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## **PROBLEMS OF DEVELOPMENT OF AN UNDERGROUND TRANSPORT INFRASTRUCTURE OF CITIES**

**Summary.** The goal of this article is to determine rational constructional and technological options for the development of underground space, in particular, the arrangement of underground parking lots under the specific hydrogeological conditions of Dnipro city. In this article, the best practices in the construction of similar facilities in the world are discussed. Arrangements for individual structural elements and structures as a whole were considered. The main resources for their implementation are determined, the most important performance indicators are calculated, their comparison is carried out and proposals for the use of individual technological concepts are developed. The experience of underground space development in Dnipro city is studied and the problems of construction of underground structures under specific difficult hydrogeological conditions are identified. The proposed technological concepts make it possible to implement such design solutions under difficult hydrogeological conditions with dense development and preservation of historical buildings in the city.

### **1. INTRODUCTION**

The permanent dynamic development of modern large cities is practically impossible without underground space development. This is due to the reduction of free territories, especially in the central part of cities, as well as due to the need to preserve historical buildings (architectural monuments). This problem becomes especially urgent due to the continuously increasing number of automobile transport vehicles. [8, 9] The best means of organizing parking places is to construct underground parking spaces during the construction of buildings as well as under streets, squares and even under already erected buildings.

At all times during the construction of housing, people have made attempts to develop the underground space. In the nineteenth century, active development of industrial tunnel building was started and, in 1939, the world's first underground garage was built in Cardiff (the USA) (it was 10.7 m deep under one square of the city) [4]. In the same scientific work, the author noted that underground space in all large cities in developed countries was actively developed in the 20th century as well. Implementation of such projects was carried out not only for transport and engineering systems but also for trading (retail) facilities and warehouses. In particular, such projects were implemented for the development of underground multi-story car parks [7, 10, 11, 16-18]. Development of underground space provides an opportunity to solve transport problems and reduce exhaust emissions to improve air quality by preserving existing buildings and conservation of terrestrial space for improvement and infrastructure [19, 20, 28].

In addition to this, use of premises in conditions of minimal temperature drop in the underground space provides an opportunity to use low-strength concrete for underlying or filling layers, and in this way, a significant number of residual products of the mining industry are utilized [21, 22]. Therefore,

despite the considerable expenses incurred during the construction of underground facilities (they are often much more expensive than equivalent overground facilities), development of underground space is more reasonable. This is due to the fact that often, there is no area for overground parking spaces in the central part of the city, and if you take into account the real value of land in these areas of the city, underground parking may be even cheaper. (This is especially true, given the possibility of long-term operation of the underground space and the minimum energy costs for its maintenance).

Therefore, from the 1950s and to date, the construction of underground facilities in the world has been very intensive and this is especially true for parking spaces. For example, in Montreal, a true multi-story underground city with an underground railway, shopping complexes and parking spaces was built. The underground pedestrian network alone takes up more than 30 kilometers [4].

Underground space is also being developed in capitals and large cities in Europe [5]. The author reasonably argues that such use is most effective for the complex redevelopment of territories in large cities. This kind of urban development ensures the creation of safe and comfortable living conditions for people, minimizing damage to the environment. In the leading world countries, there is experience in moving infrastructure facilities into the underground space to increase operational efficiency. “Up to date historical areas in such European cities as London, Paris, Barcelona, Vienna, Cologne, Principality of Monaco etc. are located on underground parking spaces and this ensures the preservation of overground monuments and historical environment” [1]. Helsinki is also keeping pace with this process. Before 2025, an entire underground city has been planned and is going to be built. The historical center of the city has been completely preserved. As an example of the complex use of underground space, the author [1] shows how such a project has been implemented in the city of Munich (Fig. 1).

