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To the question of risk management for failures of cable-stayed and prestressed bridges in Russia

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Summary

The characteristic cases of cable-stayed and prestressed bridge structures failures and collapses in Russia are considered. Some results of risk analysis methodology applied to bridge structures are given. The process of identification of potential hazards and possible failure modes, definition the critical risk of failure with respect to the bridge structures are described. In order to improve a technical condition of bridge structures and to reduce the risks of their failures and collapses, some risk management actions were suggested with respect to the cable-stayed bridge on the Russian island in Vladivostok. Some of them are given in the report. For example, an inspection monitoring system, founded on new non-destructive equipment, is developed.

Keywords: cable-stayed, prestressed structures, failures, collapses, risk management, life cycle.

Before the beginning of the XXI century, there was the only cable-stayed bridge in Russia over the river Sheksna in Cherepovets with a maximum span of 194.5 m, built in 1979. In 2000, the cable-stayed bridge was built in the Siberian city Surgut, with the largest span of 408 m. Since then, every year in Russia one or more cable-stayed highway, pedestrian and pipeline bridges are built. Now there are about 20 such bridges in Russia. Span length was gradually increased and reached 1104 m for the bridge over the Eastern Bosphorus Strait to the island “Russian” in Vladivostok, which is currently the world record. Height of the pylons of this bridge is 312m and the maximum length of cables is 580.5 m which also is a record.

Aspects of safe, reliable and efficient operation of the bridge on the Russian island were of particular relevance in the design. That's why the general design institute "Mostovik" have requested design bureau "Transmost" to develop individual system of operation, monitoring and maintenance for this bridge. It was required to consider not only unique structures, but also the surrounding environment, characterized by force and violence influences: temperature conditions, corrosion, seismic, wind and wave loads.

This article considers only some aspects related to risk management for failures of cable-stayed and prestressed bridges. The bridge on the Russian island contains both types of such load-bearing structures with a high degree of responsibility. Some data on failures and collapses of such structures were collected and analyzed during operation.

It should be noted that the failures of Russian cable-stayed bridges were hitherto insignificant. Basically, they are diagnosed as wire breaks in some rope sections, excessive dynamic vibrations and local damage from traffic. For example, on the bridge over the Ob River in Surgut several wires in areas close to the anchors on the pylon were broken. The monitoring system also identified adverse frequency spectra induced oscillations of cables. To minimize the negative dynamic effects, the bridge was equipped with additional dampers, and damaged areas were fixed by elongation of anchorage zone.

The small number of failures of cable-stayed structures in Russia is due, first, to their relatively short period of operation, initially increased attention to these structures, as well as their availability for inspection and maintenance. At this point there is another risk group which is no less disturbing - prestressed bridge superstructures. Having the same type of main load-bearing elements, as cable-stayed superstructures, most of them were operated for decades, also an inspection of prestressed elements has some difficult problems. In Russia, for various reasons, there were several collapses of prestressed bridge structures. One of the latest casualties of this kind was the collapse of the three beams on the overpass passing underneath a highway with heavy traffic. Luckily, no one was hurt, although the probability of risk was rather high.

One of the measures to prevent the abovementioned negative effects is a risk analysis, which more and more is used in Russia. Until now, evaluation of the bridge technical condition was carried out in Russian practice only in scores of safety, capacity, and durability. At the same time, the current method of total integrated assessment of technical condition for durability in scores, as was shown in practice, is not effective enough. There are many examples, where the appointment of rehabilitation works, founded on the general point estimation, does not reflect the actual required ones. Also, the problem of actions prioritizing was not solved. In large part this is because the assessment on "durability" doesn't take into account liability and danger of structures, as well as probability of risk defects and failures.

To improve efficiency of maintenance, a new methodology of bridge technical condition assessing was suggested for the bridge on the Russian island. It takes to account as the main criterium - danger in operation for supporting structures. Evaluation of reliability is fulfilled here by the risk analysis of structural elements. The present standards methodology for risk analysis of hazardous production facilities adapted for the bridge structures was adopted as analogue [1, 2].

The preparatory phase should include data analysis of supporting structures. For this purpose, bridge is divided into macronutrients, failure of which may cause events with significant damage to human life and health, the economy and the environment. There were decomposed, as such macro, different "key details", including also prestressed beams, strands, cables, anchoring elements, etc.

Also the identification of hazards inherent in macronutrients was made. For example, for prestressed or cable-stayed spans, there will be no such danger as " hit the ice", but "corrosion", "collision by vehicle" etc. Then, for each macronutrient expert estimated the maximum severity of the consequences at specific hazards.

The failure consequences severity is ranked on a 4-point scale. The probability of failure can be defined by means of probability theory, if there is sufficient statistical base. Another way is using of expertise, the knowledge and long-term observations of experts to assess a bridge [1]. In the applied management model this characteristic should be adjusted according to the results of the current survey, in accordance with the actual state of the load-bearing elements and their corresponding defects.

