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An innovative technical solution for the inclusion of a diaphragm wall into the construction system for the building of underground structures in an open pit

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Abstract: For the Russian holding company Mosinzhproekt JSC, which is equipped with highly qualified personnel, an appropriate scientific and technical base and performs the functions of a general contractor and customer for the construction of the Moscow Metro, innovative marketing as a methodological basis for the development and implementation of innovations is a significant part of its activities. This is evidenced by the experience of the holding's team of authors, who, based on an innovative marketing study of the Moscow Metro construction market, identified a target market segment and a construction system with the potential for innovative segment development if the system is equipped with the missing reliable and maintainable external waterproofing. To solve this problem, an innovation strategy was developed based on the modernization method of the target construction system, which is characterized by relatively low financial costs in developing and promoting innovations to the construction market and, as a result, an original waterproofing system with double-sided adhesion, adapted to the specific conditions of construction and operation of the construction system to be modernized, for the device reliable and maintainable external waterproofing under specified conditions. The industrial testing of the upgraded innovative construction system was carried out at the Moscow Metro facility under construction. The results of the work carried out can be considered an example of creating an effective model for the development and promotion of marketing innovations in the construction market, with low financial and time costs.

Keywords: innovative marketing; subway; target market segment; wall in the ground; pit hollows; waterproofing

1. Introduction

The article considers the solution of a set of problems that arise in the development and market promotion of innovations in the field of waterproofing of underground structures built of monolithic reinforced concrete in cut-and-cover and semi-closed pits. These issues include:

- the absence of a waterproofing system that provides the required adhesive bond to the external insulated surface of the structural parts of the lining of these structures, characterized by the lack of access to perform waterproofing work using traditional waterproofing materials;
- the absence of regulations and requirements in the regulatory framework governing the use of waterproofing of this type in the construction of tunnels and subways;
- the lack of information in the technical literature on the use of waterproofing materials of this type in the construction of tunnels and subways in cut-and-cover and semi-closed excavation pits;
- difficulties associated with overcoming barriers that arise in the development and promotion of innovations in the construction market due to:
- inertia of the construction industry and, in particular, the conservatism of construction and design organizations;
- high financial costs associated with the development and promotion of innovations in the construction market;
- the lack of a methodological basis for conducting work that helps to overcome problems that arise at the stages of development and entry of innovations into the construction market.

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The problems outlined in the first two paragraphs arose due to the lack of the ability of traditional waterproofing materials to provide continuous adhesive bond to concrete poured on the surface of the waterproofing coating pre-laid on the concrete base (secondary adhesion). This leads to a lack of adhesive bond of the waterproofing to the outer surface of the moulded tray structures and walls without hollows for backfilling the soil, in violation of regulatory requirements (Organization standard, 2013; Code specification, 2022; Code specification, 2023), leading to a loss of reliability, waterproofness, and maintainability of waterproofing and protected structures. Therefore, in order to eliminate this long-standing issue, the authors had to solve the problem of finding, developing and justifying the effectiveness of waterproofing materials that were free from this disadvantage of traditional materials.

A review of domestic and foreign scientific, technical and regulatory literature revealed only one scientifically sound source (Holter, 2015), indicating the presence of the desired type of waterproofing material produced on the basis of sprayed ethylene vinyl acetate polymer used in the construction of transport tunnels built by mining (closed) method. Studies conducted by the authors (Kobidze, et al., 2016) in order to adapt this material to the construction of underground structures in cut-and-cover and semi-closed pits have shown that the material is of high quality and capable of adhesive bond both to a pre-prepared concrete base and to the surface of concrete poured onto the surface of the waterproofing coating (double-sided adhesion) with a tear-off strength of more than 0.5 MPa, according to the requirements (Code specification, 2022). As a result, a reliable three-layer composite waterproof enclosing structure of the 'sandwich' type is formed (Shilin et al., 2003), consisting of two layers of monolithic concrete and a waterproofing layer.