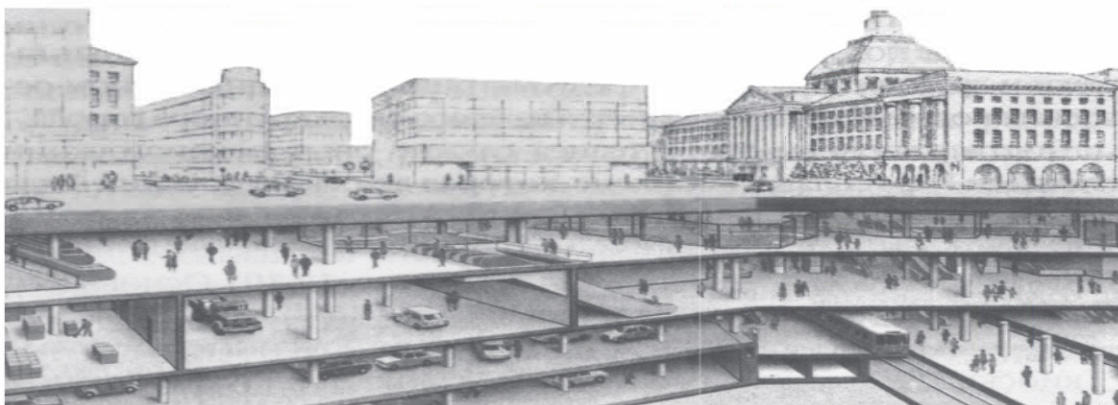


Fig. 1. A multifunctional underground complex is located under the area of Stacsbauwerk in the historical center of Munich

Therefore, the development of underground space in large cities of the world's developed countries has been ongoing over the last 50-70 years. The problem of developing the underground space is relevant for the Dnipro city.

## 2. ANALYSIS OF LITERARY SOURCES AND PROBLEM STATEMENT

Significant experience has been gained by the “Yurkevich Engineering Bureau” LLC in designing and constructing underground parking spaces during the post-Soviet period [6].

In his work, the author presented the main parameters, conditions of construction, design features and technological solutions applied for the construction of various underground parking spaces during the past 20 years. World experience should be carefully studied and used in the design and construction of underground parking lots in the difficult hydrogeological conditions of the city of Dnipro.

The importance of effective development of underground spaces has also been confirmed by the 15th World Conference of the Associated Research Centers for the Urban Underground Space (ACUUS),

held in September 2016 [3]. More than 600 participants from 34 countries took part in this conference. “Underground urbanization as a necessary condition for sustainable urban development” was one of the key topics of this conference. The vast majority of reports emphasize the need and lack of alternatives for the development of underground spaces aimed at improving the conditions for the development of infrastructure and ensuring the comfort of these areas for human existence. Therefore, according to Dimitris Kaliampkos, the president of ACUUS, a professor at the National University of Athens, “a modern city is viable only if it has a highly developed underground life, in other words, a well-organized, well-established and effectively managed underground infrastructure, including engineering and transport communications, security systems, storage facilities, etc.” [3]. In many reports, numerous examples of this successful implementation were presented.

At the conference, it was underlined that during the development of underground spaces, the most important technical task is to organize firm walling of the pit during construction and installation works. This task is especially important if the level of groundwater is high and if there are other buildings and facilities near the place of work. A “wall in the ground” is the main technical solution to this problem. Despite the fact that this technology is more than 100 years old, it is continuously and successfully developing thanks to new effective construction equipment, new technological solutions and improved quality of used materials [3].

To improve the properties of geological areas, setup of anti-filtration curtains, erecting and fixing of pit walls in the process of development of underground spaces and jet cementation of soils have been used successfully [2]. This technology is especially effective for weak water-soaked soils, including sand and subsidence grounds. Implementation of jet cementation can significantly increase the strength, deformation module and water resistance of soils. In the case of implementing this technology, the strength of cement soil samples was 13.0 MPa and the deformation modulus was up to 1,830 MPa [4]. Therefore, the implementation of jet cementation technology in conditions of Dnipro city may ensure the successful development of underground spaces in complicated hydrogeological conditions.

The valuable, cumulative experience of arranging deep pits in complex hydrogeological conditions of Shanghai is also worth considering [14]. Thanks to timely and thorough monitoring of deformations and preventive measures, we successfully completed work without damaging the surrounding buildings and underground structures. A unique experience of successful development of underground spaces was also gained in Mexico [8]. Construction works were performed not only in complex hydrogeological conditions but also in a seismically dangerous area. In Amsterdam, under the historical center of the city, timely measures were taken to eliminate the flow in the underground structures [27]. The experience gained is very important for improving development of underground spaces in cities. The scientific work [24] presents an analysis of the most effective constructions for the protection of deep pits. The authors successfully used modern software to provide an accurate definition of the bearing capability of erected constructions. The experience of restoring the bearing capability and water resistance of underground constructions is also valuable [14, 23, 26].

Thus, the experience of successful development of underground spaces in large cities worldwide is of great importance. This experience should be considered for solving problems related to development of underground spaces, which is urgently required in Dnipro city. Therefore, it is necessary to carefully analyze conditions for the construction of underground parking spaces in Dnipro city, and offer the most promising structural and technological solutions.

