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INSTITUTE OF OCEANOLOGY
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FLOATING CAISSON TYPE PNEUMO-STRUCTURE

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The defense of the dissertation will take place on --.--. 2020 at 02:00 PM in the meeting room of the Institute of Oceanology at the Bulgarian Academy of Sciences located at 40 Parvi May Street, in an open session of a five-member scientific jury consisting of:

1. Prof. Dr. Eng. Lyubomir Dimitrov - IO-BAS;
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РЕЗЮМЕ

Настоящият дисертационен труд представя разработването на нов тип плаваща пневмо конструкция, приложима в хидротехническото строителство за изграждане на гравитационни съоръжения, подложени на големи натоварвания във водна среда, практически на всякакъв вид земна основа в плитководни и дълбоководни акватории. Конструкциите могат да имат призматична или цилиндрична форма и са с пневматични средни работни камери без дъно. Транспортират се в плаващо състояние до мястото на полагане. Специалното разположение на отворените странични и затворените отгоре средни пневматични камери и някои приспособления позволяват на конструкциите да бъдат устойчиви и практически непотопяеми при транспортиране в плаващо състояние. С промяна на налягането на въздуха в камерите е възможно прецизното коригиране на газенето на конструкциите, точното им полагане на място и създаване на противоналягане във вътрешните работни камери за принудително врязване в земната основа и планирано нивелиране. След позиционирането им на земната основа, камерите на конструкциите се запълват със запълнител. При използването им като резервоари за нефт и газ горната плоча не се демонтира. Конструкциите са ефективни основно при строителството върху слаби почви. Външните натоварвания се предават предимно на основата чрез вътрешния запълнител, което води до равномерното им преразпределение. Избягва се необходимостта от каменна преразпределителна призма и прецизното (с помощта на водолази) подравняване на дъното. Отсъствието на дънна плоча допуска неравномерни слягания на земната основа. Изградените с конструкциите гравитационни съоръжения допускат съществено нарастване на деформациите на стените и увеличаване на поеманите натоварвания без влошаване на общото им експлоатационно състояние.

Abstract

This dissertation presents the results from the development of a new type of floating pneumatic structure, applicable in hydro technical engineering of the construction of gravitational facilities subjected to high loads in the aquatic environment, on virtually any type of ground in shallow and deep water areas. The structures can be with prismatic or cylindrical shape and have pneumatic medium bottomless work chambers. They are transported in a floating condition to the place of laying. The special arrangement of the open side chambers and top-closed middle pneumatic chambers and some additional devices allow the structures to be stable and practically unsinkable when transported in a floating state. By changing the air pressure in the chambers, it is possible to precisely adjust the draft of the structures, to place them precisely in place and to create a back pressure in the internal work chambers for forced incision into the ground base and perfectly planned leveling. After their positioning on the bottom ground, the chambers of the structures are filled with filler. When used as oil and gas tanks, the top plate is not removed. The structures are effective mainly in construction on weak soils. The external loads are transmitted to the substrate mainly through the internal filler, which leads to their even redistribution. The need for a stone redistribution prism and precise (with the help of divers) levelling of the underlying bottom ground is avoided. The absence of a bottom plate allows for uneven subsidence of the underlying ground. Gravitational engineering constructions built with these structures allow significant increase of the deformations of the walls and increased level of the accepted loads without deterioration of their general operational condition.

INTRODUCTION

Floating hydraulic structures are widely used in the construction of facilities for various purposes in the shelf zone. Their use leads to a significant reduction in construction time and allows the implementation of a significant volume of construction works in areas without the necessary industrial base. These structures may have their own buoyancy or such is provided by floating multi-ton mechanization or special pontoons moored to them.

Experience in the design and construction of hydro facilities consisting of thin-walled reinforced concrete gravity type structures without bottom makes us think about the feasibility of using the same approach in the design of floating caissons. In these constructions, the heavy and material-intensive bottom usually performs only technological functions when transporting the caisson in a floating state. The development of special technology and equipment for the transportation of such caissons and their immersion will allow in any case obtaining a significant economic effect and reduction of the cost of scarce materials [3].

This problem is solved with the creation of floating caisson structure of a new pneumatic type, applicable in hydro engineering for the construction of facilities subjected to high loads in the aquatic environment, on virtually all types of marine sediments in shallow and deep water.

