ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20240619105039

Original scientific paper
Received: 2024-06-19, Accepted: 2024-08-28

Estimation of the Service Life of Approach Slabs of Road Bridges Based on the Statistical Modeling Method

Olena Slavinska, Bubela Andriy, Kozarchuk Ihor*, Davydenko Oleksandr

Abstract: The article discusses the durability and reliability of a separate element – bridge approach slab, which is justified by the need to maintain a satisfactory technical condition of Ukrainian bridges in general and traffic safety on public roads with limited funding during martial law. The scope of the research is forecasting the residual service life of bridge elements (on the example of approach slabs) using probabilistic methods. Approach slabs are designed to smoothly and safely connect the road approach embankment with the bridge to gradually equalize the elastic modulus of the carriageway from a less rigid asphalt pavement on an elastic base to a more rigid one on a reinforced concrete slab. The main defects in the destruction of approach slabs are: changes in the longitudinal profile of the road due to the collapse and subsidence of the soil under the approach slabs; longitudinal and transverse cracks in the asphalt concrete pavement on the bridge approaches; and potholes that lead to an increase in the additional dynamic load on the bridge deck.

Keywords: approach slab; bridge crossing; failure; motorway; residual life; service life

1 INTRODUCTION

In road construction, technological processes are characterized by the mutual combination and influence of random phenomena caused by the heterogeneity of soils and materials, the variety of operations (crushing, damping, mixing, compaction, etc.), and the impact of various meteorological factors. That is why the values of certain quality indicators often vary in a fairly wide range.

An objective assessment of such indicators is possible based on the application of mathematical statistics. Such methods have long been widely used in engineering to assess product quality. In road construction, the use of these methods is also of great importance.

When performing a statistical assessment of product quality indicators, it is necessary to

- Estimate measurement errors, identify possible errors
- Establish the laws of distribution of indicators
- Determine confidence limits and intervals for the distribution parameters of the quality indicator being assessed
- Compare sets of measurements to identify existing patterns
- Solve problems of tolerances
- Investigate the relationship between quality indicators.

1.1 Problem Statement

Regulatory documents related to the calculation of reinforced concrete bridge elements in Ukraine do not include mechanisms for durability management, do not contain theoretical dependencies that would allow for the calculation of the element's durability, and do not include regulations for quantifying the impact of physical and mechanical characteristics of materials on the element's durability, or quantifying the impact of the environment. As a result, it turns out that the service life of reinforced concrete span structures stated in the bridge design standards is 80-100 years for Ukraine, which is unrealistic and poses a real threat to the safety of structures, as well as significant economic losses.

The problem of safe operation of bridges in Ukraine has been relevant since independence. Over the last decade of 2014-2024, the problem has become even more acute due to active hostilities and a number of other unfavorable reasons: the maintenance system does not meet modern technical standards and does not have the necessary resources for proper and timely maintenance of structures; the financing system of the road network of Ukraine does not allow the use of modern and innovative technologies for the operation and construction of bridges; Ukraine lacks a clear strategic plan for the improvement, maintenance and operation of road bridges.

The steady deterioration of bridges is the result of their complicated operation in modern conditions and not always sufficiently high quality of construction, as well as the lack of mechanisms for managing the durability of bridges, both at the design, construction and operation stages, currently under the influence of hostilities.

Today, the design life of reinforced concrete bridges is set by regulation, the design dependencies do not include the time variable, and the durability problem mainly depends on the experience and intuition of the designer.

The problem of durability of reinforced concrete elements is the subject of research by a large number of scientists, including Ukrainian ones. In modern conditions, there is a need to combine the scientific basis of research on the degradation of reinforced concrete with design requirements, construction and operation conditions, as well as to obtain a theoretical model for assessing the service life of reinforced concrete bridge elements, which would form the basis for developing a practical mechanism for managing the life cycle of bridges.

In these conditions of limited funding, it is advisable to consider the durability of individual bridge elements. The area where the approaches meet the bridge deck (Fig. 1), where the approach slabs are located, is often in an unsatisfactory technical condition.

Figure 1 Soil spillage under the approach slabs in the area where the bridge meets the approaches due to precipitation - View from the side of the bridge pillar

Figure 2 Soil spillage under the approach slabs in the area where the bridge meets the approaches due to precipitation - View from the road side

The technical condition of the bridge-approach junction directly affects traffic safety, if there is damage in the form of changes in the longitudinal profile of the road, then additional dynamic loads are also transferred to the bridge deck, which significantly reduce the durability of the bridge as a whole [1].

