ТЕОРЕТИЧНІ ТА ПРИКЛАДНІ ПРОБЛЕМИ ІНТЕЛЕКТУАЛЬНИХ СИСТЕМ ПІДТРИМАННЯ ПРИЙНЯТТЯ РІШЕНЬ

UDC 303.732.4, 519.816
DOI: 10.20535/SRIT.2308-8893.2023.1.03

# STUDY OF THE UNDERGROUND TUNNEL PLANNING. COGNITIVE MODELLING

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**Abstract**. A study of the underground tunnel planning reliability for megacities is proposed based on the use of foresight and cognitive modeling methodologies. Using the foresight methodology allows, with the help of expert estimation procedures, to identify critical technologies and build alternatives of scenarios with quantitative characteristics. For the justified implementation of a particular scenario, cognitive modeling is used, which allows to build causal relationships based on knowledge and experience, understand and analyze the behavior of a complex system for a strategic perspective with a large number of interconnections and interdependencies. The suggested study allows the reliability planning of underground tunnels on the basis of reasonable scenarios selection and justification of their creation priority.

**Keywords:** cognitive, impulse modelling, planning, scenarios, underground tunnel.

## INTRODUCTION

The global trend of increasing urbanization poses challenges for both expanding and newly developing cities. Population growth leads to an increased demand for reliable infrastructure, which in the current war times is combined with the need for increased safety and environmental awareness of the population. The use of underground space can help cities meet these increased needs while remaining compact, or find the space needed to incorporate new features into the existing urban landscape. When underground solutions are considered and evaluated from the planning or initial stages of a project, better solutions become possible. Efficient and rational placement of numerous structures of transport, energy, economic, municipal, social and creation of large-scale engineering infrastructure sets the task of strategic planning of underground space of megacities [1]. Underground urban development is a complex system in many aspects. Firstly, this system consists of many interconnected subsystems and objects. Secondly, the processes flowing in this system both during construction and operation are also complicated and in some cases poorly predictable, because they are largely related to different geological processes. The problems accompanying the underground urban planning can be referred to the weakly structured problems. Underground urbanism, which is an integral part of the modern megacity, has already gone beyond the individual local objects and is becoming a system factor in the development of cities. Let us consider urbanism as a global super-system in the form of an ordered set of structurally interconnected and functionally interdependent global systems.

The implementation of underground transport tunnel projects requires a detailed study of the surrounding facilities, taking into account the reduced capacity, increased travel time delay, fuel consumption, the number of traffic accidents, which lead to unaccounted economic losses. Thus, it becomes necessary to study and quantify the impact of construction work zones of high-speed public transport system on the transport environment, which will further help to assess economic losses due to the construction work zone of underground transport facilities [2].

According to the "optimistic scenario" over 20 km of transport tunnels can be built in Kiev in the next ten years. At the same time it is necessary to justify the expediency and reliability of the tunnel construction taking into account the development characteristic to the territory in question, the road network, and the characteristics of traffic in the area of the potential tunnel.

All of the above allows us to propose a methodology for anticipation and cognitive modeling of complex systems [3–5] for modeling and analysis of planning the development of the metropolitan underground tunnels under conditions of environmental, man-made and terrorist threats.

## RELATED PAPERS

Practical guidance on assessing the impact of soft ground tunneling in urban areas on existing structures and services is provided in paper [6]. Various empirical approaches to the definition of the surface settlement zone are summarized and the assessment of the magnitude and distribution of surface movements is compared with case history data. A tentative risk classification related to settlement and maximum slope criteria is proposed, which will allow rapid optimization of route adjustments and thereby identification of those buildings particularly at risk and requiring a more detailed assessment. Predicting anomalous geological structures before tunneling (ahead of exploration) has become an important routine in tunneling, providing particularly important a priori information for safe, economical and efficient tunneling. Article [7] analyzes the characteristics, advantages and applicability of various methods. Preliminary exploration should be aimed at determining the properties of the rock before the tunnel is closed, and not at assessing the structure. Life safety issues associated with fires and explosions are critical issues in the design of large underground structures. In [8] these issues are considered and discussed from the viewpoint of existing life safety codes.

Much attention when planning underground facilities is paid to environmental issues, reducing ground noise sources, minimizing vibrations in the environment, both caused by the railway and created by the explosion of rocks [9–11]. Actual problems of underground urbanization of the central part of Lviv are considered in [12]. The questions of interaction of natural and technogenic components during the development of the underground space of the city are covered. The main risk-forming factors in the construction of multi-level underground parking have been identified. The relief, geological structure and hydrogeological conditions of the central part of the city are analyzed. A spatial analysis of the risk-forming components of the geological environment has been carried out. Zones with varying degrees of geological risk have been identified. Reference [13] presents a numerical model for predicting vibrations and re-radiated noise in buildings caused by rail traffic. A three-dimensional numerical model capable of simulating the propagation and transmission of ground vibrations near high-speed railways is presented in [14]. It is used to study the effect of the material that makes up the embankment on the level of ground vibration at different distances from the track. The paper [15] discusses the design, installation, and also experimental and numerical evaluation of the effectiveness of a rigid wave barrier in the ground as a measure to mitigate the effects of railway-induced vibration.