### 3. PURPOSE OF RESEARCHES

The aim of this work was to determine rational variants of pit fencing during the construction of underground parking spaces under specific hydrogeological conditions of Dnipro city.

For this purpose, the following tasks were set:

- to study the experience of using rational pit fencings in various hydrogeological conditions using the example of Dnipro city;

- to analyze the possible use of well-known technologies for organizing vertical fences (walls) of curvilinear pits; and
- to develop a rational variant for organizing vertical fences (walls) of curvilinear pits.

#### 4. MATERIALS AND METHODS OF RESEARCH

In this work, research was carried out on the structural and technological variants of organization of pit fences for the construction of multi-story underground facilities in Dnipro city. For the research, the main resources for the implementation of the used and proposed options were determined. A comparison and analysis of the main indexes were performed. The main attention was paid to the cost of materials and labor of the studied structural and technological variants of the ditches. The approximate cost and duration of work of the investigated structural and technological factors of variants were analyzed; The approximate cost and duration of work of the investigated structural and technological factors of variants were analyzed, the most effective options for constructive wall mounting systems for excavation pits were identified. (arrangements that are most favorable for the specific conditions in Dnipro city).

#### 5. RESULTS OF RESEARCH ON CONSTRUCTIVE AND TECHNOLOGICAL FACTORS OF PIT FENCING VARIANTS

During the last 20 years, active development of underground spaces has been started in the process of constructing separate buildings and complexes. The most typical constructive and technological solutions are presented in Fig. 2-4. A three-story parking lot for 600 parking slots was constructed in the residential complex “Panorama” (850 apartments). The parking lot is located under residential buildings and a stylobate part with an exploited roof. Parking lots were constructed in an open way after excavation of the pit to the entire depth of the surface according to the “bottom-up” method. At the construction site, the soil mass is represented by loess loams, which in the dry state have high strength; therefore, they allow construction of a steep slope of the foundation pit walls without additional mounting (Fig. 2).

Such constructive and technological variants of construction of a parking lot were found to be most efficient in terms of cost, labor costs and construction times. There are no additional costs for pit wall strengthening. An open method of construction makes it possible to use heavy equipment and does not limit the ways of performing work. However, the implementation of this option is largely associated with the hydrogeological conditions of a particular construction site, as well as with certain structural features of the underground part of the building under construction. Therefore, this experience should be taken into account when constructing analogous facilities under similar hydrogeological conditions of construction.

The ground mass of the construction site of the Atrium trade and business center in the city of Dnipro consists of loess loams. In addition, the construction site is located in close proximity to operating multi-story buildings. Therefore, after creating a pit two meters in depth with vertical slopes, it was fenced with bored ferro-concrete piles 0.6 meters in diameter and 1.5 meters in height.

Further digging of the pit with vertical walls continued under the protection of this enclosing structure. In this pit, the underground three-story part of the building was organized according to the “bottom-up” method (Fig. 3). This constructive and technological decision provided an opportunity to use large-scale productive machinery for the excavation and construction of the underground part of the building. To reduce the cost of the resources used for the construction of the pit fence, the chief designer of the project decided to use bored ferro-concrete piles as a foundation for the outer walls of the above-ground part of the building. A part of the armature protective layer was brought down for this purpose after the pit was created. Armatures of the foundation reinforced concrete wall arranged along the perimeter of the pit were linked to the pile armatures, ensuring their joint operation.

Developed structural and technological operations made it possible to optimize the costs of developing the underground space in a limited area of the Dnipro city. However, due to the proximity of the surrounding buildings, thorough geodesic monitoring of the neighboring buildings was required.

In addition, due to the limited size of the construction site, particular attention was paid to the organization of temporary transport communications for the main work of transportation of goods and, in particular, removal of the excavated soil outside the construction site. This factor should also be taken into account when planning construction works, especially if performed in proximity to intensive road traffic or if access to the construction site is limited.

In the process of constructing the retail and business center “Kaskad-Plaza”, a supporting wall was constructed (about 14 meters high) for successful exploration of underground space and for proper arrangement of underground parking spaces (Fig. 4). Construction of this wall included bored and cast-in-place piles 620 mm in diameter and the distance between them 1.5 meters. During the construction of the pit, drill and inject anchors were organized in three tiers to provide sufficient stability to the supporting wall. To prevent subsidence of the soil, the spaces between the piles were filled with scraps of boards, which were removed after the arrangement of the backfilling of the sinuses of the pit with soil and sealing of this soil were completed. This fencing is much more reliable in comparison with that considered previously, but its construction involves significant expenses.



