STRATEGY OF UNDERGROUND CONSTRUCTION PLANNING BASED ON COGNITIVE MODELLING METHODOLOGY

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Abstract: Strategy to planning urban underground construction is considered as a tool for sustainable development concept for megapolises. The cognitive methodology, which is viewed as a decision-making process regarding behavior of complex systems in desirable future, is proposed for evaluating prospects of urban underground construction. Introducing disturbances to the vertices, the decision-maker is looking for the answer to the question: "What will happen if ...?" The conducted studies using this methodology allowed to propose a number of scenarios for assessing advisability of underground construction, considering highlighted groups of geological and technogenic factors, uncertainties of various nature and risk factor groups. The employed technique is a new tool for evaluating various risks, likelihoods of negative scenarios and related additional expenses, as early as a pre-project stage of underground construction.

Keywords: urban underground development, system analysis, uncertainty, multi-factor risks, decision-making, information technology.

ACM Classification Keywords: H.4.2. Information System Application: type of system strategy.

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Introduction

One of the characteristic features of the modern world is the growth of metropolises, the expansion of infrastructure and the growth of their population. Regulation of the urban development with the purpose of increasing ecological standards and life safety in constantly growing metropolises is one of the most urgent, though insufficiently researched and difficult world problems

[https://population.un.org/wup/, 2018]. It is leads to the search of new places to production facilities, social and other objects of human activity. The space of megacities created by man in the process of underground construction becomes a new, underground habitat, which should be comfortable and safe for humans. But the problem of developing underground territories is much wider than underground urban planning.

Recently within the framework of mining sciences, the new science "Construction geotechnology" has been developing. The subject of which study is the technologically transformed bowels of the earth [Levchenko A.N., 2007]. A significant contribution to it was made by the Russian scientist B.A. Kartosia [Kartosia B.A., 2015, 2009, 2010] The main direction is "... scientific direction – the integrated development of the underground space of the subsoil, a distinctive feature of which is the principle of priority of the work and rest level for comfort during the construction and operation of underground structures for various purposes, guaranteeing improvement of environmental and social living conditions in large cities and industrial areas ..." [Levchenko A.N., 2007]. Many personnel from geo-engineering are concentrated different methodological approaches to design problems [Bondarik G.K., 1981], [Tajdus A., Cala M. and Tajdus K., 2012], [Owen C.L. and Bezerra C., 2000]. Risks in underground space developmenty are considered in [Saługa P., 2009].

Underground urban planning is a complex system in many aspects. Firstly, this system consists of many interconnected subsystems and objects. Secondly, the processes occurring in this system during construction and during operation are also complex and in some cases poorly predictable, because they are largely associated with various geological processes. The problems that accompany underground urban development can be attributed to poorly structured problems.

A system approach to the planning of underground urban studies, based on the methodology of foresight, as a tool for the concept of sustainable development of megacities was proposed in [Pankratova N.et all, 2019],

The proposed in this paper strategy is applied to the study of underground construction objects in order to select reasonable scenarios for their future

development. All of the above allow us to propose the cognitive modelling methodology of complex systems for planning urban underground construction.

Models and methods of scognitive modelling of complex systems allow us to develop a cognitive model of the system, use it to analyze the structural properties of the system, its stability and, most importantly, analyze the possible ways of developing the system taking into account changes of its internal and external environment parameters and under various control actions.

At the design stage of underground structures, it is necessary to consider and justify the practical necessity, socio-economic expediency and technical feasibility of constructing underground structures in mining and geological conditions and under the influence of construction technology, the functional purpose of construction objects. The tasks of substantiating the necessity, feasibility, expediency, effectiveness of actions in complex systems are also included in the field of cognitive modelling tasks.

A significant advantage of cognitive models is that their composition at different stages and levels of study and description can include both quantitative (for example, "hydrostatic pressure") and qualitative (for example, "socio-economic feasibility") characteristics.

In our opinion, imitation of cognitive modelling, especially at the stage of design work on the development of the underground space, is extremely necessary.

The strategy of underground construction planning based on cognitive modeling methodology

In the framework of the foregoing, let us call the studied complex system "Natural-technical geosystem". In the study of the urban underground construction problem at the cognitive modelling methodology is used.