Ground vibration from underground tunnels is a major environmental problem in urban areas. To study this problem, various studies have been carried out, mainly based on numerical methods [16]. This article presents a study of the influence of changes in soil properties with depth (soil heterogeneity) on soil vibration from an underground tunnel. Comparison of experimental and numerical results shows that a homogeneous model can give acceptable estimates of tunnel behavior. However, a clear improvement in the estimates of soil behavior is observed when the change in soil properties with depth is taken into account in the numerical model. In [17], the range disturbed by earthworks and a model for numerical analysis of underground engineering and surface structures are determined, and the relationship between stress and deformation of surface buildings caused by deformation is obtained. The feedback of the results of the analysis with the data management of the GIS platform has been received. By comparing with the relevant standard damage assessment rules, it can provide technical support to decision makers. By analyzing and verifying the case study of the impact on buildings caused by the excavation of the underwater tunnel terminal, it is possible to ensure the safety of the above-ground buildings affected by the excavation.

It follows from the above review that one of the complex problems is underground tunnels, which ensure the vital activity of both surface and underground urban planning. This paper examines the issue of the construction of underground tunnels and the rationale for the priority of their creation.

## MODELS AND METHODS

The development of the strategy of innovative planning of underground construction development belongs to the class of weakly structured tasks, in which the goals, structure and conditions are known only partially and are characterized by a large volume of non-factors: imprecision, incompleteness, uncertainty, and fuzzy data describing the object. Such problems are characterized by many contradictions and uncertainties. The most important of them are:

- ambiguity and inconsistency of requirements for the product;
- inconsistency of goals and ambiguity of the conditions of application of the product;
- uncertainty and unpredictability of possible actions of competitors;
- infinity and unpredictability of risk situations at different stages of the product life cycle.

In these conditions, using heterogeneous, usually incomplete, empirical, experimental, casual and other background information, the developer must formalize and solve the problem of product design, in particular to formulate and justify the goals of its creation. The results of the solution of this problem should prove the practical necessity, technological possibility and economic feasibility of production of the designed product [3].

Solving approximated to reality tasks of anticipation, at its different stages use different methods of qualitative analysis in a single man-machine procedure. In this study, the method of morthological analysis is used to select the characteristic parameters of the cognitive model [4].

The cognitive approach to the solution of this problem required the definition and description of the main elements (parameters, factors, concepts), causes and consequences characterizing the natural-technical geosystem ("underground construction – environment"). As a result of cognitive modeling, scenarios of possible development of a complex system arising under the influence of changes in the internal and external environment of an underground structure must be obtained. It is especially important for knowledge and prevention of negative consequences, minimization of damage in conditions of influence of the most unfavorable combination of negative factors: external and internal static and dynamic loads, all kinds of technogenic influences inside an underground construction, harmful natural manifestations from the rock mass, etc.

A systematic approach to the modeling and scenario analysis of infrastructure planning of the megacity under environmental, man-made and terrorist threats, based on the joint application of the methodologies of foresight and cognitive modeling [18]. It is proposed to use these methodologies together: at the first stage to apply the methodology of foresight using the method of morphological analysis. The results obtained are used as background information to find ways to build an alternative of this or that scenario in the form of a cognitive map. To justify the implementation of this or that scenario alternative, cognitive modeling methodology is involved, which allows to build cause-effect relationships on the basis of knowledge and experience, understand and analyze the behavior of a complex system (SS) for a strategic perspective with a large number of relationships and interdependencies, applying a scientifically sound strategy for implementing the priority scenario [19].

Cognitive modeling begins with the development of a cognitive map of the object. A cognitive map – a structural scheme of cause-and-effect relationships in a system that interprets the judgments and views of the LPR – is constructed in order to understand and analyze the behavior of a complex system. Let the underground infrastructure in question consist of many individual elements. Two elements of the system and patterns can be depicted as separate point-to-points, and if an element is connected to an element by a causal relationship, they are connected by an oriented arc. It is quite possible that consequences can be the cause of changes in other factors. Causal chains can be quite long and complex. The analysis of cause-and-effect chains is necessary, for example, for forecasting of development of a situation, realization of various controls of processes in a system. After the cause-and-effect diagrams are constructed, the decision-making strategies in a given subject area are determined. As a result of cognitive structuration, an informal description of knowledge about the subject area is developed, which can be visualized as a scheme, graph, matrix, table or text [5].

In the study of the problem of justification of land suitability for underground tunnel construction at the first stage were used cognitive models such as a cognitive map – sign oriented graph and a functional graph in the form of a weighted sign orograph

$$G = V, E,$$

where $V$ — set of nodes $V_i \in V$, $i = 1,2,\ldots,k$, which are elements of the system under study; $E$ — set of arcs $e_{ij} \in E$; $i, j = 1,2,\ldots,N$, reflecting the relationship between the nodes $V_i$ and $V_j$; the impact can be positive (sign "+" above the arc), when the increase (decrease) of one factor leads to an increase (decrease) of another, negative (sign "-" above the arc), when the increase (decrease) of one factor leads to a decrease (increase) of another, or absent (0).