This type of enclosing structure is formed during the construction of the wall parts of the lining of underground structures in an open excavation pit without hollows for backfilling the soil, characterized by a tendency to mutual displacement of two layers of concrete structures, which are a diaphragm wall and a wall structure built close to it. At the same time, the amount of precipitation of the structure under certain operating conditions can be 5 cm (Code specification, 2019). The results of laboratory tests of the shear patterns of these structures at the specified parameters showed the inability of the waterproofing layer made of ethylene vinyl acetate with a hardness of 80 on the Shore A scale and an elongation of 80-140 % to maintain integrity and adhesive bond to both layers of the concrete structure. This pointed to:

- the unsuitability of the material for the construction of such structures and the limited use of it in the construction of underground structures in cut-and-cover and semi-closed pits;
- the need to continue work to develop a waterproofing material with double-sided adhesion, devoid of this drawback (Kobidze and Konyukhov, 2021).

2. Methods and materials

In the methodological justification of the planned work, the choice fell on an infrequently used separate area in modern marketing related to the development and promotion of innovations (innovative marketing), the object of which is not the market of goods, but the innovation market with subjects, one of which is the state. Therefore, the use of this method is particularly effective in the context of the activities of state-owned companies, for example, Mosinzhproekt Holding, which performs the function of managing the construction of the Moscow Metro in the implementation of the priorities of the state innovation program. These factors, supported by the relevant competence and administrative resources of the company, create favourable conditions for successfully overcoming the inertia of the construction industry and financial barriers in the development and promotion of innovations in the metro construction market.

As a result of the conducted marketing research, it has been established that the construction of subway station and pier structures from monolithic reinforced concrete of shallow laying is a promising target segment of the increased capacity of the innovative metro construction market, which is characterized by the presence of a competitive environment due to the distinctive features of building systems used for the construction of underground structures (Fig. 1).

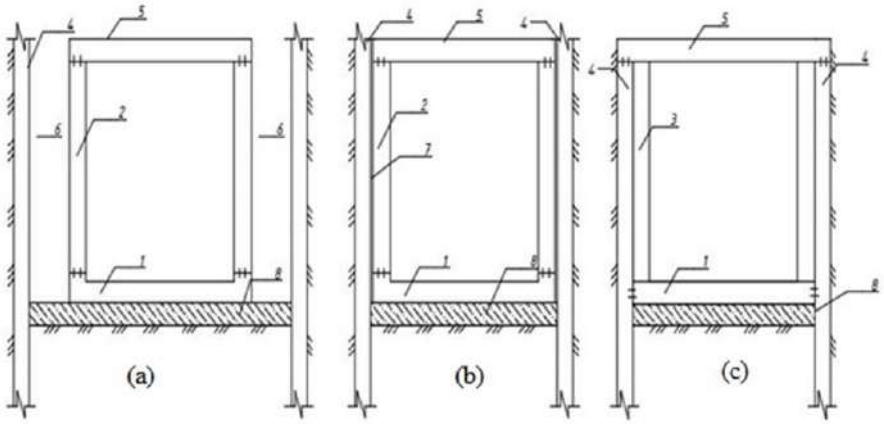


Fig. 1. Types of methods for the construction of underground structures made of monolithic reinforced concrete: (a) – cut-and-cover method with hollows for backfilling the soil; (b) – cut-and-cover method without hollows for backfilling the soil; (c) semi-closed construction method with a load-bearing diaphragm wall; 1 – tray (foundation) plate; 2 – load–bearing wall; 3 – pressure wall; 4 – excavation enclosure; 5 – coating plate; 6 – hollows for backfilling the soil; 7 – plane of mutual displacement of the walls; 8 – concrete preparation.

The construction of structures in the target segment is carried out in a cut-and-cover or semi-closed excavation. Construction in a cut-and-cover pit involves the installation of external waterproofing for structures under construction. This ensures the required waterproofing and anticorrosive protection of the enclosing structures from the effects of groundwater and reliable operation of the waterproofing coating in the 'on-hold' mode. Therefore, the method of constructing underground structures in a semi-enclosed excavation, where the load-bearing wall structure 'diaphragm wall' is protected by waterproofing from the inside, was identified as an unpromising object for innovative research.

