

*This paper investigates the local strength of reinforced-concrete slabs in a pontoon of the composite floating dock under uniform hydrostatic load.*

*A refined approach was applied to calculate the reinforced-concrete slabs considering the difference in the mechanical characteristics of concrete exposed to stretching and compression.*

*The length of the zone of fixation that impacts concrete compression and stretching has been determined, which is 0.22 lengths of the short side of the rectangular slab. To this end, preliminary calculations of stresses in slabs made from a non-composite homogeneous material were performed, at different sizes of thickness and ratios of the slabs' side lengths.*

*A finite-element model of the reinforced concrete slab was built, with its reinforcing elements in the longitudinal and transverse directions. The model accounts for differences in the mechanical characteristics, which are set separately for the compressed and stretched regions of concrete.*

*The stressed-strained state of rectangular reinforced concrete slabs has been estimated for the case of complete immersion of the pontoon in quiet water under the influence of uniform hydrostatic pressure, without taking into consideration possible dynamic loads. When simulating the bottom slabs, the length of the larger side of the supporting contour was taken equal to the distance between the longitudinal walls, based on the structural size of the dock. The length of the short side varied multiple to the longitudinal quad, making it possible to acquire data for a wide range of side length ratios, from 3.3 to 1, most characteristic of ship structures. The compressed and stretched areas of concrete were simulated separately, with the mechanical characteristics of strength and rigidity corresponding to the materials used in the construction of floating docks.*

*The charts of maximum stresses in concrete and slab reinforcement depending on the length of the short side of the supporting contour have been built. This has made it possible to determine the optimum width of the slab, which is equal to 3 m for the considered structure under predefined loading.*

*The applied approach makes it possible to optimize the size of such structures in terms of weight and material consumption*

*Keywords: floating composite dock, reinforced-concrete sections, pontoon, strength, reinforced-concrete slab, finite-element simulation*

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# OPTIMIZING THE PONTON OF A COMPOSITE DOCK WHEN CHANGING A RATIO OF THE SIDES' LENGTH IN A REINFORCED-CONCRETE SLAB

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## 1. Introduction

Shipyards often produce various floating structures for their internal operations. For example, floating docks for docking, repairing, or maintenance of vessels, floating cranes, landing stages, and pontoons to ensure the workflow and mooring of small auxiliary vessels, tugs, and working boats [1].

In world practice, metallic docks are the most widely used. The high mechanical properties of steel allow it to be used for structures of any size, while the minimum weight of the dock is achieved per 1 t of its carrying capacity (0.6...1.0 t). In addition, this predetermines the possibility of widespread use of welded

joints, providing high manufacturability, the required strength, and water resistance.

The use of concrete reinforced with mesh, fibers, or conventional round rods as a shipbuilding material has made it possible to significantly reduce the cost of manufacturing the structures. However, in this case, their weight is much larger (1.6 tons per 1 t of carrying capacity), the impact stability of such elements is insufficient, which necessitates frequent repairs of the top layer of concrete.

In terms of cost, the most effective to construct are the composite structures whose elements, designed for different loads, are made from materials of the appropriate class of strength.

Composite docks are built taking into consideration the long operation of the underwater part without repair. Among the different variants, one of the most common is the structure that includes a reinforced-concrete pontoon with steel towers [2]. A single-pontoon (inseparable) scheme ensures a more rational use of the material because, at a general deflection, loading is distributed between the towers and pontoon [3].

The use of composite slabs is not limited to the above examples of structures; they are also applied in various other sectors of shipbuilding and engineering, which is why it is an actual scientific and technical task to optimize the basic characteristics of reinforced concrete pontoon by changing the geometry and assembly design.

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## 2. Literature review and problem statement

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Study [4] proposed recommendations for improving the design and technology of building a composite floating dock based on the criteria for choosing a rational structure and taking into consideration acting regulatory requirements. However, the issues of choosing the optimal size of the design of a slab for the reinforced-concrete pontoon of the composite dock were not considered. Paper [5] reports the techniques to make a simple box-like floating pontoon-type structure; however, the issue of determining the boundaries of the stretched and compressed zones was not considered. Work [6] addresses the design and construction of concrete pontoons but it does not consider the presence of compressed and stretched zones under the influence of hydrostatic pressure at the complete immersion of the dock at different ratios of the sides' lengths.