Vector graph

$$\Phi = G, X, F(X, E), \Theta,$$

where $G$ is a cognitive map; $X$ is a set of node parameters; $\Theta$ — vertex parameter space; $F(X, E)$ — arc transformation functional.

At the third stage of cognitive modeling, a pulse process model (cognitive modeling of perturbation propagation) was used to determine the possible development of processes in a complex system and develop development scenarios [28]:

$$x_{v_i}(n+1) = x_{v_i}(n) + \sum_{j=1}^{N} f(x_i, x_j, e_{ij}) P_j(n) + Q_{v_i}(n),$$

where $x(n)$, $x(n+1)$ are the values of the index in the vertex $V_i$ at the simulation steps at the moment $t = n$ and following it $t = n+1$; $P_j(n)$ is the momentum in the vertex $V_j$ at the moment $t = n$; $Q_{v_i}(n) = \{q_1, q_2, \ldots, q_k\}$ is the vector of external momentum (disturbing or controlling actions) introduced in the vertices $V_i$ at time $n$.

Simulation cognitive modeling, especially at the design stage of underground space development, is extremely necessary. A serious reason for this may be the fact that it is necessary to anticipate and exclude or reduce the risks, which are inevitably inherent in the underground urban development. One of the complex problems is the underground tunnels providing life for both surface and underground urban development. This paper explores the construction of underground tunnels and the justification of the priority and reliability of their construction.

## CASE STUDY

Let us carry out a study of the reliability planning of two types of underground tunnels: Tunnel 1 through the built-up part of the city and Tunnel 5 through the Dnipro River. Table 1 present the data of the vertices (concepts) of the cognitive models $G_1$ of Tunnel 1.

**Table 1.** The vertices of the hierarchical cognitive map Tunnel 1

| Code | Name of the vertex | Assignment of the vertex |
|---|---|---|
| V1 | V1. State of the Tunnel 1 | Indicative |
| V2 | V2. Anthropogenic activities | Perturbing |
| V2.1 | V2.1. The Evil Mind: Fighting, Terrorism | Perturbing |
| V2.2 | V2.2. Without malice | Perturbing |
| V3 | V3. Technogenic events | Perturbing |
| V3.1 | V3.1. Technical | Perturbing |
| V3.2 | V3.2. Technological | Perturbing |
| V4 | V4. Natural disasters, weather catastrophes | Perturbing |
| V4.1 | V4.1 Shifts | Perturbing |
| V5 | V5. Protection of the object | Basic |
| V6 | V6. The scale of the impact of an undesirable event | Disturbing |
| V7 | V7. Ability to function | Disturbing |
| V8 | V8. Time to restore functioning | Disturbing |
| V9 | V9. Environmental consequences | Disturbing |
| V10 | V10. Economic consequences | Disturbing |
| V11 | V11. Consequences for life | Disturbing |
| V12 | V12. The number of injured | Disturbing |
| V13 | V13. Organizational, technical, etc. capabilities | Basic |
| V14 | V14. Investor | Basic |
| V15 | V15. Level of damage | Disturbing |
| V15.1 | V15.1. Integrity of the ruin system | Basic |
| V16 | V16. Material damage | Disturbing |
| V17 | V17. Geotechnology of construction | Basic |
| V18 | V18. Capacity of land routes | Basic |
| V19 | V19. Population | Basic |
| V20 | V20. Intensity of movement | Disturbing |
| V21 | V21. Average speed | Disturbing |
| V22 | V22. Undeground vibrations | Disturbing |
| V23 | V23. Atmospheric pollution | Disturbing |

Before using the cognitive model to determine its possible behavior of modeling analyzes the various properties of the model is fulfilled. In this case, the stability properties of the model must be analyzed. The initial cognitive map was unstable. Taking into account the weight characteristics obtained from the results of the morphological analysis, a stable cognitive map was obtained for Tunnel 1, and then and for Tunnel 5. The cognitive model was reduced to a stable form with respect to perturbations. According to the adopted criterion [5]: the maximal modulo root of the graph relation matrix characteristic equation is $M = 0.96931$. The cognitive map also is stable according to the initial value. An analysis of the ratio of the number of stabilizing cycles (5 negative feedbacks) and process accelerator cycles (3 positive feedbacks) indicates the structural stability of such a system. For structural stability, the number of negative cycles must be odd [5].

Fig. 1 shows the sustainable cognitive map $G_1$ of Tunnel 1.

The solid lines of arcs in Fig. 1 mean that with an increase (or decrease) in the signal at the vertex $V_i$, the same changes occur at the vertex $V_j$ — an increase (or decrease). The dashed lines of arcs in Fig. 1 mean: an increase (or decrease) in the pulse at the vertex $V_i$ leads to a decrease (or increase) in the pulse at the vertex $V_j$.

