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PROTECTION OF TUNNELS AS CRITICAL INFRASTRUCTURE ON THE CONNECTION NIS - VRANJE FROM THE DANGER OF EARTHQUAKE

Vukasin Vuckovic[1], Aleksandar Petrovic[2], Boban Rankovic[3]
[1] University of Defence in Belgrade, Military Academy, Veljka Lukica-Kurjaka Street No. 33, Belgrade, Republic of Serbia, vvukasin77@gmail.com
[2] University of Defence in Belgrade, Military Academy, Veljka Lukica-Kurjaka Street No. 33, Belgrade, Republic of Serbia, ale_petrovic@live.com
[3] University of Defence in Belgrade, Military Academy, Veljka Lukica-Kurjaka Street No. 33, Belgrade, Republic of Serbia, boban.rankovic@gmail.com

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Abstract: *The tunnel, as an important part of the traffic infrastructure, represents a construction solution that has always provided relief in traffic. However, the issue of construction and maintenance itself is not simple. Moreover, these buildings are mostly related to the environment that surrounds them, and therefore to all the geomorphological features, changes and processes that take place on that soil. The natural phenomenon that threatens them the most is earthquakes. This paper deals with the topic of the impact of earthquakes on tunnels as critical traffic infrastructure on the route Nis-Vranje. The issue was presented from the point of view of explaining the concept of earthquake and the susceptibility of the area to earthquakes. The focus is also on the most important legal frameworks that a tunnel must have during construction. At the end, the risk and vulnerability of the tunnel on the given route from earthquakes as a hazard was discussed.*

Key words: *tunnel, infrastructure, earthquake, danger*

1. INTRODUCTION

Since ancient times, humanity tried to facilitate the fastest possible transportation of people, the transfer of information, the transportation of goods, with the aim of the smoothest possible functioning of society and a better standard of living. In support of this, there was a continuous effort to develop and improve the traffic infrastructure in order to make life more efficient. In this way, it was possible to get from the well-trodden paths to the finest highways. A parallel problem in the traffic infrastructure is the construction of tunnels. This venture has always been a solution that would eventually prove to be profitable, primarily due to the shortening of the road section.

On the other hand, the difficulties faced by man during its construction did not decrease proportionately with the advent of new technologies. Namely, the more sophisticated the equipment for tunnel construction was, the more complex the construction requirements and construction challenges were, and it was increasingly difficult to combine modern requirements with the possibilities of tunnel construction. The roughness of the soil, the geomorphological structure, the frequency of vehicle movement on that section of the road, the threat of tunnels from natural and other disasters, are just some of the parameters that make it difficult to build them. One of the serious security threats to this type of critical infrastructure are earthquakes.

The impact of earthquakes on traffic infrastructure, as well as on all other forms of critical infrastructure, has always been enormous. The main problem that occurs with this type of danger is the impossibility of predicting and announcing them. Therefore, earthquakes represent a serious threat to this type of critical infrastructure, especially for the reason that the frequency of vehicles in tunnels is high, and the safety solutions, which will be discussed, are sometimes insufficient.

In this paper, a consideration of the impact of earthquakes on tunnels as forms of critical infrastructure is presented. The route chosen for the discussion of this topic is the Nis - Vranje route. This location was chosen for several reasons. First of all, there was no processing of this problem for the given location, also, there was no consideration of the seismological safety aspects of the tunnels built at this location. And finally, these tunnels represent high-frequency infrastructure buildings, especially in the summer season, so it is necessary to look at all aspects of earthquake risk.

2. TERM AND CHARACTERISTICS OF EARTHQUAKE AS NATURAL PHENOMENA

Earthquake occurs due to the movement of tectonic plates, the movement of the earth's crust or the occurrence of an impact, and the consequence is the shaking of the earth's crust due to the release of high energy. Epicentre is the place on the earth's surface where seismic waves first reach directly above the magmatic hearth. Earthquakes have varying consequences, including changes in geological features, damage to the anthropogenic environment, i.e. environments and objects created by man and have a great influence on human's life. Earthquakes can cause dramatic geomorphological changes, including ground movement both horizontally and vertically (Zec, 2011). Most devastating earthquakes are caused by the mutual contact of tectonic masses. Shaking, swaying, vibrations, and undulations in the Earth's crust and on its surface occur because of internal stresses and movements in the lithosphere. The common characteristic of all earthquakes is that they occur due to certain disturbances in the lithosphere. According to the causes of occurrence and the way of manifestation, earthquakes are divided into (Petrovic & Manojlovic, 2003):

