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3. Živković D.: Influence of front excavation on the state and deformity of montage lining of hydraulic pressure tunnels, Ph. D. University of Niš, 1988, pp. 95-108.
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ROLE OF BUILT HERITAGE IN 20TH C PLANNING AND DEVELOPMENT OF URBAN AREAS IN SERBIA

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Abstract. *Establishing of built heritage preservation and town and regional planning on scientific bases lasted most of 20th century. The two scientific disciplines had early application in Serbia aligned with the development in wider Eurocentric area, until the political and economic turmoil in 1990s. The role of built heritage in town and city planning has essentially changed in that time worldwide. That is partly explained by developing of scientific methodology of each of the disciplines, and partly by global changes and subsequently emerging challenges. In this paper we focused on development in Serbia, which partly reflected changes in both East and West of Eurocentric area.*

Key words: *built heritage, town and regional planning, sustainability, socio-economic development, Serbia*

1. INTRODUCTION

The paper explores how architectural heritage protection influenced the planning and development of urban areas in Serbia and obtained results in the first two decades of 21st c. The research is carried out through a brief historical review of the evolutionary approximation of the preservation of built heritage and urban planning, the consideration of the legal frameworks in which this connection was conducted within the framework of international and national experience, the results obtained and the discussion on the basis of which the conclusion is drawn.

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The link between conservation and planning principles has a long history and its development is deeply reliant on experiences that are accepted by European countries, which happens sometimes quicker and sometimes slower. The protection of the cultural built heritage has gradually evolved and it is finally officially integrated into the planning of space in the 21st century. Such a conclusion can be derived from a number of theoretical papers, international documents and successful practical examples in the world. However, there are still certain doubts which are obstacles for full acceptance of the role of the architectural heritage in planning, incl. confirming the initial principle of the conservation movement "there is no future without the past."[1] This process is limited by the Eurocentric space – meaning, which includes countries in Europe or dominantly under the European cultural influence. This paper starts from the historically determined fact – time of emerging of legal protection and legal planning in certain countries of Europe. The main reason for such decision is the following - due to the work of UNESCO, in the international documents of the 21st century, variety of approaches emerged with different grounding (e.g. in the USA protection of cultural heritage started long after protection of natural heritage, which is completely opposite from European countries). The study of the introduction of scientific methodologies in urban planning and conservation of architectural heritage in the wider Eurocentric space shows that the development of the protection of architectural heritage as an internationally accepted discipline could have emerged in the second half of the 19th century and the first half of the 20th century (see Table 1, 2 3 and 4). Social development, hence the development of urban planning in the West and Russia, took place in various manners. After the WWI and in particularly after the WWII, the crises that emerged were resolved differently in the East and the West, but on both sides, they are explainable, in simplified manner, by issue of public interest and who represented it.

Table 1 Important dates for Serbian cultural heritage protection in 19th and 20th c [2]

1844.	Founded Commission for maintenance and restoration of church and monastery buildings
1844.	Decree on banning the destruction of old towns and their ruins was adopted
1844.	Museum Serbian, today's National Museum, was founded
1932.	founded Archaeological Commission of Banovina (province)
1932. et 1934.	Law on Museums and Antiquities Protection
1946.	Law on the Protection of Cultural Monuments and Natural Rarities
1947.	Founded the Institute for the Protection and Scientific Study of Cultural Monuments of the People's Republic of Serbia
1947.	Founded Archaeological Institute in Belgrade, at SANU the Serbian Academy of Sciences and Arts
1972.	Yugoslavian Institute for the Protection of Cultural Monuments merged Republic Institute for the Protection of Cultural Monuments
1990.	Law on Cultural Property, revised 1992/1994 Law on Cultural Property, currently in use

Table 2 Historical overview of urban planning legislation in Serbia until 1985 [3, 4, 5]

1349	Dušan's Law
1772	Main instructions for inhabiting of Banat
1837	Decree on arranging the lanes in Serbia
1865	Law on towns
1885	Revised Law of towns, Regulations of cities and towns in Serbia
1894	Building law for city of Belgrade and other cities and towns
1895	Building law for city of Belgrade (known as Prince Miloš's law), revised 1898, 1900,19001,1905,1922
1900 et 1905	Royal Order of construction of designated streets in Belgrade [5]
1904	Building regulation of province Bács-Bodrog County
1913	Order on construction profession in liberated and joined territories in Kingdom SCS
1925	Guidelines for creating regulation and Plans for leveling out of cities and towns in Kingdom SCS
1931	Building law of Kingdom of Yugoslavia
1932	General instructions on creating building guidelines and orders on execution of regulation plans
1935	Building manual for city of Belgrade
1936	General guidelines for arrangement of villages
1938	Building manual for city of Novi Sad
1949	Basic order on General urban plan of Federal People's Republic of Yugoslavia
1955	General law on arrangement of municipalities and counties
1961	Law on urban and regional spatial planning of Federal People's Republic of Yugoslavia, revised 1965
1967	Resolution of basis of policy of urbanization of Socialist Republic of Serbia
1974	Law on planning and arrangement in space of Socialist Republic of Serbia, revised 1985
1989	Law on planning and arrangement in space, and on Spatial plan of Socialist Republic of Serbia

Table 3 Emerging of protection of built heritage regulation in Eurocentric space [2]

Europe	TERMINUS POST QUEM	TERMINUS ANTES QUEM
England	1745	?
France	1789	1887
Italy	Renaissance	1883
Germany	1843	
Portugal	1721	revised 1802
Spain	1884	1865
Switzerland	1886	1887
Belgium/Netherlands	1823	
Denmark	1830s	
Norway	1842	1870s
Finland	1870	
Greece	?	1814
North America	1850s	1949
Russia	?	1874
Serbia	**1844**	**1912**

Table 4 Chronological overview of urban planning emerging as scientific discipline in Eurocentric space [5,6,7]

Territory	TERMINUS POST QUEM	TERMINUS ANTE QUEM	Events
Europe	1840s	1928	
North America	1890s	1909	
Russia	1703	1917	Foundation of Sankt Petersburg
Serbia	1867	1931	The first urban plan for Dorćol/The First urban plan for Belgrade

Not only that "power" **could** have become "a litmus test of a planning theory", but at the end of the 20th century, in practice the power **did** become the litmus test of a planning as a rule ("**power**" should be understood broadly, from financial to social, from the power of individuals to the power of the community).

During the same time, through 19th and 20th century, collaborative planning has shifted from the theory of humanities to urban planning, then to the preservation of architectural heritage as a logical response to social changes. Many have pointed to the crisis of (scientific) legitimacy of urban planning, whose methods have been compromised by bureaucratic manipulations in practice [2]. The town and regional planning, as well as preservation of built heritage in **Serbia** developed in the authentic manner, yet with good awareness of the development in the wider region, in the East and the West. [3, 4, 5, 6, 7] As an example, the first urban plan for Belgrade dated only a little bit over a decade after Hausmann's plan for Paris, but in the second part of 20th century, urban planning was centralized, similar as in Russia. [4,5,7]

This research follows our paper "Role of built heritage in 20th c planning of urban areas and Eurocentric development" which provides an historic overview of development in the wider region relevant for Serbia. In this paper we focused on historic development and interdisciplinary impacts of built heritage preservation and planning of urban areas in 20th-century Serbia.

2. Development of Contemporary Built Heritage Preservation in Serbia

In Serbia, contemporary heritage preservation as scientific discipline started developing in the first half of the 19th century, following the liberation of its territories from Ottoman Empire occupation. The ruler of Serbia at the time, Prince Milos Obrenovic, announced Order of inventory of churches and monasteries of Principality of Serbia in 1832, and in 1844 Prince Aleksandar Karadjordjevic established the institution that is nowadays the National Museum in Belgrade. Prince Milos Obrenovic also founded Commission for maintenance and restoration of church and monastery buildings and adopted The Regulation of prohibition of demolishing old cities and their ruins. During 19th century, and at the beginning of 20th century until the First World War, heritage protection was, conceptually, substantially under Austrian influence. Nevertheless, it is noticed that the researches of the past in Serbia since the end of the 19th century were conducted most actively by architects, while in the countries under Austro-Hungarian rule most active researchers were art historians. This important difference reflected primarily on the technical side of conservation of individual cultural monuments, but also indirectly, on link to urban planning. Between the World Wars, there were several attempts to define and adopt adequate law (in 1922, 1932 and 1934) [6]. Also, the new inventory commission, established in 1922, focused for the first time not only on sacral, but on "all monuments".) [7]. In years after that, the excavation works started on several locations: Stobi near Skoplje (1931), Mediana (1933) and Humska Cuka (important prehistoric archaeological site from eneolithic period), both near Nish, as well as in the fortress of Belgrade and many others. [8] Further development of legislation in all European countries was very slow, and sometimes in Serbia even slower, followed by theoretically established general understanding of significance of integral preservation, which meant that measures and instruments for heritage protection were defined and announced in all planning documents [2].

Legal protection of cultural monuments is the basis for all actions related to the status of a cultural property, its technical protection, presentation and use. Most European countries have laws and other legal acts derived from relying on international documents, national doctrine and long-standing practical experience. Once brought, these national documents do not change essentially throughout time, but only improve and conform to changes that accompany the development of social consciousness, in such a way that only some articles or sections of the law or other documents are altered or partially rewritten. It is even more important that they are followed by fast harmonization with other laws with which they are closely related and mutually dependent. For example, when the law on preventive archeology in France passed in 2001, articles 11, 12 and 13 included amendments to the Urban Planning Act, the Environmental Act and the Building Heritage Act of 1941. [9]

After the Second World War, the former Yugoslavia, incl. Serbia as a member of federation, adopted important legal acts in the field of cultural heritage protection (Table 2): Decision on the Protection and Preservation of Cultural Monuments and Antiques (the first general legal act in the field of protection of cultural heritage in the newly formed Socialist Yugoslavia) and the Act on the Protection of Monuments of Culture and Natural Rarities of the Democratic Federative Yugoslavia, 1946. A year later, the first institution of protection in Serbia – Institute for the Protection and Scientific Research of Cultural Monuments of the People's Republic of Serbia was established in Belgrade. This institute, in cooperation with the Archaeological Institute in Belgrade, started collecting data on cultural heritage, listing sites into the Register of Protected Cultural Property and more [10].

As it has been stated, the monument law, also called the monumental legislation, is a special branch of the law (legal system) of a state and special legal discipline. It includes a set of legal norms governing social relations which are relevant for monuments of culture, architecture, art, history, which are defined in our actual law as immovable and movable cultural goods. The authority that a certain monument has, on the basis of the norms of an objective monument right, does or does not do something, or it requires some action or omission of it in connection with immovable or movable cultural goods (which is a subjective monument right). Monument law is a branch of public law, because it regulates social relations in which at least one party is the bearer of public or state power. It is estimated as one of the oldest legal branches in Serbia.

It is the fact that contemporary form of law is the result of work and development since mid-19th century. By 1975, the science of monument law was an integral part of administrative, civil, criminal, and international law. But, in modern terms this law is divided into domestic and international, and regarding this division into two schools, a monistic and dualistic. The monistic school accepts the unity of the monument law and the gives primacy of international law as its backbone. Serbian monumental law is closely linked with constitutional law, the law of public administration, civil law, criminal law, international law and international public and private law. But, a general monumental law in Serbia is still not sufficient because the main instruments, security and equality, could be interpreted differently and often subjectively. Safety is important because it is brought in advance, and the legal subjects know how to behave. Equality has also a significant role, because it contains general rules that have to be allied to all cases of the same type, which are solved in the same way, so that all subjects are placed in the same position [11, 12]. The Republic of Serbia does not yet have its own general act, and applies Act on the Cultural Properties of Yugoslavia from 1994. This act has been outdated in a number of the articles; it cannot respond to contemporary attitudes on the protection of cultural assets and is not in line with the act of spatial and urban planning and act of natural heritage protection. From this incompatibility, a series of difficulties arises in the integration of the preservation of built heritage and the planning of urban areas still now, in the 21st century. The care for cultural heritage from the Second World War has improved the overall awareness of the preservation of cultural assets among the common people. The shift from the protection of individual monuments of culture, to the protection of the value of archaeological sites and ambient units, special historical-cultural wholes and significant sites in the period after the Second World War had an overall positive impact on the care for heritage.

Fig. 1 Main Square in Kraljevo [13]

In period immediately after World War II, there was a lot of work in Serbia for conservators and urban planners, but the interaction was almost negligible. Considering the devastation that the country experienced during the war in urban areas, as a rule, large parts of city units were cleansed and removed; in these areas there was a significant urban reconstruction, that is, a new spatial arrangement and the construction of buildings that we call today “socialist buildings”. In many cities of Serbia, incl. Belgrade, a number of buildings, entire streets and blocks with low-rise houses (on which elements of the Balkan-Oriental forms were visible) were the prime subject of urban reconstruction. By the 1960s in some international circles, the factor of the age of the building or the whole, still played a significant role in the evaluation of the architectural heritage, and the same happened in Serbia. That is why the conservation profession focused on important individual monuments of the Middle Ages and antiquity, and there it achieved excellent results. During this time, urban planners have largely removed the urban heritage of modern times, especially heritage of 19th century and they changed the image of many cities. In some cases, the realization of urban reconstruction has not been fully achieved, and we can witness now the past evolution of the exclusion and the inclusion of the built heritage protection in the planning documents (Fig. 1 [13]) Part of square border is occupied with old buildings and another part with the building from 1960s and 1970s which is an example of unfinished reconstruction. When a larger area of urban fabric has already been remodeled by newly planned constructions, it opens the issue of endangering of the wider area, which should to be additionally protected then from losing its identity [14]. Spatial and urban plans unfortunately did not contain the integrated form of planned protection, presentation and use of the built heritage throughout the second half of the 20th c [15]. According to spatial and urban acts and other legislation, the study on cultural heritage was done apart of the plan and as such it was associated with a certain plan, but as an accompanying document. [16]

Nowadays, in Serbia, protection of cultural heritage is under jurisdiction of one national and 11 local institute, depending on significance of heritage, as well as Central Institute for Conservation (CIK). The law regarding cultural monuments (Act on cultural properties, 1992/1994 and 2011) has defined preservation of single buildings, but also included protection of wider areas and elements of urban heritage and landscape, and it was well accepted in practice. Yugoslavia was one of the founders of the United Nations, as the signatory of a charter for its foundation in 1945. After the World War II, it was the one of the founders of several international bodies whose conventions, declarations, charters and other documents, generated on the basis of theoretical and practical experience, which now serve as guidelines in the field of World Heritage. By the disintegration of Yugoslavia, several states emerged, incl. Serbia. Therefore, Serbia, as a part of the former state, and now as independent state, is involved indirectly and directly in creating international conservation doctrine from its origin, namely Venice Charter and other subsequently adopted UNESCO documents, as well as numerous European conventions and recommendations by Council of Europe [17, 18, 19]

3. Development of Contemporary Town and Regional Planning in Serbia

In the territory of Serbia, the legislative and institutional strengthening of urban planning has occurred especially between the two World Wars and after the Second WW, creating the basis for future scientific development, which successfully continued until the end of the 20th century. Urban development planning as scientific discipline, in Serbia, started developing in the middle of 19th century. Planning urban areas on the territory of nowadays Serbia emerged unevenly. With the planned development of the cities in the area of nowadays Vojvodina, which was under the rule of the Habsburg's Monarchy, began in the late 17th and early 18th centuries. For the date which would symbolically mark the beginning of the establishment of a new discipline in Serbia, suitably can serve: adoption of the first urban plan for Belgrade in 1867, or regulation of the main street of Belgrade the Knez Mihailo's street in 1868 (according to the planning designs of Emilijan Joksimovic, nominally the first Serbian urban planner), the Building Act which came in 1931 the first urban plan of Belgrade adopted in 1923, the first normative act regulating the construction of towns and vineyards in Yugoslavia or the adoption of the Ordinance on the General Urban Plan in 1949. [2]

Urban planning, applying new philosophy of space and built arrangement, started developing in designated part of the World, including in Serbia, approximately at the same time. In 20th-century Serbia, there are both western influences in urban planning, as well as the similarity with the development in Russia in accordance with the dynamics of social development in the 20th century. [20] In the course of the century, the development of ideas in Serbia was predominantly influenced by Western values. The Russian cultural influence began to intensify between two wars, with engagement in Serbia of several architects and other visual artists of Russian origin, who emigrated after the World War I, but that influence was the imperial-Russian, not communist-Russian. However, after the World War II, the socialist state order encouraged development similar to that in Russia, in terms of standardization, planned settlements and supporting infrastructure, financing of housing construction from the state budget, etc., but only to certain stage and not "all the way" like in Russia. Housing construction can be stated as indicative example: in Serbia it has never been acquired in the rigid form as it had been done in Russia, and wider, throughout the eastern bloc, because the open and free real-estate market never completely ceased to exist. [21]

After 1960s heritage protection and spatial/ urban planning in Serbia, despite the acts on planning and construction and other documents, represents a mix of different doctrines, with different European, as well as American and global influences on the entire generations of conservators and urban planners. That is why it is impossible to define the ultimate trend in planning region and towns, but rather agree there were several subsequent and overlapping trends, similar to other countries within Eurocentric influence. The main issues in this period referred to problems due to non-harmonized sector planning and dominance of physical planning, first being very dangerous for heritage protection, and second being even beneficial for it. In addition, after 1980s major political, social and economic turbulences emerged, which inevitably reflected to planning, and especially, to its implementation. There was a very specific form of various pressures that directed urban planning into non-legal flows and encouraged non-planned urbanization, which was undoubtedly most dangerous and destructive for heritage, in practice. In this way, there was a discontinuity in the reconstruction of cities, which contributed overall entropy. [21, 22]

4. Discussion on Eurocentric Impact on the Role of Cultural Heritage in Urban Planning Development in Serbia in 21st Century

In the transition period, especially during the wars in the Balkans, institutions have been weakened, but they did not ceased to exist, and the most significant consequence were demographic changes caused by the armed conflicts in 1990s. The influence of the West did not end in the previous, socialist period, and in the 1990s it was additionally updated, in order to adapt to the dominantly market economy. Through the 20th century, in Serbia there was always a will to keep urban acts in line with the needs of society and other laws and regulations, including those related to cultural heritage. In general, strengthening of the state lasted until 1985 and continued again, after 1996. Urban planning in Serbia did not lose contact with the local community, which has actively participated in decision-making, and began nominally to develop as collaborative after the act which was adopted in the 1995; physical planning has been definitely abandoned by the law from 2003, towards the gradual adoption of strategic and action planning, not excluding any other known model. These changes are very significant, reflecting the fluctuation of the influence of the state and the business sector and re-examining the effects of the established balance in practice, regarding the development of urban areas. Officially, urban acts have taken into account the architectural heritage as an acquired urban obligation, and treated the area as protected in accordance with the current understanding of the concepts of protection. In practice, this urban obligation was often subjected to various pressures and there are not a small number of cases in which parts of the already adopted plans concerning the status of the architectural heritage were subsequently changed, as a rule, to the detriment of the built heritage. That is, most often, justified by the social and economic goals, so the protection service had a difficult task to persuade the future survival of cultural heritage. In this period, the best cooperation was achieved in the plans for the renovation of the old town centers. This is undoubtedly the result of not only international documents of UNESCO, ICOMOS, ICCOM, but especially the impact of European recommendations, documents by Council Of Europe, Europa Nostra, and successful examples of the revitalization of old city centers in European countries. There are certain differences in approaches in Serbia's revitalization plans, depending on the principles and conservationists' inclination toward certain European attitudes. They move from the advocacy of new classical architecture and new urbanism (significant reliance, even replication of historical areas and buildings) to the exploration of the possibility of the old and new coexistence. [23, 24] Town and regional planning has eloped a transition period without much difficulty due to the Act adopted in 2003. The urban development that was very intensive ever since the Second World War has mitigated since 1990s, interest in rural development is nowadays on the rise, at the same time density in urban areas is decreasing contrary to the international trend. Negative demographic trends have slowed down need for urban planning along with urbanization, but it has not stopped. In the entire period after 2003, the principle of integrative planning was proclaimed.

Development of international doctrine of preservation and theoretical discourse was closely followed and participated even at the beginning of the 21st century. Serbia had its representatives in international conferences and continues active participation in the development of international doctrine. Serbian experts made efforts to take part in the international discourse regarding sustainable development of urban areas based on cultural heritage, despite political and economic problems [25, 26]. In Serbia at that time, new trend in international doctrine was largely accepted, the one which gave a significant place to topics which could be classified in three categories: **cultural tourism**, **economy** and **conservation** and **management of historical towns** [27]. New concepts of understanding heritage emerged, which required adoption of new phrases *e.g.* cultural landscape and historical urban landscape. Such innovations were acknowledged by experts, but application of such knowledge in practice has been mostly thwarted [28].

The significant change in the role of cultural heritage in urban planning begins to the greatest extent with the change in the methodology for the development of The Spatial Plan for the Republic of Serbia, which was adopted in 2010. In order to achieve this shift it was necessary to change a certain established procedure in the treatment of cultural heritage in spatial and urban plans. A comprehensive analysis of international documentation has noted that the status of the architectural heritage has significantly improved and is increasingly treated as a non-renewable resource. This view is accepted in Serbia, so this can be considered as the greatest progress by which the architectural heritage has become a strong potential for the sustainable development of the community. Cultural heritage is articulated as developmental resource, protected, managed, presented and used in a way that contributes to the establishment of regional and local identity in accordance with European standards of protection. A plan is dynamic category which changes according to contextual changes. An example for it is the institution of guidelines as "lighter", a more flexible form of set of rules for individual segments and territories. [29]

However, this promising shift in the role of architectural heritage in planning cannot be fully implemented, as there are still a whole series of obstacles. One of the basic is the lack of harmonization of legislation in the areas of protection of cultural goods and urban planning. The Act on Cultural Property has not been changed since 1994, and the legal regulation of urban planning has experienced constant changes with articles which are in conflict with the basic principles of protecting the architectural heritage. The recently adopted cultural strategy of Serbia suffers from significant remarks, so it is difficult to expect the adoption of a new, modern Act on cultural property. Even if it is brought until end of 2020, it will take a while until it begins to apply in a full scale, as well as to establish a harmonious connection with planning. In the meantime, the Eurocentric impact on the renewal of the architectural heritage continues in the circles of domestic experts moving between the new classical architecture and the new urbanism and the increasingly boldly interventions that arise by linking and conveying existing and newly designed urban areas, which means that no consensus has been reached on the role of the architectural heritage in urban planning. [29, 30]

5. Concluding Remarks

Built heritage in 21st century is strategically treated as a resource which can be used by different participants in the society. The fact is that the cultural heritage is not just a cultural resource in the regional countries, but it is also used for achieving different political and economic goals. As this opinion is imported in our environment on the basis of similar or identical treatment in other European countries, the cultural heritage can no longer be considered only as the sum of preserved historical buildings or artifacts in some area. On one hand it has a symbolic dimension, connected to the interpretation of the heritage as sacrum, but on the other hand, heritage has become a profitable market field. The difference between these two aspects is usually hazy and it very much depends on the priorities formed on the state and society level, which in Serbia are still elusive.

In the framework of the very sensitive and difficult area which combines protection, regulation and use of cultural heritage and creation of regional identities, strategic priorities defining and the way of their implementation is process itself with a number of unknown facts. Because of that, the realization of strategic priorities, which are presented and defined here, is stipulated by the number on factors, which are formed in wide spectrum of social, governmental, cultural, economic and other boundaries. Quality and speed of accomplishing proposed strategic priorities depend on the speed of removing these boundaries.

Implementation of strategic priorities does not comprise all actual priorities and some of them should be left out due to the objective overview of the current place of cultural heritage which it takes in development politics in most of the regional countries.

No doubt, the effect of global crisis has to be taken into account, although the status of built property has been, even without the crisis, in great measure put aside in the process of carrying out planned spatial transformations in Serbia. With this proposition, priority domain is defined in the areas of protection, promotion and usage of cultural heritage and creating the regional identity adapted to the current state in the area of cultural heritage, but with the possibility of further promotion, actually, if the country as a whole and society stabilize and go forward for the recovery, actually if they succeed to achieve development on the principles of sustainability.

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ULOGA GRADITELJSKOG NASLEĐA U PLANIRANJU I RAZVOJU URBANIH PODRUČJA U SRBIJI U 20. VEKU

Razvoj očuvanja graditeljske baštine i urbanističkog i prostornog planiranja na naučnim osnovama trajalo je kroz veći deo 20. veka U Srbiji se rano krenulo sa primenom ove dve naučne discipline, u korak sa njihovim razvojem u širem evrocentričnom području, sve do političkih i ekonomskih previranja devedesetih. Uloga graditeljske baštine u urbanističkom i prostornom planiranju suštinski se promenila u to vreme širom sveta. što se delimično objašnjava razvojem naučne metodologije svake od disciplina, a delimično globalnim promenama i kasnijim izazovima. U ovom radu smo se usredsredili na razvoj u Srbiji, koji je delimično odraz promena i na istoku i na zapadu evrocentričnog područja.

Ključne reči: *graditeljska baština, urbanističko planiranje, prostorno planiranje, održivost, društveno-ekonomski razvoj, Srbija*

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RISK MANAGEMENT ON RAILWAY PROJECTS: A LITERATURE VIEW

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Abstract. *Railway construction either underground or in an open area or under a bridge carries work risks. The same in the process of design, implementation or maintenance. We chose this article because it is interesting for everyone to know all the risks that occur. These risks can hinder the activities of both planning, implementation or maintenance. The purpose of this paper is to identify all the risks of railway work and to minimize the risks that occur in subsequent work. Risk identification is carried out through the study of international journal literature by taking data from 30 journals from 100 related journals. Risk analysis based on literature view is divided into Internal and External Factors. Internal Factors: (1). Technical and (2) Non-technical, External Factors (1). Technical, (2) Non-technical and (3) Legality. From the results of the pareto chart and pie diagram analysis it can be concluded that Internal Technical Factors are the most involved in the identification of this risk.*

Key words: *Railway, risk management, construction, technical, non technical, risk*

1. INTRODUCTION

The train is a mass transportation vehicle that is quite effective to carry out the transfer activities, of goods, services and other commodities. Therefore, there is the need for special attention in supporting this mass transportation. In recent years many countries have turned into developing countries and therefore the need for mass transportation that is integrated into all aspects of social, cultural, economic and others. For this reason, it is necessary to identify the risks that occur in planning, implementation and maintenance.

This paper hopes to help minimize any risks that arise later. For example the train Slipping during operation is due to a lack of maintenance (1). These events can have fatal consequences such as deaths and other impacts and the difficulty of land acquisition for the commencement of the railway project (2). This could hamper the work schedule which will later affect all aspects of life.

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2. Introduction

The writing of this article is based on a literature review study obtained online including various scientific articles relating to risks in the construction of railway construction projects which are then reviewed and synthesized to provide comprehensive information. In this research, there are 2 risks (1) Internal & (2) External.

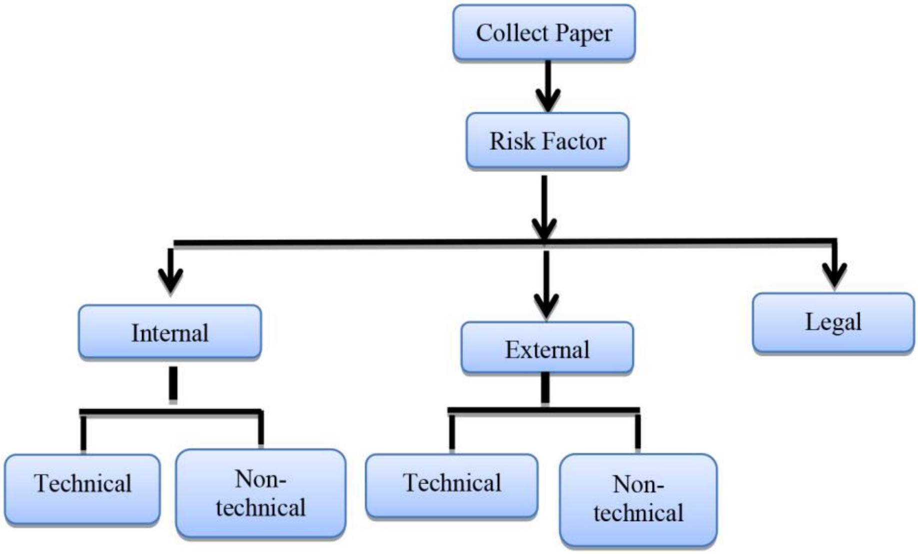

Fig. 1 Study Framework

In Figure 1, this function study framework explains how to obtain journals related to risk management on railway. The key word for the search is using the keyword railway, identify railway or risk railway.

3. Result & Discussion

The review of scientific article publications was carried out from several sources, namely: Google Scholar, Sciendo, Arce Library etc. The list of selected articles analyzed from the aspect of risk identification in railway are as shown in Table 1.

