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APPLICATION OF INCOMAT® CONCRETE-FILLED SHELLS IN THE CONSTRUCTION AND REPAIR OF THE FASTENING OF SLOPES OF NAVIGABLE RIVERS AND CHANNELS ON INLAND WATERWAYS

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The article provides information on the effectiveness of using Incomat® concrete-filled shells in the construction and repair of the fastening of slopes of navigable rivers and channels on inland waterways.

Keywords: concrete-filled shells and mats; fastening of slopes; approach channel; inland waterways.

In the range of structures used to fasten the slopes of navigable rivers and canals, until recently [1 – 3], in the practice of hydraulic engineering on the inland waterways of Russia, the following types of structures were noted as the most common:

— fastening of slopes with rockfill (i.e., basic and lightweight fastening; Figs. 1 and 2);

— fastening of slopes with reinforced concrete slabs (i.e., assembly of monolithic slabs along the contour, assembly of slabs with open joints, and monolithic slabs; Fig. 3);

— fastening of slopes using dumping with tetrahedrons (Fig. 4);

— fastening of slopes by laying tetrapods (Fig. 5).

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Recently, in the design and construction of navigable hydraulic structures on inland waterways (e.g., the dams of the approach channels of the Nizhny Novgorod low-pressure hydroelectric complex, Novosibirsk hydroelectric complex, and Kuzminsky hydroelectric complex), Incomat® concrete-filled shells and mats have been used as structures for fastening the slopes of the channels (Fig. 6).

The conditions for the use of the aforementioned types of slope-fastening structures in the construction of coast-protecting hydraulic structures on the inland waterways of Russia are presented in Table 1.

Incomat® concrete-filled textile mats constitute a volumetric textile formwork consisting of two high-strength (not less than 45 kN/m in the longitudinal direction) geofabrics of woven materials interconnected by vertical binding elements. Incomat® concrete-filled textile mats are made of polyamide and have a relative elongation of a maximum of 20% in both directions. The variable length of the vertical

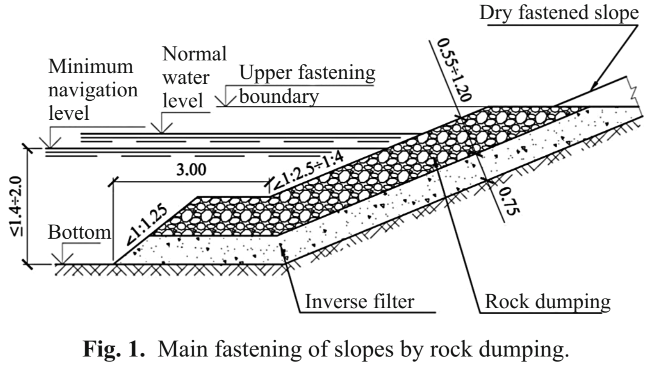

Fig. 1. Main fastening of slopes by rock dumping.

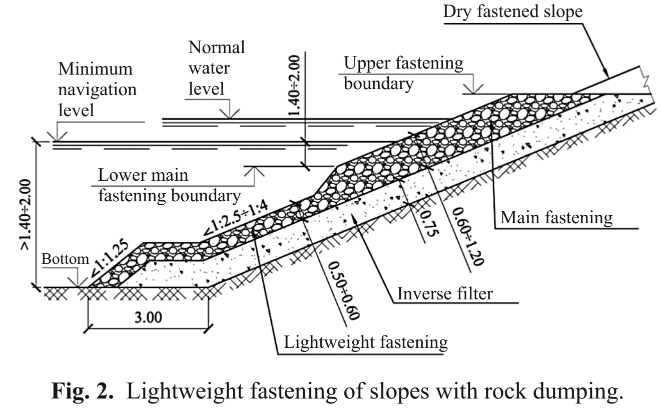

Fig. 2. Lightweight fastening of slopes with rock dumping.