Study [7] reports the numerical and field tests of the model of a moored pontoon in shallow water aimed at determining its hydrodynamic characteristics but the cases of complete immersion of the pontoon, including in quiet water, was not considered. Several papers investigated the impact exerted by various factors on the mechanical properties of concrete. For example, work [8] notes that increasing strength increases the module of elasticity of concrete, which improves its performance in a combination with steel fittings. Article [9] notes the positive impact of reinforcing admixtures on the water absorption and increased stability of the resulting concretes in terms of the number of freezing cycles.

Study [10] reported the estimation of the strained state of a concrete slab with steel reinforcement, which shows a certain underload of both the reinforcement and a large part of the concrete. The authors justified a reduction in the diameter of the reinforcement for the manufacture of slabs for immovable pontoons at an unchanged thickness of the base; the excess strength should be higher due to the protective layer of a reinforcement coating.

Thus, when simulating the strained state of slabs it is necessary to take into consideration the differences in mechanical characteristics and deformation patterns of the stretched and compressed zones of concrete.

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## 3. The aim and objectives of the study

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The aim of this study is to determine the optimal geometric parameters for a reinforced-concrete slab of the composite dock's pontoon, taking into consideration the differences in the deformation of the compressed and stretched zones of concrete. This could allow for the maximally full and accurate consid-

eration of patterns in concrete performance in order to improve the reliability of the structure, minimize the consumption of material, and the cost of making reinforced-concrete pontoons.

To achieve the set aim, the following tasks have been solved:

- to perform the preliminary calculation of slabs made from a non-composite homogeneous material in order to determine the boundaries of the stretched and compressed zones at different values of thickness and ratios of the sides' lengths;
- to estimate the bottom's composite slabs under the influence of hydrostatic pressure at the complete immersion of the dock, without taking into consideration possible dynamic loads at different ratios of the sides' lengths.

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## 4. The study materials and methods

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SolidWorks software package (patented in the USA) was used to investigate the strength of the reinforced-concrete slabs of pontoon under uniform pressure. The Simulation unit of this package performs an estimation analysis based on a finite-element method. This method is a universal tool to study complex engineering structures under different conditions of loading them. To calculate the strained state, we adopted one of the variants of a finite-element method – solution in displacements. Since the accepted basic unknowns are nodal displacements, it is possible to determine them after the construction of a rigidity matrix of the discrete model of the structure. It is possible to define the rigidity matrix based on the assumption about the nature of changes in the components of displacements or stresses.

The simulation employs spatial tetrahedral finite elements (an example of splitting a slab into its elements is shown in Fig. 1) whose final deformed state is determined by the displacements of ten nodular points along the three coordinate axes ( $x, y, z$ ). The basic dependences within a finite-element method for this shape are well known and considered, for example, in [11].

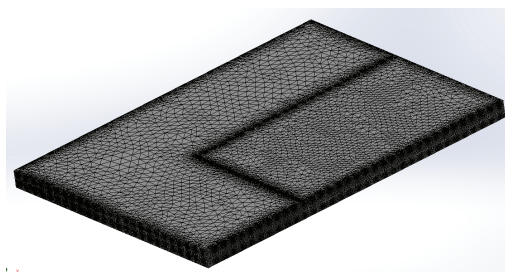


Fig. 1. Example of splitting a model into finite elements

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## 5. Determining the boundaries of stretched and compressed zones at different values of thickness and ratios of the lengths of the sides

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### 5. 1. Preliminary calculation

In order to refine the estimation scheme of concrete slabs in the slipway deck and bottom, we performed a preliminary calculation of slabs made from a non-composite homogeneous material in order to determine the boundaries of the stretched and compressed zones at different values of thickness and ratios of the sides' lengths for the case of a rigid clamping on the support contour. To establish the dependence of the distribution of the compressed and

stretched zones on thickness, we estimated three rectangular models of a concrete slab whose dimensions in the plan are 3,000×7,000 with a thickness of 120, 160, and 200 mm. A transverse uniform hydrostatic load of 92 kPa, which corresponds to the pressure at full immersion at the main plane level with a dry compartment, was accepted as an estimated load.

