

Article

To the Issue of Assessment of the Technical Condition of Underground Structures of Buildings

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Abstract: A survey and assessment of the technical condition of basement and semi-basement structures in public buildings aged 60 to 130 years were conducted to evaluate their suitability for use as basic shelters. Based on the survey results, the most adverse impacts were identified, including changes in groundwater levels, improper building operation, and the characteristic damages to underground structural elements. Structural solutions were proposed to eliminate the consequences of these damages. The reviewed cases indicate that the vertical and horizontal waterproofing systems used during construction cannot perform their function throughout the building’s entire life cycle. When designing new buildings, waterproof materials should be used for the enclosing structures of underground premises. While this may have a higher initial cost than membrane or coating waterproofing, considering life-cycle costs, it can provide a positive economic effect and improve the quality and comfort of the indoor environment.

Keywords: technical condition assessment; damage; waterproofing; reinforcement corrosion; loess soil; flooding; settlement



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1. Introduction

The analysis of the building’s life cycle, cost, and impact on the environment from the beginning of construction, throughout operation, and during deconstruction is one of the key components of design and new construction. Life cycle assessment methods for existing buildings include ways to modernize, repair, or reconstruct buildings, which can extend the building’s life cycle. This, in turn, can reduce life cycle costs and environmental impact [1]. An alternative to building reconstruction and extending its life cycle is deconstruction (dismantling an existing building and constructing a new one using partially recycled materials) or demolition followed by new construction [2]. Even considering existing models

for material reuse and construction waste management [3,4], the financial and energy costs of these approaches may be higher than those of building reconstruction [2]. Continuous monitoring of the technical condition of structures is crucial for safe operation, which is carried out visually and through non-destructive testing methods, allowing for decisions regarding further building operation, strengthening methods, and reconstruction [5–9].

Carrying out repair work and building reconstruction, which may include the reconfiguration of interior spaces, changes in functional purpose, and bringing the building's structures and spatial planning solutions in line with existing regulatory requirements, is one of the ways to extend the building's life cycle.

The underground part of the building requires attention during design and construction [10] and during the building's operation. A popular trend in modern urban planning, especially in densely populated areas, is the integrated use of underground space, such as constructing multi-level parking lots, retail and warehouse spaces, cafes, and other facilities.

As can be seen from the daily chronicle of military conflicts and large-scale hostilities, especially in Ukraine nowadays, there is a great social need for numerous reliable and easily accessible underground shelters for civilians. The existing basement and semi-basement premises were either not in use or were utilized as technical facilities. With the need to bring them into proper operational condition for potential use as basic shelters, many inspections were conducted on basement and semi-basement premises in public and residential buildings. Typical damages were identified, and a comprehensive analysis was carried out on the influencing factors affecting the “natural soil foundation–foundation–underground part of the building–above-ground structures”. As geotechnical practice shows, this area is also relevant for reconstructing buildings and structures.

In addition to the social and economic advantages of underground construction, there are also purely geotechnical achievements, such as cutting through the upper layers, whose soils often have unique properties (subsidence, swelling, high organic content, anthropogenic origin, and significant compressibility). This makes it possible to choose more robust and less compressible soils as the bearing layer of the natural foundation base and, therefore, to sometimes refuse to use piles.

However, the downside of building projects with a developed underground component is the need to (1) protect it from groundwater during construction and operation and (2) ensure that the absolute and relative settlements of the foundation of the surrounding buildings do not exceed their maximum regulatory values, which depend on the technical condition of the existing facilities.

According to European [11,12] and national standards [13,14], the builder must ensure a sufficient level of reliability (dependability, maintainability, and durability) of the system: “natural soil foundation–foundation–underground part of the building–above-ground structures”. Therefore, for new constructions and reconstruction projects, standards limit the maximum settlement values of the foundations S_u , the relative difference in these settlements $(\Delta S/L)_u$, and the tilt of structures i_u , among other factors.

In addition to the aforementioned specific properties of soils, dangerous engineering and geological processes, such as area flooding, landslides, mechanical suffosion, karst, and artificial impacts, significantly complicate the system's design. The following groups of causes of full or partial failure of the system are often identified [15–17]:

1. Errors in engineering and geological surveys (such as insufficient scope; incorrect evaluation of soil parameters, particularly with unique properties; incorrect or absent prediction of groundwater level changes; neglecting the possibility of temporary underground water formation; ignoring the history of the formation of the engineering–geological conditions of the site; and other factors);

2. Errors in designing this system (such as failure to account for soil property changes, incorrect selection of the system's calculation scheme, deviations from norms, and other factors);
3. Failures of the system related to changes in the properties of the foundation and other components due to construction work (such as deficiencies in construction dewatering, prolonged cyclic wetting, drying, freezing of the upper bearing layer in open excavations, poor compaction of backfill soil, incorrect object conservation, and other factors);
4. System failures during operation (such as non-standard or unaccounted-for operational load, waterproofing and surface protection defects, and other factors).

As practice shows, the greatest danger to underground structures in heavily urbanized areas is the long-term and seasonal flooding of territories [18]. In our view, an essential development for improving the reliability of calculations in geotechnical design is the recent proposal by a group of geotechnical engineers from the Netherlands, Spain, and the United Kingdom [19] to introduce probabilistic approaches in forecasting groundwater level changes, including extreme annual values, in the new edition of the Eurocode.

