

Risk-Based Design of Bridges

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Abstract: - Bridges belong to critical elements of transport infrastructure. Therefore, it is necessary in the highest extent to address all relevant risks (namely those that are related to ageing of fittings and components of technical facilities and with dynamic development of environment in time) in the preparation of the terms of references and in the design process. In order to design the bridges with these properties, it is not enough to respect only valid standards and norms and good practice, but they also need to be respected data on all possible risks and their combinations. For this it is necessary to use measures identified in the risk management plan for design, which specifies local conditions and possibilities. This paper shows model of procedure which combines norms and risk analysis results.

Key-Words: - Critical infrastructure; bridges; risk; risk sources; decision support system; risk management plan; risk-based design procedure.

Received: June 13, 2021. Revised: January 4, 2022. Accepted: January 25, 2022. Published: February 21, 2022.

1 Introduction

For security and development, the human society needs bridges on transport infrastructure that provide services, which are safe, i.e. they reliably perform their functions and they have good coexistence with their surroundings, even under critical conditions. In order to ensure that requirement, it is necessary in the highest extent to address all relevant risks (namely those that are related to ageing of fittings and components of technical facilities and with dynamic development of environment in time) in the preparation of the terms of references and in the design process [1,2]. It is necessary to note that present legislation is directed to bridge reliability [3]; i.e. not to bridge safety. In this case an inventory of risk sources is limited; it is missing a number of sources of risks, which are important for the safety of bridges.

Present knowledge [1,2,4,5] shows that for design of safe bridges, it is not enough to respect only valid standards and norms and procedures of a good practice. At designing, they also need to be respected data on all possible risks and their combinations, and for this aim it is necessary to use measures identified in the risk management plan

for design, which specifies local conditions and possibilities [6,7].

It is necessary to use the correct design creation methodology, which considers the relevant risks. Because such methodology has not been specified yet, the article proposes the risk-based design methodology, which has been verified in practice in frame of project [8]. In article, they are presented: list of the causes of risks for bridges based on the world data; decision support system as a basis for risk evaluation; risk management plans for designing; and risk-based design procedure for bridges.

2 Results of Research

On the basis of studies from available 56 sources from around the world, it has been compiled a database containing the data about the failures of bridges [9]. The database contains the data since the year 1297 on 381 failures of bridges. Due to the fact that the bridges belonging to critical infrastructure are complex technical facilities, the data has been processed by methods that use engineering disciplines working with risks, namely the Ishikawa diagram, decision support system and risk management plan [10]. Using the decision support system is clear from the Figure 1 [11]; aim

is long-term solution and safety.

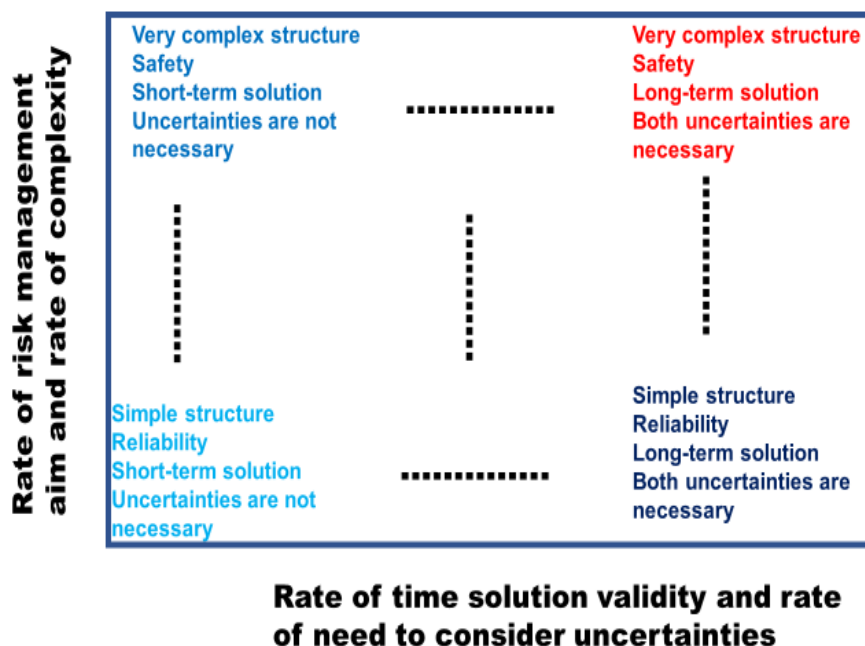


Figure 1. Scoring the important aspects for working with the risks of bridges.

