ПРОБЛЕМИ ПРИЙНЯТТЯ РІШЕНЬ ТА УПРАВЛІННЯ В ЕКОНОМІЧНИХ, ТЕХНІЧНИХ, ЕКОЛОГІЧНИХ І СОЦІАЛЬНИХ СИСТЕМАХ

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MORPHOLOGICAL MODEL FOR UNDERGROUND CROSSINGS OF WATER OBJECTS[1]

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Abstract. The construction of morphological model is considered for undesirable events regarding urban objects, as well as the consequences of such events, including interruption of operation, feasibility and time of restoration, material damage and casualties, ecological risks. Using this model, two-stage modified morphological analysis was conducted for two types of objects: pipe and tunnel depressed sewers. The results of comparison for depressed sewer crossings using the developed model are demonstrated both for the whole multitude of potential undesirable events and for the specific scenarios of sabotage, landslide, operational damage. The advantage of a tunneled depressed sewer over a pipe one is justified from the standpoint of minimization of technogenic and ecological risks of sewage draining.

Keywords: ecological risks; technogenic risks; underground infrastructure; sewage draining; system methodology; morphological analysis; depressed sewer crossing.

INTRODUCTION

Managing urban development with the purpose of increasing ecological standards and life safety in continuously growing metropolises is one of the most urgent but simultaneously complex and insufficiently researched world problems [1]. Underground communications that support human activities are one of the most difficult problems of urban planning in metropolises. Significant advantages of underground crossings beneath water objects and through coastal underground infrastructure comprise a large part of underground construction agenda in the influence zone of water objects [2, 3]. Impact analysis of structures adjacent to an underwater tunnel is more complex compared to the case of ordinary tunnels. Currently an empirical division method of zonal influence of structures adjacent to the tunnel is common but it generates a tangible uncertainty. Therefore, actual design and construction require identifying exact influence zones using theoretical calculations given in [4]. In [5] a bunch of topics regarding tunneling is presented, tracking the evolution of methods and tools from analytical to computing periods. In [5] a review of recent studies and the classifications of methods is also given, followed by several problems for anisotropic rock structures using finite element

[1] The presented results were obtained in the National Research Fund of Ukraine project 2020.01/0247 «System methodology-based tool set for planning underground infrastructure of large cities providing minimization of ecological and technogenic risks of urban space».

method, and the application of the artificial intelligence tools is considered for data interpretation and estimation of relative importance of parameters related to the problem of surface sinking caused by tunnels. Papers [6, 7] also employed various numerical methods for assessing the influence zone of structures adjacent to a tunnel.

World concepts of ecologization of urban space pay significant attention to the capacities of underground space to take over the functions of the most hazardous and risky surface structures and communications, providing minimization of ecological and technogenic risks in large cities [8]. These trends are also seen in the General Plan of Kyiv city up to 2025, where a large-scale development of underground infrastructure was envisioned, although its implementation lags behind the planned indicators.

PROBLEM STATEMENT

One of the critical infrastructure objects in Kyiv is the system of sewage transfer from the right to the left Dnipro river bank. Bortnychi aeration station, which was issued over $1 billion for reconstruction by Japanese government, holds the risks of a technogenic catastrophe on a national scale, as all the sewage from the right-bank Kyiv and neighboring towns of the capital agglomeration is transferred between the river banks by a group of metal pipes on the Dnipro river bottom. Their service life is long past due, and the implemented protection system in the form of polyethylene hoses pulled through pipes, is only a temporary emergency measure. A technical pipe burst or a sabotage might ruin the ecological safety down the whole Dnipro river current. To compare the system of pipe and tunnel depressed sewer crossings, and to form recommendations regarding planning an underground Dnipro river crossing tunnel, a morphological model was constructed, and testing of construction variants was conducted.

The purpose of the morphological model is to describe the undesirable events that can potentially impact the chosen underground urban object or a type of objects. These undesirable events include natural emergencies and disasters, as well as technogenic or anthropogenic events (including those with malicious intent: military actions, terrorism acts). The result of the modeling is the analysis of expected consequences for the object, the opportunity to compare different objects or their designs by their stability and capacity to withstand various harmful events.

The modeling was performed using the two-stage modified morphological analysis method (MMAM) [9, 10], where the first stage describes the multitude of potential undesirable events, and the second stage analyzes the consequences of these events in different aspects. A feature of this study is that the relations between the parameters of undesirable events, and their consequences, fundamentally differ for various objects and types of objects, which is why each single object requires not only filling in the initial assessment of alternatives as was the case in previous studies [11–13], but also a separate evaluation of the cross-consistency and dependency matrices.

CONSTRUCTING A MORPHOLOGICAL MODEL OF UNDESIRABLE EVENTS FOR DEPRESSED SEWER CROSSINGS OF DNIPRO RIVER

To pick the critical characteristic parameters of undesirable events and their consequences, a legislative and normative database of documents regarding the threats to human safety and urban space was processed. The analysis allowed to select three main characteristic parameters of undesirable events, relevant for this research:

Parameter 1: Undesirable event type. Only the prior cause, or a trigger, of an undesirable event is considered. Obviously the undesirable events can start a chain reaction: for example, an explosion causes a fire, which causes destruction etc. However, in the study, all of the disruptive processes following the initial impact, are treated as consequences. Considering all possible chains of undesirable events is impossible and irrational.