In this case, it is advisable to consider the reliability and durability of the road-bridge junction to ensure acceptable traffic safety and good technical condition of the bridge in conditions of limited funding.

1.2 Publications Overview

The application of the Markov chain method to assess the service life of bridge elements is described in a large number of research papers. The change in bridge states is a random process, so the service life of bridges is related to the probabilities of condition transitions. A bridge service life prediction model using a Markov chain was developed to reflect the stochastic nature of bridge condition and service life. The paper [2] includes a discussion of the Markov chain concept, the development and application of a Markov chain service life prediction model, and a comparison of service life predictions using a statistical approach (degradation curve constructed using regression analysis) and a Markov chain approach. Markov chain service life prediction has an advantage over the statistical regression approach because it can be used not only to estimate the average service life of a number of bridges but also for each individual bridge. In addition, the Markov chain prediction is based on the current condition and age of the bridges, therefore it is simple and can be updated with new information on the condition assessment and age of the bridge. However, it should be noted that this study was based on a statistical analysis of condition ratings. Condition ratings are subjective judgements that can be biased and therefore can affect the results of service life predictions.

In order to reduce the bias of certain judgements, a mathematical model for assessing the condition of a bridge using fuzzy set theory was developed in [3]. The reliability and accuracy of service life predictions can be significantly increased by applying the bridge condition assessment model in the process of its inspection.

A method of predicting the condition of structures and facilities based on the use of machine learning and artificial intelligence is relevant and promising. In particular, the paper [4] proposes the concept of using machine learning (ML) algorithms for more accurate prediction of bridge pavement wear. The results showed that ensemble ML algorithms were able to predict the condition of the bridge deck significantly more accurately than individual models when “optimal” characteristics were used.

The results of this study will improve researchers' understanding of the most important parameters that can influence the deterioration of a bridge pavement. The study allows maintenance services to better understand the performance and life expectancy of bridges using machine learning. Such knowledge can help bridge owners to be proactive in planning maintenance and repair, developing capital maintenance programs to ensure that funds allocated for bridge maintenance, rehabilitation and repair are properly and efficiently allocated.

In the absence of extensive failure statistics, the paper [5] proposes to use a probabilistic-physical approach to assessing durability. The main parameters of the probabilistic model with DM-distribution of failures are the average rate of change of the determining parameter and the coefficient of variation of the generalized degradation process.

The probabilistic-physical method proposed in the article, based on the study of the dynamics of change in the determining parameter, allows calculating the residual service life of road bridge elements with consideration of the appearance of cracks and predicting the full service life.

The probabilistic-physical method based on the DM-distribution of failures takes into account the random nature of destruction (degradation) processes, which are irreversible, with monotonous realizations and develop at a constant rate. This method provides more adequate calculation results and, in some cases, reduces the operating costs of facilities.

High-quality collection of information on bridge failure parameters, bridge structures and a probabilistic-physical approach to assessing the actual technical condition of the facility provide more accurate calculation results and allow predicting when their maximum permissible value will be reached.

The paper [6] presents a detailed assessment of the remaining service life of a repaired bridge using the Joint Committee on Safety of Structures (JCSS) reliability analysis method based on the structural load-bearing capacity (LBC) of the bridge and the design load. Using finite element analysis (FEA), the bending moment on the control section of the bridge was determined under the most unfavorable loading conditions and the ultimate LBC of the bridge was verified. Subsequently, static and dynamic tests were carried out on the rehabilitated bridge, where the FEA analysis was used to determine the load and capacity for the control section. A time-dependent reliability index was developed for the rehabilitated bridge using probabilistic distributions of the capacity and design load variables and the remaining service life was determined. This study predicts the remaining service life of the bridge based on a large amount of data that is relevant for future maintenance and life cycle management of bridges.

The paper [7] presents a comparative study of two service life prediction models (Life-365 and NCHRP report 558). The service life prediction analysis was performed on corroded bridge piers. To assess the existing condition of the structure and obtain the parameters required for the analysis, a review of the existing bridge documentation, visual inspection and concrete damage survey, field sampling and testing, and laboratory tests were carried out. A good agreement was obtained between the results of the Life-365 and NCHRP report 558 analyses.