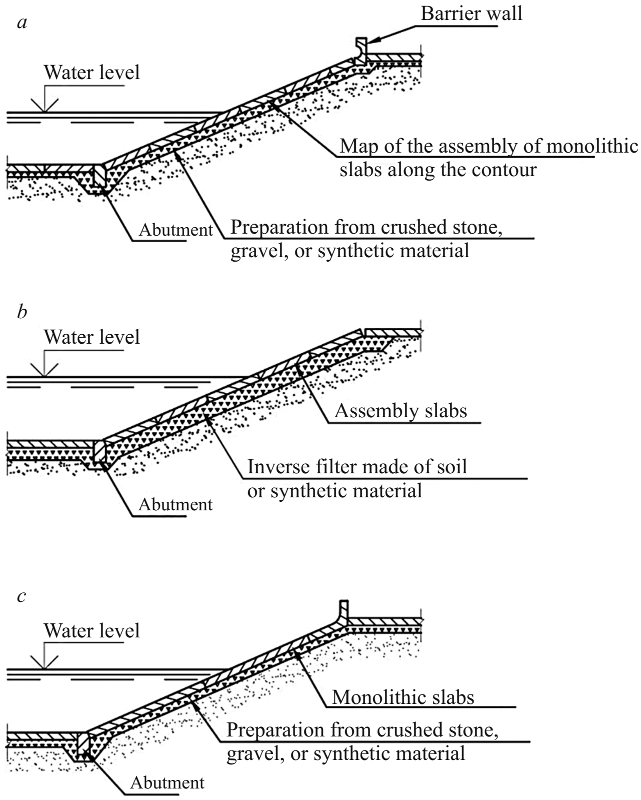

Fig. 3. Fastening of slopes with reinforced concrete slabs: (*a*) assembly of monolithic slabs along the contour; (*b*) assembly of slabs with open joints; (*c*) monolithic slabs.

binding elements integrated into the mat enables the fabrication of structures with various thicknesses. The inner space of the mat is filled with concrete mixture using pumping equipment. The thickness of these filled mats varies from 8 to 60 cm. Because of the strength of the geofabrics and the presence of vertical binding elements, Incomat® is highly resistant to deformation during filling with concrete mixture. The system is highly adaptable to existing foundations and can follow complex slope geometries. The possibility of the one-time production of mats with an area of up to 1000 m^2 significantly increases the productivity of concreting when forming an Incomat® fastener by reducing interruptions in work and minimizing auxiliary manipulations. Additional elements that can be used for the equipment of the Incomat® system simplify the installation process. Thus, industrial zipper fasteners help avoid mechanical stitching of cloth on-site. Through the anchor loops, the expanded panels are fixed securely on the surface of the slope, thus avoiding their displacement. The concrete sleeves help avoid cuts in the cloth used to connect the concrete pipeline. One of the key advantages is the capability to use the material underwater because it helps solve problems without lowering the water level or completely draining the reservoir. In this case, Incomat® is fixed in the underwater position, after which the concrete mixture is injected into the shell. Moreover, this can be done both in the underwater zone on the slope and in the case of

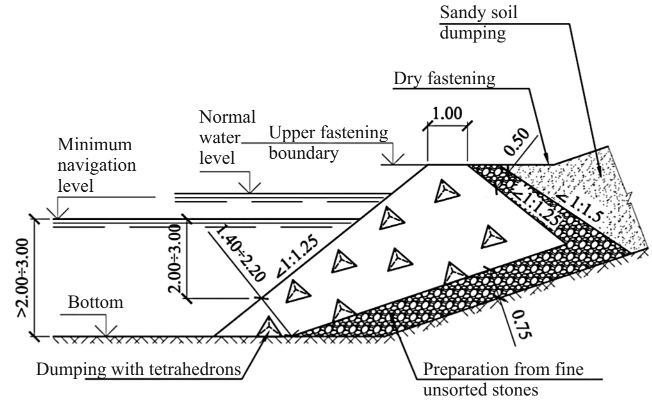

Fig. 4. Fastening slopes using dumping with tetrahedrons.

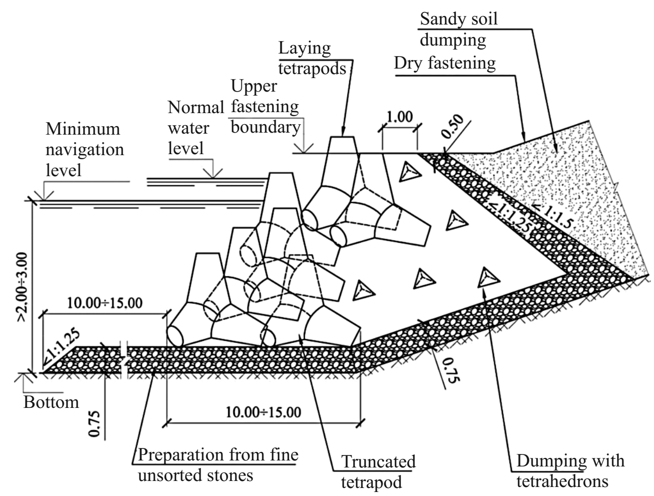

Fig. 5. Fastening of slopes by laying tetrapods.