The Ukrainian experience [20–22] and corresponding methods of comprehensive inspections of the condition of underground construction structures [23] are also helpful. Due to the urgent need to use basements and semi-basements as simple shelters, the results of such inspections provided recommendations for the further safe operation of these structures and the buildings as a whole. Each method of assessing the technical condition of underground structures based on the inspection results has its specifics, such as the following:

- The condition of buildings before and after external influences from adjacent underground construction is considered [24];
- The so-called stability of structures and their components is assessed based on statistical and engineering studies, considering the parameters of soils and rocks, new underground structures, and others [25];
- In the “fuzzy logic model”, the input variables are the assessments of the technical condition of individual elements of the structure (underground structure, load-bearing walls, ceilings, roof, and other elements) and the technical condition of the structure as a whole [26]. Thus, none of these original approaches is universal.

It is also advisable to monitor the technical condition of structures during construction and subsequent operation, i.e., to monitor the safety of underground structures by, for example, recording the “stress–deformation” ratio of the foundation soil during loading and unloading [27,28].

Attention is drawn to the new Chinese practice of creating a “comprehensive assessment of underground space resources” for individual cities (regions) based on the results of inspections of the system “foundation–foundation–underground part of the building–above-ground structures” evaluation of its technical condition and monitoring data [29]. The influence of microbial-induced carbonate precipitation treatment factors on the strength characteristics of loess soils is considered in [30]. The characteristics and methods of controlling the formation of cracks in underground tunnel structures are described in [31], analyzing the dependence of crack formation on the lining grade and the depth of the tunnel.

The next step in solving the problem of reducing the risks of underground structure operation under potential flooding conditions is the creation of mathematical models of this process by Austrian and Ukrainian specialists [32,33]. For example, a model for predicting groundwater level changes in Kharkiv was developed, which considers essential water balance components (groundwater replenishment from atmospheric sources, addi-

tional replenishment from underground waters, evaporation, and water extraction from underground sources).

There are also well-known examples of testing the modern “safe, optimized, and sustainable” design approach to the system: “soil foundation–foundation–underground part of the building–above-ground structures” [34].

The protection of the underground part of existing buildings from flooding often includes the following [35–37]: the installation of various drainage and water diversion systems, organization of open water drainage from sumps, elimination of drainage-free areas, regrading of surfaces away from buildings, restoration of waterproofing and drainage systems, creation of clay seals, and anti-filtration screens.

Thus, based on the analysis of the current state of the issue, this work aims to systematize information about typical constructions and the materials of the buildings’ underground parts, the impacts they experience, and the damage caused by these impacts.

2. Methods

The premises’ underground structures suffer damage during operation and require reinforcement. The deterioration of the operational characteristics of load-bearing and enclosing structures is often associated with the cessation of the premises’ operation (heating, ventilation, and so on) and the impact of external factors, including aggressive ones.

The inspection of the condition of underground building structures, the assessment of their technical condition, the design of repairs and reinforcements, and the execution of urgent works to restore damaged objects are carried out by regulatory documents [13,23]. This study presents an analysis of the impacts on underground building structures, as well as an assessment of defects and damages based on the inspection results of five objects in the Poltava region. Recommendations for improving the operational condition of the structures are provided based on the current regulatory documents in Ukraine. The recommendations were developed as part of technical inspection reports and design documentation for repair work.

According to the methodology for inspecting underground building structures and documenting the results, the classification features of the object’s damage category, the estimated degree of damage to the object as a whole, and general recommendations for further operation are determined. These recommendations include performing restoration work through routine repairs, major repairs, or urgent demolition of the object, if necessary.

3. Results

The underground part of buildings and structures is subjected to a complex range of impacts considered during their design and operation. Distinguishing underground structures by their purpose can include foundation structures and structures that combine load-bearing and enclosing functions. Typical structures of basement premises and their characteristic damages include the following:

- Concrete (prefabricated and cast in situ) load-bearing structures—non-sealed, exposed to aggressive influences, such as chemical corrosion of concrete (e.g., basements of industrial buildings, electrolysis, fertilizers, and other factors);
- Reinforced concrete wall structures—corrosion of reinforcement in walls and ceilings, destruction of the protective concrete layer, leaks from above, tree roots, and condensation, among others;
- Older structures—rubble or brick constructions with lime mortar—show destruction of the lime matrix, collapse of masonry, frost damage, vault destruction, and others;
- Steel–brick ceilings—corrosion of metal beams, cracks in vaults, and falling ceiling elements, among others;

- Wooden structures—affected by rot, primarily in their bearing areas.

The sites of the studied objects are located within the Poltava loess plateau, which consists of Quaternary loams and sandy loams. The thickness of the loess layer is 8.0–8.5 m, but when wet, there is no soil settlement from its weight.

The upper layer of loess soils is typically composed of heavy silty clay loams, which are macroporous and, in a saturated state, range from stiff plastic to soft plastic. They have a porosity coefficient of $e = 0.8–0.95$ and the following geotechnical parameters in a saturated state: internal friction angle: $\varphi = 17–20^\circ$, Cohesion: $c = 18–24$ kPa, and deformation modulus: $E = 4–7$ MPa.

The lower layer of loess soils is generally composed of light silty clay loams, which are also macroporous and, in a saturated state, range from soft plastic to fluid. They have a porosity coefficient of $e = 0.85–1.0$ and the following geotechnical parameters in a saturated state: internal friction angle: $\varphi = 17–24^\circ$, Cohesion: $c = 10–15$ kPa, and deformation modulus: $E = 2.5–5$ MPa.