1. Tectonic earthquakes most often occur as a result of today's movements and disturbances in the labile parts of the Earth's crust. These movements are caused by contraction in the zones of the crown mountains and faulting in the peripheral parts. The largest number of earthquakes is related to these tectonic movements and disturbances, about 90% of all earthquakes belong to them;

2. Volcanic earthquakes are characteristic of volcanically active areas. Most often they occur as a precursor to volcanic eruptions or during volcanic activity;

3. Primordial earthquakes are associated with karst regions where underground cavities occur. Due to the action of groundwater, these cavities grow, but their stability decreases. This is how the ceilings in caves and pits collapse, and the resulting earthquakes are transmitted to the surface as tremors, and

4. Artificial earthquakes occur during explosions. The strongest earthquakes are caused by underground atomic explosions. Artificial earthquakes can be caused by the filling and emptying of large reservoirs of water in the karst.

Figure 1 shows the effect of an earthquake:

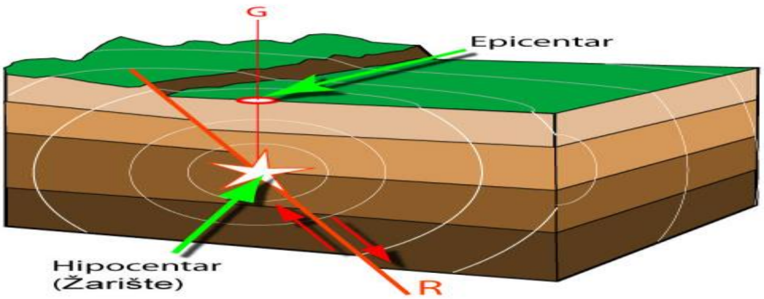

Figure 1. Earthquake effect
Source: (http://geografijagimnazijakgsasa.blogspot.com//)

Another parameter that needs to be defined is the magnitude of the earthquake. It represents a relative measure of the energy released during an earthquake. It is an unnamed number, and common magnitude values range from 1 - 9, although the magnitude scale is open on both the top and bottom. Very weak earthquakes can also have a negative magnitude (since the magnitude is defined by a logarithmic function). Thus, the magnitude is the equivalent energy measure of an earthquake related to its focal point, which means that it does not depend on the depth of the hypocentre. In honour of seismologist Charles Richter, who in 1935 mathematically defined magnitude as an energy measure of earthquakes, this earthquake parameter is also called Richter's magnitude (seismo.co.me, 2016).

The strength of an earthquake is measured on various scales. The most widely used are the Richter and Mercalli scales. The Richter scale divides earthquakes according to the amount of energy (magnitude) released in the hypocenter of the earthquake. The Mercalli scale (from 1 to 9) and the Richter scale (from 1 to 12) cannot be compared, because they give completely different data. According to the Richter scale, earthquakes are divided according to the amount of energy that is released in the hypocenter of the earthquake, while according to the Mercalli scale, they are divided according to the acceleration of points on the ground surface that occurs at the point of measurement. A common abbreviation for the Mercalli scale is MSC (seismo.co.me, 2016).

3. TUNNELS – CRITICAL INFRASTRUCTURE WITH STRICT LEGAL STANDARDS

Critical infrastructure consists of systems, networks, facilities or their parts, which interruption of functioning, or the interruption of goods or services delivery, can have serious consequences on national security, health and lives of people, property, the environment, the safety of citizens, economic stability, i.e. endanger the functioning of state. Critical infrastructure is divided into energy, traffic, water management, food supply infrastructure, health, financial, telecommunication and information infrastructure, environmental protection infrastructure, the functioning of state authorities and emergency services, and science and education infrastructure (Methodology of preparation and content of disaster risk assessment). This paper deals with the topic of the branch of traffic critical infrastructure, tunnels.