**5. 2. Calculation of the maximum consolidated stresses in reinforced-concrete slabs at different ratios of the sides' lengths**

When simulating the bottom's slabs, the length of the larger side of the supporting contour was taken equal to the distance between the longitudinal walls, 6,700 mm, based on the structural dimensions of the dock. The length of the short side ranged multiple to the longitudinal quad of 500 mm; it equaled 2000, 3000, 4000, 5000, and 6000 mm. A model of a 6,700×6,700 mm square slab was also built as a boundary case of a 1:1 length ratio. The diameter of the reinforcement in the longitudinal direction along the short sides is as follows: at the top of the slab, 16 mm; at the bottom of the slab, 22 mm; the diameter of the reinforcement in the transverse direction is 12 mm. Uniform hydrostatic pressure on the slab corresponds to a complete immersion of the dock at an empty compartment; it amounts to 92 kPa. The supporting contour of the slab, including the reinforcement, is rigidly fixed. To reduce the number of finite elements and simplify the calculation procedure, we applied the conditions of the symmetry of the slab's fasteners and load, which made it possible to consider only 1/4 part of it. The materials used were the most common ones in the manufacture of composite docks: A-III grade steel with a yield strength of  $\sigma_y=390$  and an elasticity module of  $E=2.0 \times 10^5$  MPa; heavy concrete, category B50, with a ultimate strength at compressive state of  $\sigma_{u-}=36$  MPa, a ultimate strength at tensile state of  $\sigma_{u+}=2.3$  MPa, and an elasticity module at compressing of  $E=0.38 \times 10^5$  MPa. The elasticity module at stretching was adopted to equal  $E=0.11 \times 10^5$  MPa, taking into consideration the reduced resistance of concrete at stretching and the possibility of microcrack formation. The strength reserve coefficient for the concrete and reinforcement at bending is taken equal to  $k=1.4$ , according to [13]. Thus, the permissible stresses amounted to: for steel in all cases  $[\sigma]=245$  MPa; for compressed concrete  $[\sigma]=26$  MPa; for tensile concrete  $[\sigma]=1.6$  MPa.

The simulation employed an adaptive grid of finite elements with a thickening near the reinforcing elements and transition lines from the stretched to compressed zones. The reinforcement was simulated by the same spatial tetrahedral elements; the reinforcement scheme and the example of splitting are shown in Fig. 2. Reinforcement works with concrete jointly, that is, the displacements of nodes of the reinforcement and concrete elements at common points are the same. The compressed and stretched concrete volumes are simulated by separate arrays with different mechanical characteristics; the condition for compatibility of their operation is also the same displacements in common nodes.

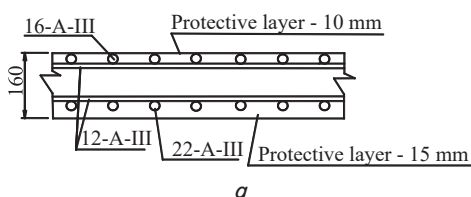


Fig. 2. The reinforcement of a reinforced-concrete slab: a – working scheme; b, c – splitting into finite elements

**6. Results of calculating the strength of a slab for the composite non-assembly pontoon of a floating dock**

**6. 1. Establishing the boundaries of the compressed and tensile volumes of a rigidly fastened slab under the influence of uniform transverse pressure at different thicknesses and ratios of the lengths of the sides of the slab**

Fig. 3, 4 show the distribution diagrams of the consolidated stresses in the slab, which were built using the Solid-Works software package. Blue color denotes compressed zones (stresses with a negative sign), red color – tensile zones (stresses with a positive sign).

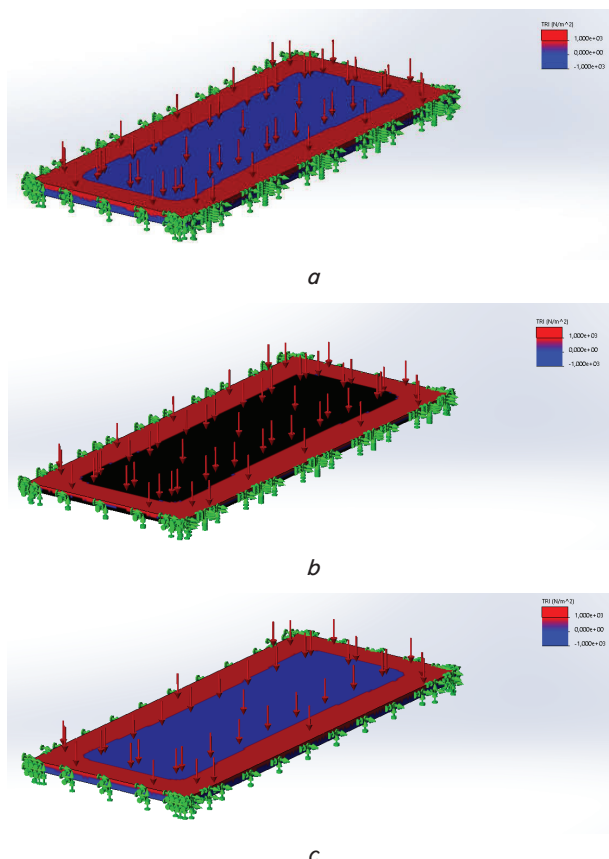
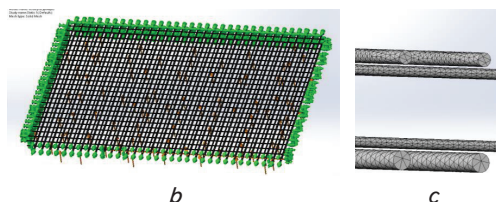