Fig. 2. Erection of the underground parking lot for the residential complex “Panorama”

The complexity, cost of materials, the depth of the pit and, therefore, the cost of such a design is much higher than those that were previously considered. However, this option of fencing provided reliable protection of the foundation pit against collapse of the soil during construction and retained the stability of buildings located in the immediate vicinity of the trade and business center. In addition, using this method, work can be carried out on a very small construction site (in the indicated project, the structures for attaching the walls of the pit went beyond the construction site by no more than 2 meters).

The above experience in the development of underground spaces in the city of the Dnieper can be successfully used in difficult hydrogeological conditions and the dense location of the construction site. However, in the central part of the city, hydrogeological conditions differ significantly from the conditions of the highland part of the city. Fig. 5 shows a typical geological section in the area of Heroyiv Maydanu Square.

The greatest difficulty during the construction of underground parking areas under such hydrogeological conditions lies in preventing the entry of water into the pit. If the water level is 3-4 meters over the surface level (it may be significantly higher in spring), the pressure of the water column

increases significantly as the pit is created. Construction of a pit in such conditions without reliable vertical fencing of pit walls is in fact impossible. At the same time, the fence should have not only the minimum necessary strength and resistance to deformation, but also the necessary water resistance.



Fig. 3. Erection of underground stories of the retail and business center “Atrium” under the protection of a vertical pit fence constructed by bored reinforced concrete piles

In Dnipro city the experience of constructing vertical rectangular fence walls of ditches in difficult hydrogeological conditions at arrangement of subway entrances is gained. For these purposes, trench “walls in the ground” were constructed with 3-meter-long grips. This turned out to be a constructive and technological solution that could also be implemented during the development of underground parking spaces in such hydrogeological conditions, but only for straight walls.

A curvilinear wall fencing must be considered for the construction of parking ramps. Fencing by the bored-secant pile is the most appropriate for these purposes. During the implementation of this constructive and technological solution, odd cast-in-place piles or continuous flight augering piles (according to newer and more effective technology) are located at a distance 1.7-1.8 of pile diameter between their centers. After the curing of the odd concrete piles, even reinforced concrete piles are installed between them.

With this technology, a strong durable watertight wall in the ground can be constructed, even a curvilinear one. However, this technology has a number of significant drawbacks. A considerable volume of concrete in odd piles must be destroyed in the process of boring holes for pair piles. The complexity of performing a well between piles is several times greater than performing a well in a soil mass. In addition, an expensive boring tool with a diamond tip that wears out quickly has to be used when to destroy concrete of odd piles. However, the main difficulty lies in keeping the drill in the vertical position. Even when installed properly, it often slips off the odd piles and as a result of this, it becomes difficult to drill a vertical hole down to the required depth and construct a high-quality “wall in the ground” made of bored-secant piles.

To eliminate the above-mentioned shortcomings of the “wall in the ground” made of bored-secant piles, we proposed a new technical solution (Fig. 6), which is protected with a patent for useful model No. 123707 [25].

The outline of the proposed method is as follows: in the first stage, monolithic reinforced concrete bored (cast-in-place) odd piles or auger cast odd pile (1, 3, 5, 7) with a reinforcing cage are installed at a distance of about 1.6 pile diameter from each other.



Fig. 4. Fencing of pit walls during construction of the retail and business center “Kaskad Plaza”