The developed universal model contains six alternatives for main types of undesirable events:

- explosion;
- fire;
- landslide, landfall, subsidence of soil;
- weather cataclysm;
- operational damage or structural failure;
- disruption of operation without damage.

It should be noted that for some of the objects, specific undesirable event types from the universal model are impossible (e.g. a fire for an underwater depressed sewer pipe). This alternative receives the initial value "0" and thus does not participate in the following MMAM procedure.

Parameter 2: Undesirable event origin. Four alternative origins for undesirable events were chosen:

- anthropogenic with malicious intent (terrorism, sabotage, military action);
- anthropogenic without malicious intent (human errors, negligence, non-compliance to construction and operation safety);
- technical, technological (malfunctions, technical failures, damage due to technological factors, corrosion, etc.);
- natural (atmospheric, hydrospheric, lithospheric perturbation, natural disasters).

Parameter 3: Undesirable event scale. Five alternatives of undesirable event scale were considered:

- separate structural or functional element of the object, or a separate section;
- several structural or functional elements of the object, or several sections;
- the object as a whole;
- the object and its neighboring objects;
- city region and more.

Studying catastrophes of larger scale was beyond the scope of this research, as only the consequences of an undesirable event for a single urban object were modeled. That is why the larger scale disasters were united in an alternative "city region and more".

Using the chosen parameters, a morphological table for general description of a multitude of undesirable events was constructed (Table 1). The morphological set for this table comprises of 120 configurations.

Table 1. Description of undesirable events

Parameter	Alternative
1. Undesirable event type	1.1 Explosion
	1.2 Fire
	1.3 Landslide, landfall, subsidence of soil
	1.4 Weather cataclysm
	1.5 Operational damage or structural failure
	1.6 Disruption of operation without damage
2. Undesirable event origin	2.1 Anthropogenic with malicious intent
	2.2 Anthropogenic without malicious intent
	2.3 Technical, technological
	2.4 Natural
3. Undesirable event scale	3.1 Separate structural or functional element of the object, or a separate section
	3.2 Several structural or functional elements of the object, or several sections
	3.3 Object as a whole
	3.4 Object and its neighboring objects
	3.5 City region and more

Obviously the table parameters are notably interrelated, so the model construction requires estimating and taking into account their cross-consistency matrix; moreover, this matrix should be separately assessed for each individual studied object type, as the undesirable events' parameters might have different relations for different types of objects.

The morphological table for the second stage of research contains the parameters of consequences of undesirable events, and their alternatives. As the consequences are sufficiently diverse, their comprehensive description required 8 parameters (Table 2).

Table 2. Description of consequences after undesirable events

Parameter	Alternative
A. Integrity of the object and its parts	A.1 No damage or negligible damage
	A.2 Damage may be undone without interruption of operation
	A.3 Damage may be undone with interruption of operation
	A.4 Damage is irreversible
B. Operational capacity	B.1 Object may perform all of its functions
	B.2 Object may perform a portion of its functions
	B.3 Object stops functioning
C. Potential to transfer functions to other objects	C.1 Object's functions can be transferred without limitations
	C.2 Object's functions can be transferred with some limitations
	C.3 Object's functions can be transferred with significant limitations
	C.4 Object's functions cannot be transferred
D. Operation restore time	D.1 Operation restore time is unnecessary
	D.2 Operation restore time up to 7 days
	D.3 Operation restore time up to 1 month
	D.4 Operation restore time up to 1 year
	D.5 The object cannot be restored during 1 year

Continued Tabl. 2

Parameter	Alternative
E. Casualties	E.1 None
	E.2 Up to 10 persons
	E.3 10–50 persons
	E.4 50–200 persons
	E.5 More than 200 persons
F. Affected citizens	F.1 None
	F.2 Up to 10 persons
	F.3 10–100 persons
	F.4 100–1000 persons
	F.5 More than 1000 persons
G. Material damage	G.1 Up to 100 minimum wage values (MW)
	G.2 100–1000 MW
	G.3 1000–10000 MW
	G.4 More than 10000 MW
H. Ecological consequences	H.1 No tangible ecological consequences
	H.2 Slight, local, short-term worsening of the ecological situation
	H.3 Significant long-term worsening of the ecological situation in a large area
	H.4 Ecological catastrophe

To create a complete morphological model, the following assessments are necessary:

- preliminary probability estimates for alternatives of undesirable events;
- cross-consistency matrix estimates for alternatives of undesirable events;
- dependency matrix estimates for alternatives of undesirable events and their consequences.

This data was obtained using expert assessment. Preliminary probability estimates for alternatives of undesirable events were obtained using questions in the following form:

Please rate how likely is **Undesirable event type – Explosion**

Impossible	Very unlikely	Unlikely	Somewhat unlikely	Average	Somewhat likely	Likely	Very likely

The questions regarding cross-consistency and dependency matrices were put in the following form:

How does **Undesirable event type** influence **Integrity of the object and its parts**?