The caisson has a prismatic (Fig. 1.3.) or cylindrical shape (Fig. 1.4.) and is bottomless. It is divided by transverse and longitudinal inner walls into several side and middle chambers. The side chambers are open at the top and bottom for increasing the cross-sectional moment of inertia of the water mirror and using of the attached water mass in case of oscillations during transportation. The middle chambers are closed at the top with a reinforced concrete slab or an inventory steel or reinforced concrete cover and provide the lifting buoyancy. They are equipped with equalizing valves, through which the air pressure in the middle chambers is created and corrected. Air tight hatches are built into the upper plate through which, after equalization of the pressure and immersion of the caisson, it is filled with filler (Fig. 1.3.). The inner walls are fitted with holes located at a distance from the base, in accordance with the size of the caisson and the volume of the middle chambers (item 9 on Fig. 1.3.), which does not allow the reduction of metacentric height below the critical one during transportation [1].

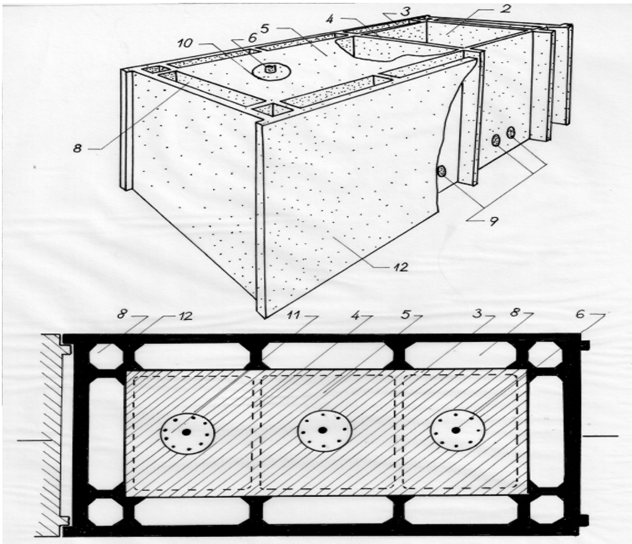


Fig.1.3. Prismatic pneumatic-type caisson

2. Inner chambers; 3. Longitudinal air tight walls of the inner chambers; 4. Transverse air tight walls of the inner chambers; 5. Inventory upper cover; 6. Air pressure/release valve; 8. Side open chambers; 9. Stabilizing openings; 10. Air tight hatch; 11. Outside chamber walls; 12. Haunches

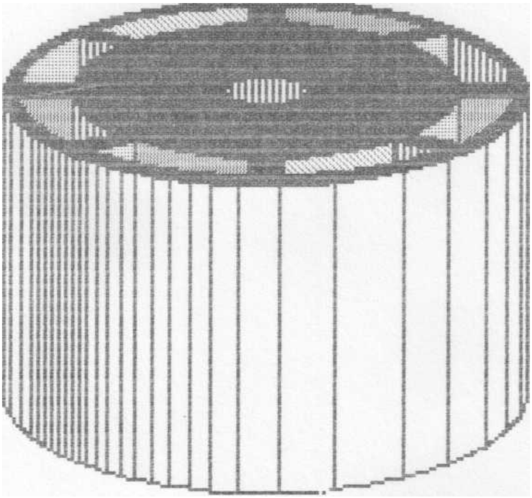


Fig. 1.4. Cylindrical pneumatic-type caisson

The advantages of the new type of floating caisson for construction of hydro facilities are:
- the construction can be used on any type of construction soils in practice;
- the structure is more efficient in the construction on weak marine sediments due to the nature of interaction with the ground;
- the loads on the structure are absorbed by the internal filler, which allows their even redistribution;
- the need for a stone prism and precise leveling of the bottom with the use of diving work is avoided;
- there is no bottom plate, intolerant to uneven deformations;
- the stresses in the walls of the chambers, as well as the deformations of the cross sections are insignificant;
- the caisson allows a significant increase of the deformations with the increase of the applied loads without weakening of the structure to a state, even close to the limit one, due to the plastic nature of its destruction;
- in case of perforation of the outer wall, as a result of wave pressure, the open side chambers behind it act as wave-quencher;

- the caisson can be made of prefabricated reinforced concrete elements.