It is also worth noting that loess soils (loess) are typically silty clays and sandy loams with a characteristic property of collapsibility. This means that upon wetting, they undergo additional deformation—subsidence—beyond regular settlement, reducing their mechanical properties. Loess soils are relatively homogeneous, containing more than 50% silt particles ranging from 0.05 to 0.005 mm. They also have a significant amount of quickly and moderately soluble salts and many pores, cracks, and cavities of various sizes. In a low-moisture state, loess can maintain a nearly vertical slope but quickly disintegrates upon water exposure. When saturated, especially under dynamic loads, it acquires properties similar to quicksand. Loess is typically light yellow or light brown. In its dry state, it has a powdery texture to the touch. These characteristics allow geotechnical engineers to identify loess soil and incorporate preventive measures to reduce or eliminate subsidence effects in project designs.

The mechanical properties of loess soil in its natural state and after wetting differ significantly. For example, the wetting of loess soils in the Poltava region to a water saturation coefficient of $S_r = 0.9$ leads, on average, to a 2.7–3 times reduction in the deformation modulus (E), decrease in the internal friction angle (φ) by $3–4^\circ$, and 2.5–3 times reduction in Cohesion (c).

Unfavorable physical and geological processes at the sites include subsidence phenomena (soils of loess origin due to wetting from above—domestic leaks from water-carrying communications and atmospheric waters from drainage-free areas around buildings—and from below, due to the general rise in groundwater levels in cities, have practically entered a “degraded” state, and part of them has been classified as weak (very compressible) soils with a deformation modulus $E < 5$ MPa) and flooding of the area; the total thickness of the non-structural (anthropogenic) deposits is up to 2 m.

The foundations of all the buildings were built by removing soil on a natural base consisting of degraded loess loams. The load-bearing layer is often composed of heavy, silty, stiff-plastic loam, with an underlying layer of light silty loam, from soft plastic to fluid plastic.

It is also worth noting the significant impact on underground structures and their foundations from the fact that in urban areas, groundwater levels rise in almost all cities due to the ageing of water-carrying communications (older than 50 years) and the increase in uncontrolled leaks from them.

Below, we will discuss in more detail the underground structures of buildings, their damages and defects, and the proposed methods of reinforcement and bringing them to an operational state based on the inspection of basement premises carried out to assess the possibility for the dual use of these premises, including as protective structures.

3.1. Shelter That Has Been Out of Operation

The inspected premises were initially designed and constructed as shelters [21]. Given its specific location and purpose, it was also used as a shooting range. The structure has not been in use for over 20 years. The foundation slab and walls of the shelter are made of cast in situ reinforced concrete, and the ceiling is prefabricated reinforced concrete. The ceiling is covered with waterproofing consisting of 2–3 layers of fiberglass and topped with soil and grass.

The primary defect of the shelter is water permeability. During inspection, the water level was between 20 and 30 mm, but the humidity plaster indicates that the water level was about 600 to 700 mm (Figure 1a). This level of flooding is attributed to both the failure of the external drainage system around the building and the water permeability of the prefabricated and monolithic reinforced concrete enclosing structures of the floor and walls. According to the provided design, the drainage system was installed as a ring drain 6–7 m below the ground surface, beneath the foundation slab. The drainage system consists of round asbestos-cement pipes with slits every 30 cm, laid in trays and covered with coarse and medium sand. The pipe slope is approximately $i = 0.005$. Wells are constructed at the corners of the shelter and along the middle of its long sides.



Figure 1. Primary defects of the inspected basement shelter that has been out of operation: (a) damage to the finishing layer and erosion of the shelter's wall and floor structures due to prolonged water exposure and saturation; (b) corrosion damage to the reinforcement of precast reinforced concrete roof panels, formation of corrosion-induced crack, deterioration of protective plaster, and efflorescence.

The long-term semi-flooded condition of the basement has led to the following damages (Figure 1): destruction of the floor structures (such as rotting and others); corrosive wear of metal network structures—ventilation, heating, water supply, electricity, and sewage systems; corrosive damage to the working reinforcement of the prefabricated reinforced concrete ceiling panels (corrosion thickness 1–2 mm, bulges, damage to protective plaster, and efflorescence); accumulation of semi-rotted debris—remnants of furniture and equipment.

The condition of the load-bearing building structures can be assessed as condition 3—unsuitable for normal operation, while the condition of all the networks is condition 4—emergency, destroyed.

Considering that the damage to the basement occurred due to the cessation of use (suspension of dewatering, groundwater pumping in the 1990s, and heating), restoring the shelter requires not only one-time capital expenditures for repairs but also ongoing costs (for water pumping and heating) to maintain the premises' operational state. Therefore,

when deciding to restore the basement's properties, it is essential to also consider these ongoing maintenance costs.

Thus, to restore the operation of the basement, the following measures have been recommended [21]:

1. Installation of low-voltage safe lighting (for wet conditions);
2. Cleaning up debris and remnants of the floor, corroded networks, and damaged plaster;
3. Restoration of water collection sumps; alternatively, installing 80 mm gravel fill and a new 60–80 mm reinforced concrete floor with water collection pits from which water should be pumped out and diverted outside the basement, preferably into a storm sewer;
4. Restoration of ventilation (both exhaust and supply). If the basement's purpose changes, natural aeration can be arranged.