Underground structures in a cut-and-cover pit are built regardless of the presence or absence of hollows for backfilling the soil. In the case of hollows, waterproofing is applied directly to the outer surface of the permanent wall structure, and in the absence of hollows, to the inner surface of the temporary diaphragm wall structure, which in this case acts as a protective layer of waterproofing. All other things being equal, the hollows construction method has undoubted technical, economic and competitive advantages due to (Table 1):

- the absence of labour-intensive and resource-intensive excavation work related to excavation, transportation to the dump and backfilling of soil into the hollows;
- there is no need to install a protective layer of waterproofing against damage when performing backfilling work;
- reducing the construction time of an underground structure in the absence of listed works in the construction chain.

In addition to the above, after the completion of backfilling work, expensive diaphragm walls structures used as temporary geotechnical structures for fencing the excavation pit lose their original function, turning into a useless structure buried in the ground. At the same time, the diaphragm wall also acquires a negative function, becoming an enclosing structure of stagnant wall drainage with increased hydrostatic pressure, formed as a result of filling the hollows with compacted sand and its saturation with groundwater and topsoil, which, as a rule, contains pollutants that increase the aggressiveness of the backfilling soil.

Under the given conditions, the possibility of direct contact of contaminated groundwater with overpressure and waterproofing coating of walls increases the risk of reducing the durability of the material and, in case of damage, the corrosion resistance of reinforced concrete of the protected structure and the occurrence of active (pressure) leaks in transport structures. As a result, the operational reliability of structures decreases and the operating costs for eliminating these defects increase.

Table 1. Comparison of the cost of additional work during the construction of an enclosing wall structure of an underground structure erected in an open pit with pit hollows and without pit hollows.

Name of the works	The cost of the work according to the estimate, in the price level for March 2023, in rubles	
	A pit with pit hollows	A pit without pit hollows
Excavation of the ground in the excavation with relocation and disposal	2 587,94	408,04
Installation of the leveling wall of the excavation enclosure (diaphragm walls)		3 977,30
Waterproofing protection with extruded polystyrene foam boards	1 394,16	
Backfilling of pit hollows at the walls of the excavation	4 513,56	
Total	8 495,66	4 385,34
Saving for every 1 m^2 of wall erected without pit hollows	8 495,66-4 385,34= 4110,32 руб./m^2 = 48%	

Currently, contrary to the above analysis, the dominant application in the practice of metro construction is a cut-and-cover method with hollows for backfilling the soil.

Such an illogical situation is based on an unresolved long-standing technical problem, in particular, the main condition for the installation of traditional waterproofing materials (bitumen polymer surfaced rolls, polymer compositions based on polyurea and methyl methacrylate resin) used in accordance with regulatory standards in the field of metro engineering (Code specification, 2022; Code specification, 2023; Organization standard, 2013), is the availability of access to the insulated surface of the protected structure. This condition exists only when waterproofing the external insulated surface of walls with hollows for backfilling the soil and coating plates, and is absent when waterproofing tray plates and walls erected without hollows for backfilling the soil (see Fig. 1).

In the absence of hollows, the wall structure of the underground structure is built close to the diaphragm wall (enclosure of the excavation). Therefore, for the external insulated surface of the erected wall, as well as for the tray plate, there is no access to perform waterproofing work. As a result, under these conditions, traditional materials are adhesive fixed to the accessible surface of the excavation fence (diaphragm walls) before the walls of the structure are erected and for concrete preparation – before concreting the tray plate.

The lack of adhesion to the wall and to the tray plate deprives waterproofing of reliability and maintainability, and the method of constructing structures without hollows for backfilling loses market competitiveness, since in the case of even single local damage to the waterproofing, uncontrolled migration of water occurs under the entire area of the waterproofing coating, in violation of the requirement (Code specification, 2022), leading to flooding the protected wall and the tray plate, to the loss of waterproofing and anti-corrosion protection by the structures, the restoration of which is achieved by a device behind the wall and a tray plate of unacceptably expensive veil waterproofing using injectable polymer compounds. Therefore, the elimination of the described problem is an urgent problem that needs to be solved.

3. Discussion

The results of the marketing analysis revealed the following:

1. A potentially promising object for the development of an innovative marketing construction product of the target segment, competitive in the innovative metro construction market, is a construction system based on the construction of underground structures in an open pit without hollows for backfilling, which differs from the competitive construction systems of the segment by better technical and economic indicators and short construction time.