II. GOALS AND TASKS OF THE RESEARCH

The aim of the dissertation is to investigate theoretically and experimentally the characteristics of a floating caisson of a new pneumatic type and to justify its applicability in hydro engineering, through analyzing its advantages and disadvantages compared to existing and other used structures.
To achieve this goal in the dissertation the following tasks should be solved:
1. Determining the draft, water displacement and the margin of navigability depending on the size of the air column in the inner chambers of the caisson;
2. Determining the dependence of the water displacement from the height of the air column in the inner chambers;
3. Obtaining the curve of the centers of values of the caisson;
4. Studying of the buoyancy and stability of the caisson in wave conditions;
5. Theoretical studies of the buoyancy and resistance of the caisson to wave conditions;
6. Calculation of the acting forces and the allowable conditions for getting solution;
7. Determination of the initial stability;
8. Dimensioning of the stability at large angles of roll;
9. Model hydrodynamic tests of floating caisson type pneumatic construction;
10. Determination of static stability;
11. Towing tests on still water;
12. Seaworthy tests of a floating caisson model.

III. MATERIALS AND METHODS

III.1. Description of the new structure

The floating gravitational pneumatic-type caisson facility is a representative of the so-called "pneumatic technologies" in the world hydrotechnical practice and achieves its navigability due to the increased air pressure in the inner chambers on the principle of the diving bell.

The compensation openings located in the walls of the inner chambers at a pre-sized distance from the lower part of the caisson, play an important role in the sustainable transportability and practical unsinkability. They allow the maximum roll and trim angle to be set in advance so as not to allow the formation of a negative recovery moment and overturning of the caisson. At the geometrically predetermined maximum allowable roll and trim angles, the water level in the inner chambers reaches the level of the compensating holes, the compressed air begins to flow out through them until a positive recovery moment is restored, which increases the caisson draft and stabilizes it [1]. An important condition for the transportation of the floating caisson of a new type is to ensure the air tightness of the inner work compartments.

III.2. Airtightness of the new structure

One of the most important things in the construction and operation of concrete pneumatic type caissons structures is to ensure airtightness of the structure for air pressure values up to 2 bar (0.2 MPa) [4].

For an approximate preliminary assessment of the airtightness of the concrete without taking into account the water saturation, a gas permeability coefficient can be used (the volume of gas seeping through the wall of a suitable material with a thickness of 1 m and a cross section of 1 sq. m for one hour at pressure difference on both sides of the wall 1 mm of mercury). The amount of gas in volume V that passes through the wall with thickness l, cross section F for time z at pressure difference P1 - P2 is determined by the expression:

$$V = \mu \frac{F.(P1 - P2).z}{l} \quad [m^3] \qquad 3.2.1.$$

where: for the air $\mu = 0.04$ – for heavy concrete;
for bituminized material $\mu = 0.01$ [8];
for water saturated normal concrete in varies between $10^{-16} \div 10^{-18}$ m^3.

The study results of air permeability dependence on the increase in cement consumption allow for better explanation of the protective properties of concrete with higher cement content, the air permeability coefficient of which is for example 10 times lower than the air permeability coefficient at normal cement content.

Reinforced concrete walls and slabs, manufactured technologically correctly and vibrated, are considered to be enough airtight even without plaster layer on them.

There are many ways to ensure airtightness of the concrete during construction [4]:

- Use of slowly hardening Portland cement which has a relative surface area of more than 3000 cm. /g.;
- The water and the main raw material must be clean;
- The water / cement ratio should be in the range $0.4 \div 0.5$;
- The grain size of the stone material must be constant, the fine-grained stone material must be in moderate quantities and the maximum size of the material must not exceed 32 mm;
- If possible, plasticizers and improvers (softeners, retarding components, etc.) are added to the concrete, which should be previously examined for their impact on the concrete.

To maintain stability and possibility for corrections of the draft during the transportation of the caisson in a floating state, a continuous connection is provided with a compressor station, which is located on board the towing vessel.

III. 3. Interaction with bottom sediments of contour hydrotechnical structures - floating caisson of a new type with pneumatic support

This problem can be solved by the method of pre-driving, leveling of the caisson and distribution of the stress on the base under the contact points of the knives of the structure with the bottom [2].
The essence of this method is in the creation of back pressure (vacuum) in selected or in all closed from above inner work chambers of the caisson, after its positioning in the correct place. As a result, a certain volume of water rises to a predetermined level above the water level in the surrounding water area. The weight of the raised volume of water is distributed below the main contour of the caisson, loads the bottom sediments and allows it to be driven in to the bottom to the designed level and its leveling. This can be repeated until the desired effect is obtained [2].
The method is explained theoretically when considering the basic equation of hydrostatics (Fig. 3.3.2.).

