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MULTI-CRITERIA ASSESSMENT METHODS FOR THE EFFECTIVENESS OF PROTECTIVE STRUCTURES IN EMERGENCY SITUATIONS

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Abstract. This article examines the assessment of the effectiveness of protective structures used in emergency situations not on the basis of a single technical indicator, but on the basis of a set of interrelated criteria such as structural strength, capacity, engineering support, evacuation convenience, readiness for management, sanitary and hygienic condition, inclusiveness, and operational sustainability. Based on an analysis of the regulatory and legal documents of the Republic of Uzbekistan in the field of civil protection and protection from emergencies, international practical recommendations, and scientific sources, a multi-criteria assessment model consisting of eight blocks for protective structures was proposed. The model includes weight coefficients, standardization rules, threshold criteria, and an integrated rating method. In addition, sensitivity analysis was carried out using the example of three conditional facilities under a baseline scenario, a safety-priority scenario, and an access-and-egress-priority scenario. The results showed that structures with higher safety and accessibility may not always be inferior to facilities with larger capacity, while management and engineering systems significantly affect the stability of the final score. The proposed approach has practical significance for inventorying protective structures, determining repair priorities, comparing territorial needs, and increasing the level of preparedness for emergencies.

Keywords: emergency situation, protective structure, multi-criteria assessment, integrated score, weight coefficient, evacuation, engineering support, inclusiveness, sustainability.

Introduction. In today's conditions, where natural, technogenic, and mixed forms of emergencies are becoming increasingly complex, protective structures should be regarded not merely as passive objects that serve as shelters, but as active engineering systems that help preserve the population, buy time, ensure continuity of management, and organize the work of rescue forces. Therefore, when assessing the effectiveness of such a structure, it is not sufficient to consider only wall thickness, capacity, or location in isolation. Practice shows that in some cases a structurally strong facility may be inconvenient from the standpoint of evacuation, while a high-capacity facility may remain weak in terms of sanitation or readiness for management.

The Law of the Republic of Uzbekistan “On Civil Protection” interprets protective structures as a set of engineering structures specially intended to protect the population and production personnel [1]. This law states that civil protection facilities include protective structures, command posts with complexes of above-ground buildings, and separate and attached shelters and radiation protection spaces [1]. This means that when assessing the effectiveness of protective structures, one should consider not only the internal volume of the building, but also its management, communication, engineering, and service systems as an integrated whole.

In addition, the Law "On the Protection of the Population and Territories from Natural and Technogenic Emergencies" defines protection from emergencies as one of the priority directions of state policy [2]. The regulation on the state system for the prevention and elimination of emergencies also specifically notes, among the tasks of the engineering service, the supervision of the accumulation and availability of the stock of protective structures in peacetime, as well as the engineering support of force operations in flood zones, major fires, natural disasters, and the elimination of the consequences of major accidents [3]. Therefore, the approach to assessing effectiveness should also be legally linked to the condition, sufficiency, and level of preparedness of the facility.

At the international level as well, understanding risk, managing risk, investing in resilience, and preparing for an effective response are recognized as priority areas [4]. In urban resilience assessment tools, the practice of expressing infrastructure resilience to disasters in scores, identifying deficiencies, and prioritizing them is widely used [5]. The safety index developed for healthcare institutions demonstrates the need to jointly account for structural, non-structural, and management capacity [6]. This approach also confirms the need to move away from one-sided indicators in assessing protective structures and toward an integrated view.

The problem is that practical assessments of protective structures are often conducted in the form of checklists, but differences in weights among criteria, mandatory threshold criteria, and sensitivity across different scenarios are usually not analyzed sufficiently. As a result, it becomes difficult to make scientifically grounded decisions about which facility should be repaired first, in which area a new structure is needed, and which facility is better suited to a particular type of hazard.

In this regard, the purpose of this article is to develop a comprehensive multi-criteria model for assessing the effectiveness of protective structures in emergency situations and to substantiate the structure of the criteria, weight coefficients, standardization methods, threshold criteria, and the procedure for integrated rating. The approach proposed in the article can serve as a practical decision-making tool for territorial management bodies, civil protection services, design organizations, and facility managers.

Literature review. In recent years, a multi-criteria approach has become increasingly prominent in scientific studies on the selection of protective and temporary shelter facilities. The main reason is that, under emergency conditions, many requirements that may conflict with each other must be satisfied simultaneously: the facility must be safe, have sufficient capacity for the population, provide open access routes, have resources such as water and electricity, be located near medical points, and create suitable conditions for management and control.