2.1 Sources of risks that disturb the bridge safety

Analysis of bridges' failures database [9] shows that the human is as the creator of the bridges, as well as the bearer of their destruction. The human factor unduly applied leads to individual errors in designing, building and construction, and also to errors in management of traffic operation on the bridges. Inspections carried out after breakdowns in bridges, often as one of causes of the collapse of bridge have identified the human error, namely especially in safety management of bridge during the lifetime [2].

It goes on the errors associated with: neglecting the major disasters in the territory in which the bridge is located, or underestimating their sizes; non-respecting the All-Hazard-Approach principle [12]; the wrong terms of references, errors in the project; errors in calculations, low robustness of the design, etc.; and faulty planning and the coordination of measures for the management of priority risks.

Figure 2 shows the ranking of causes of failures of bridges. Causes of failures caused by errors related to design phase are denoted by red arrow. Examples of case studies of bridges collapsed due to errors in design in last fifty years are given in [2,9,13].

As the sources of accidents or failures of bridges are: one big phenomenon (natural or technological disaster or human failure); and occurrence of minor errors, realization of which in short time period is dangerous, although the impacts of separate individual errors are manageable by prepared response measures. Because the second case is more frequent, the combination of dangerous events in design ought to be also considered.

2.2 Decision support system as a basis of risk evaluation

Due to reality that bridge collapses are caused in ca 80% by combinations of several risk sources [2,9,14], for risk assessment the Decision Support System (DSS) allowing to consider all contributions to risk was constructed. DSS for risk assessment of technical facilities at designing [15] (for obtaining the building permit) was adapted for bridges considering:

- the bridge is socio-cyber-physical system,
- knowledge on human factor manifestations, which are given in Figure 2,
- competences for providing the finances for risk management; the highest competences have the top management [16],
- responsibility principle used in Europe [17].

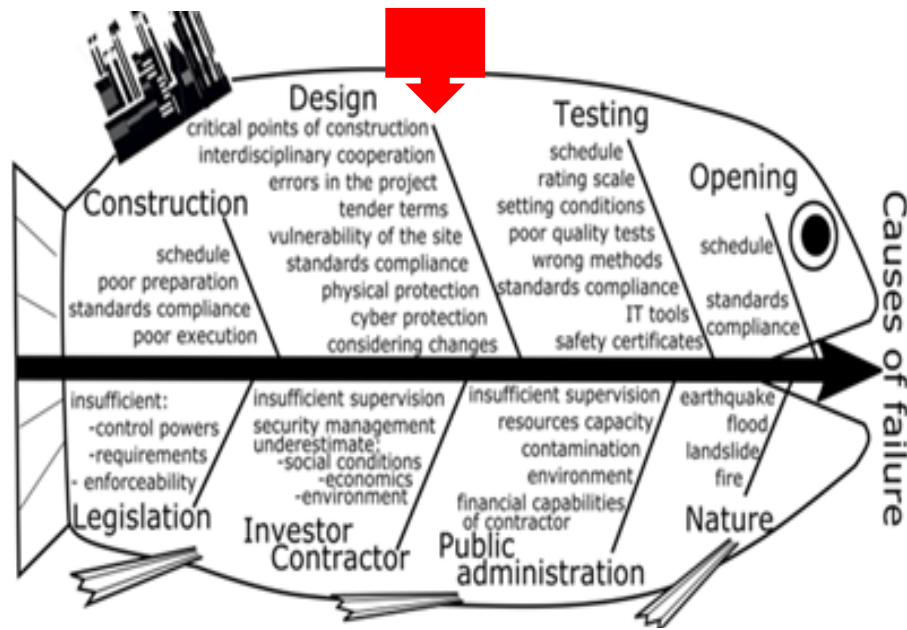


Figure 2. The causes of the failures of bridges on the roads and railroads. Red arrow shows the causes originated in the design stage.

