Southeastern Europe Tunnelling Conference (SETC-2025)
1-3 October 2025, Belgrade, Serbia

DOI: 10.5937/SETC25034B

Revealing the latent potential and social value of underground infrastructure development

Andreas Benardos[a] and Doris Skenderas[a]*

[a] National Technical University of Athens, School of Mining and Metallurgical Engineering, Athens, Greece; abenardos@metal.ntua.gr, skenderasdoris@metal.ntua.gr

Abstract: In an era of accelerating urbanization and spatial constraints, the strategic use of underground infrastructure is gaining increasing importance as a sustainable, long-term solution. Despite their recognized advantages—such as improved mobility, reduced travel time and emissions, enhanced safety, and preservation of surface land—underground projects often face reluctance due to high capital costs, technical complexity, and extended return-on-investment periods. This paper aims to reassess the value proposition of underground infrastructure by highlighting its broader socio-economic benefits and demonstrating a holistic evaluation framework that supports more informed decision-making. A real-world tunnel case between Melissourgoi and Theodoriana in Greece is analyzed, showcasing how a relatively small infrastructure investment can yield disproportionately large benefits in terms of accessibility, regional development, and environmental performance. Quantified indicators such as vehicle operating cost, travel time savings, and accident cost reduction reveal annual savings for the users of the infrastructure, allowing cost recovery within just 4–5 years, depending on traffic volume. To further support comparative evaluations, the study also presents the Tunnel-to-Road Equivalent Length (TREL) ratio—a decision-support tool that considers traffic volumes (AADT), geotechnical conditions (GSI), and life-cycle cost–benefit parameters. Results indicate that while geotechnical conditions impact construction costs, traffic volume is the dominant factor in determining long-term economic viability. Finally, the paper advocates for integrating social and economic impact assessments into early-stage project planning, enabling a fairer evaluation of underground alternatives, as the latent social benefits presented by underground infrastructure solutions can shift the decision towards the "going underground" option.

Keywords: underground infrastructure; decision support; life cycle cost-benefit analysis; socio-economic evaluation

1. Introduction

The rapid pace of urbanization and population growth has led to intensified pressure on existing urban infrastructure. With land being a finite and increasingly contested resource, the strategic development and utilization of underground space have become increasingly important in modern societies, offering an effective and sustainable alternative solution. Across the world, governments are turning to underground solutions, from metro transit systems to highway tunnels, to address urban congestion and geographic barriers. Underground transportation projects, such as road tunnels and metro systems, have emerged as pivotal components of modern infrastructure, facilitated mobility while preserving valuable surface land (Kaliampakos and Benardos, 2008).

However, the development of underground infrastructure is often marred by perceptions of high initial investment costs, long construction durations, and technical risks, which frequently result in cost overruns and schedule delays (Flyvbjerg et al., 2002; Paraskevopoulou et al., 2022). This can dissuade stakeholders and policymakers from pursuing such projects, even when their long-term benefits significantly outweigh the costs. Despite these challenges, underground infrastructure provides numerous advantages. These include reduced travel times, lower CO_2 emissions, decreased accident rates, less traffic congestion, and uninterrupted 24/7 operation (Benardos and Skenderas, 2025).

*Corresponding author: abenardos@metal.ntua.gr (A. Benardos).

Moreover, these systems can reclaim surface space for green areas or urban development and stimulate regional economic growth (Kaliampakos et al., 2024).

Based on the above, the provision of a clear understanding of the net costs and net benefits offered by underground projects is the key issue for reaching a well-balanced and rational decision. Of course, this is something that requires not only the surficial data that can be easily assembled, but also needs to take into account the whole life cycle costing of the project (Daub, 2023). Finally, emphasis is required in depicting the social value of the project, that is, gathering and monetizing its impact on its users or the communities that it serves (Soleymani and Ismail, 2022).

