Criticality and Risks of Bridges

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***Abstract*— The paper deals with risks and criticality of bridges because they are the critical spots of critical infrastructure, which is the important public asset. In detail, it pursues the risks and criticality of bridges on over ground roads and railroads from the view of ensuring the safety of this important element of critical infrastructure. It gives the results of research carried out by critical assessment of causes of collapses of important bridges by help of historical data from the whole world. By critical analysis of data, it determines the causes of risks that led to bridge failures. For safety improvement in practices, it gives the items, the contributions of which to criticality need to be monitored and respected in the bridge design and operation.

***Keywords*—**Bridge; critical infrastructure, criticality, risk, safety.

I. INTRODUCTION

The bridges on the roads and railways are critical elements of transport infrastructure. From this reason they belong to important public assets and it is necessary to ensure so they may be safe, even in critical situations. The subject of the submitted work is:

- to explain the problems of the management of the safety of critical infrastructure that respects the current concept of safety (i.e. the integral safety that respect the system understanding and the changes in time and space [1]) based on the system, proactive and strategically target access to the objects and the world in which we live [2],
- to show the significant causes of the bridges failures,
- to gather evidence for an evaluation of the criticality of the bridges.

Submitted work respects the concept of the UN "Resilient Nation" (the last version of that concept is the UNDP programme of December 2012) [3]. This concept is based on the assumption that the occurrence of disasters, the human vulnerability and partly other public assets vulnerabilities and the size of the impacts of disasters on the assets of the human system are not going to decrease over time, but rather increase. Therefore, for ensuring the safety and development of people it is important the functionality of both, the highly reliable public administration and the safe critical infrastructure in the wider concept than it understands today's legislation [4], [5].

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With regard to knowledge in [1], [2], [6], it means that critical infrastructure would also include the green infrastructure, the education infrastructure, the research infrastructure and the infrastructure of care on people. Green infrastructures are the systems that make up the environment, i.e. the nature. Grey infrastructures are the man-made systems that provide some or all of the public services. Therefore, there is a very close link between the human and the infrastructure, i.e.: human needs infrastructures, because without their services the quality level of human life would be significantly worsened; and the infrastructures need humans, as without the human intervention they would not develop, they would not be sustainable and they would constantly malfunctioned. The human (human factor) is therefore the management, i.e. and control element of any infrastructure. Therefore, the work builds on the work on the safety and risks of complex technological systems [1], [6].

II. SAFETY AND CRITICALITY

The safety is understood as a structured set of anthropogenic measures and activities by which the human ensures both, the human security and the man-made systems safety [1], [2]. To ensure the current human needs, it goes on the integral safety, i.e. on the safety, which includes several protected assets of different nature at a time [2]. Based on current knowledge, the safety is understood as an emergent property of the system, on which the system existence depends; it is the most hierarchical property of the system. The aim of the critical infrastructure safety is to ensure the safe territory, safe communities, safe infrastructures and the daily protection of the citizens from the perspective of providing the certain services that people need for life [2].

Infrastructures have been, are and will be the public asset, because they provide the daily needs of citizens, i.e. energy, water, food, information, etc. and also the survival of the human society at critical situations depends on them. On the basis of current knowledge, they represent the complex open systems in the dynamically varying world that is affected by both, the processes that take place independently on man, and the processes that man creates consciously or unconsciously by his operation and behaviour.

From the perspective of the current knowledge, it is necessary to make clear that the basis for the management of critical infrastructure safety is mainly the analysis and assessment of the risks associated with mutual links in the critical infrastructure sectors and throughout the critical infrastructure. From this reason, at risk identification it is necessary to use also the cross-cutting criteria because the significant risks are associated with links and flows of various kinds among the infrastructures which constitute the open systems of systems [1].

The assessment of the criticality of the individual systems (sectors) of critical infrastructure and the whole critical infrastructure is not a trivial matter, because in different situations the sectors and the whole have different roles, i.e. the role active, reactive, critical or damping (but not additive). For example, the existence of several variants of the electricity supply in a specific location reduces the energy infrastructure criticality, but it increases the cost, which it is not acceptable for human society in many cases. That finding and the above facts show that the issue of critical infrastructure is live, and that in it there are a number of open issues. Therefore, we need to perform thorough research of problems with aim to find measures for critically reduction, and to implement its results in practice.