At the first stage cognitive models a sign oriented graph (1) and a functional graph in the form of a weighted sign digraph are used [Gorelova G.V.and Pankratova N.D., 2015], [Langley P. et all, 2006], [Abramova N.A. and Avdeeva Z.K., 2008], [Avdeeva Z.K.and Kovriga S.V., 2018], [Kovriga S.V. and Maksimov V.I., 2001], [Kulba V.et all, 2002], [Maksimov V.I., 2001]

$$\boldsymbol{G} = \langle \boldsymbol{V}, \boldsymbol{E} \rangle. \tag{1}$$

The cognitive map G corresponds to the square matrix of relations A_{G}

$$\mathcal{A}_{G} = \left\{ \boldsymbol{a}_{ij} \right\} = \begin{cases} 1, \text{ if } V_{i} \text{ is connected with } V_{j}, \\ 0, \text{ otherwise.} \end{cases}$$

Vector Functional Graph

$$\Phi = \left\langle G, X, F(X, E), \theta \right\rangle,$$

where *G* is a cognitive map; *X* is the set of vertex parameters; F(X, E) is the arc transformation functional, θ is the space of vertex parameters. If a

$$F(X,E) = F(x_i, x_j, e_{ij}) = \begin{cases} +\omega_{ij}, & \text{if rising / falling } X_i, \\ entails & rising / falling } X_j, \\ -\omega_{ij}, & \text{if rising / falling } X_i, \\ entails & falling / rising } X_i \end{cases}$$

then there is a weighted sign digraph, in which ω_{ij} is the weight coefficient.

In the case of studying the hierarchy systems, cognitive maps of individual levels can be combined into a hierarchical map [Gorelova G.V.and Pankratova N.D., 2015], [Langley P. et all, 2006]

$$I_{G} = \langle G_{k}, G_{k+1}, E_{k} \rangle, k = 1, 2, 3, ..., K$$

where G_k and G_{k+1} are cognitive maps of k and k+1 levels, respectively, whose vertices are connected by arcs E_k .

At the second stage of cognitive modeling, to study the properties of the cognitive model the methods of structural stability and perturbation resistance analysis are applied [Gorelova G.V.and Pankratova N.D., 2015], [Kulba V.et all, 2002], methods for analyzing model connectivity (simplicial analysis) [Atkin

R.H., 1997], [Atkin R.H. and Casti J., 1977] and graph theory methods [Casti J., 1979]. The results of the analysis were compared with the available information on underground construction.

At the third stage of cognitive modeling, to determine the possible development of processes in a complex system and develop development scenarios, the impulse process model (modeling the propagation of disturbances in cognitive models) is used [Kulba V.et all, 2002], [Roberts F., 1978]:

$$\mathbf{x}_{v_i}(n+1) = \mathbf{x}_{v_i}(n) + \sum_{v_j:e=e_{ij}\in E}^{k-1} f(\mathbf{x}_i, \mathbf{x}_j, \mathbf{e}_{ij}) \mathbf{P}_j(n) + \mathbf{Q}_{v_i}(n), \qquad (2)$$

where x(n), x(n+1) are the values of the indicator at the vertex V_i at the simulation steps at time t = n and the next t = n+1; $P_j(n)$ is the momentum that existed at the vertex V_j at the moment t = n. $Q_{V_i}(n) = \{q_1, q_2, ..., q_k\}$ is the vector of external pulses (disturbing or controlling actions) introduced to the vertices V_j at time moment n.

Modelling of Underground Constraction

First step. Cognitive Model Development. Table 1 presents data on the vertices (concepts) of the hierarchical cognitive model without reference to a specific territory, in a generalized form. We used generalizing concepts (indicators, factors), independent of the specifics, which can be disclosed and taken into account in the future when developing the lower levels of the hierarchical model. Figure 1 shows a hierarchical cognitive map I_G : "Natural-technical geosystem". In Table 1 and Figure 2, the vertices of the upper (first level) are denoted as $I - V_i$, i = 5, 11, 13, 15, 16. In Table 1, in the column "vertex assignment", vertices that play a different role in the cognitive system are highlighted.