In the model proposed by Manuela Marques Lalane Nappi, Vanessa Nappi, and Joãoun Carlos Souza for the selection of collective and temporary shelters, nine major criteria were identified, including safety, urban infrastructure, physical suitability, cultural suitability, environmental comfort, universal accessibility, economic aspects, and location [8]. Based on the expertise of 23 practitioners, the authors determined the weights and showed that "people's safety," "cultural suitability," and "accessibility of the location" were among the most important criteria [8]. This conclusion is also important for the issue of protective structures, because even a structure with a high level of safety may lead to low effectiveness during an emergency if access to it is poor or it is inconvenient for users.

Using open global data, Sara Godshall and her co-authors developed a multi-criteria decision model for selecting shelter points in multi-hazard areas and showed that it is possible to determine optimal locations even in low-data regions [9]. This approach is particularly relevant for areas

where the database has not been fully formed or where inventory data are scattered across different sources. Under the conditions of Uzbekistan as well, because discrepancies may occur between passport data and the actual technical condition of some facilities, it is necessary to combine remote monitoring, field inspection, and multi-criteria assessment.

Jinghai Xu and co-authors proposed a multi-criteria location model for placing earthquake evacuation shelters from an urban planning perspective [10]. Jia Yu and Jiahong Wen, in assessing the spatial distribution of urban emergency shelters, developed a methodology for determining the level of satisfaction based on criteria while taking into account differences in population density between daytime and nighttime [11]. The main scientific conclusion arising from these studies is that the same facility may produce different results at different times and under different scenarios; therefore, the assessment system should not be static but sensitive to scenarios.

Muhammad D. J. Alam and co-authors showed that when selecting shelter locations during evacuation, criteria should be considered in three stages—identifying candidates, screening, and evaluating them—while environmental factors, structural characteristics, proximity to emergency services, and transport factors should be used together [12]. Sagnik Bera and co-authors proposed a model for selecting shelter locations in mountainous areas while taking into account the disruption of roads under rain-induced flood and landslide hazards [13]. These results indicate that when assessing the effectiveness of protective structures, criteria such as external connectivity, continuity of the road network, and safe distance from hazard zones must be included as mandatory elements.

Eda Atmaca and co-authors separately identified such criteria as land slope, proximity to water sources, road network, distance to medical points, material supply, and site type for emergency assembly areas and temporary shelters [14]. These criteria are particularly important in assessing above-ground and semi-underground protective structures. This is because, at the initial stage of an emergency, not only the internal structural strength of a facility but also the quality of its connection to the external environment affects overall survivability.

A systemic view of assessment is also observed in international practical guidelines. The United Nations Office for Disaster Risk Reduction offers a scoring tool for urban resilience [5]. The World Health Organization recommends jointly assessing structural safety, non-structural elements, and emergency management capacity for healthcare facilities [6]. The Sphere Handbook, in turn, puts forward the principle of a safe, adequate, and people-centered living environment as a key criterion [7]. Thus, when assessing the effectiveness of protective structures, legal requirements, technical condition, and the human factor should be integrated within a single methodological framework.

The literature analysis shows that the main advantage of existing approaches lies in the breadth of the criteria covered, while their main drawback is that they are often limited to a specific region or a specific type of hazard. For this reason, it is scientifically and practically important to develop an assessment model adapted to the conditions of Uzbekistan, but harmonized with international experience, including threshold criteria and based on sensitivity analysis.



Figure 1. Illustrative real photograph of the internal condition of an underground protective structure.

Research methodology. The main purpose of the study is to substantiate a unified, consistent, and practically applicable multi-criteria method for assessing the effectiveness of protective structures in emergency situations. To achieve this goal, the following tasks were carried out:

first, all criteria encountered in legal and scientific sources were grouped;

second, weight coefficients were proposed for the criterion blocks; third, a rule was developed for bringing indicators to a uniform scale; fourth, threshold criteria that preliminarily determine whether a protective structure is fit or unfit for use were identified; fifth, the sensitivity of the model was tested on a conditional example.

Methodologically, the study relied on regulatory and legal analysis, comparative analysis, synthesis of expert conclusions, weighted integrated assessment, and scenario-based sensitivity analysis. The regulatory and legal analysis was carried out on the basis of the laws of the Republic of Uzbekistan and organizational documents in the field of emergency situations [1–3]. The comparative analysis compared the composition of criteria found in international practical recommendations and scientific articles [4–14].