This paper aims to reveal the latent value of underground transportation solutions by examining both their socio-economic benefits and their broader strategic relevance. It begins with an in-depth assessment of a real-world example, a small mountainous tunnel project in Greece, demonstrating how underground infrastructure can deliver transformative impacts in terms of accessibility, safety, and regional development. Building on the insights from this case, the paper introduces a generalized, holistic evaluation framework designed to support comparative analyses between tunnel and surface road alignments. This framework integrates life-cycle cost-benefit analysis (LCCBA) and introduces the Tunnel-to-Road Equivalent Length (TREL) ratio as a decision-support tool. Together, these cases illustrate a continuum, highlighting how underground infrastructure can be systematically assessed, justified, and prioritized within long-term development strategies.

2. Costs and benefits from the development of underground projects

2.1. Main issues to consider

The development of an infrastructure project is often associated with a vast amount to be spent that will eventually develop a new set of prevailing conditions that can either solve problems or improve the performance of a system. Thus, the decision to proceed with a certain project requires a comprehensive assessment of the costs as well as the impacts that will be brought and that can be quantified properly so as to have the required indicators for assessing the most prominent and most beneficial alternative.

The initial costs that can be measured under a simple financial framework are associated with the capital expenditures and the operation and maintenance required throughout the lifespan of the project. On the other side, the development of the new infrastructure brings either new benefits to its users and society in general or decreased cost conditions by employing the new infrastructure over the previous one. These socio-economic costs (or benefits) are related to the costs affecting the impacts and indirect economic costs generated by the project's development (e.g., travel time costs, CO_2 emissions cost, accident, noise or traffic disruption costs, fuel cost, etc. (OECD, 2017).

Despite these compelling benefits, underground projects have historically struggled to attract investment due to their high initial costs and risk profiles (Godard and Hugonnard, 1989). Large tunneling and metro projects are capital-intensive; for example, expanding a subway network costs on the order of $200 million per kilometer to recent estimates, while annual operating and maintenance expenses, approx. 2% of the initial investments add further to lifecycle costs (Blankespoor et al., 2024). Such heavy upfront expenditures, combined with typically long payback periods, make financiers and officials cautious (Godard and Hugonnard, 1989). Moreover, many high-profile underground projects have incurred substantial budget overruns and schedule delays pattern documented by Flyvbjerg et al. (2002) in a study of global infrastructure projects. This track record feeds a perception that "underground space development is an expensive venture" fraught with uncertainty, prompting some stakeholders to favor cheaper surface solutions or to postpone needed investments.

However, focusing only on immediate costs can be misleading. A growing body of research and project experience shows that the latent social and economic benefits of underground infrastructure often far outweigh the initial expense when examined over the long term. These benefits, improved connectivity, time savings, safety gains, environmental protection, and induced economic development tend to accumulate for decades after construction. If properly quantified and monetized, they can counterbalance the costs and make a strong case for tunneling solutions (Benardos and Skenderas, 2025).

To assess and reveal to the full extent this latent potential of underground space projects, the following 2 cases are presented. The first utilizes a singular small-scale project having a clearly defined scope, cost, and impacts generated, while the second utilizes a more generic approach that entails a greater set of features to be considered, and more particular geotechnical conditions encountered, and the time discounting principle that can be a significant parameter for the financial valuation of major infrastructure projects.

2.1.1. Monetizing the Socio-Economic Benefits for the Melissourgoi – Theodoriana Tunnel Project

The proposed development project is a mountainous road tunnel between the villages of Theodoriana and Melissourgoi, which are located in the area of Central Tzoumerka, Epirus, Greece. These two settlements are located approx. 10 km apart, but, due to topographical constraints, their connection is now rather difficult as they are connected through an existing circular road network, almost 75 km in length, resulting in a travel time of approximately 2.5 hours and raising concerns about safety and accessibility. For the evaluation of the Melissourgoi–Theodoriana tunnel project, the analysis captures not only the development cost but also the tangible and intangible benefits accruing from its operation, comparing them with the current, less efficient road alternative.