Table 1 Risk Management Identification

No.	Paper Identity	Risk Identification					Result
		Internal		External			
		Technical	Non-technical	Technical	Non-technical	Legal	
1.	(Allan M. Zarembski, 2006)	v	x	v	x	x	Reduction in rail damage by 30% or more.
2.	(Abdelaziz Berrado, El-Miloudi El-Koursi, Abdelghani Cherkaoui & Moha Khaddour, 2011)	v	x	x	x	x	The use of functional diagrams for modeling operations in LC from the perspective of LC actors.
3.	(Ratnaningsih, Dhokhikah, & Fitria, 2018)	v	v	v	x	x	Future work should focus on (1) a more thorough investigation of the differences between the three models, (2) expanding the model to the railway network, (3) expanding the model to better consider station considerations; (4) broadening the model to be taken into account traffic schedules to more realistically determine channel closing costs and speed reductions instead of using fixed costs values; and (5) expanding the model to determine optimal program interventions over several years..
4.	(Guanghong Ma, Huimei Luo, & Jianjun Zheng, 2017)	v	v	v	v	v	The use of BIM is proposed to reduce risk losses.
5.	(MOU Ruifang, WU Yan, 2011)	v	x	x	x	x	Construction methods and geological conditions are the main risk factors for tunnel and underground projects
6.	(J.-R. Pastarus, S. Sabanov, & T. Tohver, 2007)	v	v	v	v	v	Transportation of oil shale from mines and casts to consumers by train causes many technical, economic, ecological and juridical problems.
7.	(Piotr Smoczyński, & Adam Kadziński, 2016)	x	x	v	v	v	Certain hazards associated with railway maintenance, - determine the interface between risk management carried out under the railway maintenance system and risk management related to infrastructure manager
8.	(Li Qing, Liu Rengkui, Zhangm Jun, & Sun Quanxin, 2014)	v	x	x	x	x	Developing RCPQRMIS in detail by first analyzing standard data and then forming a dynamic quality risk tracking model, a quality risk pre-warning model, and an automatically generated quality risk publicity model.

9.	(Serdar Dindar, Sakdirat Kaewunruen, & Min An, 2017)	v	x	x	x	x	An accurate estimate of the high level of risk posed by the rail participation system is very important for companies and organizations to operate the entire railway system without safety concerns.
10.	(Jana Sekulová, Eva Nedeliaková, 2015)	x	x	v	v	x	Risk assessment of passengers
11.	(Yang Xuebin, Du Wen, & Li Zongping, 2009)	v	x	x	x	x	Establishing supply logistics optimization model selection modes, and obtaining algorithms.
12.	(G. N. Young, S. P. DiBenedetto, & V. Hutchison, 2016)	v	x	x	x	x	Use of multi-sensor geophysical technology
13.	(Zeng, 2015)	x	x	x	v	v	Funding and market risks must be taken by the private sector
14.	(Zhang, 2009)	x	v	x	x	x	Through risk-based safety management, can find and solve security problems in the railway system more effectively and comprehensively.
15.	(Asa Boholm, 2010)	v	x	x	x	x	Incorporate risk analysis in expert practical knowledge.
16.	(Johan M. Sanne, 2008)	x	v	x	x	x	Reducing the need to take risks through corporate actions will reduce the risk of job loss
17.	(Sunduck, 2000)	v	v	v	v	x	Risk on railway construction in internal and external
18.	(Flammini, Andrea Gaglione, et al, 2009)	x	v	x	v	x	Analyze critical infrastructure methods
19.	(C. van Gulijk, Peter Hughes & M. Figueres-Esteban, 2015)	x	v	x	x	x	Computerized in supporting safety and risk management in the GB railway and in other risk domains
20.	(Qiyu Shen, 2016)	v	v	x	x	v	Risk assessment method in this paper is reasonable and reliable. The analysis process is simple and easy to understand and operate, and the evaluation result is in accordance with the actual situation.
21.	(Yung-Cheng, Kuan-Ting Chen, 2017)	x	x	v	x	x	Using a computing system.
22.	(Xianbo Zhao, Xianbo Zhao, 2012)	v	x	x	x	v	Identification of the most critical risks associated with implementing ICJV underground rails in Singapore and checking the differences in RC values and risk factor ratings according to contractor characteristics.
23.	(Terry Morgan, 2011)	x	v	x	v	x	There is a range of risks which contractors are best placed to Manage: (a) labour shortages arising from new immigration quotas (b) constructability of new stations on constrained central London sites (c) the impact of Crossrail works on its neighbours and on London and the south east as a whole.

24.	(Ploywarin Sangsomboon, Song Yan, 2014)	v	v	v	v	v	Risk reduction (44.19 percent), risk-retention (53.49 percent), and risk transfer (25.58 percent)
25.	(Vishwas, Gidwani, 2017)	v	x	v	x	x	Using risk management in the context of construction project management.
26	(Zhao Teng, et all, 2013)	v	x	x	x	x	The use of the AHP method depends on experience, knowledge and expert judgment.
27	(Pastarus, et all, 2007)	v	x	x	x	x	Using risk analysis / assessment methods
28	(T.H. Nguyen, Bhagavatulya, F. Jacobs3)	v	v	x	x	v	Momentification of the contract is based on the following factors: 1. Design issues 2. Problems related to material availability 3. Clearly defines the role of project team members 4. Delay damage 5. Contingency plans in terms of personnel leaving the project or uncertainty in terms of material availability 6. Establishing standard for communication policy
29	(David Bray,	v	x	x	x	x	Using the ALARP Framework
30	(Joseph Berechman, Qing Wu2, 2006)	v	x	x	x	x	Developing the method of mounting probability distributions, regression analysis and simulation models

Table 1 is a continuation of figure 1. From what has been obtained from figure 1 is broken down again into the category of internal risk (technical or non technical) or external (technical or non technical or legality) and what results are obtained. From grouping table 1, it will aim to group which factors contribute most to the railway work process with the following result.

Table 2 Result Risk Identification

No	Paper Identity	Risk Identification	Result
1.	(Allan M. Zarembski, 2006)	Technical Internal & External	Reduction in rail damage by 30% or more.
2.	(Abdelaziz Berrado, El-Miloudi El-Koursi, Abdelghani Cherkaoui & Moha Khaddour, 2011)	Technical Internal	The use of functional diagrams for modeling operations in LC from the perspective of LC actors.
3.	(Ratnaningsih, Dhokhikah, & Fitria, 2018)	Technical Internal, External & Non- Technical Internal, Legal	Future work should focus on (1) a more thorough investigation of the differences between the three models, (2) expanding the model to the railway network, (3) expanding the model to better consider station considerations; (4) broadening the model to be taken into account traffic schedules to more realistically determine channel closing costs and speed reductions instead of using fixed costs values; and (5) expanding the model to determine optimal program interventions over several years.

4.	(Guanghong Ma, Huimei Luo, & Jianjun Zheng, 2017)	Technical Internal, External & Non- Technical Internal, External,Legal	The use of BIM is proposed to reduce risk losses.
5.	(MOU Ruifang, WU Yan, 2011)	Technical Internal	Construction methods and geological conditions are the main risk factors for tunnel and underground projects
6.	(J.-R. Pastarus, S. Sabanov, & T. Tohver, 2007)	Technical Internal, External & Non- Technical Internal, External,Legal	Transportation of oil shale from mines and casts to consumers by train causes many technical, economic, ecological and juridical problems.
7.	(Piotr Smoczyński, & Adam Kadziński, 2016)	Non- Technical Internal, External & Legal	Certain hazards associated with railway maintenance, - determine the interface between risk management carried out under the railway maintenance system and risk management related to infrastructure manager
8.	(Li Qing, Liu Rengkui, Zhangm Jun, & Sun Quanxin, 2014)	Technical Internal & Non- Technical Internal, External,Legal	Developing RCPQRMIS in detail by first analyzing standard data and then forming a dynamic quality risk tracking model, a quality risk pre-warning model, and an automatically generated quality risk publicity model.
9.	(Serdar Dindar, Sakdirat Kaewunruen, & Min An, 2017)	Technical Internal	An accurate estimate of the high level of risk posed by the rail participation system is very important for companies and organizations to operate the entire railway system without safety concerns.
10.	(Jana Sekulová, Eva Nedeliaková, 2015)	Non- Technical Internal, External,	Risk assessment of passengers
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12.	(G. N. Young, S. P. DiBenedetto, & V. Hutchison, 2016)	Technical Internal	Use of multi-sensor geophysical technology
13.	(Zeng, 2015)	Non-technical External & Legal	Funding and market risks must be taken by the private sector
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15.	(Asa Boholm, 2010)	Technical Internal	Incorporate risk analysis in expert practical knowledge.
16.	(Johan M. Sanne, 2008)	Technical External	Reducing the need to take risks through corporate actions will reduce the risk of job loss
17.	(Sunduck, 2000)	Technical Internal, External & Non- Technical Internal, External	Risk on railway construction in internal and external

18.	(Flammini, Andrea Gaglione, et al, 2009)	Technical External & Non-technical External	Analyze critical infrastructure methods
19.	(C. van Gulijk, Peter Hughes & M. Figueres-Esteban, 2015)	Technical External	Computerized in supporting safety and risk management in the GB railway and in other risk domains
20.	(Qiyu Shen, 2016)	Technical Internal & External	Risk assessment method in this paper is reasonable and reliable. The analysis process is simple and easy to understand and operate, and the evaluation result is in accordance with the actual situation.
21.	(Yung-Cheng, Kuan-Ting Chen, 2017)	Non- Technical Internal	Using a computing system.
22.	(Xianbo Zhao, Xianbo Zhao, 2012)	Technical Internal & Non-technical Legal	Identification of the most critical risks associated with implementing ICJV underground rails in Singapore and checking the differences in RC values and risk factor ratings according to contractor characteristics.
23.	(Terry Morgan, 2011)	Technical External & Non-technical External	There is a range of risks which contractors are best placed to Manage: (a) labour shortages arising from new immigration quotas (b) constructability of new stations on constrained central London sites (c) the impact of Crossrail works on its neighbours and on London and the south east as a whole.
24.	(Ploywarin Sangsomboon, Song Yan, 2014)	Technical Internal, External & Non- Technical Internal, External, Legal	Risk reduction (44.19 percent), risk-retention (53.49 percent), and risk transfer (25.58 percent)
25.	(Vishwas, Gidwani, 2017)	Technical External & Non-Technical Internal	Using risk management in the context of construction project management.
26	(Zhao Teng, et all, 2013)	Technical Internal	The use of the AHP method depends on experience, knowledge and expert judgment.
27	(Pastarus, et all, 2007)	Technical Internal	Using risk analysis / assessment methods
28	(T.H. Nguyen, Bhagavatulya, F. Jacobs3)	Technical Internal, External & Non-technical Legal	Momentification of the contract is based on the following factors: 1. Design issues 2. Problems related to material availability 3. Clearly defines the role of project team members 4. Delay damage 5. Contingency plans in terms of personnel leaving the project or uncertainty in terms of material availability 6. Establishing standard for communication policy
29	(David Bray,	Technical Internal	Using the ALARP Framework
30	(Joseph Berechman, Qing Wu2, 2006)	Technical Internal	Developing the method of mounting probability distributions, regression analysis and simulation models

Table 3 Scoring - technique of risk management.

No	Technique of risk management	Frequency	Accumulative Freq.	%	acc. %
1	Technical Internal	22	22	36%	36%
2	Non-Technical Internal	12	34	20%	56%
3	Technical External	10	44	16%	72%
4	Non-Technical External	9	53	15%	87%
5	Legal	8	61	13%	100%
	Total	61		100%	

All data in Table 3 has to recap into the form of a table, then we scoring based on the table and pie diagram at figure 2, then resulting in data like table 3, the conclusion drawn from this discussion is based on pareto analysis & diagram pie, as shown Figure 2 & 3, below:

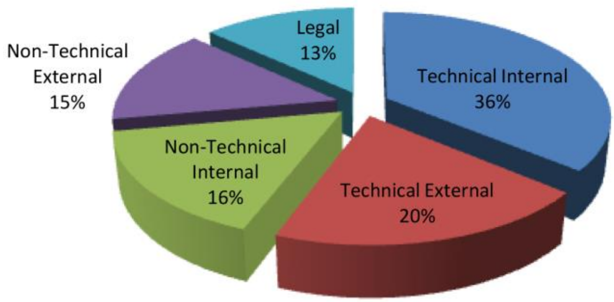

Fig. 2 Percentage results of risk identification

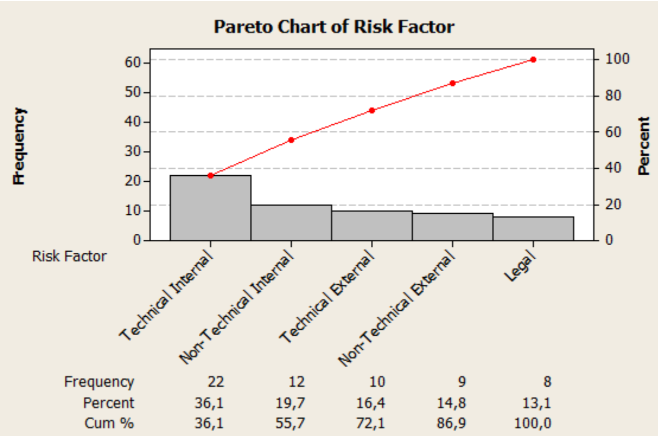

Fig. 3 Pareto Chart

From the pie chart above, the most significant influence is risk identification at (1) 36% Technical Internal, (2) Technical External 20%, (3) Non Technical Internal 16%, (4) Non Technical 16%, (5) Non Technical External 15% & (6) Legal 13% and from the pareto chart internal technical is the most significant.

4. CONCLUSION

The railway project is a mass project that greatly impacts the national economy of a country. This is because it can support all aspects of the economy. But the railway project is a project that has a very large investment value from planning to the maintenance stage. Moreover, there are still many accidents that occur. Therefore it is necessary to identify risks to reduce the risk itself. From the literature view, the results show that internal engineering factors are very influential 36%. So our suggestion in the process of railway projects should be emphasized more on these factors but without ignoring other factors in the hope of reducing the risk of railway project. However, judging from the Pareto analysis it shows the most significant internal technical results, so this section needs to be considered because the basic principle of Pareto states that for many events, about 80% of the effect is caused by 20% of the causes.

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UPRAVLJANJE RIZICIMA ŽELEZNIČKIH PROJEKATA: PREGLED LITERATURE

Izgradnja železnica kako pod zemljom tako i na otvorenom ili ispod mostova nosi radne rizik. Rizici su prisutni i procesu dizajniranja, implementacije ili održavanja. Odabrali smo ovaj članak jer je svima zanimljivo da znaju sve rizike koji se javljaju. Ovi rizici mogu ometati aktivnosti planiranja, implementacije ili održavanja. Svrha ovog rada je da identifikuje sve rizike železničkog rada i da minimizira rizike koji se javljaju u budućem radu. Identifikacija rizika vrši se proučavanjem međunarodne literature u časopisima uzimanjem podataka iz 30 časopisa iz 100 povezanih časopisa. Analiza rizika zasnovana na literaturi podeljena je na unutrašnje i spoljne faktore. Unutrašnji faktori: (1). Tehnički i (2) netehnički, spoljni faktori (1). Tehnička, (2) netehnička i (3) zakonitost. Iz rezultata analize pareto grafikona i dijagrama sa isečcima može se zaključiti da su unutrašnji tehnički faktori najviše uključeni u identifikaciju ovog rizika.

Ključne reči: *železnica, upravljanje rizikom, građevinarstvo, tehnički, netehnički, rizik*

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MATHEMATICAL INTERPRETATION OF SEISMIC WAVE SCATTERING AND REFRACTION ON TUNNEL STRUCTURES OF CIRCULAR CROSS-SECTION

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Abstract. *Mathematical interpretation of the elastic wave diffraction in circular cylinder coordinates is in the focus of this paper. Firstly, some of the most important properties of Bessel functions, pertinent to the elastic wave scattering problem, have been introduced. Afterwards, basic equations, upon which the method of wave function expansions is established, are given for cylindrical coordinates and for plane-wave representation. In addition, steady-state solutions for the cases of a single cavity and a single tunnel are presented, with respect to the wave scattering and refraction phenomena, considering both incident plane harmonic compressional and shear waves. The last part of the work is dealing with the translational addition theorems having an important role in the problems of diffraction of waves on a pair of circular cylinders.*

Key words: *circular tunnel, seismic waves, scattering, refraction, Fourier–Bessel series*

1. INTRODUCTION

In a boundless medium of homogeneous characteristics, seismic waves propagate without interruption, with a constant velocity and along a certain path. The presence of an inhomogeneity in the ground properties generally produces a significant influence on waves propagating through the medium.

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The wave, which emanates from infinite depth in one of the media, is called the *incident wave*. After impinging on inhomogenity (obstacle), the path of the wave propagation is changed, i.e. waves reflect and refract in indistinct patterns depending on the shape and properties of irregularity and surrounding ground. When an incident body wave, propagating through elastic medium, arrives at any discontinuity (e.g., free surface, empty cavity, crack), it will be fully returned back into the medium (*reflected waves*). This is the special case of the second medium that cannot transmit mechanical waves, like a vacuum or air, when the incident wave is completely reflected. For the case of incident seismic waves arriving at the contact surface with another elastic medium (e.g., another ground layer or tunnel lining), a part of its energy will be transmitted into the other medium (*refracted waves*), whereas the remaining energy will return back into the first medium (*reflected waves*) [1].

When excited by the undisturbed incident wave, the obstacle acts as a secondary source by emitting waves radially outward from itself. The deviation of the wave from its original path is considered to be *diffraction*, whereas the radiation of secondary waves from the obstacle is referred to as *scattering*. Diffraction and scattering result in amplification and deamplification of the incident seismic waves in the region near the obstacle, which stands for a phenomenon known as *dynamic stress concentration* [2].

The methods of studying the diffraction of elastic waves are not much different from those concerning other types of waves, owing to physical similarity and mathematical analogy. Nevertheless, there is an additional difficulty in the analysis, as the incident wave diffraction phenomenon in isotropic elastic medium is associated with the coexistence of two types of scattered waves with distinct wave propagation velocity, in contrast to one acoustical or electromagnetic wave in air. In order to understand the nature of the reflected and the refracted waves, the case of wave propagation in two-layered elastic formation is considered, as illustrated in the following figure (Fig. 1).

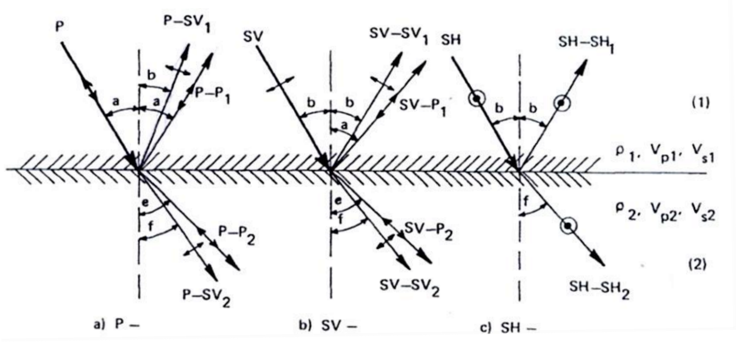


Fig. 1 Breaking down of elastic wave at the boundary between two elastic media [1]

In general, it should be anticipated that a P-wave incident on the interface of two elastic media will give rise to reflection and transmission of P-waves, but also to reflection and transmission of transverse SV-waves with the displacement polarised in vertical plane. Similarly, the vertical component of an S-wave (SV-wave) will cause the appearance of a reflected SV-wave and a P-wave, as well as a refracted SV-wave and a P-wave. The horizontal component of the S-wave (SH-wave), however, is associated with occurrence of only S-waves: a reflected SH-wave and a refracted SH-wave.

If a body has a finite cross-sectional dimension, such as a circular cylinder of infinite length, waves bounce back and forth between the bounding surfaces. Although it is very difficult to trace the actual reflections in that case, it can be observed that the general direction of energy transmission is in a direction parallel to the bounding surfaces, and it is said that the waves are propagating in a waveguide. Hence, there is a standing wave across the cross-section of the body and a travelling wave in the direction of the waveguide [3].

2. Bessel Functions and Certain of Their Properties

The subsequent brief introduction to Bessel functions and their most important characteristics for analysis of the elastic wave diffraction and scattering problem has included the works of Mow and Pao [2], Abramowitz and Stegun [4], Watson [5], and Ivanov [6].

2.1. Bessel's equation

The second-order differential equation of the form:

$$x^2 \frac{\mathrm{d}^2 y}{\mathrm{d}x^2} + x \frac{\mathrm{d}y}{\mathrm{d}x} + (x^2 - \nu^2) y = 0 \tag{1}$$

is known as *Bessel's equation of order ν*. It is characterised by two singular points: the regular singular point $x = 0$ and the irregular singular point $x = \infty$.

The constant ν defines the order of the Bessel functions found as the solution to the Bessel's differential equation and can take on any real-numbered value. In case of cylindrical problems, the order of the Bessel function is an integer value ($\nu = n$).

Considering that the Bessel's differential equation is a second-order equation, there must be two linearly independent solutions. Typically the general solution is given as:

$$y = AJ_\nu(x) + BY_\nu(x) \tag{2}$$

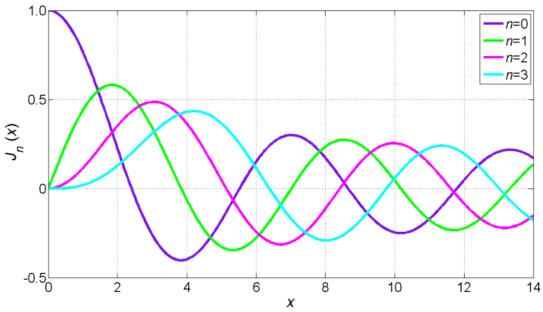
The functions $J_\nu(x)$ and $Y_\nu(x)$ are the solutions of Eq. (1).

The former is called the *Bessel function of the first kind of order ν*, whereas the latter is called the *Bessel function of the second kind of order ν* and is sometimes referred to as a Weber function or a Neumann function $N_\nu(x)$.

2.2. Bessel function of the first kind

The Bessel functions of the first kind of integer order $n = 0, 1, 2,$ and 3 are shown in Fig. 2.

From Fig. 2 it is perceivable that J_n are oscillatory functions and, in fact, they resemble damped trigonometric functions. In particular, the behaviour of J_0 looks like a cosine curve with slight damping, whereas J_1 resembles that of the sine function. In addition, the graph illustrates the property of the Bessel function that, as n is being of a higher value, the Bessel function starts up much slower. After this initial sluggish start for larger values of n, the functions behave roughly like a sine (odd n) or cosine (even n) multiplied by a magnitude factor that decays slowly as $x \to \pm\infty$.



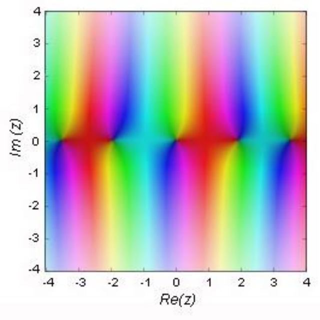
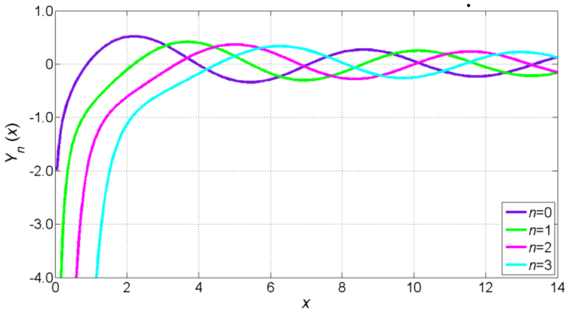


Fig. 2 Presentation of the Bessel functions of the first kind of integer orders: (left) on the real line for n = 0, 1, 2, 3; (right) in the complex plane

2.3. Bessel function of the second kind

Based on Fig. 3, it is obvious that as $x \to 0$ all $Y_n(x) \to -\infty$ due to the logarithmic singularity. Therefore, plots start a little away from 0. The functions with the higher values of n diverge to infinity (-∞) more rapidly as x tends to 0. After the initial divergence, the functions settle into the familiar damped oscillation. $Y_n(x)$ is neither an even nor odd function of x.



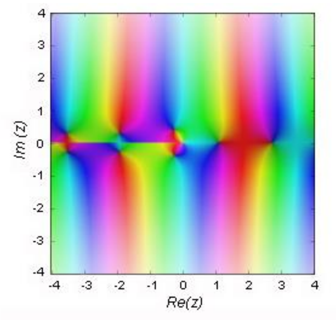


Fig.3 Presentation of the Bessel functions of the second kind of integer orders: (left) on the real line for n = 0, 1, 2, 3; (right) in the complex plane

Considering the two functions J and Y of any order, e.g. J_0 and Y_0, on the same graph (Fig. 4), it is perceptible that for larger x they resemble damped trigonometric functions differing only in a phase shift.

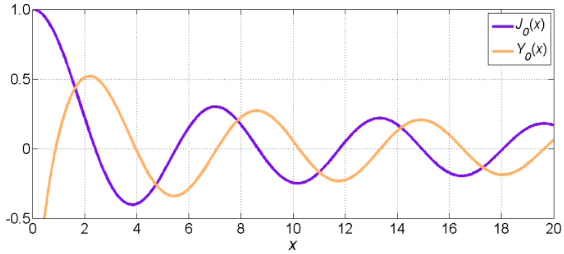


Fig. 4 Presentation of the Bessel functions of the first and second kind of order n = 0

2.4. Hankel functions of the first and second kind

The Hankel functions of order v represent the complex sum of the Bessel functions of the first and second kind (in which $\mathrm{i} = \sqrt{-1}$ designates the imaginary unit):

$$H_v^{(1)}(x) = J_v(x) + \mathrm{i}Y_v(x) \tag{3}$$

$$H_v^{(2)}(x) = J_v(x) - \mathrm{i}Y_v(x) \tag{4}$$

The functions $H_v^{(1)}(x)$ and $H_v^{(2)}(x)$ are called the *Hankel functions of the first* and *second kind of order v*, respectively, and are also known as the Bessel functions of the third kind. Owing to the linear independence of the Bessel function of the first and second kind, the Hankel functions provide an alternative pair of solutions to the Bessel differential equation. Both of the functions are infinite at x = 0 and their fruitfulness is related to their behaviour for large values of x, in other words, the series cannot be used for very large values of x. The behaviour of the Hankel functions can be introduced through the properties of J and Y (Figs. 5 and 6).

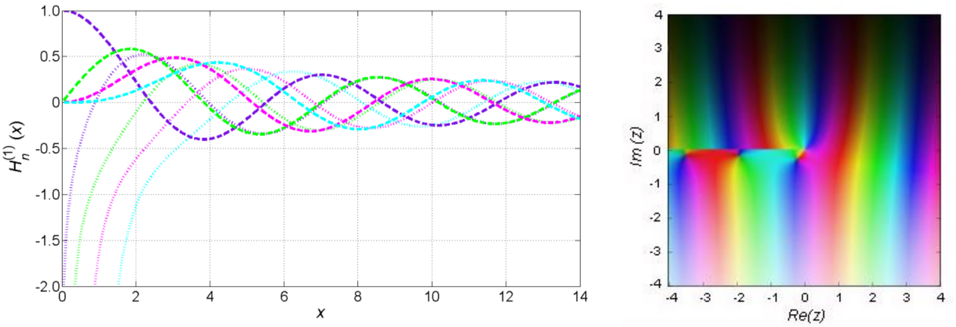


Fig. 5 Presentation of the Hankel functions of the first kind of integer orders: (left) on the real line for n = 0, 1, 2, 3; (right) in the complex plane

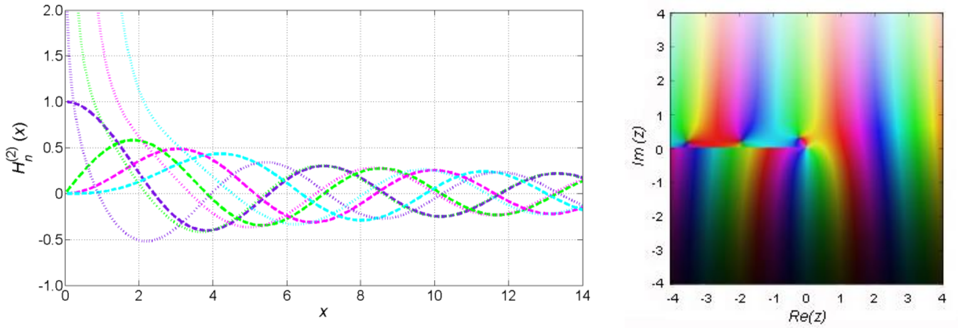


Fig. 6 Presentation of the Hankel functions of the second kind of integer orders: (left) on the real line for n = 0, 1, 2, 3; (right) in the complex plane

3. Wave Equations and Solution in Cylindrical Coordinates

In vector notation, **displacement equations of motion**, which govern the motion of a homogeneous, isotropic, linearly elastic medium of infinite extent, are a system of partial differential equations of the following form [3]:

$$(\lambda+\mu)\boldsymbol{\nabla}\boldsymbol{\nabla}\cdot\mathbf{u}+\mu\nabla^2\mathbf{u}+\rho\mathbf{f}=\rho\ddot{\mathbf{u}} \tag{5}$$

where dots over a quantity mean the partial derivative with respect to time t, ρ is the mass density, λ and μ are known as Lame's constants, $\mathbf{u}$ and $\mathbf{f}$ are displacement vector and force vector, respectively, whereas $\boldsymbol{\nabla}$ is the vector differential operator (nabla) and ∇^2 is the Laplacian, given as follows (with $\mathbf{e}_1$, $\mathbf{e}_2$, and $\mathbf{e}_3$ being the unit vectors of the coordinate axes x_i):

$$\boldsymbol{\nabla}=\frac{\partial}{\partial x_1}\mathbf{e_1}+\frac{\partial}{\partial x_2}\mathbf{e_2}+\frac{\partial}{\partial x_3}\mathbf{e_3} \tag{6}$$

$$\nabla^2=\frac{\partial^2}{\partial {x_1}^2}+\frac{\partial^2}{\partial {x_2}^2}+\frac{\partial^2}{\partial {x_3}^2} \tag{7}$$

3.1. Displacement potentials and reduction to wave equations

The previously presented system of equations (Eq. 5) implies three displacement components. One of the possibilities the system to be uncoupled is to express the components of the displacement vector in terms of derivatives of potentials.