Because the qualified work with risks ensures the human security and development [2], it is necessary to introduce the work with the risks into practice. In harmony with present knowledge [1], [2], [3], [6] this means a new look at the problems of reality, and on the way to their solution. It is necessary reality problems to restructure and partial problems reliably to address. It is necessary to start with reality concept represented by mutually interconnected systems the different nature, which describes the model system of systems [1], [2].

Criticality is understood as the limit state of the system, which is significant to the stability of the system [2] and shall be assessed according to: potential damage to the lives and health of people. It is considered as the possible damage on it in major accidents in the objects of infrastructure, nuclear or chemical plants; loss of functionality of targeted action, which has a certain mission. Its size is assessed according to the extent of the affected territory (e.g. at failure of the navigation system), or according to the economic damage in business (e.g. from losses that causes the banks´ disruption).

Criticality of the complex object (***C***) is the rate with which it may occur in connection with the activities of the reference object to the injury of persons, the destruction of material, damage or other big losses. The relationship applies:

$$C = S * O * B$$

where ***S*** is the severity of the largest impact of the given disaster (i.e. the given harmful phenomenon); ***O*** is the probability of the occurrence of the disaster; and B is the conditional probability that at a given disaster, the most serious impact occurs.

Criticality indicates a certain threshold for the reference object. If its values are below this threshold, so the state is demanded, and vice versa. In the technical area, the criticality is an antonym to the safety.

III. DATA ON FAILURES OF BRIDGES AND METHOD OF RESEARCH

From findings in [1], [2], it follows that the spots in the technological system (object, the infrastructure, business, territory) are the places, in where happen the basic technological processes and subject to the specific provisions for the safety in normal, abnormal and critical conditions. According to data in [7] such spots on transport infrastructure are the bridges.

To avoid the economic destabilization of the business units, and other industrial areas, it is necessary to pay special attention to bridges on the roads and railways, which are the critical elements of transport infrastructure. If we want to control the transport system in order to ensure its safety and development, so we need to know the priority aspects, on which depend the achievement of objectives and that we need to focus attention, i.e. measures and activities [2].

For research of causes of bridge failures, we compiled in the first the database from 98 world sources; it contains 2035 bridge failures [7]. The database starts with a description of the breaking of the bridge over the River Forth at Stirling in Scotland in September 1297. The failure was caused due to congestion of soldiery during the war, namely the battle on the Stirling Bridge, which was the first war for the Scottish independence [8], Figure 1.

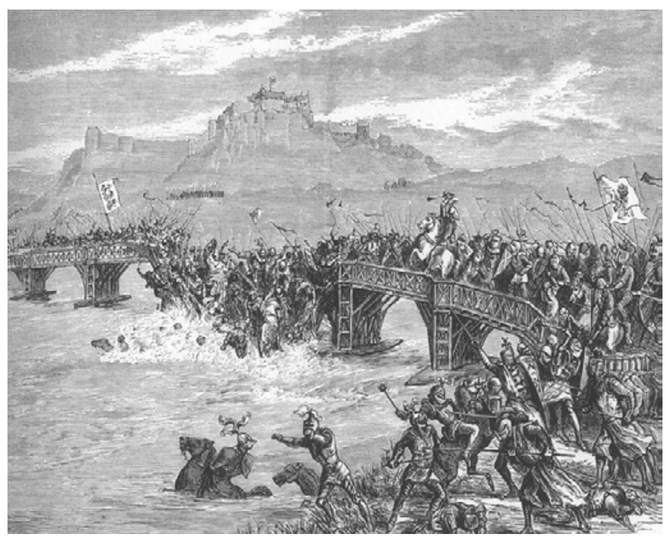

Fig. 1 Victorian view on the bridge breaking during the battle of Stirling [8]

Some of bridge collapses were accompanied by many victims. E.g., Figure 2 shows the ruins of the locomotives, six cars and a railway bridge on the Whangaehu River [9] caused by bridge collapse in December 24, 1953 in the New Zealand at the municipality of Tangiwai. The Whangaehu River Rail Bridge was damaged by volcanic lahare a few minutes before a passenger train ran on it. The disaster consequence was that 151 people died. It was the worst New Zealand train crash. Subsequent investigation revealed that the accident caused the collapse of the Tephra dam, which held the nearby Crater Lake of Mount Ruapehu, and to create a large lahar Whangaehu River, which destroyed one of the bridges at Tangiwai, just a few minutes before [9].