An important aspect of the proposed model is that not all criteria are equal. For example, a facility in which serious deficiencies are identified in structural strength and level of protection should not rank highly simply because it has a good water reserve or convenient location. For this reason, the model is based on a two-layer logic: at the first layer, threshold criteria screen the facility, and at the second layer, a weighted integrated score is determined.

From the standpoint of practical use, the model is applied in three stages. The first stage is the collection of passport data and field inspection data. The second stage is scoring and standardization by criteria. The third stage is calculating the overall score, comparing alternatives, and setting priorities. In this way, the method serves not only scientific analysis, but also management decision-making.

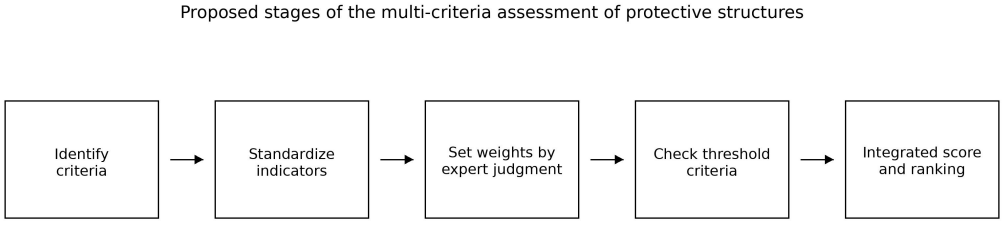


Figure 2. Proposed stages of the multi-criteria assessment of protective structures.

Based on the literature, regulatory documents, and practical needs, eight major blocks and twenty-four indicators were selected to assess the effectiveness of protective structures. Each block reflects not an isolated aspect of the facility, but its overall survivability and suitability for management.

Block	Content	Main indicators	Weight
1. Structural strength and level of protection	The actual condition of the main load-bearing part of the structure, the covering, doors, and internal safety elements.	Condition of deformations and cracks; condition of protective doors and closing elements; risk of secondary collapse of parts.	0.24
2. Capacity and location efficiency	Ability to accommodate the population, as well as rational distance from the hazard zone and level of territorial coverage.	Usable area and capacity; safe distance from the hazard source; territorial coverage and suitability for nearby population groups.	0.16
3. Engineering support and living conditions	The systems that ensure internal life in the structure and minimum living comfort.	Ventilation and air exchange; water, electricity, backup resources; internal microclimate and comfort of placement.	0.15
4. Access, egress, evacuation, and external connectivity	Speed of access to the object, clarity of directions, and degree of connection to external road networks.	Main and backup access routes; evacuation route and signs; connection to transport and road networks.	0.14
5. Management, communication, and operational readiness	Ability to activate the facility in emergency mode, establish	Communication means; duty and activation procedures;	0.11

	communication, and continue management.	internal management and monitoring means.	
6. Sanitation and hygiene, medical proximity, and environmental safety	A block related to users' health, hygiene, and prevention of secondary risks coming from the environment.	Sanitary unit and waste management; proximity to medical assistance; secondary hazards such as flooding, smoke, and toxic substances.	0.10
7. Inclusiveness and user convenience	Convenience and safety of use for people of different ages and for persons with limited mobility.	Ramps and barrier-free access; convenience of internal corridors and placement; provision of information in visible and understandable form.	0.06
8. Operating cost and recovery speed	Resources required to maintain the structure, prepare it for operation in the short term, and restore it after damage.	Current maintenance cost; possibility of rapid repair; availability of backup equipment and service.	0.04

Results and analysis. The proposed weights should be viewed not as absolute final values, but as an initial configuration based on literature analysis and practical expert logic. The largest share was assigned to structural strength and level of protection, because if a serious structural defect exists, the remaining positive indicators cannot compensate for the facility's main function. Capacity and engineering support were placed in second and third positions, because in an emergency a protective structure must be able to accommodate people and maintain minimum living conditions.

The reason for assigning a relatively high share to access/egress and external connectivity is related to a situation often observed in practice: even if the internal condition of the facility is satisfactory, overall effectiveness decreases if it cannot be reached quickly or if the emergency exit does not function. Management, communication, and operational readiness are necessary not merely to preserve the structure, but to use it in a real operating mode.