2. The reasons for the low competitiveness of the specified construction system of the target market segment at the time of the innovation work were:

- lack of technology for reliable and maintainable external waterproofing for constructed structures;
- lack of a regulatory framework for the installation of reliable and maintainable waterproofing for structures of the type in question.

These reasons created an insurmountable barrier to the advancement of the construction system to the market.

Based on the above, a strategy for innovative work has been developed, including solving the following tasks:
1. Organization of scientific research on a conceptual basis, according to which the waterproofing coating should exhibit:

- adhesive bond not only to the accessible surface of the excavation fence and concrete preparation (concrete base), but also to the inaccessible surface of the monolithic wall of the structure, erected close to the waterproofing coating of the excavation fence and the tray plate (the ability of waterproofing to double-sided adhesive bond);
- resistance to abrasion and loss of integrity of the waterproofing layer and its adhesive bond to both structures under the conditions of the expected mutual displacement of the excavation fence and the wall structure with a draft of the structure from 2-2.5 cm (established by the results of long-term observations) to the possible permissible maximum values of 5 cm (Code specification, 2019).

2. Amendments to the regulatory framework in the field of metro construction, fixing the requirements for the rules of design and installation of reliable and maintainable waterproofing for structures erected in an open pit without hollows for backfilling.

4. Results

The implementation of innovative research and development activities has yielded the following results. The most effective type of waterproofing material suitable for solving the tasks has been selected and modified. These are sprayable compositions based on a thermoplastic elastomer with double-sided adhesion, modified by fibre reinforcement of the front layer of the coating (2 mm) from a non-woven geotextile fabric with a density of 250 g/m^2, impregnated with a sprayable waterproofing compound.
It is confirmed that the material in question, applied, like traditional technology, to a concrete base and a diaphragm by a high-performance mechanical method of airless spraying, according to the conceptual version, provides adhesive adhesion (at least 0.5 MPa) according to the requirements (Code specification, 2022; Organization standard, 2013), not only with a concrete base, but also with an inaccessible outer surface of the tray plate and wall, erected without hollows for backfilling the soil, laid on waterproofing by monolithic concreting. As a result, particularly reliable, three-layer waterproof sandwich-type enclosing structures are formed (Shilin, et al., 2003), consisting of a protective layer of waterproofing in the form of concrete preparation and a diaphragm wall, a layer of protected structure (tray, permanent load-bearing wall) and a waterproofing membrane located between them with double-sided adhesion to reinforced front layer (Fig. 2 and Fig. 3) (Kobidze et al., 2016; Kobidze et al., 2023). The operational reliability of these structures in conditions of high hydrostatic pressure is ensured by the joint operation of three components of the following structures:

- reliable protective waterproofing layers made of reinforced concrete, located on the side of the impact of groundwater, sensing the hydrostatic pressure of the waters, ensuring the operation of the waterproofing layer in a favourable ‘pressure’ mode;
- protected structures as pressure structures designed to withstand expected hydrostatic pressures (Code specification, 2022);
- a waterproofing layer trapped between two concrete structures, due to its two-way adhesion, ensures the solidity, water resistance and reliable functioning of the entire structure.

In the case of residual high humidity of the concrete base, they are coated with a thin (3 mm) protective waterproof and anti-corrosion layer of polymer cement composition.

The test results confirmed the high elasticity of the specified material and its ability to develop reversible elastic deformations under tension with a recovery coefficient of at least 90 % of the original length of the sample and a relaxation time of 15 minutes after the cessation of external forces (Table 2).

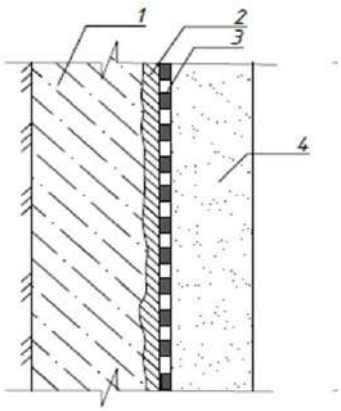


Fig. 2. Monolithic wall structure, erected without hollows for backfilling the soil, with external waterproofing with double-sided adhesion: 1 – a diaphragm wall (enclosure of the excavation); 2 – levelling layer (reinforced fine-grained concrete, monolithic reinforced concrete); 3 – sprayed seamless waterproofing made of thermoplastic elastomer 6-8 mm with a front layer of 2 mm reinforced with geotextile cloth; 4 – tunnel lining wall made of monolithic reinforced concrete, erected without hollows for backfilling the soil.

