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RESEARCH ARTICLE

Pavement Fatigue Degradation Phenomenon Assessment Based on Multi-load FWD Data and Stochastic Process Evaluation

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Abstract

On the example of the road pavement of a semi-rigid structure, this paper presents the concept of the parameters estimation of the experimental section tested after 30 years of use. In the context of the lack of technical history data of the analyzed road section, the resultant (conventional multilayer system, which is pavement and its subgrade) stiffness was analyzed in relation to the moment it was built. The analysis was performed using the concept of multilevel loadings, with the use of FWD-type equipment. The considerations are related to the slope coefficients of linear regression obtained on the basis of a research program in the range of the loads up to 90 kN. There were compared the differences between slope of the regression function for the force-deflection relation between the results of the deflection measurements of the test section after 30 years of use and the slope coefficients for the pavement structure parameters estimated on the basis of both expert judgments and computer simulations, as well as the back forecast. For the forecast, the properties of the stochastic process determined by the Poisson distribution were used.

Keywords

fatigue life degradation · pavement · multilevel FWD load tests · stochastic process

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1 Introduction

The pavement engineering and related technologies must mainly take into account the influence of multiple sources: extreme temperatures, time-related variable properties of the used materials, snow, rain, the properties of pavement subgrade, traffic load, and maintenance policy. These issues were discussed very systematically in the paper [24] and although its contents refer to the pavements localized in the areas with the cool climate, many of the elements included there can be applied to any type of pavement and varied climatic zones. In any case, these are just some factors that demonstrate the range of the pavement degradation phenomenon and, above all, their stochastic nature. The most complex observations of pavement degradation in time domain are probably ensured by the measurements results analysis of pavement sections in natural conditions. Among them, the most relevant are those that relate to the full-scale accelerated pavement testing [2, 20]. The paper [10], on the basis of pavement deflection measurements values tested both in single-load and multilevel-load tests in the range from 17 kN to 70 kN, describes a method of prediction of the rutting depth. There were confirmed a satisfactory compatibility between these quantities for a wide range of road pavement structures. It is worth noting here that it might provide a basis for the development of small-scale accelerated pavement testing approach. The accelerated test series, using the FWD-type unit, were also initiated during the preparation of the report [4]. It was noticed there that the deflection ratio obtained from multi-load level deflections may predict the type and quality of the base/subgrade materials. At the same time, the true hypothesis says that the difference in the multi-load deflections small yield information related to the future performance of pavements. The characteristic feature of construction materials fatigue phenomenon assessment is their randomness [17]. At the basis of the description of cyclic phenomena (fatigue phenomena) lies the theory of cracks initiation. And the most appropriate mathematical description of the fatigue phenomenon are the theories of stochastic processes [17]. The microscopic initiation of cracks in the pavement layers bonded with any binder is subject to considerable uncertainty, both in relation to the speed of the cracks development and its direction. A stochastic collocation method to solve mixed mode fatigue crack growth problems with uncertain parameters was proposed in [15]. Analysis of the pavement cracking initiation based on the use of probabilistic duration modeling techniques is shown in [16]. Duration techniques enable the stochastic nature of pavement failure time to be evaluated as well as censored data that are rather unavoidable due to variable nature of pavement materials. In the work [5], authors described a Markov model that is utilized to predict the probability distribution of pavement crack depths with respect to cumulative ESAL (Equivalent Single Axle Load) count. The proposed model was considered promising for predicting average crack growth parameters in continuous media. Using the Markov model for a given service life was also introduced by [1]. A stochastic approach was developed to estimate the required design thickness for flexible pavement, using additional stochastic-based factors that are mainly the initial and terminal transition probabilities. Markov models are commonly used probabilistic models for pavement deterioration processes [9, 14]. Generally, Markov models start with the estimation of transition probabilities, defined as probability with which the pavements transit from one state to another. Exploring variability in various pavement properties, more precise predictive models can be obviously created. The processes involved in the introduction of variability during the construction of pavements are not simple random processes but often methodical steps, with clearly defined scopes of influence [6]. Spatial statistics that do offer a number of insights into the nature of variability in pavements is discussed in [7]. It is possible, producing a semi-variogram, to show the range over which one can expect to see correlation between measurements. This is important for choosing sampling locations and frequencies for quality control. Performing uncertainty analysis of simulation based models, authors of article [23] found that sampling based approaches are most suited for use with Mechanistic-Empirical Pavement Design Guide, known as the MEPDG. From the two most widely used sampling approaches (Monte Carlo simulation and Latin Hypercube Sampling, LHS), the LHS method is recommended for pavement performance simulation as it often displays similar accuracy to Monte Carlo sampling with an order of magnitude fewer samples. Finally, to perform a dynamic analysis of pavement structures, one of the indispensable considerations is the stochastic pavement load. The frequency energy distribution analysis, which is performed in [18], reveals that the frequency distribution of stochastic loads depends on the kinds of vehicles. For the heavy vehicle, more than 80% loads are concentrated in the $0 \div 4$ [Hz] range and 10% loads in the $8 \div 20$ [Hz] range. This is useful information since pavement material responses are frequency dependent.

