Design Features of Transport Facilities

R R Kazaryan¹ and D A Pogodin¹
¹Department of Technology and Organization of Construction Production, Moscow State University of Civil Engineering, 26 Yaroslavskoe shosse, Moscow, 129337, Russia

E-mail: r.kazarian@mail.ru

Abstract. The provisions of the theory of probability and mathematical statistics are widely used in the design of transport facilities, the organization of construction and operation of roads. This is because traditional deterministic calculations often lead to errors or miscalculations due to the probabilistic nature of the geometric and strength characteristics of pavement layers, structures, building materials. The elastic moduli of the subgrade, the subbase, the base, and the pavement may deviate from the values taken in deterministic calculations by 10–20% upward or downward. In the production process, it is impossible to precisely maintain the thickness of the structural layer, which is reflected in the acceptance rules for finished layers (deviations from the design thickness of up to 10% are allowed). These deviations may constitute an unfavourable combination reducing the strength of the structure and reliability of the road as a whole.

1. Introduction

Ensuring a given reliability of a transport facility requires consideration of probabilistic factors at both the design stage and the construction and operational stages of the facility (Fig. 1).

RELIABILITY OF A TRANSPORT FACILITY

ENSURED

AT THE DESIGN STAGE
AT THE CONSTRUCTION STAGE
AT THE OPERATIONAL STAGE

Figure 1. An integrated approach to ensuring the reliability of a transport facility.

The need for an integrated approach can be seen from the following example. If miscalculations are made when designing a bridge, it will not be able to function normally regardless of the high level of technology implementation in construction, the quality of materials and structures, and also regardless of compliance with the requirements of operation of the commissioned object. And vice versa, a high-quality project does not guarantee the reliability of the bridge if the requirements for the quality of
materials, technologies and the rules for operating the bridge are not met during the construction process (for example, permissible loads are exceeded).

In this regard, the very concept of “reliability of a transport facility” should be considered in order to understand the features of the design of transport facilities, taking into account the reliability factor [1–9].

2. Materials and methods

The basis of the feasibility study of the reliability indicators of a facility is based on the condition:

$$C_\Sigma = C_{con} + C_{op} + C_f \cdot n_f \rightarrow \min$$

(1)

where $C_\Sigma$ – the total cost of construction and operation of the facility, which has an appropriate reliability indicator, for the estimated period of operation; $C_{con}$ - the cost of construction of the facility with a given reliability indicator; $C_{op}$ - the cost of operation of the facility, not depending on the occurrence of failures; $C_f$ - the cost of eliminating one failure; $n_f$ - the number of failures for the estimated period of operation.

The construction reliability indicator ($I_r$) affects the cost of construction and the number of failures, i.e.

$$C_{con} = f(I_r)$$

(2)

$$n_f = \varphi(I_r)$$

(3)

therefore, the optimal reliability of the transport facility ($I_{r, opt}$) should be calculated in accordance with the condition:

$$\frac{dC_\Sigma}{dI_r} = 0$$

(4)

The calculation of the reliability of the transport facility must begin at the design stage, when a fundamental design decision has already been made (length of a bridge, number and length of spans, bridge layout, etc.). But for this, it is necessary to have a mathematical model of expected failures (at least their expected distribution over time). To do this, you can use the “a priori model of failures” built by expertise. The a priori model can be built on the basis of using the methods of probability theory. In some cases, it is possible to design a facility, a structure with a given reliability, without resorting to forecasting probable failures, but based only on a statistical analysis of the quality of materials and the level of technology. The concept of reliability is inseparably connected with the concept of quality (quality of materials, quality of work during construction and operation, quality of a project, etc.).

3. Results

The reliability criterion is considered to be the probability that the facility will retain its basic parameters at least for a given time during its operation under the specified conditions.