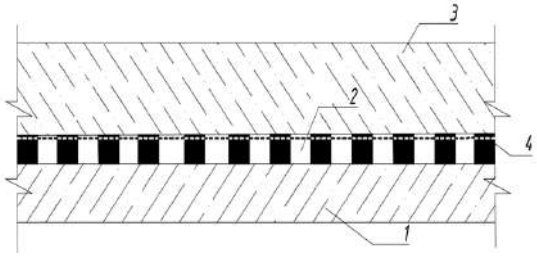


Fig. 3. Tray plate with external waterproofing with double-sided adhesion: 1 – reinforced concrete preparation; 2 – sprayable seamless waterproofing made of thermoplastic elastomer 6-8 mm with a front layer of 2 mm reinforced with geotextile cloth; 3 – tray plate.

The ability to double-sided adhesive adhesion of the specified type of waterproofing material has been confirmed (above the regulatory requirement of at least 0.5 MPa) both with a concrete base (primary adhesion) and with the surface of concrete laid by monolithic concreting on a ready-made waterproofing coating (secondary adhesion).

The test results confirmed the high elasticity of the material and its ability to develop reversible elastic deformations under tension with a recovery coefficient of at least 90% and a relaxation time of 15 minutes after the cessation of external forces (Table 2).

Table 2. Elongation and elastic deformations of thermoplastic elastomer waterproofing material.

№	Parameters	Relative lengthening, %	Восстановление
1	Before the trials	1900	≥ 90
2	After thermal aging (T= +70 °C)	1970	≥ 90

The high resistance of the 6-8 mm thick waterproofing layer to deformation loads (while maintaining integrity and double-sided adhesion) was confirmed when the concrete layer of the sample imitating the wall structure of the structure was shifted by the maximum allowable value for testing equipment of 8.3 cm (Fig. 4).

(a)

(b)

Fig. 4. Testing of a layer of sprayed waterproofing with double-sided adhesion, laid between two wall structures, for shear resistance: (a) Sample during shear tests; (b) Sample after testing.

As can be seen from Table 3 and Fig. 4, the pressure value when the sample is shifted by the specified 8.3 cm is only 0.020 MPa with a waterproofing layer with double-sided adhesion of more than 0.5 MPa. This contributed to the fact that the plane of deformation of the waterproofing layer during the shear load passed through the middle of the waterproofing coating, which at the same time retained its integrity, bilateral adhesion and thickness in the uncoated area between adjacent concrete layers of the test sample.

Table 3. Testing of a sample of a wall structure with a waterproofing layer with double-sided shear adhesion (the test surface area of the sample is 24200 mm^2).

№	Load time, s	Load, N	Deformation (displacement), mm	Shear pressure, MPa
1	31	207	5.0	0.008262037
2	61	257	10.0	0.010257698
3	121	318	20.0	0.012692405
4	181	378	30.0	0.015087198
5	241	442	40.0	0.017641645
6	301	487	50.0	0.01943774
7	361	503	60.0	0.020076351
8	421	505	70.0	0.020156178
9	480	507	80.0	0.020236004
10	494	513	83.0	0.020475483

According to the ratio of the Shore hardness scale A, due to the reinforcement of the 2-millimeter face layer of the waterproofing coating with a non-woven geotextile cloth with a density of 200-250 g/m2, the material of the initially soft category acquires an average hardness, which makes it possible to seamlessly perform general construction work on concreting the foundation plate under construction site conditions.

The national standard regulating the rules of work during the construction of the subway (Code specification, 2022), at the suggestion of the authors, has been amended to include requirements for the rules of design and installation of reliable and maintainable waterproofing for structures erected in an cut-and-cover pit without hollows for backfilling (Kobidze and Konyukhov, 2022).