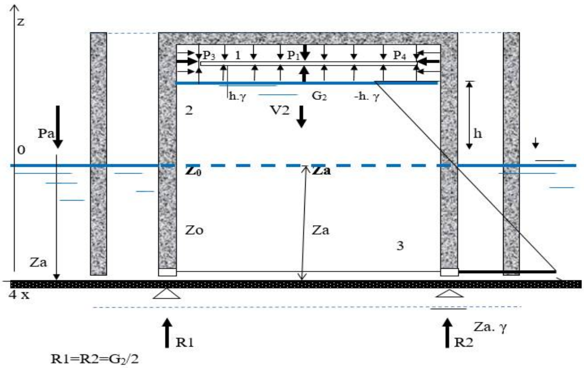


Fig. 3.3.2. Loads and effects

The weight G2 of the raised and retained water volume is distributed below the main contour of the caisson, which is driven into the ground, and represents an overweight, acting additionally to the weight of the caisson itself, while subtracting the part of the caisson which is under water.

III.4. Variety of options for implementation, purpose, geometric shapes and structural elements

An important feature is the ability to manufacture the caisson in any shape depending on the purpose, while observing some simple principles for maintaining buoyancy and stability during transportation.

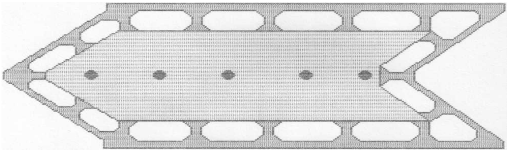


Fig. 3.4.1. Shiplike shape of pneumatic-type floating caisson

It is also of interest what possibilities offer the use of the side chambers of the caisson. When perforated in their outer walls, they act as wave-quenching chambers. To this end, the shape, dimensions and sizing of these chambers correspond to the navigability of the caisson and the wave action [3].
In connection with the utilization of natural gas sources on the Bulgarian coast, a project for capture, collection and transportation of gas has been developed, which is based on the use of floating caisson of a new type as a basic structure (Fig. 3.4.4.).

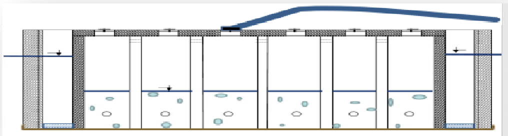


Fig. 3.4.4. Use of the caisson for capture of natural gas sources.

III.5. Methodology for determining the main elements of the caisson

The dimensions of the cross-section of the caisson should be determined taking into account the height of the structure, the loads acting on it and the physical and mechanical properties of the bottom sediments and they shall be based on the dimensional stability of the structure while checking the buoyancy and stability of the caisson. The length of the caisson should not exceed three times its height. The body of the caisson is divided by internal transverse walls to increase its strength and in case of large width also by longitudinal walls, which form sections with smaller dimensions: longitudinally on the caisson usually 3 - 4 m and transversely 4 - 5 m.

In the side walls of the inner work chambers, at a pre-sized distance from the bottom, compensation openings with an area of 0.015 to 0.025 m2 are left to ensure the recovery moment in case of large roll and trim during transportation. In order to lower the center of gravity of the structure in the transverse walls of the internal work chambers holes are made with a diameter of 2 to 5 m with an oval or rectangular cross section (Fig. 3.4.3.). The top plate can be monolithic or inventory depending on the purpose of the caisson. It is equipped with vents for compressed air supply. In case of monolithic construction, the upper plate is equipped with airtight hatches through which the filling of the sections is done with some kind of filler. The diameter and location of the hatches depend on the way the caisson is filled and to ensure accessibility to all compartments. The minimum wall thickness and the top plate of the caisson is determined by the condition to ensure the required thickness of the protective layers of concrete in the optimal location of the reinforcement in the cross section of the walls and should not be less than 15 cm. According to the requirements for durability, the thickness of the outer walls and the top plate are assumed to be equal to 25 - 30 cm, and the inner walls 15 - 20 cm.

In severe hydrological conditions, the width of the sections bordering the outer walls is recommended to be taken from 1 to 1.5 m and in operational condition to be filled with concrete.

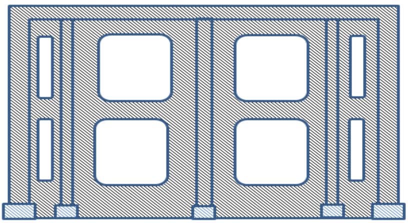


Fig. 3.4.3. Intermediate walls with large openings and thickening of the knives of the structure.