2 Motivation, objective and research methods

The description of pavement degradation particularly observed in the existing pavements of minor importance is inconvenient at least for two reasons. The first concerns archiving the information on pavement parameters, where due to the range of the task, it is difficult to control them, ensuring the reliability of database and its completeness (pavement age, history of traffic load, materials used, changes in soil moisture in time domain, and many others). In the second case, the process of pavement degradation over time significantly increases the uncertainty of the phenomenon characteristics. This implies that the stochastic processes based particularly on the results of small-scale accelerated tests can be an attractive basis for this type of analysis. In view of the above, the paper hypothesizes that the hybrid of the pavement deflection measurement results, obtained with the use of the FWD multi-load approach, and the properties of the stochastic process determined by Poisson distribution, leads to reasonable stiffness estimation of pavement and its subgrade at a given time in the past.

2.1 The stochastic mechanism of pavement damage accumulation

A random process can be useful to model the progression of pavement attributes over time, where the evolution is random rather than deterministic. The theory of stochastic processes [17] includes a group of mathematical methods that are particularly useful to describe the fatigue phenomenon in asphalt mineral mixtures [11], which at present is still not a standard. Stochastic process (random process) is a function where a random event is related to its arguments. This event may be the elements of fatigue degradation processes, which are observed when the particular media is subject to cyclic loads, which means the road pavements also fit within the scope of these considerations. The counting process, which is taken under consideration in the paper, is called a stochastic process, counting k events that occurred before a certain moment. If the passing time is marked as the variable t (the beginning value is equal to 0), in the general case, the counting process $N(t)$ is a function that: **A)** takes values in the set $N_0 = 0, 1, 2, \dots, n$, **B)** is not decreasing, **C)** for $s < t$ the difference $N(t) - N(s)$ is the number of events that occurred in the time interval from the time s to time t. Such a counting process $N(t)$, $t \geq 0$ in which:

- $N(0) = 0$
- the number of events in the two separable intervals is independent
- the number of events in the time interval of length is given by a Poisson distribution

is called the stochastic Poisson process with intensity $\lambda(\lambda \geq 0)$. For the interval from 0 to t this distribution is expressed by the relation (1).

$$P\{N(t) = k\} = \exp^{-\lambda t} \frac{(\lambda \cdot t)^k}{k!} \tag{1}$$

where: λ = average number of events occurred per time unit ($\lambda > 0$), $k = 0, 1, 2, \dots, n$. The example of realization of the paths characteristic for this process is illustrated in Figure 1. The process described with the equation (1) is a special case of the non-homogeneous Poisson process, where the intensity parameter depends on time $\lambda(t)$. In the case which is taken into account in this paper, the value λ is constant, and therefore the process is called the homogeneous Poisson process.