From the above parameters a matrix "probability - the severity of consequences" is formed (risk matrix). Then the failure criticality for all load-bearing macronutrients is calculated by algorithm which is set out below. According to calculation results, a number of important operations of risk management carried out: the ranking according to influence of defects on failure, the definition of inspections cyclic recurrence, prioritizing of rehabilitation work and others. After a period, corresponding to a current cyclic recurrence, inspection is renewed and the current state of bridge elements is determined again, also after completion rehabilitation works, with development of existing and new defects. Accordingly, cyclic recurrence of inspections for specific cases may be different, depending on the condition and the hazard of operation (risk). Quantitative evaluation of reliability, or the probability of failure-free operation can be carried out in relation to the highway bridge on the basis of studies for railway bridges [3]. The next dependence is got by means of method of multiple regression analysis:

$$K_{rf} = 391.3745\, P_{f1} - 866.2475\, P_{f2} + 479.44\, P_{f3}\ , \qquad (1)$$

where K_{rf} - a relative measure of failure-free operation in points; P_{fi} - the probability of failure-free operation.

We take this assessment as a quantitative indicator of the analysis, effects and criticality of failures. Let's rank the probability of failure, occurring in the elements of the bridge, by a 4-point scale, Table 1.

Table 1. Ranking the probability of failure-free operation of the bridge

	Probability of failure index (when an item i - the dangers) - Vi			
	1	**2**	**3**	**4**
Failure-free operation index	P = 0,9999	P = 0,9990	P = 0,9900	P = 0,9750

Ranking of the bridge elements, depending on the severity of the consequences of failure, which is the expert for each selection (macronutrients), is presented in Table 2.

Table 2. Ranking of the elements depending on the severity of the consequences

	Index of the failure consequences severity j - the element Sj			
	1	**2**	**3**	**4**
Danger of operation	Minor consequences	Serious consequences	Significant consequences	Disastrous consequences

Minor consequences, as measured by 1 point, mean that component failure can cause a decrease in the long-term performance of the object (for example, reduced longevity). Serious consequences (2 points) - refusal element may cause difficulty of the current operation of the facility (eg, reduction of speed), transport damage, injury to persons. Significant consequences (3 points) - refusal element can cause restriction of the performance of the object (for example, short-term cessation of movement, partial closing movement, reduced capacity), the loss of a single vehicle, injury and death of several people.) Catastrophic consequences - the refusal element may interfere with operation of the facility for an extended period, the loss of many vehicles, the death of many people. Severity is a characteristic that depends on the design features of the bridge, its location, the traffic on and under the bridge and is subject to adjustment only when you change these settings. Matrix “probability - the severity of consequences" is given in the table 3.

Table 3. Matrix “probability - the severity of consequences "for bridge elements

		Index of the failure consequences severity j - the element Sj			
Failure	**Probability of failure index Vi**	**1**	**2**	**3**	**4**
Rare P = 0,9999	**1**	1	2	3	4
Possible P = 0,9990	**2**	2	4	6	8
Probable P = 0,9900	**3**	3	6	9	12
Frequent P = 0,9750	**4**	4	8	12	16

Where the critical risk of failure for element K_{ij} is calculated as the product of V_i on S_i, amounting from 1 to 16, depending on the degree of responsibility of an element MS and the probability of failure:

$$K_{ij} = V_i S_j, \tag{2}$$

where V_i - probability of failure index, when the danger “i” exists; S_j - index of the failure consequences severity, where “ j’ – No. the element.

The above method of risk analysis has been applied, in particular, for optimization equipment monitoring system of the bridge on the Russian island. In order to assess the potential savings over the 80-year life cycle, a number of scenarios was considered and reviewed. For example, the minimum option involves a much smaller investment of resources in monitoring equipment. In such a case, setting the minimum number of sensors can't prevent the full set of anomalies and latent defects in the supporting structures of the bridge. This approach leads to premature wear of significant elements, and requires massive reconstruction: the replacement of the cables and parts of structures. To bring the technical condition of the bridge to the normal one, in this case we need an overhaul in 30 years (likely replacement up to 10% of cables). After 55 years and 75 years we will need an upgrade of facilities with the probability of the replacement of 25% of cables respectively.

But to implement the best option was adopted, providing installation of such a combination of equipment that will recognize the appearance of defects in the elements of the bridge in the early stages. In addition, the tension force in cables will be monitored continuously in automatic mode, which will give an opportunity to make current adjustment, if necessary, using the control measuring systems and jacks.

Sufficient set of accelerometers contemplated in the optimal variant, will give a detail picture of vibrations in structures. This data, combined with a strong strain gauge control will optimize the natural frequencies and the cycles of loading for cables and supporting structures, for example, by means of different dampers.

As a result, a number of risk management measures, provided in the best option to minimize the negative impact of fatigue phenomena, life span of cables and supporting elements may be prolonged for a period of 80 years. The latter circumstance allows virtually eliminate the risk of failure of critical structural stressed elements: break cables, brittle fracture of metal, what minimizes the risk of collapse of the bridge.

The script for better risk management option involves an implementing of preventive and adjustment works approximately every 10 years to maintain a good technical condition of the bridge. Overhaul is needed in this case in 60 years. Cost analysis of both options shows that for the 80-year life-cycle period, the cost saving on the rehabilitation works will be 180 million dollars as minimum.

Currently, the monitoring system for optimal variant of the risk strategy is installed on the bridge. This solution will allow optimize the life cycle parameters, substantially reduce an annual maintenance cost while improving travel safety, reliability and durability.

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