By applying the *Helmholtz decomposition theorem* [3], the displacement fields can be represented as superposition of longitudinal and transverse vector components. This procedure is known as the *Helmholtz decomposition of a vector*, and it states that any vector field can be expressed as the sum of the gradient of a scalar field φ and the curl of a vector field $\boldsymbol{\psi}$:

$$\mathbf{u}=\boldsymbol{\nabla}\varphi+\boldsymbol{\nabla}\times\boldsymbol{\psi} \tag{8}$$

where φ stands for the *scalar displacement potential* and $\boldsymbol{\psi}$ represents the *vector displacement potential*. Substituting the displacement representation (Eq. 8) into Eq. (5) and considering that $\boldsymbol{\nabla}\cdot\boldsymbol{\nabla}\varphi=\nabla^2\varphi$ and $\boldsymbol{\nabla}\cdot\boldsymbol{\nabla}\times\boldsymbol{\psi}=0$, the equation of motion (when body forces are neglected) can be rewritten as:

$$\boldsymbol{\nabla}[(\lambda+2\mu)\nabla^2\varphi-\rho\ddot{\varphi}]+\boldsymbol{\nabla}\times\left[\mu\nabla^2\boldsymbol{\psi}-\rho\ddot{\boldsymbol{\psi}}\right]=0 \tag{9}$$

and it is clearly satisfied if:

$$\mathrm{c}_\mathrm{P}^2\nabla^2\varphi=\ddot{\varphi} \tag{10}$$

$$\mathrm{c}_\mathrm{S}^2\nabla^2\boldsymbol{\psi}=\ddot{\boldsymbol{\psi}} \tag{11}$$

where c_P and c_S are the corresponding wave propagation velocities in the elastic medium:

$$c_P=\sqrt{\frac{\lambda+2\mu}{\rho}} \tag{12}$$

$$c_S = \sqrt{\frac{\mu}{\rho}} \tag{13}$$

The wave arising from $\nabla\varphi$ is the primary wave (P-wave) with propagation velocity c_P, whereas the one from $\nabla \times \boldsymbol{\psi}$ is the secondary wave (S-wave) with propagation velocity c_S. The displacement potentials φ and $\boldsymbol{\psi}$ satisfy a scalar and a vector wave equation, respectively. Equations (10) and (11) are uncoupled wave equations.

Since $\boldsymbol{\psi}$ gives rise to a shear wave, the resolution of a plane shear wave into SV-wave and SH-wave (Fig. 7) suggests that $\boldsymbol{\psi}$ may be decomposed into two parts. The first part is a vector along a preferred direction, usually one of the coordinate axes, e.g. $\mathbf{e}_3$, and the other one is perpendicular to the first vector, i.e. in the x_1Ox_2-plane. Consequently, the following expression arises:

$$\boldsymbol{\psi} = \psi\mathbf{e_3} + \nabla \times (\chi\mathbf{e_3}) \tag{14}$$

where ψ and χ are two scalar functions.

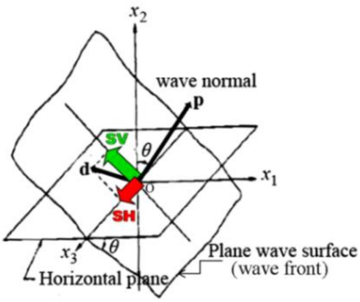


Fig. 7 Polarisation of S-wave

Taking into consideration the Helmholtz decomposition theorem for representation of the displacement fields as the superposition of longitudinal and transverse vector components, the displacements are obtained in the following form:

$$\mathbf{u} = \nabla\varphi + \nabla \times (\psi\mathbf{e_3}) + \nabla \times \nabla \times (\chi\mathbf{e_3}) \tag{15}$$

in which the second member $\nabla \times (\psi\mathbf{e_3}) = \nabla(\psi) \times \mathbf{e_3}$ is perpendicular to the unit vector $\mathbf{e}_3$, whereas the third component is defined by the unit vector $\mathbf{e}_3$. If $\mathbf{e}_3$ is taken along the wave normal, ψ and χ give rise to the plane SV- and SH-wave, respectively. Scalar potentials φ, ψ, and χ satisfy the following scalar wave equations:

$$\begin{aligned} \mathrm{c}_\mathrm{P}^2\nabla^2\varphi &= \ddot{\varphi} \\ \mathrm{c}_\mathrm{S}^2\nabla^2\psi &= \ddot{\psi} \\ \mathrm{c}_\mathrm{S}^2\nabla^2\chi &= \ddot{\chi} \end{aligned} \tag{16}$$

The wave equations reduce to the familiar Helmholtz equation for steady-state response [3]. Steady-state solutions are considered to be of the following form:

$$\varphi(x_i, t) = \phi(x_i, \omega)\, \mathrm{e}^{-\mathrm{i}\omega t} \tag{17}$$

where x_i are coordinates of the position vector **x**.

If a steady-state solution of the form given in Eq. (17) is substituted into the wave equation with inhomogeneous terms:

$$\nabla^2 \varphi(x_i, t) - \frac{1}{c^2} \ddot{\varphi}(x_i, t) = -F(x_i, \omega)\, \mathrm{e}^{-\mathrm{i}\omega t} \tag{18}$$

the following equation is introduced:

$$\nabla^2 \phi(x_i, \omega) + k^2 \phi(x_i, \omega) = -F(x_i, \omega) \tag{19}$$

where $k = \omega/c$ is the so-called wavenumber, which represents the number of wavelengths L over 2π ($k = 2\pi/L$), ω is circular frequency $\omega = 2\pi f$ (radians per unit time) with f being the frequency (in Hz), and c is the wave propagation velocity.

The homogeneous form of Eq. (19) is called the space form of the wave equation, which is known as *Helmholtz equation.*

3.2. Solutions to the Helmholtz equation in cylindrical coordinates

If the function φ is of the form $\varphi(r, \theta, z, t) = \phi(r, \theta, z, \omega)\, \mathrm{e}^{-\mathrm{i}\omega t}$, it must satisfy the Helmholtz scalar wave equation (the homogeneous form of Eq. (19)) that in the system of cylindrical coordinates (r, θ, z) has the following form:

$$\nabla^2 \phi(r, \theta, z, \omega) + k^2 \phi(r, \theta, z, \omega) = 0 \tag{20}$$

in which case the Laplacian is defined as:

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2} \tag{21}$$

The corresponding wave functions are usually derived by separating the variables in the wave equations (*method of separation of variables* [2]). If the particular solution to Eq. (20) is sought in the form of the product of three functions:

$$\phi(r, \theta, z) = R(r)\, \Theta(\theta)\, Z(z) \neq 0 \tag{22}$$

where each of these functions depends only on one coordinate, then the Helmholtz equation can be separated into three ordinary differential equations, one for each coordinate at the time:

$$r^2 R'' + rR' + (k^2 r^2 - \nu^2) R = 0 \tag{23}$$

$$\Theta'' + \nu^2 \Theta = 0 \tag{24}$$

$$Z'' + \gamma^2 Z = 0 \tag{25}$$

in which ν and γ are separation constants.

The equation with the variable r is the *radial function*, whereas the other two are *angular functions*. Therefore, the product of the radial and angular functions constitutes the cylindrical wave functions. The solutions for Θ and Z are:

$$\Theta = \mathrm{e}^{\pm \mathrm{i}\nu\theta} \tag{26}$$

$$Z = \mathrm{e}^{\pm \mathrm{i}\gamma z} \tag{27}$$

The solutions of the equation for Θ (θ) are sines and cosines of the argument $\nu\theta$. For most problems of interest, Θ must be single valued, i.e. Θ ($\theta + 2\pi$) = Θ (θ), in which case ν can only be zero or an integer n. In addition, the solutions should be continuous functions of θ, with continuous derivatives, thus requiring $\nu = n$.

The equation Eq. (22) is the Bessel ordinary differential equation, and accordingly, its solutions are Bessel functions. The solution to $R(r)$, when $\nu = n$, can be expressed in terms of either the Bessel functions of the first and second kind, J_n (kr) and Y_n (kr), or the Hankel functions of the first and second kind, $H_n^{(1),\,(2)}(kr)$. The choice of the radial function is dependent upon the physics of the problem.

As it has been discussed in Section 2.2, the function J_n (x) is regular at the point $x = 0$. Therefore, this function is ordinarily used for constructing a general solution to Eq. (20) inside the cylindrical region containing within itself $r = 0$, thus representing the waves that propagate towards the interior of the cylinders.

On the other hand, functions $H_n^{(1),(2)}(x)$, when are combined with the time factor $e^{-i\omega t}$, represent cylindrical waves generated by a source on an obstacle. At the point $x = 0$, these functions have a logarithmic singularity. The function $H_n^{(1)}(kr)\ e^{-i\omega t}$ represents a diverging or outgoing cylindrical wave; that is, the waves as generated by a circular barrier propagating away from its centre. Similarly, the function $H_n^{(2)}(kr)\ e^{-i\omega t}$ represents a converging or incoming cylindrical wave. The boundary condition at $r = \infty$ in this problem eliminates the latter from the scattered waves. Namely, the scattered waves should satisfy the equations of motion and at infinity, in the unbounded region outside the cylinder, the condition of radiation (the Sommerfeld radiation conditions [3]), and by that, these functions represent outgoing waves that emanate from the origin of the circular cylinder. Therefore, only the function with $H_n^{(1)}(kr)$ can be used in a definition of the scattered wave field.

Accordingly, the particular solutions to the Helmholtz equation (Eq. (20)) will be the following functions:

$$J_n(kr)\ e^{in\theta} e^{i\gamma z} \tag{28}$$

$$H_n^{(1)}(kr)\ e^{in\theta} e^{i\gamma z} \tag{29}$$

The separation constants γ and k may be referred to as propagation constants in z and r directions, respectively, although they are related by Eq. (20) as $k^2 = \omega^2/c^2 - \gamma^2$, and are to be determined from the corresponding boundary conditions of the problem. Thus, for example, if a wave is propagating in the xOy-plane, then ϕ will be independent of z and $\gamma = 0$. It follows that $k = \omega/c$, which is the common definition of the wavenumber. Generally, the separation constant γ could be complex. Therefore, the field is not necessarily periodic along the z-axis.

Bessel's equation, given by Eq. (1) at the beginning, is applicable in those cases when the solution is oscillatory in r and exponential in z. In other problems, the homogeneous boundary conditions are on the surfaces of constant z, making the solutions oscillatory in z. In those cases, the separation constant has a sign opposite to that in the presented Bessel's equation, and the resulting radial displacement is the *modified Bessel equation*, in which case the solution are the modified Bessel functions of the first and second kind, I_n (kr) and K_n (kr), respectively.

4. Wave Functions Expansion Method

The essence of the method of wave functions expansion is in expressing the corresponding waves in terms of a series of wave functions [2]. In finding the solution of diffraction problems by this method, the diffracting body is usually represented in the form of a sum of a known primary field and an unknown secondary field scattered on barriers. The field inside the scattering body is taken in the form of an infinite series of primary wave functions, not having singularities in the volume of the body, whereas the field outside is superposed in the form of an infinite series of primary wave functions that satisfy the condition of radiation at infinity. The unknown coefficients in the series expansion are determined from the magnitude of the incident waves and the appropriate boundary conditions.

This method has gained importance and is widely used due to the rapid convergence of the series solution. The fast convergence of the series solution is achieved in particular for the case of low-frequency waves with long wavelengths (i.e., small wavenumber k), and in the neighborhood of the obstacle (i.e., small x), whereas for the case of much shorter incident wavelengths (high frequencies), or for greater distances from the obstacle, the series solution converges considerably slower.

Nevertheless, only regular-shaped scatterers, such as circular, elliptical, and parabolic cylinders, spheres, etc., are suitable for this method. For problems approximated by plane strain and anti-plane strain, this method is applicable to scatterers of circular, elliptical, or parabolic cross-section, because the obstacle must be of the shape of a long cylinder.

As circular-cylinder-shaped scatterers are in the focus of this study, for this concern, in the subsequent part the general solutions for wave equations in circular cylinder coordinates will be presented, considering the steady-state time-harmonic waves. Having in mind that the transient solution is usually determined based on the steady-state solution, accordingly, no generality is lost in the presentation.

5. Steady-state Solution for a Cavity and a Tunnel under Incident Plane Harmonic Waves

For the purpose of the following presentation of the steady-state solution concerned with incident plane harmonic waves, an obstacle (cavity/tunnel) is assumed to be a long, uniform cylinder with a circular cross-section in a boundless medium, which is referred to a coordinate system as shown in Fig. 8. It is common to take the axis of the cylinder along the z-direction, and the wave normal **p** of a plane wave, in general case, to be inclined to the z-axis (oblique incidence).

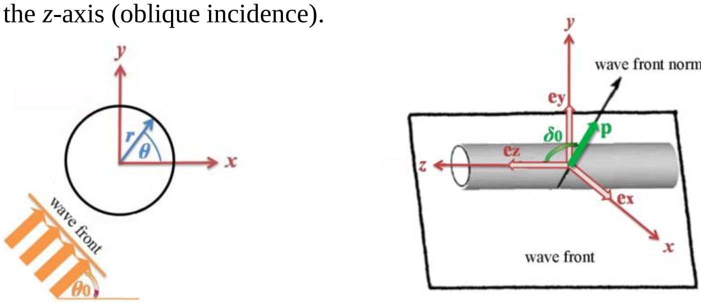


Fig. 8 Plane wave geometry

According to Fig. 8, the unit vector **p** makes an angle δ_0 with the z-axis (out-of-plane incidence angle) and its projection in the xOy-plane is at an angle θ_0 relative to the x-axis (in-plane incidence angle), i.e. θ_0 is the angle that the normal of intersection between the xOy-plane and the wave front makes with the x-axis. Accordingly, for $\theta_0 = 0$ the incident seismic waves will be parallel to xOz-plane, whereas for $\theta_0 = \pi/2$ the incident waves are parallel to yOz-plane. On the other hand, for $\delta_0 = \pi/2$ the plane-strain conditions are valid. In case when the propagation vector is at an arbitrary angle with the longitudinal cylinder axis, a full three-dimensional treatment of the problem is required. Yet, the solution can be formulated in a manner for which the plane-strain approximation can be applied.

5.1. Expansion of incident plane waves for cylindrical wave functions

5.1.1. Incident plane harmonic P-wave in cylindrical coordinates

The incident plane P-wave in polar coordinates, in general case, is represented by infinite Fourier–Bessel series [2, 3]:

$$\varphi^{inc}(r,\theta,z,t) = \varphi_0\, \mathrm{e}^{\mathrm{i}k_P z\cos\delta_P}\, \mathrm{e}^{-\mathrm{i}\omega t} \sum_{n=-\infty}^{\infty} \mathrm{i}^n J_n(k_P r\sin\delta_P)\, \mathrm{e}^{\mathrm{i}n(\theta-\theta_0)} \tag{30}$$

For the potential φ^{inc} in Eq. (30), the z-dependence is separated from the remaining space and time variables. By introducing the relations $\alpha = k_P \sin\delta_P$ and $\gamma_P = k_P\cos\delta_P$, the expansion of the plane P-wave for the cylindrical wave functions is found to be:

$$\varphi^{inc}(r,\theta,z,t) = \varphi_0\, \mathrm{e}^{\mathrm{i}(\gamma_P z-\omega t)} \sum_{n=-\infty}^{\infty} \mathrm{i}^n J_n(\alpha r)\, \mathrm{e}^{\mathrm{i}n(\theta-\theta_0)} \tag{31}$$

where α is the **compressional wavenumber** and $\alpha^2 = {k_P}^2 - {\gamma_P}^2 = \omega^2/{c_P}^2 - {\gamma_P}^2$.

In *plane-strain conditions* ($\delta_P = \pi/2$), when $\gamma_P = 0$, the compressional wavenumber will be of the form $\boldsymbol{\alpha = k_P = \omega/c_P}$ (Section 3.1).

5.1.2. Incident plane harmonic S-wave in cylindrical coordinates

Scattering due to each component of S-wave can be treated independently.

In accordance with this, the expansion of the plane S-wave for the cylindrical wave functions in terms of Fourier–Bessel series is of the following form:

$$\psi^{inc}(r,\theta,z,t) = \psi_0\, \mathrm{e}^{\mathrm{i}(\gamma_S z-\omega t)} \sum_{n=-\infty}^{\infty} \mathrm{i}^n J_n(\beta r)\, \mathrm{e}^{\mathrm{i}n(\theta-\theta_0)} \tag{32}$$

$$\chi^{inc}(r,\theta,z,t) = \chi_0\, \mathrm{e}^{\mathrm{i}(\gamma_S z-\omega t)} \sum_{n=-\infty}^{\infty} \mathrm{i}^n J_n(\beta r)\, \mathrm{e}^{\mathrm{i}n(\theta-\theta_0)} \tag{33}$$

in which β is the **shear wavenumber** referring to the relations $\beta = k_S\sin\delta_S$ and $\gamma_S = k_S\cos\delta_S$, from what follows that $\beta^2 = {k_S}^2 - {\gamma_S}^2 = \omega^2/{c_S}^2 - {\gamma_S}^2$.

Likewise the case of an incident P-wave, considering *plane-strain conditions*, $\delta_S = \pi/2$, thus implying that $\gamma_S = 0$ and the shear wavenumber is of the form $\boldsymbol{\beta = k_S = \omega/c_S}$.

5.2. Scattered wave field around a cavity

Considering a circular cylindrical cavity, the incident wave, upon impinging on its contour, will be fully reflected. In accordance with the Huygens' principle [3], after the boundary of the cavity has been struck by the incident wave, each particle on the cavity contour acts as a secondary source generating waves that propagate away from the structure. Thus generated waves constitute the scattered waves. The solution to the diffraction problem, which is based on direct application of the Huygens' theory and satisfies the condition of radiation at infinity, is always unique.

5.2.1. Scattered wave field induced by an incident plane harmonic P-wave

When the incident P-wave arrives at the contour of an empty circular cylindrical cavity, it will be fully returned back into the medium. For the case of an elastic, homogeneous, isotropic medium, two waves are reflected from the boundary – a P-wave with component φ and an S-wave with components ψ and χ. In accordance with the discussion presented in Section 3.2 and the particular solution to the Helmholtz equation in circular coordinates given by Eq. (29), the **scattered waves** are assumed as:

$$\varphi^{scat}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_P z-\omega t)} \sum_{n=-\infty}^{\infty} A_n(\omega)\, H_n^{(1)}(\alpha r)\, \mathrm{e}^{in\theta} \tag{34}$$

$$\psi^{scat}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_S z-\omega t)} \sum_{n=-\infty}^{\infty} B_n(\omega)\, H_n^{(1)}(\beta r)\, \mathrm{e}^{in\theta} \tag{35}$$

$$\chi^{scat}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_S z-\omega t)} \sum_{n=-\infty}^{\infty} C_n(\omega)\, H_n^{(1)}(\beta r)\, \mathrm{e}^{in\theta} \tag{36}$$

where the superscript "*scat*" has the meaning of the scattered field.

The shear wavenumber of the scattered S-waves is related to the compressional wavenumber of the incident P-wave by $\beta^2 = {k_S}^2 - {\gamma_P}^2 = \omega^2/{c_S}^2 - {\gamma_P}^2 = \kappa^2 {k_P}^2 - {\gamma_P}^2 = {k_P}^2(\kappa^2 - \cos^2\delta_P)$, where the coefficient $\kappa = c_P/c_S = k_S/k_P$ as a function of Poisson's ratio ν is:

$$\frac{c_P}{c_S} = \kappa = \sqrt{\frac{\lambda+2\mu}{\mu}} = \sqrt{\frac{2(1-\nu)}{1-2\nu}} \tag{37}$$

Therefore, the **total wave field** then would be:

$$\begin{cases} \varphi = \varphi^{inc} + \varphi^{scat} \\ \psi = \psi^{scat} \\ \chi = \chi^{scat} \end{cases} \tag{38}$$

The unknown scattering coefficients A_n, B_n, and C_n are to be determined for appropriate boundary conditions that must be satisfied on the surface of the body.

The appropriate **boundary condition** for a cylindrical cavity of radius b is a traction-free surface at $r = b$ ($0 \leq \theta \leq 2\pi$), i.e. vanishing radial stress and shear stress components:

$$\begin{cases} \sigma_{rr} = 0 \\ \sigma_{r\theta} = 0 \qquad r = b \\ \sigma_{rz} = 0 \end{cases} \tag{39}$$

The corresponding stresses are in terms of the displacement potentials due to all the waves (see Appendix). The coefficients for each order of n are obtained in the closed form. The stress and displacement fields are determined once the coefficients are known.

5.2.2. Scattered wave field induced by an incident plane harmonic S-wave

The scattering problem considering an incident plane S-wave can be solved in the same manner as the case of a plane P-wave. Namely, **scattered waves** induced by an incident S-wave are also representable by Eqs. (34)–(36), only with the relation of the compressional wavenumber of the scattered P-waves to the shear wavenumber of the incident S-wave given by $\alpha^2 = k_P{}^2 - \gamma_S{}^2 = \omega^2/c_P{}^2 - \gamma_S{}^2 = k_S{}^2/\kappa^2 - \gamma_P{}^2 = k_S{}^2(1/\kappa^2 - \cos^2\delta_S)$.

Considering that $\kappa = c_P/c_S > 1$ (the longitudinal wave velocity c_P is always greater than the transverse wave velocity c_S), the wave number α will be imaginary whenever $\cos\delta_s \geq 1/\kappa^2$. By that, the Hankel function $H_n^{(1)}$ $(\mathrm{i}\alpha r)$ changes to the nonoscillatory modified Bessel function of the second kind K_n (αr) [2]. The value $\delta_s = \cos^{-1}(1/\kappa^2)$ represents the critical angle, which is the same as the angle for the case of the total reflection of an SV-wave by a plane surface. For values below the critical angle, the scattered P-wave becomes the surface wave that decays rapidly away from the surface of cylinder.

The **total wave field**, considering the case of an incident plane harmonic S-wave scattered by an empty circular cylindrical cavity embedded in an elastic medium, is:

$$\begin{cases} \varphi = \varphi^{scat} \\ \psi = \psi^{inc} + \psi^{scat} \\ \chi = \chi^{inc} + \chi^{scat} \end{cases} \tag{40}$$

Lastly, it could be concluded that it is easy to calculate displacements and stresses in the medium around a cylindrical cavity as long as the unknown coefficients are determined. Using the boundary conditions on the surface of the cavity (Eq. (39)), along with the condition of radiation at infinity of the secondary wave field scattered by the cavity contour, and with the orthogonality conditions provided by the sinusoidal functions [3], the unknown coefficients could be determined for each order of n.

5.3. Scattered and refracted wave fields for a tunnel

5.3.1. Scattered wave field induced by an incident plane harmonic waves

The analysis of wave motion considering a tunnel of infinite extent with an elastic lining of arbitrary thickness laid in an infinite elastic medium, which is treated as an elastic hollow circular cylinder, can be carried out in a completely analogous manner. If the elastic constants and the density of the medium λ_{med}, μ_{med}, and ρ_{med} are different from those of the tunnel lining (λ_{lin}, μ_{lin}, and ρ_{lin}), for an incident plane P- or an incident S-wave there are still two reflected waves, as in the previuosly considered case of a cavity, expressed in terms of the corresponding potentials:

$$\varphi^{scat}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{p_{med}}z-\omega t)} \sum_{n=-\infty}^{\infty} A_n(\omega)\, H_n^{(1)}(\alpha_{med} r)\, \mathrm{e}^{in\theta} \tag{41}$$

$$\psi^{scat}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{s_{med}}z-\omega t)} \sum_{n=-\infty}^{\infty} B_n(\omega)\, H_n^{(1)}(\beta_{med} r)\, \mathrm{e}^{in\theta} \tag{42}$$

$$\chi^{scat}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{s_{med}}z-\omega t)} \sum_{n=-\infty}^{\infty} C_n(\omega)\, H_n^{(1)}(\beta_{med} r)\, \mathrm{e}^{in\theta} \tag{43}$$

5.3.2. Refracted wave field in the tunnel lining

If the refracted waves are considered as **propagating waves** [2, 7, 8] there are two refracted waves that propagate outwards from the inner boundary of the liner and two refracted waves that propagate towards the inside of the liner from its outer boundary. Therefore, there will be two inward propagating waves and two outward propagating waves, and then the total displacement potentials in the tunnel lining are:

$$\varphi^{ref}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{p_{lin}}z-\omega t)} \sum_{n=-\infty}^{\infty} \left[D_n(\omega)\, H_n^{(1)}(\alpha_{lin} r) + E_n(\omega)\, H_n^{(2)}(\alpha_{lin} r)\right] \mathrm{e}^{in\theta} \tag{44}$$

$$\psi^{ref}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{s_{lin}}z-\omega t)} \sum_{n=-\infty}^{\infty} \left[F_n(\omega)\, H_n^{(1)}(\beta_{lin} r) + G_n(\omega)\, H_n^{(2)}(\beta_{lin} r)\right] \mathrm{e}^{in\theta} \tag{45}$$

$$\chi^{ref}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{s_{lin}}z-\omega t)} \sum_{n=-\infty}^{\infty} \left[L_n(\omega)\, H_n^{(1)}(\beta_{lin} r) + M_n(\omega)\, H_n^{(2)}(\beta_{lin} r)\right] \mathrm{e}^{in\theta} \tag{46}$$

where the superscript "*ref*" stands for the refracted field. The $H_n^{(1)}$ and $H_n^{(2)}$ terms in the series represent the outward and inward propagating simple harmonic circular waves, respectively.

Alternatively the four refracted waves in the liner might be thought as **standing waves**, that is, the waves being confined in the tunnel lining [3, 9]. In the solutions of the Bessel equations the cylindrical Bessel functions of the second kind have to be retained. Accordingly, the total displacement potentials in the tunnel lining are:

$$\varphi^{ref}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{p_{lin}}z-\omega t)} \sum_{n=-\infty}^{\infty} \left[D_n(\omega)\, J_n(\alpha_{lin} r) + E_n(\omega)\, Y_n(\alpha_{lin} r)\right] \mathrm{e}^{in\theta} \tag{47}$$

$$\psi^{ref}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{s_{lin}}z-\omega t)} \sum_{n=-\infty}^{\infty} \left[F_n(\omega)\, J_n(\beta_{lin} r) + G_n(\omega)\, Y_n(\beta_{lin} r)\right] \mathrm{e}^{in\theta} \tag{48}$$

$$\chi^{ref}(r,\theta,z,t) = \mathrm{e}^{\mathrm{i}(\gamma_{s_{lin}} z-\omega t)} \sum_{n=-\infty}^{\infty} [L_n(\omega)\, J_n(\beta_{lin} r) + M_n(\omega)\, Y_n(\beta_{lin} r)]\, \mathrm{e}^{in\theta} \quad (49)$$

Both variants have been tried in the study [10]. The trials have revealed that if the refracted waves are represented in terms of propagating waves, a solution will fail in obeying the corresponding boundary conditions at the tunnel–ground interface, in particular for the case of a stiff liner in a soft rock. Moreover, the convergence of the solution based on this representation of refracted seismic waves has not been accomplished with respect to the case of two structures in close proximity. According to these conslusions, in derivation of the solution, the representation of refracted waves in terms of standing waves has been employed. In the author's opinion, this representation is more realistic, since it is rather difficult to trace the refraction of waves across a lining with thickness of finite dimension; so that, transmitted waves are considered to be reflected back and forth between the two surfaces, thus resulting in a standing wave across the tunnel lining cross-section.