2.2 Multi-loaded pavement deflections

The multi-load concept used in the experiment includes an analysis of the test results in which the pavement loading is also within the range of overloads. The paper [13] shows that the dependence between the deflections in the load axis and the forces in the range of 0 to 90 kN is linear. This means that the relationship of the force-pavement deflection and its subgrade (Equation (2)), can be used for linear normalization of any deflection value from this interval.

$$U_2(F_2) = \frac{F_2}{F_1} \cdot U_1(F_1) \tag{2}$$

where: F_2 = load, for which the $U_2(F_2)$ deflection value is searched, F_1 = load, for which the $U_1(F_1)$ deflection value is known. As a result, the regression functions describing the force-deflection relationship are linear. In fact, the slope of these linear functions (parameter $tg\alpha$) determines the resultant stiffness of the tested pavement structure and its subgrade. It is assumed that in reference to the relationship between such defined stiffness decrease and the progressive degradation of the pavement, there is a certain alternative for the fatigue pavement properties assessment compared to the classical analysis using the fatigue criteria.

3 Methodology

Often the archival information on the parameter values, related to the existing pavements of different types and relevant in the procedures for determining the pavement degradation, is missing. In a situation where the test results of deflection measurements are analyzed at a specific time of its life cycle, someone may need the information data from the time when it was built. The calculation of the characteristics in the form of fatigue damage (understood as the ratio of the cumulative traffic that occurred in the analyzed road section to the fatigue life calculated with mechanistic methods), it may be difficult in the context of obtaining reliable data on archival traffic load. The proposed concepts of tools that can be helpful in this regard are presented in the following paragraphs.

3.1 Test section

The deflection measurements were performed in the path of the right wheel of the truck on the experimental section with a length of 8 km. For the tests, a FWD device designed by the authors was used, described in detail in the paper [12]. The procedure for a single measurement point consisted of one trial load and then three further loading sets equal to (3 x 50, 3 x 70, 3 x 90) kN. Two traffic lanes were tested, with 89 measuring points on the left lane and 90 points on the right lane. Thickness of the layers was assumed according to the interpretation of the results of ground-penetrating radar tests (GPR method). The GPR tests were carried out in selected road cross-sections, and their locations were correlated with the location of the pavement deflection measurement points. For the purpose of the GPR equipment calibration, the control samples were drilled from the pavement layers of finite thickness (a total of 10 samples were cut). The scheme of present semi-rigid pavement test section structure and the view of the samples drilled from the asphalt layers are shown in Figure 2a. Detailed thickness of both pavement layers of GPR sections are shown in Figure 2b.

The analysis of the results of the calculation of the pavement limit states with the mechanistic method (parameters in Table 1) showed that admissible level of fatigue life is exceeded, and the value of the fatigue damage D in the majority of pavement section fulfills the condition $D \geq 100\%$. The decisive fatigue criterion indicates the exceeded limit states of asphalt layers. The results of these calculations are based on estimated archive traffic due to the lack of data, particularly in relation to the first 15 years of use of that pavement. It should be emphasized that such a situation in the case of Polish roads happens relatively often, because there has been no organized statistics so far.

Tab. 1. Basic physical properties of the base course of asphalt concrete

Sample	Density	Air volume	Bitumen volume
symbol	g/cm^3	% by volume	% by weight
A	2.429	6.7	3.5
B	2.624	2.0	5.8
C	2.559	2.3	5.2
D	2.598	2.3	4.8
E	2.590	1.3	6.1

The results of the compressive strength test of cylindrical samples drilled from the subgrade show that the average value is equal to 13 MPa, which is a concrete class C12/15 (acc. to European standard). For the calculations presented in the paper it is assumed that the minimum value of the elastic modulus of this layer, when the pavement was put into use, was most likely equal to approximately 12 000 MPa. For the subgrade, it is also assumed that at the time when the pavement was built, the standard requirements for the secondary deformation modulus were fulfilled. Therefore, it is assumed that $E_{subgrade}$ modulus was approximately close to $Ev2 \approx 120$ MPa.