The outer and the partition walls of the inner work chambers should be dimensioned as slabs clamped on three sides in the transverse walls and the upper monolithic slab, with a height

equal to 1.5 l_p (where l_p - the distance between the axes of the transverse walls of the slab within one compartment).
For sizing the wall cross section below 1.5 l_p from the top plate, where the effect of wall clamping in the top plate becomes neglectably small, like a giant massif, the wall is conditionally divided into strips 1 m wide and each strip is dimensioned like a continuous beam, the supports of which are the transverse walls. In the preliminary calculations, the formulas for a beam clamped at both ends can be used.

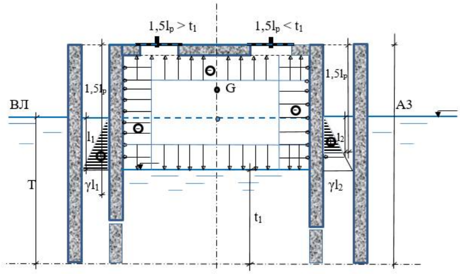


Fig. 3.5.1. Loads on the outer walls of the inner work chambers of the caisson.

The calculated load from the hydrostatic pressure of the water and the pressure from the compressed air in the inner work chambers of the caisson (Fig. 3.5.1.) allows using ready-made tables for determining the force in the plates.
During transportation, the top plate is subjected to compressed air pressure, from the bottom up, the value of which is calculated by the formula:

$$Pp = \rho.w.g.(T - t1) \qquad 3.5.1.$$

where w- density of the sea water; T- draft of the caisson; t1- height of water column in the inner work chambers of the caisson (Fig. 3.5.1.).
When loading the top plate with evenly distributed load from the air pressure, the maximum bending moment Mp will be at the point of clamping of the plate and for its calculation we can use ready-made tables.
In particularly critical cases, it is desirable to check the stiffness of the caisson as a spatial structure for bending and torsion, arising from uneven support of the stone bed or uneven

subsidence of the caisson. The methods and requirements for the reinforcement of the caisson do not differ from those set out for the giant massif.

III.6. Conclusions

It follows from the above that in hydrotechnical engineering in the construction of port facilities with the help of floating pneumatic type caisson structures the novelty is the study of the buoyancy and stability of the new facility, as well as its interaction with the waves during towing to its location.

IV. RESULTS

IV.1. Theoretical studies of buoyancy and stability of the caisson

IV.1.1. Determination of draft, water displacement and margin of buoyancy depending on the size of the air column in the inner work chambers of the caisson.

Since the position of a floating body depends on the weight and the strength of the buoyancy, it is necessary to consider the conditions of equilibrium under the condition of simultaneous action of these two forces.

A body shall be immersed in the liquid until the buoyancy force (of the water displacement) Fb becomes equal to the weight of the body D and shall rotate until the center of gravity of the displaced liquid B and the weight G are at a vertical line, then the body assumes a position of stable equilibrium.

The pushing force of the buoyancy, according to Archimedes' law, is equal in magnitude and opposite in direction to the weight of the fluid displaced by the body.

This is a condition for the body to swim. It is necessary, but not sufficient for the caisson to sail on the set waterline. Since the force of gravity D and the pushing force $Fb = \gamma.V$ act in the vertical direction, the second condition for equilibrium is the need for placement on a same vertical line the center of gravity (c.g.) and G in the pushed volume of the liquid V (Fig. 4.1.1.1). This condition does not determine the type of equilibrium. The distance between points B and G (Zg - Zb) can be positive or negative.

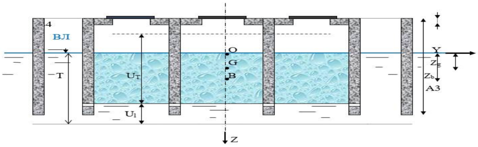


Fig. 4.1.1.1. Basic values of the equilibrium navigation of the caisson and coordinate system, determining its position relative to the water surface.