Fig. 3. Stress distribution diagrams: a – a slab measuring 200×3,000×7,000; b – a slab measuring 120×3,000×7,000; c – a slab measuring 160×3,000×7,000

The above diagrams demonstrate the distribution of areas of the compressed and tensile zones for slabs made from a homogeneous isotropic material does not depend on thickness at deviations within 25 % of the reference value of 160 mm, which covers almost the entire range of thickness used in practice.

Fig. 4 shows an example of the estimation diagrams for slabs 160 mm thick with different aspect ratios.



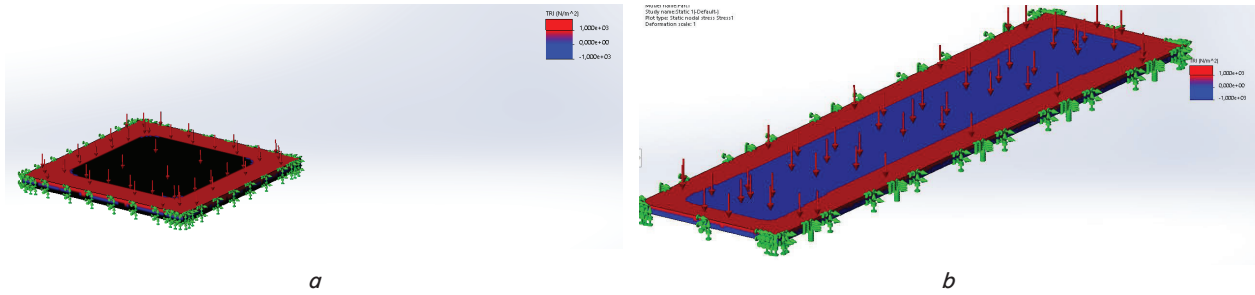


Fig. 4. Stress distribution diagrams: *a* – a slab measuring  $160 \times 3,000 \times 3,000$ , the ratio of sides' length is 1:1, *b* – a slab measuring  $160 \times 3,000 \times 12,000$ , the ratio of sides' length is 1:4

The diagrams in Fig. 4 clearly show that the nature of stress distribution also does not depend on the change in the ratio of the sides' lengths.

### 6. 2. Determining the maximum stresses in reinforced slabs with a different ratio of sides' lengths

SolidWorks software package was used to calculate stresses in the models of reinforced slabs with different

widths of short sides. The data acquired were imported into the tabular processor Microsoft Excel, which was applied to build the charts (Fig. 5–7) of maximum stresses in the concrete and reinforcement depending on the width of the short side of the slab. It is possible to determine the rational width of the pontoon slab from the charts by using the dashed lines corresponding to the level of permissible stresses.

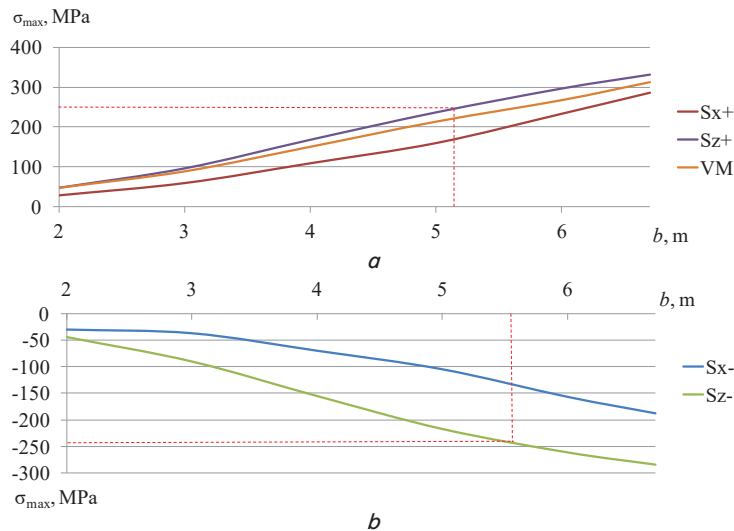


Fig. 5. Maximum stresses (MPa) depending on the length of the short side of the slab (m): *a* – in the upper reinforcement; *b* – in the lower reinforcement