Although the weights of the criteria for sanitation and hygiene, inclusiveness, and operating costs were set relatively lower, they are not secondary. On the contrary, these indicators play a decisive role in longer-term use, the safety of women, children, the elderly, and persons with disabilities, as well as in maintaining internal order and health. Therefore, despite their lower weight, some indicators from these blocks are also applied as mandatory conditions within the system of threshold criteria.

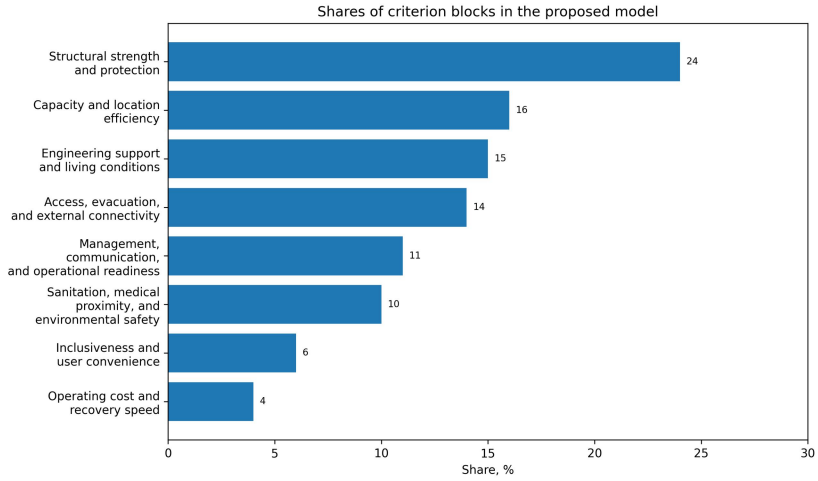


Figure 3. Shares of the criterion blocks in the proposed model.

Indicators may be expressed in different units. For example, usable area may be measured in square meters, proximity to a medical point in distance, and the condition of ventilation in expert scores. Therefore, all indicators are first converted to a single scale from 0 to 1.

For beneficial indicators, that is, those for which the condition of the facility improves as the value increases, the following standardization rule is used:

xij = (aij - amin) / (amax - amin)

Here, xij is the standardized value of the i-th indicator for the j-th object, aij is the observed actual value, and amin and amax are the minimum and maximum bounds of that indicator.

For indicators for which the condition of the facility improves as the value decreases, such as excessive proximity to a hazard source or the time required for repair, the inverse formula is applied:

xij = (amax - aij) / (amax - amin)

After that, the overall integrated score for each object is determined as follows:

Bj = 100 × (Σ wi × xij) × Pj

Here, wi is the weight of the i-th criterion, and Pj is the threshold coefficient related to the j-th object. If the object meets all mandatory requirements, Pj = 1. If certain serious deficiencies are identified, Pj takes reducing values such as 0.85, 0.70, or 0.50. If a very dangerous deficiency is present, the object is directly recognized as unfit for use and excluded from the rating.

The following interpretation of the integrated score is recommended: 90–100 points—very high effectiveness; 75–89 points—high effectiveness; 60–74 points—medium level; 45–59 points—low level; 0–44 points—unsatisfactory or not recommended for use.

Threshold criterion	Requirement	Effect
Functionality of the access route	The main access route must be practically usable, and the door opening must be fully operational and safe.	If not met, a reducing coefficient of 0.70 is applied to the object.
Emergency exit	At least one emergency exit must exist and must not be	If not met, the object cannot receive a score higher than 60

	blocked.	points.
Ventilation or air exchange	Minimum air exchange in the internal environment must be ensured.	If not met, the object is not recommended for use.
Flooding and toxic flow risk	The location of the object must be satisfactory in terms of secondary flooding, toxic liquid flow, or accumulation of heavy smoke.	If a serious risk is identified, the object is excluded from the rating.
Activation of communication and management	Communication means or their backup variant must be activated within a short period.	If not met, the management block of the object is reduced to zero.
Minimum sanitation	A sanitary unit or an alternative sanitation solution must be available.	If not met, a reducing coefficient of 0.85 is applied.

To demonstrate the operating logic of the proposed model, three conditional objects were selected. Object A is an underground structure with good structural condition but medium capacity; Object B is a structure with large capacity and convenient access routes, but slightly lower structural strength than Object A; Object C is structurally satisfactory, but weak in access/egress, management, and inclusiveness indicators.