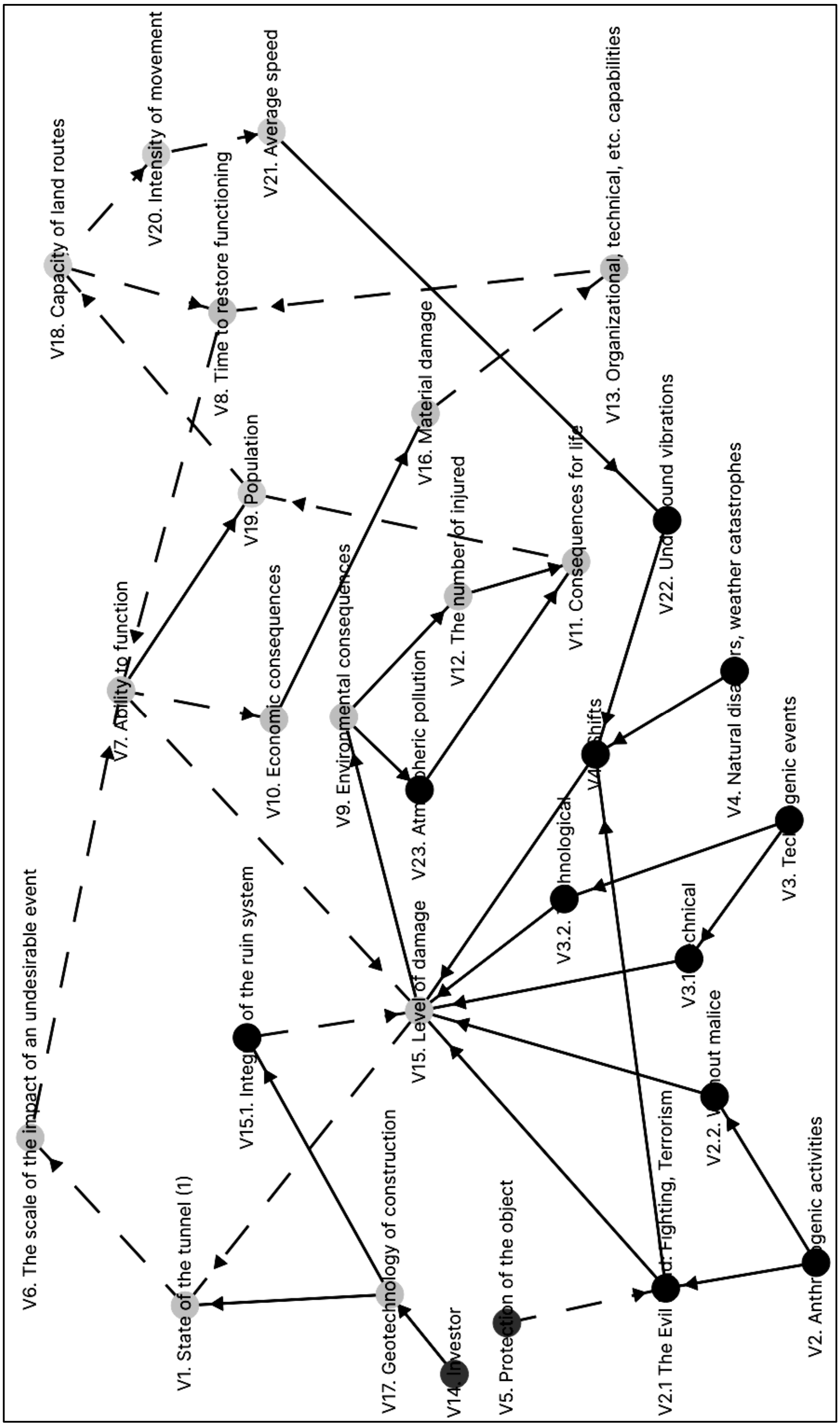


*Fig. 1*. Sustainable cognitive map $G_1$ of Tunnel 1

Now analyze the model 2 connected with cognitive map $G_2$ Tunnel 5 presented in Fig. 2. Vertices V2–V23 of the cognitive map $G_2$ correspond to the vertices of the cognitive map $G_1$ shown in Table 1. Vertices V1, V24 for the cognitive map $G_2$ Tunnel 5 are added to the model 2 (Table 2).