1. Undesirable event type: 1.1. Explosion									
How does 1.1. Explosion influence the weight of A.1. Negligible damage	Significantly decreases	Notably decreases	Moderately decreases	Slightly decreases	Does not in-fluence	Moderately increases	Moderately increases	Notably increases	Significantly increases
How does 1.1. Explosion influence the weight of A.2. Damage may be undone without interruption of operation	Significantly decreases	Notably decreases	Moderately decreases	Slightly decreases	Does not influence	Moderately increases	Moderately increases	Notably increases	Significantly increases

Continued

1. Undesirable event type: 1.1. Explosion									
How does 1.1. Explosion influence the weight of A.3. Damage may be undone with interruption of operation	Significantly decreases	Notably decreases	Moderately decreases	Slightly decreases	Does not influence	Moderately increases	Moderately increases	Notably increases	Significantly increases
How does 1.1. Explosion influence the weight of A.4. Damage is irreversible	Significantly decreases	Notably decreases	Moderately decreases	Slightly decreases	Does not in-fluence	Moderately increases	Moderately increases	Notably increases	Significantly increases

The model was implemented for two chosen critical urban infrastructure objects: depressed sewer as a complex of pipes at the bottom of Dnipro river, and the project of a tunneled depressed sewer beneath the Dnipro river (Fig. 1).

Input estimates of undesirable event alternatives, as well as the results of taking into account the cross-consistency matrix by the MMAM procedure for these estimates, are given in Table 3.

Table 3. Normalized input probabilities of undesirable events, and the results after taking their interdependency into account

Parameter	Alternative	Normalized input probabilities		Probabilities factoring interdependency	
		Depressed sewer		Depressed sewer	
		Pipes	Tunnel	Pipes	Tunnel
1. Undesirable event type	1.1 Explosion	0,232	0,212	0,440	0,107
	1.2 Fire	0,000	0,030	0,000	0,022
	1.3 Landslide, landfall, subsidence of soil	0,286	0,303	0,198	0,366
	1.4 Weather cataclysm	0,071	0,030	0,002	0,000
	1.5 Operational damage or structural failure	0,232	0,303	0,247	0,414
	1.6 Disruption of operation without damage	0,179	0,121	0,113	0,090
2. Undesirable event origin	2.1 Anthropogenic with malicious intent	0,372	0,250	0,550	0,154
	2.2 Anthropogenic without malicious intent	0,163	0,036	0,006	0,001
	2.3 Technical, technological	0,302	0,464	0,409	0,631
	2.4 Natural	0,163	0,250	0,035	0,214
3. Undesirable event scale	3.1 Separate structural or functional element of the object, or a separate section	0,019	0,500	0,056	0,617
	3.2 Several structural or functional elements of the object, or several sections	0,019	0,313	0,053	0,368
	3.3 Object as a whole	0,302	0,125	0,533	0,015
	3.4 Object and its neighboring objects	0,302	0,031	0,197	0,000
	3.5 City region and more	0,358	0,031	0,160	0,000