The scientific significance of the conditional example is that it shows that the multi-criteria model does not automatically give preference to large capacity, but instead produces results in combination with safety, ease of use, and management readiness. The table below presents standardized values for the major criterion blocks for each object.

Criterion block	Weight	Object A	Object B	Object C
Structural strength and protection	0.24	0.86	0.72	0.90
Capacity and location efficiency	0.16	0.78	0.91	0.63
Engineering support and living conditions	0.15	0.82	0.76	0.70
Access, egress, and external connectivity	0.14	0.74	0.85	0.59
Management, communication, and operational	0.11	0.69	0.80	0.55

readiness				
Sanitation, medical proximity, and environmental safety	0.10	0.81	0.68	0.66
Inclusiveness and user convenience	0.06	0.72	0.79	0.52
Operating cost and recovery speed	0.04	0.66	0.71	0.61
Overall integrated score	1.00	79.8	78.5	66.4

Table 3. Results of the integrated assessment for three conditional objects.

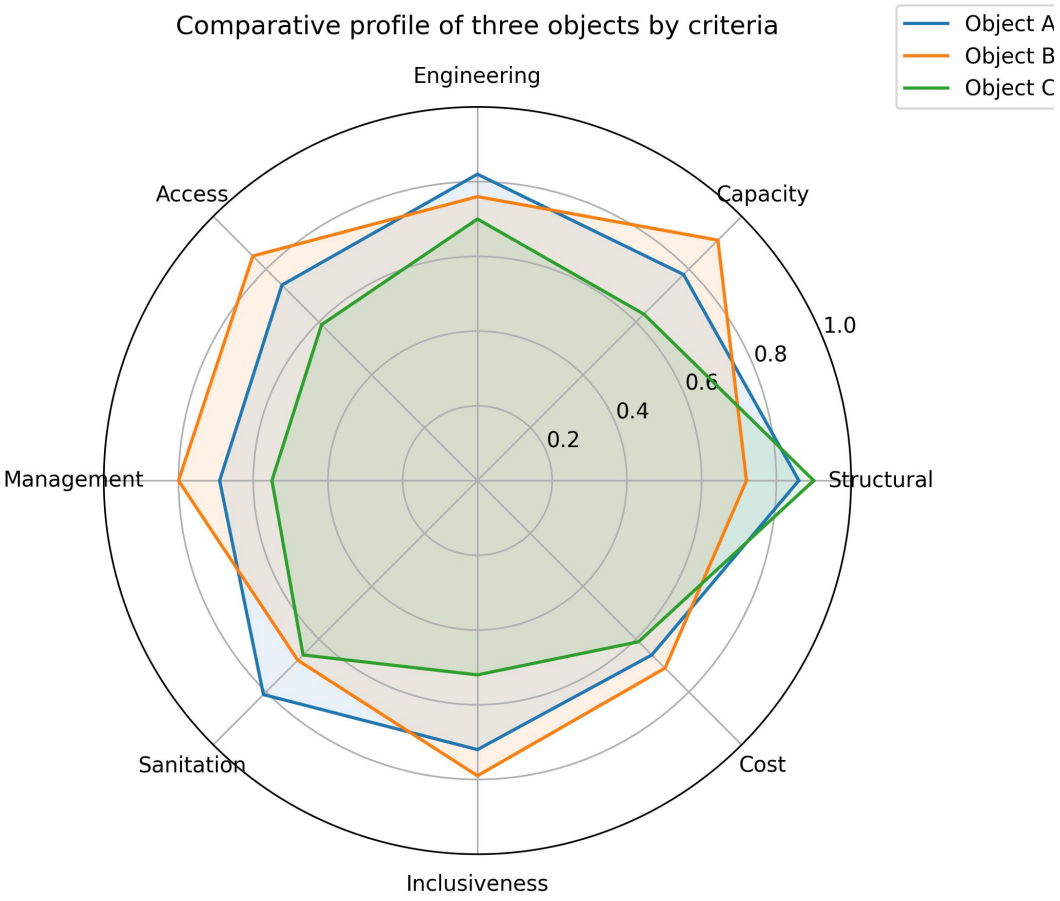


Figure 4. Comparative profile of three objects by criteria in the conditional example.