This is the minimal cost option; implementing these works will allow the facility to be used immediately after completion (expenses—lighting, water pumping, and ventilation), which is essential for providing the population with the simplest shelters. Capital repairs are necessary for prolonged, comfortable basement use as a simple shelter and other purposes. In addition to measures 1–4 listed above, the following additional measures are recommended:

5. Restoration of drainage and external dewatering systems.
6. Roof repair of the basement:
 - Removal of soil fill;
 - Restoration of waterproofing (applying new waterproofing or asphalt concrete screed);
 - Installation of a 300 mm thick polystyrene concrete insulation, $\gamma_o = 100\text{--}150 \text{ kg/m}^3$;
 - Asphalt concrete screed with a thickness of $\delta = 60\text{--}80 \text{ mm}$;
 - Filling with clay and soil mixture with a 400–500 mm thickness.
7. Restoration of heating in the basement.
8. Restoration of water supply and sewage networks.
9. Restoration of interior finishing.
10. Restoration of furniture and furnishing of the premises.

3.2. Basement of the Historical Gymnasium Building in Poltava Region

A historical gymnasium building, approximately 110 years old, was inspected in the Poltava region [22]. Over its lifetime, the building has been used as an educational facility and for military accommodation. The building has a U-shaped layout and is two stories high, with a functional basement under part of the structure and an attached single-story gymnasium. The building's structural design is frameless, with longitudinal and transverse load-bearing walls. The walls are brick, with a thickness of 85 to 64 cm. The foundation and base of the building were examined through excavation pits. The foundations are made of brick, with 2.5–3.5 m depth. The subsoil consists of subsidence-prone soils.

The blind area around the building is in poor condition and unfit for use (Figure 2a). The layout of the surrounding area contributes to the accumulation of atmospheric water and its localized infiltration into the foundation base, resulting in the formation of a water-logged area. External engineering networks and wells are located around the building but are no longer used. Their poor technical condition has led to water accumulation in these areas. A mechanical suffusion of the soil was observed, causing subsidence of the asphalt blind area around the building.



Figure 2. Relevant defects of the inspected historical gymnasium building in the Poltava region: (a) the pavement around the building is in an unfit condition, and the site grading promotes the accumulation of atmospheric water, leading to its localized infiltration into the foundation base; (b) deterioration of the interior wall surfaces in the basement due to capillary moisture rise, resulting in plaster damage and efflorescence formation.

Dampness was detected on the basement walls (Figure 2b). Frost-induced damage was recorded in areas where rain gutters were previously damaged and in the dampened plinth areas due to the water-logged sections around the building. Furthermore, neither the foundations nor the building itself is suited for subsidence-prone soil conditions (the foundations lack reinforcement, there are no monolithic reinforced concrete belts, the load-bearing walls are not reinforced, and other factors).

To ensure the building's continued safe operation, it is recommended that the old engineering networks within a 30 m radius of the building be inspected. Any damaged engineering networks should be dismantled, and the surrounding area should be improved. Vertical grading around the entire building, sloping away from the structure, should be performed, and a blind area at least 2 m wide with a clay barrier should be constructed.

To restore the horizontal waterproofing layer of the load-bearing brick walls, it is recommended to inject hydrophobic solutions into the structure at the level of the first-floor slab in a continuous strip, as detailed in [22].

3.3. The Basement of an Administrative Building in Poltava

The basement serves as a simple shelter in an administrative building in Poltava. The building is historically from the late 19th century, originally constructed as a private estate. It is a two-story structure with a load-bearing wall system. The building's dimensions are 23.55×16.65 m, with the highest roof point reaching +13.00 m. A basement is located under part of the building (Figure 3), and no groundwater was detected.



(a)



(b)



(c)



(d)

Figure 3. Primary defects of the basement in the administrative building in Poltava: (a) deterioration of the interior wall surfaces in the basement, with efflorescence appearing on the walls; (b) corrosion damage to the basement ceiling structures, along with efflorescence on the wall surfaces; (c) destruction of the brick masonry of the basement walls; and (d) disruption of the air-moisture balance within the premises.

The foundations of the load-bearing walls are strip-type and made of brick. The ceiling above the basement consists of cylindrical brick vaults supported by steel beams (I-beams Nos. 18–20), plastered internally with cement mortar.

Corrosion of the steel beams is most pronounced in axes 4–6, where significant dampness of the load-bearing brick walls was also observed. Above the basement ceiling, a wooden floor has been laid over the ballast backfill.

The walls are brick, with wedge-shaped arches above the doors and windows. The facades on sides 6-1 and A-E are plastered and painted, while the courtyard facades feature exposed brickwork (painted in axes E-A). Due to a disruption in the thermal and moisture regime, the basement walls and part of the first-floor walls are affected by mold and mildew.

Problems: The disruption of the air–moisture regime has led to corrosion of the steel ceiling beams and mold formation on the walls. The destruction of the external waterproofing layer in the soil has caused the degradation of the brickwork, leading to mold formation and other issues.

To restore the operational characteristics of the building's underground part, the following works are recommended:

1. Repair the utilities around the building.
2. Dig a trench along the foundation.
3. Clean the wall of dust, dirt, and irregularities.
4. Apply an adhesive primer.
5. Install vertical waterproofing using coating methods.
6. Backfill with clay soil of optimal moisture, compacted in layers.
7. Install asphalt pavement with a clay barrier.

The interior finishing repairs involve removing the plaster layer, cleaning the wall, applying antiseptic treatment, and reapplying cement–sand plaster.

