Elefterija Zlatanovic
PhD, Assistant Professor
University of Nis
Faculty of Civil Engineering and Architecture - Nis
Aleksandra Medvedeva 14, 18000 Nis, Serbia
elefterija.zlatanovic@gaf.ni.ac.rs

Vlatko Sesov
PhD, Full Professor
University "Ss. Cyril and Methodius" of Skopje
Institute of Earthquake Engineering and Engineering Seismology (IZIIS) – Skopje
Todor Aleksandrov 165, 1000 Skopje, North Macedonia
vlatko@iziis.ukim.edu.mk

Dragan Lukic
PhD, Full Professor
University of Novi Sad
Faculty of Civil Engineering – Subotica
Kozaračka 2a, 24000 Subotica, Serbia
drlukic.lukic@gmail.com

Zoran Bonic
PhD, Associate Professor
University of Nis
Faculty of Civil Engineering and Architecture - Nis
Aleksandra Medvedeva 14, 18000 Niš, Serbia
zoran.bonic@gaf.ni.ac.rs

Nebojsa Davidovic
PhD, Assistant Professor
University of Nis
Faculty of Civil Engineering and Architecture - Nis
Aleksandra Medvedeva 14, 18000 Niš, Serbia
nebojsa.davidovic@gaf.ni.ac.rs

STATE-OF-THE-ART OF SEISMIC DESIGN CODES FOR TUNNELS AND UNDERGROUND STRUCTURES

Transportation networks, with tunnels as their integral parts, are considered to be of paramount importance when the risk under strong earthquakes is considered. Namely, accessibility of roads affects the speed and the scope of the emergency measures to be provided in the very immediate post-earthquake emergency and relief operations. In addition, the seismically induced damage to the infrastructure could severely affect the economy of a region due to the time required to restore the functionality of the network. Moreover, underground structures are quite often located under densely populated urban areas. Considering all the former facts, these structures require very high standards in terms of their stability and safety.

In this respect, the paper is dealing with an overview of the current state of achievements in the area of seismic design codes for underground facilities, with an aim to point out to that nowadays, in spite of a significant step forward in the scientific–research work concerning seismic analysis of tunnels over the past decade or two, yet, even in the most developed countries, there still exists a lack of systematic and precisely established seismic design rules for tunnels and underground structures, which are of huge importance.

Keywords: tunnel structures, seismic performance, seismic design, codes

1. INTRODUCTION

Contemporary streams of everyday life point out the fact that the today necessity for using space under the ground is the greatest than ever. The steady rise of population in large cities, density of transportation, and need for storage capacity have led, inevitably, to an increased use of underground structures in modern civilisation. These facilities are a vital part of the infrastructure of the modern society and are used for a wide range of applications (Fig. 1), including highways, railways, subways, material storage, water transport and sewage, as well as scientific purposes as the CERN in Switzerland.

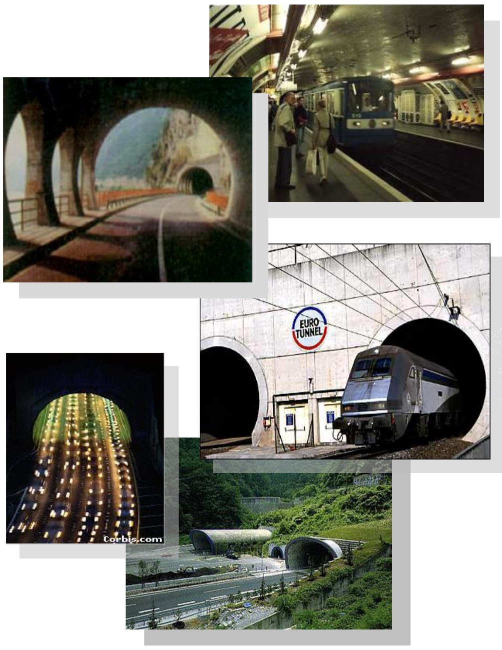

Figure 1. Contemporary tunnel structures and underground facilities

Thus, for the reasons of the overpopulation and the lack of space, tunnels and underground structures have a significant role in the development of urban areas. Some of these areas are prone to frequent earthquakes. More than fifty percent of the world population live in urban areas, whereas over seventy percent of that population live in earthquake prone areas. The Balkan region is in the seismic active area.