The calculation results showed that, in the baseline scenario, Object A ranked first with 79.8 points, Object B second with 78.5 points, and Object C third with 66.4 points. Object A achieved

an advantage in the overall score due to high results in structural strength, engineering support, and sanitation and hygiene. Although Object B was strong in capacity, access/egress, and management, its relatively lower indicators in the structural and sanitation blocks slightly reduced its final score.

The example of Object C leads to a particularly important scientific conclusion. Its structural indicator is not poor, but shortcomings in access/egress, management, inclusiveness, and external connectivity significantly reduced the overall score. This situation shows that, under emergency conditions, “strong but difficult-to-use” facilities are insufficient from the standpoint of real effectiveness. One thing should not be forgotten in interpreting the results: the multi-criteria model is not an absolute verdict, but a system that supports decision-making. As the composition of experts, territorial characteristics, hazard type, population density, and duration of use change, the weights and some criteria may also be revised. For example, in industrial zones with high chemical risk, the weight of hermetic sealing and filtration-ventilation increases; in areas with high flood risk, the weight of elevation and drainage systems is increased. Therefore, the most correct way to apply the model is to use it together with scenario analysis. In this case, the baseline score reflects the general condition, while a safety-priority scenario, an evacuation-priority scenario, or a long-term accommodation-priority scenario enables decision-makers to choose the most suitable option for different situations.

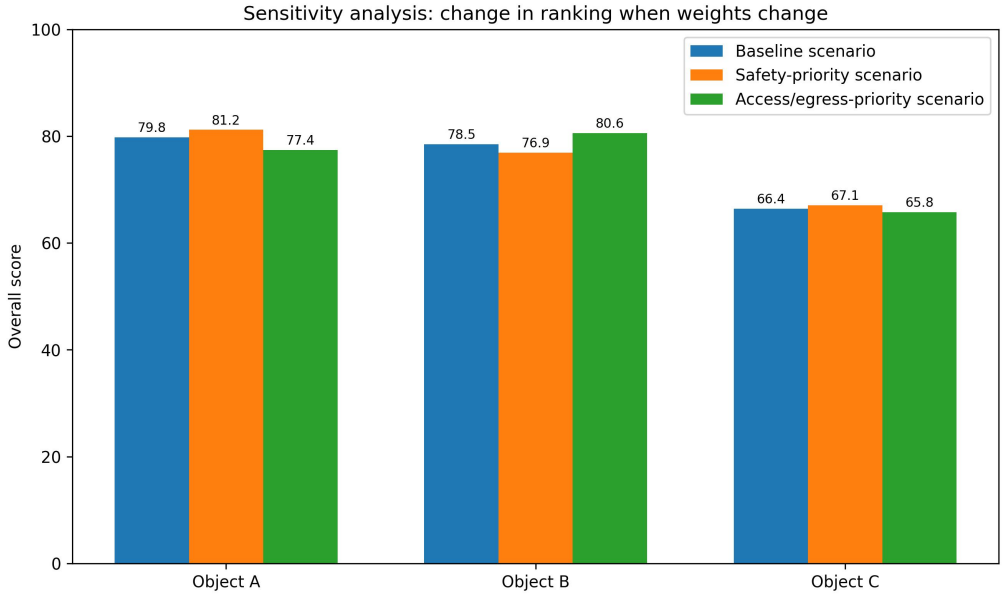


Figure 5. Sensitivity analysis result: change in ranking when weights change.

Sensitivity analysis showed that the difference between Objects A and B is not very large. Under the safety-priority scenario, Object A’s score increased to 81.2 points, while Object B fell to 76.9 points. Under the access/egress-priority scenario, Object B moved into first place with 80.6 points. Such a result indicates the high practical value of the methodology: by determining which scenario is primary, the decision-maker can more accurately resolve the issue of repair, equipment provision, or selection of a backup facility. In international practice as well, assessment tools are used across several priority dimensions. Urban resilience indicators consider infrastructure, management, and preparedness not sequentially, but simultaneously [5]. In assessing the safety of healthcare institutions, structural, non-structural, and management capacity are also considered within a single system [6]. The approach proposed in this article adapts that integrated thinking to the assessment of protective structures.

Another important aspect is inclusiveness. International documents specifically note that persons with disabilities, older people, children, and other vulnerable groups suffer more during emergencies [15]. The existence of scored requirements for taking into account the needs of persons with disabilities in evacuation, shelter, and shared living spaces requires the inclusion in the assessment of protective structures of such elements as ramps, visible signs, barrier-free routes, and understandable information systems [15]. Another advantage of this model for the multi-criteria assessment of the effectiveness of protective structures is that it links the stages of inventory, repair programming, and planning of new structures. If, in a certain area, all facilities are structurally satisfactory but weak in sanitation and communication, the direction of investment becomes clear.