3.4. Basement of a Two-Story School Building in Poltava

The two-story building with a basement (Figure 4) was partially designated as a shelter and a shooting range, while the attic remains unused. Built in 1956, it is frameless, has longitudinal load-bearing walls, and follows a wall construction scheme. The building has a C-shaped layout with dimensions of axes A-K of 21.04 m and axes 1–13 of 52.44 m.



Figure 4. Flooding of the school basement rooms: destruction of the lime matrix in the joints and moisture saturation of the brick structures in the basement.

The floor above the basement (Figure 5) consists of a reinforced concrete slab approximately 140 mm thick. The groundwater level was found to be 2.8–2.9 m from the surface, with fluctuations up to 1 m higher (Figure 4). This is significantly affected by leaks from water-bearing networks. In some areas, due to the absence of organized drainage, atmospheric water accumulates and infiltrates the loose backfill soil.



Figure 5. General view of the sub-basement slab: corrosion damage to the reinforcement bars of the floor slabs and destruction of the concrete protective layer.

The condition of the foundations was examined through excavation pits in the basement (Figure 4). It was determined that the foundations of the load-bearing walls are strip-type, made of rubble stone and brick, and laid directly on natural soil. The width of the foundation base is 700 mm and 500 mm, with a foundation depth of 500 mm and 600 mm from the basement floor and 2700 mm to 2800 mm from the ground surface to the basement floor.

No vertical or horizontal waterproofing of the foundations was found. The overall technical condition of the foundation structures is satisfactory.

Cracks in the load-bearing wall are caused by the saturation of the loess subsidence layer, which leads to a significant decrease in the soil's mechanical properties. As a result, the foundation base became overloaded by more than 30%.

The overall condition of the building is assessed as transitioning from satisfactory (condition 2) to unsuitable for normal use (condition 3). At the same time, the condition of most load-bearing structures is rated as satisfactory, but some (in particular, the sub-basement reinforced concrete slab, some parts of which have 100% wear of the working reinforcement (Figure 5), and the waterproofing of certain sections of the basement walls) are rated as condition 3, meaning unsuitable for normal use.

To restore the operational characteristics of the underground part of the building, the following works are recommended:

1. Install a water collection sump in the basement with a volume of 0.5–1 m³, ensuring the proper slope of the floor and drainage channels to collect water and continuously pump it into the city's stormwater drainage system. The basement floor should have removable wooden gratings for free water drainage.
2. Considering the degradation of loess soils due to water exposure over the last 30–40 years, it makes sense to install gypsum markers on the walls and monitor crack openings every quarter. If cracks are detected, measures should be taken to increase the rigidity of the wall structures, including installing tie rods, frame braces, portal ties, or others, according to a specially developed project.
3. The basement slab with 100% wear of the working reinforcement should be reinforced by installing steel frames along the walls and beams to strengthen the slab. Anchors should be glued into holes and secured with nuts and locknuts. Corrosion

protection of the reinforcement structures must be applied using water-resistant paint in two coats over primer.

4. Corroded reinforcement should be cleaned with steel brushes, and the protective layer of concrete should be restored by plastering with a cement–sand mortar.
5. Prevent any impact or damage to the additional steel supports under the staircase stringers.
6. Increase the width of the foundation’s waterproofing perimeter to 2.5 m, directing drainage away from the building.
7. Restore the exterior finish to prevent further deterioration of the brick masonry.
8. During the restoration of the building’s enclosing structures, it is advisable to insulate the external walls.
9. Clean debris from the attic and restore ventilation channels.
10. Repair damaged reinforced concrete structures.
11. Clear the surrounding area of trees (no closer than 5 m from the trunk to the building walls) and bushes (no less than 1.5 m). If possible, move decorative plantings (flowerbeds and garden beds) as far from the walls as possible, and if not, avoid intensive watering of these areas.
12. If the building’s deformations continue, the foundations should be strengthened using the well-proven method of reinforcing the loess soil layer with soil-cement elements [35].

3.5. The Basement of the Academic Building of the University in Poltava

The academic building has four floors and a basement (Figure 6) and is rectangular in shape plan. Its structural layout consists of longitudinal and transverse load-bearing walls. The load-bearing structures of the building are made of brick masonry, with floors constructed of precast and, in some areas, monolithic reinforced concrete.



Figure 6. Specific defects of the academic building: (a) damaged pavement around the building, allowing water to flow through the wall and flood the basement; (b) deterioration of the basement wall surfaces due to plaster damage and efflorescence formation.

The foundations under the load-bearing walls are strip foundations on natural soil made of prefabricated reinforced concrete elements (FL slabs and FBS blocks). The foundation depth varies from 2.7 to 3.7 m, depending on the terrain. Visual inspection revealed localized chips, spalling, damage to the plinth’s plaster layer, and local damage to the waterproofing perimeter. There are no foundation deformations that would disrupt the building’s normal operation. The technical condition of the foundations is classified as satisfactory.

The recommended works for restoring the operational parameters of the underground part of the building are as follows:

1. Excavation of a trench along the foundation with a depth of 3000 mm and a width of 1000 mm, with slope bracing.
2. Cleaning the wall of dust, dirt, and uneven surfaces.
3. Application of an adhesive primer.
4. Installation of vertical waterproofing using a coating method.
5. Installation of vertical insulation for the foundation using extruded polystyrene foam (e.g., TECHNONICOL CARBON ECO) (35 kg/m^3) with a thickness of 150 mm, applied with contact adhesive.
6. Installation of PLANTER-geo profiled membrane.
7. Backfilling with clay soil of optimal moisture content, with layer-by-layer compaction.
8. Installation of an asphalt blind area with a clay lock.

