Calibration of the prediction model for fatigue damage accumulation in asphalt courses of flexible pavements for the conditions specific to the Russian Federation

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Abstract. The article dwells on the asphalt pavements fatigue life matter. The authors suggest a fatigue damage prediction technique based on the NCHRP modified model and the MMOPP model of structural deterioration of asphalt courses. The research resulted in the fatigue cracking main algorithms verification and calibration performance prediction based on the analysis of actual conditions of the M4 Don Highway pavement which makes it possible to significantly improve the prediction results reliability for the conditions specific to the Russian Federation.

Introduction

Facing the modern high-speed high-density traffic, asphalt pavements are exposed to the multi-cycle impact from vehicles which have dynamic nature and are one of the driving factors of pavement service quality deterioration and damaging thereof. It is known that asphalt damage under the impact of repetitive loads is induced by fatigue processes, i.e. by emergence and accumulation of microdefects with gradual reduction of strength over time.

Fatigue life of asphalt pavements was researched in the works of B.S. Radovsky, E.V. Uglova, O.A. Sall, and others. The increasing interest to the matters of fatigue damage of pavements is accounted for the increasing traffic on the one part and reduction of actual service life of asphalt pavements on the other part. That is why according to many foreign pavement design methods, calculation of fatigue of the bending course material is considered crucial for specification of the required thickness of pavement courses [1, 2, 3, 4].

Development of a similar technique is of significant academic and research interest for the Russian practices too since changeover to the western systems of asphalt course mix designing based on maintenance of their service properties has been emerging over recent years.

Fatigue damage prediction technique

The following technique shown in the flow diagram (refer to Figure 1) is suggested for the fatigue damage prediction in asphalt courses.

The following input data are needed:
- pavement structure (material, thickness, number of courses);
- stress-strain properties (modulus of rigidity, Poisson ratio) of the applied materials depending on the temperature (for materials with organic binder) and the humidity (for soils);
- value of the design load and the number of its application (traffic intensity);
- horizontal tensile strain from the design load at the bottom boundary of asphalt courses and the base course.

![Flow chart of calculation based on fatigue damage](image)

**Figure 1.** Flow chart of calculation based on fatigue damage

The $\epsilon_f$ horizontal tensile strain is obtained by calculation according to the layered elastic theory (LET) depending on the load, thickness of courses and the pavement in question materials stress-strain properties [4].

The $N_f$ design load applications maximum number within the period in question up to the fatigue failure is calculated in accordance with the NCHRP modified fatigue model of the University of Minnesota (refer to formula 1). It specifies the maximum number of applications of the design load that the pavement is capable of enduring before it fails. i.e. before fatigue damage begins to appear [5,6].
\[ N_f = C_{f0}K_f\epsilon_f^{Kf_2} \left( \frac{E_f \cdot 1000}{6.97} \right)^{Kf_1}, \]  

(1)

where \( N_f \) stands for the repetitions permissible number within the \( f \) period up to the fatigue failure;
\( C_{f0}, K_f, K_{f2}, K_{f3} \) stand for calibration factors;
\( \epsilon_f \) stands for the horizontal tensile strain at the bottom of the asphalt courses package caused by application of the design load within the \( f \) period;
\( E_f \) stands for the asphalt bottom course rigidity modulus within the period in question, MPa.
\( C_{f0}, K_f, K_{f2}, K_{f3} \) ratios are calibrated according to the data collected at the highways of the state of Minnesota in 2006 and take on the following values: \( C_{f0} = 0.314; \ K_f = 1.2; \ K_{f2} = -3.291; \ K_{f3} = -0.854 \) [7,8].

The \( N_f \) permissible number of repetitions from formula 1 is used for prediction of fatigue damage from application of loads within the pavement service life. Calculation of accumulation of asphalt pavement fatigue damage is done with the use of the cumulative damage hypothesis known as the Miner’s hypothesis (refer to formula 2). According to this hypothesis, the fatigue damages caused by the different values deformations are summed. The pavement fatigue damage occurs when the sum of relative damages with all the levels of stress amplitudes reaches one [1,7].

\[ D = \sum_{f=1}^{\infty} \frac{A_f}{N_f(E_f; \epsilon_f)} \]  

(2)

where \( D \) stands for the cumulative damage proportion;
\( N_f \) stands for the permissible number of applications of loads within the \( f \) period with the \( E_f \) modulus of rigidity of the bottom course of the asphalt pavement and the \( \epsilon_f \) horizontal tensile strain;
\( A_f \) stands for the actual number of applications of the design load within the \( f \) period;
\( F \) stands for the total number of calculation periods.