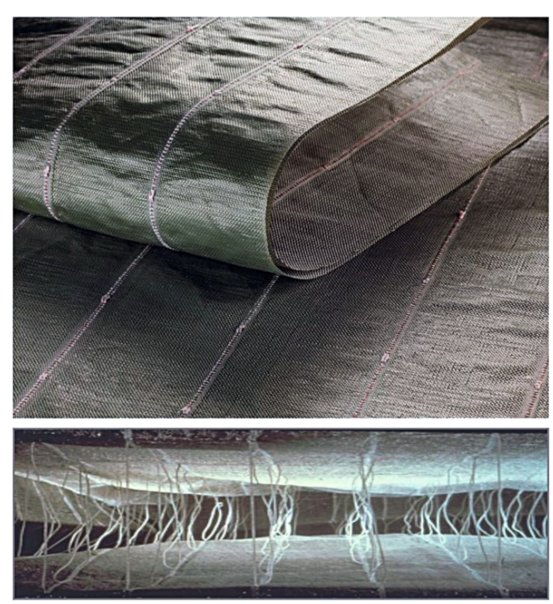

Fig. 6. General view of Incomat®: (*a*) outside; (*b*) inside.

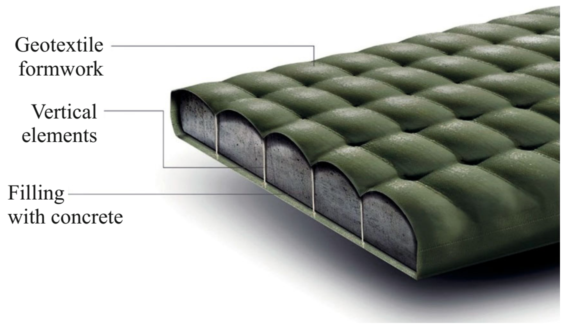

Fig. 7. Structure of Incomat® Standard.

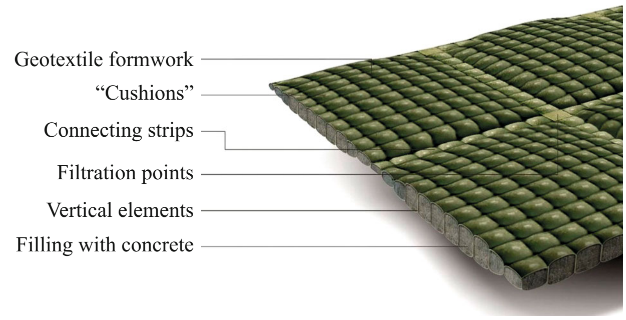

Fig. 8. Structure of Incomat® Flex.

the horizontal position of the mat at the bottom of the water reservoir when performing waterproofing activities. In both cases, diving works are required to control the uniform distribution of the concrete mixture inside the shell.

To date, the following types of concrete-filled mats are the most common:

1. Incomat® Standard is ideal for erosion control and waterproofing when the concrete slab is required to have a constant cross-sectional thickness and the concrete-filled mat needs to be waterproof (Fig. 7).

Incomat® Standard enables concreting underwater, on slopes of increased steepness, and in areas with complex geometries. Vertical binding elements retain the invariability of the geometric parameters of the geotextile shell and its constant thickness. This system is suitable for the reconstruction of canals and waterproofing of water reservoirs.

2. At high hydrostatic loads, the Incomat® Flex water-permeable mats with a high weight per unit area are required. Incomat® Flex consists of individual "cushion" blocks that are tapered along the contour (Fig. 8).

This solution creates a so-called hinge zone. Integrated filtration points in stress concentration zones facilitate the release of hydrostatic pressure. Vertical binding elements impart Incomat® Flex with two-dimensional flexibility and resist stresses when the soil settles underneath the concrete-filled mat.