When comparing the variants of the road structure, the structure shown in (Fig.2) was chosen.

| $h_1= 5$ cm | $E_1=2600$ MPa | fine-grained asphalt concrete |
|------------|----------------|-----------------------------|
| $h_2= 5$ cm | $E_2=2400$ MPa | coarse asphalt concrete      |
### Initial data for calculations:

1. Deviations of the thickness of the structural layers ($\sigma_{hi}$) from the design values are 10% (but not more than 10% of the number of measurements made). They are determined statistically by the method described in the second lecture.
2. Statistical deviations of the moduli $E_i$ from the average values shown in Figure 2 are 15–20% ($\sigma_{Ei}$).
3. The minimum value of the strength factor ($F_S$) at which the structure loses its performance is 0.8.
4. The specified lifetime of the road structure is set at 18 years.
5. The specified level (probability) of the failure-free operation of the road is 0.95 ($P_{\text{fail.-free oper.}} = 0.95$); probability of failure $Q(t)$ is: $Q(t) = 1 - P = 0.05$.

It is required to clarify the indicators of the road structure, taking into account the probabilistic nature of the geometric and strength characteristics of the layers, ensuring the probability of failure-free operation of the road of at least 0.95.

On the basis of standard methods, we find the average elastic modulus of the pavement:

$$E_{av} = \frac{\sum_{i=1}^{n} h_i E_i}{h_1 + h_2 + \ldots + h_n} = \frac{5 \cdot 2600 + 5 \cdot 2400 + 30 \cdot 1000 + 30 \cdot 200}{5 + 5 + 30 + 30} = 871 \text{MPa}.$$ 

Taking into account the elastic modulus of the subgrade $E_0$, we find the equivalent modulus of the road structure.

$$E_E = \frac{E_0}{1 - \frac{2}{\pi} \left(1 - \frac{1}{n^{3.5}}\right) \arctg \left(\frac{h}{D}\right)},$$

where

$$n = \frac{3.5 \sqrt{\frac{E_{vp}}{E_0}}}{\sqrt{\frac{E_{vp}}{E_0}}}$$

and $D = 32,6 \text{cm}$

Transforming the formula for $E_E$, we get:

**Figure 2.** Scheme of the road structure.
The dispersion of the elastic modulus of the roadbed $E_0$ can be found from the condition that the spread of the actual values of $E_0$ relative to the expected value is 15-20% (point 2 of the initial data). For calculation, we take the average value of this interval, which is equal to 0.18. Having accepted the assumptions about the normal distribution law of the $E_0$ and using the three-sigma rule, we write down:

$$0.18E_0 = 3\sigma_{E_0}$$

or:

$$\sigma_{E_0} = 0.06 \cdot 80 = 4.8MPa; \quad \sigma_{E_0}^2 = 23MPa.$$

Similarly, we find the dispersion of the deformation modules of the pavement structural layers:

$$\sigma_{E_1}^2 = (0.06E_1)^2 = (0.06 \cdot 2600)^2 = 24336MPa^2;$$

$$\sigma_{E_2}^2 = (0.06E_2)^2 = (0.06 \cdot 2400)^2 = 20736MPa^2;$$

$$\sigma_{E_3}^2 = (0.06E_3)^2 = (0.06 \cdot 1000)^2 = 3600MPa^2;$$

$$\sigma_{E_4}^2 = (0.06E_4)^2 = (0.06 \cdot 200)^2 = 144MPa^2.$$

The dispersion of the thickness of the pavement layers can be calculated based on the dependence of the probability theory, according to which the dispersion of the sum of independent random variables is equal to the sum of their dispersions, i.e.

$$\sigma_h^2 = \sigma_{h_1}^2 + \sigma_{h_2}^2 + \sigma_{h_3}^2 + \sigma_{h_4}^2. \quad (8)$$

To determine $\sigma_{h_i}^2$, let’s use the three-sigma rule again:

$$0.1h_i = 3\sigma_{h_i} \quad \text{or} \quad 0.033 \cdot 5 = \sigma_{h_i}; \quad \sigma_{h_1} = 0.165 \quad \sigma_{h_1}^2 = 0.027$$

Similarly, $\sigma_{h_2} = 0.165; \quad \sigma_{h_2}^2 = 0.027; \quad \sigma_{h_3} = \sigma_{h_4} = 0.033 \cdot 30 = 0.99; \quad \sigma_{h_3}^2 = \sigma_{h_4}^2 = 0.980.$

$$\sigma_h^2 = 0.027 + 0.027 + 0.980 + 0.980 = 2.014cm^2$$

Now it is possible to calculate the dispersions $E_{av}$ and $E_E$.