Historically, underground facilities have experienced a lower rate of damage in comparison with surface structures, and initially, tunnel structures were designed with no regard to seismic effects. Namely, being confined by the surrounding medium (soil/rock), these structures have long been assumed to have good seismic performance, unless they are located within active faults or within liquefied soil zones. Therefore, in a quite long time, earthquake-induced tunnel damage did not take enough attention as it was the case with surface structures. Nevertheless, some underground structures have experienced significant damage in recent large earthquakes, including the 1995 Kobe earthquake in Japan, the 1999 Chi-Chi earthquake in Taiwan, as well as the 1999 Kocaeli earthquake and the Duzce earthquake in Turkey. As the tunnel number and its seismically induced damage and failure increased, the widely accepted idea that tunnels and underground structures are invulnerable to earthquakes has appeared to be illusive, and this problem has attracted the attention of experts and scientists around the world, reviving the interest in the associated design and analysis methods.

The seismic response of tunnels, and in general of underground structures, is significantly different from that of above-ground facilities. Therefore, the design of underground facilities, in order to withstand earthquake-induced loading, has aspects that are quite different from the seismic design of surface structures and is unique from several viewpoints. Namely, the features of tunnels make their seismic behaviour distinct from most surface structures, among which the most notable are their complete enclosure in soil or rock as well as their significant length.

Since the overall mass of a tunnel structure is usually small in comparison with the mass of the surrounding medium (soil or rock), consequently, the inertia of the surrounding ground is large relative to the inertia of the structure, and the stress confinement provides high values of radiation damping. Therefore, the seismic response of tunnel structures is mainly controlled by the imposed strain field and its interaction with the structure, and not by the inertial characteristics of the structure itself [14]. Because of the restriction of the surrounding medium, it is unlikely that they could move to any significant extent independently of the medium or be subjected to vibration amplification. In comparison with surface structures, which are generally unsupported above their foundations, the underground structures can be considered to display appreciably greater degrees of redundancy due to the support from the ground. These are the main factors contributing to the better earthquake performance data for underground structures than their aboveground counterparts [16].

As a consequence of the constraint by the surrounding medium (soil or rock), the deformation shapes of underground structures and super-structures are different. The deformation of the underground structure under horizontal seismic loads appears a shear shape mainly, whereas the super-structure bears a combined action of moments, shear forces, and torques. Between the medium and underground structure the soil–structure interaction exists, which is under seismic impact to a great extent more complex in comparison with that one considering surface structures. Accordingly, the restriction of the surrounding ground cannot be neglected, which is different from super-structures, in which case only foundations are exposed to soil–structure interaction and vibrations of soil particles imposed to foundations are being transmitted to a structure above the ground. On the contrary, when it comes to tunnel structures, soil–structure interaction effects are induced along an overall contour of the structure, and a shape of interaction depends mainly on a type of a construction procedure, i.e., on a methodology of excavation and installing of a tunnel support system.

For long structures such as tunnels, different ground motions may be encountered by different parts of the structure (the motion could vary significantly in amplitude and phase along tunnel's length), and travelling wave effects must be considered. This spatial incoherence may have a significant impact on the response of the structure, since it tends to increase the strains and stresses in the longitudinal direction. There are four major factors that may cause spatial incoherence: wave-passage effects, extended source effects, ray-path effects caused by inhomogenities along the travel path, and local soil site effects [6].

Earthquake damage to tunnel structures is also proved to be better correlated with ground particle velocity and displacements than acceleration.

A number of studies [6,12,15,16] have indicated that the damage of tunnels is influenced by numerous factors, which could be grouped in three major aspects. The first one is the earthquake motion in terms of the earthquake intensity, the spectrum characteristics, etc. The second aspect is the structure condition of the tunnel, such as (non)existance of lining, its integrality, and the construction quality. The third aspect is related to the tunnel environment conditions in terms of the properties of the surrounding medium, overburden depth, running across the fault zone, and so on.