The construction cost of the tunnel has been estimated using two parallel methodologies: (i) an empirical model based on as-built tunnel cost data from Greek projects and (ii) a detailed cost breakdown based on a bill of quantities derived from the design phase. Both approaches comply with official Greek guidelines and state contracting principles. The estimated development cost for the tunnel ranges between €16.7 million and €23.6 million (excluding VAT).

The benefits arising from the proposed infrastructure are multifaceted, impacting several domains (Kaliampakos et al., 2024):

- Travel Time Reduction: The tunnel enables a direct connection between Melissourgoi and Theodoriana, reducing the travel time from approximately 2.5 hours to just 20 minutes. The existing 75 km circuitous route will be replaced by a 16 km tunnel alignment. This dramatic reduction in travel time enhances regional connectivity and reduces isolation, especially for mountainous communities facing aging populations and demographic decline.
- Improved Accessibility: The tunnel significantly improves local accessibility across the broader Tzoumerka region. Travel time reductions of up to 70% between key settlements (e.g., Pramanta to Theodoriana) and 26% for regional links (e.g., Pramanta to Trikala) result in up to 15% increase in the ARI (gr) accessibility index, according to prior studies.
- Tourism and Regional Development: Enhanced connectivity will promote regional tourism by consolidating the Tzoumerka area into a more coherent travel destination. Reduced distances and shorter travel times are expected to increase the inflow and retention of visitors, contributing to the economic revitalization of the region.
- Environmental Impact: The tunnel solution introduces significant environmental advantages. Unlike surface road alternatives, it minimizes visual and ecological disruption to the sensitive mountainous landscape. CO_2 emissions are also reduced due to shorter travel distances and times. Furthermore, construction-phase impacts are reversible and of low to moderate intensity.

To quantify the benefits in monetary terms, the analysis focused on three main factors: (i) vehicle operating costs, (ii) travel-time value, and (iii) accident costs. Thus, CO_2 emissions reduction and regional development benefits haven't been included. Having the afore-mentioned impacts the values used to conclude the assessment, using value data from Greek conditions, vehicle operating cost at €0.20/km, time value at €10.7/h per passenger, and normalized accident cost at €256,000 per event, the annual use/service cost was calculated under different AADT (Average Annual Daily Traffic) scenarios, for the usage of light vehicles only (Kaliampakos et al., 2024).

In Fig. 1, the overall service cost/user cost of the new project and the currently used ring road (do-nothing alternative) is given, over several Average Annual Daily Traffic (AADT) scenarios. For an AADT of 300, the tunnel scenario yields an annual service cost of approx. €1 million, compared to million €6 for the road alternative. This results in annual savings for the users of the infrastructure of €5 million. When the AADT rises to 500 or even 1000, this difference escalates to 7.5 million and 17.4 million, respectively. The difference between the service cost of the infrastructure represents direct economic gains to its users in the form of monetized time savings, reduced fuel and maintenance costs, and improved road safety features. This represents the basis on why to pursue new infrastructure, to create new, improved conditions that will finally redistribute and diffuse the benefits to society (Kaliampakos et al., 2024).