The repair of interior finishes includes removing the plaster layer, cleaning the wall, applying antiseptic treatment, and applying cement–sand plaster.

3.6. Qualitative and Quantitative Indicators of Defect and Damage Recurrence

Based on the survey results of underground building structures, histograms were constructed to describe the qualitative and quantitative indicators of the recurrence and size of defects in structures located below ground level. Most of these histograms exhibit an asymmetric distribution, resembling either a lognormal or exponential distribution.

Regarding specific damage histograms, the following observations can be made:

- An analysis of the histograms built from the inspection results of the non-operational shelter (Section 3.1) reveals that the distribution of reinforcement corrosion damage and efflorescence follows an almost normal pattern, with a peak occurrence of damage in the range of 50–60% corrosion damage in both histograms (Figure 7a,b);
- The damage histograms for the gymnasium in the Poltava region (Section 3.2) indicate that the majority of damages are minor, including both efflorescence and frost-induced deterioration of the building's brick walls (Figure 7c,d);
- In the basement of the administrative building (Section 3.3), most reinforcement bars exhibit minor corrosion damage (up to 40%), while efflorescence on the walls ranges from 40% to 80%, affecting over 80% of the inspected walls (Figure 7e,f);
- The basement structures of a two-story school (Section 3.4) exhibit significant damage to the reinforcement bars of monolithic floor slabs. The histogram indicates that the vast majority (>90%) of the bars have corrosion wear exceeding 50%, while the depth of limestone matrix leaching is predominantly within 1–2 cm (Figure 8a,b);
- An analysis of histograms based on the basement structures of a university (Section 3.5) reveals that most efflorescence on the walls is localized, affecting less than half of the surface and appearing as isolated spots. As for the damage to the protective concrete layer caused by the expansion of corrosion products, floor panels with significant damage (more than five defects) are rare, occurring in only 3–4 panels out of 20 (Figure 8c,d).