The dispersion $E_{av}$ ($\sigma_{E_{av}}^2$) is determined based on the dependency:
From here, $\sigma_{E_x}^2$ is calculated on the basis of the theorem on the dispersion of the product of independent random variables:

$$\sigma_{E_x}^2 = \left( \frac{h_1}{h} \right)^2 \sigma_{E_1}^2 + \left( \frac{h_2}{h} \right)^2 \sigma_{E_2}^2 + \left( \frac{h_3}{h} \right)^2 \sigma_{E_3}^2 + \left( \frac{h_4}{h} \right)^2 \sigma_{E_4}^2 =$$

$$= \left( \frac{5}{70} \right)^2 \cdot 24336 + \left( \frac{5}{70} \right)^2 \cdot 20736 + \left( \frac{30}{70} \right)^2 \cdot 3600 + \left( \frac{30}{70} \right)^2 \cdot 144 = 914.29 \text{ MPa}^2.$$  

To find the $\sigma_{E_x}^2$, it is necessary to differentiate the dependence $E = f(E_0, E_{av}, h)$ by each of the arguments. We get:

$$\frac{dE_x}{dE_0} = 1.85; \quad \frac{dE_x}{dE_{av}} = 0.53; \quad \frac{dE_x}{dh} = 7.25.*$$

$$\sigma_{E_x}^2 = \frac{dE_x}{dE_0} \cdot \sigma_{E_0}^2 + \frac{dE_x}{dE_{av}} \cdot \sigma_{E_{av}}^2 + \frac{dE_x}{dh} \cdot \sigma_{h}^2 =$$

$$= 1.85 \cdot 23 + 0.53 \cdot 914.29 + 7.25 \cdot 2.014 = 632.98 \text{ MPa}^2.$$  

From here, $\sigma_{E_x} = \sqrt{632.98} = 25.16 \text{ MPa. (MegaPascal-1MPa=9.81 kg/cm}^2\text{)}$  

Let us return to the condition of the problem: it is necessary to assess the reliability of the planned structure, i.e. determine the probability of failure-free operation for 18 years. Since $E = 583.9 \text{ MPa},$ and $F_{\text{min}} = 0.8,$ $E_{\text{fact}} \geq 0.8 \cdot 539.9 \approx 431.92 \approx 432 \text{ MPa},$ the probability of failure-free operation ($P(t)$) can be written in the form:

$$P(0 \leq E_0 \leq 432) = \frac{1}{2} \left[ \Phi \left( \frac{432 - 583.9}{\sqrt{2} \cdot 25.16} \right) - \Phi \left( \frac{0 - 583.9}{\sqrt{2} \cdot 25.16} \right) \right] = \frac{1}{2} \left[ -\Phi(4.28) + \Phi(16.4) \right] \approx 0.$$  

This means that with given indicators $E_i$ and $h_i$, the probability of failure-free operation will be close to unity.

4. Discussion
The considered example concerns the design of structures of a transport facility. But the design process has a wider interpretation as a process of developing projects for organizing construction (POC) and method statements (MS). The term "work organization design" (WOD) has been formed, where statistical methods for ensuring reliability also find their application. In this paper, the aspect of reliability appears in the form of the probability of timely project implementation. In the accepted method of organizing construction work, the placement of equipment by work zones and objects is reflected. The performance of each machine is a random variable with an expected value and root-mean-square deviation calculated on the basis of statistical reporting on previously performed work [1-9].

5. Conclusions
The problem of reliability is a complex technical and economic problem. Any increase in durability and reliability of the structure, quality of materials and construction and installation works, as a rule, entails an increase in cost. In many cases, it turns out to be more profitable to ensure high reliability of the structure at the design stage than to spend large amounts of money on its repair and maintenance at the operational stage. As the reliability of a transport facility, it is necessary to take its indicator that
characterizes the preservation of normal working capacity for a given period of time while ensuring regulatory (predetermined) operating conditions of the facility [1-9].

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