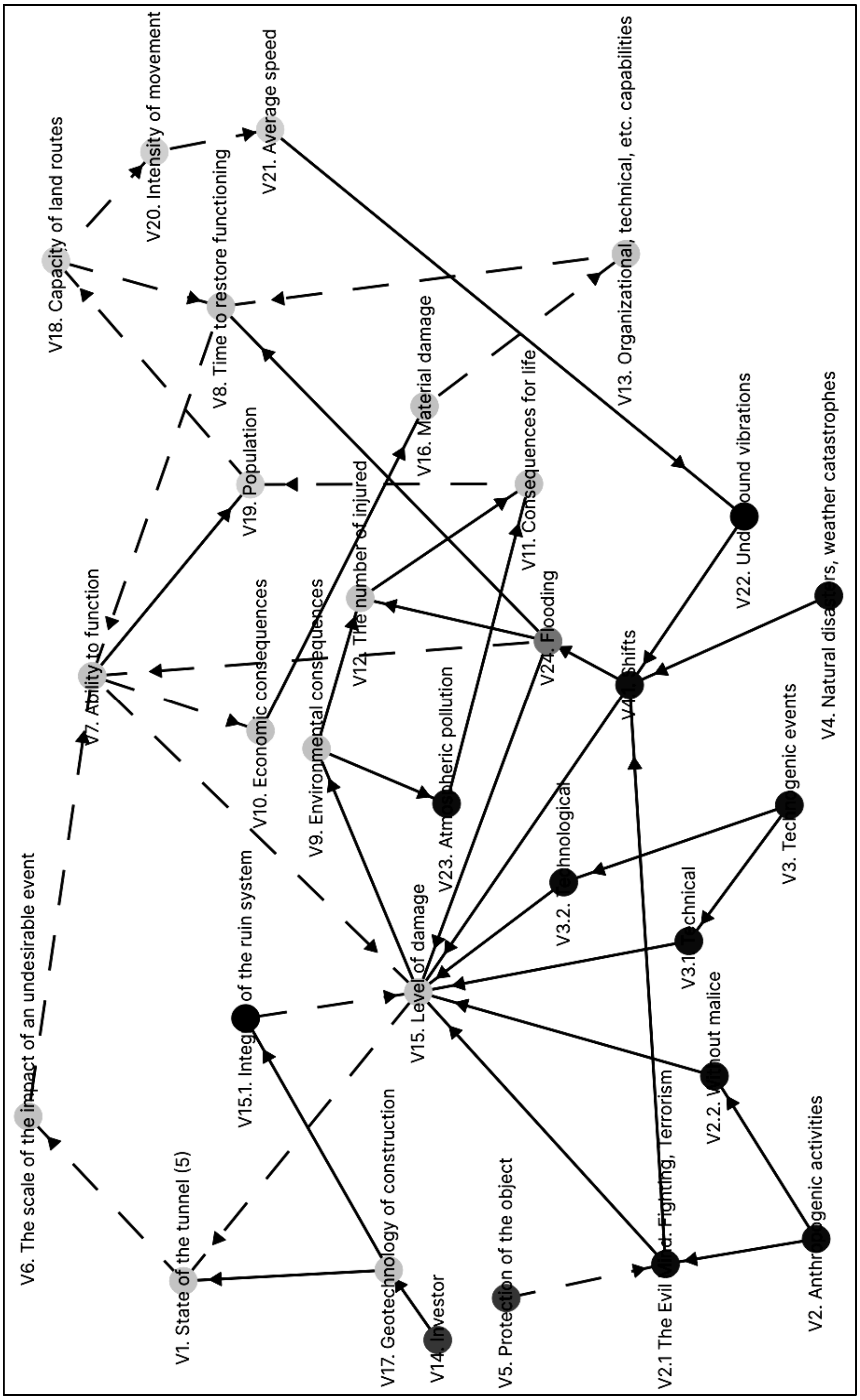


*Fig.* 2. Sustainable cognitive map “Tunnel 5”

According to the adopted criterion [5]: the maximal modulo root of the graph relation matrix characteristic equation is $M = 0.99902$. The cognitive map also is stable according to the initial value.

**Table 2.** The vertices of the hierarchical cognitive map $G_2$ Tunnel 5

| Code | Name of the vertex | Assignment of the vertex |
|---|---|---|
| V1 | State of the Tunnel 5 | Indicative |
| V24 | Flooding | Perturbing |

An analysis of the ratio of the number of stabilizing cycles (15 negative feedbacks) and process accelerator cycles (3 positive feedbacks) indicates the structural stability of such a system [5].

## NUMERICAL INVESTIGATIONS. IMPULSE MODELING

Involving impulse modeling, is investigated the planning reliability of the tunnels in question under different types of impacts on them. Figs. 4–9 show the distribution of pulse processes for the three scenarios.

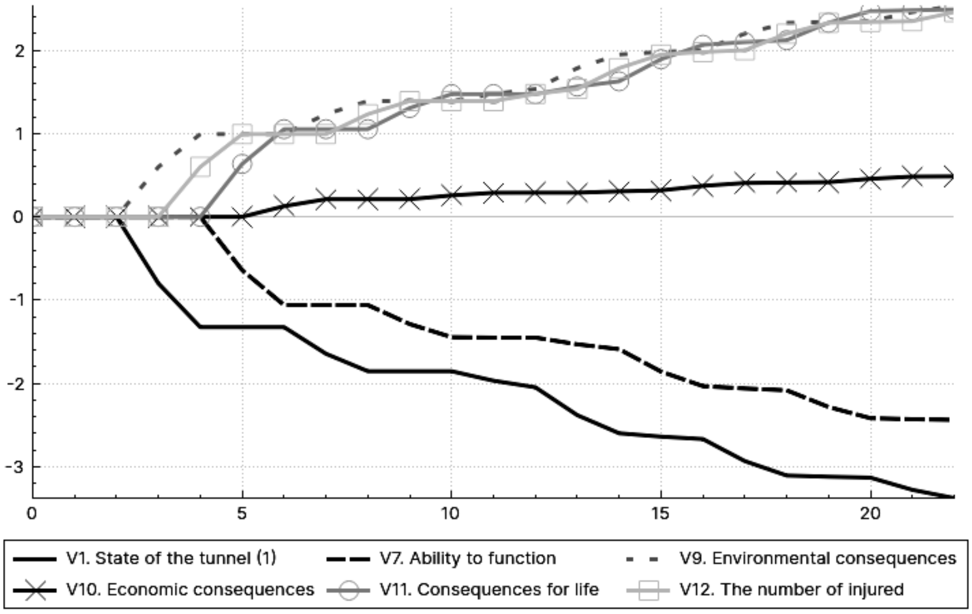


*Fig. 3.* The distribution of pulse processes for the Tunnel 1 (Scenario 1)