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Table 1. The vertices of the hierarchical cognitive map "Natural-technicalgeosystem"

Code	Vertex explanation	Vertex assign- ment
$I - V_{11}$	The viability of the underground urban development	Indicative
$I - V_{13}$	Disasters, extreme and emergency situations	Perturbing
$I - V_{15}$	Environmental risks	Perturbing
$I - V_{16}$	Economic risks	Perturbing
$I - V_5$	Genetic type and lithological composition of soils	Basic
V ₁	Mountain and hydrostatic pressure, seismic impact	Basic
V ₂	Surface Load Static Load Index	Basic
V ₃	The indicator of the static load of the surrounding soil massif	Basic
V_4	Existing underground facilities	Disturbing
<i>V</i> ₆	Estimated soil resistance	Basic
V ₇	Aquifers and High Water	Disturbing
V ₈	ReliefTypeandMorphometry	Basic
V ₉	Engineering and geological processes	Disturbing
V ₁₀	Mining construction technologies	Regulating
V ₁₂	The level of comfort of work and rest during the construction and operation of underground structures	Indicative
V ₁₄	Construction, operational, managementrisks	Disturbing
V ₁₇	Staffqualifications	Regulating
V ₁₈	Industrial Safety	Basic
V ₁₉	Quality and construction time	Regulating

The cognitive model is a simulation model that makes it possible not to conduct an experiment on a "living" system, but to simulate its behavior and possible future development under the influence of various factors, generating new knowledge about the system. This allows you to justify management decisions in a given situation.

The second stage of modeling. Before using the cognitive model to determine its possible behavior, the second stage of modeling analyzes the various properties of the model is fulfilled. In this case, the stability properties of the model must be analyzed.

Impulse sustainability. The cognitive model I_G was not resistant to perturbations according to the accepted criterion [Atkin R.H., 1997], [Atkin R.H. and Casti J., 1977], [Roberts F., 1978]: the maximum modulo M root of the characteristic equation of the matrix of relations of the graph I_G is |M| = 1,82 > 1 (must be less than 1).



Figure 1. Hierarchical cognitive map I_{G} "Natural-technical geosystem"

Connectivity matrix														
- Infl./ Dep.	V1	V2	V3	V 4	I-V5	V6	V 7	V 8	V9	V10	I-V11	V12	I-V13	V14
V1	Х			1.0					-1.0	1.0		Ĭ		
V2		Х		1.0		-1.0			-1.0	1.0	1.0			
V3			Х	1.0	1.0	-1.0		1.0	-1.0	1.0				
V4	-1.0			Х		-1.0			1.0	-1.0	1.0			
I-V5	1.0		1.0		Х	1.0			-1.0					
V6	1.0		1.0			Х								
V7						-1.0	Х	1.0	-1.0		1.0		1.0	
V8							1.0	Х	1.0					
V9 ~	1.0					-1.0			Х				-1.0	-1.0

Figure 2. The fragment of the cognitive map I_G relationship matrix A_G "Naturaltechnical geosystem

Structural stability. An analysis of the ratio of the number of stabilizing cycles (35 negative feed-backs) and process accelerator cycles (33 positive feedbacks) indicates the structural stability of such a system [Roberts F., 1978].

The given example of the analysis of the cycles of the cognitive model showed the variety of cycles of cause and effect relationships that exist in complex systems. There are 68 of them in the analyzed system. Without an appropriate theoretical analysis, there is a great risk of the human factor in making managerial decisions, because its consequences may not be obvious due to the complexity of interactions in the system.

Analysis of system connectivity, simplicial analysis. Immersed in the study of the structure of the cognitive model, it is desirable to conduct a simplicial analysis of the properties of its connectivity. Such an analysis is carried out in order to study and understand the topological properties of the model and, accordingly, other connectivity faces of the complex system under study that are not detected in the above analysis. According to R.H. Atkin and J. Casti, connectedness is the essence of the concept of a large system [Atkin R.H. and Casti J., 1977]. The connectivity properties of blocks (simplexes) characterize the "deep" connections of the cognitive model, the connections of its simplexes, and not just the vertices, as in the cognitive map. A simplex is formed by each vertex, which is the reason that some other vertices interact with each other.

The third stage of modeling. Scenario analysis is designed to forecast possible trends in the development of situations on the model. To generate scenarios of the development of the system, impacts are introduced into the vertices of the cognitive map in the form of a set of impulses. The impulse process formula has the form (2).