5. Conclusion

As a result of the conducted research:

- by modifying the initial thermoplastic sprayed composition, a type of innovative waterproofing materials with double-sided adhesion has been developed, eliminating the contradiction between the regulatory rules for the design and installation of waterproofing for underground structures erected in an cut-and-cover pit. On this basis, the national standard for metro construction (Code specification, 2022) has been amended accordingly;
- a simple, technological and innovative method and design solution have been developed based on the use of sprayed waterproofing with double-sided adhesion for reliable waterproofing of structural parts of monolithic reinforced concrete lining of underground structures characterized by lack of access to an external insulated surface for waterproofing work.

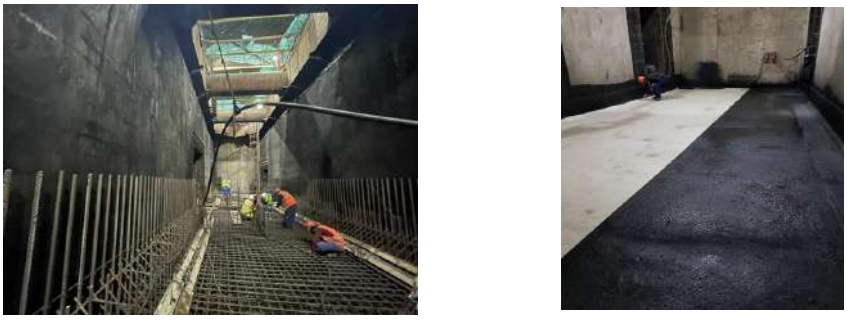
Through marketing research:

- the area of construction of underground structures made of monolithic reinforced concrete in an open pit has been established as a target segment of increased capacity for the innovative metro construction market;
- the choice of an open method of constructing underground structures without hollows for backfilling soil as an object for innovative development from among the target segment's construction systems based on modernization, characterized by reduced capital and indirect financial costs at the stages of development and promotion of innovations in the construction market.

A marketing innovation has been developed in the form of an open-pit construction system for backfilling the soil, created on the basis of system modernization by replacing unreliable traditional waterproofing systems with one-sided adhesion with a developed sprayable waterproofing with two-sided adhesion, fully adapted to the specific conditions of construction and operation of these structures, which gave them an undoubted competitive advantage over others the construction systems of the target segment.

The effectiveness of a model for the development and promotion of marketing innovations in the construction market with low financial and time resources has been tested and demonstrated, implemented under the auspices of a state-owned construction company focused on addressing the priorities of the state program for the innovative development of the country's construction industry.

For the first time, pilot industrial application of innovative structural and technological solutions for the construction of sandwich-type multilayer enclosing composite structures with a waterproofing layer with double-sided adhesion was carried out at the Moscow Metro facility, where structures were built in an open pit with and without hollows for backfilling the soil (Fig. 5).



(a) **(b)**

Fig. 5. General view of the work during the installation of sprayed waterproofing with double-sided adhesion: (a) installation of a metal frame on waterproofing laid on diaphragm walls and on concrete preparation, before concreting wall structures without hollows for backfilling the soil and a tray plate; (b) installation on a primed

waterproofing base of geotextile canvases intended for subsequent spraying with a waterproofing compound to form a fibre-reinforced 2-millimeter front layer.

An inspection of the premises of the waterproofing structures after 2.5 years of operation showed that the enclosing structures are in a dry state, confirming the reliability and operability of the operated waterproofing system under specified operating conditions over the past period.

To date, the developed innovative structural and technological solutions based on sprayed waterproofing with double-sided adhesion have found application in the construction of four underground facilities of the Moscow and St. Petersburg subways with structures erected without hollows for backfilling the soil. In order to further promote innovation in the construction market, work is underway to expand the raw materials and regulatory framework of the developed waterproofing system; with the organization of events to attract potential consumers of innovations (seminars on the basis of Mosinzhproekt, field technical meetings). This purpose is also served by participation in scientific and technical conferences, publications in specialized journals, etc.

The experience of performing waterproofing works in construction conditions has shown that the customer needs to ensure stable quality indicators of the laid waterproofing coating:

- on a contractual basis, link the manufacturer of the product (supplier) and the contractor of waterproofing works as a collective responsible subject for the quality of the supplied products and the waterproofing work performed at a specific facility;
- organize strict control over the production process;
- oblige the contractor construction company to organize measures to ensure that the specified heat and humidity conditions are met, as well as to protect the waterproofing during the laying and hardening period from the 'human factor', precipitation and groundwater.

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