The complete DSS for building permit of designed facility is in [15]. It has n=32 criterions. Its example adapted for bridge is in Table 1. The criterions are evaluated by scale (0-5) with the philosophy “the higher number, the higher risk” [18]. For the DSS application in practice, they are used two scales, namely the auxiliary scale derived in [19] for evaluation of real impacts, Table 2 and the second scale for the evaluation of the entire checklist for integral

risk judgement, Table 3. The way of risk judgement based on the DSS result is described in [14].

The assessment of Table 1, hereafter given, assumes that all criteria have the same weight. Practical examples [9] show that in many cases some criteria are more important than others, and therefore, it is necessary to assign them higher weight, and to change data in Table 2 by appurtenant way. It means that the procedure is site and sector specific.

Table 1. Checklist for assessing the risk for needs of Building permit; A – assessment; N – note.

Criterion	A	N
The rate in which the terms of references of the bridge are processed by a legal entity which has:		
- knowledge of: regulations; risks in the site to which the technical facility is placed; technical system, which constitutes a bridge; models and theories associated with accidents and failures; methods of analysis, management and settlement of risks; management of the enterprise (finance, human resources, organization, technology, innovations...),		
- knowledge and capabilities for: the application of the results of methods of risk analysis and evaluation; implementation of the methodology for analysing and assessing the risks adapted to the problem; emergency and crisis management; analysis of situations / activities / accidents; the transformation of policy into actual action; the conversion of accident statistics into action plans; strategic planning; hierarchy of problems; finding the right information and learning; critical analysis; designing the right solutions; written and spoken communication; carrying out the synthesis; and adapting the wording intended for the public,		
- ethic.		
The rate in which the terms of references of the bridge consider the impacts of disasters that are possible in the territory under the All-Hazard-Approach.		
.....		

The rate in which the terms of references of the bridge consider local vulnerabilities and, where is necessary also regional ones: anomalies and non-homogeneity of geological structure; reality that in territory there are sources of domino effects, i.e. warehouses or product lines with hazardous substances, fuel stations, etc.		
.....		
The rate in which the bridge project respects the size of the criticality associated with priority disasters (a combination of hazard size, vulnerability and sizes of impacts on assets), including the human failures, and proposes measures to ensure safety; at the same time it is based on an assessment of whether the proposed measures cannot be a source of new dangers and where they cannot be dealt with (e.g. ignorance or too much costs), it proposes technical measures, in management systems or organizational ones.		
.....		
The rate in which the bridge project considers critical sites of building structure and includes the right measures based on an assessment of the risks targeted to their safety, i.e. to ensuring the reliability and operation ability under abnormal and critical conditions (barriers, reserves, back-up).		
.....		
The rate in which the bridge project considers results of the public's comments on the bridge project.		

Table 2. Auxiliary scale for determination of rate of risk planned bridge [18]; *p* – annual insurance, ABT-the annual budget of territory governance.

Domain	Risk rate	Classification criterion
Social		<i>By accident or failure of bridge, it is affected:</i>
	0	less than 50 humans
	1	50 - 500 humans
	2	500 - 5000 humans
	3	5 000 – 50 000 humans
	4	50 000 – 500 000 humans
	5	more than 500 000 humans
Technical and Economic		<i>Accident or failure of bridge causes damages:</i>
	0	less than 0.05 <i>p</i>
	1	equal to <i>p</i>
	2	between <i>p</i> and 0.05 ABT
	3	between 0.05 ABT and 0.075 ABT
	4	between 0.75 ABT and 0.1 ABT.
	5	higher than 0.1 ABT.
Environment		<i>Accident or failure of bridge causes:</i>
	0	very low damages of environment
	1	damages of environment with which the nature cope during the acceptable time
	2	moderate damages of unrenovable resources of nature and natural reservations.
	3	medium damages of unrenovable resources of nature and natural reservations
	4	unreturnable damages of unrenovable resources of nature and natural reservations
	5	devastation of landscape, unrenovable resources of nature and natural reservations

Table 3. Scale for determining the planned bridge risk rate; N = 160.

The level of risk	Values in % N
Extremely high – 5	More than 95 %
Very high – 4	70 - 95 %
High – 3	45 - 70 %
Medium – 2	25 – 45 %
Negligible – 0	Low than 5 %

The evaluation of real cases according to the Table 1 needs to be performed by a team of specialists from the different fields independently; in practice, according to [5,14], it works the team consisting of:

- worker of public administration responsible for the land use planning,
- worker of public administration responsible for the territory development,
- representative of planned technical facility,
- competent representative of the professional institution for the technical facility safety assessment, for example from the state technical inspection,
- representative of the Integrated rescue system.