Fig. 2 Ruins of the locomotives, six cars and a railway bridge on the Whangaehu River [9]

Many injures was also at bridge collapse on January 18, 1977 in Australia; the municipality of Sydney, the Western suburb of Granville. At the road over the rail travel, the Bold St. Bridge struck down by derailed train, and its supporting pillar crashed on two other passenger trains; the consequence - number of: dead - 83; injured - 210, affected 1300 people. It is the largest rail disaster in Australian history [10].

Very strong Loma Prieta earthquake on October 17, 1989 in California, damaged more than 100 bridges on the highways, and even those most famous Bay Bridge and Cypress Street Viaduct [11], [12], which led to the tightening of standards for the determination of seismic risk in the construction of bridges [11]. Figure 3 documents the damage to the famous viaduct in Oakland.

Data in [7] was processed by critical analysis and they were classified according to bridge collapses causes.

Fig. 3 Failure of Cypress Viaduct Bridge at Loma Prieta earthquake [12]

IV. RESULTS

The analysis of data in [7] shows that the collapses of bridges with its share of any country. The number of data on the breakdowns of bridges in the individual time periods grows as it expands the number of information sources. E.g., according to [7], [13], it is recorded the following number of breakdowns as follows:

- period 1297-1899 number = 33,
- period 1900-1949 number = 25,
- period 1950-1999 number = 65,
- period 2000-2016 number = 99.

According to the data in [7], [13], it is reality that some concrete and steel bridges collapsed:

- during the construction as a result of bad design or bad construction or bad anchor,
- due to external causes,
- during the renovations or repairs, etc.

Many professional publications include information regarding the collapse of a suspension bridge across the Ohio River in Tacoma (USA), which would had to ensure the linking the Mainland and the Olympic Peninsula – the bridge was opened on July 1, 1940 and it broke on November 7, 1940 due to bad considering the aerodynamic forces on the design; prior to the breakage it is noticeably moved as a result of the wind (the participants described the strange wave), and, therefore, the police has banned entry to its surroundings [7], [13].

The analysis of more than 80 information resources, listed in [7], [13], shows that the causes of the collapse of bridges are:

- natural disaster (earthquake, flood, hurricanes, typhoons, tornadoes, hurricanes, landslides, avalanches, subsoil liquefaction; the power of accumulated ice floes; force accumulated large and bulky items
- large temperature differences and other particularly

unfavourable meteorological conditions,
- bump of vehicle to bridges,
- fire of vehicles on the bridge,
- explosion of vehicle on the bridge,
- mechanical damage of the bridge by vehicle,
- traffic accident on the bridge,
- errors in the design of the bridge as: bad load combinations; an underestimation of the size of the potential disasters; underestimation of resonance in the construction; an underestimation of vibration; underestimation of aerodynamic forces; underestimation of geotechnical vulnerabilities in the bedrock, etc.,
- errors in the construction and design such as: poor quality material (often depleted concrete); hidden defects in the material; bad anchors; errors in the joints of the components; poor execution of bridge arches, etc.,
- errors in operation, such as: lack of maintenance; neglected repairs; the absence of timely repairs; frequent congestion; corrosion; the fatigue cracks in the material; an underestimation of the ageing, etc.,
- sabotage and the terrorist attacks.

The human factor manifests at both, the errors at individual operations and the errors in the management of traffic on the bridges. Inspections carried out after breakdowns in bridges, often as the cause of the bridge collapse under consideration have identified a combination of several of the above reasons, it is often human error in them, especially in the safety management during the life of the bridge.

To determine the criticality of the bridges we performed an extensive literature search also [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], from which it follows that it is necessary to assess all the parameters that affect the overall safety of each bridge, i.e., factors that are associated with:
- the design and construction,
- disasters in the territory in which the bridge is located,
- the operation,
- management of transportation in the territory,
- maintenance of bridge structures,
- the speed of vehicles on the bridge,
- finance for repair and maintenance,
- quality management object,
- planning and coordination of measures for the management of priority risks.