Tunnels are underground structures in the form of tubes open at both ends, placed horizontally or at a slight incline, and through them passes a railway, road, canal or waterway, which connect two parts of the road separated by an obstacle that cannot be overcome in any other way (Petkovic, 2016). This paper deals with the problem of road tunnels. In support of this, some of the main legal norms that must be respected during their construction are the following (Official Gazette of RS No. 41/18 and 95/18):

- For tunnels, where the expected traffic load will be greater than 10.000 vehicles per traffic lane per day for a period of 15 years, the construction of two tunnel tubes with one-way traffic is planned;

- The number of traffic lanes, except for the stop lane, must be the same in the tunnel and outside the tunnel;

- In new tunnels that do not have a stop lane, emergency lanes are provided to be used in the event of a breakdown or accident;

- Emergency exits are built in the new tunnels, if the traffic load is greater than 2.000 vehicles per traffic lane per day;

- Whenever the conditions of the terrain allow it, outside the tunnel with two or more tunnel tubes, a passage through the dividing belt is made possible to provide the emergency services with access to each tunnel tube;

- In an existing tunnel with a two-way traffic flow longer than 1.000 m and a traffic load of more than 2.000 vehicles per traffic lane per day, in which there are no stop lanes, the feasibility and effectiveness of the application of stopping surfaces must be evaluated;

- The lighting of the tunnel is carried out in such a way as to enable adequate visibility during the day and at night in the entrance/exit zones of the tunnel, as well as in their interior;

- The lighting of the evacuation routes in the tunnel is placed at a height of no more than 1.5 m so as to ensure sufficient visibility;

- Emergency stations are constructed as cabins or recesses in the side wall, and are located near the tunnel portal on the outside and inside the tunnel, at a distance between them that cannot be more than 150 m in new tunnels, and not more than 250 m in existing tunnels;

- Emergency stations contain at least one telephone or other means of communication in case of emergency and two fire extinguishers and

- In case of danger in the tunnel, all tunnel tubes are immediately closed to traffic.

3.1. Location and characteristics of the tunnel on the route Nis - Vranje

On the Nis - Vranje route, 4 tunnels have been built so far, but 2 tunnels were built in the second half of the 20th century and do not represent the forms of traffic infrastructure covered by the Roads Act. The reason is that these tunnels are not longer than the 500m prescribed by law and there is almost no traffic frequency on those routes. This paper deals with the more recent tunnels, the Manajle and Predejane tunnels on Corridor 10. This corridor is one of the most important pan-European traffic corridors that passes through Serbia and connects Austria, Hungary, Slovenia, Croatia, Serbia, Bulgaria, Macedonia and Greece.

The Manajle tunnel, 1804m long, is located on the southern branch of Corridor 10, highway E75, on the section Caricina Dolina - Vladicin Han, and was built according to the principle of two separate tunnel tubes. The tunnel is equipped with the most modern telecommunication systems, traffic equipment and signaling. It is also equipped with video surveillance, a radio communication system, SOS stations, niches for sheltering broken down vehicles, a fire alarm system, a system for detecting and monitoring toxic gases in the tunnel and speed measurement. The tunnel pipes are interconnected by passages, which are intended for pedestrians and emergency vehicles. Tunnel pipes have extensions, they are connected by passages for eventual evacuation. There are passages for vehicles every 600 meters, and for passengers every 300 meters (danas.rs, 2017).

The Predejane tunnel, 1085m long, is also located on the southern branch of Corridor 10, highway E75. This tunnel was also built in a system of two separate tubes that are interconnected in certain places for possible evacuation and emergencies and is one of the longest tunnels in Serbia. It is equipped with the same systems as the aforementioned Manajle tunnel, and with sophisticated equipment, safety is guaranteed. What these two tunnels have in common is that they represent tunnels with a length of over 1000m and a frequency of over 2000 vehicles per day, in this regard, they are subject to the requirements mentioned, which concern tunnels in the Roads Act (episasee.com, 2020).