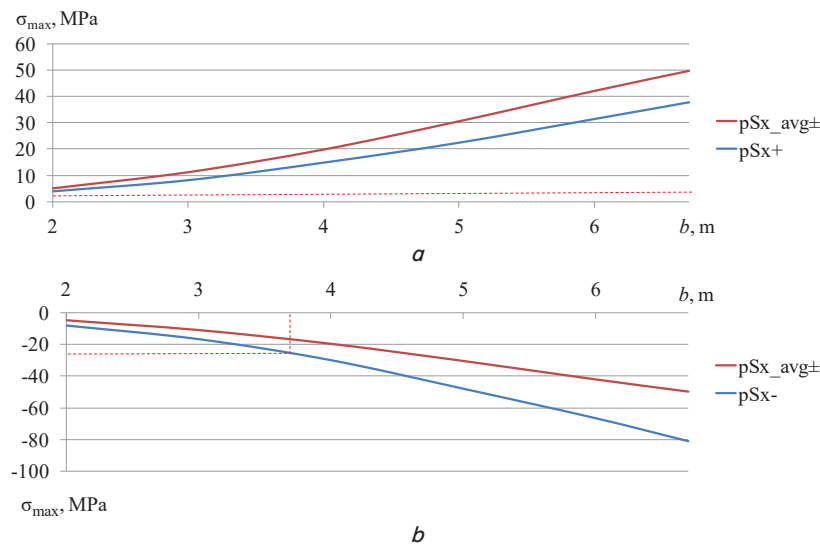


Fig. 6. Maximum stresses on short edges (MPa) depending on the length of the short side of the slab (m): *a* – in the upper layers of concrete, *b* – in the lower layers of concrete



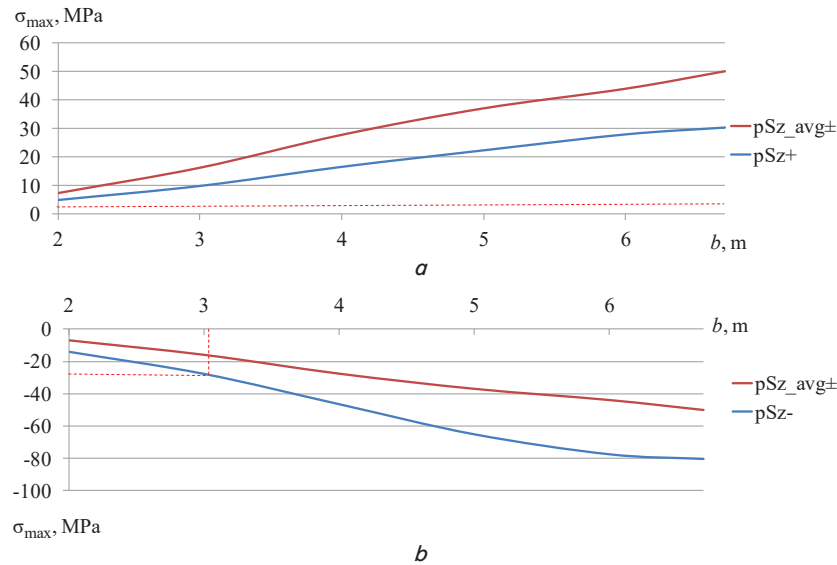


Fig. 7. Maximum stresses (MPa) on long edges depending on the length of the short side of the slab (m): *a* – in the upper layers of concrete, *b* – in the lower layers of concrete

In Fig. 5–7, the following designations are used: *S<sub>x</sub>* – normal stresses along the long edges of the slab; *S<sub>z</sub>* – normal stresses along the short edges of the slab; VM – consolidated stresses by the Mises theory; *pSz\_avg±* – average stress in concrete along short edges; *pSz+* – the largest stresses in tensile concrete along short edges; *pSz-* – the largest stresses in compressed concrete along short edges; *pSx\_avg±* – the average stress in concrete along long edges; *pSx+* – the largest stresses in tensile concrete along long edges; *pSx-* – the largest stresses in compressed concrete along long edges.