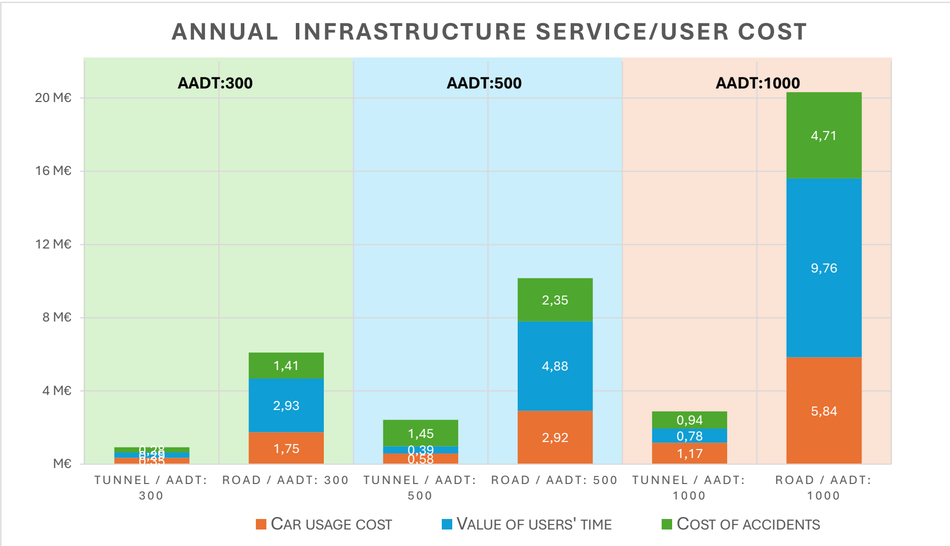


Fig. 1. Comparison of the annual infrastructure service/user cost (veh.oper.cost, travel-time cost, accident cost) between the proposed tunnel project and the current surface road option, concerning AADT values.

2.1.2. Tunnel to Road Equivalent Length (TREL) Ratio

Benardos and Skenderas (2025) presented a more thorough and well-structured approach. The analysis is focused on a life cycle perspective to evaluate the alternatives in the long term, and thus, the proposed methodology deployed entails implementing a gate-to-gate LCC analysis combined with a conventional CBA, to evaluate a project's market and non-market costs and benefits in a long-term perspective, resulting in a Life Cycle Cost-Benefit Analysis (LCCBA) (Benardos and Skenderas, 2025).

As in the previous case presented, the benefits deriving from the infrastructure are travel time savings, reduction in vehicle operating costs and fuel consumption, accident costs, etc. These are compared against capital requirements covering the construction, electrical, and mechanical installations, as well as operation and maintenance costs. Nevertheless, in establishing a more generic framework of analysis, the construction cost data also takes into account the differentiation of geotechnical conditions that are crucial for capital expenditure. The data is coming from a Greek tunnel construction dataset (Paraskevopoulou and Benardos, 2013) that has recorded the as-built construction cost, while all cost values have been adjusted to 2020 prices, setting them all to a common reference period.

In addition to the above feature, all financial/economic data is used in a discounted cash flow approach, in an attempt to minimize the impact of time in the valuation of the project. For the latter, the economic valuation from a societal perspective is selected, focusing on deriving the Economic Net Present Value

(ENPV) of the project over a 30-year evaluation period ($ENPV_{30}$), minimizing long-term forecasting errors and being aligned with the European Commission's suggestions (European Commission, 2015).

The adopted methodological framework enables a comprehensive and comparative evaluation of infrastructure development alternatives, particularly between surface road and tunnel solutions. The cost analysis is structured around key influencing parameters: the total length of each infrastructure option, the Annual Average Daily Traffic (AADT), and the site-specific geotechnical conditions that significantly impact construction complexity and associated expenditures. By incorporating these variables, the approach allows for realistic scenario modelling and the assessment of cost variations under changing traffic demands and ground conditions.

To provide a consistent basis for comparison, the Tunnel-to-Road Equivalent Length (TREL) ratio is introduced. This metric expresses the length of a tunnel that would be economically equivalent to a given length of surface road, taking into account not only direct construction costs, but also operational, environmental, and socio-economic factors. The TREL ratio thus functions as a decision-support tool, facilitating the evaluation of cost-effectiveness between alternatives. It allows stakeholders to account for the higher unit costs typically associated with tunnel construction while recognizing the long-term benefits tunnels may offer, such as shorter travel distances, reduced environmental impact, improved safety, and lower ongoing user/service costs (Benardos and Skenderas, 2025).