3.2. The impact of natural disasters on tunnels

Tunnel construction carries always new risks to human life and various types of property that must be taken into account. Due to the different terrains, geological conditions, anthropogenic elements, but also the great influence of natural disasters that can lead to collapse and other types of endangerment of tunnels, there must be a calculation of the impact of all factors. Many of the mentioned elements are subject to influence and change, however, the impact of natural disasters represents a range of dangers that are almost impossible to control (Sang, Sungjin & Junseo, 2020).

Research in South Korea was conducted on 277 tunnel tubes of various constructions and degrees of modernity. The topic was the impact of natural disasters on tunnels. The conclusion was that the anthropogenic factor greatly influenced and influences the development of certain climatic phenomena, and thus also natural disasters. Therefore, the term "natural" disaster can be considered and whether it is an adequate description of a disaster as a phenomenon if humans influence it through their actions and development. The impact of natural disasters on tunnels as elements of critical infrastructure is enormous (Sang, Sungjin & Junseo, 2020). The dangers that can threaten tunnels as natural disasters are (Methodology of preparation and content of disaster risk assessment):

- **earthquakes** - which are very difficult, almost impossible to identify. The seismic activity of an earthquake leads to ground shaking, and thus to the instability of the entire tunnel architecture, because ground vibrations are directly transmitted to the structure. For these reasons, earthquakes represent the most serious threat to every type of infrastructure, including tunnels. An example of such a disaster is collapse of the Long Xi tunnel in China as a result of the Wenchuan (Szechuan) earthquake in 2008, during which the entire tunnel structure collapsed within a few minutes;

- **Escarpments, landslides and erosions** - these phenomena usually follow heavy rainfall and threaten every type of critical infrastructure. According to research, 86.4% of the surface in Serbia became erosive after the floods (Raskovic & Mrdja, 2013). In this regard, escarpments, erosions and landslides directly affect the tunnels by endangering the ground on which the tunnels are located, whether they threaten the approaches to the tunnel tubes, or the entire structure. An example of such a disaster is the Jammu tunnel in India in 2022, where a landslide destroyed the entire tunnel;

- **floods** - occur as a result of heavy rainfall, and often after sudden melting of snow. The result is an increased water level of the rivers that overflow and flood the surroundings of their bed. The danger of the tunnel from this type of danger is small in terms of damage to the structure of the tubes, but the danger of flooding inside and thus preventing the frequency of traffic is high. An example of this threat is the Tapovan tunnel in India in 2021. Other phenomena that can threaten the tunnel as a form of critical infrastructure are not characteristic of this climate (tsunamis, typhoons, volcanoes, etc.).

The sensitivity of the tunnel to earthquakes is obvious. Tests performed on tunnels can never predict all circumstances, and often even the smallest parameters affect the outcome of the entire catastrophe. Therefore, the tunnel's vulnerability to earthquakes is obvious. In order to prove this thesis, in Table 1, examples of tunnels that experienced disasters under the influence of earthquakes can be observed (Zhang, Yujing & Kazuhiko, 2020):

Table 1: The impact of earthquakes on tunnels

Year	Location	Magnitude	Impact on tunnels
1964	Niigata (Japan)	**7.5**	Largely damaged 20 road tunnels
1970	Tonghai (China)	**7.7**	Severe damage to the tunnel, especially the arches
1971	Los Angeles (USA)	**6.6**	Some serious damage to the mountain tunnel that runs through the Thelma Fault and minor damage to 3 other mountain tunnels
1995	Hyogoken-Nanbu (Japan)	**7.2**	20 tunnels were damaged, 10 of which require reconstruction
1999	Chi–Chi (Taiwan, China)	**7.6**	Damage to 57 tunnels, of which 14 were seriously damaged, 11 were moderately damaged and 23 were slightly damaged
2004	Niigataken-Chuetsu (Japan)	**6.8**	50 tunnels were damaged, 25 of which require reconstruction
2008	Wenchuan (China)	**8**	55 tunnels were damaged, of which 15 were seriously damaged, 13 were moderately damaged and 27 were slightly damaged

From the attached table, it can be concluded that earthquakes have an obvious impact on tunnels as infrastructure buildings. With this detailed analysis, it is not only possible to determine the magnitude that causes damage to the tunnels. However, it can also be seen from the attached that the most seismic soils in the world are precisely the far east due to the frequent movement of the lithospheric plates.