3.2 The set of reference values

In the first approach to determining the hypothetical parameters of the analyzed pavement, which correspond to the moment of time in which it was built, a set of tests described in the preceding paragraph was used. Following the example of the material parameters of particular layers, an artificial disorder in the form of the so-called white noise was added to their value. It is assumed that the values obtained by this method,

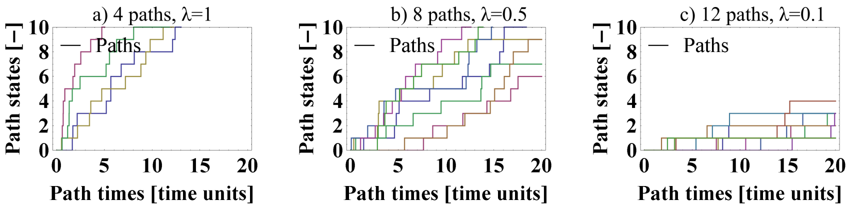


Fig. 1. Typical samples of stochastic process paths generated by a stationary Poisson distribution in a period of 0 to 20 with the intensity λ

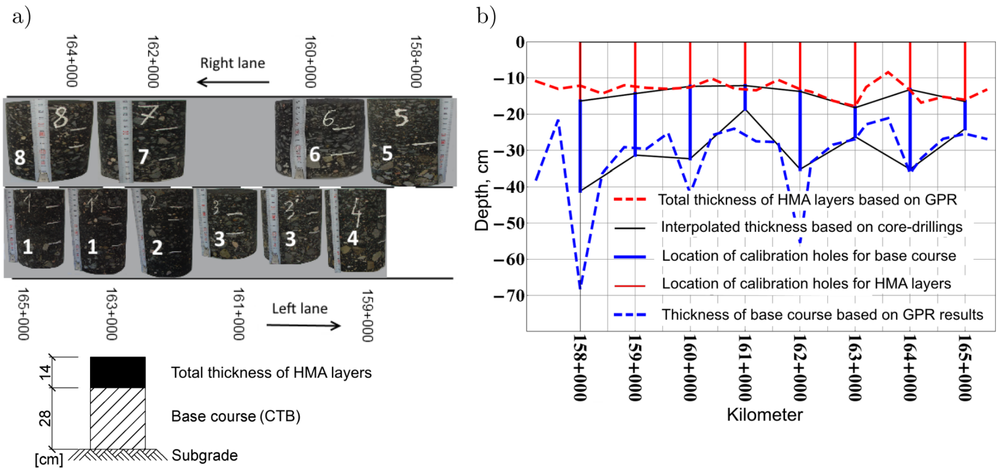


Fig. 2. Elements of the road pavement structure for the test section of 8 km length: a) view of the samples drilled from the asphalt layers with the cross-section scheme and the average thickness of layers, b) the thickness of the layers obtained on the basis of the GPR results with the GPR location of the calibration holes (vertical lines)

which describe the pavement model simulate, similar to the real, statistical parameters range when it was new. In consequence, when building the pavement models, the parameters of its layers were drawn from the population of the normal distribution in the range $X \pm 2\sigma$ (double standard deviation around the average value). The average moduli values of the layers, that simulate the behavior of the new pavement and their standard deviations, are based on the expert knowledge. The details of white noise parameters with respect to the model layers considered here are shown in Figure 3.

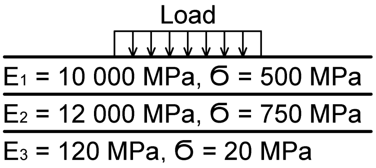


Fig. 3. List of parameters of white noise (Gauss distribution parameters for each layer of the analyzed pavement)

Legend:

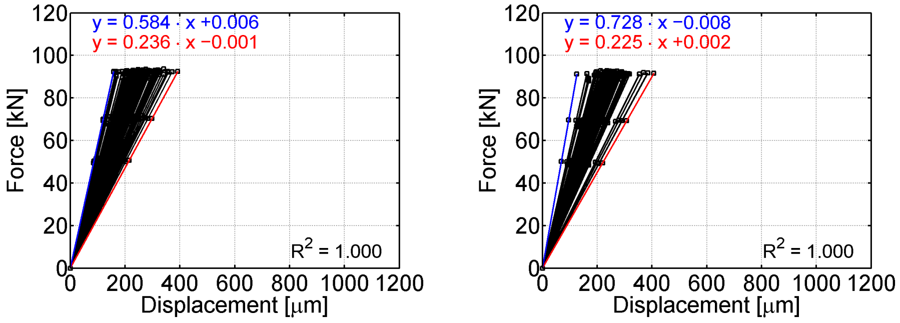
E_i	stiffness and elasticity moduli
σ	standard deviation
Load	loaded circular area of 15 cm of radius