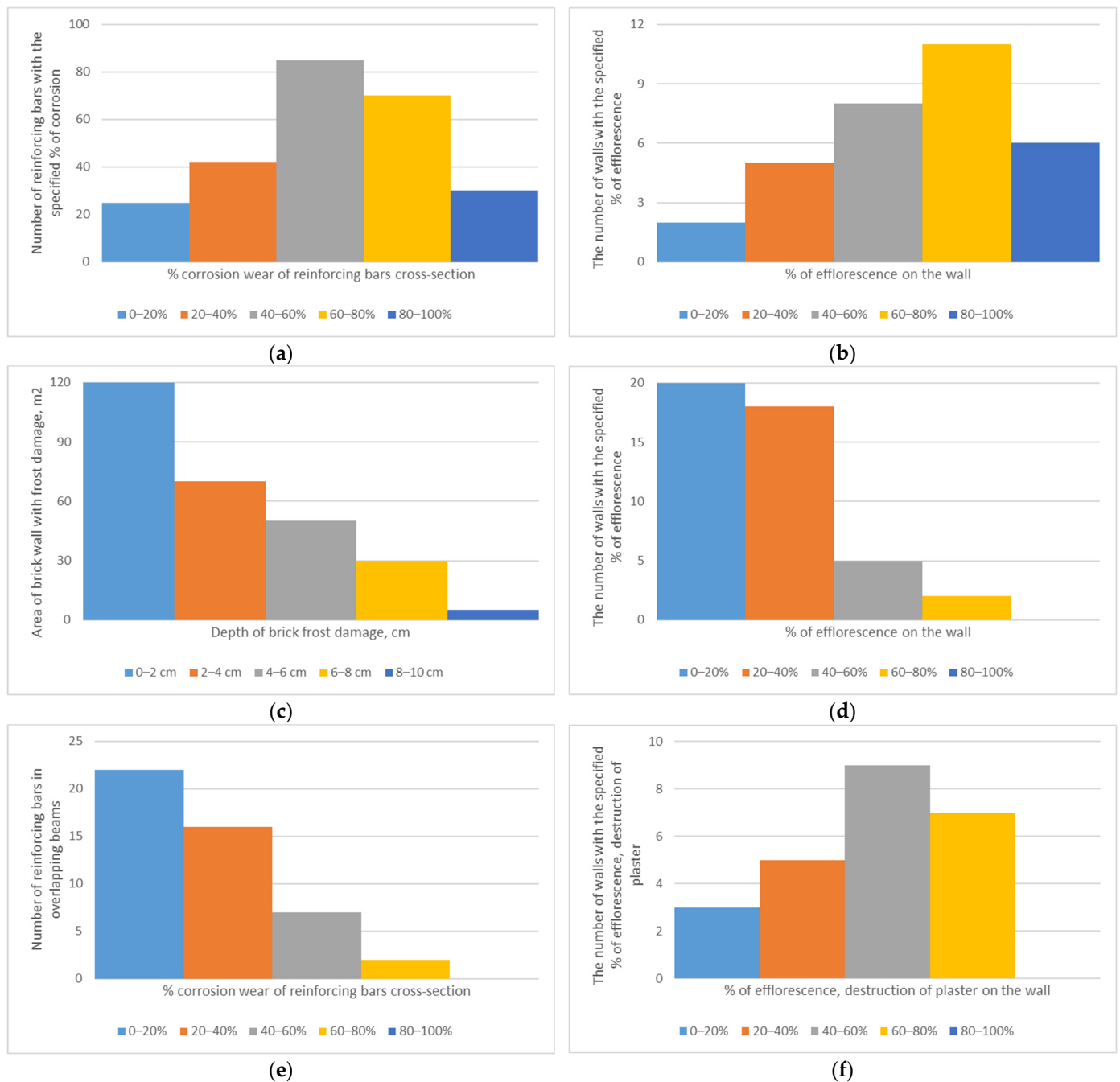


Figure 7. Analysis of damage recurrence in the inspected basement premises: (a) distribution of corrosion wear of reinforcement bars in the structures of the non-operational shelter; (b) distribution of efflorescence area on the wall surfaces of the non-operational shelter; (c) distribution of frost-induced brick deterioration depth relative to the defect area on the walls of the gymnasium building in the Poltava region; (d) distribution of efflorescence area on the wall surfaces of the basement premises in the gymnasium building in the Poltava region; (e) distribution of corrosion wear of the reinforcement bars in the basement structures of the administrative building; and (f) distribution of efflorescence area on the wall surfaces of the basement premises of the administrative building.

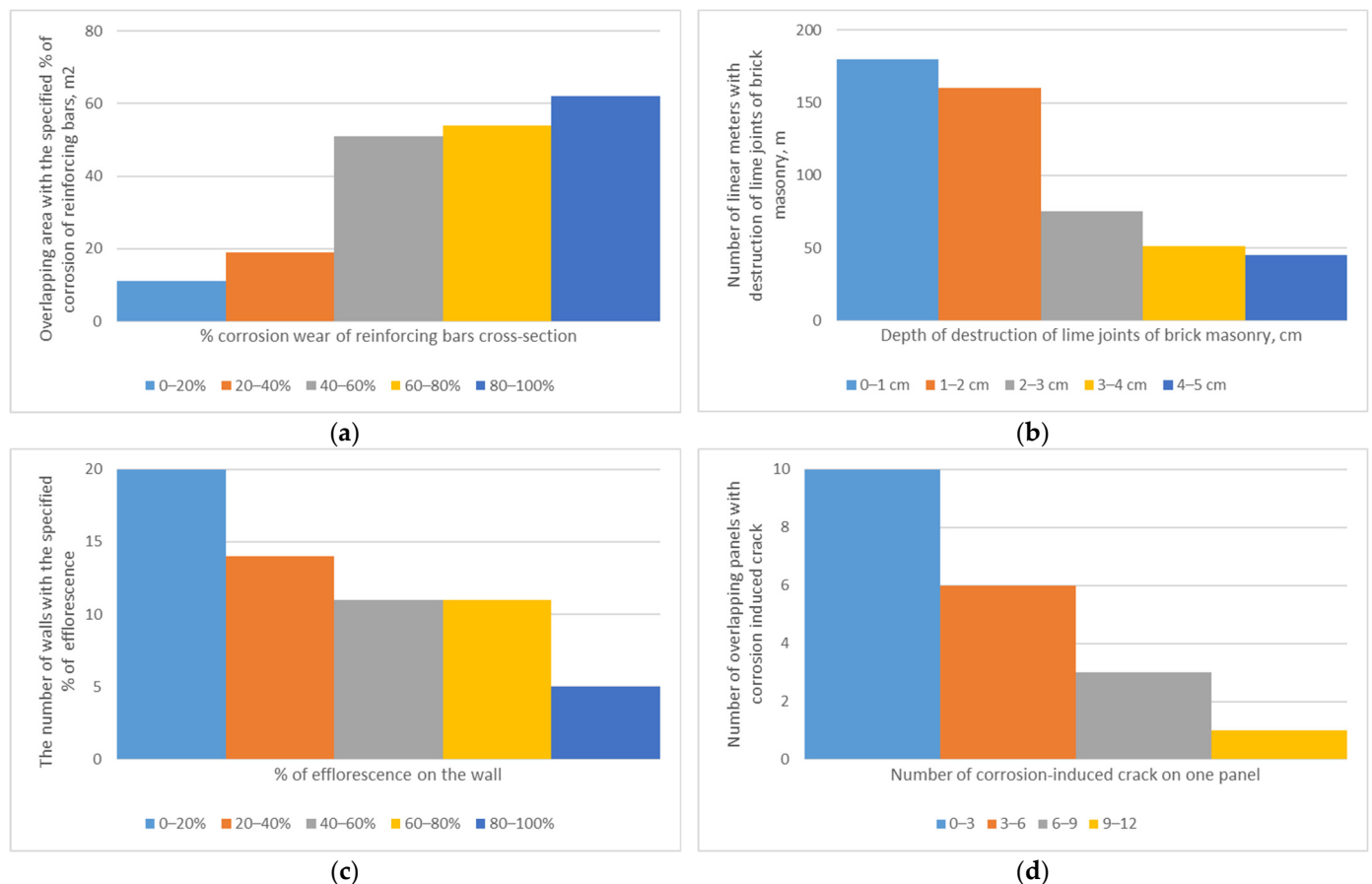


Figure 8. Analysis of damage recurrence in the inspected basement premises: (a) distribution of corrosion wear of reinforcement bars in the floor slabs of the two-story school building; (b) distribution of the depth of mortar joint leaching in the brick walls of the basement part of the two-story school building; (c) distribution of the area of efflorescence on the wall surfaces of the basement premises of the university building; and (d) distribution of damage to the floor slabs of the basement premises of the university building.