The residual service life of bridge structures is traditionally assessed using the AASHTO S-N curves in a deterministic manner. In this approach, the fact that a structural component has already undergone n_{cs} load cycles does not affect the expected fatigue life. However, the data obtained due to the fact that the structure has undergone n_{cs} cycles should theoretically change future estimates of survival and life expectancy based on conditional probability theory. To do this, it is necessary to develop conditional survival (reliability) functions for a specific stress range and fatigue part category. Survival analysis methods and conditional probability theory can provide the necessary computational tools to achieve this.

The paper [8] discusses the theoretical basis for probabilistic fatigue life estimation based on well-established survival analysis methods (and conditional survival models). The implications of incorporating conditional endurance into estimates of expected remaining fatigue life of bridges are discussed for the various AASHTO fatigue design categories. The results indicate that the inclusion of conditional survival has an important impact on the residual fatigue life of bridges

The approach proposed in [8] based on endurance analysis can calculate the remaining fatigue design life even if n_{cs} exceeds the fatigue limit based on AASHTO S-N curves for a certain stress range and detail category.

In the study [9], the remaining service life expressions for different service conditions were established using the random process analysis method when the reinforcement rebar of a beam bridge began to corrode, the concrete cracked due to reinforcement corrosion and the bridge reached the limit state. The results show that the reinforcement of a concrete girder bridge begins to corrode after the bridge has served 10.07-10.97 years. When the corrosion depth of the rebar is 0.047 mm, the concrete begins to crack, which consequently leads to an acceleration of the corrosion rate of the reinforcement, and when the corrosion depth is 1.591-1.595 mm, the girder bridge will reach the ultimate state of load-bearing capacity.

The paper [10] proposes a framework for predicting the remaining service life based on the reliability of existing deteriorated structures, separately taking into account random and epistemic uncertainties. A Bayesian probability box (p-box) is developed to model epistemic uncertainty by taking into account the limits of the distribution parameter, while random uncertainty is modelled as an exact distribution function. The method allows to automatically update the results and limits of the remaining service life (RSL) estimation by deploying the data of regular and repeated inspections of bridges, which are usually available in practice. For validation, the method is applied to a real reinforced concrete bridge with a corrosion defect in the steel reinforcement. The results show a significant variance in the RSL prediction given the imprecision of the data, which strongly emphasizes that epistemic uncertainty should be taken into account when making decisions related to existing bridges. In fact, for the given example, accounting for epistemic uncertainty in rebar corrosion can almost double the probability of failure.

The reviewed works mainly consider an integrated approach to assessing the condition of the bridge and its service life, without considering individual elements. Accordingly, the aim of this study is to assess the service life of approach slabs at bridge crossings based on the methods of mathematical statistics and probability theory.

2 RESEARCH METHODOLOGY

To statistically assess quality indicators and perform comparative analysis, it is necessary to know the law of distribution of random variables. In road construction, according to the research of the road quality research laboratories of the National Transport University, the law of normal distribution of variables is preferable.

In addition, the following distributions can be used.

The Weibull distribution is most commonly used for reliability indicators, for example, to describe the distribution of failures and service life of road pavements:

$$f(x) = n \cdot \mu^n \cdot x^{n-1} \cdot \mathrm{e}^{-\mu^n \cdot x^n}, \qquad (1)$$

where n, μ are the parameters of the distribution law; x – argument (usually time).

The Poisson distribution is used to analyse random discrete short-term events, for example, the analysis of road and utility vehicles, equipment operation at asphalt and cement plants, etc. The probability of occurrence of the number of events x = 1, 2, 3, ... per unit of time according to the Poisson law is:

$$P(x) = \frac{m^x}{x!} \cdot \mathrm{e}^{-m} = \frac{(\lambda \cdot t)}{x!} \cdot \mathrm{e}^{-\lambda \cdot t}, \qquad (2)$$

where x is the number of events in a given time period t; λ – density, i.e., the average number of events per unit of time; $(\lambda \cdot t) = m$ – average number of events in time t.

Based on the analysis of physical factors, a hypothesis about the type of distribution is put forward, which is tested according to statistical criteria.

The adequacy of the distribution function, i.e., the assessment of the consistency of the experimental and theoretical distributions, is established by the Fisher's, Pearson's χ^2, and Kolmogorov's criteria.