3. The Incomat® Filterpoint has been developed for erosion control of slopes with low hydrostatic loads (Fig. 9).

The Incomat® Filterpoint consists of two layers of woven fabric connected by equidistant filtration points. The special design of the Incomat® Filterpoint ensures that the exact geometry of the foundation can be followed, thereby minimizing the risk of voids under the mat.

4. In those cases where the technical task, in addition to the mechanical protection of the slope, provides for its landscaping, it is advisable to use Incomat® Crib, which has a lattice structure of tubular elements filled with concrete (Fig. 10).

Intermediate rectangular cells remain unfilled after concreting and function as large filter areas. Alternatively, these cells can be filled with soil for subsequent landscaping. Therefore, Incomat® Crib has an esthetically pleasing appearance.

The installation of the Incomat® system always starts with the preparation of the base. It should be flat and free from tree roots and sharp foreign bodies that can damage the geotextile. When using Incomat® Flex, Filterpoint, and Crib, a filter nonwoven fabric must be placed between the concrete-filled mats and the base.

Anchoring the geotextile mat on the ridge of the slope can be performed using a steel pipe or an anchor trench. When laying on slopes of more than 10 m with a ratio of

TABLE 1. Application Conditions of Different Types of Slope-Fastening Structures

Type of slope-fastening structure	Application conditions			
	Fastening height H, m	Wave height h, m	Ice thickness t_{max}, m	Note
Rock dumping, main fastening	≤2.0	≤1.0	≤1.0	$m = 2.5 – 4$, $t_1 = 0.55 – 1.2$ m
Rock dumping, lightweight fastening	≤4.0	≤0.0	≤1.0	$m = 2.5 – 4$, $t_1 = 0.6 – 1.2$ m $t_2 = 0.5 – 0.6$ m
Assembly of concrete slabs with open joints	≤4.0	≤1.5	≤1.0	$m = 2.5$, $t_1 = 0.2$ m
Assembly of monolithic reinforced concrete slabs along the contour	≤9.0	≤2.0	≤0.8	$m = 2.0 – 4$, $t_1 = 0.25$ m
Monolithic reinforced concrete slabs	≤12.0	≤2.5	≤1.0	$m = 2.5 – 4$, $t_1 = 0.3 – 0.6$ m
Incomat® concrete-filled shells	≤12.0	≤2.5	≤1.0	$m = 2.0 – 3$, $t_1 = 0.1 – 0.6$ m
Dumping with tetrahedrons	≤9.0	≤2.0	≤1.0	$m = 2.5 – 4$, $t_1 = 1.4 – 2.2$ m
Laying of tetrapods	≤15.0	≤3.0	≤1.5	$B = 15.0$ m

Note. m, Sloping; t_1, fastening thickness; B, width of fastening with tetrapods along the bottom.

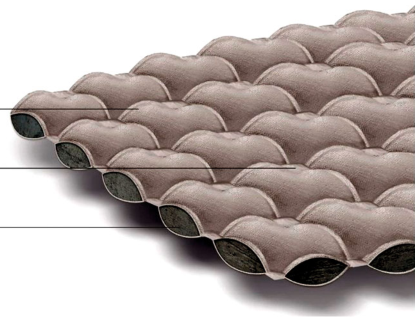

Fig. 9. Structure of Incomat® Filterpoint.

Fig. 10. Structure of Incomat® Crib.

more than 1 : 3, additional fixation of the geotextile along the length of the slope is required.

The mats are filled with concrete mixture through the concrete sleeves. To fill the Incomat® mats, high-flow self-compacting concrete of at least B25 class and frost resistance of at least F300 is used. The cone flow diameter must be at least 60 cm, and the rounded aggregate must have a particle size of no more than 10 mm. The water-to-cement ratio is generally 0.50 to 0.65. The concrete mixture has good fluidity and can be supplied through thin pipelines to nearly any height. Meanwhile, delamination of the concrete mixture does not occur, and its colloidal properties and adhesion capability do not decrease. To ensure the hydration of cement at low temperatures, the use of plasticizers is proposed.

To substantiate the regulated characteristics of Incomat® concrete-filled mats, numerous field tests and studies of their operating conditions have been performed.