The resulting value is the median for each criterion, and in cases of great variance of the individual values in the one criterion it is necessary, so that the worker of public administration responsible for land use planning may ensure further investigation, on which each assessor shall communicate the grounds for his / her review in the present case, and on the basis of panel discussions or brainstorming session, the final value is determined.

Table 4. Risk management plan for bridge designing.

Risk area	Risk description	Probability of occurrence Risk impacts size	Risk mitigation measures
Public administration	As a result of absence of a State strategy on SCPS design focused on safety, it is possible to enforce current political interests, requirements of coercive groups or the failure to cope with extreme political situations (war, terrorist attacks), which in turn leads to reduction in human living standard and safety of citizens, economic instability, etc.	Probability: Large Impacts: Large	Measures: To develop the relevant State strategy and adapt the Building Act Execute: Prime minister Responsibility: Parliament chairman
	Due to lack of competence of public authority in overseeing the SCPS design there is an extension of construction, problems in commissioning, accidents accompanied by enormous ex-	Probability: Large Impacts: Large	Measures: To adapt the Competence Act and the laws associated with it. Execute: Prime Minister

Table 1 serves for protection against problems that impede to building permit issue. Table shows that big role plays the human factor, namely at way of execution of critical tasks of designing (terms of references compilation, use of knowledge on compilation of safe design etc.) and at professionalism of supervision performed by the public administration directed to public interest. This procedure of usefulness of the DSS was successfully tested in the frame of project [8].

2.3 Risk management plan for designing

The risk management plan is recommended by ISO 31010 [7]. It is after prevention principles the second important tool for the bridge design. For creating this top-quality safety management tool, they are considered both, the current knowledge and experience on risks associated with bridges; including defects in the area of design; totally 32 cases were identified. It is prepared in the form of table.

The aim of risk management plan is to ensure the safe bridge operation. Two actors are considered - public administration, which supervises activities in the territory including the bridge with aim to ensure the safety of territory and citizens, and designer, who is responsible for the safety of design of bridge, which also includes the protection of the surroundings and inhabitants.

Risk management plan for bridge designing was obtained by adaption of the model plan for technical facility [5,15]; Table 4 shows example. The usefulness of bridge risk management plan has been tested in the frame of project [8].

	penditure from the public budget, disruption of citizens security.		Responsibility: Parliament chairman
	As a result of errors in the authorized designer selection, the project is of poor quality, which sooner or later will disrupt the construction or operation and lead to accidents accompanied by enormous expenditure, disruption of citizens safety and problems with public administration.	Probability: Medium Impacts: Large	Measures: Change of designer Execute: Authorized investor worker Responsibility: Investor director
Future operator As a result of a poor estimate in the field of supplier – customer relations, the project is based on unrealistic data, which sooner or later will lead to disrupts the construction or operation of a SCPS, enormous expenditure, disruption of citizens safety and problems with public administration.	Probability: Medium Impacts: Large	Measures: To force investor to perform remedy Execute: Authorized future operator worker Responsibility: Future operator director
Authorized designer As a result of a poor quality or non-cooperative team of project processors, the project is of poor quality and it leads sooner or later to disruption of construction or operation, enormous expenditure, citizens safety and problems with public administration.	Probability: Medium Impacts: Large	Measures: To introduce rules for team cooperation Execute: Authorized designer team worker Responsibility: Authorized designer team director

2.4 Risk-based design procedure for bridges

Each bridge is located in an area in which there are many sources of risk, the manifestations of which may damage both, the bridge and its surroundings. Based on the fact that bridge is a complex object of socio-cyber-physical form, which is located in a dynamically variable territory in which there are a number of sources of risk, we set out in the first part the requirements for the bridge project. In doing so, we consider:

- requirements of applicable standards as well as the principles of risk engineering,
- with regard to complexity, we apply risk engineering methods both, the simple ones (linear and tree) and the multi-criterial ones.