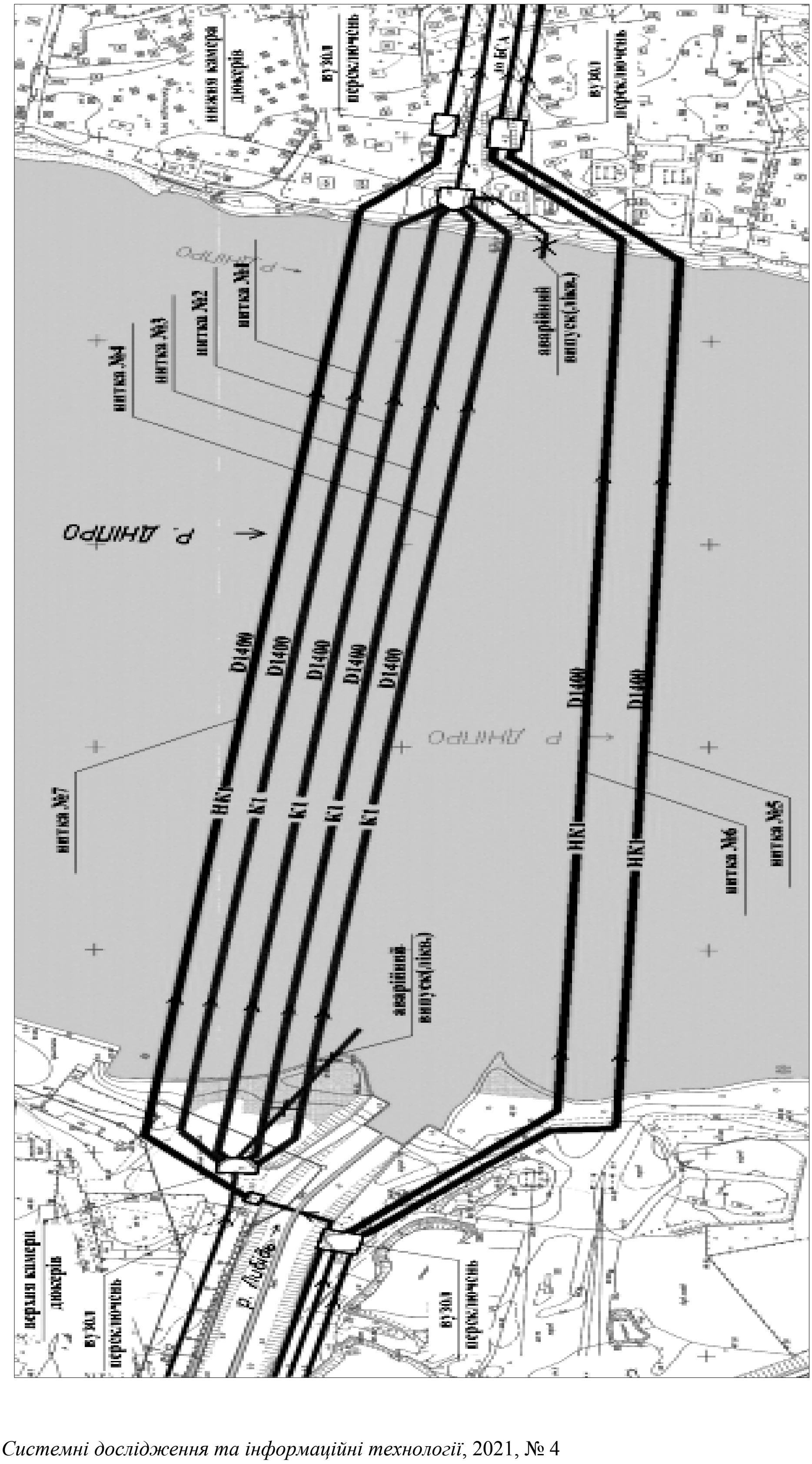

Fig. 1. A depressed sewer crossing of Dnipro river in Kyiv as a complex of pipes

Using the assessments obtained at the first stage (Table 3), and the dependency matrix values, the consequences analysis results were computed via the second stage MMAM procedure. The resulting evaluation is presented in Table 4.

Table 4. Undesirable event consequences considering the emergence of any possible undesirable event

Parameter	Alternative	Estimate	
		Depressed sewer	
		Pipes	Tunnel
A. Integrity of the object and its parts	A.1 No damage or negligible damage	0,018	0,051
	A.2 Damage may be undone without interruption of operation	0,021	0,417
	A.3 Damage may be undone with interruption of operation	0,544	0,530
	A.4 Damage is irreversible	0,416	0,001
B. Operational capacity	B.1 Object may perform all of its functions	0,000	0,269
	B.2 Object may perform a portion of its functions	0,019	0,656
	B.3 Object stops functioning	0,981	0,075
C. Potential to transfer functions to other objects	C.1 Object's functions can be transferred without limitations	0,005	0,025
	C.2 Object's functions can be transferred with some limitations	0,100	0,561
	C.3 Object's functions can be transferred with significant limitations	0,322	0,401
	C.4 Object's functions cannot be transferred	0,574	0,014
D. Operation restore time	D.1 Operation restore time is unnecessary	0,000	0,004
	D.2 Operation restore time up to 7 days	0,009	0,455
	D.3 Operation restore time up to 1 month	0,174	0,524
	D.4 Operation restore time up to 1 year	0,570	0,017
	D.5 The object cannot be restored during 1 year	0,246	0,000
E. Casualties	E.1 None	0,966	0,992
	E.2 Up to 10 persons	0,034	0,008
	E.3 10–50 persons	0,000	0,000
	E.4 50–200 persons	0,000	0,000
	E.5 More than 200 persons	0,000	0,000
F. Affected citizens	F.1 None	0,000	0,811
	F.2 Up to 10 persons	0,000	0,006
	F.3 10–100 persons	0,021	0,006
	F.4 100–1000 persons	0,427	0,038
	F.5 More than 1000 persons	0,551	0,140
G. Material damage	G.1 Up to 100 minimum wage values (MW)	0,001	0,464
	G.2 100–1000 MW	0,259	0,512
	G.3 1000–10000 MW	0,431	0,024
	G.4 More than 10000 MW	0,309	0,000
H. Ecological consequences	H.1 No tangible ecological consequences	0,000	0,894
	H.2 Slight, local, short-term worsening of the ecological situation	0,142	0,105
	H.3 Significant long-term worsening of the ecological situation in a large area	0,500	0,001
	H.4 Ecological catastrophe	0,357	0,000

Table 4 allows to make several comparative conclusions:

- generally an underwater tunnel provides for better resistance to potential damage in case of any undesirable events. Parameter A (Integrity of the object and its parts) has the same most probable alternative A.3 – "Damage may be undone with interruption of operation" for both objects (with weights 0,544 for pipes, and 0,530 for an underground tunnel), however the second most significant alternative is A.4 – "Damage is irreversible" for pipes (with 0,416 weight), while in case of an underground tunnel the same is true for alternative A.2 – "Damage may be undone without interruption of operation" (with 0,417 weight), and the weight of A.4 – "Damage is irreversible" is close to zero for an underground tunnel. This situation is even more demonstrative for parameter B (Operational capacity): a depressed sewer in the form of pipes has the weight 0,981 of B.3 – "Object stops functioning", pointing at very low resistance to damage in case of undesirable events. For comparison, the weight of the same alternative for an underground tunnel is 0,075, meaning that it is highly resistant to total cease of its operation;
- when considering parameter C (Potential to transfer functions to other objects) it is worth noting that in the studied concept of the underground tunnel, the existing system of pipes is not dismantled but left as a reserve system, which can explain the weights received by alternatives of this parameter for the underground tunnel: C.2 – "Object's functions can be transferred with some limitations" has value 0,561, and C.3 – "Object's functions can be transferred with significant limitations" with value 0,401. A depressed sewer in the form of pipes has the highest weights for alternatives C.4 – "Object's functions cannot be transferred" (value 0,574), and C.3 – "Object's functions can be transferred with significant limitations" (value 0,322);
- parameter D (Operation restore time) also shows advantage of the underground tunnel over underwater pipes. The alternatives with the highest weight are D.4 – "Operation restore time up to 1 year" (value 0,507) and D.5 – "The object cannot be restored during 1 year" (value 0,246) for underwater pipes. As for the underground tunnel, its alternatives with the highest weight are D.3 – "Operation restore time up to 1 month" (value 0,524) and D.2 – "Operation restore time up to 7 days" (value 0,455);
- similar results were obtained for parameter G (Material damage). Underwater pipes have the following ranking of alternatives: G.3 – "1000–10000 MW" (value 0,431), G.4 – "More than 10000 MW" (value 0,309), G.2 – "100–1000 MW" (value 0,259), and the underground tunnel has the following ranking: G.2 – "100–1000 MW" (value 0,512), G.1 – "Up to 100 MW" (value 0,464), meaning that the process of restoring an underground tunnel generally takes nearly up to 10 times less resources compared to the underwater pipes;
- parameter E (Casualties) is not tangible in this study due to the nature of the considered objects. Direct casualties are close to impossible, since the process of transferring sewage is mostly automated, without human presence. The importance of this parameter will be more significant for other types of urban objects;
- the estimation results for parameter F (Affected citizens) again proves the results obtained for previous parameters. Since the operation will most likely be disrupted in case an undesirable event happens to underwater pipes, the affected urban population will be very high (F.5 – "More than 1000 persons", with weight 0,551). An underground tunnel received the highest weight for alternative F.1 – "None", with weight 0,811. Intermediate alternatives F.2 – "Up to 10 persons", F.3 – "10–100 persons" in both cases received very low values, since disrupting