**Scenario 1.** Let’s conduct a study for Tunnel 1 and Tunnel 5. Assume to the vertex V2.1 — The Evil Mind: Fighting, Terrorism the control action is introduced $Q = (q_{V_1} = 0, \ldots, q_{V_{2.1}} = +1, \ldots)$. Figs. 3 and 4 show the distribution of pulse processes for the Tunnel 1 and Tunnel 5.

The first scenario is needed to analyze the consequences of strong explosions directed at the tunnel. Based on the simulation results, it can be concluded that Tunnel 1 is more resistant to threats associated with a clear intention, namely terrorist acts and hostilities. This is primarily due to the underwater dislocation of

Tunnel 5. A large explosion could cause the tunnel to flood, resulting in a larger impact than the same scenario in the case of Tunnel 1.

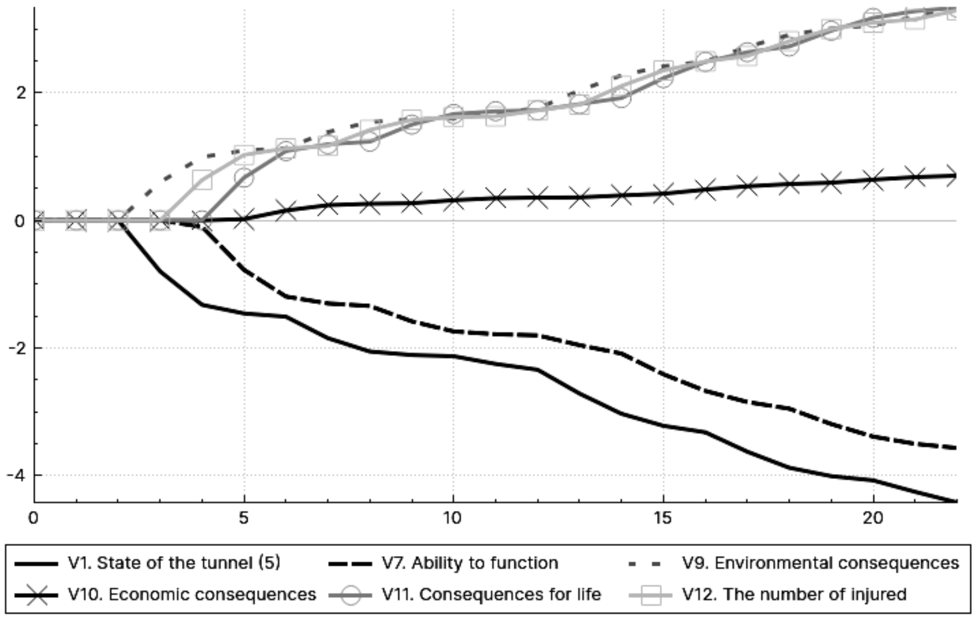


*Fig. 4.* The distribution of pulse processes for the Tunnel 5 (Scenario 1)

**Scenario 2.** Assume to the vertex V4.1 – Shifts the control action is introduced $Q=(q_{V_1}=0,\ldots,q_{V_{4.1}}=+1,\ldots)$. Figs. 5 and 6 show the distribution of pulse processes for the Tunnel 1 and Tunnel 5.