Tunnels are crucial facilities in transportation network, and occurrence of a seismic event can cause a loss of human lives and damage to the infrastructure. It could severely influence the rescue operations and repair work after earthquake directly due to intermission of the transportation network and affect the economy of a region considering the time required to restore the functionality of the network.

2. SEISMIC DESIGN CODES FOR TUNNEL STRUCTURES

Considering that quite often tunnels are located under densely populated urban areas, these structures require very high standards concerning their stability and safety. Nevertheless, even in the most developed industrial countries there is a perceptible discrepancy between presently relevant regulations for underground structures, particularly with respect to earthquake activity, and the requirements for design and construction of safe and cost-efficient underground facilities.

2.1 SEISMIC DESIGN CODES IN JAPAN

During the Hyogoken Nanbu (Kobe) earthquake in Japan in 1995 urban facilities in Kobe city were seriously destructed. In this large earthquake, some subway stations and tunnels suffered extensive damage (Figs. 2 and 3), which was the first case of severe earthquake-induced damage to modern underground facilities [11,12,18].

Although it was believed that underground structures are not at great seismic risk unless they are located within active faults or within liquefied soil zones, the experience in the Kobe earthquake showed this conviction to be incorrect.

Figure 2. The seismic damage of the Daikai subway station (above) and the road subsidence above the station (below) [13]

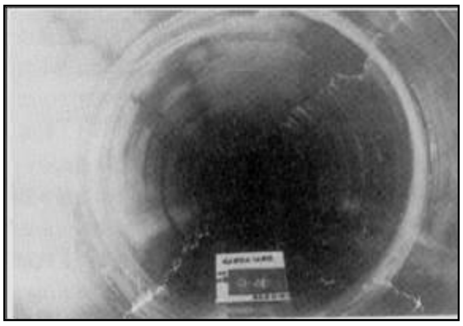

Figure 3. Damage to metro tunnel segments during the 1995 Kobe earthquake [12]

The Kobe earthquake has stirred the sharp rise in demand for rational seismic design regulations for urban underground structures.

Earthquake-resistant codes in Japan, in particular after the Kobe earthquake in 1995, have been revised by adopting two design levels representing low-to-moderate and strong earthquakes.

There are “Standard Specifications for Tunnelling” [9], published by the Japanese Society of Civil Engineers, considering mountain tunnels, shield tunnels, as well as cut-and-cover tunnels. As to the seismic analysis of shield tunnels, on the basis of the seismic deformation method, calculation approaches based on the bedded-beam model with corresponding ground-springs and structural joint-springs have been proposed. The earthquake-resistant calculation of shield tunnels employs elastic analysis.

According to the “Standard Specifications for Concrete Structures – Design” [10], in order to maintain the required seismic performance of underground structures, it is recommended to consider the use of structures and materials designed for enhancing flexibility.

2.2 SEISMIC DESIGN CODES IN USA

Although seismic design regulations are highly developed in the United States of America, there is an absence of proper codes in the area of seismic design of tunnel structures. The ASCE/SEI 7-10 Standard “Minimum Design Loads for Buildings and Other Structures” [1], published by the American Society of Civil Engineers, is not dealing with underground structures. As it is highlighted in Chapter 15 “Seismic design requirements for non-building structures”, buried utility lines and their appurtenances are excluded from the scope of the non-building structure requirements.

For tunnel structures, Chapter 13 of the “Technical Manual for Design and Construction of Road Tunnels” [5], proposed by the Federal Highway Administration, is giving good practice. It provides general procedure for seismic design and analysis of tunnel structures, which are based primarily on the ground deformation approach, as opposed to the inertial force approach typical for above-ground structures. In other words, the structures should be designed to accommodate the deformations imposed by the ground. Nevertheless, the recommended procedure is not standard or regulation.