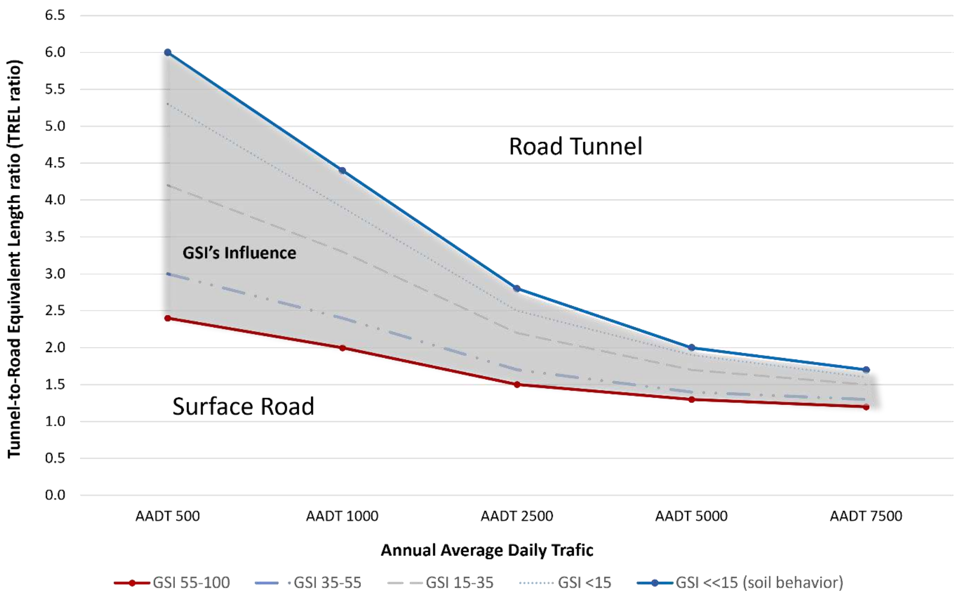
The results of the analysis are given in the following Table 1 and Figs 2 (a) and (b) (Benardos and Skenderas, 2025). For example, from Table 1, it can be seen that for GSI in the range of 15-35, 1 km of tunnel construction has the equivalent cost of 11.3 km of surface road (or 1 km of tunnel can replace 11.3 km of surface road). This ratio is either shortened in case of having better geotechnical conditions as the construction tunnel cost drops and cost equivalency can be reached with reduced road length - meaning that a tunnel can be more promising alternative to replace shorter road distances - or elongated when more adverse conditions are encountered and construction cost increases, having more adverse final performance over a surface road alternative. Likewise, when considering also the operation phase of the infrastructure, an increase of AADT value results to a significant drop in the length of surface road that can be replaced, meaning that the tunnel alternative can be utilized in decreased road lengths. Hence, for the same GSI category (12-35) for an ADDT of 1,000 cars, the TREL ratio drops to 3.3, or even further to 1.7 when an AADT of 5,000 is foreseen (Benardos and Skenderas, 2025).

Table 1. Tunnel to Road Equivalent Length ratio (TREL ratio) (adapted from Benardos and Skenderas, 2025).

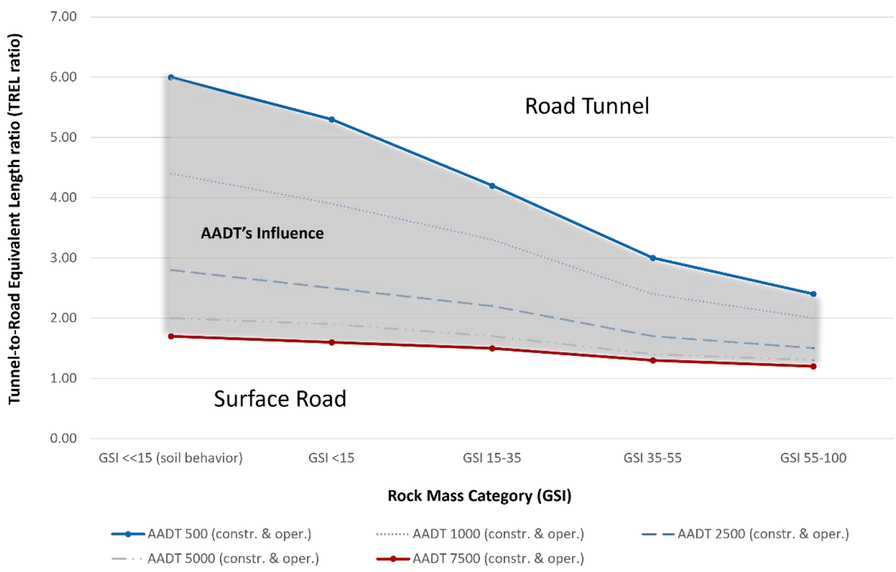
		Geotechnical Conditions - Rock mass category (GSI)				
		55-100	35-55	15-35	<15	<<15 (soil behavior)
Construction only		4.4:1	6.2:1	11.3:1	15.5:1	16.6:1
Annual Average Daily Traffic (AADT)	500	2.4:1	3.0:1	4.2:1	5.3:1	6.0:1
	1,000	2.0:1	2.4:1	3.3:1	3.9:1	4.4:1
	2,500	1.5:1	1.7:1	2.2:1	2.5:1	2.8:1
	5,000	1.3:1	1.4:1	1.7:1	1.9:1	2.0:1
	7,500	1.2:1	1.3:1	1.5:1	1.6:1	1.7:1