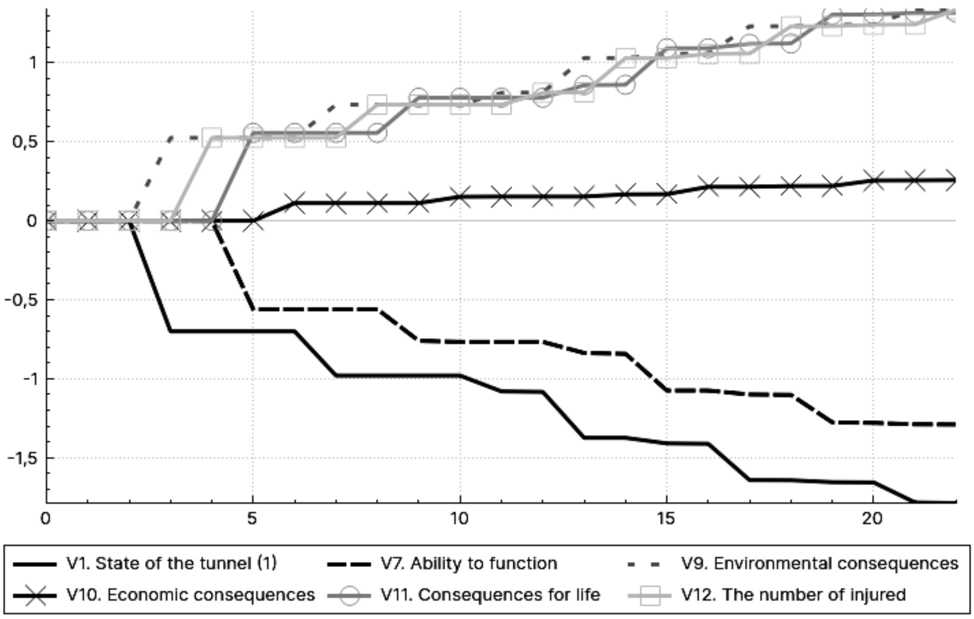


*Fig. 5.* The distribution of pulse processes for the Tunnel 1 (Scenario 2)

This scenario is needed to analyze the impact of natural factors on each tunnel. As in the previous scenario, Tunnel 1 turned out to be more stable. The reason still remains the possibility of tunnel flooding due to hard rock shear, which significantly affects the performance of the tunnel.

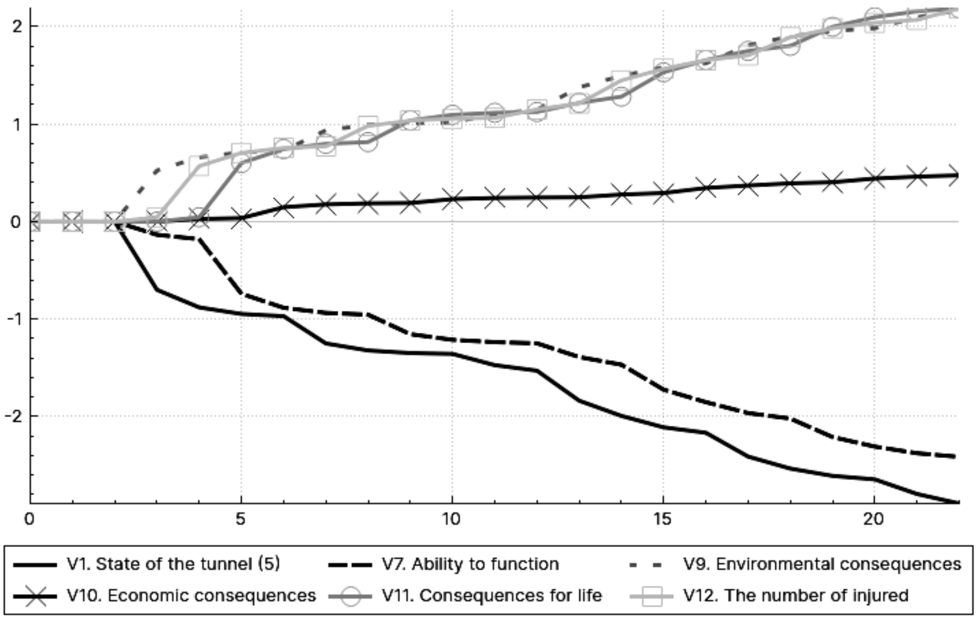


*Fig. 6.* The distribution of pulse processes for the Tunnel 5 (Scenario 2)

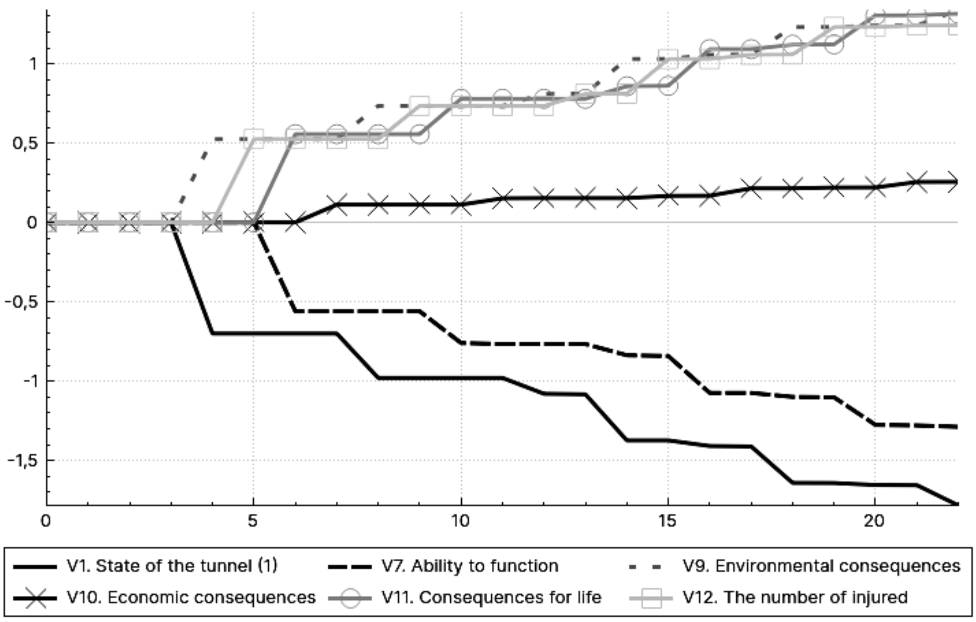


*Fig. 7.* The distribution of pulse processes for the Tunnel 1 (Scenario 3)

**Scenario 3.** Assume to the vertex V3 – Technogenic events, the control action is introduced $Q = (q_{V_1} = 0, \ldots, q_{V_3} = +1, \ldots)$ . Figs. 7 and 8 show the distribution of pulse processes for the Tunnel 1 and Tunnel 5.

