceeds the time delay between peaks of ATC displacements recorded on pavements without defects.

It is possible to quantitatively characterize the obtained results by calculating the damping coefficients of individual layers of road pavements using formulas:

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}},$$

$$\delta = \ln \frac{A_1}{A_2} \cdot \Delta t^{-1},$$

where δ is the damping logarithmic decrement;

A_1, A_2 are the extrema of amplitude-time characteristics of displacements recorded in field conditions;

Δt is the delay time between the extrema of amplitude-time characteristic recorded by individual sensors.

We presented the results of numerical modeling in [31]. It showed that the greatest influence on change in time delay in the zone closest to the impact point (0–0.25 m) is associated with a change in mechanical parameters of the asphalt-concrete layers. The changes in time delay in the middle and in the far zones relative to the impact point are mainly associated with mechanical characteristics of layers of base and subgrade soil, respectively. Thus, the data recording and determination of mechanical characteristics, taking into account analysis of the amplitude-time characteristics of displacements recorded under shock loading, are an urgent task requiring further detailed study.

4. Conclusion

1. A mathematical model of dynamic stress-strain state of a multilayer half-space in an axisymmetric setting has been developed. It allows constructing design bowls of elastic deflections on the surface of non-rigid road pavements, for installations with various parameters of impact loading;

2. The developed method was tested in the field conditions on a section of the M-4 DON highway. The developed mathematical model was used as a base for AEM software package creating. The elastic moduli of road pavement layers were calculated using the AEM software package created by the authors and they were compared with that calculated by the Belarusian technique described in normative document TKP 140. It was established that the obtained results are generally described by a common pattern of changes along the length of the examined section of road. We believe it confirms the adequacy of the used bowl processing algorithms.

3. The damping coefficient is proposed to use as an additional indicator characterizing the structural state of road pavement layers. It is calculated based on the ratio of amplitudes between the extrema of the amplitude-time characteristics and the time delay between them. For the asphalt concrete layers it is calculated in the zone near to the impact point (0–0.25 m), for the base layers (0.25–1.25 m.) it is calculated in the middle zone, for the soil subgrade it is calculated in the far zone (1.25–2.25 m). These results were obtained using mechanical and mathematical modeling, the results of which are presented in [31]. Within the framework of the presented task, the obtained results can be used to further improve the presented approach with regard to determine the actual elastic moduli of the road pavement layers, as well as the actual damping coefficients.

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