In Figs 2 (a) and (b), this is presented graphically; the first graph is how the geotechnical conditions influence the TREL ratio concerning the geotechnical conditions, while the second is just the opposite, exploring the influence of the AADT's values in the TREL ratio, while also counting the geotechnical conditions in the form of GSI values.

Ultimately, the integration of the TREL ratio into the decision-making process enhances transparency and consistency, enabling planners and decision-makers to identify the most sustainable and value-generating solution in line with technical feasibility and regional development objectives.



(a)



(b)

Fig. 2. (a) Impact of geotechnical conditions on the Tunnel-to-Road Equivalent Length (TREL) with respect to AADT. (b) Influence of AADT Tunnel-to-Road Equivalent Length (TREL) with respect to the rock mass categories (GSI) encountered during construction (Benardos and Skenderas, 2025).

3. Discussion - Conclusions

The selection between a tunnel and a surface road alignment is not always the clearest and most straightforward decision, as many parameters tend to fog the view of the stakeholders. The paper attempts to provide a clear statement on the value given by underground solutions.

This is evidenced by the analysis of the Mellisourgoi–Theodoriona tunnel alternative which demonstrates that the proposed tunnel alignment presents a robust investment with substantial socio-economic returns. The quantified benefits are significant, with annual savings enabling the full recovery of construction costs in just 4 to 5 years, depending on traffic volume. Beyond financial returns, the tunnel offers strategic value by improving mobility, stimulating regional development, and fostering environmental stewardship.

The addition of the comprehensive methodological framework and the introduction of the TREL ratio is particularly useful to accurately take into account biases in the form of geotechnical conditions and time valuation issues in a single index. The generalized tunnel vs. road analysis reinforces the idea that underground solutions often shine when evaluated in a holistic, long-term context. It provides evidence that, under a wide range of realistic conditions, a tunnel can deliver more net value than a surface road, especially as traffic grows. Some key takeaways from the study include:

- Traffic volume is the primary driver of cost-efficiency. Higher AADT means more users reap the travel time and cost benefits, thus justifying the tunnel's high initial cost more quickly. In high-traffic corridors, tunnels are highly advantageous if they shorten the route at all significantly.
- Geotechnical difficulty, while impacting construction cost, is a secondary factor in economic viability. Difficult ground raises a tunnel's cost, but in scenarios with substantial traffic, the incremental user benefits still outweigh these extra costs. However, in low-traffic cases, bad ground can indeed tip the balance against a tunnel by requiring an impractically large distance saving to justify it. Thus, both factors should be weighed, but one should not automatically dismiss tunnels due to geology without considering traffic and benefits.
- Underground alternatives generally have higher socio-economic value than surface roads for equivalent service, when one accounts for all external benefits. This stems from the fact that tunnels often enable superior service (shorter travel, less environmental impact) that is not captured in a simple construction cost comparison. The holistic analysis confirms the "generally stated opinion" that, beyond pure finances, tunnels provide broad societal advantages over roads in many cases.