5.3.3. Total wave fields in the surrounding medium and the tunnel lining

Considering the medium, the resultant waves are determined by superposing the incident and the reflected waves, whereas the refracted waves are the only ones in the tunnel lining.

Hence, for the case of an *incident P-wave*, the **total wave outside the cylinder** is given by:

$$\begin{cases} \varphi_{med} = \varphi^{inc} + \varphi^{scat} \\ \psi_{med} = \psi^{scat} \\ \chi_{med} = \chi^{scat} \end{cases} \quad (50)$$

whereas for the case of an *incident S-wave*, the total wave field in the surrounding medium is:

$$\begin{cases} \varphi_{med} = \varphi^{scat} \\ \psi_{med} = \psi^{inc} + \psi^{scat} \\ \chi_{med} = \chi^{inc} + \chi^{scat} \end{cases} \quad (51)$$

On the other hand, the **total wave field inside the tunnel lining**, both for the case of *an incident P-wave* and the case of *an incident S-wave*, will be:

$$\begin{cases} \varphi_{lin} = \varphi^{ref} \\ \psi_{lin} = \psi^{ref} \\ \chi_{lin} = \chi^{ref} \end{cases} \quad (52)$$

5.3.4. Boundary conditions

Considering the case of a tunnel structure, the resulting nine sets of unknown expansion coefficients in the above presented equations are comprised of three for the reflected waves and six for the refracted waves. To solve for these unknowns, corresponding boundary conditions in terms of six equations at the outer radius $r = b$ and three equations at the inner radius $r = a$ should be used.

Most of analytical and numerical models are based on the assumption that the contact between the lining and the surrounding medium is of perfect nature. Accordingly, the **no-slip boundary conditions** at the lining–ground adjoining surface ($r = b$, $0 \leq \theta \leq 2\pi$) are continuity of the radial and the shear stresses and displacements across the interface for reasons of equilibrium:

$$\begin{cases} \sigma_{rr_{,med}} = \sigma_{rr_{,lin}} & u_{r_{,med}} = u_{r_{,lin}} \\ \sigma_{r\theta_{,med}} = \sigma_{r\theta_{,lin}} & u_{\theta_{,med}} = u_{\theta_{,lin}} \\ \sigma_{rz_{,med}} = \sigma_{rz_{,lin}} & u_{z_{,med}} = u_{z_{,lin}} \end{cases} \qquad r = b \tag{53}$$

Considering the inner lining surface ($r = a$, $0 \leq \theta \leq 2\pi$), **stress-free boundary conditions** should be prescribed:

$$\begin{cases} \sigma_{rr_{,lin}} = 0 \\ \sigma_{r\theta_{,lin}} = 0 \\ \sigma_{rz_{,lin}} = 0 \end{cases} \qquad r = a \tag{54}$$

In many elastodynamic problems, however, the bond between the liner and the surrounding ground may be imperfect [11, 12].

The spring model is one of the popular models for describing a wide range of contacts between the liner and surrounding ground, from perfect contact to disconnected media [8, 9]. Using this concept, the general boundary conditions to be applied at the interface of the elastic tunnel lining and the surrounding medium are:

$$\begin{cases} \sigma_{rr_{,med}} = \sigma_{rr_{,lin}} & \sigma_{rr_{,med}} = k_r(u_{r_{,med}} - u_{r_{,lin}}) \\ \sigma_{r\theta_{,med}} = \sigma_{r\theta_{,lin}} & \sigma_{rr_{,med}} = k_\theta(u_{\theta_{,med}} - u_{\theta_{,lin}}) \\ \sigma_{rz_{,med}} = \sigma_{rz_{,lin}} & \sigma_{rz_{,med}} = k_z(u_{z_{,med}} - u_{z_{,lin}}) \end{cases} \tag{55}$$

where k_r, k_θ, and k_z are radial, transverse, and axial stiffness (bonding) parameters per unit length, respectively.

The values of these parameters are infinity, with the normal, tangential, and axial stresses being finite quantities, for the case of *perfectly bonded interface* (i.e., *no-slip contact*), in which case the normal, tangential, and axial stresses and displacements are continuous at the interface. When $k_r \rightarrow \infty$, $k_z \rightarrow \infty$, and $k_\theta \rightarrow 0$, which implies that $\sigma_{r\theta} = 0$, the *full-slip condition* (i.e., *perfect slip with no friction*) in *r*-θ (transverse) direction has been defined. The intermediate values of these parameters correspond to the *imperfect contact* (i.e., *loose contact*) in the given direction. In the case when all of the stiffness parameters tend to 0, and therefore, $\sigma_{rr} \rightarrow 0$, $\sigma_{r\theta} \rightarrow 0$, and $\sigma_{zz} \rightarrow 0$, implying that no waves are transmitted from the surrounding medium to the tunnel lining, the case equivalent to the case of a tunnel without liner (cavity) applies.

Based on Eqs. (50)–(52), consequently, the stresses in the medium will depend on incident and scattered wave potentials, whereas the stresses in the cylinder are contributed by refracted waves only.

Using the equations for the stresses and displacements (see Appendix), with the proper cylindrical functions, the unknown scattering and transmission coefficients can be determined by simultaneous algebraic equations.

6. TRANSLATIONAL ADDITION THEOREMS FOR CYLINDRICAL WAVE FUNCTIONS

In many difrraction and scattering problems, waves of one characteristic shape (coordinate system) that are incident upon a boundary of some other shape (coordinate system) need to be considered. In such cases, it is difficult to satisfy boundary conditions on that surface. Namely, Bessel functions are not algebraic functions, and they are not simply periodic functions, and particularly, that they are not doubly periodic functions. Consequently, it is not possible to express $J_n(kr_i + kr_j)$ as an algebraic function of $J_n(kr_i)$ and $J_n(kr_j)$. That is to say, that Bessel functions do not possess addition theorems in the strict sense of the term [5].

Nevertheless, a class of mathematical relationships called *wave transformations* (*translational addition theorems for bi-cylindrical coordinates*) exists, which overcomes this difficulty in many cases by allowing the fields scattered by the various interfaces to be studied, all referred to a common origin.

Fig. 9 illustrates two systems of Cartesian rectangular coordinates O$_1$, x_1, y_1 and O$_2$, x_2, y_2 with identically oriented and parallel respective axes, and the polar coordinate systems r_1, θ_1 and r_2, θ_2 related to them by the corresponding conversion formulas. The point P of the plane xOy is an arbitrary point.

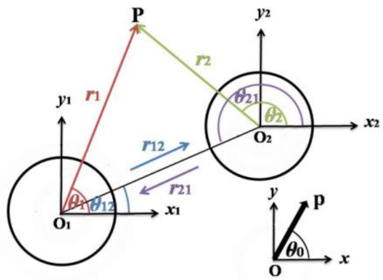


Fig. 9 Addition theorem for cylindrical wave function (reproduced after [6]).

The addition theorems are of the following form [6]:

$$J_n(kr_i)\,\mathrm{e}^{\mathrm{i}n\theta_i} = \sum_{m=-\infty}^{\infty} J_{n-m}(kd)\,J_m(kr_j)\,\mathrm{e}^{\mathrm{i}(n-m)\theta_{ij}+\mathrm{i}m\theta_j} \qquad d \gtrless r_j \qquad (56)$$

$$H_n^{(1),(2)}(kr_i)\,\mathrm{e}^{\mathrm{i}n\theta_i} = \sum_{m=-\infty}^{\infty} H_{n-m}^{(1),(2)}(kd)\,J_m(kr_j)\,\mathrm{e}^{\mathrm{i}(n-m)\theta_{ij}+\mathrm{i}m\theta_j} \qquad d > r_j \qquad (57)$$

$$H_n^{(1),(2)}(kr_i)\,\mathrm{e}^{\mathrm{i}n\theta_i} = \sum_{m=-\infty}^{\infty} H_{n-m}^{(1),(2)}(kr_j)\,J_m(kd)\,\mathrm{e}^{\mathrm{i}(n-m)\theta_j+\mathrm{i}m\theta_{ij}} \qquad d < r_j \qquad (58)$$

in which θ_{ij} (i, j = 1, 2, $i \neq j$) is angle between the OjOi line and the x_i-axis, and d is the distance between two neighbouring structures.

With the above relationships between d and r_j, all the presented expansions converge absolutely and uniformly.

Formulae in Eqs. (56)–(58) allow each Bessel or Hankel wave function written in an i-th system of coordinates (i = 1 or i = 2) to be expressed through the same wave functions, but written in another, the j-th system of coordinates ($j \neq i$; j = 2 or j = 1).

These formulas play a significant role in the problems of scattering of waves on several circular cylinders. By using them, the dynamic interaction between closely spaced structures is fully taken into consideration. The appropriate relationship to be used, in order to determine unknown scattering coefficients, would be the equation for which the condition that the bodies are not tangent to one another is satisfied (i.e., $r_i < d$).

7. Summary and Concluding Remarks

Tunnels are crucial facilities in transportation network, and occurrence of a seismic event can cause a loss of human lives and damage to the infrastructures. It could severely influence the rescue and repair work after earthquake directly due to intermission of the transportation network and affect the economy of a region due to the time required to restore the functionality of the network. In addition, there is a lack of systematic and precisely established seismic design rules for tunnels that are of great importance [13]. 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 [10].

If it is possible to establish a realistic constitutive model for material behaviour, identify the boundary conditions, and combine these with the equations of equilibrium and compatibility, an exact theoretical solution on the seismic response of tunnel structures can be obtained. A closed-form solution is the ultimate method of analysis, in which all solution requirements are satisfied and the theories of mathematics are used to obtain complete analytical expressions defining the full behaviour of the problem.

The mathematical tool, presented in this work, completes the necessary background required for the exact analysis of the problem of seismic wave scattering and refraction on a circular cylindrical cavity or tunnel of infinite length, or the problem accompanying two closely located circular cylinders, embedded in a homogeneous, elastic, isotropic medium of infinite extent. Essential advantage of the exact analytical solution is in terms of better accuracy, thus offering the best benchmark for comparison with other solutions obtained by more conventional simplified asymptotic approaches or numerical methods.

Appendix

A.1. Displacement components in terms of displacement potentials

$$u_r = \frac{\partial \varphi}{\partial r} + \frac{1}{r}\frac{\partial \psi}{\partial \theta} + \frac{\partial^2 \chi}{\partial r\, \partial z} \tag{A.1}$$

$$u_\theta = \frac{1}{r}\frac{\partial\varphi}{\partial\theta} - \frac{\partial\psi}{\partial r} + \frac{1}{r}\frac{\partial^2\chi}{\partial\theta\,\partial z} \tag{A.2}$$

$$u_z = \frac{\partial\varphi}{\partial z} + \left(\frac{\partial^2\chi}{\partial z^2} - \nabla^2\chi\right) \tag{A.3}$$

A.2. Stress components in terms of displacement potentials

$$\sigma_{rr} = \lambda\left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{1}{r}\frac{\partial u_\theta}{\partial\theta} + \frac{\partial u_z}{\partial z}\right) + 2\mu\frac{\partial u_r}{\partial r} =$$

$$= \lambda\nabla^2\varphi + 2\mu\left[\frac{\partial^2\varphi}{\partial r^2} + \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\psi}{\partial\theta}\right) + \frac{\partial^3\chi}{\partial r^2\,\partial z}\right] \tag{A.4}$$

$$\sigma_{\theta\theta} = \lambda\left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{1}{r}\frac{\partial u_\theta}{\partial\theta} + \frac{\partial u_z}{\partial z}\right) + 2\mu\left(\frac{u_r}{r} + \frac{1}{r}\frac{\partial u_\theta}{\partial\theta}\right) =$$

$$= \lambda\nabla^2\varphi + 2\mu\left[\frac{1}{r}\left(\frac{\partial\varphi}{\partial r} + \frac{1}{r}\frac{\partial^2\varphi}{\partial\theta^2}\right) + \frac{1}{r}\left(\frac{1}{r}\frac{\partial\psi}{\partial\theta} - \frac{\partial^2\psi}{\partial r\,\partial\theta}\right) + \frac{1}{r}\left(\frac{\partial^2\chi}{\partial r\,\partial z} + \frac{1}{r}\frac{\partial^3\chi}{\partial\theta^2\,\partial z}\right)\right] \tag{A.5}$$

$$\sigma_{zz} = \lambda\left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{1}{r}\frac{\partial u_\theta}{\partial\theta} + \frac{\partial u_z}{\partial z}\right) + 2\mu\frac{\partial u_z}{\partial z} =$$

$$= \lambda\nabla^2\varphi + 2\mu\left\{\frac{\partial^2\varphi}{\partial z^2} + \left[\frac{\partial^3\chi}{\partial z^3} - \frac{\partial}{\partial z}(\nabla^2\chi)\right]\right\} \tag{A.6}$$

$$\sigma_{r\theta} = \mu\left(\frac{1}{r}\frac{\partial u_r}{\partial\theta} + \frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r}\right) =$$

$$= \mu\left\{2\left[\frac{1}{r}\frac{\partial^2\varphi}{\partial r\,\partial\theta} - \frac{1}{r^2}\frac{\partial\varphi}{\partial\theta}\right] + \left[\frac{1}{r^2}\frac{\partial^2\psi}{\partial\theta^2} - r\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\psi}{\partial r}\right)\right] + 2\left[\frac{1}{r}\frac{\partial^3\chi}{\partial r\,\partial\theta\,\partial z} - \frac{1}{r^2}\frac{\partial^2\chi}{\partial\theta\,\partial z}\right]\right\} \tag{A.7}$$

$$\sigma_{rz} = \mu\left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r}\right) =$$

$$= \mu\left\{2\frac{\partial^2\varphi}{\partial r\,\partial z} + \frac{1}{r}\frac{\partial^2\psi}{\partial\theta\,\partial z} + \left[2\frac{\partial^3\chi}{\partial r\,\partial z^2} - \frac{\partial}{\partial r}(\nabla^2\chi)\right]\right\} \tag{A.8}$$

$$\sigma_{\theta z} = \mu\left(\frac{\partial u_\theta}{\partial z} + \frac{1}{r}\frac{\partial u_z}{\partial\theta}\right) =$$

$$= \mu\left\{\frac{2}{r}\frac{\partial^2\varphi}{\partial\theta\,\partial z} - \frac{\partial^2\psi}{\partial r\,\partial z} + \left[\frac{2}{r}\frac{\partial^3\chi}{\partial\theta\,\partial z^2} - \frac{1}{r}\frac{\partial}{\partial\theta}(\nabla^2\chi)\right]\right\} \tag{A.9}$$

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MATEMATIČKA INTERPRETACIJA RASIPANJA I REFRAKCIJE SEIZMIČKIH TALASA U PRISUSTVU TUNELSKIH OBJEKATA KRUŽNOG POPREČNOG PRESEKA

U fokusu ovog rada je interpretacija difrakcije i rasipanja seizmičkih talasa u polarno-cilindričnim koordinatama primenom odgovarajućeg matematičkog aparata. U radu je najpre dat pregled nekih od najznačajnijih svojstava cilindričnih Bessel-ovih funkcija, koje su podesne za matematičko opisivanje problema difrakcije i rasipanja seizmičkih talasa. Takođe, dat je prikaz jednačina koje predstavljaju osnovu tzv. metode ekspanzije talasnih funkcija (wave function expansion), u polarno-cilindričnim koordinatama i za slučaj seizmičkih talasa sa ravnim frontom. Prikazana su i rešenja primenom metode ekspanzije talasnih funkcija za slučaj nepodgrađenog tunelskog otvora i slučaj podgrađenog tunelskog objekta, sa aspekta fenomena rasipanja i refrakcije seizmičkih talasa, pod uticajem incidentnih harmonijskih P-talasa i S-talasa sa ravnim frontom. Na kraju rada prezentovane su i teoreme translatornog sabiranja (translational addition theorems), koje imaju važnu ulogu u matematičkom rešavanju problema difrakcije i rasipanja seizmičkih talasa u prisustvu dva blisko položena tunelska objekta.

Ključne reči: *kružni tunel, seizmički talasi, rasipanje, refrakcija, Fourier–Bessel-ovi redovi*

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RISK IDENTIFICATION IN TUNNEL CONSTRUCTION PROJECT: A LITERATURE REVIEW

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Abstract. *Every construction project is always faced with the possibility of various occurrence kinds of risks. The higher the level of complexity of a project, the greater the level of risk that might happen to the project. Based on historical data from tunnel construction many problems and even failure of tunnel construction caused by various factors has been noted and it can have an impact on project delays. A risk management is expected to reduce the adverse impact of risks faced during construction work. Tunnel construction needs management handling with high risk, so it is necessary to identify risks that can minimize bad risks. A risk management is expected to reduce the adverse effects of risks faced in a construction work. It is necessary to perform risk identification to manage the risks that we will face. To successfully improve the performance of tunnel projects, we need to identify various risk factors in a project for efficient project fulfillment. The research method begins with an extensive literature review by reviewing at least 48 journal, journal papers, review articles to provide a list of the main risk factors which are also added to the expertise to achieve a list of final risk factors that contain all risks that may be encountered during road construction. This analysis involves the identification, classification of various risks involved in the construction of a tunnel construction project.*

Key words: *Risk, Tunnel Construction, Tunnel Project, Risk Identification*

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1. INTRODUCTION

Risk identification based on failed knowledge does not change the traditional risk identification process, but it is a complement (Xue & Zhou, 2017). Traditional risk identification process is generally simplified to 4 steps: clear objectives, data collection, identification of potential risk factors, identification of project risk events, where risk factors can be divided into risk factors and risk environment (Xue & Zhou, 2017).

Tunnel safety is defined like a safety and protection of persons, property, and surround of structure, which is given by result of risk evaluation, solution reasoning in point of risks, fire-safety structure solution and solution of structure influence on environment, protection of monuments, nature and countryside (Schlosser et al., 2014). Risk management is very necessary for construction work with high level of project risk and risk. Tunnel construction is one project that has a high level of risk, Because the construction conditions are below the surface and Number of factors that must be bypassed the tunnel. The conceptual model consists of three hierarchies and three stages and thirteen factors are chosen as assessment indices. The multiple indicators are categorized as karst hydrogeological and geological engineering conditions, construction factors and feedback information for risk management. (X. Wang et al., 2019). Many risk factors affect the overall safety risk of tunnel operation. Some of them, such as driver and vehicle condition, are also difficult to quantify (B. Zhou et al., 2020). Based on the results of the risk evaluation, risks can be divided into three types: acceptable risk, acceptable risk after mitigation, and unacceptable risk (Bai et al., 2014). Human errors have recurrent patterns and typically include poor technology, slack management, and inadequate hazard handling (Wen Liu et al., 2018). Natural causes of accidents in mechanical tunnel excavation include adverse hydrogeological conditions, groundwater, heavy rainfall, soft soil layers, etc. (Wen Liu et al., 2018). Tunnel projects are inherently risky mainly because of the variability and unpredictable nature of geologic conditions (Klein & O'Carroll, 2017). Tunnel construction is a critical scope in this project because its impact greatly affects the total cost and duration of the project, so the impact of risk identification must be known and identified critically, precisely and correctly in determining the level of project risk. Risk factor identification is the foundation of risk management (H. Zhou et al., 2020). Tunneling projects find themselves involved in the situation where unexpected conditions threaten the continuation of project (Fouladgar et al., 2012). Risk is any event that can prevent / hinder the progress of a planned project, or the success of its completion.

Risks can be identified from a variety of different sources. Some risks can be identified quite clearly and can be identified before the project starts. While other risks can only be identified during the project cycle. Risks can be identified by anyone involved in the project. Some risks are inherent in the project itself, while there are risks stemming from full external influence outside the control of the project team.

2. RESEARCH METHOD

This paper is based on a literature review obtained online including various related articles from trusted sources and those related to "risk identification", "risk management", "safety risk", "tunnel projects". So we get 48 journals which are then selected and reviewed to provide comprehensive information.

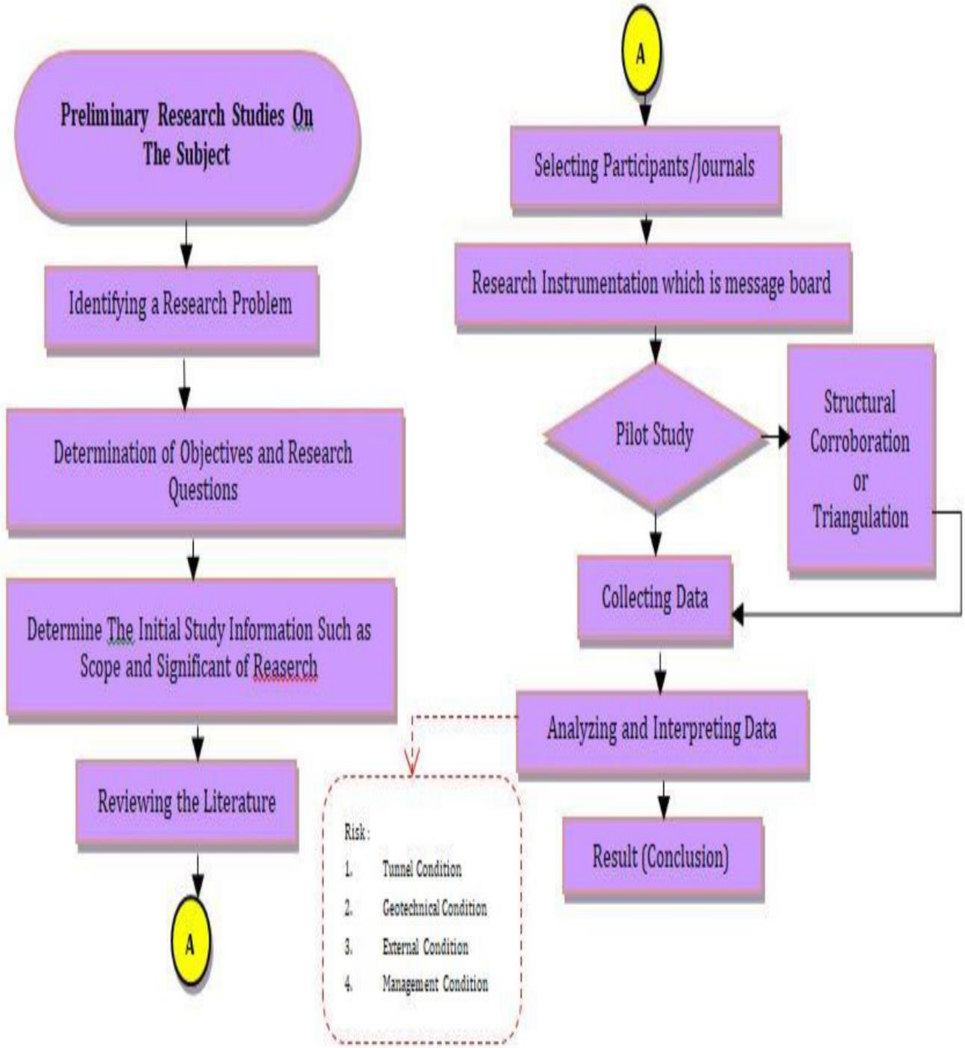

Fig. 1 Research Framework

The list of selected articles is analyzed from the aspect of risk identification in the tunnel construction project as shown in Table 1.

Table 1 Existing Literature review of Risk Identification in Tunnel in Construction Projects

No	Authors	Risk Identification				Result
		Tunnel Condition	Geotechnical Conditions	External Condition	Management Condition	
1	(F. Zhao et al., 2017)	v	v	x	x	In this study, the Bayesian method is proposed to decide the TBM type selection. The advantages and disadvantages of these three TBM (GTBM, SSTBM, DSTBM) are analyzed in detail. 80 cases which were excavated by TBM are collected to get the prior probability. In considering all the risks, the structure of the Bayesian Network model for TBM type selection is established
2	(T. Zhao et al., 2018)	v	v	x	v	This study investigated safety events of various severity levels in metro tunneling excavation. An original data set consisting of 243 event reports was compiled into a database of relevant events in metro tunneling excavation. The database was modular and fully structured, which could be further adapted and scaled to incorporate new reports and optimize analysis results.
3	(J. Zhou et al., 2017)	v	v	v	v	Risk-related regularities on defects of tunnels, obtained from past tunnel projects, is regarded as potential very helpful in risk management. A large amount of defects detection data for railway tunnels is collected in autumn every year in China. It is extremely important to discover the regularities knowledge hidden in database.

4	(H. Zhou et al., 2020)	v	v	v	x	The relationship between the quality and the risk was established using the 4M1E categories as the bridge to integrate the quality and risk measures so that risk could be better quantified by deterministic quality measures. Using D-S evidence theory and FME, the quality data were stratified and fused to avoid the subjectivity in the current expert scoring practices to assess risk.
5	(Jancarikova et al., 2017)	v	x	x	x	Conclusions from EMUT and calculation of the incident´s risk can identify the most common incidents and try to prevent them in the future. It is clear that the trend of increasing of traffic intensity as well as constantly increasing the number of incidents will continue in the upcoming years.
6	(Kembłowski et al., 2017)	v	x	x	x	The process of decision-making in public procurement of construction projects during the preparation and implementation phases ought to be supported by risk identification, assessment, and management. Typically once the risks have been assessed a decision-maker has to consider risk-management activities that minimise the risk events (mitigating factors).
7	(Qiu et al., 2020)	v	v	v	x	The generally regarded as an indicator of tunnel safety is the crack, they said it was one of the most common lining deteriorations. This study can provide a reference for the safety assessment of cracked lining tunnels in seismically active areas and help to determine the reinforcement measures and time more reasonably.

8	(Xue & Zhou, 2017)	v	v	v	v	There are two limits in this paper, on the one hand, managers need to be more rational towards failure, people pay too much attention to success, but unwilling to admit failure, fail to reverse thinking in risk identification. On the other hand, the study of failure knowledge is not perfect enough and it is difficult to quantify the issue. This paper is to put forward a method, much more quantitative work should be done for further study
9	(Andreotti & Lai, 2019)	v	v	v	v	The seismic risk of this kind of infrastructures is generally disregarded even if the post earthquake investigations have proven that tunnels are exposed to seismic risk because several degrees of seismic damage have been recorded. In this sense, a comprehensive risk analysis of mountain tunnels should include also the seismic risk.
10	(Baji et al., 2017)	v	x	v	v	The significance of this is that timely maintenance on components for identified failure modes has the potential to prevent catastrophic structural failures and hence extend the service life.
11	(Benekos & Diamantidis, 2017)	v	x	v	v	Safety measures shall be implemented also on the basis of cost-benefit and social acceptance considerations. Risk acceptance criteria need a broader appraisal and a periodic review based on the safety performance of the tunnels and on the current socio-economical situation.

12	(Borghetti et al., 2019)	v	x	v	v	These curves represent the societal risk, defined as the number of people who can be affected by a certain damage (in this case death). These curves are determined considering the number of people involved in the accident (event) and the duration of their exposure to the potential damage.
13	(Cao & Kalinski, 2017)	v	v	x	x	An assessment approach in terms of reliability indices is developed to predict the allowable design values and evaluate the ground movement by the displacement-controlled method.
14	(Chen et al., 2019)	v	x	v	v	In this paper, the isolation effect of dust masks in tunnel construction was taken into account for the first time, and the dust exposure concentration of workers was corrected by a unique formula according to the inward leakage (IL) and filtration efficiency (FE). The results showed that the isolation of masks obviously reduced the health risk, in which health risk was drastically reduced by 82% under ideal isolation effect and by 26% under actual isolation effect.
15	(Deng, 2018)	v	v	v	v	The construction of a super-long water-conveyance tunnel involves many aspects, such as geological disaster control and response, equipment operation and maintenance, construction safety, quality assurance, investment control, and environmental protection. A TBM geological prospecting system was established that could achieve real-time tracking and detection; if necessary, advanced geological drilling can verify geological situations and help to establish an emergency response plan.

16	(Dong et al., 2018)	v	v	v	v	This paper developed the KIM to visualize the safety knowledge flow in risk management. In the tunnel construction risk management, what safety knowledge was required, who owned it were highlighted by the KIM, and why was it hard to acquire was answered as the knowledge flow barriers were identified.
17	(Fabbri, 2019)	v	v	v	v	This article describes the management and allocation of risks, the procurement strategy, the adopted contractual models, contract and dispute management, and the financing model. These were some of the successful aspects that permitted the Gotthard Base Tunnel to be constructed in accordance with the agreed-upon level of quality, without exceeding the budget, and fully within the time schedule.
18	(Fu et al., 2017)	v	v	x	v	The first grade index “shield launching and arrival stage” is taken as the example to make the risk assessment in this study. There are 10 sub-indexes in shield launching and arrival stage. The expert discussion group is composed of tunnel engineering experts, technical personnel from research institutes, technical personnel from designing institutes and technical personnel from project departments.
19	(Jiang et al., 2019)	v	v	v	x	A quantitative health inspection and assessment system is proposed. Acquisition of a lining surface image with a resolution of 0.5 mm/pixel improves the precision of crack detection.