the sewage system immediately causes harm to living conditions of a large number of people, underlining the critical nature of this urban infrastructure element;

- the parameter H (Ecological consequences) is one of the most convincing to prove the advantage of a depressed sewer as an underground tunnel compared to underwater pipes, as the ecological consequences in case an undesirable event happens are mostly negligible for an underwater tunnel (alternative H.1 – "No tangible ecological consequences" with weight 0,894), while disruptions for underwater pipes bear very harmful impact for ecology (alternatives H.3 – "Significant long-term worsening of the ecological situation in a large area" with weight 0,500, H.4 – "Ecological catastrophe" with weight 0,357), denoting much higher ecological risk.

Thus, an underground tunnel for a depressed sewer outperforms underwater pipes under almost all of the criteria, and for some important criteria this advantage is overwhelming.

The modified morphological analysis method allows also to conduct inference "what-if" analysis, selecting a configuration, or a group of configurations that contain a specific type of threats at the first stage. Respectively, at the second stage the consequences are shown only for a chosen type of threat, allowing to model and compare different scenarios.

In this study three scenarios of undesirable events were taken, determined by the configurations of the MT at the first stage:

Scenario 1 (sabotage through undermining): 1.1 – Explosion, 2.1 – Anthropogenic with malicious intent, 3.2 – Several structural or functional elements, or several sections;

Scenario 2 (technogenic threat): 1.5 – Operational damage and/or destruction of object or its parts, 2.3 – Technical, technological, 3.2 – Several structural or functional elements, or several sections;

Scenario 3 (natural threat): 1.3 – Landslides, landfalls, subsidence of soil, 2.3 – Technical, technological, 3.3 – Whole object.

Also scenario 4 was considered – an undefined sabotage, which specifies only the origin of the event – 2.1, «Anthropogenic with malicious intent», leaving the exact details undetermined to better understand the multitude of potential military and sabotage threats.

The results of modeling for scenario 1 are shown in Fig. 2–5. The results for a depressed sewer in the form of a complex of pipes are labeled "Pipes", and the tunneled depressed sewer is labeled "Tunnel".

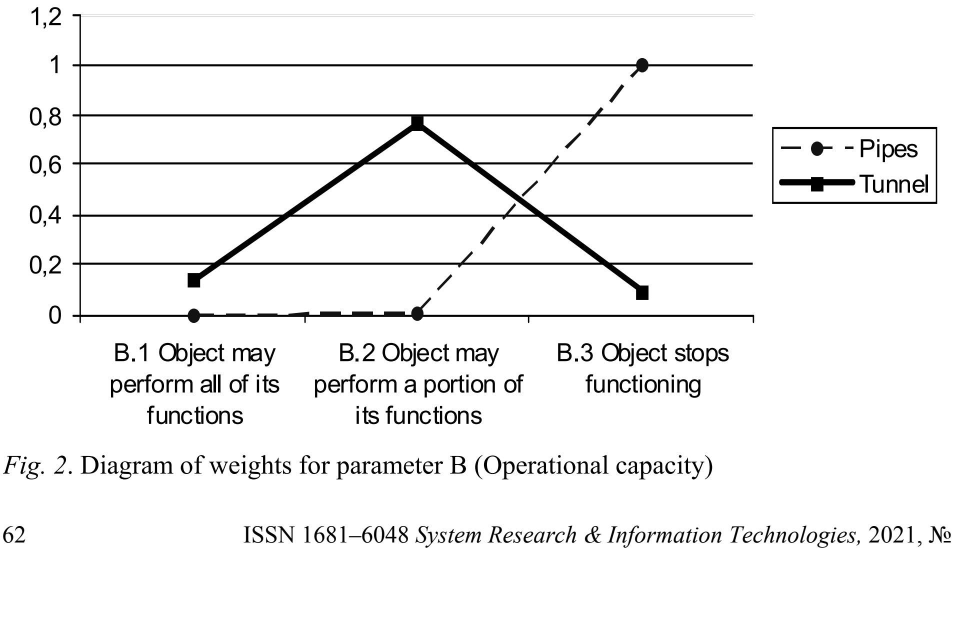

Fig. 2. Diagram of weights for parameter B (Operational capacity)