Structural deterioration of the asphalt pavement courses is designed in accordance with the model set forth in the MMOPP (refer to formula 3). MMOPP is the Danish research program for development of pavement design standards created by the Road Standards Group for the Design of Road Pavements [9].

\[ E_{f+1} = E_f \left[ 1 - 0.5 \left( \frac{\epsilon_f}{\epsilon_{deformation}} \cdot \left( \frac{VB}{10} \right) \right)^n \left( \frac{A_f}{K_fCP_f} \right) \right]^{(1)} \]

(3)

where \( E_{f+1} \) stands for the modulus of rigidity following application of the design load, MPa;
\( E_f \) stands for the modulus of rigidity prior to application of the design load, MPa;
\( \epsilon_f \) stands for deformation at the bottom of the asphalt course within the \( f \) period;
\( \epsilon_{deformation} \) stands for the permissible deformation at the bottom of the asphalt course following 106 trips of the design load;
\( VB \) stands for the bitumen content in the asphalt, %
\( n = 5.62 \) stands for the fatigue model ratio (Kirk’s ratio);
\( A_f \) stands for the number of applications of the design load within the \( f \) period;
\( CP_f = 10^6 \) stands for the calibration ratio.
\( K_f \) stands for the temperature correction factor which makes the material less damageable at high temperatures (refer to formula 4);

The \( K_f \) temperature ratio is calculated according to the following formula:

\[ K_f = C_1 \cdot 10^{\left( \frac{(r_f + C_2)}{C_3} \right)} \]  

(4)

The asphalt pavement courses are designed in accordance with the model set forth in the MMOPP (refer to formula 3). MMOPP is the Danish research program for development of pavement design standards created by the Road Standards Group for the Design of Road Pavements [9].
where $T_f$ stands for the temperature of the asphalt course within the f period, °C; $C_1$, $C_2$, $C_3$ stand for the constants depending on the $T_f$ temperature according to Table 1.

### Table 1. Constants in the temperature correction factor

| $T < 16^\circ C$ | $16^\circ C < T < 21^\circ C$ | $T > 21^\circ C$ |
|------------------|-----------------------------|------------------|
| $C_1$            | 0.0005                      | 0.22             |
| $C_2$            | 17.8                        | -16              |
| $C_3$            | 12.8                        | 7.6              |

**Calibration of the fatigue damage model**

Let us perform calculation of the existing pavement located on the M-4 Don Highway on the section 777+000 km to 801+000 km. The package of works for estimation of residual life performed in 2016 has shown that the state of this section does not correspond to the norm. Over the main part of the section length there are critical pavement defects and non-satisfactory roughness in both directions with the strength however satisfying the requirements. On the basis of the above it should be concluded that within 6 years of the pavement operation the maximum number of applications of the design load based on the fatigue damage criterion has been reached.

The section in question is characterized by the following parameters:

- road section category – Ib;
- number of lanes: 4;
- pavement type – heavy-duty;
- road climatic area – IV (Construction Standards and Regulations SNiP 2.05.02-85);
- design load: A1 100 kN;
- year of commissioning of the facility: 2010 (restoration);
- pavement structure (refer to Table 2).

### Table 2. Pavement structure on the section in question

| No. | Course      | Material                                      | Thickness, [cm] |
|-----|-------------|-----------------------------------------------|-----------------|
| 1   | Surface     | Stone mastic asphalt SMA-15 on polymer-modified asphalt PMA 60 | 5               |
| 2   |             | Open-graded coarse asphalt                     | 7               |
| 3   | Base course | Open-graded coarse asphalt Grade I             | 7               |
| 4   |             | Lean concrete B5.5 (M75)                       | 15              |
| 5   |             | Dry-bound fractioned macadam                  | 15              |
| 6   |             | Fractioned macadam 40-70                      | 18              |
| 7   | Subgrade    | Loam soil                                     | -               |

To optimize calculations the convention is that the air temperature is 0 °C in winter, 30 °C in summer, 10 °C in spring and autumn. And the $W/W_m$ relative humidity of the subgrade is 0.6 in winter, 0.65 in summer, 0.7 in spring and autumn.

Stress-strain properties of the materials depending on temperature and humidity (for soils) are set forth in Table 3.

### Table 3. Stress-strain properties of the materials

| No. | Material     | Modulus of rigidity, [MPa] | Poisson ratio | Temperature |
|-----|--------------|----------------------------|---------------|-------------|

4
|   | Stone mastic asphalt SMA-15 on polymer-modified asphalt PMA 60 | 0 °C | 10 °C | 30 °C |   |
|---|---------------------------------------------------------------|------|------|------|---|
| 1 | 12000                                                        | 7025 | 1350 | 0.35 |
| 2 | Open-graded coarse asphalt                                    | 15000| 5900 | 1100 |
| 3 | Open-graded coarse asphalt Grade I                            | 15000| 5900 | 1100 |
| 4 | Lean concrete B5.5 (M75)                                      | 870  | 870  | 870  | 0.25 |
| 5 | Dry-bound fractioned macadam                                  | 450  | 450  | 450  | 0.45 |
| 6 | Fractioned macadam 40-80                                     | 270  | 270  | 270  | 0.45 |
| 7 | SOIL: Loam*                                                  | 72   | 54   | 46   | 0.45 |

*The soil stress-strain properties are specified in relation to W/W season-wise.