20	(Kouchami-Sardoo et al., 2019)	v	v	v	v	Bayesian Belief Networks (BBNs) provide a useful approach to address real-world problems, where available data and knowledge are disparate, limited or uncertain. The results showed that weather and management factors were the most important parameters affecting wind erosion risk.
21	(Lei et al., 2011)	v	v	v	v	Significant progress has been made for the risk management of tunnel collapse. During the advancement of excavation, a combined use of analytical (probabilistic) and numerical methods is probably the most efficient approach to check continuously the actual conditions encountered and apply the counter-measures in a timely manner, which should have a wider application in collapse risk assessment and management.
22	(Lin et al., 2020)	v	v	x	x	Water inrush disaster seriously affects the safety of karst tunnel construction. It is essential to assess the risk level of water inrush in karst tunnels accurately, and take some effective countermeasures to reduce the damage to the project.
23	(Wenli Liu et al., 2018)	v	v	v	v	The sensitivities of input variables to different output para- meters are apparently discrepant, and the crucial input variables with high GSI (e.g., X1, X3, X4, X5, X7, X8, and X9) need to be exactly controlled and managed during the tunnel operation, which helps to reduce the tunnel responses and risks. Then, decision making from the results of sensitivity analysis can help enhance the knowledge of de- signers and aid them to optimize the design or management scheme of the tunnel operation when confronting similar tunnels.

24	(Lundin & Antonsson, 2019)	v	x	x	v	In this paper a flexible approach is proposed to assist the competent authority to characterize the decision-problem with regards to the major risk aspects, making it possible in some cases during to be able to justify a decision of tunnel category with alternative approaches to a QRA. Furthermore, in addition to the framework a simple risk analysis approach based on the prescriptive Swedish requirements for road tunnels is developed and presented. With this method an appropriate tunnel category can be derived by the competent authority with less resources and competence compared to make a complete QRA.
25	(Maruvanchery et al., 2020)	v	v	x	v	The present study presents the risk assessment and evaluation of early time and cost predicting tools for large-scale underground cavern projects. Underground construction is always associated with inherent risks due to limited knowledge of existing geological conditions prevailing at the site as well as because of other uncertainties. These projects involve multiface excavation for large volume caverns. The results show that the outputs agree well with the actual construction time in Project A and can predict construction cost and time at the 95% confidence level.

26	(Ntzeremes & Kirytopoulos, 2019)	v	v	v	v	Due to the tunnels' complexity, important parameters for the safe operation of tunnel systems have significant uncertainty. These parameters include: (a) the traffic, (b) the trapped users behaviour during evacuation, (c) the response of the tunnel personnel in activating the mechanical ventilation or the traffic interruption, (d) the fire behaviour and (e) the environmental conditions.
27	(Ntzeremes et al., 2020)	v	x	v	v	With a view to enhance road network's safety, it is crucial to focus primarily on its critical infrastructures, one part of which is tunnels. Bearing in mind that trapped-users' performance can strongly determine a tunnel's level of safety, this paper proposes an evacuation simulation model for increasing the efficiency of quantitative risk assessment.
28	(Pan et al., 2019)	v	x	v	v	This research contributes to (a) the state of knowledge by integrating Bayesian networks with copula, contributing to a more robust risk assessment by accurately modeling the complex dependence structure of risk factors; (b) the state of practice by providing guidelines of the whole-life-cycle safety control for complex systems under uncertainty and randomness, which not only prevent structural failure in advance but also control risk after accident occurrence.

29	(Providakis et al., 2019)	v	v	x	v	Ground settlements caused by tunnelling excavations are particularly important in urban areas, with greater relevance in soft soils. Estimating the settlement risk to adjacent buildings is an important consideration for tunnel planning, design and construction. An example case study of such a system is provided to illustrate the methodology, and thereby demonstrates both that adjustments to the location (alignment) of the tunnel can have a major impact on the risk of settlement-related damage.
30	(Cerić et al., 2011)	v	x	x	v	Risk identification follows project phases. For each identified risk in a particular phase it is necessary to determine risk probability and risk impact, and calculate the corresponding risk exposure.
31	(W. Wang & Fang, 2017)	v	x	v	v	At the meantime, the risk management is the key to the success of the project. This paper is based on questionnaire survey to identify the risk factors of utility tunnel project in PPP mode, and uses SPSS 19 to test the reliability of the questionnaire.
32	(Z. Z. Wang & Chen, 2017)	v	v	v	v	Metro construction is typically a highly complicated project associated with various potential risks. Safety risk analysis and management of metro construction have attracted broad attention because of their close relationship to public safety.

33	(F. Wang et al., 2019)	v	v	v	v	Knowledge capture and reuse are critical in the risk management of tunneling works. This study applies non-parametric BNs, which only require the elicitation of the marginal distribution corresponding to each node and correlation coefficient associated with each edge, to develop a knowledge-based expert system for tunneling risk analysis.
34	(Xiong et al., 2018)	v	v	v	v	Because it is difficult to determine adverse geological conditions along a tunnel in the early stages of construction, 3D geological modeling often lacks sufficient borehole or section data.
35	(Xu et al., 2015)	v	v	v	v	This paper proposes a fuzzy analytic network process to evaluate the risk for Beijing subway tunnel construction using NATM. Firstly, the risk breakdown structure (RBS)–work breakdown structure (WBS) was introduced for risk identification and 5 major risk factors of the construction projects were identified. The risk control system was shown to be effective and ensure the success of tunnel excavation.
36	(Y. Zhang et al., 2019)	v	v	v	v	This paper, with the aim of predicting, monitoring, and diagnosing risk factors for tunnel-induced damage, provides a new framework that integrates the advantages of rough set (RS), cloud model (CM), and Bayesian network (BN). This research contributes to (a) the state of knowledge by providing a novel risk analysis approach that is capable of handling fuzziness, uncertainty, and dynamics in factor characterization; and (b) the state of the practice by providing insights into a better understanding of how to predict, control, and diagnose risks under given observations.

37	(X. P. . Zhou et al., 2017)	v	v	v	v	To account for the perspectives of all parties involved in mechanical tunneling projects, we consulted previous literature and engineering practices to compile a questionnaire, and data were collected from the survey to distill information for the variables of interest.
38	(Fortunato et al., 2012)	v	v	v	v	This finding served as the impetus for the present study, which aimed to identify and evaluate the safety and health risks associated with the design elements and construction management practices implemented to achieve LEED certification.
39	(S. Zhang et al., 2019)	v	v	v	v	Many potential and uncertain safety risk factors must be identified during these types of projects. Therefore, a model is proposed to conduct safety risk identification and improve decision quality
40	(Yu et al., 2017)	v	v	v	v	A probabilistic risk analysis method of diversion tunnel construction simulation is proposed. It enables comprehensive and effective risk analysis of tunnel construction by considering both ordinary risk factors and risk events, which facilitates accurate estimation of construction schedule and effective development of schedule plan.
41	(Hu & Huang, 2014)	v	v	v	v	The purpose of two documents is to indicate to owners what is recommended industry best-practice for risk management and present guideline or code to designers as to the preparation of a comprehensive tunnel risk management system in China.

42	(Pennington & Richards, 2011)	v	v	v	v	Tunnels represent some of the most demanding civil engineering projects due to the inherent uncertainty of the ground and the requirement to accurately predict ground behavior in advance of construction, and related risk consequences in construction.
43	(Fouladgar et al., 2012)	v	v	v	v	The main purpose of this paper is to propose a risk evaluation approach of the problems that might be encountered during tunneling operation.
44	(Klein & O'Carroll, 2017)	v	v	v	v	This is mainly due to the inherent uncertainty involved with geologic conditions and our limited ability to accurately predict geotechnical conditions in advance of construction.
45	(Bai et al., 2014)	v	v	v	v	Application of the proposed multiphase risk-management method is illustrated with a case study, which shows that the most appropriate and economical risk-management method can be achieved and the established objectives of construction quality and timeline can also be ensured;
46	(Teetes et al., 2017)	v	v	v	v	The concept of risk management is based upon prioritizing uncertainty based on the likelihood of risks to occur and the severity of the consequences of those risks. A qualitative risk assessment and analysis focuses on raising the awareness of all concerned to the major risks involved in the design and construction and providing a structured basis for actions to mitigate these risks.

47	(X. P. . Zhou et al., 2017)	v	v	v	v	The 15 risk factors faced by the PPP pattern in the underground comprehensive utility tunnel project are distributed at five levels, and there is a progressive relationship between the various levels of factors. The high-risk factors are affected by the low-level factors.
48	(Wen Liu et al., 2018)	v	v	v	v	The results enlightened on the understanding of the interactions and causal relationships between risk factors in mechanical tunneling, and provided a guideline for improving safety management.

Remarks: v=discussed x=not discussed

Based on the analysis of the contents of the 48 journals in the above table, it was found that the aspect of risk in tunnel construction that has the highest percentage is project risk.

Table 2 The recapitulation of selected journals analyzed

Tunnel Condition							
1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
Soil Geotechnical Condition							
1	2	3	4	7	8	9	13
15	16	17	18	19	20	21	22
23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38
39	40	41	42	43	44	45	46
47	48						
External Condition							
3	4	7	8	9	10	11	12
14	15	16	17	19	20	21	23
26	27	28	31	32	33	34	35
36	37	38	39	40	41	42	43
44	45	46	47	48			
Management Condition							
2	3	8	9	10	11	12	14
15	16	17	18	20	21	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48

Remarks:

= Risk Identification = Research Journals

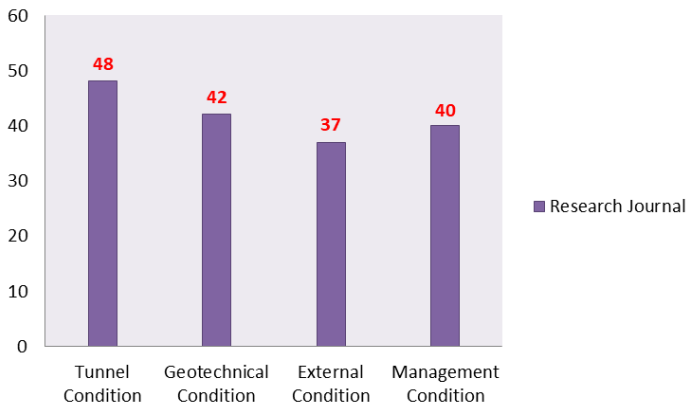

Fig 2. List of Journal's Risk Conditions

3. Result and Discussion

3.1. Tunnel Condition Risk

Generally when mechanized excavation is selected as the construction method, the most important problem is related to selection of the most appropriate TBM and its performance prediction in each geotechnical conditions (F. Zhao et al., 2017). It must be emphasized that there are numerous risk factors in metro tunneling excavation, and it is impossible or unnecessary to exhaustively analyze every risk factor(T. Zhao et al., 2018). Hence, in this research, risk factors were screened and consolidated, such that (1) easily identifiable and manageable risks were excluded (e.g., product quality issues, grout concentration, location of discharge, etc.), (2) risk factors with low probability and no catastrophic consequences were dismissed (e.g., sudden outage of water or electricity, suspended engineering, etc.), and (3) risk factors with different causes but similar consequences were combined (e.g., working face instability was considered as one single risk factor regardless of whether the root cause was sand, soil geology, or confined water) (T. Zhao et al., 2018). Tunnels with different structures may suffer different defects, because they have their own characteristics with various types of materials, geologies, environments, etc. Different defects lead to different potential failures(J. Zhou et al., 2017). Tunnel management and maintenance should pay attention to these kinds of tunnel structures(J. Zhou et al., 2017). The current practices in risk assessment and management have three limitations that have become the major barriers to their adoption in managing the risks in undersea tunneling projects (H. Zhou et al., 2020).

Modern tunneling construction typically uses a tunnel boring machine (TBM), which is a shield machine that can achieve a high-level of mechanized construction to improve productivity and enhance safety (H. Zhou et al., 2020). The tunnels are specific engineering structures, which are constructed in order to shorten transport routes and improve road safety (Jancarikova et al., 2017). Previous studies mostly analyzed concrete tunnel lining in linear elasticity (Qiu et al., 2020). Through monitoring the internal force such as axial force and bending moment of structures, the possible location of cracks and the failure state of linings can be determined (Qiu et al., 2020). The risk identification of shield tunnel construction based on failure knowledge is a complement and perfection to the existing risk identification methods (Xue & Zhou, 2017). Managers need to increase the weight of known risk factors identified from the failure project, and incorporate the unknown risk factors into the system of the existing risk factors (Xue & Zhou, 2017). The explosion-proof lamp as the change tool for the blade is an unknown risk factors (Xue & Zhou, 2017).

Although tunnels are usually less vulnerable than above-ground structures, the seismic risk may actually be greater since a minor damage may still result in great losses (Andreotti & Lai, 2019). In particular, as discussed more in detail in the first case study presented hereinafter, tunnels are part of a wider network and even a small damage to a single component (e.g. waterproofing system) may compromise the serviceability of the whole network (Andreotti & Lai, 2019). The tunnel is an essential infrastructure that plays a pivotal role in transportation network, economy, prosperity, social well-being, quality of life and the health of its population (Baji et al., 2017). From the tunnel system that can cause a variety of potential deficiencies such as seepage, cracking, delamination, drainage, convergence and settlement of the layer structure can cause catastrophic failures and economic losses (Baji et al., 2017). Most collapses of tunnel structures in the world are related to tunnel deterioration with catastrophic consequences (Baji et al., 2017). The accident of tunnel case cannot be easily identified. There are several factors influencing the accident rate in a road tunnel such as traffic volume, tunnel configuration, gradient, driver education, dimensions and alignment, lighting conditions, etc (Benekos & Diamantidis, 2017). Identification of the possible dangers connected with the tunnel system (Borghetti et al., 2019). Safety in tunnels can be improved through actions concerning infrastructures, equipment and management procedures (Borghetti et al., 2019). The identification and evaluation of these provisions requires an analysis that can make the costs and benefits of each action emerge, so that a choice (decision) can be made on the effectiveness, priority and sequence of actuation of these safety measures (Borghetti et al., 2019).

In the study, the risk factors include: (i) soil shear strength; (ii) the ground water table; (iii) concrete lining segment strength; and (iv) pile bearing capacity (Cao & Kalinski, 2017). This paper presents a risk analysis of shield tunneling construction based on the computational results from three-dimensional simulation of two metro system projects in China (Cao & Kalinski, 2017). With a quantitative approach for evaluating risk factors in shield tunneling construction is investigated with the concern of ground movement (Cao & Kalinski, 2017). Risk factors influence the safety of shield tunneling construction at each stage (Cao & Kalinski, 2017). In this paper, a health risk assessment model in the field of public environmental health was employed to quantitatively assess the occu- pational exposure of tunnel construction workers (Chen et al., 2019).

Tunnel safety is defined like a safety and protection of persons, property, and surround of structure, which is given by result of risk evaluation, solution reasoning in point of risks, fire-safety structure solution and solution of structure influence on environment, protection of monuments, nature and countryside (Schlosser et al., 2014). The main differences between urban road and highway tunnels lie in the characteristics of limited plane wiring , diversified cross section, high standard of fire and ventilation design, high requirement of tunnel entrance landscape , and high utilization rate (B. Zhou et al., 2020).

The principal risks (or hazards) to the safety in tunneling can be identified as follows (Lei et al., 2011): (1) Unforeseen or unexpected ground conditions; (2) Variable and mixed face conditions (fine sand layer); (3) Ground loss/collapse at the face, causing inundation and/or large settlements; (4) Man-made obstructions or hazards to tunneling, including utility services and unexploded bomb; (5) Human errors. Three factors of tunnel structure may disturb the surrounding excavation environment, such as the cover-span ratio (C1), covering depth (C2), and tunnel diameter (C3) (Y. Zhang et al., 2019).

3.2. Geotechnical Condition Risk

Human errors have recurrent patterns and typically include poor technology, slack management, and inadequate hazard handling. Natural causes of accidents in mechanical tunnel excavation include adverse hydrogeological conditions, groundwater, heavy rainfall, soft soil layers, etc (Wen Liu et al., 2018). With regard to mechanical tunnel excavation, it was found that only 10% of the accidents could be completely attributed to natural causes, whereas 30% of accidents resulted purely from human errors and 60% of accidents occurred because of the combination of human mistakes and natural mishap (Wen Liu et al., 2018). In fact, challenging geological conditions ranked only as the second biggest risk factor in the analysis, although geological conditions have been traditionally considered the topmost source of accidents in metro tunneling excavation (T. Zhao et al., 2018). Due to it is not conductive to our studies, the geological classification method based on the firmness and density of the rocks and soils is applied into this study (J. Zhou et al., 2017). As the shield machine drills through the underground space, the high water pressure, complex geological conditions, and pore water trapped in unstable rocks can cause water seepage and gushing that can result in devastating accidents on a large scale (H. Zhou et al., 2020). As such, in setting the range for the blade speed measure of the driving parameters of the shield machine risk factor, the difference between the actual speed and the control speed, which is determined based on the geological environment and site conditions rather than the actual speed, is used to incorporate the cross-category influences of the risk factors (H. Zhou et al., 2020). The design data and geological investigation indicate that the ground formation which the tunnels pass through is mudstone mixed with sandstone, and the upper stratum to the surface is silt and silty clay with a thickness of about 0–3 m (Qiu et al., 2020). Due to the specificity of hydrogeological conditions as well as the selection and operation of shield machine in the construction of shield tunnel, the risk identification of shield tunnel must be combined with the construction process, this is called the dynamic process of risk identification (Xue & Zhou, 2017). Even when the seismic action is not a critical issue (e.g. tunnels located in zones of low seismic activity), the design of mountain tunnels is generally associated with a high level of risks due to a whole series of uncertainties involved (e.g. complex geological environments, limited data, difficult topographical conditions, sophisticated construction technology) (Andreotti & Lai, 2019). There are risk factors in the construction of protective tunnels by investigating the mechanism of ground movement and developing an index system for stability with respect to land settlement, including spatial conditions of the nearest infrastructure and geotechnical conditions at the construction site (Cao & Kalinski, 2017). The geotechnical challenge is to understand the ground movement mechanism around the tunnel associated with the disturbance of in-situ soil in the longitudinal direction and the reconsolidation with varied pore pressure in the transverse distribution (Cao & Kalinski, 2017). The most commonly encountered geotechnical risks for tunnels are (Pennington & Richards, 2011): (1) Excessive or unexpected groundwater inflow, (2) Unstable ground or unanticipated ground behavior, (3) Limited response capability due to confined working environment, (4) Poor judgment or error in design, (5) Incompatible selection of means and methods, (6) Poor on-site management and communication, (7) Control.

3.3. External Condition Risk

Due to lack of sufficient data, this study has just considered the potential risks of defects resulted from tunnel structures (J. Zhou et al., 2017). However, other factors caused by environment, management, operation, disaster and so on should also be taken into consideration (J. Zhou et al., 2017). This paper highlighted the important effect of the longitudinal cracks in the permanent lining on the seismic capacity of tunnels by a modified deformation-based pseudostatic analysis (Qiu et al., 2020). This analysis employed a reconstructed damaged plasticity constitutive model of reinforced concrete to simulate the propagation of lining cracks (Qiu et al., 2020). The risk factors that caused the failure of the project which are reverse identified by FCTA approach (Xue & Zhou, 2017). According to the analysis above, the improper use of explosion-proof lamp as the change tool for the blade is the risk factor, the harmful methane gas and the shortage of security intention, together led to the occurrence of the explosion (Xue & Zhou, 2017). The seismic risk of this kind of infrastructures is generally disregarded even if the post-earthquake investigations have proven that tunnels are exposed to seismic risk because several degrees of seismic damage have been recorded (Andreotti & Lai, 2019). Implementation of the proposed maintenance strategy to a case study tunnel confirms the applicability of the strategy in maintenance of tunnel structures (Baji et al., 2017). In assessing risk the uncertainties of the influencing parameters is of major importance and should be dealt with (Benekos & Diamantidis, 2017). Risk in itself cannot be accepted unless compared with the benefit it brings (Borghetti et al., 2019). Risk acceptance is a very complex matter that has been studied evenby sociologists and psychologists, because it involves aspects tied to perception, level of instruction, social status and religion (Borghetti et al., 2019). These curves represent the societal risk, defined as the number of people who can be affected by a certain damage (in this case death) (Borghetti et al., 2019). These curves are determined considering the number of people involved in the accident (event) and the duration of their exposure to the potential damage (Borghetti et al., 2019).

Remarkable achievements have been made in TBM tunneling in many projects; however, the risk of frequent accidents cannot be eradicated, for the following reasons (Deng, 2018): (1) **Lack of perception.** A TBM lacks scientific methods and effective means to quickly perceive information about the surrounding rocks and the operating conditions of its equipment and key components; therefore, feedback between the rock and the machine is delayed, (2) **Lack of decision-making.** Due to a lack of tunneling evaluation and of effective means to make intelligent decisions, practical tasks mainly rely on human experience rather than on scientific bases. This shortcoming may result in low efficiency and resource waste, and may furthermore lead to serious incidents such as collapse and machine blockages, (3) **Lack of a platform.** Due to the lack of a necessary platform for information exchange and analysis, massive information on TBM tunneling is not saved and analyzed effectively. It is also urgently necessary to develop the use of information technology, the Internet of Things, big data and intelligent algorithms, and other key technologies in TBM construction projects, in order to achieve innovative breakthroughs in platform establishment.

3.4. Management Condition Risk

Many inherently risky industries improve their safety management by learning from near-miss incidents (T. Zhao et al., 2018). The construction industry is starting to manage incidents that can result in work accidents and improve safety, and several studies have been carried out to introduce systems to manage incidents that can result in work accidents during construction (T. Zhao et al., 2018). Risk management has become one of the most important tasks in construction management (Xue & Zhou, 2017). The most important purpose of risk management is to reduce the probability of risk occurrence and mitigate the impact of risk, therefore, most of the existing literatures focus on risk control, and the risk response measures from the perspective of the owners, contractors and subcontractors (Xue & Zhou, 2017). Traditionally, risks have been managed indirectly through the engineering decisions taken during the design and construction phases (Andreotti & Lai, 2019). This way of doing translates into a non- objective evaluation of the risks and a nonscientific risk management (Andreotti & Lai, 2019). On the other hand, the systematic risk assessment and management techniques can be used to control the risk level within an acceptable range (Andreotti & Lai, 2019). The significance of this is that timely maintenance on components for identified failure modes has the potential to prevent catastrophic structural failures and hence extend the service life (Baji et al., 2017). It can be concluded that the proposed framework can help tunnel operators and asset managers develop a risk cost optimised maintenance strategy for tunnels under their management (Baji et al., 2017). From this perspective, risk analysis can be seen as a useful instrument for supporting decisions when evaluating the safety of the tunnel system, identifying those infrastructure, equipment and management procedures which guarantee greater benefits in terms of expected risk reduction and at the same cost (Borghetti et al., 2019). Safety in tunnels can be improved through actions concerning infrastructures, equipment and management procedures (Borghetti et al., 2019). Considering, for example, the societal risk associated with a road tunnel, mitigation through the introduction of measures (related to infrastructure, equipment and management procedures) must be compared with the possible expected advantages (benefits), for example the reduction in travel time, road accidents, atmospheric and noise pollution (Borghetti et al., 2019). Technical personnel safety management is a known risk factor, but it is not implemented in place, it is necessary to increase their weight in the assessment of risk factors (Xue & Zhou, 2017).

Construction management: According to the project reports, it was not likely to have sufficient time for design and technical review (Lei et al., 2011). Strong and urgent social demand for the release of traffic congestion urged decision makers to hurry, which in turns engineers and construction workers involved in the project urged to hurry (Lei et al., 2011). The over-demand and insufficient time affected normal civil engineering process considerably (Lei et al., 2011). These situations were unfavorable in performing safe construction (Lei et al., 2011).

3.5. Result

Table 3 Mapping research journals based on risk factor

Factor	Research Journal
Tunnel Condition Risk	
Cover-span ratio	36
Covering depth	36 41 42 43 44 45 46 47 48
Tunnel diameter	1 2 3 4 15 36
Geological Condition Risk	
Soil quality	36 41 42 43 44 45 46 47 48
Friction angle	1 2 3 4 17 36
Compression modulus	36
Soil cohesion	20 36
Poisson ratio	36
Soil Density	20 36 41 42 43 44 45 46 47 48
Factor	Research Journal
External Condition Risk	
Relative stiffness	36
Bridge intact conditions	36 41 42 43 44 45 46 47 48
Structure configuration	36 41 42 43 44 45 46 47 48
Current condition	1 2 3 4 15 20 36 41 42 43
Tunnel diameter	20 44 45 46 47 48
Friction angle	36
Management Condition Risk	
Rate of soil loss	36
Construction method	36 39
Management level	36 39

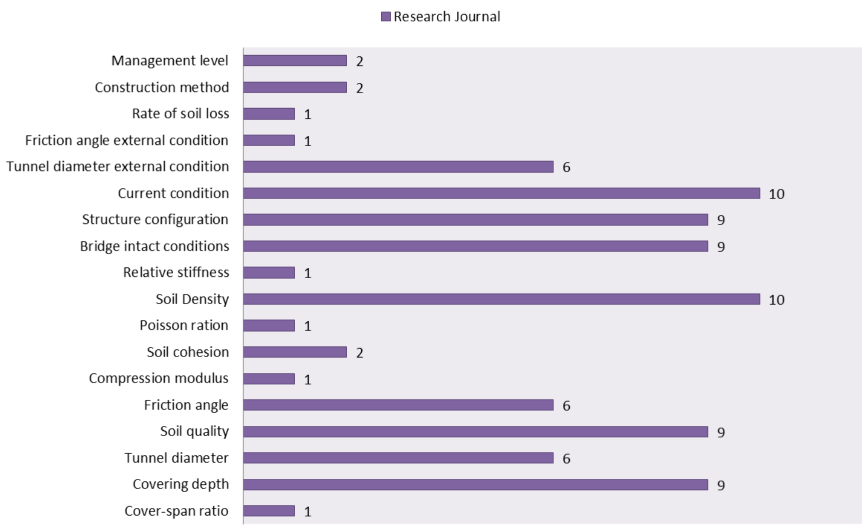

Fig 6. Bar charts of Factors Risk Conditions

Based on a compilation of available literature, a list of risks is compiled along with the boundary criteria based on the factor of influence on potential hazards as shown in Figure 7.

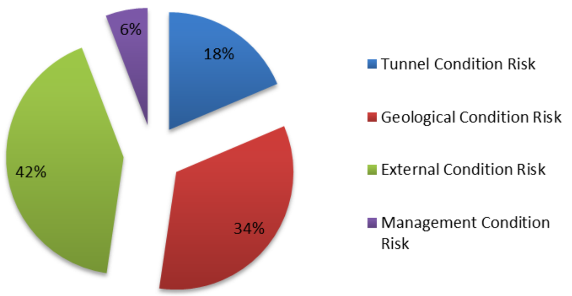

Fig 7. Risk Criteria Factor of Influence on Potential Hazards]

4. Conclusion

Every construction project is always faced with the possibility of various occurrence kinds of risks. The higher the level of complexity of a project, the greater the level of risk that might happen to the project. Risk Identification process includes activities that identify potential risks that might occur in a project. In general the risks that must be considered in road tunnel planning consists of: Unstable slopes or rocks falling on road alignments and tunnel portal, Problems with construction through fault zones, low rock mass strength, lack of stability and compression conditions, Potential environmental effects, such as deterioration and vibration, Changes in the face of natural water, water entering into excavation work, Rock cavity, Earthquake load, Tunnel length, Number of parallel tunnels and number of lanes, Tunnel cross section geometry, Vertical and horizontal alignment, Structure type, Directional or two-way traffic, Traffic volume of each tunnel (including distribution time), Risk of congestion (daily or seasonal), Access time for emergency services, Number and percent of heavy transport vehicles, The amount and percent of types of traffic that transport dangerous goods, Characteristics of access roads, Tunnel entry points and exits, Lane width, Speed of plan, Geographical and meteorological environments, Special characteristics, for example the location of the tunnel is under water or under buildings.

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IDENTIFIKACIJA RIZIKA U PROJEKTIMA IZGRADNJE TUNELA: PREGLED LITERATURE

Svaki građevinski projekt uvek je suočen s mogućnošću raznih vrsta rizika. Što je nivo složenosti projekta veći, to je veći nivo rizika projekta. Na osnovu istorijskih podataka izgradnje tunela zabeleženi su mnogi problemi, pa čak i neuspesi u izgradnji tunela uzrokovani raznim faktorima koji imaju uticaj na kašnjenje projekata. Očekuje se da će upravljanje rizicima smanjiti negativni uticaj rizika na građevinske radove. Kod izgradnje tunela potrebno je upravljanj visokim rizikom, pa je neophodno identifikovati rizike koji mogu minimizovati loše rizike. Očekuje se da će upravljanje rizikom smanjiti negativne efekte rizika sa kojima se suočavaju građevinari, i potrebno je sprovesti identifikaciju rizika kako bismo upravljali rizicima s kojima ćemo se suočiti. Da bismo uspešno poboljšali izvođenje projekata tunela, moramo identifikovati različite faktore rizika u projektu radi efikasnog ostvarenja projekata. Metoda istraživanja započinje opsežnim pregledom literature i pregledom najmanje 48 časopisa u preglednim člancima kako bi se pružila lista glavnih faktora rizika koji se takođe dodaju ekspertizi kako bi se postigla lista konačnih faktora rizika koji sadrže sve rizike koji se mogu susresti tokom izgradnje puta. Ova analiza uključuje identifikaciju, klasifikaciju različitih rizika koji su uključeni u izgradnju projekta izgradnje tunela.