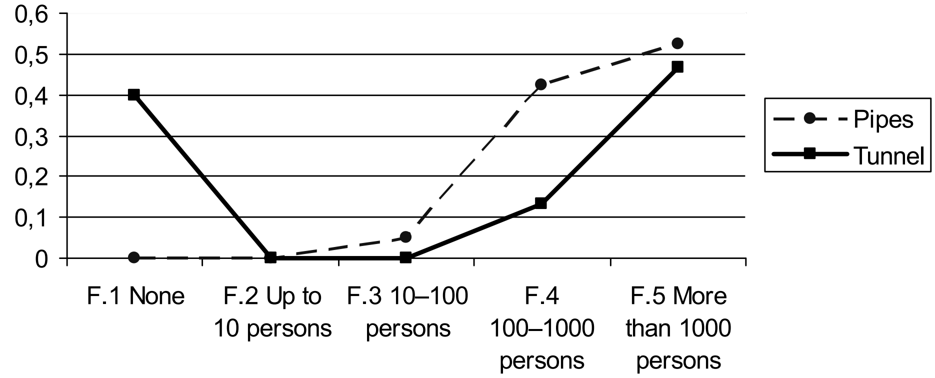

Fig. 3. Diagram of weights for parameter F (Affected citizens)

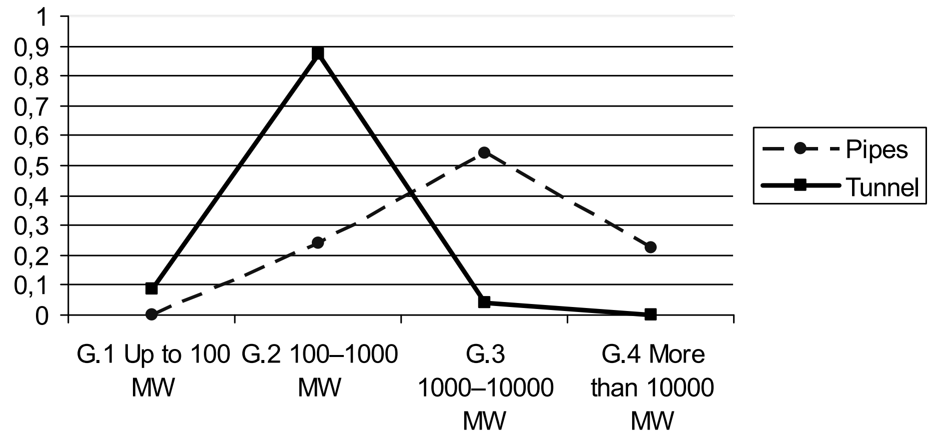

Fig. 4. Diagram of weights for parameter G (Material damage)

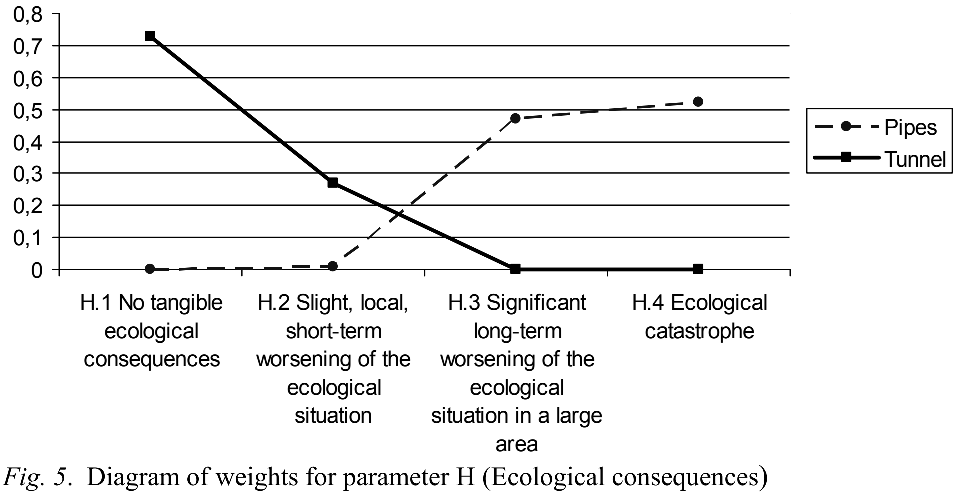

Fig. 5. Diagram of weights for parameter H (Ecological consequences)

Diagrams allow to compare and evaluate scenarios for underwater pipes and underground tunnels. It is notable that the most disruptive event (explosion) leaves a small chance of full operation for a depressed sewer in an underground tunnel (with 0,142 weight), whereas the underwater pipes have zero chance of performing all or a part of functions (Fig. 2). Even in the case of an explosion, an underground tunnel retains high chance of performing a part of functions (weight appr. 0,8). Affecting living conditions of population is the only criterion where the results of underwater pipes and an underground tunnel are relatively close, as disrupting any kind of sewage system will have radical consequences for a large portion of Kyiv population (Fig. 3). Material damage for an underground tunnel mostly falls in the alternatives up to 1000 minimum wages (weight 0,87) for repair of casing, hydroisolation etc., while for the underwater pipes an explosion means total destruction with expenses on restoration and elimination of ecological damage, up to 10000 minimum wages and even more (total weight 0,76 – Fig. 4). Diagram for parameter H (Ecological consequences) is also very significant. A burst of sewage into Dnipro river may lead to an ecological catastrophe for the whole river basin. As the diagram in Fig. 5 clearly shows, an explosion in an underground tunnel does not impact the ecological situation (weight 0,73), as it lies tens of meters beneath the river bottom, and damage to casing will not impact the situation. Local short-term worsening of ecological situation (weight 0,27) may be caused by an exposure of sewage to underground waters, but it does not have a threatening scale. On the other hand, a disruption of underwater pipes causes an ecological catastrophe (weight 0,52) or at least a significant long-term worsening of the ecological situation in a large area (weight 0,47).