Figure 6. Illustrative real photograph of a sign indicating a protective structure.

The first recommendation is to establish a unified digital passportization system for all protective structures. The passport should record not only the year of construction and capacity, but also structural condition, the access/egress scheme, engineering networks, backup equipment, communication means, sanitary condition, and inclusiveness indicators. These data make it possible to update the multi-criteria assessment periodically.

The second recommendation is to form an expert group with the participation of territorial management bodies, design organizations, and civil protection services, and to adapt the weight coefficients to the characteristics of the area. Applying the same weights to mountainous areas, industrial areas, dense urban areas, and rural areas is not always correct.

The third recommendation is to turn the list of threshold criteria into a practical inspection checklist. In particular, a simple but strict sheet is needed that allows rapid inspection of the main access route, emergency exit, ventilation, flood risk, communication means, sanitary minimum, and fire safety.

The fourth recommendation is to link assessment results to investment and repair decisions. In many cases, instead of a one-time comprehensive repair, a step-by-step improvement strategy by criterion blocks is more appropriate. For example, in the first stage, access/egress and sanitation

can be improved; in the second stage, communication and backup electricity; in the third stage, internal adaptation works.

The fifth recommendation is to incorporate training and test results into the integrated score as well. There may be a difference between paper readiness and real deployment speed. Therefore, it is advisable to assess as a separate indicator the results of periodically opening the facility, testing directions, admitting the population, and verifying internal management in practice.

The sixth recommendation is to treat inclusiveness not as a secondary issue, but as an integral part of overall effectiveness. If a person in a wheelchair cannot enter the structure, if a visually impaired citizen cannot find the route, or if there is no safe internal zone for children, the overall score of such a facility decreases in real life. Thus, inclusiveness is not an additional ornament, but safety itself.

The seventh recommendation is to display multi-criteria results on a map and combine them with territorial coverage. This approach shows near which mahalla, industrial hub, or social facility protection capacity is insufficient. As a result, decisions on constructing a new structure or reconstructing an existing one become much more well-founded.

Conclusion and recommendations. Assessing the effectiveness of protective structures in emergency situations has a multi-factor and multi-stage character. This study has shown that it is not sufficient to assess a protective structure only on the basis of structural condition or capacity. Real effectiveness is determined by the interrelationship of structural strength, location, engineering support, ease of evacuation, readiness for management, sanitation and hygiene, inclusiveness, and operational sustainability.

The article proposed a multi-criteria model consisting of eight blocks and twenty-four indicators. The scientific novelty of the model lies in combining threshold criteria with a weighted integrated score in one system. This approach not only clearly shows comparative differences between facilities, but also identifies deficiencies that are absolutely unacceptable from the standpoint of safety.

The conditional practical test demonstrated that the advantage between Objects A and B may shift depending on the scenario, while the example of Object C showed that seemingly auxiliary indicators such as management, access/egress, and inclusiveness have a significant effect on the overall score. Thus, the multi-criteria approach increases flexibility and accuracy in decision-making.

In practical terms, the model can be used for passportization, inventory, ranking of protective structures, formation of priority repair programs, identification of shortages by territory, and substantiation of the location of new structures. In the future, it would be appropriate to further improve this method by enriching it with data from real facilities, remote monitoring, training results, and territorial hazard maps.

The following table is recommended as a short assessment sheet that can be filled in on site during a practical inspection. It is especially convenient at the screening stage before detailed calculations.

Item	Inspection question	Status	Comment
1	Is the main access route open and safe?	Yes / No	
2	Is an emergency exit available?	Yes / No	
3	Is ventilation or air exchange	Yes / No	

	functioning?		
4	Is there a backup source of water and electricity?	Yes / No / Partly	
5	Does the usable internal area correspond to the designated capacity?	Yes / No / Partly	
6	Is the minimum sanitation requirement ensured?	Yes / No	
7	Is there a communication means or backup communication?	Yes / No	
8	Are ramps and barrier-free access available?	Yes / No / Partly	
9	Are the direction signs visible and understandable?	Yes / No / Partly	
10	Can the facility be activated within a short period?	Yes / No / Partly	

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