Let us introduce perturbations Q of different sizes (normalized) to any of the vertices, as well as to their combination. In connection with a large number of theoretically possible variants of introduced disturbances, it is expedient to develop a plan for a computational experiment before excluding pulse simulation, eliminating at least almost impossible variants. Introducing disturbances to the vertices, the decision-maker is looking for the answer to the question: "What will happen if ...?"

The CMLS software system allows, in the process of pulse modeling and analysis of the obtained results, to introduce control or disturbing influences at any modeling step. It is allows to change (correct) scenarios in model dynamics, to determine the effects that bring the processes closer to the desired.

Let us present the results of pulse modeling in third scenarios.

Scenario No.1. Assume good technology is used in underground construction. To the vertex V_{10} , the control action is introduced $q_{10} = +1$, the perturbation vector $\mathbf{Q} = \{ q_1 = 0, \dots, q_{10} = +1, \dots, q_{19} = 0 \}$.

Figures 3a,b shows graphs of pulsed processes. For the convenience of visual analysis of the image, the graphs of pulsed processes in the vertices V_{10} , $I - V_{13}$, $I - V_{15}$, $I - V_{16}$, $I - V_{11}$, $I - V_5$ are represented by two figures: Figure 3a – from the first to the sixth step of modeling and Figure 3b from the sixth to tenth step of modeling. The image of pulsed processes at a larger number of simulation steps is not necessary, because system behavior trends under these conditions are already evident.

Modeling scenario No. 1, it is advisable to analyze whether changes in Mining construction technologies (V_{10}) can and in what way affect other vertices of the cognitive model. As can be seen from the graphs in Figures 3a,b, positive changes in V_{10} can contribute to positive trends in the development of vertices at the top hierarchical level: up to the 5th and 6th steps of the modeling, the declining trends of Disasters, extreme and emergency situations ($I - V_{13}$), Environmental risks ($I - V_{15}$), Economic risks ($I - V_{16}$), Genetic type and lithological composition of soils ($I - V_5$), The viability of the underground urban development ($I - V_{11}$) is growing. Further, the oscillatory mode manifests itself



Figure 3a. Graphs of pulsed processes, from the first to the sixth step of modelling. Scenario No.1 Figure 3b. Graphs of pulsed processes, from the sixth to tenth step of modelling. Scenario No.1

more and more in changing situations. All this may indicate that a single positive change in one of the vertices of the system model may not be enough to exclude the negative impact of risks and other negative influences. Scenario No.2. Suppose that the possibility of the simultaneous occurrence of all risks is increasing in the system. Disturbing effects are appearing $q_{14} = +1$, $q_{15} = +1$, $q_{16} = +1$, there is perturbation vector $Q = \{q_1 = 0, \dots, q_{14} = +1, q_{15} = +1, q_{16} = +1, \dots, q_{19} = 0\}$.

Pulse simulation results are presented in Fig. 4a for vertices $V_{14}, I - V_{15}, I - V_{16}, I - V_{11}, I - V_{13}, V_{17}, V_{18}V_{19}$ V1 and Fig. 4b for vertices $V_{12}, V_{17}, V_{18}, V_{19}V_{10}$.

The simulation results of the second scenario show an extremely unfavorable option for the development of situations in the system. With increasing risks, as







can be seen from Figures 4a, 4b all indicators of the system fall at both the first and second levels of the hierarchy. This observation forces one to make a decision on the search for the necessary counteraction to the situations that have arisen.

Consider the third scenario. Suppose improving Engineering and geological processes (V_9), Mining construction technologies (V_{10}), Staff qualifications (V_{17}), Quality and construction time (V_{19}), but there are Disasters, extreme and emergency situations ($I - V_{13}$).

Scenario No.3. Control actions $q_9 = +1$, $q_{10} = +1$, $q_{17} = +1$, $q_{19} = +1$, $q_{13} = +1$, the perturbation vector $Q = \{q_1 = 0, \dots, q_9 = +1, q_{10} = +1, \dots, q_{13} = +1, \dots, q_{13} = +1, \dots, q_{19} = +1\}$.