The distribution of pulse processes for the Tunnel 5 (Scenario 3) is shown in Fig. 8. This scenario demonstrates the resilience of tunnels to industrial threats. In contrast to the previous scenarios, the numerical differences between the results obtained are not so significant. This may indicate the similarity of tunnels to industrial threats. However, Tunnel 1 still showed greater resilience to such scenarios.

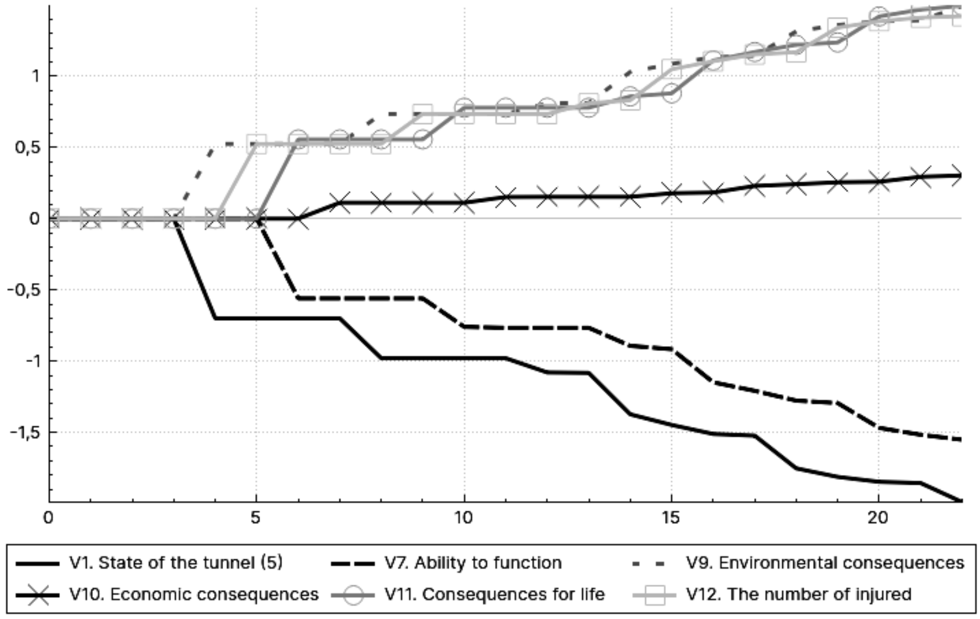


*Fig. 8.* The distribution of pulse processes for the Tunnel 5 (Scenario 3)

## CONCLUSION

Modeling of scenarios of possible processes of events development in the analyzed types of underground tunnels is carried out under the influence of various external disturbances and control impulse influences. The results of the conducted cognitive modeling make it possible to judge that cognitive models that systematize and structure different information about the tunnel underground construction system correspond to the real system and can be used to anticipate possible processes of development of situations in the system under the influence of various disturbing and controlling factors. The developed author's software complex allows in the process of pulse modeling and analysis of the obtained results to introduce controlling or excitatory influences at any stage of modeling. This allows changing (correcting) scenarios in the dynamics of model creation, determining effects that bring processes closer to the desired ones. The developed system approach is applied to the study of planning reliability of underground tunnels of different types in order to choose reasonable scenarios for their future development.

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*Received 07.09.2022*

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**ДОСЛІДЖЕННЯ ПЛАНУВАННЯ ПІДЗЕМНИХ ТУНЕЛІВ. КОГНІТИВНЕ МОДЕЛЮВАННЯ** / Н.Д. Панкратова, Д.І. Мусієнко

**Анотація.** Запропоновано дослідження надійності планування підземних тунелів для мегаполісів на основі використання методологій форсайту та когнітивного моделювання. Методологія форсайту дозволяє за допомогою процедур експертного оцінювання виявити критичні технології та побудувати альтернативи сценаріїв з кількісними характеристиками. Для обґрунтованої реалізації того чи іншого сценарію використовується когнітивне моделювання, яке дає змогу побудувати причинно-наслідкові зв’язки на основі знань та досвіду, зрозуміти та проаналізувати поведінку складної системи на стратегічну перспективу з великою кількістю взаємозв’язків та взаємозалежностей. Запропоноване дослідження дозволяє планувати надійність підземних тунелів на основі вибору обґрунтованих сценаріїв та обґрунтування пріоритетності їх створення.

**Ключові слова:** когнітивне, імпульсне моделювання, планування, сценарії, підземні тунелі.