2.3 SEISMIC DESIGN CODES IN RUSSIA

The latest edition of the seismic standards in the Russian Federation is named SP14.13330.2014 [4] and represents the latest version of the seismic design code SniP II-7-81. In contrast to the European norms, it is a single document that covers everything needed from foundations to fire safety. In Section 7.9, which is dedicated to tunnel structures, general recommendations in terms of the application of the appropriate type of lining depending on the level of seismicity and the use of antiseismic expansion joints are given. When it comes to the calculation procedure, in Section 8.4 the impact of an earthquake is to some extent defined through the corresponding dynamic coefficients.

2.4 SEISMIC DESIGN CODES IN THE EUROPEAN UNION

In the countries of the European Union, standards for the seismic design of structures are implemented in Eurocode 8.

In particular, the European Standard EN 1998-4 “Eurocode 8: Design of structures for earthquake resistance – Part 4: Silos, tanks, and pipelines” [3] specifies principles and application rules for the seismic design of above-ground and buried pipeline systems, as well as storage tanks and silos of different types and uses.

In addition, the European Standard EN 1998-5 “Eurocode 8: Design of structures for earthquake resistance: Foundations, retaining structures, and geotechnical aspects” [2], as Part 5 of the European seismic regulations, has established requirements, criteria, and rules for earthquake-resistant design of different foundation systems and retaining structures, as well as for soil–structure interaction under seismic action. Yet, provisions related to the seismic design of tunnel structures are not provided within the scope of these Standards.

2.5 SEISMIC DESIGN STANDARDS IN SERBIA

Standards in the Republic of Serbia are being prepared in accordance with the European standards and related documents.

In the area of seismic design, there are SRPS EN 1998-4 [7] and SRPS EN 1998-5 [8], which are related to the corresponding European Standards. Accordingly, as in the case of Eurocode 8, SRPS standard prescriptions and guidelines do not specifically address the issue of seismic design of underground structures.

Previously, the “Collection of Yugoslav regulations and standards for engineering structures” [17] was published, in which within the part “Actions on structures”, a draft version of “Regulations on technical rules for the design and calculation of engineering structures in seismic areas” has been proposed. This version of the regulations envisaged the methodology of determining the seismic ground pressure on underground and buried facilities. It was the beginning of raising awareness about the importance of aseismic design when it comes to underground structures, as well as the beginning of putting this issue in the framework of standards. In spite of this concept, which at that time represented a big improvement in practice of standardisation, however, this draft is kept at the level of ideas and proposals, and never entered into force.

3. CONCLUDING REMARKS

By reviewing the existing standards and codes for aseismic design of structures, the conclusion that could be drawn is that there is a lack of systematic and precisely defined seismic design rules for tunnels and underground structures that are of paramount significance. The worst scenarios related to severe damage and failure of tunnels, experienced particularly during recent earthquakes, impose a necessity for a deeper consideration in terms of aseismic design and construction of these types of structures.

In addition, when it comes to twin-tunnel structures, it should be noted that investigations of the mutual effects of closely spaced tunnels are still staying in the preliminary stage. For that reason, particularly the case of closely running tunnel structures should be turned into an important direction of further development of seismic design codes, where the aspect of their minimum seismically safe distance should be an issue of all concerns [19].

Taking all into account, it should be said that a serious task lies ahead. This work is an attempt to draw attention to the extreme importance and urgency of solving the issue of overall stability and safety of underground facilities (therefore, also under dynamic conditions in addition to static ones), as it demonstrates the call for consideration of the effects of seismic events in the design codes as the key parameters in aspects involving aseismic design and construction of tunnels and underground structures.

Acknowledgements

The authors gratefully acknowledge the support of the “SEEFORM PhD Programme (South Eastern European Centre for PhD Formation in Engineering)”, financed by the German Academic Exchange Service (DAAD).

The support of the Ministry of Education, Science, and Technological Development of the Republic of Serbia in the frame of the scientific–research project “Development and improvement of methods for analysis of the soil–structure interaction based on theoretical and experimental research” TR36028 (2011–2020) is also greatly appreciated.