The results of pulse modeling are presented in Figure 5a for vertices $I - V_{13}, V_9, V_{10}, V_{19}, I - V_{15}, I - V_{16}, V_{18}, V_{17}, I - V_{11}$ and Figure 5b for vertices $V_{17}, V_{18}, V_{19}, I - V_{11}, V_{12}, V_{14}, I - V_{13}$.



Figure 5a. Graphs of pulsed processes. Scenario No.3

Figure 5b. Graphs of pulsed processes. Scenario No.3

An analysis of the results of impulse modeling according to scenario No.3 shows that the introduction of control actions to the vertices of Engineering and geological processes (V_9), Mining construction technologies (V_{10}), Staff qualifications (V_{17}), Quality and construction time (V_{19}), but there are Disasters, extreme and emergency situations ($I - V_{13}$) can counteract the negative impact of possible disasters and extreme situations, reducing the impact of economic, environmental and technological risks. Thus, scenario No.3 can be considered favorable: industrial safety is increasing.

We present the simulation results in one more scenario No.4. Assume that construction, operational, management risks can be reduced. In this case, the impulse actions initiate 6 vertices of the model and the synergistic effect of their joint action is investigated. The modeling of this scenario of the situations development on the model is carried out in order to determine whether it is necessary or not to strengthen the impact on the system to achieve good indicators.

Scenario No.4. Control actions $q_9 = +1$, $q_{10} = +1$, $q_{17} = +1$, $q_{19} = +1$, $q_{13} = +1$, the perturbation vector $Q = \{q_1 = 0, \dots, q_9 = +1, q_{10} = +1, \dots, q_{13} = +1, q_{14} = -1, \dots, q_{17} = +1, \dots, q_{19} = +1\}$.

The results of pulse modeling are presented in Figure 6a for $I - V_{13}, V_9, V_{10}, V_{14}, V_{17}, V_{19}$ and Figure 6b for vertices $V_{12}, V_{14}, V_{15}, V_{16}, V_{18}, I - V_{11}$.

Analysis of the simulation results of Scenario No.4, which differs from scenario No.3 by the addition of an impulse $q_{14} = -1$, simulating the possibility of reducing Construction, operational, management risks showed the following. The combined positive impact of six factors on the system leads to the possibility of the appearance of desirable trends in situations throughout the system. So, there are tendencies of improvement (growth) of the underground urban development viability, the level of comfort, work and rest during the construction and operation of underground structures, Industrial Safety while reducing all types of risk and reducing Disasters, extreme and emergency situations.

Let us compare the simulation results of Scenarios No.1, No.2, No.3 and No. 4, using the capabilities of the CMLS software system. Scenario No.4 can be considered the best of those considered, although its results are not too different from the results of scenario No.3. If you set the task of minimizing the cost of resources for the particular scenario implementation, then perhaps scenario No.3 will be the best, with fewer control actions in the system. A comparison of the results of scenarios No.3 and No.4 with the results of scenario No.1, in which the control action is applied to only one vertex, shows that it is inferior to scenarios No.3 and No.4. If we compare the simulation results of scenario No.2 with the results of other scenarios, it is obvious that without countering possible risks, the development scenarios of the Natural-technical geosystem system will be extremely pessimistic.



Figure 6a. Graphs of pulsed processes. Scenario No.4

Figure 6b. Graphs of pulsed processes. Scenario No.4

Conclusion

The developed system strategy is applied to the study of underground construction objects in order to select reasonable scenarios for their future development. 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 modelling of scenarios for possible processes of the events development in the analyzed complex system is carried out under the influence of various internal and external disturbances and control impulse effects. The results of the conducted cognitive modeling make it possible to judge that the cognitive models, which systematize and structure various information about the underground construction system, correspond to the real system and can be used to anticipate the possible processes of situations in the system under the influence of various disturbing and controlling factors. The developed author's software system CMLS allows in the process of pulse modeling and analysis of the obtained results to introduce control or exciting actions at any stage of modeling. This allows to change (correct) scenarios in the dynamics of creating a model, to determine the effects that bring the processes closer to the desired. The developed methodology and tools made it possible to combine the assessment of the impacts and relationships of geological factors, technogenic and structural-functional types for the study of the underground objects construction.

Further work: It is planned to use the proposed strategy for creation scenarios for real geotechnological objects of underground construction. This material is an important formalysed part and shows the possibility of making a decision in conditions of geological uncertainty and multifactorial risks.

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