Water tightness tests. In 2016, within the framework of the research conducted by the Department of Civil Engineering of the University of Applied Sciences of Münster, the tightness of the Incomat® Standard geosynthetic concrete-filled mat was quantified [4]. Based on a set of experiments, the water permeability coefficient of the Incomat® Standard concrete-filled mat was determined to be $k = 3.1 \times 10^{-12}$ m/sec. This result confirms that the Incomat® Standard system can be used in projects requiring complete waterproofing of the base.

Environmental safety studies. Environmental protection is one of the most important problems in the construction of hydrotechnical structures. Because Incomat® concrete-filled mats are used in aquatic environments, the validation of their environmental safety was required. In 2011, Germany developed and implemented the "Guideline for Hygienic Assessment of Elastomers in Contact with Drinking Water (Elastomer Guideline)" [5]. Incomat® has been tested for compliance with sanitary requirements. Research results have shown that Incomat® is not harmful to water and can be used in aquatic ecosystems.

Determination of roughness. Roughness refers to the microgeometry of solid matter and determines its most important operational properties in hydraulic calculations of structures. To perform the most correct hydraulic calculations of channels protected by Incomat® concrete-filled mats, experimental studies were performed in the Rhine-Westphalian Technical University in Aachen (Germany) to determine the roughness of Incomat® [6]. Thus, the roughness of the fabric was 4.2×10^{-4} m, and the roughness of the Incomat® Standard mat filled with concrete was 3.9×10^{-3} m.

Ice load tests. Research work on testing Incomat® mats for resistance to ice loads was performed in 2014 at the Samara State University of Architecture and Civil Engineering [7]. The need to study this issue was associated with the use of Incomat® mats, primarily in Russia at hydraulic engineering facilities. In accordance with SP 38.13330.2012 "Loads and Impacts on Hydraulic Structures," a combination of both field and laboratory tests was performed. The field tests included the construction of a landfill in the water area of the River Volga in the Samara region, where the ice thickness reaches more than 0.7 m. For the laboratory tests, a stand was built on which the material samples were destroyed to determine their ultimate compressive strength. The research results indicated the possibility of using Incomat® concrete-filled mats under ice loads, as well as utilizing equations to calculate the thickness of a concrete slab depending on the ice cover thickness and other factors.

The results of the technical and economic comparisons between bank protection structures using Incomat® concrete-filled mats and the most common alternative options are presented in Table 2.

Thus, the results of the technical and economic comparisons between bank protection structures using Incomat® concrete-filled mats and bank protection structures made of assembly and monolithic reinforced concrete slabs show the high feasibility of using Incomat® concrete-filled mats in the construction of slope-fastening structures for navigable rivers and canals on inland waterways. Recently, Incomat® concrete-filled shells and mats have been used all over Russia in the construction and reconstruction of fastenings for the slopes of navigable rivers and canals on inland waterways (Figs. 11 – 13).

Bank protection of the approach embankment of the Kirovsky bridge in Samara (2010 – 2014). The Kirovsky bridge in Samara is an important infrastructure project that increases the efficiency of international transit traffic between the Russian Federation and the Republic of Kazakhstan. The bridge over the River Samara is one of the

Fig. 11. Waterproofing a pool with Incomat® Standard.

Fig. 13. Combined use of Incomat® Filterpoint and Crib.

Fig. 12. Fastening of slopes with Incomat® Flex.

five largest cable-stayed bridges in Russia. The total length of the bridge crossing route is 11 km, with road category 1B and six traffic lanes. The width of the traffic lane is 3.75 m, and the dividing strip is 3.0 m.

The embankment of the approach to the bridge crossing passes through a flooded plain area. To prevent the destruction of the embankment slopes of the groundwork by streams, waves, ice, and random mechanical and atmospheric influences, the project provided for their protection with Incomat® Flex concrete-filled mats. Because of the specially selected composition of the concrete mixture, it became possible to pour concreting at subzero temperatures nearly all year round, with a total concreting area of approximately 300,000 m^2. The use of Incomat® technology in this project was approximately 20% more economical than the traditional laying of reinforced concrete slabs (Fig. 14).