Next, we will consider the law of *normal distribution*, as the most common in road construction. After obtaining the statistical series, the average values of the indicator $\bar{x}$, the range R, the standard deviation σ and the coefficient of variation c_v are calculated. The probability density of the normal distribution law is expressed by the following relationship:

$$f(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot \mathrm{e}^{-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2}. \tag{3}$$

The empirical density function of the distribution is represented graphically by a histogram of frequencies – relative frequencies – a step graph consisting of rectangles with bases of partial variation intervals of length $h = x_k - x_{k-1}$ and heights n_k/h. Here k is the number of intervals of the variation series. For series close to the normal distribution, the approximate value of the number of intervals (an integer) is determined by the Staggers' formula:

$$k = 1 + 3{,}322 \cdot \lg(N), \tag{4}$$

where N is the size of the variation series (sample size).

To establish adequacy, during the construction of an experimental graph of the normal distribution, centering ($\bar{x} = 0$) and normalization ($\sigma = 1$) are performed. As a result, a tabular function is obtained, and the transition from it to the specified function is performed by decentering and deformalizing of the tabular function.

If it is needed to plot the integral function of a normal distribution law, the following expression is used:

$$F(x) = \int_{-\infty}^{x} \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot \mathrm{e}^{-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2}. \tag{5}$$

If this function is centered by $(x - \bar{x})/\sigma = t$, then the centered and normalized normal distribution function will have the form:

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} \mathrm{e}^{-0{,}5t^2} \mathrm{d}t. \tag{6}$$

where $t = (x - \bar{x})/\sigma$.

Here is a methodology for establishing the adequacy of the normal distribution law. The task is formulated as follows: to establish the law to which the phenomenon under study is subject, and to test the plausibility of the statistical hypothesis at the accepted significance level α.

1) To solve this problem, the sample size N is divided into k intervals. For each interval, the lower M_l and upper M_u margins of values are set. One of the intervals is taken as a false zero M_0.

The lower M_{l0} and upper M_{u0} margins of the intervals relative to false zero are calculated:

$$M_{l0} = M_l - M_0, \tag{7}$$

$$M_{u0} = M_u - M_0. \tag{8}$$

The midpoints of the intervals are determined:

$$x_{mi} = 0{,}5(M_{l0} + M_{u0}). \tag{9}$$

2) Next, the experimental (trial) frequencies of falling into each interval are calculated:

$$P_{ei} = \frac{m_{ei}}{N}, \tag{10}$$

where m_{ei} are the experimental frequencies (the number of times an event occurs).

Then the accumulated frequencies ΣP_{ei} are summed over the intervals.

3) The function under study is centered and normalized.

To do this,

$$t_i = \frac{x_{mi} - \bar{x}}{\sigma}, \tag{11}$$

is calculated and tabulated probability densities $f(t)$ at $\sigma = 1$ are established:

$$f(t_i) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot \mathrm{e}^{-\frac{1}{2}t_i^2} = \frac{1}{\sqrt{2\pi}} \cdot \mathrm{e}^{-\frac{1}{2}t_i^2}. \tag{12}$$

4) Then the theoretical probabilities of falling into the intervals are calculated:

$$P_{mi} = \frac{f(t_i) \cdot \Delta x}{\sigma}, \tag{13}$$

where Δx is the length of the interval.

Theoretical frequencies are calculated next:

$$m_{mi} = P_{mi} \cdot N. \tag{14}$$

5) After that, the adequacy of the theoretical curve is determined. Adequacy is confirmed if

$$P\left(\chi^2, \nu\right) > \alpha, \tag{15}$$

where χ^2 is Pearson's criterion of coherence:

$$\chi^2 = \sum_{i=1}^{n} \frac{\left(m_{ei} - m_{mi}\right)^2}{m_{mi}}, \tag{16}$$

where ν is the number of degrees of freedom:

$$\nu = k - S, \tag{17}$$

where k is the number of intervals (groups) of a large sample or the number of measurements in one interval in the analysis of a single-series experiment;

S is the number of relationships used, i.e., the number of available dependencies (parameters).

In Eq. (15), $\alpha = 0{,}01$ is usually assumed.

3 METHOD VERIFICATION

To verify the applicability of the normal distribution law to the failure of approach slabs at bridge crossings and to check the adequacy of the above methodology, a sample of 200 surveyed prematurely failed reinforced concrete approach slabs was used. For this purpose, it is necessary to find the law to which this phenomenon – slab failure – is subject, to establish its compliance with the law of normal distribution, as well as to determine the average service life of slabs (time between failures) and to build a residual life curve depending on the service life (the accepted normative service life of slabs before overhaul is $T_n = 20$ years).

Let's solve the problem according to the above methodology. The actual service life of the slabs T_a is taken as a random variable in the sample, with a range of R from 6 to 24 years.