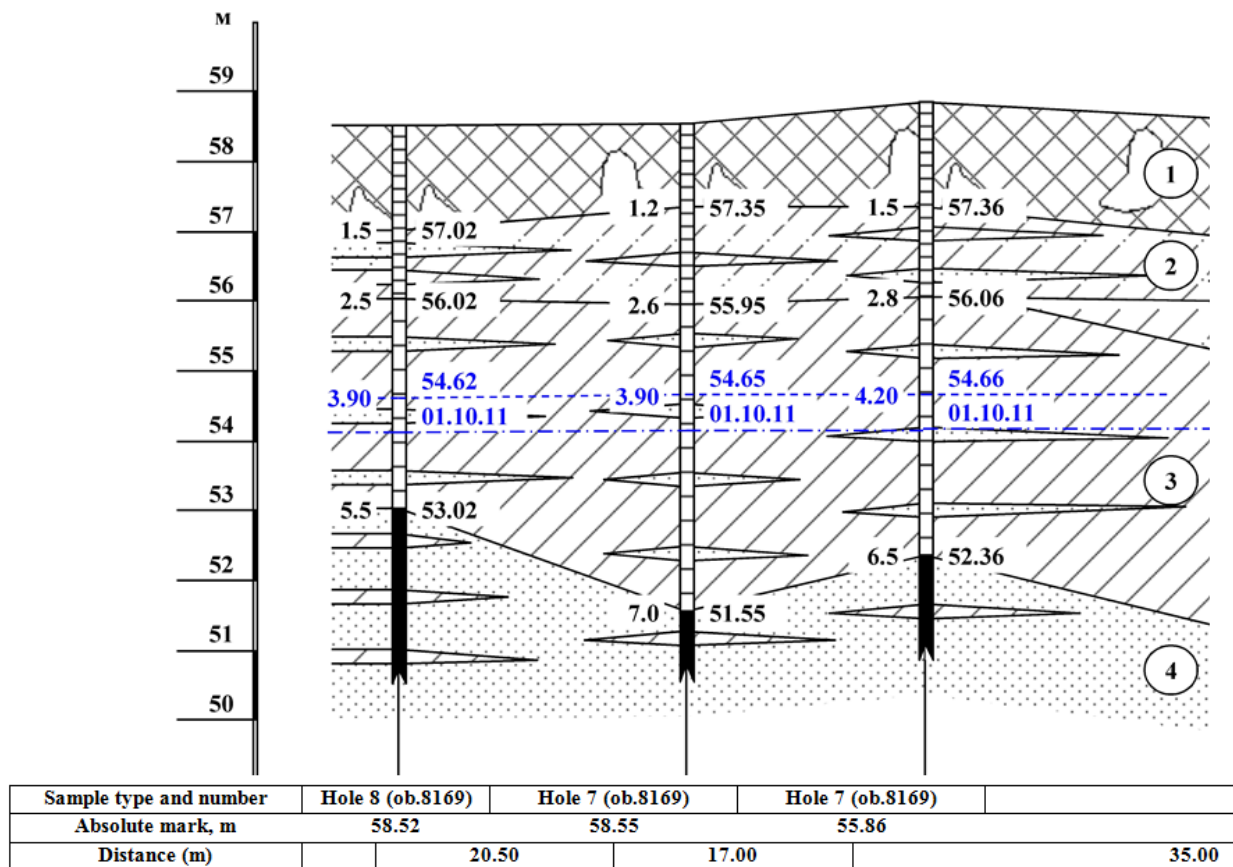


Fig. 5. Typical geological section in the area of Heroyiv Maydanu Square, Dnipro city: 1 - fill-up grounds – black hard clayey sands; 2 - yellow, gray-yellow, gray, dark gray clayey sands, 3 - brown-gray and yellow gray hard dusty loams; 4 - glass sands (yellow and bright yellow)

In the second stage, after the odd pile is filled with concrete at least to 30% of its strength, even soil–cement piles are set between them by three-component jet grouting of soils (Fig. 7).

Three-component jet grouting of soils ensures the required level of soil washout and movement of very small particles of soil to the surface using the “airlift” effect. In addition, the surface of previously installed reinforced concrete piles is washed and cleaned in places of their contact with the soil–cement piles. By regulating technological parameters of the process of organizing soil–cement piles by three-component jet grouting of soils (pressure of water, air, speed of the monitor movement, cement consumption), the newly installed piles can be firmly connected to those set previously without their destruction. According to the proposed technology, it is possible to arrange reliable stable fencing of pits of practically any configuration in terms of the necessary physical and mechanical characteristics of concrete, providing the necessary strength, water resistance and deformability.

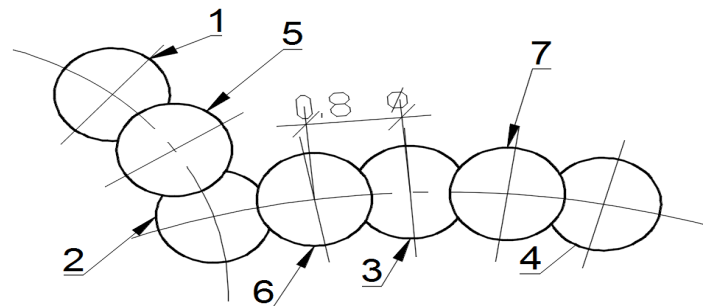


Fig. 6. Arrangement of piles during the construction of pit wall fencing: 1, 2, 3, 4 - reinforced concrete piles of the first turn; 5, 6, 7 - soil–cement piles of the second turn