Reconstruction of the Kuzminsky hydroelectric complex, Ryazan region (2014 – 2016). The Kuzminsky hydro-

TABLE 2. Results of the Technical and Economic Comparisons of Bank Protection Structures

Indicators	Bank protection with Incomat® concrete-filled mats	Bank protection with assembly reinforced concrete slabs	Bank protection with monolithic reinforced concrete slabs
Class (grade) of concrete	Hydrotechnic V25 (M350)	Hydrotechnic V25 (M350)	Hydrotechnic V25 (M350)
Durability (regulated by the service life of concrete), years	50 – 100	50 – 100	50 – 100
Productivity of works, m^2 per shift	400 – 600	70 – 100	300 – 350
Time of works on the arrangement of 100 m^2 of coating, h	1.7	11.1	2.6
Possibility of laying underwater	Yes	Yes	Yes, but laborious and inefficient
Presence of seams and joints (additional costs for sealing)	No	Yes	Yes
Need to use heavy lifting equipment in construction	No	Yes	Yes
High labor and time costs at the construction site	No	Yes	Yes
Presence of "wet" processes at the construction site	Concrete pouring is leveled by the presence of a shell	No	Yes
Maintainability	Possibility of spot repairs without dismantling large areas and preserving the bottom layer of the shell and, accordingly, the inverse filter	Complete replacement of the reinforced concrete plate and the inverse filter	Partial replacement of the reinforced concrete plate and the inverse filter
Cost, % (Incomat® is accepted 100%)	100	200	130

Fig. 14. Bank protection of the approach embankment of the Kirovsky bridge.

Fig. 15. Reconstruction of the approach channels of the Kuzminsky gateway.

electric complex is part of the Moskva – Oka gateway system and one of the main transport facilities on the River Oka. Incomat® Flex concrete-filled mats were used 400 m downstream with a slope length of 25 m to protect the approach section to the gateway from erosion by water (a project of Aquatic). The Incomat® system was also used to fasten the slope with a total area of approximately 10,000 m^2 of the site of the administration and amenity block as a protective measure against flooding. The technical and economic comparisons of the alternative options based on the principles of cost and installation speed showed that the use of Incomat® mats is the most effective solution (Fig. 15).

Reconstruction of the Novosibirsk gateway (2017 – 2019). The Novosibirsk shipping gateway is located in the headwaters of the Novosibirsk hydroelectric power plant and has been in operation since 1961. The length of the reinforced part of the upper approach channel to the gateway is 3350 m (1810 m at the right-bank dam and 1540 m at the left-bank dam), the width along the bottom of the channel is 40 m, and the ratio of the slope is 1:3. To fasten the underwater part of the channel slopes, Incomat® Flex 20. 118 mats with a thickness of 20 cm (a project of Aquatic) were used. The concrete pouring works were performed during the internavigation period (i.e., November to March) at temperatures below –30°C. The Incomat® technology enabled the rapid, cost-effective, and strategic reconstruction of the region's waterways (Fig. 16).

Fig. 16. Reconstruction of the approach channels of the Novosibirsk gateway.

Incomat® Standard concrete-filled mats were designed by the specialists of the "Gidrotekhekspertiza" Expert Center on Safety of Hydraulic Structures as fastening for the underwater part of the slopes of the dams of the upper and lower approach channels to the navigable gateway of the projected Nizhny Novgorod low-pressure hydroelectric complex and as fastening for the bottom of the approach channels in the area of the gateway heads and approach walls. The fastening length along the length of the approach channels was more than 2.2 km (approximately 1 km upstream and more than 1.2 km downstream). The total fastening area was approximately 200,000 m^2. The effectiveness of using Incomat® concrete-filled mats as fastening for the underwater part of the slopes of the dams and the bottom of the approach channels to the gateway has been confirmed by experts from the Federal Agency for State Expertise "Glavgosekspertiza Rossii."

CONCLUSIONS

1. The technical and economic comparisons of bank protection structures using Incomat® concrete-filled mats have demonstrated the high feasibility of using Incomat® concrete-filled mats in the construction of fastenings for the slopes of navigable rivers and canals on inland waterways.

2. Incomat® concrete-filled casings and mats meet all environmental safety requirements, do not contaminate water, and can be used in aquatic ecosystems.

3. In Russia, the use of Incomat® concrete-filled casings and mats was beneficial to the construction and reconstruction of fastenings for the slopes of navigable rivers and canals on inland waterways under ice loads, e.g., when fastening the slopes of the approach canals of the Kuzminsky and Novosibirsk gateways, as well as the approach embankment of the Kirovsky bridge in the city of Samara.

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