The actual traffic intensity is specified according to the data obtained through monitoring at the traffic intensity monitoring station (TDMS) located at 801+500 km and set forth in Table 4.

Table 4. Annual average daily traffic at the TDMS M-4 Don 801+500 km

| Year | passenger cars | minibuses, small-scale trucks | single motor vehicles, buses | motor vehicle trains up to 13 m | motor vehicle trains 13..18 m | long motor vehicle trains longer than 18 m | Per day |
|------|----------------|--------------------------------|------------------------------|--------------------------------|-------------------------------|-----------------------------------------------|---------|
| 2013 | 8 294          | 1 293                         | 910                          | 666                            | 4 567                         | 2 023                                         | 17 753  |
| 2014 | 7 150          | 2 503                         | 1 160                        | 584                            | 4 952                         | 1 843                                         | 18 191  |
| 2015 | 6 676          | 4 395                         | 1 721                        | 1 148                          | 4 945                         | 1 696                                         | 20 581  |
| 2016 | 7 182          | 2 893                         | 839                          | 1 248                          | 4 724                         | 607                                           | 17 492  |

The total number of applications of the design load per each year will be evenly distributed throughout the year and the calculations will be performed. The calculation results with the $C_{f0}$, $K_{f1}$, $K_{f2}$, $K_{f3}$ input calibration ratios are set forth in Table 6.

Table 6. Results of calculation with the input calibration ratios

| Year | Total design number of applications of the design load to the point on the pavement surface |
|------|------------------------------------------------------------------------------------------|
| 2010 | 981566                                                                                   |
| 2011 | 1035553                                                                                  |
| 2012 | 1092508                                                                                  |
| 2013 | 1152596                                                                                  |
| 2014 | 1191026                                                                                  |
| 2015 | 1297479                                                                                  |
| 2016 | 1046122                                                                                  |
As shown in Table 4 the pavement has not reached the limit. This points to the fact that the NCHRP modified fatigue model of the University of Minnesota, namely its calibration ratios, does not reflect the actual pavement damage correctly.

Let us design (calibrate) it by the $C_{f0}$, $K_{f1}$, $K_{f2}$, $K_{f3}$ ratios for local conditions by the method of generalized reduced gradient (GRG). The method of generalized reduced gradient is developed from the method of reduced gradient (MRG) and it may be used to solve nonlinear programming problems with nonlinear limiting functions. The underlying concept of the GRG method is to reduce the dimension of the problem by elimination of dependent (basic) variables and use the MRG method for obtaining the descent direction as a criterion for determination of optimality too.

The problem of optimization (searching for the optimal $C_{f0}$, $K_{f1}$, $K_{f2}$, $K_{f3}$ ratios) is put as follows (refer to formulas 5 and 6):

$$D = \frac{\sum_{j=1}^{F=72} A_f}{N_f(C_{f0}; K_{f1}; K_{f2}; K_{f3})} \to 1 \quad (5)$$

$$\begin{cases} C_{f0}; K_{f1} > 0 \\ K_{f2}; K_{f3} < 0 \end{cases} \quad (6)$$

**Summary**

Based on the optimization results the calibration ratios took on the following values: $C_{f0} = 0.313$; $K_{f1} = 1.157$; $K_{f2} = -3.069$; $K_{f3} = -0.876$.

With the use of optimized calibration ratios in calculations the pavement reached the limit within 6 years of operation which reflects the actual pavement damage. The results of calculation with the new ratios are set forth in Table 7.

**Table 7. Results of calculation with the new calibration ratios**

| Year | Modulus of rigidity of the asphalt bottom course, [MPa] | Proportion of fatigue damage per year | Accumulation of the proportion of fatigue damage year-wise |
|------|------------------------------------------------------|--------------------------------------|--------------------------------------------------------|
| 2011 | 14989                                                | 0.145279611                          | 0.145279611                                           |
| 2012 | 14974                                                | 0.153303666                          | 0.298583277                                           |
| 2013 | 14959                                                | 0.171440703                          | 0.47002398                                            |
| 2014 | 14944                                                | 0.177175731                          | 0.647199711                                           |
| 2015 | 14929                                                | 0.193015892                          | 0.840215603                                           |
| 2016 | 14914                                                | 0.155614631                          | 0.995830234                                           |
Thus, for the first time it became possible to develop a mechanistic-empirical method of flexible pavement design according to the fatigue damage criterion based on the NCHRP modified fatigue model and calibrated with the data obtained use at the M4 Don Highway.

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