For the simulation calculations, classical Burmister's definition of the Layered Elastic Theory (LET) model was used, described in [3,8,19,21,22]. Models were built with the properties which are as close as possible to the real pavement structure of the test section, whose age was estimated at 30 years. The static load model was taken into account, thus mitigating the adverse effects of the assumptions of constant Poisson's ratios ($\nu = 0.3$) for each layer [19] and reducing the number of required model parameters. For the thus prepared models, a series of deflection calculations on the surface of the highest layer in its structure were performed. The obtained results were taken as a set of reference values in relation to the road pavement whose age is just 30 years.

4 The resultant stiffness of the layered system

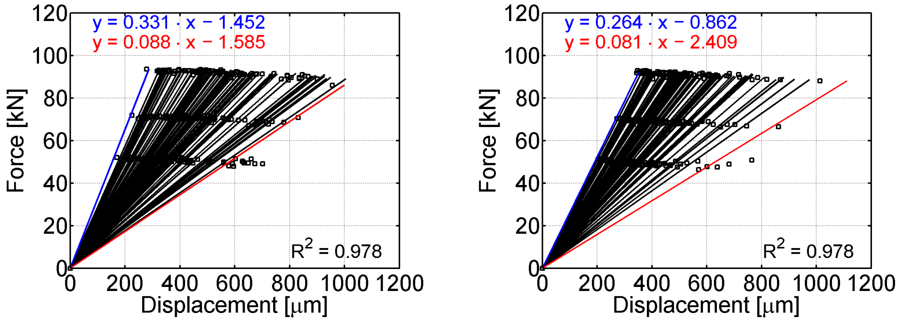
Following the methodology, two sets of slope coefficients values were obtained. The first set contains the values calculated for regression functions based on a simulated model of new pavement. In the second one, the slope values are determined for the relationship between the force and deflection of the pavement and its subgrade, based on the quantities measured in situ when the pavement has reached the age of 30 years. The results are shown in Figure 4, where the colors red and blue highlight the regression functions with extreme fitting parameters. It can be said that the presented results relate to the same pavement construction, but of different ages. The results in Figures 4a and 4b, therefore, are likely to relate to the new pavement results (the results are the effect of the use of parameters modelled on the expert knowledge, distorted with white noise). However, in reference to the results shown in Figures 4c i 4d, the resultant stiffness of the real pavement and its subgrade after 30 years of use is shown.

The average value of the slope coefficients of the regression lines for the in-situ measurements of pavement deflections in the



a) left lane

b) right lane



c) left lane

d) right lane

Fig. 4. Regression functions for the force-deflection relationship based on the results of: a) and b) calculations for models with simulated parameters as for new pavement, c) and d) the in-situ measurements after 30 years of using the pavement

load axis is: 0.178 and 0.180 [rad] for the left and right lane respectively. Similarly, the slope coefficients of the simulated new pavement amount to 0.364 and 0.378 [rad]. If it is assumed that the value of the slope of regression lines determines the resultant stiffness of the pavement and its subgrade, the decreasing value of this quantity is an increase of its degradation in time function.

4.1 The comparison of the slope coefficient

For the obtained values of the slope coefficients of regression lines shown in Figure 4, the form of the probability density function (PDF) was set. Matching log-normal distribution functions for both the new pavement models obtained in accordance with the presented methodology and that after 30 years of use are summarized in Figure 5. The parameters of these density functions are summarized in Table 2.

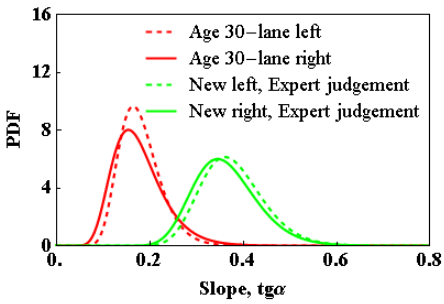


Fig. 5. Probability density function (PDF) for the log-normal distribution of the slope coefficients tgα of regression lines determining the force-deflection relationship (in the case of the "New" pavement models, these values are distorted with white noise)

The obtained results sets, two for each of the lanes, are the basis for further considerations related to the use of stationary Poisson processes.