1) The sample size is divided into k intervals according to Eq. (4)

$$k = 1 + 3{,}322 \cdot \lg(N) = 1 + 3{,}322 \cdot \lg(200) \approx 9, \tag{18}$$

in $\Delta x = 2$ years. We set the lower M_l and upper M_u margins of the intervals. For a false zero with a maximum of the experimental frequency, we take

$$M_0 = 0{,}5 \cdot (6 + 24) = 15 \text{ years}, \tag{19}$$

and calculate the intervals relative to the false zero using Eq. (7), (8) (data from Tab. 1). We establish the midpoints of the intervals x_{mi} according to Eq. (9) and the experimental frequencies m_{ei} (the number of times the actual service life of the approach slabs falls into each interval) (Tab. 1).

2) We calculate the experimental frequencies by intervals according to Eq. (10) (data from Tab. 1):

$$P_{e1} = 4/200 = 0{,}02, \tag{20}$$

$$P_{e2} = 6/200 = 0{,}30, \text{ etc.} \tag{21}$$

Then we find the sum ΣP_{ei}.

Fig. 1 shows a histogram of the experimental frequencies of failure of approach slabs, on the basis of which we make a preliminary conclusion that it follows the law of normal distribution. To test this hypothesis, it is necessary to build a theoretical curve and determine the Pearson's χ^2 criterion.

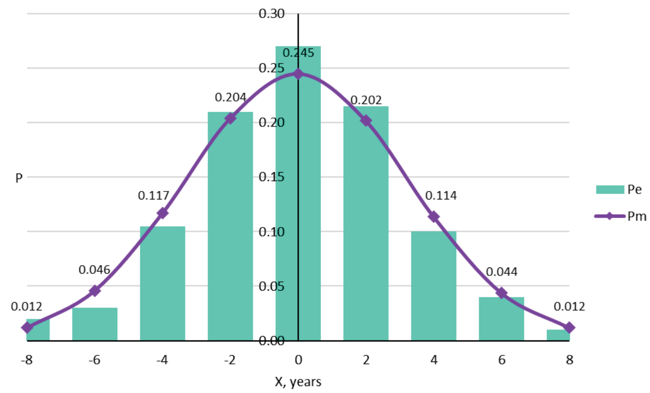

Figure 3 Experimental frequencies (P_e) and theoretical equalization curve (P_m) of the normal distribution law of the service life of approach slabs

3) To build the tabular function of the normal distribution law, we center the real function. To do this, we first calculate the mathematical expectation $m(x)$ and the standard deviation σ.

We calculate the experimental (trail) mathematical expectation of the deviation of T_a from false zero:

$$m(x) = \sum_{x} \left(x \cdot P(x)\right) = \sum_{x} \left(x_{mi} \cdot P_{ei}\right). \tag{22}$$

This implies that the center of the experimental distribution is shifted towards the bigger side from the assumed false zero by only 0,03 years. The average time between failures of approach slabs (time between failures) is 15 – 0,03 ≈ 15 years instead of the standard 20 years. Thus, there are objective reasons (insufficient quality of design, construction, and maintenance of the slabs) that caused premature wear of the approach slabs.

Next, the statistical variance is calculated as follows:

$$D = \sum_{i=1}^{q} \left(x_{mi} - m(x)\right)^2 \cdot P_{ei}. \tag{23}$$

The unbiased estimate of the standard deviation:

$$\sigma = \sqrt{D \cdot \frac{k}{(k-1)}}. \tag{24}$$

In accordance with Eq. (3), the experimental distribution is expressed in terms of the law of normal distribution.

Next, the function is centered and normalized. Based on the data, tabular probability densities $f(t_i)$ (data from Tab. 1) are established according to $f(t_i)$ ($t_1 = -2{,}448$; $t_2 = -1{,}834$).

4) Next, we calculate the theoretical frequencies Eq. (13), (14). Fig. 1 shows a leveled theoretical curve (P_m)

of the normal distribution law of the service life of approach slabs.

5) To check the adequacy of the distribution, we calculate the χ^2 criterion using Eq. (16).

Using Eq. (17), we determine the number of degrees of freedom. Next, we determine the p-value (probability value, or asymptotic significance) of the distribution:

$$p = 1 - \mathrm{CDF}\left(\chi^2, \nu\right), \tag{25}$$

where *CDF* is the cumulative distribution function of the probabilities of a normal distribution; it is determined by special tables, ready-made functions of software systems, or the following expression:

$$\mathrm{CDF}_n\left(x, \nu\right) = \int_0^x \frac{t^{\frac{\nu-2}{2}} \cdot \mathrm{e}^{-\frac{1}{2}}}{2^{\frac{\nu}{2}} \cdot \Gamma\left(\frac{\nu}{2}\right)} \mathrm{d}t, \tag{26}$$

where Γ is the gamma function.