Ključne reči: *rizik, izgradnja tunela, projekt tunela, identifikacija rizika*

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TRIANGULAR DISTRIBUTION AND PERT METHOD VS. PAYOFF MATRIX FOR DECISION-MAKING SUPPORT IN RISK ANALYSIS OF CONSTRUCTION BIDDING: A CASE STUDY

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Abstract. *Decision-making in construction bidding represents a complex process due to the present risk. Risk or uncertainty cannot be ignored and should be treated as a constituent of decision-making. The paper aims to emphasize the importance of probability theory by comparing insufficiently applicable methods in practical bidding. The triangular distribution and the PERT method belong to three-point estimate techniques, while payoff matrices represent a multi-criteria approach. Also, selected methods belong to quantitative techniques for risk cost analysis. Still, the risk costs determination of the unit costs and the total costs of bids is often based on an intuitive approach. Therefore, compared results of the triangular distribution, PERT method, and payoff matrix techniques (minimin, minimax, expected monetary value, and expected opportunity loss) indicate the significance of risk costs estimating in tendering. The analysis of the results showed some overlaps in risk costs values obtained by the PERT method and expected monetary value technique. Those are due to the specificity of the chosen practical example and cannot be adopted as a rule. This means that selected methods and techniques are very useful for all bid estimation. The paper proved the complexity of decision-making, where the primary goal is to award a contract.*

Key words: *bidding, risk, cost, unit cost, total cost, bid price*

1. INTRODUCTION

Bidding represents a complex process in the construction industry due to a significant number of factors that affect uncertainty and risks in decision-making. The uncertainty consideration in cost estimation benefits all parties involved in a tendering and contract realization. Cost risk and profit estimating must be considered in terms of the contract's specificities and the types of bill of quantities. Unit price contracts are the most commonly used in developing countries. However, all construction contracts based on unit prices have

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some parts with lump-sum items [1] - [3] Risk assessment in the bidding phase can be performed by quantitative and qualitative techniques. Quantitative techniques do not analyze risks mathematically in assessing the probability of occurrence. Instead, those use a professional approach to arbitrate the likelihood and impact on cost risk [0]. In addition, quantitative risk analysis provides a cost for each bill of quantity items. Also, it uses different techniques for cost risk applying in the bidding phase. Quantitative risk analysis in construction project management consists of three basic types [4]:

- technical performance analysis
- schedule risk analysis
- cost risk analysis

Therefore, the subject of this research is the comparative cost risk analysis that investigates the risk related to the unit cost of items from the bill of quantity. The comparative analysis was performed with the triangular distribution method, PERT method, and payoff matrix.

Construction contracts for projects like highways, railways, and other infrastructure are mostly complex and based on unit prices. This means each item from the bill of quantity is assigned with a specific unit price. The unit price consists of unit cost and profit. Besides, unit costs contain labor costs, material costs, construction machinery costs, and indirect costs. The unit cost estimation precedes the harmonization of construction norms, labor costs, and construction machinery costs per hour. Also, construction norms harmonization is in correlation with the project's specificity. Besides, this process directly affects unit costs and potential risks. Thus, construction norms and costs per hour were denoted as follows:

CNL - labor norm; hour per unit (h / (m^2, m^3, t, ...))
CNM - material norm; hour per unit (h / (m^2, m^3, t, ...))
CNCM - construction machinery norm; hour per unit (h / (m^2, m^3, t, ...))
CHL - labor cost; monetary per hour (€ / h)
CHM - material cost; monetary per unit (€ / (m^2, m^3, t, ...))
CHCM - construction machinery cost; monetary per hour (€ / h)
IF - indirect cost factor (project + company)

It is important to emphasize that capacity - q - is inversely proportional to the norm, i.e., q = 1/CN [5]. Based on the above mentioned, item unit costs - most likely - in the bill of quantity according to Eq. 1 are:

$$UC_i = (CNL_i \times CHL_i + CHM_i + CNCM_i \times CHCM_i) \times (1 + IF_i), \quad (€ / (m^1, m^2, m^3, t,...)) \tag{1}$$

According to Eq. 2, the total cost of an item is:

$$C_i = UC_i \times Q_i \qquad i = 1, 2, ..., n \tag{2}$$

Where:
Q_i – Quantity of an item (m^1, m^2, m^3, t,...)
n – Number of the bid items
According to Eq. 3, the total bid costs - BC - are:

$$BC = \sum_{i=1}^{n} C_i \tag{3}$$

According to Eq. 4, the final bid price - BP - consists of the total costs, increased by the profit rate - P -, and VAT.

$$BP = BC + P + VAT \tag{4}$$

The bidders can choose different profit rates of bid items after unit costs estimation. Also, an equal profit rate can be added to each item or group of items.

The contractor's relation to bidding risk is still based on the harmonization of the input cost with the project's specificity. In addition, contractual clauses are a substantial part of risk management and decision-making. It means that despite the norm harmonization, and the stated unit costs, variations are still present in estimating [5]. This problem can be solved by probabilistic methods, although resistance is still present in the practice bidding. Nevertheless, potential contractors began applying optimistic and pessimistic costs in the bidding phase. It means that unit costs were intuitively estimated (optimistic, most likely, and pessimistic). Such an approach led the author to analyzes and compares unit costs by applying probabilistic estimation methods in decision-making.

Variations frequently occur within the estimated construction norms due to insufficiently detailed geomechanical parameters and uncertain availability of construction components and systems. These variations directly affect unit costs and profit (unit prices). Whereas contractors still use deterministic techniques in estimating unit costs, an application of a triangular estimation and PERT method (Three-Point Estimate) can simplify the decision-making. Payoff matrices can also simplify the decision-making under cost variations and for an altered state of nature.

Methods choice was influenced by the traditional aversion to the application of probability theory in project management. Also, cost estimation methods are chosen for comparison and analysis and do not require special software and complex staff training.

2. Selected Literature Review

A three-point estimate is a valuable technique for cost risk estimation. This estimation technique involves the cost selection based on optimistic, pessimistic, and the most likely values. Two commonly used three points estimates are based on the triangular and beta distribution (PERT) [6] - [8].

The triangular distribution is commonly used as a subjective description with limited sample data. It is based on lower limit data, mode, and upper limit data. Also, the triangular distribution possesses the possibility of choosing a confidence interval, where the upper and lower limits can be exceeded within a predefined percentage [9] - [12]. The triangular distribution technique for the cost risk analysis was proposed first by J. M. Neil (1982) [13]. Also, one of the estimation techniques suggested in the Project Management Body of Knowledge (PMI) is the three-point estimate based on the triangular and beta distribution – PERT – method. Furthermore, the triangular probability distribution was used as a substitution for the normal distribution [13].

It is important to emphasize that the area under the triangular distribution represents the probability of the cost occurrence. Therefore, decision-making for each bid item and the total cost of the bid consists of four steps [13], [14]:

- estimating optimistic cost (o), pessimistic cost (p), and most likely unit costs (m) according to Eq. 1
- probabilities of project costs
- cumulative probabilities of unit costs
- finding the bid costs

Comparing obtained costs with associated probabilities to the general expression for three-point estimation of triangular distribution can be very practical and useful (Eq. 5) [15]:

$$C_i = (o_i + p_i + m_i)/3 \tag{5}$$

The PERT is a useful technique for cost risk estimating in bidding. Although developed for the American Polaris missile program in the 1947s, this technique has found application in all scientific areas for assessment of various data. The characteristic of this technique is basing on a beta distribution and an optimistic, pessimistic, and most likely assessment (time, cost risk). Also, PERT uses the Central Limit Theorem (CLT) for estimating cost risks with associated probabilities. The cost estimate of the bill of quantities items is determined, according to Eq. 6 [15] - [17].

$$C_i = (o_i + 4 \times p_i + m_i)/6 \tag{6}$$

C_i is estimated cost; o = optimistic estimate; p = pessimistic estimate; m = most likely estimate.

The standard deviation is determined, according to Eq. 7:

$$SD_i = (p_i - o_i)/6 \tag{7}$$

SD represents the standard deviation; p = pessimistic estimate; o = optimistic estimate**.**

Unit costs decision-making for each bid item, and the total cost of the bid consists of four steps [18] - [20]:

- decompose the project into items (bill of quantity)
- estimate the UC value and SD for each item
- calculate the BC value for the total project according to Eq. 3
- calculate the SDP value for the total project according to Eq. 8,

$$SDP = \sqrt{\sum_{i=1}^{n} SD_i} \tag{8}$$

The EC and SD values are used to convert the project estimates to confidence levels as follows:

- the confidence level for EC value +/-1.000 × SD is 68.27%
- the confidence level for EC value +/-1.150 × SD is 75.00%
- the confidence level for EC value +/-1.645 × SD is 90.00%
- the confidence level for EC value +/-2.000 × SD is 95.45%
- the confidence level for EC value +/-3.000 × SD is 99.73%

Given that multicriteria approaches are rarely used in practical cost estimation, payoff matrices can be a valuable tool for problem-solving with uncertainties [21] - [23]. This technique consists of five different strategies: finding the maximin or minimax, maximax or minimin, minimax regret, expected monetary value (EMV), and expected opportunity loss (EOL) of each item, and a total bill of quantities [24], [25]. Also, decision-making using payoff matrices consists of determining decision alternatives and states of nature [26], [27]. This technique is used in a quantitative and qualitative approach to problem-solving. Besides, in the quantitative approach, states of nature are economic, while in the qualitative decision-making, alternative weights are intuitively assigned [4].

The results of the payoff matrices provide the decision-maker with several possible choices. Also, the last step using the payoff matrix (EMV), which is based on probability, enables a more precise insight into the decision made consequences.

3. METHODOLOGY FOR ESTIMATING AND ANALYZING THE COMPARED COST RISK IN THE BIDDING PHASE

The proposed methodology has consisted of two basic's parts. Furthermore, parts are consisted of estimation of cost variations with associated probabilities according to the triangular distribution, PERT method, and Payoff matrix. Comparison and analysis of the obtained results are integral for both techniques. This can be indicated as in Fig. 1:

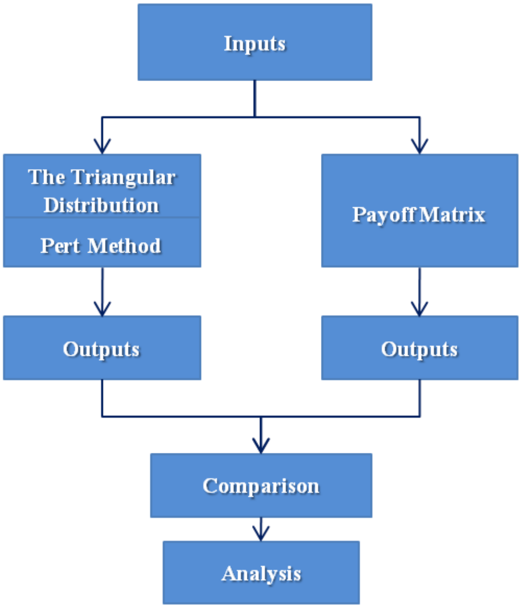


Fig. 1 General procedure of the proposed methodology

Although the triangular and beta distribution technique (PERT method) differs in terms of the most likely value, an identical number of steps are required to determine costs with associated probabilities. Respecting such specifics, the same algorithmic process of estimating item unit prices of the bill of quantities can be adopted.

A specific procedure/algorithm for the cost risk estimation under the triangular distribution and the PERT method (first part) is as shown in Fig. 2:

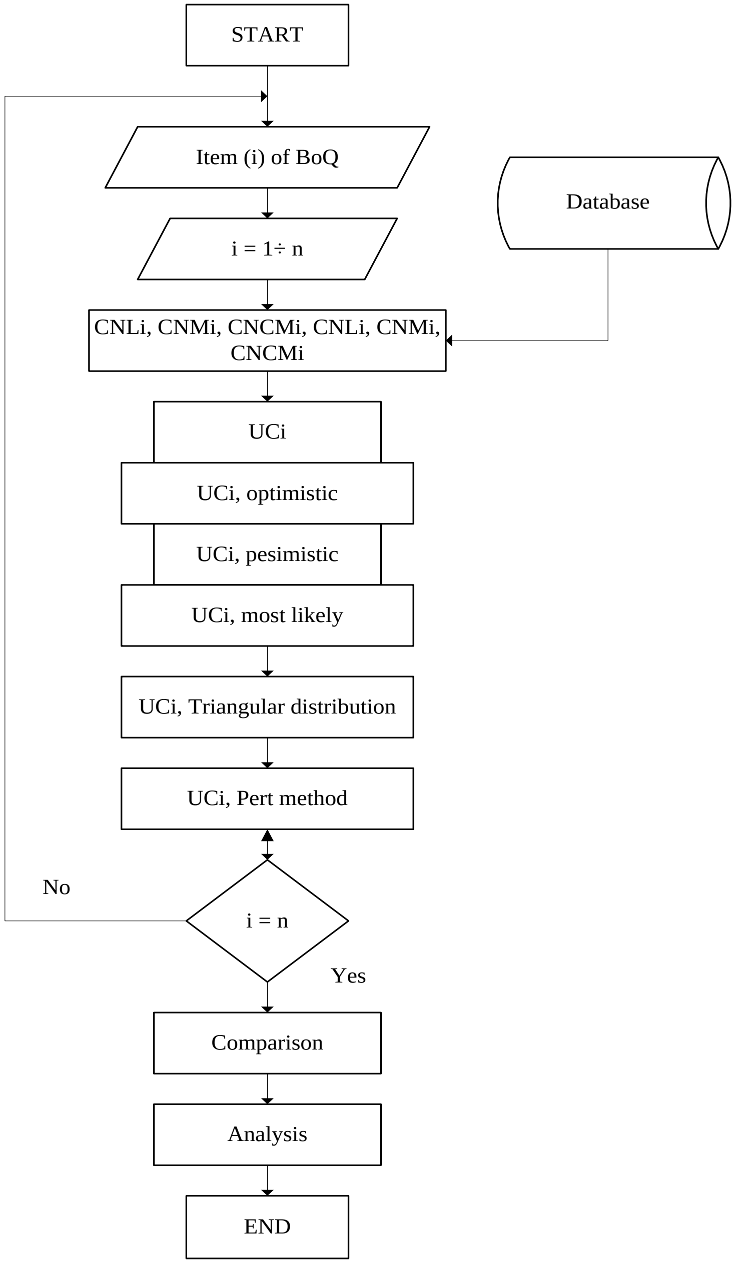


Fig. 2 Algorithm for the cost risk estimation, comparison, and analysis under the triangular distribution and the PERT method

The second part of the proposed methodology is cost risk assessment using payoff matrices. An algorithm of this technique is as shown in Figure 3:

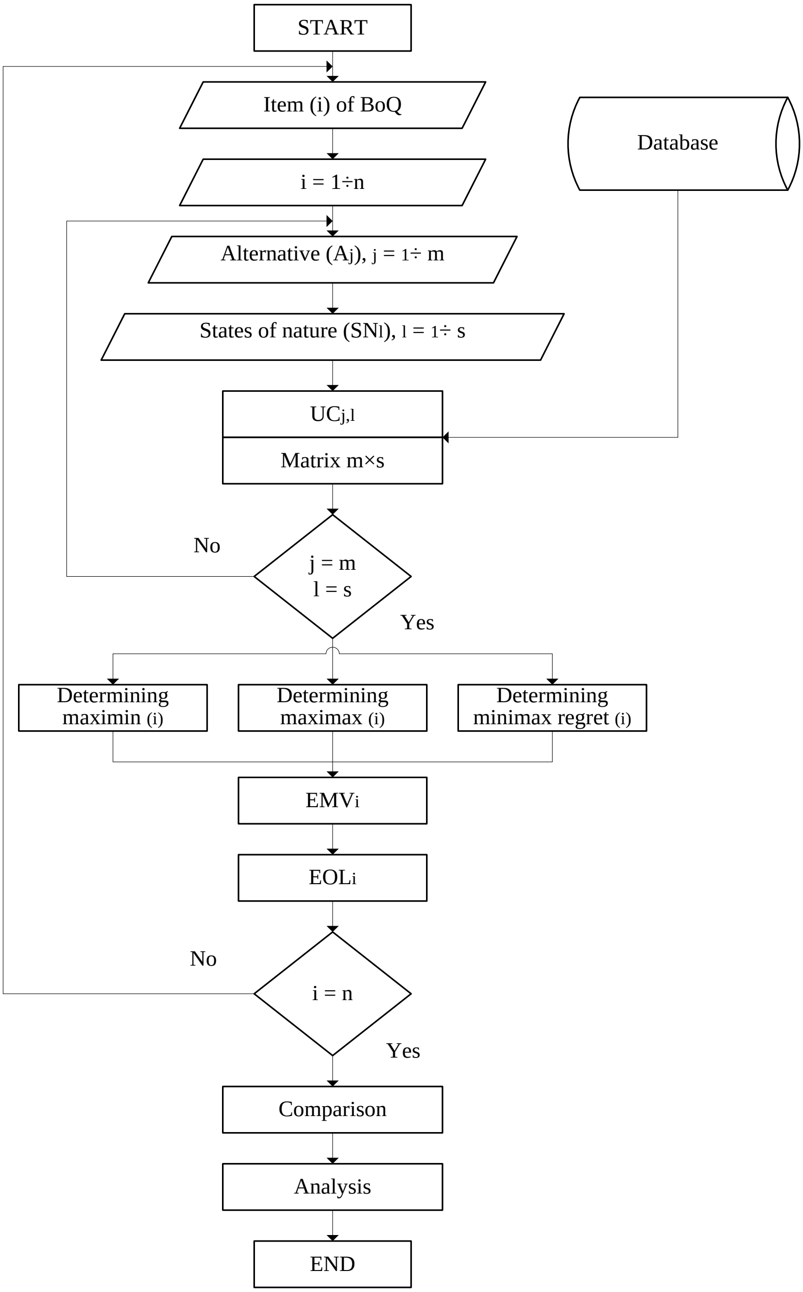


Fig. 3 Algorithm for the cost risk estimation, comparison, and analysis under the payoff matrices

The payoff matrices offer a wide range of possible solutions to the decision-maker. This feature is a consequence of the five strategies that are integral parts of the chosen technique – minimax, minimin, minimax regret, expected monetary value (EMV), and expected opportunity loss (EOL) [26], [27].

Minimax represents the lowest cost risk value of all maximum values for given alternatives and states of nature. Analogously, minimin is the lowest value among all alternative minimums. Besides, determining minimax regret represents the possible opportunity lost. Also, this cost risk estimation represents the determination of the minimum loss in the case of wrong decision-making. The final step in the payoff matrix technique is the expected monetary value (EMV). EMV is determined by summing the multiplied values of each state of nature with the probability of occurrence. This technique can be recognized as an alternative to a three-point estimation. The last step in estimating the cost risk using payoff matrices is the expected opportunity loss (EOL). Expected opportunity loss can be realized as a variation of the expected monetary value. An aim of this approach is minimizing the expected opportunity loss, rather than maximizing the expected monetary value. *Testing of the proposed methodology will be performed on a practical example from the bill of quantity in the bidding phase*.

4. Illustrative Example

The proposed methodology was applied to the practical example of the pavement rehabilitation bill of quantity. Table 1 shows the items with quantities and estimated unit costs in the bidding.

Table 1 Part of the bill of quantity for asphalt pavement

Item	Text	Quantity	Unit	Unit Cost (€/m^2)			Total Cost (€)		
3	Asphalt Constructions			O	ML	P	O	ML	P
3.1	Apply AC 32 TS 50/70, thickness 12 cm	11000	m2	18.53	18.84	19.23	203,830.00	207,240.00	211,530.00
3.2	Apply AC 16 BS 25/55-55 A, thickness 6 cm	11000	m2	12.60	12.79	13.22	138,600.00	140,690.00	145,420.00
3.3	Apply AC 11 DS 25/55-55 A, thickness 4 cm	11000	m2	11.26	11.53	11.84	123,860.00	126,830.00	130,262.00
Net	Bid Sum						466,290.00	474,760.00	487,212.00

4.1 Probability Estimation by Triangular Distribution

The characteristic graph of the triangular distribution with item unit costs is as shown in Fig. 4.

The probability of occurrence (p) of each item is determined through the ratio areas of triangles 1 and 2, to the total area under the curve. This can be indicated by Eq. 9 and Eq. 10:

$$\textit{Probability (3.i.1) = Area of 3.i.1 / Total Area of item 3.i} \tag{9}$$

Respectively,

$$\textit{Probability (3.i.2) = Area of 3.i.2 / Total Area of item 3.i} \tag{10}$$

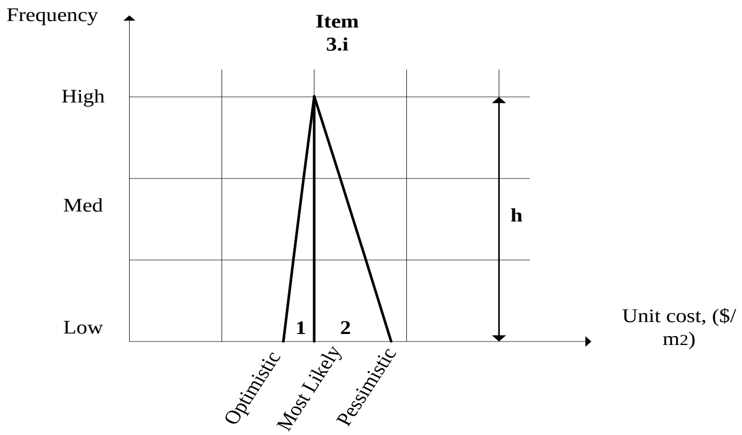


Fig. 4 Triangular distribution of the unit cost for item 3.i

The obtained values, according to Eq. 5 and Eq. 6 are as shown in Table 2:

Table 2 Probability of Occurrence

Triangle	Area	Probability of Occurrence (p)
3.1.1	0.5×(207,240.00 - 203,830.00) h = 1,705.00h	A3.1.1/(A3.1.1+A3.1.2) = 1,705.00/(1,705.00+2,145.00) = 0.44
3.1.2	0.5×(211,530.00 - 207,240.00) h = 2,145.00h	A3.1.2/(A3.1.1+A3.1.2) = 2,145.00/(1,705.00+2,145.00) = 0.56
3.2.1	0.5×(140,690.00 - 138,600.00) h = 1,045,00h	A3.2.1/(A3.2.1+A3.2.2) = 1,045.00/(1,045.00+2,365.00) = 0.31
3.2.2	0.5×(145,420.00 - 140,690.00) h = 2,365.00h	A3.2.2/(A3.2.1+A3.2.2) = 2,365.00/(1,045.00+2,365.00) = 0.69
3.3.1	0.5×(126,830.00 - 123,860.00) h = 1,485.00h	A3.3.1/(A3.2.1+A3.3.2) = 1,485.00/(1,485.00+1,716.00) = 0.46
3.3.2	0.5×(130,262.00 - 126,830.00) h = 1,716.00h	A3.3.2/(A3.2.1+A3.3.2) = 1,716.00/(1,485.00+1,716.00) = 0.54

4.1.1 Probabilities and Cumulative Probabilities of Project Cost

After finding the probabilities of occurrence for each area under the distribution curve, all possible combinations follow. Each combination is assigned by cost based on the midpoint and the corresponding probabilities of occurrence. These data are as shown in Table 3:

Table 3 Probability of Cost Occurrence for the Project

Combination of Item Zones	Cost Base on Midpoint (€)	Probability of Occurrence
A3.1.1+A3.2.1+A3.3.1	470,525.00	0.44 × 0.31 × 0.46 = 0.062744
A3.1.1+A3.2.1+A3.3.2	473,726.00	0.44 × 0.31 × 0.54 = 0.073656
A3.1.1+A3.2.2+A3.3.1	473,935.00	0.44 × 0.69 × 0.46 = 0.139656
A3.1.1+A3.2.2+A3.3.2	477,136.00	0.44 × 0.69 × 0.54 = 0.163944
A3.1.2+A3.2.1+A3.3.1	474,375.00	0.56 × 0.31 × 0.46 = 0.079856
A3.1.2+A3.2.1+A3.3.2	477,576.00	0.56 × 0.31 × 0.54 = 0.093744
A3.1.2+A3.2.2+A3.3.1	477,785.00	0.56 × 0.69 × 0.46 = 0.177744
A3.1.2+A3.2.2+A3.3.2	480,986.00	0.56 × 0.69 × 0.54 =0.208656
SUM		1.00

Data from Table 3 need to be arranged in ascending order of costs with corresponding probabilities. This is as shown in Table 4:

Table 4 Combined Probability of Cost Occurrence for the Project

Combination of Item Zones	Cost Based on Midpoint (€)	Probability of Occurrence
A3.1.1+A3.2.1+A3.3.1	470,525.00	0.0627
A3.1.1+A3.2.1+A3.3.2	473,726.00	0.0737
A3.1.1+A3.2.2+A3.3.1	473,935.00	0.1397
A3.1.2+A3.2.1+A3.3.1	474,375.00	0.0799
A3.1.1+A3.2.2+A3.3.2	477,136.00	0.1639
A3.1.2+A3.2.1+A3.3.2	477,576.00	0.0937
A3.1.2+A3.2.2+A3.3.1	477,785.00	0.1777
A3.1.2+A3.2.2+A3.3.2	480,986.00	0.2087
SUM		1.0000

The final costs of all possible combinations vary from **€**470,525.00 to **€**480,986.00, as shown in Table 4. The further step is determining the cost frequencies and cumulative probabilities. The following data are as indicated in Table 5:

Table 5 Probability of Project Cost Occurrence

Project Cost (€)	Frequency of Occurrence	Joint Probabilities	Cumulative Probability
465,850.00 (min)	-	0.0000	0.0000
470,525.00	1	0.0627	0.0627
473,726.00	1	0.0737	0.1364
473,935.00	1	0.1397	0.2761
474,375.00	1	0.0799	0.3559
477,136.00	1	0.1639	0.5199
477,576.00	1	0.0937	0.6136
477,785.00	1	0.1777	0.7913
480,986.00	1	0.2087	1.0000
487,212.00 (max)	-	0.0000	1.0000

The final costs and the project price determination are typically based on preliminary data and a key decision on profit rate.

4.1.2 Finding the Bid Cost and Bid Price

The target cost represents the total of the most likely cost of each bid item. For the analyzed part of the bill of quantity, the total cost is €474,760.00. For the stated target cost, according to Fig. 5, the confidence level is 0.3790. In cases where the contractors cannot accept a certain level of confidence, they can set the desired level. In this case, it can be assumed that the bidder will be satisfied with the ratio of 0.75:0.25, i.e., 3:1. The 75 % confidence level results in a higher cost than the target cost. In this case, the corresponding *confidence-limit cost* is ***€477,746.00***. The difference between confidence limit cost and target cost is the *contingency fund*. In this case, it is €2,986.00.

If a profit rate of 7% is assumed, the bid price is according to Eq. 11:

$$\text{Bid price} = \text{Target cost} + \text{Contingency fund} + \text{Profit} \tag{11}$$

Bid price = 474,760.00 + 2,986.00 + (474,760.00 + 2,986.00) × 0.07 = €511,188.22

4.2 Probability Estimation by PERT Method

Unit costs and total costs for the analyzed practical example, according to Eq. 6, Eq. 7, Table 1, and a confidence level of 75% are as shown in Table 6:

Table 6 Estimating total item costs and project cost by PERT method

Item	Asphalt Constructions		Unit Cost (€/m2)			Total Cost (€)		
3	Quantity	Unit	Optimistic	Most Likely	Pessimistic	Basic	Min	Max
3.1	11000.00	m2	18.53	18.84	19.23	207,386.67	205,910.83	208,862.50
3.2	11000.00	m2	12.60	12.79	13.22	141,130.00	139,822.83	142,437.17
3.3	11000.00	m2	11.26	11.53	11.84	126,907.00	125,679.95	128,134.05
Net Bid Sum						475,423.67	473,101.51	477,745.83

According to Table 6, the total costs are within an interval of minimum and maximum value (€473,101.51 ÷ €477,745.83). The total bid price is determined by adopting a profit rate of 7%, to compare with the triangular distribution technique.

Min. bid price = 473,101.51 + (473,101.51 × 0.07) = €506,218.58

While the maximum bid price is:

Max. bid price = 477,745.83 + (477,745.83 × 0.07) = €511,118.04

4.3 Estimation by Payoff Matrix

The availability of the construction technology process is the most uncertain input in deciding the unit costs and total project costs. This feature of construction systems imposes the need to form more *alternatives* in the selection of the most likely scenario. Also, variations in average building norms have a significant impact on project cost estimates. These characteristics of construction production processes represent alternatives and criteria (*states of nature*) in the cost-risk analysis, using payoff matrices.