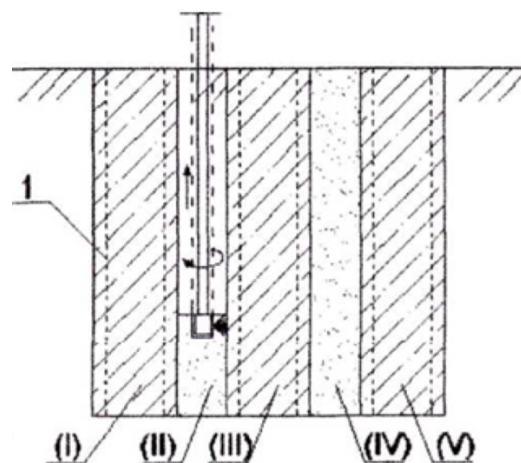


Fig. 7. Scheme of organizing pair piles by three-component jet grouting of soils: I, III, V - reinforced concrete piles of the first turn; II, IV - soil–cement piles of the second turn; 1 - reinforcement cage

## 6. ANALYSIS OF USE IN DNIPRO CITY AND PROPOSED CONSTRUCTIVE AND TECHNOLOGICAL PARAMETERS OF PIT FENCING VARIANTS

The simplest and the least labor-intensive variant, requiring fewer resources (including fewer financial resources), presupposes erection of underground parking sites without the construction of pit fences. Implementation of this variant requires slightly larger volumes of earthwork operations for organization of natural slopes and further filling of pit hollows. However, when using modern high-performance excavators and other equipment for transportation, laying and sealing of the soil, the cost of conducting these works is much less than that for the construction of vertical walls of the pits, but this variant may be used for the construction of underground parking sites only in stable soils in which



the groundwater layer is lower than the bottom of the pit. In addition, this variant is not suitable for use in the limited conditions of city housing systems when there are already buildings in close proximity to the constructed pit. In this case, reliable fencing of the pit is required, even if the pit is created in dense strong soils and the groundwater level is low enough.

The most acceptable variant of constructing vertical walls of pits is with reinforced concrete bored piles or cast-in-place piles. The method of their device is widely practiced; but necessary technical means, well-trained personnel, as well as experience in performing this type of work. Engineers have also gained a sufficient level of qualification for performing calculations and design of such fences. Significant reduction of labor, material, technical and thus financial costs during the construction of such fences can be achieved by combining structures with the foundation of the building being constructed.

If it is necessary to use additional pit mounts with a vertical pile fence, anchors are the most appropriate for this purpose. Despite the significant labor intensiveness and cost of this fencing, it is stable and reliable, and so the open space of the pit provides the possibility of using large-sized machines with increased productivity. In Dnipro city, specialized companies can reliably arrange such fixing of pit vertical walls, carry out all the necessary tests and ensure good quality of the works carried out. Significant difficulties in strengthening the pit wall can arise in the case of the presence of low strength soils at the location of the anchor. In addition, it is necessary to obtain permission to create a quarry from the owners of adjacent territories of organizations that control construction work.

It is much more difficult to construct pit fencing during construction of underground parking sites in the central part of Dnipro city, where in addition to compacted buildings with historical buildings, there are complex hydrogeological conditions. During the design and construction of underground parking lots in this part of the city, it is advisable to use the experience gained in the organization of subway entrances in these hydrogeological conditions. There are well-developed constructive and technological solutions for fencing the rectilinear part of pits by means of trench "walls in the ground". Construction of such walls under the protection of trench walls in trenches (developed as a suspension of bentonite clay) is also suitable for performing analogous tasks during the development of underground parking spaces. However, in Dnipro city, in such complex hydrogeological conditions, no experience has been reported of arranging curvilinear pit walls during the construction of parking ramps. The construction solution proposed in the patent for a useful model [25] may be proposed as one of the most effective variants. Implementation of this solution can ensure reliability of fencing that leads to a significant reduction in required resources.

## 7. CONCLUSIONS

This article describes the solution to the following tasks related to the definition of rational variants of pit fencing during the construction of underground parking areas in the specific hydrogeological conditions of Dnipro city:

- the experience of using rational pit fenceings in various hydrogeological and city planning conditions of Dnipro city has been studied, and the most effective of these has been determined;
- well-known methods for the construction of vertical fences (walls) of curvilinear pits have been analyzed, and their advantages and disadvantages have been determined; and
- a rational variant for the construction of vertical fences (walls) of curvilinear pits has been developed; the proposed option provides strength, stability, water tightness of the enclosing system of the pit and minimizes the amount of resources for realization.

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