During transportation, the caisson floats at a constant water displacement and weight load, and therefore the position of p. G will be constant with respect to the dimensions of the caisson's body. Maintaining this condition, it will be possible to change the draft of the caisson due to the change in the size of the air column in the internal work chambers beyond the minimum (T - U1) providing the necessary buoyancy force Fb and the constant water displacement (Fig. 4.1.1.1.). As a result p.G can occupy different positions relative to the plane of the waterline.
To express the second condition for the equilibrium of the caisson, we introduce a coordinate system and parameters determining its position relative to the water surface (Fig. 4.1.1.1.).
Let's assume that the free-floating caisson is in equilibrium and its draft is such that the segment GB is vertical and both points G and B lie in the plane of symmetry. In such an arrangement, the axes Oxyz of the hull can be fixed so that Oxy lies in the plane of the waterline, where point O is the center of gravity of the plane of the waterline and the axis Ox is directed forward, as shown in (Fig. 4.1.1.1.). The Ox and Oy axes will be the main central axes of the waterline plane. In this situation, the coordinates Xb and Yb of the center of water displacement must be equal to Xg and Yg center of gravity of the caisson. For the considered draft in the absence of roll and trim ($\varphi = \Theta = 0$), the equation for the equilibrium of the caisson can be written in the form:

$$D = \gamma.V = Fb = Fa \text{ (aerostatic)};$$
$$Xb = Xg \text{ или } Xb - Xg = 0$$
$$Yb - Yg = 0 \qquad 4.1.1.2$$

If a small angle of the trim ϴ relative to the axis Oy is now transmitted to the caisson (Fig. 4.1.1.2.), then the waterline ВЛ will be at an angle ϴ relative to the axis Ox.

The second equilibrium condition will be satisfied if GB ⊥ ВЛ because D and Fb always act in the vertical direction. To keep on the same line D and Fb we can write in the form:

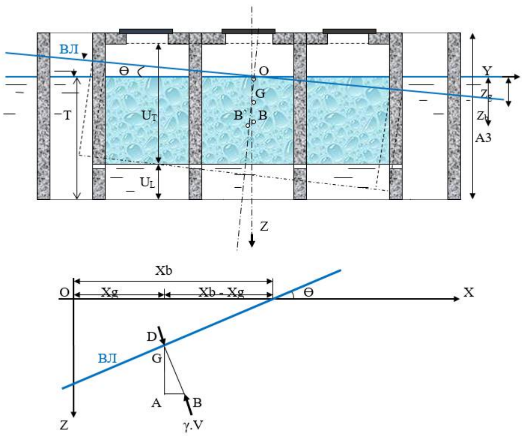
$$\frac{Xb - Xg}{Zb - Zg} = tg\Theta \qquad 4.1.1.3.$$

Therefore, when trampling the caisson with a trim, for the condition for its equilibrium it can be written:

$$D = \gamma.V$$
$$Yb - Yg = 0 \qquad 4.1.1.4$$
$$(Xb - Xg) - (Zb - Zg).tgO = 0$$

Similarly, if a small roll is given to the caisson, the equilibrium condition can be written as:

$$D = \gamma.V = Fb$$
$$Xb - Xg = 0 \qquad 4.1.1.5$$
$$(Yb - Yg) - (Zb - Zg).tg\Theta = 0$$



Фиг. 4.1.1.2.

If the structure floats on an arbitrary waterline (at $\Theta \neq 0$ and $\varphi \neq 0$), then the general equilibrium equations can be written in the form:

$$\begin{aligned} D &= Fb \\ (Xb - Xg) - (Zb - Zg).tg\Theta &= 0 \\ (Yb - Yg) - (Zb - Zg).tg\varphi &= 0 \end{aligned} \qquad 4.1.1.6.$$

IV.1.2. Dependence of the displacement on the height of the air column in the internal work chambers

The displacement curve is graphically represented by the function:

$$V = f.(T) \qquad 4.1.2.1.$$

and shows the change in volume displacement V depending on the change in draft T, assuming that the caisson floats in a vertical state.

The caisson floats at constant displacement and weight load. It follows from this that the displacement curve will be a straight line (Fig. 4.1.2.1.).

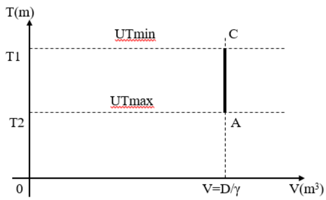


Fig. 4.1.2.1. Curve of the caisson's displacement

The nature of the curve will depend on the shape of the structure. In our case, the areas of all waterlines are the same during the voyage. As the draft increases from 0 to T1 (section OA), the caisson will rest on the bottom. When the height of the air column in the middle work chambers reaches its minimum value UTmin, necessary to maintain an air volume with displacement $V = D / \gamma$ for the stable navigation of the caisson, it rises from the bottom and remains floating at the maximum possible draft T1. With a further increase of the air column in the work chambers, the draft of the caisson decreases and the height of the air column reaches its maximum value UTmax at the minimum possible draft of the caisson T2. When changing the draft from T1 to T2, the magnitude of the displacement and the weight load will remain constant - $V = D / \gamma$.