Results of morphological modeling with fixed parameters, corresponding to scenarios 2–4, are shown in the diagrams at Fig. 6–9.

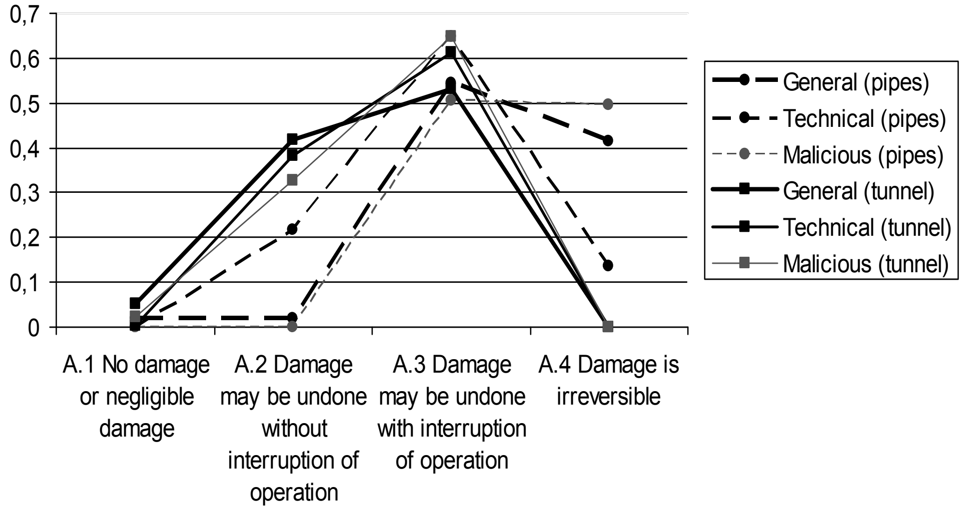

Fig. 6. Diagram of weights for parameter A (Integrity of the object and its parts)

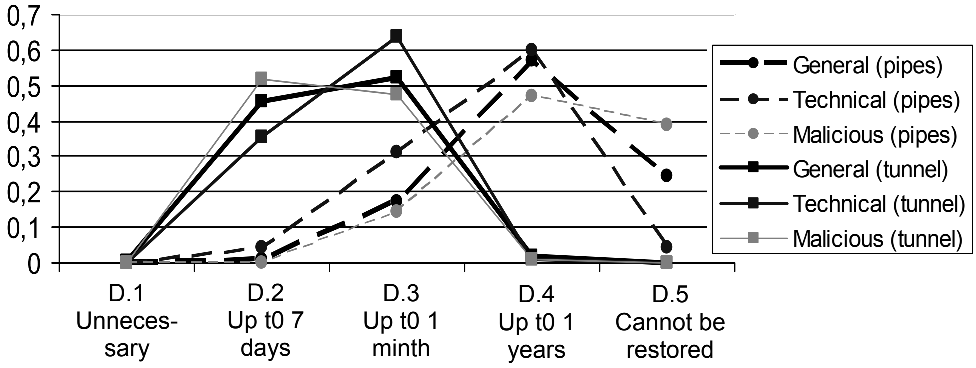

Fig. 7. Diagram of weights for parameter D (Operation restore time)

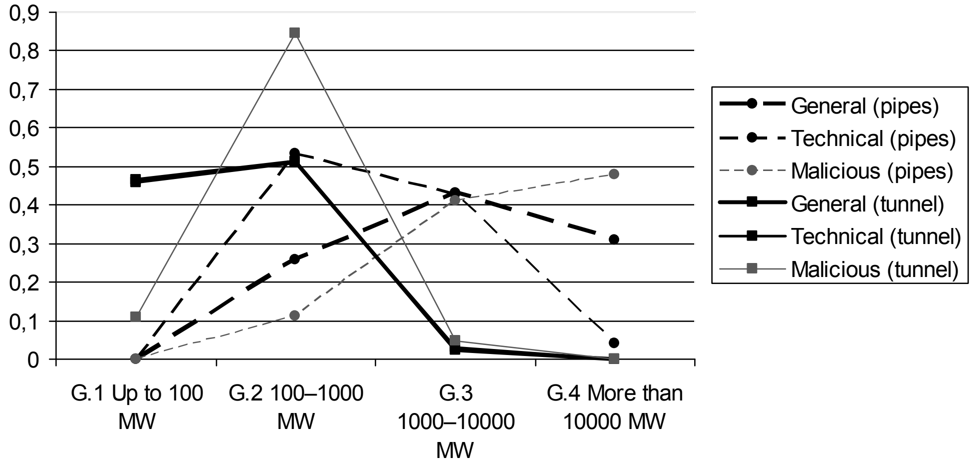

Fig. 8. Diagram of weights for parameter G (Material damage)