4. ENDANGERMENT OF TUNNELS FROM EARTHQUAKE ON THE RELATION NIS - VRANJE

Engineers involved in the construction of tunnels adhere to the thesis that tunnels are naturally resistant to earthquakes for a wide range of years, unless they are hit by an earthquake of great magnitude [5]. This perspective is supported by relevant data on tunnels throughout history. Research that was done on 71 tunnels. Parameters that are always taken into account when considering the impact of seismic waves on tunnels are "Peak ground acceleration" (PGA) and "Peak ground velocity" (PGV) (Downing & Rozen, 1998).

The damage done by the earthquake was ranged from slight cracking to the entire collapse of the structure. The tunnels that were investigated were in California, Alaska, and Japan. This research led to the following conclusions (Jaramillo, 2017):

- Tunnel collapse only occurs under extreme conditions;

- No damage is read when PGA is less than 0.19 g (ground acceleration 9,81 m/s) and PGV is less than 0.2 m/s,

- Small to moderate damage occurs when PGA is up to 0,5 g, and PGV is up to 0,9 m/s;

- Greater damage occurs when PGA is greater than 0,5 g and PGV is greater than 0,2 m/s;

- Tunnels are much safer than all other above-ground forms of traffic infrastructure and

- Earthquakes with an intensity of less than 7 degrees MSC cannot cause any damage to modern tunnels.

4.1. Endangerment of the tunnels Manajle and Predejane

The tunnels in question were built in 2019 and represent objects of traffic critical infrastructure that are at the very top of construction in these areas. A year after the opening of the tunnel, numerous regular tests were carried out by the Corridor of Serbia and the foreign company "Az Virt" regarding safety and security. After three weeks of testing, both tunnels passed the tests and were declared safe. JP "Roads of Serbia" also participated in the testing (plutonlogistics.com, 2020). From the above, it can be concluded that the tunnels were built in such a way that they meet the provisions of the Rulebook on the minimum safety requirements that a tunnel on a public road must meet from the point of view of traffic safety and the Rulebook on how to manage a tunnel.

In support of that, PGA and PGV parameters, which are basic when assessing and testing the impact of seismic action, are important when considering the safety of the mentioned tunnels. According to the research of this part of the Balkans, it was shown that the PGA ranges from 0,03g to 0,06g, and that the PGV ranges from 0,11 m/s to 0,13 m/s. These data indicate that the earthquakes that occurred in the past century are not dangerous for tunnels as a type of infrastructure in these areas (Eposito & Lervolino, 2011). Finally, as the last parameter, you should look at the seismological map of Serbia for the return period of 95 years made in the MSC scale, shown in Figure 2:

Figure 2. Seismological map for a return period of 95 years
Source: (http://195.222.96.83:18000/)

From the attached, the Predejane tunnel is located in the V-VI MSC intensity zone, and the Manajle tunnel is located in the VI MSC intensity zone. Therefore, the conclusion that follows from this is that the tunnels are located in the safe zone from earthquakes, because the scale does not exceed VI MSC.

5. CONCLUSION

Earthquakes represent one of the most dangerous natural disasters that can strike any form of critical infrastructure. When it comes to tunnels and their vulnerability, the problem must be seen from several aspects. Therefore, the paper gives an overview of the measures and norms that must be met during the construction of the tunnel in order to make it safe. After that, all the parameters that are taken into account when assessing the vulnerability of tunnels, obtained from previous earthquakes that caused damage to tunnels in the previous period, were presented. At the end, the conclusion of the endangerment of the tunnels on the Nis - Vranje route was given, considering each aspect individually.

From the attached it can be concluded that the Manajle and Predejane tunnels are newly built tunnels, safe, secure, but also that they are located in a zone that is not seismically active. However, the safety and protection of the tunnel in every sense of the word must not only include the assessment of the infrastructure object and its vulnerability. In support of this, adequate measures must be taken to reduce risks of any kind, such as regular testing, arrangements, maintenance of facilities, new designs and more. Only such work can achieve the protection of tunnels as a critical infrastructure, as mentioned in the title, because the safety of human lives is a priority and continuous goal.

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