Based on knowledge [2,5,14,20-27] and experience of practice [9], the bridge design relates to:

- implement the preventive measures with regards to serious risks considering the idiom 'limits and conditions',
- enable the mitigation and reactive measures to be implemented in all respects to prepare a qualified response (personnel, responsibilities, procedures, material, technology), because the world is evolving dynamically.

In designing, it is very important how the designer divides the real bridge risks mastering [25,26], see bow-tie diagram in Figure 3: in design by preventive measures, or only at response. In the

second case, the designer must in design prepare qualified measures for response.

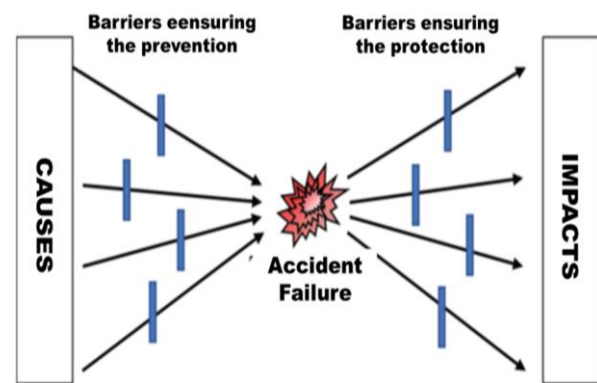


Figure 3. Separation of countermeasures between design and response [25].

The technique for compilation of bridge risk-based design is the following:

- to identify sources of risks for the bridge site considering the All-Hazard-Approach,
- to determine hazards for all relevant disasters and identify their impacts,
- to determine set of relevant disasters D1, D2, ..., Dn,
- to determine the bridge construction process – component C1, interface I1, component C2, interface I2.....

- to adapt the DSS [5] for the real bridge in real conditions (example of which is in Table 1) for risk rate assessment,
- to use Table 2 for risk judgement (risk category: 0 and 1 – risk acceptable; 2 and 3 – risk ALARA; and 4 and 5 risk is unacceptable),
- to propose components and their interfaces according the valid norms and standards,
- to apply procedure: to determine risks of C1, I1, C2 considering the DSS and disasters D1, D2, ..., Dn; to judge these risks by help of Table 2; to decide – if risk value is: acceptable no corrections are need; ALARA it is necessary to insert in design procedure measures enabling the response; unacceptable it is necessary to change material, way of interconnections of components, technology of interfaces etc. + again to judge risk. After achievement of satisfying result, they are added subsequent interface and component and the procedure is repeated up to the last component.

The example of risk-based design procedure is shown in Figure 4. Above procedure of generation of bridge risk-based design is tested in the frame of project [8].

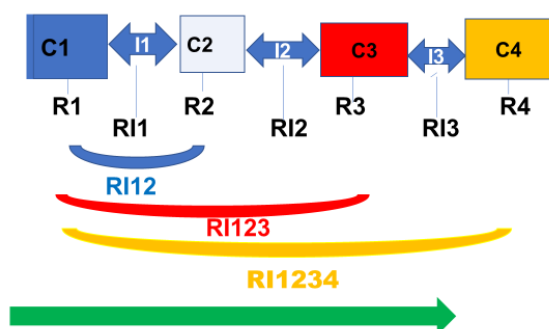


Figure 4. Example of technique for compilation of bridge risk-based design

3 Conclusions

The research showed that:

- each bridge design has a certain danger. The designer art is to select such solution that is optimal, i.e. it is sufficiently safe and it is possible to realize with regard to investor and public administration options. The near the same holds for manufacturer' skill (craftsmanship) at realization,
- impressive and low robust designs with insufficient safety margins often fail sooner or later,
- wrongly determined limits and conditions for critical bridge parts lead to frequent disturbances

up to serious accidents; they are not able to react to condition changes.

The analysis of accessible legislations revealed that rules in force do not:

- require to follow the operation process safety in designing, and this occasionally leads to problems at operation,
- consider in design the combinations of dangerous events in short time interval, which are causes of the most bridge accidents and failures.

To improve the bridge safety, the article shows the methodology of risk-based design compilation, which fulfil demands of ISO 9000 [6] and ISO 31010 [7] and has been tested in practice under project [8].

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Acknowledgement: Author thanks for the EU project RIRIZIBE-CZ.02.2.69/0.0/0.0/16-018/0002649 and the TAČR project PRKODI, No. CK01000095.