Since, according to condition Eq. (15), 0,618 > 0,010, the adequacy is established, i.e., the experimental histogram follows the law of normal distribution.

Table 1 Statistical parameters of the intervals of the normal distribution of the service life of approach slabs

	Interval								
	1	2	3	4	5	6	7	8	9
M_l	6	8	10	12	14	16	18	20	22
M_u	8	10	12	14	16	18	20	22	24
M_{l0}	–9	–7	–5	–3	–1	1	3	5	7
M_{u0}	–7	–5	–3	–1	1	3	5	7	9
x_{mi}	–8	–6	–4	–2	0	2	4	6	8
m_{ei}	4	6	21	42	54	43	20	8	2
P_{ei}	0,020	0,030	0,105	0,210	0,270	0,215	0,100	0,040	0,010
ΣP_{ei}	0,020	0,050	0,155	0,365	0,635	0,850	0,950	0,990	1,000
t_i	–2,448	–1,834	–1,220	–0,605	0,009	0,624	1,238	1,852	2,467
$f(t_i)$	0,020	0,074	0,190	0,332	0,399	0,328	0,185	0,072	0,019
P_{mi}	0,012	0,046	0,117	0,204	0,245	0,202	0,114	0,044	0,012
m_{mi}	2	9	23	41	49	40	23	9	2
x_{exti}	–9	–7	–5	–3	1	3	5	7	9
t'_i	–2,756	–2,141	–1,527	–0,912	0,316	0,931	1,545	2,160	2,774
ΣP_{fail}	0,003	0,016	0,063	0,181	0,624	0,824	0,939	0,985	0,997
ΣP_{res}	0,997	0,984	0,937	0,819	0,376	0,176	0,061	0,015	0,003

6) Continuing the analysis of the experimental data, we build an integral function. To calculate the function of failure probabilities, we accept the extreme boundaries in the intervals x_{exti} (Tab. 1). The results of centering and normalizing of the deviation $t'_i = [x_{exti} - m(x)]/\sigma$ are also shown in Tab. 1. Based on these data and according to Eq. (12), the points of the integral function or probabilities of slabs failure P_{fail} are obtained.

Tab. 1 also shows the probability function of operative (working) condition of the approach slabs (curve of residual life):

$$P_{res} = 1 - P_{fail}. \tag{27}$$

The functions P_{fail} and P_{res} are shown in Fig. 3. As can be seen from the graph, 100% of the residual life corresponds to an actual service life of 6 years, 75% corresponds to 14,4 years, and 50% – to 15,4 years. For the law of normal distribution, the service life of the approach slabs equal to the mathematical expectation is characterized by equal values of the probability of failure and operative (working) condition.

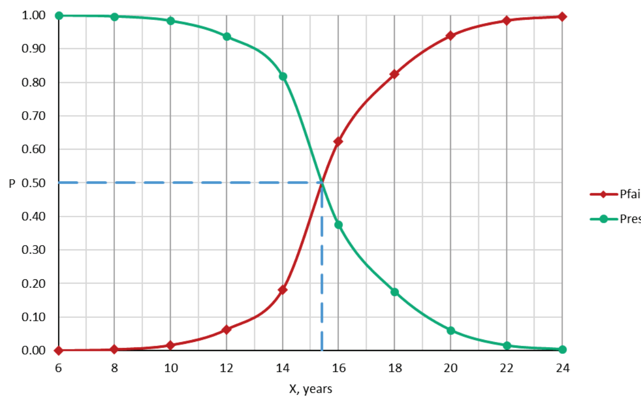

Figure 4 Functions of service life of approach slabs: P_{fail} – failures; P_{res} – residual life (working condition)

7) Next, we calculate the confidence interval for the probability P_c = 95%:

$$CI = \overline{x} \pm \delta = \overline{x} \pm t_s \frac{\sigma}{\sqrt{k}}, \tag{28}$$

where t_s is the Student's criterion; it is used for small samples or a small number of intervals (usually up to 30 items) and is determined according to a special table depending on the accepted significance level (or confidence level) and the number of degrees of freedom calculated by the Student's density function, i.e.:

$$p(x) = \int_{-\infty}^{x} \frac{\Gamma\left(\frac{\nu+1}{2}\right)}{\sqrt{\pi \cdot \nu} \cdot \Gamma\left(\frac{\nu}{2}\right)} \left(1 + \frac{t^2}{\nu}\right)^{-\frac{\nu+1}{2}} \mathrm{d}t. \tag{29}$$

For a confidence probability P_c = 95% (which corresponds to a significance level of α_2 = 0,05 for a two-sided test or α_1 = 0,025 for a one-sided test) and the number of degrees of freedom ν = 6, the Student's criterion t_s is 2,447.