4.2 Stochastic processes application

If we accept the hypothesis that a stationary Poisson process [11, 17] can be included in the description of the pavement damage accumulation, immediately the following question arises: How the pavement degradation state, shown in Figure 5, can be described by a pseudo-random function generated with this process? Referring to the results listed in Table 2, it is known that the probability density functions for the slopes of regression lines, constructed on the basis of the results of pavement deflection tests in-situ (case: Age 30), these are log-normal functions. The average parameters describing these distributions are equal $\alpha = 0.17$ and $\beta = 0.05$, and their form can be expressed with the equation (3).

$$PDF\,(t) = \frac{\left(\sqrt{2\pi\beta}\right)^{-1}\cdot \exp^{-\frac{\beta^{-2}}{2}\cdot(-\alpha+Log[t])^2}}{t} = \frac{\gamma_1\cdot \exp^{-\gamma_2\cdot(-\alpha+Log[t])^2}}{t} \qquad (3)$$

The calculation of the wanted variables (γ_1, γ_2 and α) in the equation (3) tend to estimate these quantities on the basis of the known parameters of the PDFs (here for the pavement parameters which were tested after 30 years of use), and outputs of stochastic processes. With reference to the form of the process given by the relationship (1) it is also known that: 1) $N(t)$ - is a stationary Poisson process, 2) t - means the time interval in

Tab. 2. Summary of PDF parameters for the log-normal distribution for the slope of regression lines shown in Figure 4

Slope values tgα for the case of	Lane	Mean value [rad]	Standard dev. [rad]	Pearson χ^2 p-value	Power of decision
Age 30	Left	0.1777	0.0560	0.108	strong
	Right	0.1799	0.0445	0.201	strong
New	Left	0.3644	0.0695	0.218	strong
	Right	0.3783	0.0676	0.232	strong

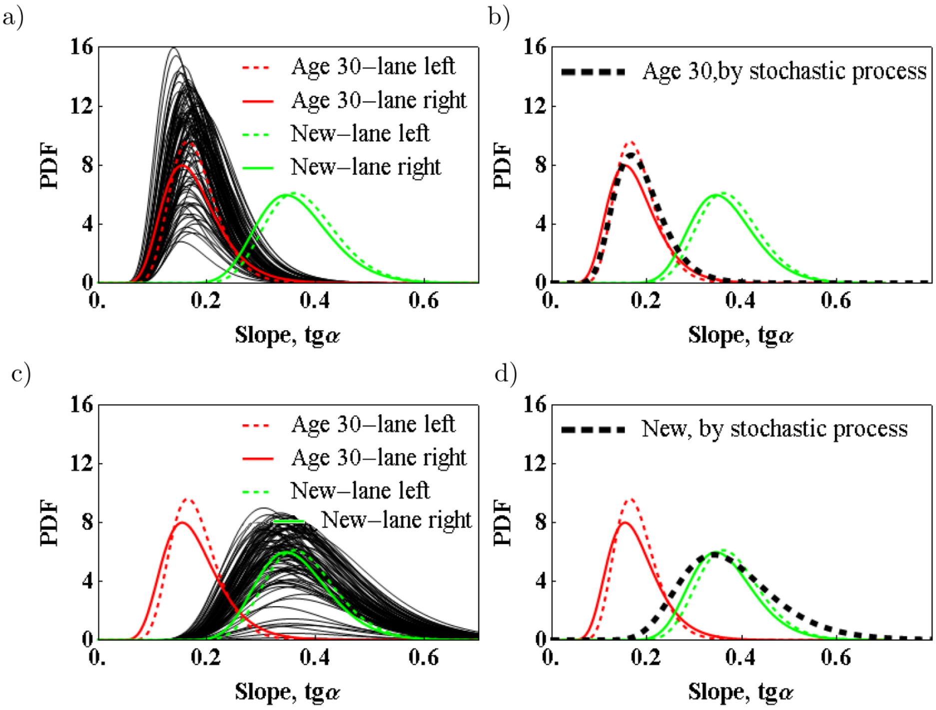


Fig. 6. The probable distributions of the regression functions slope values as the effect of the 100 tracks of Poisson process application: a) for generating the PDFs parameters of the pavement at the age of 30 years, b) averaged probability density function for the 30-year-old pavement, c) for generating the PDFs parameters of the new pavement, d) averaged PDF form indicating the slope at the time of the pavement was built