**6. 3. Determining the optimum width of the reinforced-concrete slab**

The dimensions of the short side should obviously not exceed the minimum value, which corresponds to the maximum stresses in the lower compressed layers of concrete in the middle of the long sides. The same position of dangerous points corresponds to those determined in the calculations of steel rectangular slabs. Thus, at the specified load level, the size of the short side of the reinforced concrete slab should not exceed 3 m (Fig. 7, *b*). The reinforcements in both directions are obviously underloaded, which gives the reason to recommend reducing their diameters or using reinforcement of a smaller class of strength. As it was predicted, in the stretched areas of concrete stresses exceed permissible ones (Fig. 6, *a*, 7, *a*), which must lead to the occurrence of microcracks and reduced resistance of concrete in stretched areas.

**7. Discussion of results of studying the stressed-strained state of the reinforced-concrete pontoon**

The results from preliminary calculations allow us to argue that the width of the region of stretching the upper layers and compressing the lower layers of the slab near the supporting contour (Fig. 2) is almost independent of the slab thickness. In addition, the relative width of the tensile zone does not depend on the ratio of the sides' lengths in the considered range from 1:1 to 1:4 (Fig. 3) and is about 22 % of the length of the short side of the slab. This value coincides with the value of the joined belt of the stiffener, working in

conjunction with the plate edge in case of buckling of flooring slabs [14, 15].

Our findings lead to the following conclusion: when simulating composite reinforced-concrete slabs, one can consider them to be stretched from the side of the applied load at a distance of about 0.22 lengths of the short side of the supporting contour. Such slabs should be considered compressed in the middle part of the slab from the side of the applied load and, on the contrary, stretched from the opposite side. That would account for the difference in the mechanical characteristics of concrete and its resistance in the stretched and compressed zones. The slab, in this case, can be considered rigidly fixed on four sides of the supporting contour, taking into consideration its large thickness, as well as the symmetry of fastenings and loads.

Our calculations of maximum stresses in the slab reinforcement and concrete (Fig. 5–7) revealed significant underload of the reinforcement and overload in the stretched areas of concrete. Simulating the reinforcement, as well as the compressed and stretched volumes of concrete, by separate bodies has made it possible to derive better results and to improve accuracy. The calculation of a concrete slab without reinforcement according to the theory of rigid plates produces maximum stresses, for the case of the determined optimum width of 3 m, at the level of ±5.6 MPa, which, for the compressed zone, yields an error of 4.5 times in a dangerous direction, which is not acceptable at all. Thus, calculation of the reinforced structures should employ other methods, such as, for example, proposed in this work.

The application of a given calculation technique is limited only by the general shortcomings of a finite-element method and can be extended to other similar structures. Although our study has been carried out for a specific design with the specified strength and geometric parameters, this approach makes it possible to choose the optimal dimensions of rectangular reinforced slabs also of other geometric dimensions, reinforcement, and load. The disadvantages of such a technique include the need to assign several precise geometric models, which, in turn, leads to an increase in the time and volume of calculations.

The models did not estimate the possible dynamic load, the initial deflection of the slab, the possibility of additional

stresses due to the torsion and general bend of a dock, which may certainly be taken into consideration in further studies. Also of interest is to examine models with different reinforcement parameters, which take into consideration the operational patterns of compressed and stretched areas. Systematization of such data would make it possible to build appropriate empirical dependences to select the type, quantity, and size of reinforcing elements for a slab.

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## 8. Conclusions

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1. We have performed the preliminary calculation of slabs made from a non-composite homogeneous material in order to determine the boundaries of tensile and compressed zones at

different values of thickness and ratios of the sides' lengths. It was found that the distribution of areas of the compressed and stretched zones for plates made from a homogeneous isotropic material does not depend on thickness at the deviations within 25 % of the reference value of 160 mm. It was also established that at a different ratio of the sides' lengths the length of the zone of influence of the boundary effect is 0.22 lengths of the short side of the slab and does not depend on this ratio.

2. The result of processing the solutions obtained is the established rational width of the slab for the case considered, which is 3 m at a design length of 6.7 m, the accepted thicknesses, and schemes of reinforcement. Such an estimation approach could be used to optimize the strength size of rectangular elements in the reinforced-concrete structures during their design.

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