Thus:

$$CI = 15{,}4 \pm 2{,}45 \frac{3{,}26}{\sqrt{9}} = 15{,}4 \pm 2{,}7 \text{ years}. \tag{30}$$

This means that with a confidence level of 95%, it can be stated that the service life of precast approach slabs on bridges will be at least 15,4 – 2,7 = 12,7 years and no more than 15,4 + 2,7 = 18,1 years. As can be seen, for both values, the actual probable service life of the slabs is lower than the normative service life (12,7 < 20 years; 18,1 < 20 years).

Let us determine the failure rate of approach slabs in classical formulations [11]:

$$\lambda(t) = \frac{f(t)}{1 - F(t)}, \tag{31}$$

where $f(t)$ is the density of the time distribution; $F(t)$ is an integral function of time on the interval $[0, t]$.

4 DISCUSSION

During the inspection of bridges in Ukraine, usually only the above-ground part of the bridge structures is inspected by means of instruments. Detection of defects and damage to underground elements is possible only in case of significant destruction (Fig. 1) or by indirect signs such as: soil subsidence in the areas of approach slabs; transverse and longitudinal cracks in the asphalt pavement above the approach slabs; change of the design position of the backwall of the bridge; destruction of the embankment of the bridge abutment cone, etc.

The current model of expert evaluation of bridges in Ukraine considers the bridge as a whole as a summation of the reliability of all groups of elements with an emphasis on load-bearing structures: span structure, piers, and foundations. This model does not allow to rank bridges by the need to repair minor bridge elements with limited funding when there is an urgent need to ensure traffic safety for users of public roads with acceptable reliability of the structure.

The proposed study estimates the residual service life of precast approach slabs. The predicted residual life and service life of monolithic approach slabs are expected to be longer than that of precast slabs. This is due to the technological efficiency of construction, i.e., the absence of longitudinal seams which are present in precast slabs. This is confirmed by the study proposed in the paper [12], where the statistical service life of monolithic bridges is 23% longer than precast bridges. However, in Ukraine, precast approach slabs are preferred as a cheaper and simpler technological solution.

Obviously, there is a need in Ukraine to develop a model for expert evaluation of bridges that will take into account the need and phasing of repairs of minor elements, such as approach slabs, with limited funding in the medium term.

When applying such an expert model of technical condition assessment to predict the service life and residual life of approach slabs, it becomes necessary to collect additional statistical input data, namely: the height of the approach embankment; width, length, thickness and number of approach slabs; the method of their connection; the presence and type of waterproofing of approach slabs; the presence of drainage structures; the type of soil of embankment; the average annual rainfall in the region, etc. All these statistical data can be used as initial parameters for further improvement of the service life prediction model based on mathematical statistics and probability theory.

5 CONCLUSIONS

1) The proposed study proves that the statistical sampling of the service life of approach slabs obeys the normal distribution law.

2) The obtained failure rate of approach slabs will be used in further studies to develop an expert model for assessing the technical condition of bridges, as well as to obtain an indicator of the need for maintenance measures for planning the life cycle cost of Ukrainian bridges.

3) An experimental study showed an average service life of transition approach of 15,4 years, while the average service life of bridges in Ukraine is 50 years [12]. In this case, during the life cycle of operation, the approach slabs on the approaches to the bridge require at least three repairs. This should be taken into account when developing an operation project and a financial plan for bridge maintenance by the balance holding organizations.

4) Probabilistic approaches to forecasting the residual service life of bridge elements are the most convenient in the absence of a centralized maintenance system and can be used in conditions of limited funding, while ensuring acceptable accuracy of the results with a confidence level of 95% – 2,7 years (for approach slabs).

5) The bridge as a whole can be considered as a group of elements. Approach slabs are an element of a bridge in the area where the road meets the bank pier. In case of defects and destruction of the approach slabs, the bridge as a whole continues to perform the functions laid down in the design, but the safety of traffic on the road, durability and reliability of the entire structure are significantly reduced.