Three *alternatives,* for different availability values, are envisaged in the analyzed example. Also, three expected variations of building norms were selected as criteria (*states of nature*). The Table for the analyzed example should be created as is shown in Table 7:

Table 7 Alternative costs depending on variations of construction norms

Decision alternative	ACN × (1+0.05) SN1	Average Construction Norm ACN	ACN × (1- 0.05) SN3
System Availability - 0.99 (D1)	442,975.50	451,022.00	462,851.40
System Availability - 0.95 (D2)	466,290.00	474,760.00	487,212.00
System Availability - 0.90 (D3)	492,195.00	501,135.55	514,279.33

4.3.1. Determining Minimax

The first step of this technique is determining minimax. Minimax is the minimum cost among the maximum alternative values, as shown in Table 8. Minimax is €462,851.40 for decision alternative D1.

Table 8 Minimax alternative cost

Decision alternative	Minimum Payoff
System Availability – 0.99 (D1)	462,851.40
System Availability - 0.95 (D2)	487,212.00
System Availability - 0.90 (D3)	514,279.33

4.3.2. Determining Minimin

Minimin is the minimum cost among the minimum alternative values, as shown in Table 9. Minimin is €442,975.00 for decision alternative D1.

Table 9 Minimin alternative cost

Decision alternative	ACN × (1+0.05) SN1
System Availability - 0.99 (D1)	442,975.50
System Availability - 0.95 (D2)	466,290.00
System Availability - 0.90 (D3)	492,195.00

4.3.3 Determining Minimax Regret

Minimax regret represents the possible opportunity lost. The minimum of all maximum regrets is as shown in Table 9. Minimax regret is €0,000.00 for decision alternative D1.

Table 10 Minimax regret for cost risk occurrence

Decision alternative	ACN × (1+0.05) SN1	Average construction norm (ACN)	ACN × (1-0.05) SN3
System Availability - 0.99 (D1)	0.00	0.00	0.00
System Availability - 0.95 (D2)	23,314.50	23,738.00	24,360.60
System Availability - 0.90 (D3)	49,219.50	50,113.55	51,427.93

4.3.4. EMV

EMV could be the most appropriate approach because it takes into account the probabilities of event costs. This part of payoff matrices represents a very useful tool for well-experienced bidders. This means that the possibility of choosing probabilities could favorite the most likely scenario. The determined probabilities for SN1, SN2, and SN3 are 0.15, 0.75, and 0.1. EOL values are as shown in Table 11. The lowest cost assessment given the probabilities of all conditions is preferring the D1 alternative (*System Availability* = 0.99) for an EMV of €450,997.97.

Table 11 Expected monetary value for cost risk occurrence

EMV D_i	Total Cost (€)
EMV D1	450,997.97
EMV D2	474,734.70
EMV D3	501,108.85

4.3.5. EOL

Expected opportunity loss represents a variation of the expected monetary value. In this part, the probabilities of occurrence were multiplied by the minimax regret values from Table 9. This technique aims to minimize the expected opportunity loss, rather than maximizing the expected monetary value. The determined probabilities for SN1, SN2, and SN3 are 0.15, 0.75, and 0.1. EOL values are as indicated in Table 12. The minimum expected opportunity loss is €0.000.00 for alternative D1.

Table 12 Expected opportunity loss for cost risk occurrence

EOL D_i	Cost (€)
EOL D1	0,000.00
EOL D2	23,736.74
EOL D3	50,110.88

The results obtained using the payoff matrices indicate the importance of decision alternative D1 in the decision–making. It is crucially significant to emphasize before discussing and comparing results. Namely, the costs of alternative D1 for altered states of building norms are based on the system availability of 0.99999, i.e., 1.0. This availability of construction production systems is not likely in practical examples, although it is envisaged as one of the alternatives. The reason for such an approach is to emphasize the importance of the expected failure states in project realization, with the associated risks. This means that alternative D1 is set up to warn inexperienced project managers of certain system failures and their impact to cost risk estimation. Therefore, the obtained results must be corrected without taking into account alternative D1. Table 13 shows the already stated (incorrect) and corrected values of cost risk strategies within the payoff matrices.

Table 13 Payoff matrix - cost risk results

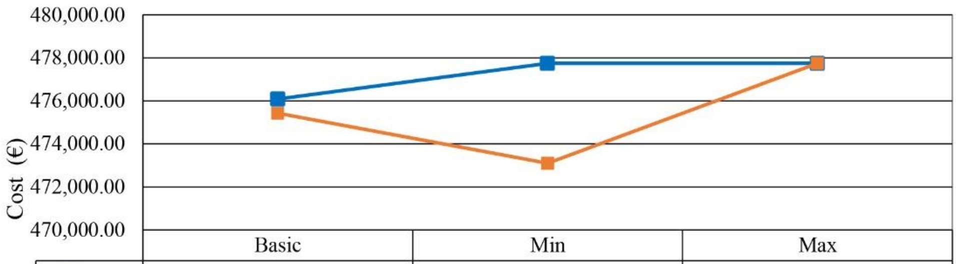
Payoff Matrix	Cost Risk (€)	Payoff Matrix	Cost Risk (€)
Results	Correct	Results	Incorrect
Minimax - D3	487,212.00	Minimax – D1	462,851.40
Minimin - D2	466,290.00	Minimin – D1	442,975.50
Minimax Regret - D3	25,905.00	Minimax Regret - D1	0,000.00
EMV - D2	474,734.70	EMV - D1	450,997.97
EOL - D2	23,736.74	EOL - D1	0,000.00

5. Results Comparison and Discussion

After comparing the results of the triangular distribution and the PERT method, the next step is comparing the outputs with the payoff matrix results.

5.1. Triangular Distribution vs. Beta Distribution (PERT Method)

The total bid costs (BC) according to Eq. 5 for the triangular distribution, and Eq. 3 are €476,087.00. Similarly, the total bid costs according to Eq. 6 for the PERT method and Eq. 3 are €475,423.67. The total costs for the confidence level of 75% according to the triangular distribution (TD) and PERT method (PM) are *€477,746.00* (TD), i.e., interval (*€473,101.51 ÷ €477,745.83*) for PM. According to Eq. 5 and Eq. 6., the total costs of TD are higher than the total costs of PM by 0.14%. The total costs of both techniques for a confidence level of 75% are equal in the case of the upper limit of the PM interval. Namely, according to the PM and the lower limit of the interval, there is a possibility to choose the costs of €473,101.51 ÷ €477,745.83. This means that those costs should be reduced by €4,644.32 compared to the stated costs. The bid costs, according to Fig. 5 are within the limited area of minimum and maximum value.



	Basic	Min	Max
T. D.	476,087.00	477,746.00	477,746.00
P.M	475,423.67	473,101.51	477,745.83

Fig. 5 Triangular distribution vs. PERT method

5.2. Minimax and Minimum vs. Expected Monetary Value – Payoff Matrix

The EMV value is based on the probabilities for each state of nature. Due to the comparison with the triangular and beta distribution (PERT), that follow in the next chapter, the preferred probability of occurrence of 75% was chosen. According to Fig. 5, there is a deviation of the minimax and minimin concerning EMV. Namely, the value of EMV cost is close to the middle of the interval determined by minimax and minimin. In this case, the EMV value of *€474,734.70* represents a reference value in the decision-making.

According to Fig. 1, the final step in decision-making is comparing the results of all researched techniques.

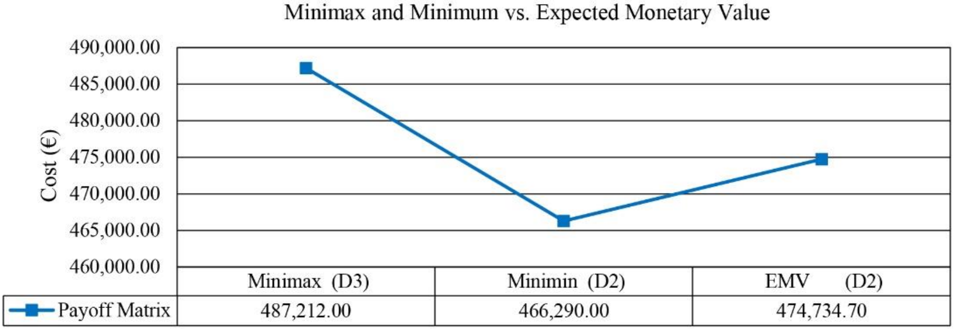


Fig. 6 Comparison of the Payoff strategies

5.3. Triangular Distribution and PERT Method vs. Payoff Matrix Strategies

Fig. 7 and Fig. 8 show the cost risk values of the applied techniques. Results are presented by two figures due to the interval limits of the PERT method. Fig. 7indicates all the obtained results with the minimum value of the PERT method (strategy 1).

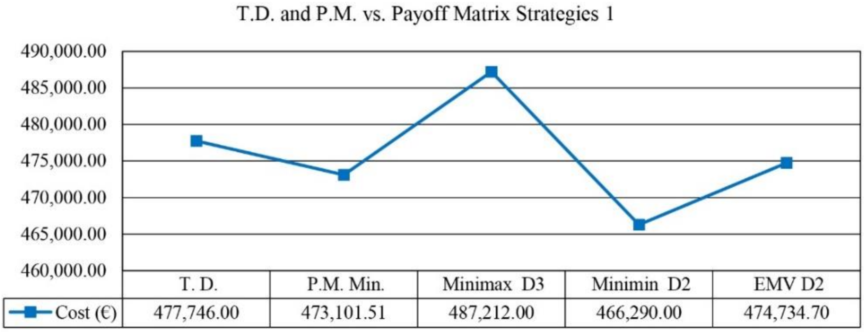


Fig. 7 Graph of all results obtained with the minimum value of the PERT method

Also, Fig. 8 shows all results with the maximum value of the PERT method (strategy 2).

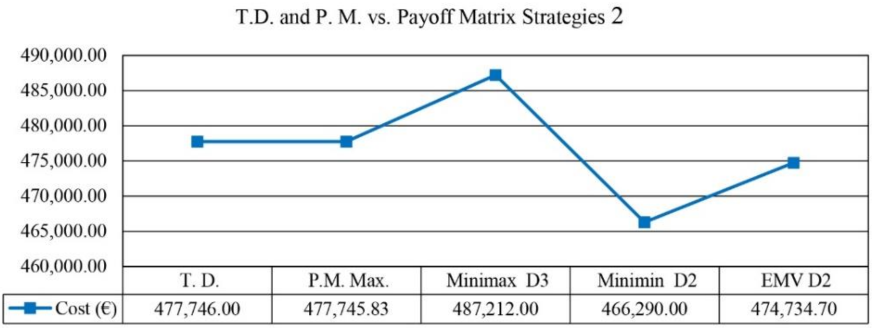


Fig. 8 Graph of all results obtained with the maximum value of the PERT method

The value of minimax refers to alternative D3, with the availability of 0.9. The stated value should not be taken into account due to a significant deviation from the others. Besides, the average availability of optimally maintained building systems in practice is around the value of 0.95. Also, the minimin D2 is the minimum cost that can jeopardize the competitiveness of the bid and potential losses in the event of a contract award. Besides, considering the obtained values is based on theoretical and practical experience in bidding. Hence, decision-making can be presented as a choice between the two alternatives, as indicated in Fig. 9 and Fig. 10.

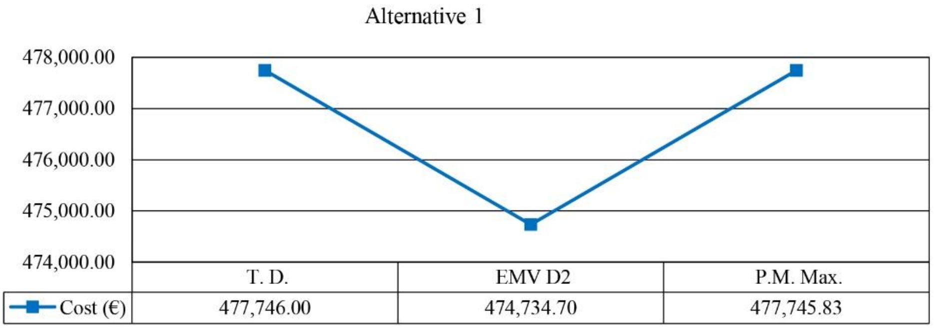


Fig. 9 Alternative 1 with P. M. Maximum

Analogous to alternative 1 is alternative 2, with the maximum value of the used PERT method (Fig. 10).

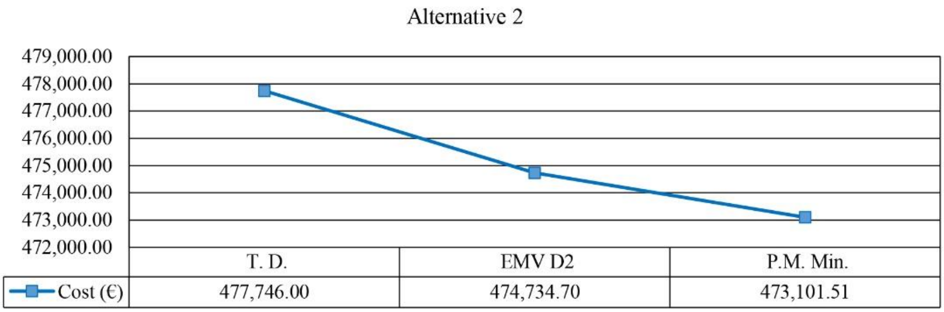


Fig. 10 Alternative 2 with P. M. Minimum

In such situations, the decision-maker should decide on the narrowest possible interval of the final bid costs. In a specific example, the cost variation interval can be further reduced by taking into account the following values:

- mean value obtained by the PERT method (without variation)
- most likely value for the availability of 0.95, and average building norms (Table 6, Payoff Matrix)

So, decision-making is simplified, as shown in Fig. 11:

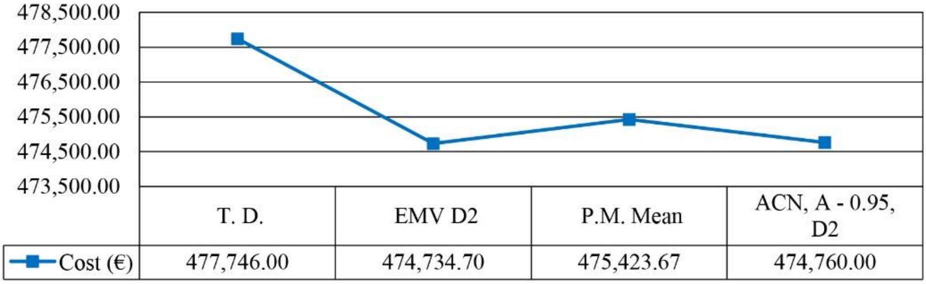


Fig. 11 Decision-Making Chart

The results of the cost risks, according to Fig. 11, emphasize the importance of the EMV technique with multiple aspects. Primarily, EMV represents the minimum costs that are within the confidence interval of the PERT method. Also, EMV refers to alternative D2 with a system availability of 0.95. Besides, the differences between the EMV value and other techniques are 0.1%. The triangular distribution was not taken into account in the decision-making due to a greater deviation from the others.

These cost ratios and the reasons for the final decision-making are clearly illustrated by Fig. 12.

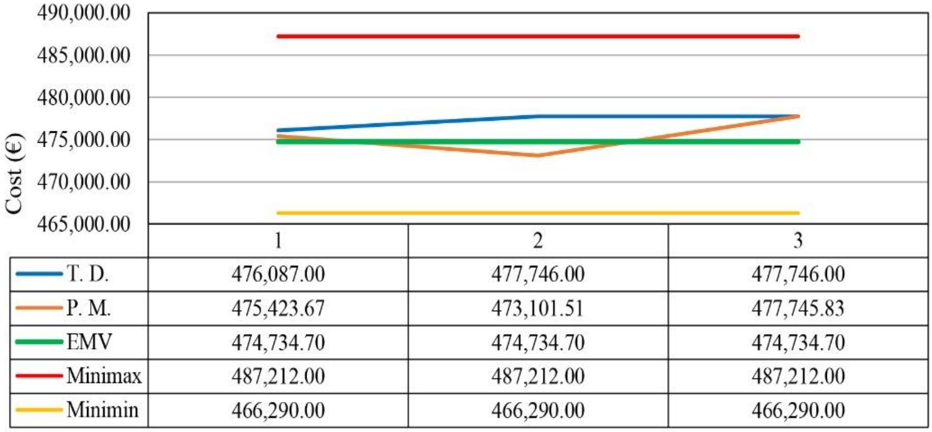


Fig. 12 The ratio of adopted costs (EMV) to the results of the analyzed techniques

Due to the total bid cost of *€474,734.70* and a profit rate of 7%, a pre-bid layout is as shown in Table 13:

Table 13 Pre-bid layout

Item	Text	Quantity	Unit	Unit Cost (€/m2)	Total Cost (€)
3	Asphalt Constructions				
3.1	Apply asphalt base layer AC 32 TS 50/70, thickness 12 cm	11000.00	m2	18.83	207,076.85
3.2	Apply asphalt binder layer AC 16 BS 25/55-55, thickness 6 cm	11000.00	m2	12.82	140,988.50
3.3	Apply asphalt surface AC 11 DS 25/55-55 A, thickness 4 cm	11000.00	m2	11.52	126,669.35
Cost bid sum					*474,734.70*
Profit 7%					33,231.43
VAT 20%					*101,593.23*
Gross bid sum					*609,559.35*

Bids contain unit prices without division into unit costs and profit in practical examples. With this approach, contractors protect the company policy. Therefore, the final bid form is as shown in Table 14:

Table 14 Final bid

Item	Text	Quantity	Unit	Unit Price (€/m2)	Total Price (€)
3	Asphalt Constructions				
3.1	Apply asphalt base layer AC 32 TS 50/70, thickness 12 cm	11000.00	m2	20.14	221,572.23
3.2	Apply asphalt binder layer AC 16 BS 25/55-55, thickness 6 cm	11000.00	m2	13.71	150,857.69
3.3	Apply asphalt surface AC 11 DS 25/55-55 A, thickness 4 cm	11000.00	m2	12.32	135,536.21
Net bid sum					507,966.13
VAT 20%					*101,593.23*
Gross bid sum					*609,559.35*

5. CONCLUSION

The most important part of construction bidding relates to determining real cost inputs. Assessing building norms for each project is the most complex task in the costing process. Due to variations in building norms, the potential contractor anticipates several scenarios before decision-making on the final bid costs and bid price. The paper used known methods for estimating bid cost probabilities of occurrence.

The results of the analyzed techniques confirmed the assumptions of the decision-making complexity in the cost risk bidding. Namely, relations between optimistic costs, pessimistic costs, and most likely costs influenced the choice of research techniques.

By testing the techniques on a specific example, the results of the PERT method and Expected Monetary Value were matched. This means that EMV was in the cost range obtained by the PERT method.

The minimax cost significantly deviated from the most likely costs and those listed above. Also, minimax costs have a high probability of a non-competitive bid. Besides, minimin costs have a high probability of contract awards and potential losses during the project realization. The results got by the triangular distribution method have small deviations from the mean of the PERT method for the same confidence level. Figure 12 indicates the grouping of cost risk values got by the PERT method, the triangular distribution method, and the EMV method.

The uncertainty of the obtained results is confirmed by the difference of 4.80%, between the minimax and minimin technique. Besides, the differences among other technique results are in the range of 0.1 to 1%. Also, the mentioned techniques influenced compromise solutions due to the same probability of cost risk occurrence. In this case, it is EMV.

It is important to emphasize that the chosen technique provides the highest probability of minimum costs and the highest probability of occurrence of the given profit in case of winning the tender. Also, finding results represent the complexity and uncertainty within cost risk in construction bidding and decision-making.

For further research of cost risk with the same methods, it is necessary to vary the probabilities of occurrence, i.e., compare results for different confidence limits of 50% to 95%.

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POREDJENJE METODE TRIANGULARNE DISTRIBUCIJE I PERT METODE SA MATRICAMA RANGIRANJA ZA PODRŠKU ODLUČIVANJU U ANALIZI RIZIKA GRADJEVINSKIH PONUDA: ANALIZA SLUČAJA

Donošenje odluka u gradjevinskom nadmetanju je složen proces zbog prisutnog rizika. Rizik ili neizvesnost ne može se zanemariti i treba biti tretirati kao sastavni deo donošenja odluka. Cilj rada je da naglasi važnost teorije verovatnoće upoređivanjem nedovoljno primenljivih metoda u praktičnom nadmetanju. Metoda trougaone raspodele i PERT metoda pripadaju troparametarskim tehnikama procene, dok matrice rangiranja predstavljaju višekriterijumski pristup. Takođe, odabrane metode spadaju u kvantitativne tehnike za analizu troškova rizika. Određivanje jediničnih troškova i ukupnih troškova ponuda, još uvek se vrši na osnovu intuitivnog pristupa. Prema tome, upoređeni rezultati trougaone raspodele, PERT metode i tehnike matrice rangiranja (minimin, *minimax, očekivana novčana vrednost i očekivana mogućnost gubitka) ukazuju na značaj procene troškova rizika na tenderima. Analiza rezultata pokazala je preklapanje vrednosti troškova rizika dobijenih PERT metodom i tehnikom očekivane novčane vrednosti. Navedeni rezultati su posledica specifičnosti izabranog praktičnog primera i ne mogu se usvojiti kao pravilo. To znači da su odabrane metode i tehnike veoma korisne za sve procene ponuda. Rad je dokazao složenost odlučivanja, gde je primarni cilj dodela ugovora.*

Ključne reči: *nadmetanje, rizik, trošak, jedinični trošak, ukupni trošak, cena ponude*

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APPLICATION OF MODERN TYPES OF STEEL IN CONSTRUCTION FROM THE ASPECT OF MATERIAL PROPERTIES ACCORDING TO EUROCODE 3

UDC 693.814

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Abstract. *This subject is often discussed by researchers since it is an interesting topic in terms of the behavior of materials found in a building. Metal in construction is a point of interest for designers, suppliers, and builders due to logistical and time management advantages. Based on the researchers' information mentioned in the references, the project aims to provide details on the modern techniques for applying steel in construction according to current standards.*

Key words: *modern types of steel, properties material, Eurocode 3.*

1. INTRODUCTION

Eurocode 3 or EN 1993-1-1 is the document where all the specifications for steel structures are described. Eurocode 3 is concerned only with resistance, serviceability, durability, and fire resistance of steel structures. Other requirements, e.g., concerning thermal or sound insulation, are not covered. (En.1993.1.1.2005.Pdf, n.d.)

The choice of steel grade is detailed in EC3, where various requirements are specified. It is essential to choose the steel grade according to the mechanical material properties, respect the ductility requirements, and know the toughness and through-thickness properties. Also, the classification of steels is based on the minimum yield strength for a specific temperature. (Hechler et al., 2015)

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The steels that go through a thermomechanical (TM) rolling process have more benefits than standard steels. Another modern way to produce steels is using the Quenching and Self-Tempering (QST) process, which is more advanced than the thermomechanical (TM) rolling techniques. Both procedures are explained below in the third chapter.

2. MATERIALS

2.1. Structural steel, connecting devices, and other prefabricated products

The structures made of steel should be conformed to the steel grades recognized and listed in Standard (En.1993.1.1.2005.Pdf, n.d.). Explaining this statement, the available steel grades need to have specific values for yield strength f_y and ultimate tensile strength f_u based on the dimension of the element's thickness t. There are two cases when the element's nominal thickness should be under 40 mm, or between 40 mm and 80 mm. Table 3.1 from Eurocode 3 includes the values described above.

The steel structures require a minimum level of ductility detailed in terms of limits for the ratio f_u/f_y, the elongation, and the ultimate strain ε_u. The National Annex defines these limits with recommended values, and the steel grades from Table 3.1 should satisfy these requirements.

Another information to take into consideration is the through-thickness properties. The EN 1993-1-10 standard defines a guideline to choose the adequate through-thickness properties, and the required quality class can be found in EN 10164, in table 3.2. Table 2.1 from EN 1993-1-10 defines the maximum permissible element thickness related to a steel grade, its toughness quality, the stress level, and the temperature. All the values are determined, considering the fatigue by applying a fatigue load to a member with an assumed initial flaw. In this case, the damage should be considerably less than the full fatigue damage and it permits the evaluation of the "safe period" specified for damage tolerance, according to EN 1993-1-9. The "safe period" may also cover the full design of a structure.

The structural steels must contain four crucial material coefficients for a structural analysis to be performed. These are the modulus of elasticity E, shear modulus G, Poisson's ratio in elastic stage ν, and the coefficient of linear thermal expansion α.

Structural steels have different options for connecting the elements (En.1993.1.8.2005-1.Pdf, n.d.), and all joints should have a design resistance to satisfy all the design requirements to create the structure. The fatigue load should be included and meet the principles from the Standard. It is essential to define the partial safety factors γ_M for joints. Table 2.1 from EN 1993-1-1 describes all these factors.

Choosing the joints depends on the distribution of internal forces and moments assumed in the analysis. It is recommended for a significant vibration to use the following jointing methods: welding, bolts (with locking devices, preloaded bolts, or other types), injection bolts, and rivets.

2.2. Introduction about durability for steel structures

EN 1990 is the document that covers in a detailed way the durability of steel structures. During the design of a system, all the factors that may affect the execution should be considered. Some of the essential elements are the mechanical wear from fatigue and the parts that are susceptible to corrosion. If the internal humidity does not increase by more than 80%, then the corrosion protection can be ignored.

The structure should be designed so that its working life would not affect the structural performance in terms of its environment and anticipated level of maintenance (En.1990.2002.Pdf, n.d.). A few criteria should be considered for a durable structure, such as the intended or foreseeable use of the system, the expected environmental conditions, and the soil's properties. All the criteria are listed in EN 1990 in the durability chapter.

2.3. Structural analysis

The initial assumptions and the calculation model should reflect a structure's behavior for a particular limit state for the entire design and each component, such as the cross-sections, members, and joints. This structural modeling is better described with more details in EN 1993-1-5 and EN-1-11.

The global analysis depends on the structure's deformed geometry's effects if it modifies the structure's behavior significantly. Therefore, it is essential to determine the internal forces and moments using the first-order analysis through the initial geometry or the second-order analysis defined by the deformations' influence.

Considering the second-order analysis's imperfections, it is mandatory to verify the frames' stability or parts. The second-order effect can be accounted for totally by the global study, including the imperfections. It can also be accounted for partially by the worldwide analysis and partly through the members' stability checks.

There is another method of analysis considering the material non-linearities. In this case, the internal forces and moments may be determined using elastic global or plastic global studies. The finite element model analysis is described in EN 1993-1-5. The elastic global calculations are based on the material's linear stress-strain behavior when the global plastic analysis describes the effect of non-linearity calculations for a structural system.

Another critical aspect of the structural analysis is to know the role of the cross-sections. Their classification is relevant and helps identify the resistance and rotation capacity where its local buckling resistance limits the cross-section. Regarding the variety, four classes are defined. The difference between them is based on plastic or elastic behavior, the rotation capacity, and the cross-section's local buckling.

3. THE APPLICATION OF MODERN TYPES OF STEEL IN CONSTRUCTION

3.1. The choice of the steel grade according to EC3

As explained above, the type of steel material conforming to steel grades are listed in **Table 1 (a, b)** attached below. It is divided into two parts for hot-rolled structural steel and hollow structural sections.

Based on the mechanical properties, the nominal values for f_y and f_u are defined by adopting the values from the product standard, $f_y = R_{eh}$, and $f_u = R_m$.

Table 1a Nominal values of yield strength and ultimate tensile strength for hot-rolled structural steel

Standard and steel grade	Nominal thickness of the element t [mm]			
	$t \leq 40$ mm		$40\ mm < t \leq 80$ mm	
	f_y [N/mm^2]	f_u [N/mm^2]	f_y [N/mm^2]	f_u [N/mm^2]
EN 10025-2				
S 235	235	360	215	360
S 275	275	430	255	410
S 355	355	⟦AC2⟩ 490 ⟨AC2⟧	335	470
S 450	440	550	410	550
EN 10025-3				
S 275 N/NL	275	390	255	370
S 355 N/NL	355	490	335	470
S 420 N/NL	420	520	390	520
S 460 N/NL	460	540	430	540
EN 10025-4				
S 275 M/ML	275	370	255	360
S 355 M/ML	355	470	335	450
S 420 M/ML	420	520	390	500
S 460 M/ML	460	540	430	530
EN 10025-5				
S 235 W	235	360	215	340
S 355 W	355	⟦AC2⟩ 490 ⟨AC2⟧	335	490
EN 10025-6				
S 460 Q/QL/QL1	460	570	440	550

Table 1b Nominal values of yield strength and ultimate tensile strength for hollow structural sections

Standard and steel grade	Nominal thickness of the element t [mm]			
	$t \leq 40$ mm		$40\ mm < t \leq 80$ mm	
	f_y [N/mm^2]	f_u [N/mm^2]	f_y [N/mm^2]	f_u [N/mm^2]
EN 10210-1				
S 235 H	235	360	215	340
S 275 H	275	430	255	410
S 355 H	355	510	335	490
S 275 NH/NLH	275	390	255	370
S 355 NH/NLH	355	490	335	470
S 420 NH/NLH ⟨AC2⟧	420	540	390	520
S 460 NH/NLH	460	560	430	550
EN 10219-1				
S 235 H	235	360		
S 275 H	275	430		
S 355 H	355	510		
S 275 NH/NLH	275	370		
S 355 NH/NLH	355	470		
S 460 NH/NLH	460	550		
S 275 MH/MLH	275	360		
S 355 MH/MLH	355	470		
S 420 MH/MLH	420	500		
S 460 MH/MLH	460	530		

3.2. Weldability of modern steel grade

Welding is substantial in the case of structural steel because it depends on the steel's hardness. Thus, the standards are included the rules for lowering the yield strength for thicker plates because it was visible that the required yield strength decreased when the material thickness increased. (Hechler et al., 2015)

In order to verify a product, it is necessary to conform it to a tensile test. The result defines the stress-strain curve, explained in Figure 1, where f_y and f_u values can be determined.