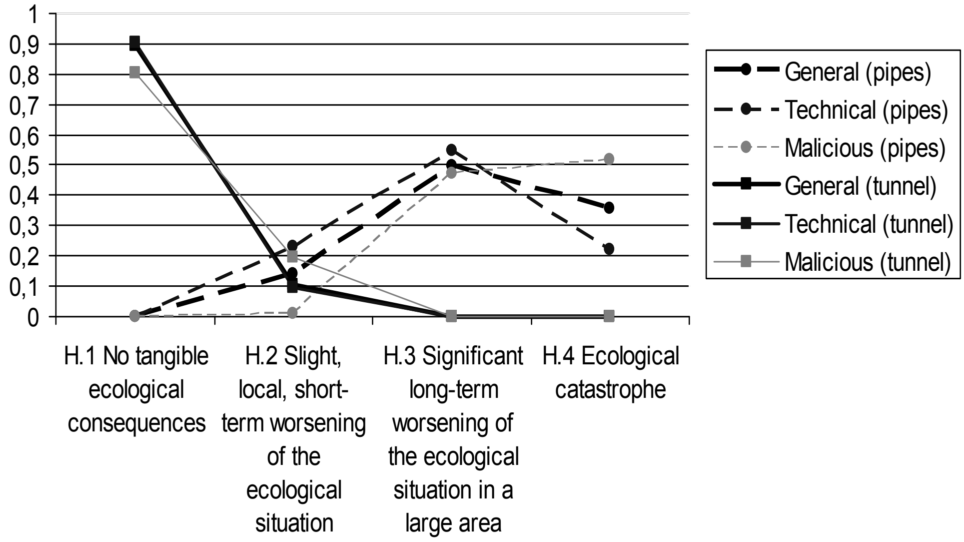

Fig. 9. Diagram of weights for parameter H (Ecological consequences)

Diagrams in Fig. 6–9 once again visibly confirm the advantage of an underground tunnel over underwater pipes, obtained in the modeling results, and this advantage is present in any scenarios.

CONCLUSIONS

The conducted analysis proves that a depressed sewer as a system of pipes is a vulnerable infrastructure object that may be a target for sabotage or a terrorist attack with catastrophic consequences for urban safety, and ecology. Simultaneously the obtained results demonstrate high reliability of a tunneled depressed sewer under conditions of military or sabotage threats, and justify the advisability of transferring the respective part of the urban infrastructure into underground space.

The comparison of scenarios shows that intentionally created undesirable events (sabotage, terrorism acts) generally cause more severe consequences, with higher damage if compared to undesirable events of natural or technogenic origin. The developed technique and tool set of modified morphological analysis can be applied for comparison of other infrastructure objects, laying the ground for a system strategy of developing urban underground space aimed at the minimization of military, technogenic and natural threats. The authors propose the inclusion of a tunneled depressed sewer into the General Plan of Kyiv city.

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МОРФОЛОГІЧНА МОДЕЛЬ ПІДЗЕМНИХ ПЕРЕХОДІВ ВОДНИХ ОБ'ЄКТІВ / Н.Д. Панкратова, Г.І. Гайко, І.О. Савченко

Анотація. Розглянуто побудову морфологічної моделі небажаних подій щодо урбаністичних об'єктів, а також наслідки цих подій включно з порушенням здатності до функціонування, можливістю і термінами відновлення роботи, матеріальними збитками і людськими втратами, екологічними ризиками. На основі цієї моделі застосовано двохетапний модифікований метод морфологічного аналізу для двох типів об'єктів: трубних і тунельних каналізаційних дюкерів. Наведено результати порівняння дюкерних переходів із використанням розробленої моделі як для випадку всієї множини потенційних несприятливих подій, так і для випадку конкретних сценаріїв диверсії, зсуву ґрунтів, експлуатаційних пошкоджень. Обґрунтовано перевагу тунельного дюкера над трубним з точки зору мінімізації техногенних та екологічних ризиків відведення стічних вод.

Ключові слова: екологічні ризики, техногенні ризики, підземна інфраструктура, відведення стічних вод, системна методологія, морфологічний аналіз, дюкерний перехід.

МОРФОЛОГИЧЕСКАЯ МОДЕЛЬ ПОДЗЕМНЫХ ПЕРЕХОДОВ ВОДНЫХ ОБЪЕКТОВ / Н.Д. Панкратова, Г.И. Гайко, И.А. Савченко

Аннотация. Рассмотрено построение морфологической модели нежелательных событий относительно урбанистических объектов, а также последствий этих событий, включая нарушение способности функционировать, возможность и сроки возобновления работы, материальный ущерб и человеческие потери, экологические риски. На основе этой модели применено двухэтапный модифицированный метод морфологического анализа для двух типов объектов: трубных и туннельных канализационных дюкеров. Приведены результаты сравнения дюкерных переходов с использованием разработанной модели как для случая всего множества потенциальных нежелательных событий, так и для случая конкретных сценариев диверсии, сдвига грунтов, эксплуатационных повреждений. Обосновано преимущество туннельного дюкера над трубным с точки зрения минимизации техногенных и экологических рисков отведения сточных вод.

Ключевые слова: экологические риски, техногенные риски, подземная инфраструктура, отведение сточных вод, системная методология, морфологический анализ, дюкерный переход.