which the analyzed section was subject to the mechanisms of fatigue damage accumulation, and thus t is from 0 to t_k ($t_k = 30$ years · 360 days), 3) k - is the number of events (path states) that occurred from 0 to t_k. Consequently, generating the realization of 100 paths of stochastic process, requested values γ_1, γ_2 and α were calculated according to the scheme:

- $\gamma_1 = \mathrm{Log}[10^{-3} \cdot \mathrm{N}(t)]$ - with the intensity λ of stochastic process equal to pseudo random real number from 0 to 1
- $\gamma_2 = \mathrm{Log}[\mathrm{N}(t)]$ - where the intensity λ assumed equal to the value of the standard deviation of the PDF for *Age*30 variant, that is $\lambda = 0.05$
- $\alpha = \mathrm{Log}[10^{-3} \cdot \mathrm{N}(t)]$ - for the intensity which corresponds to average value of the PDF for *Age*30 variant divided by ten, that is $\lambda = 0.17/10$.

The results of these calculations are shown in Figure 6.

5 Summary and conclusions

The analysis of pavement reaction in conditions of overloads is primarily an attempt to enrich the analysis based on the results of the pavement deflection tests carried out in a non-standard way. The concept of pavement deflection tests under multi-level load plans, belongs to the category of accelerated tests, and aims to explore methods of study and verification of multilayer systems fatigue properties, so different types of pavements, not just those with a semi-rigid structure. Both the fatigue degradation source and the development of pavement layers damage are not a smooth and ordered phenomenon. Therefore, the fatigue degradation process is treated here as a random process that is rather discrete than continuous and is characterized by a random number of jumps of random values. In such conditions, it is possible to use the stochastic processes in the evaluation of the fatigue pavement degradation and its subgrade. This paper assumes the reference in the form of pavement deflection measurement results of the 3-layer semi-rigid structure. The randomness of its degradation as a time function is shown by the probabilistic mechanism of probability density changes of the slope coefficients of regression lines describing the relationship between force and deflection values in the range of loads up to 90 kN using the FWD-type device. Estimating the parameters of the probability density function for the set of slope values indicated at the moment of pavement life cycle time, the likely changes of their value in time are estimated using the properties of the stochastic process with intensity of the Poisson process. In relation to the tests carried out in this paper, it was noted that the value of the slope of regression lines of the force-deflection relationship marked in overloads conditions, in some way determines the resultant stiffness of the pavement and its subgrade. In conjunction with the mechanisms of the stochastic Poisson process, these results appear to be an interesting information medium about the change of its value as a function of time, because in general the decreasing value of this quantity is an increase of degradation. Although the results described here are in the testing phase, and need to be verified on a larger number of pavement construction cases, the hypothesis is true and encourages further research in this area.

Anyway, one needs to remember that the pavement degradation is a complex phenomenon which introduces several parameters affecting the pavement strength such as: a) real traffic load, b) environmental conditions and drainage, c) variation of mechanical properties in time, d) maintenance strategy. All of them are stochastic variables, and modeling of pavement degradation phenomenon should include rheological models in order to represent “to the best” the mechanisms of the damage accumulation of the constitutive materials, and should not contend with a simplified model based only on modulus of rigidity of the pavement. Pavement degradation phenomenon is a continuous time-dependent stochastic process, and should include the pavement degradation rate especially at advanced pavement service life, whereas the Poisson model is a memory less stochastic process, i.e. the average number of events per unit time is constant. Non-homogeneous Poisson process or stochastic Markov forecasting models should provide more realistic prediction of the pavement degradation phenomenon with presented methodology.

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