Because some risks are inherent for each bridge, it is necessary to compile the risk management plan [6]. In this risk management plan of a particular bridge it is necessary to give the method of settlement of failures and the relevant responsibilities in the layers of the safety management system:

1. In the area of the entire transport infrastructure in particular it goes on cope with:
   - the weaknesses in security against external influences,
   - the occurrence of internal random failures of the system,
   - the occurrence of internal system fault equipment
   - failures in processes, human error, lack of resources,
   - conflicts between safety and security requirements,
   - incorrect or insufficient identification of affecting factors,
   - bad work with risks, choice of method, scale definitions, risk assessment,
   - bad responsibility, incompetency, dependencies and lack in credibility of entities.
2. In areas where the superior systems are connected by flows or couplings with the subordinate or secondary systems, it goes in particular on the prevention of:
   - transmission of erroneous and confusing information, i.e. the errors on entry or on exit systems
   - interruption of information and material flows,
   - carrying out the mutually affecting functions,
   - disturbance of the surrounding systems and implementation of relevant hazards.
3. In the fields of the connection between the individual layers of the safety management system in particular it goes on the prevention of:
   - the application of erroneous methodologies for hazard identification and for the risk analysis from higher levels of the safety management system (SMS),
   - misunderstanding to the requirements and information from other layers of SMS,
   - transmission of fault conditions in the case of their occurrences from one layer to another,
   - missing or failing the input information.
4. On the interfaces of infrastructure with the surrounding environment, it goes on preventing the unforeseen events and attacks:
   - change in the conditions for the operation of the State,
   - intentional damage,
   - targeted attacks.

Based on above data and procedures for determination of criticality of complex technological facilities [1], [5], [6], it is necessary in determining the criticality of the bridges on the highways and roads of the first class to assess the following factors:
- the impact of possible natural disasters and the frequency of occurrence of extreme disasters,
- the impacts of climate and of meteorological conditions and the frequency of extreme conditions,
- the impact of the possible bumps of vehicles into the bridge, and the frequency of their occurrence,
- the impact of possible fires vehicles on the bridge and the frequency of their occurrence,
- the impact of the possible explosion of vehicles on the bridge and the frequency of their occurrence,
- the impact of possible mechanical damage of the bridge by the vehicle and the frequency of their occurrence,
- the impacts of possible traffic accidents on the bridge and the frequency of their occurrence,
- the impacts of errors in the bridge design as: bad load combinations; an underestimation of the size of the potential disasters; underestimation of resonance in the construction; an underestimation of vibration; underestimation of

aerodynamic forces; underestimation of geotechnical vulnerabilities in the bedrock, etc.,

- the impact of possible errors in the construction and design such as: poor quality material (often depleted concrete); hidden defects in the material; bad anchors; errors in the joints of the components; poor execution of bridge arches, etc.,
- the impact of possible errors in the operation, such as: lack of maintenance; neglected repairs; the absence of timely repairs; frequent congestion; corrosion; the fatigue cracks in the material; an underestimation of the ageing, etc.,
- the impact of possible changes caused by aging, corrosion of the steel reinforcing bar as: bridges; layering concrete slabs; the large width of cracks in concrete structures; fatigue of steel structures; big stress in steel structures, etc.),
- the impact of possible sabotage and the frequency of their occurrence,
- the effects of possible terrorist attacks and the frequency of their occurrence,
- the demands on service ability from the perspective of the territory,
- claims to serve the Defence point of view,
- the demands on service ability from the perspective of industry,
- the demands on service ability from the perspective of integrated rescue system,
- the demands on service ability from the perspective of social needs of citizens,
- economic losses caused by the malfunction of the bridge for more than 14 days,
- the level of physical protection of the bridge
- the level of an advance deployment of the priority components of the bridge
- level of securing alternative routes,
- the level of bridge safety management (safety culture, the bridge's safety management system – phase: prevention, preparedness, response, recovery).

V. CONCLUSION

The article deals with the bridges that are spots of traffic critical infrastructure, which is an important public asset. In detail, it is dedicated to the criticality and the risks of bridges on the roads and railways from the standpoint of ensuring the safety of an important element of the critical infrastructure. It describes the results of research conducted by a critical evaluation of the causes of the collapses of important bridges on the basis of historical data and using the critical analysis of professional publications dealing with the theme. The conclusion summarizes the items to be included in determining the criticality of specific bridges.

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