Further increase of the draft T> T1 makes it impossible to keep the caisson in a floating state, because the first condition for sailing of the bodies (Fb <D) will be violated and the caisson will descend to the bottom.

To determine the relationship between draft T and the height of the air column in the work chambers UT we consider the function:

$$T = f.(UT) \qquad 4.1.2.2.$$

Geometrically, the height of the air column depending on the draft can be determined by the equation:

$$T = (D + M3.U1)/S, \qquad 4.1.2.3.$$

where

M3 – area of the cross section of the work chambers of the caisson;

UT – height of the air column in the work chambers for draft T;

S – area of the cross section of the waterline;

U1 – distance from the bottom to the waterline in the work chambers.

As long as the displacement and the weight load of the caisson do not change during the voyage, the change of draft is carried out exclusively and only by changing the air volume (or air column UT) in the work chambers of the caisson at constant air pressure in them.

The graphical representation of this dependence is given in (Fig. 4.1.2.2.), where the dependence T = f. (UT) is shown. The effective range of the change in draft T depending on the air column in the middle work chambers of the caisson UT is closed in the rectangle ACML. The line T1M represents a limitation of the draft resulting from the inability to sail with positive buoyancy at T> T1. This restriction corresponds to the air column in the work chambers UTmin = p = Fb / M3 and corresponds to the PC line in (Fig. 4.1.2.2.)

The line T2L represents a limitation of the minimum draft of the caisson T2 at the maximum height of the air column in the working chambers UTmax = Q, which represents the full geometric height of the working space of the inner working chambers of the caisson, shown by the lines QM in the graph (Fig. 4.1.2.2 .)

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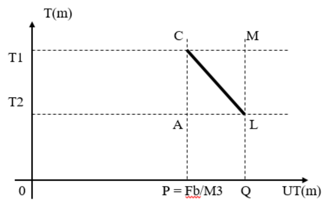


Fig. 4.1.2.2. Change of the draft of the caisson T depending on the size of the air column in the work chambers

IV.2. Studies of the buoyancy and stability of the caisson in wave conditions

IV.2.1. Theoretical studies of the buoyancy and resistance of the caisson to waves

In mechanics we distinguish three types of static equilibrium: stable; unstable and indifferent equilibrium. At the same time, the stability of the floating body can be large or small, i.e. resilience has a dimension that we will not only establish but also measure.
There is another difference. The floating body can only be stable.
The state of indifferent equilibrium is considered unstable.
We distinguish between stability, which corresponds to small deviations from the accepted position of equilibrium or initial stability and resistance to large deviations.

This distinction is made because at infinitesimal angles of deviation it is possible to make a series of assumptions and to obtain relatively simple mathematical dependences. The caisson, as a solid body has six degrees of freedom in space. Accordingly, the deviations of the caisson from the equilibrium position can be divided into three translational displacements and three angular shifts relative to the main central axes defined on (Fig. 4.1.1.1.). It is necessary to assess the balance and stability of the caisson for selected relatively independent deviations.

In the presence of a positive navigability with respect to vertical displacements, we will consider this equilibrium to be stable.

IV.2.2. Impact forces and acceptable conditions for resolution

The control of the forces perpendicular to the surface of the water acting on the caisson of a new type at small and large angles of roll have the following formula:

$$G + \gamma.V + Pe = 0 \qquad 4.2.2.1.$$

where:

G – weight of the caisson;

γ – relative weight of the water;

V – volume of the water displacing bodies on both boards;

Pe – total pressure of the air inside the caisson's body acting in vertical direction.

It goes without saying that V = V1 + V2, where V1 is the displacement of the board inside the water, and V2 is the displacement of the board outside the water.

$$Pe = P.Sn, \qquad 4.2.2.2.$$

Sn – vertical projection of the air cushion

To simplify sizing, we allow the following conditions:

1. In the process of tilting the weight of the caisson does not change, namely: $\gamma.G = const$, $\gamma .V = const$, $P.Sn = const$.
2. As long as V does not change, then at large rolls on both sides the sum of the wedge-shaped volumes entering and leaving the water will be unchanged.
3. The buoyancy of the air volume is fixed, the internal volume of the air volume also does not change, and the plane separating the

air and the water in the work chambers is parallel to the inclined plane of the water surface.