It gives decision-makers a concrete threshold to consider when debating a tunnel investment. By establishing "how much longer can a road be before a tunnel is worth it," the TREL approach injects clarity into early project debates that are often clouded by uncertainty or bias. It encourages a direct comparison of alternatives on the basis of comprehensive cost-benefit outcomes, rather than merely comparing construction bids or initial budgets. In doing so, it helps reveal the latent value of tunnels that might be overlooked if one looked only at construction cost per kilometer (where tunnels fare poorly against open roads).

Hence, efforts like the ones presented in the paper strengthen the arsenal of those advocating for underground space development, while at the same time providing a structured threshold for decision-makers to seriously consider this option. Beyond the technical and financial metrics, what truly enhances the credibility of such projects is the systematic recognition of the broader societal value they generate, benefits that are often overlooked in conventional evaluations. These social benefits and the value offered to the community are key to "uncovering and monetizing the latent social benefits" of going underground, thereby shifting the cost–benefit calculus in favor of underground space development.

References

Benardos, A., Skenderas, D., 2025. Exploring the true cost of infrastructure transit projects: Road vs Tunnel alternatives. *Tunnelling and Underground Space Technology*, 162, 106624. https://doi.org/10.1016/j.tust.2025.106624

Blankespoor, B., Dasgupta, S., Wheeler, D., 2024, February 14. Riding into a greener future: How widespread use of subways could slash CO_2 emissions. World Bank Blogs.
Daub, 2023. Recommendations for the Determination of Lifecycle Costs for Tunnels. www.daub-ita.de
European Commission, 2015. Guide to cost-benefit analysis of investment projects: economic appraisal tool for Cohesion Policy 2014-2020. Publications Office. https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf
Flyvbjerg, B., Holm, M. S., Buhl, S., 2002. Underestimating Costs in Public Works Projects: Error or Lie? *Journal of the American Planning Association*, 68(3), 279–295. https://doi.org/10.1080/01944360208976273
Godard, J. P., Hugonnard, J. C., 1989. Appraisal of underground urban public transportation projects. *Tunnelling and Underground Space Technology*, 4(1), 31–41. https://doi.org/10.1016/0886-7798(89)90030-8
Kaliampakos, D., Benardos, A., 2008. Underground space development: Setting modern strategies. WIT Transactions on the Built Environment, 102, 1–10. https://doi.org/10.2495/US080011
Kaliampakos, D., Benardos, A., Nomikos, P., Marinos, V., Zevgolis, I., 2024. Developing Mountainous Tunnels in Greece—The Case of the Melissourgoi Tunnel. In Proceedings of the 18th Conference of the Associated Research Centers for the Urban Underground Space, ACUUS 2023, 1–4 November; Singapore, Editors:Wei Wu, Chun Fai Leung, Yingxin Zhou, Xiaozhao Li. pp. 195–200. https://doi.org/10.1007/978-981-97-1257-1_26
Paraskevopoulou, C., Benardos, A., 2013. Assessing the construction cost of Greek transportation tunnel projects. *Tunnelling and Underground Space Technology*, 38, 497–505. https://doi.org/10.1016/j.tust.2013.08.005
Paraskevopoulou, C., Dallavalle, M., Konstantis, S., Spyridis, P., Benardos, A., 2022. Assessing the failure potential of tunnels and the impacts on cost overruns and project delays. *Tunnelling and Underground Space Technology*, 123, 104443. https://doi.org/10.1016/j.tust.2022.104443
OECD (2017). Quantifying the Socio-economic Benefits of Transport. https://doi.org/10.1787/9789282108093-en
Soleymani, H. R., Ismail, M., 2022. Challenges and new trends in infrastructure life cycle cost analysis. *International Journal of Sustainable Building Technology and Urban Development*, 13(2), 221–230. https://doi.org/10.22712/susb.20220018