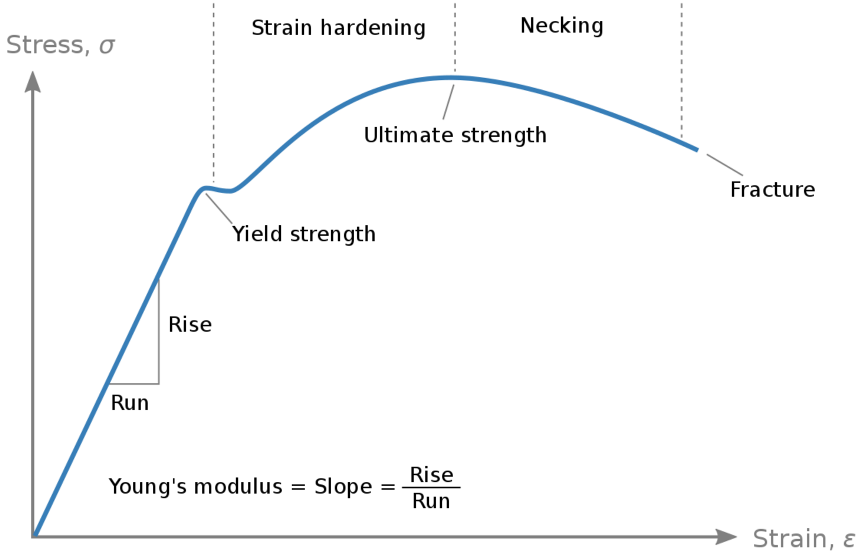

Fig.1 Stress-strain curve

Besides, there is an essential connection between material strength and weldability, which refers to the common alloy type. This material is characterized by poor weldability because of its reduced resistance and higher alloying content. Again, for keeping the thick products' good weldability, a thermomechanical rolling process can be used at the point where high strength steel can be produced without a significant carbon increase. The steels that go through a thermomechanical (TM) rolling process have more benefits, like reduced scale formation, excellent cold formability, best flatness, and cuttability.

This process has many benefits for steel material. The paper "The Right Choice of Steel" (Hechler et al., 2015) provides an excellent example by using TM steel where the economic factor is well evaluated. The model is referring to a column with known dimensions that requires 8 hours of welding. Using the TM steel in HISTAR quality, one-third of the welding time can be saved.

3.3. Fabrication of modern types of steels according to EC3

A stylish way to produce steels is using the Quenching and Self-Tempering (QST) process. For example, heavy hot-rolled H-beams made through the QST process in high strength structural steel grades perform better in terms of weldability characteristics. Lucien Weber explained in his paper "Histar High-Performance Hot-Rolled Beams" (Weber, 2003) why the QST process is more advanced than thermomechanical (TM) rolling techniques. The reason is that TM is limited by the mechanical power of the rolling mills due to the high deformation rates that this process implies. Another limitation is the impossibility of substantial reduction of the carbon in steel and improving its weldability. The QST process includes the TM rolling to cover these limits.

The QST technique is based on water and rolling heat usage. Treatment of heavy steel beams comprises applying a homogeneous temperature on the element's entire cross-section before introducing it in the cooler bank. Therefore, substantial temperature differences on the cross-section can be eliminated. An example with different results is defined in one of the reports of JFE Bars&Shapes, (On-Line Quenched and Self-Tempered High Strength Steels.Pdf, n.d.), where the hardness distribution of the horizontal cross-section displays a U-curve distribution corresponding to the cooling characteristics (see Fig. 2). The above layer has high hardness, so it has good resistance, while the middle one has low hardness and high ductility and toughness. Combining them results in high fatigue strength and bending strength in the entire round bar, so in an outstanding balance of strength and toughness. A computer controls the parameters of this industrial process.

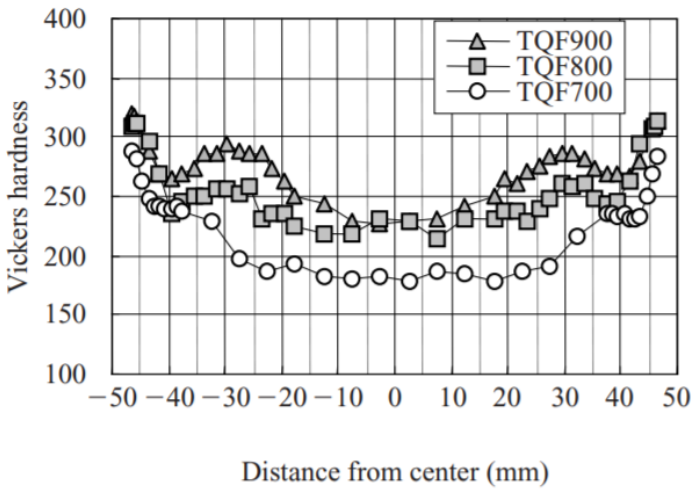

Fig. 2 Hardness curves of a cross-section

During the QST process, due to the lower carbon values compared to the conventional structural steel grade, the weldability and steel grades' ductility are significantly improved.

To avoid the cracks and fragile parts of an element or in the base material, during welding or during a seismic action, it is mandatory to have an established level of toughness of the steel material. In the QST technique, the steel can be supplied with a better toughness at low temperatures. This is why HISTAR grades are more used and more appreciated in the construction of offshore platforms.

Another advantage of the QST process is the well-being of a structure regarding ductility, good characteristics for seismic actions, or other actions that comprise the beams' bending. During bend tests and after it, at high temperatures such as 180º, the HISTAR elements do not show any cracks. The bending test was also made on different welding procedures or heat inputs. It was shown that after the welding without preheating, the welding does not affect the ductility of QST steels.

3.4. Example of modern types of steel in high importance structures

Lucian Weber's study (Weber, 2003) explained the difference between HISTAR 460 and other types of steel in high-rise buildings. Using HISTAR 460 helps reduce the columns' weight with an average of 15-25% compared to S355, and with 45% compared to S235. It can also be used in the design, where columns with concrete core are needed, supporting all the lateral loads. Accordingly, the benefits of using HISTAR in columns with regular buckling lengths go to an economic impact by reducing the costs. Also, regarding the design, it is a reason to reduce the weight of the structure. An example is the Mapfre Tower from Barcelona, Spain, where a diagram was made to show the weight savings in gravity columns using HISTAR 460 (see Fig. 3).

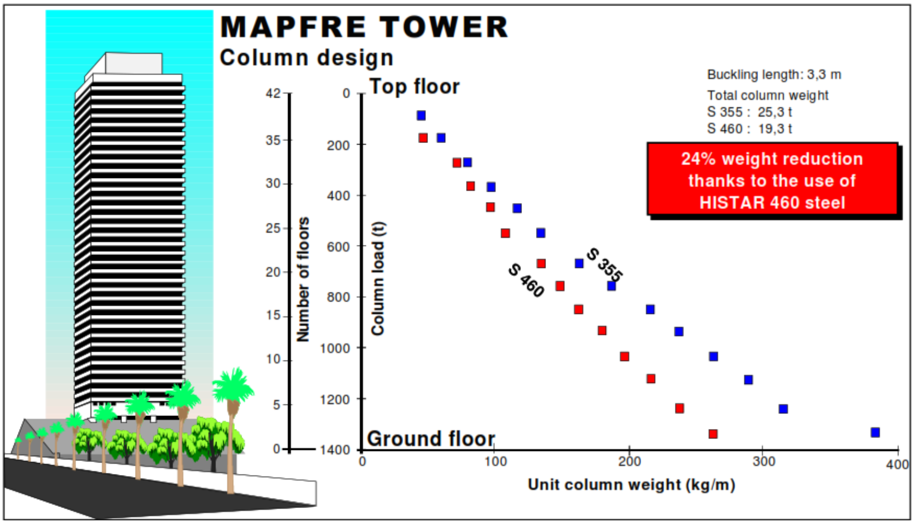

Fig. 3 Weight savings in gravity columns using HISTAR 460 for Mapfre Tower

It is suitable to use HISTAR for trusses for tension and compression members with short buckling length, which allows a weight reduction of 15% compared to the S355 type. This reduction is a function of the truss span and the importance of the dead loads (Weber, 2003), easily implemented on bridges. An example is the WD-57 bridge in

Poland (see Fig. 4), where rolled I-beams in the structure's network arches were used. The engineers choose this option to optimize the construction costs and the building time, and due to the structural analysis, less steel was needed to resist the high compression forces in the arches (Lorenc et al., 2018).

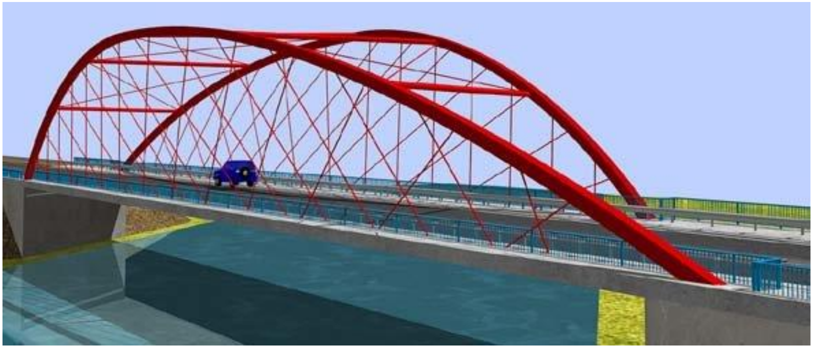

Fig. 4 Net-arch bridge with rolled I-sections in Poland (WD-57 Bridge)

Based on its efficiency, another bridge in Poland, the MS-15 Bridge with a 120m span length (see Fig. 5), was constructed using the same procedure. For this bridge, steel profiles in HISTAR 460 steel grade were used. In this case, the arches were delivered in pieces assembled by the builders using welded site joints. The beams had weld access holes (see Fig. 6) to allow for a residual stress reduced joint.

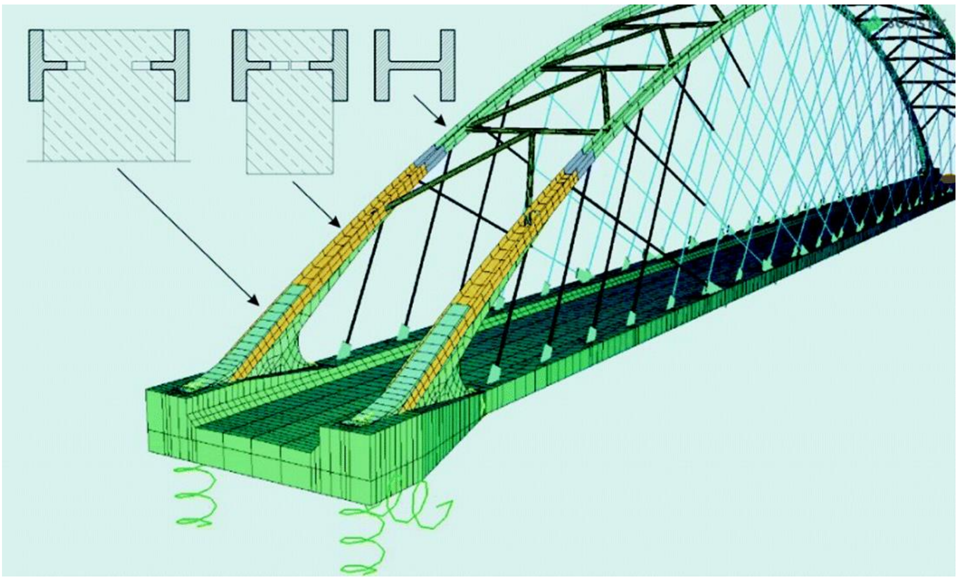

Fig. 5 MS-15 Bridge with 120 m span length in Poland

Fig. 6 Beam with weld access holes

4. CONCLUSION

The modern types of steel can be considered optimal for energy-saving and process saving. This is the reason why, for example, HISTAR steels are the right choice instead of conventional structural steels. The grounds also include the shortest time for the preheating procedure. Besides, the costs and time can be saved for this type of steel. For HISTAR steels, the cost savings are the results of weight reduction and the fabrication process in high loaded columns, truss members, bridge structures, or strong column-weak beam concept.

Thanks to the modern types of steel, the efficiency of bridge constructions can be optimized, regarding time, efficiency, cost-saving, and sustainability. Besides, the solutions with hot-rolled sections are more economical for bridges.

The steels that go through a TM rolling process have more benefits, like reduced scale formation, excellent cold formability, best flatness, and cuttability. Another modern way to produce steels is using the QST process, which is more advanced than TM rolling techniques. The rolling mills' mechanical power limits the TM due to the high deformation rates that the process implies.

The favorable combination of high strength, high toughness at low temperatures, and easy weldability also make these new steel grades very suitable for offshore applications. (Hechler et al., 2015).

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PRIMENA SAVREMENIH TIPOVA ČELIKA U KONSTRUKCIJAMA SA ASPEKTA OSOBINA MATERIJALA PREMA EVROKODU 3

Istraživači često raspravljaju o ovoj temi a posebno u pogledu ponašanja čelika kao materijala koga najčešće srećemo u građevinarstvu. Primena čelika u građevinarstvu je posebno zanimljiv ne samo za projektante, dobavljače već i za izvođače radova zbog niza logističkih prednosti. Na osnovu analiziranih podataka u ovom radu je detaljno analizirana mogućnost primene savremenih vrsta čelika u građevinskim konstrukcijama prema Evrokodu 3 sa aspekta mehaničkih karakteristika čelika kao materijala.

Ključne reči: *savremene vrste čelika, karakteristike materijala, Evrokod 3*

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DEFORMATION INDETERMINACY IN GLOBAL ANALYSIS OF STEEL STRUCTURES WITH SEMI-RIGID JOINTS

UDC 624.014.2:519.6

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Abstract. *This paper shows the procedure for determination of deformation indeterminacy within global analysis of steel constructions with semi-rigid joints, as well as the analysis of deformation indeterminacy within the approximate deformation method. In this paper there has been a detailed comparative analysis with criteria of cinematic system stability and division on steel frame with semi-rigid connections to systems with movable and immovable joints.*

Key words: *steel constructions, deformation model, semi-rigid connections.*

1. INTRODUCTION

The extension of classical deformation method that has been applied for global analysis of steel constructions with semi-rigid joints has been conducted in paper [1]. The process of calculation of steel linear systems with semi-rigid joints in function of the rotational rigidity of joints as a realistic parameter for determination of the stress field of both the joint itself and the construction as a whole has been given. Expressions for determination of bending moments at the ends of semi-rigidly connected elements within steel constructions and conditional equations for determination of deformation indetermined values at an approximate deformation method under static load of the First order theory have been given for introduced rotation rigidities of realistic connections.

This paper shows the procedures for determination of deformation indeterminacy within the global analysis of steel constructions with semi-rigid connections as well as the analysis of deformation indeterminacy of steel constructions within the approximate deformation method.

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2. CONNECTIONS BETWEEN THE COMPONENTS OF KNOTS MOVING WITH SEMI-RIGID JOINTS AND BARS LENGTH SHIFTING

Relations between displacement components of nodes i and k - (u_i, v_i, u_k, v_k) and the length change (δl_{ik}) of the member ik that connects the two nodes are derived by comparing these two nodes and the length of the member before deformation, l_{ik}, and after deformation, $l_{ik} + \delta l_{ik}$, (Fig. 1).

The coordinates of the nodes i and k are denoted by (x_i, y_i) and (x_k, y_k), and the angle between the longitudinal axis of the nondeformed member ik and the axis O_x of the arbitrary coordinate system O_{xy} (valid for all members) is denoted by α_{ik} (Fig. 1). After the nodes i and k, as the result of the member deformation, change their position to i' $(x_i + u_i, y_i + v_i)$ and k' $(x_k + u_k, y_k + v_k)$, the member length would change from δl_{ik} to $l_{ik} + \delta l_{ik}$, and angle α_{ik} would change by $\delta\alpha_{ik} = \psi_{ik}$ and become $\alpha_{ik} + \psi_{ik}$. Also, the member would rotate for the angle ψ_{ik}. The node displacement components of nodes i and k are denoted by u_i, v_i, u_k, v_k . Figure 1 shows that:

$$(x_k + u_k) - (x_i + u_i) = (l_{ik} + \delta l_{ik}) cos(\alpha_{ik} + \psi_{ik}), \tag{1}$$

$$(y_k + v_k) - (y_i + v_i) = (l_{ik} + \delta l_{ik}) sin(\alpha_{ik} + \psi_{ik}). \tag{2}$$

In case of small displacements:

$$cos(\alpha_{ik} + \psi_{ik}) \approx cos\ \alpha_{ik} - \psi_{ik} sin\ \alpha_{ik},$$

$$sin(\alpha_{ik} + \psi_{ik}) \approx sin\ \alpha_{ik} + \psi_{ik} cos\ \alpha_{ik},$$

which means that equations (1) and (2), disregarding small values of the higher order, can be written as:

$$u_k - u_i = \delta l_{ik} \cos\alpha_{ik} - l_{ik}\psi_{ik} \sin\alpha_{ik}, \tag{3}$$

$$v_k - v_i = \delta l_{ik} \sin\alpha_{ik} + l_{ik}\psi_{ik} \cos\alpha_{ik}. \tag{4}$$

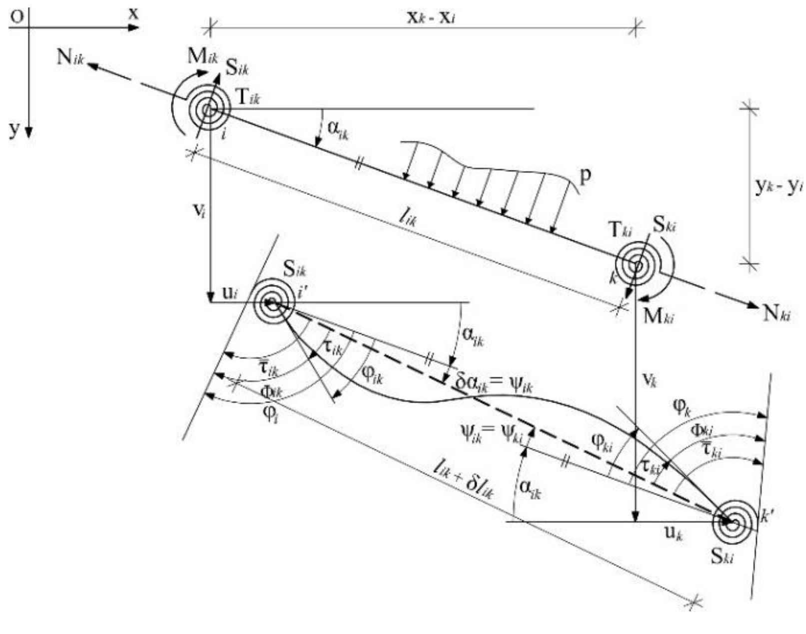

Fig. 1 Straight semi-rigidly connected member at its ends (before and after deformation)

By solving these equations with respect to δl_{ik} and ψ_{ik} we get:

$$\delta l_{ik} = (u_k - u_i)\cos\alpha_{ik} + (v_k - v_i)\sin\alpha_{ik}, \quad (5)$$

$$\psi_{ik} = \frac{v_k - v_i}{l_{ik}}\cos\alpha_{ik} - \frac{u_k - u_i}{l_{ik}}\sin\alpha_{ik}. \quad (6)$$

The change of the member length δl_{ik} is purely deformation value which is equal to zero when the bar is undeformed. Thus, the equation (5) shows the relation between nodes displacement components and the deformation value of bar δl_{ik}. The total number of these equations for the entire system is equal to the number of members within the system, i.e., z_s.

The rotation angle of the member ψ_{ik} is not a purely deformational value and can exist even when the member is undeformed. Thus, equation (6) does not represent the relation between the displacement components of nodes and deformation value of the member.

3. Deformation Unspecifity within Global Analysis of Steel Constructions with Semi-rigid Connections of Approximate Deformation Method

Papers [2], [3], [4], [5], [6] and [7] show that the influence of axial forces on the deformation of frames that are widely applied in steel constructions, do not significantly affect the internal force values at cross-sections of the structural system, thus can be neglected. This significantly reduces the number of deformational indetermined values [5], [6] and [7] which makes this method very convenient for global analysis of steel constructions with semi-rigid connections.

Once the influence of the axial forces on deformations are neglected, the changes of the lengths of the members will only depend on temperature oscillations. The relationships between the component displacements of nodes and the changes lengths of members (5) are as follows:

$$\delta l_{ik,t} = (u_k - u_i)\cos\alpha_{ik} + (v_k - v_i)\sin\alpha_{ik}, \quad (7)$$

Where, according to [6], $\delta l_{ik,t}$ is given by the equation:

$$\delta l_{ik,t} = \int_i^k \alpha_t t^o dl. \quad (8)$$

If t^o is constant on the entire member length, which is actually very common [7], then:

$$\delta l_{ik,t} = \alpha_t t^o l_{ik}. \quad (9)$$

Displacement components u_i, v_i, u_k, v_k, beside from z_o boundary condition of supports [7], now have to satisfy z_s compatibility conditions of node displacements according to equation (7), denoted by $z_o + z_s$:

$$n = 2k - (z_o + z_s). \quad (10)$$

The number of unknown angles φ of node rotation within the approximate deformation method is the same as within the accurate deformation method [7], i.e., equal to m – a number that represents the number of nodes with is at least one semi-rigid connection [1], hence the total number of deformation indeterminates of the structural system within the approximate deformation method *(d)* equals to:

$$d = m + n = m + [2k - (z_o + z_s)]. \quad (11)$$

4. Conclusion

In the analysis of equation (11) taking in consideration whether the number of mutually independent conditions [5], [7] and (7) is equal, smaller or larger than the number of displacement components of the nodes u_i, v_i, u_k, v_k, three different cases can occur:

1. Case where:

$$z_o + z_s = 2k \Rightarrow n = 0 \longrightarrow d = m, \tag{12}$$

i.e., the number of compatibility conditions of nodes displacements $(z_o + z_s)$ is equal to the number of nodes displacement components and if all the conditions are mutually independent, the displacements of all of the nodes can be determined only from deformation conditions and thus be expressed by the function of temperature oscillations and supports displacements, i.e., rotation of clamping as:

$$u_i = u_{i,t} + u_{i,c}, \tag{13}$$

$$v_i = v_{i,t} + v_{i,c}, \tag{14}$$

where $u_{i,t}$ and $v_{i,t}$ are the node displacement components due to temperature oscillations and $u_{i,c}$ and $v_{i,c}$ are node displacement components due to supports displacements, i.e., rotation of clamping. Once there are no temperature oscillations and the supports do not move, when there is no clamping rotation, the conditions (7) are homogenous, thus the displacement components of all nodes are equal to zero. These frame-like structural systems of steel constructions with semi-rigid connections are called systems with immovable nodes. In these cases, the deformation indeterminate values are only the rotation angles of nodes (φ). Hence, the number of deformation indeterminates (d) of these systems is equal to m.

2. Case where:

$$z_o + z_s > 2k \Rightarrow n < 0, \tag{15}$$

if the number of conditions for displacement compatibility of nodes $(z_o + z_s)$ is larger than the number of displacement components and if there is $2k$ mutually independent conditions, the system also has immovable knots. When the supports do not move, i.e., the clampings do not rotate and the temperature oscillations are nonexistent, the displacements u_i, v_i, u_k, v_k of all the nodes of the system must equal to zero. Here as well, those deformation indeterminate values are only the rotation angles of nodes (φ) and the of deformation indeterminacy is equal to m. However, [7] shows the difference among systems with ideal connections at nodes, where the analyzed systems where those where the condition number (7) is equal to the number of displacements, and those where the number of conditions overcomes the number of displacements. When it comes to steel frame systems with semi-rigid joints, where the number of conditions (7) is equal to the number of displacements, i.e., when the relation (12) is valid, the displacement components due to temperature oscillations and support movements – clamping rotation, can be specifically determined from condition (7) and expressed through equations (13) and (14). If the number of conditions (7) overcomes the number of displacements, in general case there are no displacements that will satisfy all the conditions. Neglecting the influence of axial forces on deformation, the incompatible deformation conditions are derived. In order to determine displacements of nodes due to temperature oscillations and support displacement – clamping rotation for these systems, the influence of axial forces on deformations must be taken into consideration [7].

3. Case where:

$$z_o + z_s < 2k \Rightarrow n > 0, \tag{16}$$

if the number of conditions of displacement compatibility of nodes $(z_o + z_s)$ is smaller than the number of displacement components, some displacements can be chosen arbitrarily, with keeping all of the conditions satisfied [7]. When it comes to steel frame constructions with semi-rigid joints, the nodes can move even when there are no temperature oscillations and when supports are not moving – the clamping's are not rotating. Hence, these systems are called the systems with moving nodes. Apart from *m* angle rotations, deformation indetermined values are:

$$n = 2k - (z_o + z_s), \tag{17}$$

which represent the independent displacement components of nodes (u and v).

For the systems with movable nodes, the number of independent equations [7] is smaller than the number of indeterminate displacement components of u and v by the value of *n*. In order to express displacements of nodes with equations (7), n more equations must be added:

$$F_j(u_i, v_i) = \Delta_j, j = 1, 2, \ldots, n. \tag{18}$$

The system of equations (7) and (18) can be solved if functions $F_j(u_i, v_i)$ are mutually independent and independent from functions of displacement of nodes at the right side of equations (7). Movements at nodes are thus dependent on support displacements and temperature oscillations that are considered in equations (7) and values $\Delta_j, j = 1, 2, \ldots, n$ (equal 18), which are referred to as displacement parameters in [6] and [7].

Once the comparative analysis of previously presented cases and systems stability criteria is conducted [7], it can be seen that the criteria by which the structural systems are divided into systems with movable and immovable nodes are nothing more than criteria to determine whether the truss created by z_s members and z_o supports, obtained by removing all the clamping's and semi-rigid joints and replacing them with pinned joints, is cinematically stable or unstable. Trusses formed in this way from the systems with immovable nodes are cinematically stable (simple or multiple), whilst the systems with movable nodes are those which have a labile system truss.

Division of systems with immovable nodes systems where relation (12) can be applied and those on which relation (15) applies corresponds to division of cinematically stable system trusses to simply cinematically stable and multiple cinematically stable, i.e., to statically determined and statically undetermined trusses.

It is known that, when it comes to statically determined truss systems, support displacements, i.e., the node movements and temperature oscillations do not cause internal forces, thus determination of node displacement is purely geometrical and needs to be solved by construction of Williot's displacement diagram.

When it comes to statically undetermined truss systems, support displacements, clamping rotation and temperature oscillations cause internal forces that affect the displacements, hence it is impossible to determine node displacement while neglecting the influence of axial forces on the deformation of the system. Node displacements of these systems are determined by well-known methods for determination of statical displacement of undetermined structural systems.

Determination of node displacement and member rotation of cinematically labile system truss is based on the determination of mechanism of movement, while the number of displacement parameters $n = 2k - (z_o + z_s)$ represents the number of degrees of freedom of truss system which is equal to minimal number of elements that needs to be added in order to turn the truss into a stable system.

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DEFORMACIJSKA NEODREĐENOST U GLOBALNOJ ANALIZI ČELIČNIH KONSTRUKCIJA SA POLU-KRUTIM VEZAMA

U ovom radu prikazan je postupak za određivanje deformacijske neodređenosti u globalnoj analizi čeličnih konstrukcija sa polu-krutim vezama kao i analiza deformacijske neodređenosti u približnoj metodi deformacija. U radu je detaljno izvršena komparativna analiza sa kriterijumima o kinematičkoj stabilnosti sistema i podeli na čelične ramovske nosače sa polu-krutim vezama na nosače sa pomerljivim i nepomerljivim čvorovima.

Ključne reči: *čelične konstrukcije, metoda deformacije, polu-krute veze.*

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