4. Discussion

Based on the conducted survey of underground parts of buildings and structures with different designs and purposes, as well as their foundations, it can be concluded that the system “natural soil base–foundation–underground part of the building–above-ground structures” is subjected to a complex set of impacts, namely, the following:

- Annual and seasonal fluctuations in groundwater levels and flooding of the surrounding areas significantly affect the bearing capacity and deformability of the building foundations. Water saturation of the soil mass from “above” (household leaks from water-bearing utilities and atmospheric water from undrained areas around buildings) and “below” (due to a general rise in groundwater levels in urban areas) has led to the degradation of loess soils, classifying many as highly compressible. The rise in groundwater levels causes water to filter through the floor and walls of basement spaces.
- Soil moisture affects the vertical surfaces of underground structures, increasing their humidity, reducing thermal resistance, and posing a corrosion threat to reinforced structures. Therefore, it is necessary to restore vertical waterproofing and insulate the foundation zone.
- Horizontal waterproofing must protect against the upward spread of moisture from underground to above-ground structures.

- Damage or absence of a blind area around the building. Improper surface grading around a building typically results in localized water saturation of the underground structures, their soil base, and foundations. This can affect the structure itself, causing excessive moisture and damage. It may lead to uneven settlement of the foundations in certain soil types, resulting in cracks and other defects in the building's load-bearing and enclosing structures.
- Proximity of trees and shrubs to the building. Excessive watering of plants can lead to localized water saturation of foundation bases and backfill, while the root systems of trees may impact the structures.
- Damage to water supply and sewage networks around the building results in localized water saturation of the foundations and structures. Worn-out networks in the soil often have ruptures and defects that cause either minor leaks or significant soil moisture, as well as mechanical soil erosion (suffusion).
- Damage to water supply and sewage systems inside the building can cause localized water saturation of structures, ranging from small leaks to persistent water accumulation in basement areas, potentially leading to aggressive environmental effects.
- The destruction of the building's roof drainage system causes water saturation of walls and underground structures.
- Condensation of moisture on underground structures occurs due to inadequate room ventilation, affecting the surfaces of these structures.
- Operational impacts on structures include mechanical damage, unauthorized openings, exposure to aggressive environments, and more.
- Additionally, damage during repair work, such as mistakenly removing fragments of load-bearing structures (walls), mistaking them for partitions, or excessively increasing the load on structures, foundations, and bases (e.g., during reconstruction), can harm load-bearing structures.
- Defects that occurred during construction should also be considered.

Analyzing the damage and defects in the underground parts of buildings, their foundations, and the causes and factors leading to the partial or complete failure of the system “natural soil base–foundation–underground part of the building–above-ground structures” allows for the selection of rational overall measures to bring the structures back to an operational state. This includes the mandatory restoration of vertical and horizontal waterproofing of the building's walls and organizing proper ventilation and drying of the basement. If possible, groundwater lowering should be performed. Additionally, restoring the clay lock and blind area and maintaining water-bearing utilities in working condition are highly beneficial measures. Given the dual purpose of underground spaces, including use as protective shelters, insulating the foundation zone is also advisable when possible.

The analysis of characteristic defects and damages, as well as their causes, can be taken into account when planning current and major repairs, reconstruction, and new construction, thereby improving the maintainability of underground building structures. Standard vertical and horizontal waterproofing solutions, such as films and mastics, are not maintainable. Once their sealing properties are lost, they lead to damage not only to the protected structures but also to other building elements. The application of water-impermeable materials will help eliminate associated adverse effects and damages, such as high indoor humidity, salt deposits on enclosing structures, and corrosion of reinforcement in reinforced concrete elements that are not in direct contact with the soil but still suffer from corrosion due to high humidity in underground spaces. When designing new buildings, it is essential to incorporate water-impermeable materials for underground enclosure structures. While this may initially increase construction costs, considering the expenses over the entire life cycle, it will have a positive economic effect.

5. Conclusions

Based on the assessment of the technical condition of underground building structures and foundations with a service life of 60–130 years, the most unfavorable factors affecting these structures have been identified. These factors include the rise in groundwater levels due to flooding caused by soil mass saturation from above (household leaks from water supply systems and atmospheric water from non-draining areas around buildings) and from below (general groundwater level rise in urban areas), improper building operation, such as uncontrolled leaks from water supply systems, unaddressed non-draining areas near building walls, damaged or absent pavement around foundations, closely planted trees, and lack of proper ventilation. The formation of non-draining areas around buildings and the destruction of pavement are consequences of the subsidence of water-saturated loess soils, which have effectively degraded, with some classified as highly compressible. These factors are primarily responsible for the corrosion of reinforcement in reinforced concrete structures, salt deposits on wall surfaces, frost-induced destruction of brick walls, and leaching of the lime matrix in brick masonry joints. Eliminating the consequences of such damages is possible but is a labor-intensive and financially costly procedure. The analyzed cases provide strong evidence that when designing new buildings, it is necessary to incorporate waterproof materials for the enclosing structures of underground spaces. Although this will initially increase construction costs, considering the expenses over the entire life cycle, it will yield a positive economic effect. Using standard vertical and horizontal waterproofing solutions in the shape of films and coatings is not repairable. Once their integrity is compromised, they lead to damage not only to the protected structures but also to other parts of the building. The application of waterproof materials will help eliminate associated adverse effects and damages, such as high indoor humidity, salt deposits on enclosing structures, and the corrosion of reinforcement in reinforced concrete elements. Even without direct contact with the soil, these elements suffer from corrosion due to excessive moisture in underground spaces.

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