Acknowledgment

The research reported in this publication was supported by the National Research Foundation of Ukraine under award number 2022.01/0142 "Development of a load model based on the actual parameters of heavy rolling stock to determine the carrying capacity of road bridges during their restoration and operation in the war and post-war periods".

6 REFERENCES

[1] Davydenko, O. (2022). Topical problems of elements of bridge crossing abutments and adjacent approaches. *Implementation of the innovative materials and technologies in the field of design, construction, and exploitation of the objects of transport infrastructure during Great Construction program* (pp. 16-20). National Transport University. https://doi.org/10.33744/978-966-632-317-3-2022-2-16-20

[2] Jiang, Y. & Sinha, K. C. (1989). Bridge service life prediction model using the Markov chain. *Transportation research record*, *1223*(1), 24-30.

[3] Tee, A. B., Bowman, M. D. & Sinha, K. C. (1988). A fuzzy mathematical approach for bridge condition evaluation. *Civil Engineering Systems*, *5*(1), 17-24. https://doi.org/10.1080/02630258808970498

[4] Rashidi Nasab, A. & Elzarka, H. (2023). Optimizing machine learning algorithms for improving prediction of bridge deck

deterioration: A case study of Ohio bridges. *Buildings*, *13*(6), 1517. https://doi.org/10.3390/buildings13061517

[5] Cespedes Garcia, N. V. (2023). Residual resource of bridges and bridge structures. *Mathematical machines and systems*, *3*, 151-157. https://doi.org/10.34121/1028-9763-2023-3-151-157

[6] Zhuang, Y., Easa, S. & Lu, P. (2023). Reliability analysis of residual service life of restored concrete bridge. In *Proceedings of the Institution of Civil Engineers-Bridge Engineering, 176*(1), 13-26. Thomas Telford Ltd. https://doi.org/10.1680/jbren.21.00032

[7] Al-Shammari, A. & Afzali, M. (2022). Remaining service life assessment of bridge abutments using different models: Comparative study. *Special Publication*, *351*, 19-37. https://doi.org/10.14359/51734672

[8] Tabatabai, H. & Nabizadeh, A. (20229. Remaining Fatigue Life Assessments of Steel Bridges Based on Conditional Survival Analyses. *The 5th Istanbul Bridge Conference (IBridge2022)*, Istanbul, Turkey. Paper ID: 08, 1-11.

[9] Zhang, L.-Y., Sun, L.-M., Guo, X.-D. & Dong, L.-J. (2014). Study of remaining service life of concrete girder bridge. *Bridge Construction*, *44*(5), 63-68.

[10] Alam, J., Neves, L. A., Zhang, H. & Dias-da-Costa, D. (2022). Assessment of remaining service life of deteriorated concrete bridges under imprecise probabilistic information. *Mechanical Systems and Signal Processing*, *167*, 108565. https://doi.org/10.1016/j.ymssp.2021.108565

[11] Melchers, R. E. & Beck, A. T. (2018). *Structural reliability analysis and prediction*. John Wiley & sons. https://doi.org/10.1002/9781119266105

[12] Davydenko, O. (2016). Statistical prediction of the technical condition of road bridges in Ukraine. *Bridges and tunnels: theory, research studies & practice*, (10), 4-12. https://doi.org/10.15802/bttrp2016/96130

Authors' contacts:

Olena Slavinska, professor
Department of Transport Construction and Property Management,
National Transport University,
1, Mykhaila Omelianovycha - Pavlenka Str.
Kyiv, 01010, Ukraine
elenaslavin9@gmail.com

Andriy Bubela, professor
Department of Transport Construction and Property Management,
National Transport University,
1, Mykhaila Omelianovycha - Pavlenka Str.
Kyiv, 01010, Ukraine
bubelaandrey84@gmail.com

Ihor Kozarchuk, assistant professor
(Corresponding author)
Department of Transport Construction and Property Management,
National Transport University,
1, Mykhaila Omelianovycha - Pavlenka Str.
Kyiv, 01010, Ukraine
igor.a.kozarchuk@gmail.com

Oleksasndr Davydenko, assistant professor
Department of Bridges, Tunnels and Hydrotechnical Structures,
National Transport University,
1, Mykhaila Omelianovycha - Pavlenka Str.
Kyiv, 01010, Ukraine
oleksandr.davydenko@ntu.edu.ua