REFERENCES

[1] ASCE (2010), “ASCE/SEI 7-10 Standard: Minimum Design Loads for Buildings and Other Structures”, American Society of Civil Engineers, Los Angeles, USA.

[2] CEN (2004), “EN 1998-5 Eurocode 8: Design of Structures for Earthquake Resistance – Part 5: Foundations, retaining structures, and geotechnical aspects”, European Committee for Standardisation, Bruxelles, Belgium.

[3] CEN (2006), “EN 1998-4 Eurocode 8: Design of Structures for Earthquake Resistance – Part 4: Silos, tanks, and pipelines”, European Committee for Standardisation, Bruxelles, Belgium.

[4] FAUFCC (2014), “SP14.13330.2014 Construction in Seismic Regions”, Federal Centre for Regulation, Standardisation, and Conformity Assessment of Technical Construction, Moscow, Russia.

[5] FHWA (2009), “Technical Manual for Design and Construction of Road Tunnels – Civil Elements”, Publication No. FHWA-NHI-10-

034, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, USA.

[6] Hashash, Y. M. A., Hook, J. J., Schmidt, B., Yao, J. I.-C. (2001), “Seismic design and analysis of underground structures”, Tunnelling and Underground Space Technology, Vol. 16, pp. 247–293.

[7] ISS (2012), “SRPS EN 1998-4 Eurocode 8: Design of Structures for Earthquake Resistance – Part 4: Silos, tanks, and pipelines”, Institute for standardisation of Serbia, Belgrade, Serbia.

[8] ISS (2012), “SRPS EN 1998-5 Eurocode 8: Design of Structures for Earthquake Resistance – Part 5: Foundations, retaining structures, and geotechnical aspects”, Institute for standardisation of Serbia, Belgrade, Serbia.

[9] JSCE (2006), “Standard Specifications for Tunnelling”, Japanese Society of Civil Engineers, Tokyo, Japan.

[10] JSCE (2007), “Standard Specifications for Concrete Structures: Design”, Japanese Society of Civil Engineers, Tokyo, Japan.

[11] Konagai, K. (2005), “Data archives of seismic fault-induced damage”, Soil Dynamics and Earthquake Engineering, Vol. 25, pp. 559–570.

[12] Lanzano, G., Bilotta, E., Russo, G. (2008), “Tunnels under seismic loading: a review of damage case histories and protection methods”, In G. Fabbrocino and F. Santucci de Magistris (Eds.), Strategies for Reduction of the Seismic Risk, pp. 65–74.

[13] Liu, J., Liu, X. (2008), “Pushover analysis of Daikai subway station during the Osaka-Kobe earthquake in 1995”, Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China.

[14] Ornthammarath, T., Corigliano, M., Lai, C. G. (2008), “Artificial neural networks applied to the seismic design of deep tunnels”, Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China.

[15] Pakbaz, M. C., Yareevand, A. (2005), “2-D analysis of circular tunnel against earthquake loading”, Tunnelling and Underground Space Technology, Vol. 20, pp. 411–417.

[16] Wang, J.-N. (1993), “Seismic Design of Tunnels: A State-of-the-art Approach”, Parsons, Brinckerhoff, Quade and Douglas, Inc., New York.

[17] YASE (1995), “Collection of Yugoslav regulations and standards for engineering structures”, Yugoslav Association of Structural Engineers, Belgrade, Serbia.

[18] Yoshida, N. (1999), “Underground and buried structure”, In Seco e Pinto (Ed.), Earthquake Geotechnical Engineering, Balkema, Rotterdam.

[19] Zlatanović, E. (2016), “Contribution to the Methods of Seismic Analysis of Twin-Tunnel Structures”, Doctoral dissertation, SEEFORM PhD Programme, Institute of Earthquake Engineering and Engineering Seismology (IZIIS) of Skopje, University “Ss. Cyril and Methodius” of Skopje, Republic of Macedonia, Skopje, July 2016, 223 pages.