4. As a static inclined we will assume that the pressure inside the air cushion is uniform.

IV.2.3. Initial stability

When determining the initial stability of a new type of floating caisson, the moment of the equalizing forces looks like this:

$$Mk = Mk1 + Mk2$$

4.2.3.1.

We consider an element with length ∂L of the caisson, perpendicular to the plane of the sheet. A small roll angle is assigned to this element. We believe that the volume of water displaced by the caisson remains unchanged.

The stability of the caisson is maintained by the redistribution of the hydrostatic force of the submerged volume of the hull at present roll (trim). At the same time, the pressure in the air volume impairs the stability

$$M\kappa = M\kappa 1 - Pb(\Theta).Sb(\Theta).lb(\Theta) \qquad 4.2.3.2.$$

where:

$Pb(\Theta)$ – pressure inside the air volume;

$Sb(\Theta)$ – the area of the water mirror at the boundary between water and air in the inner work chambers at a roll angle Θ;

$lb(\Theta)$ – the arm of the reduced support force from the air volume.

The restoring hydrostatic moment of the submerged part of the caisson is determined using the classical method of A.N. Krilov [12]:

$$M\kappa 1 = (lf - a.\sin\Theta).D, \qquad 4.2.3.3.$$

where:

lf – arm of the stability of the shape;

$$lf = Y.\cos\Theta + Z.\sin\Theta \; ; \qquad 4.2.3.4.$$

$$Y = \int_0^{\Theta} re.\cos O.dO; \quad Z = \int_0^{\Theta} re.\sin O.dO \; ; \qquad 4.2.3.5.$$

re – metacentric radius of the caisson;

$$re = \frac{Ie(\Theta)}{D}, \qquad 4.2.3.6.$$

where $Ie(\Theta)$ - moment of inertia of the waterline area.
The wedge-shaped volume coming out of the water and the wedge-shaped volume entering the water are equal; the inclined plane along the waterline, passing through the plane of positive buoyancy, intersects with the central longitudinal plane of the caisson and for the given case the formula for sizing the initial stability is completely usable.
The moment of equalizing force:

$$M\kappa = \frac{L}{4} . tg\Theta . [B'^3 - b^3 - 4.P.b.h], \qquad 4.2.3.7.$$

where L – length of the caisson's board;
B`– width of the caisson (reduced);
b – width of the air volume;
h – height on the vertical line from the surface at the border between the water and the air in the work chambers while moving from the center of gravity;
P – pressure inside the air volume.

IV.2.4. Dimensioning of stability at large roll angles

As shown in Fig. 4.2.4.1., the wedge-shaped cross-section part entering the water and the wedge-shaped cross-section part leaving the water are not the same, as the section entering the water includes part of the top plate and does not have a complete profile. As far as the volume of the wedge entering the water differs from the volume of the wedge leaving the water, the waterline will be adjusted:

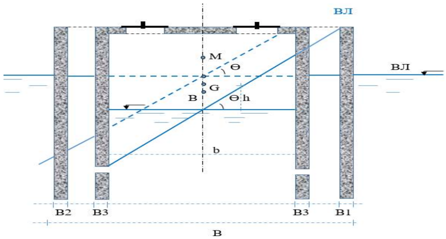


Fig. 4.2.4.1. Caisson resistances at large roll angles.

According to the assumed condition that the volume of the air volume at large roll angles does not change, the plane of separation of water and air is parallel to the inclined plane.

In this case:

$$P_{\Theta} = P$$

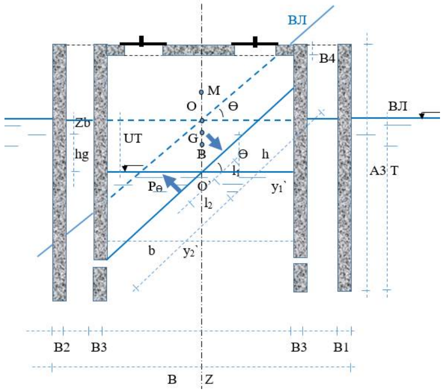
$$Sn_{\Theta} = Sn \qquad 4.2.4.2.$$

This tells us that the area of separation of water from air does not change.

However, the two immersion sides of the plane separating the water from the air, after the transition of the sharp angle upwards to the air volume, become asymmetrical with respect to the inner walls of the airbag (air volume) along the central plane of the caisson cross section. If the condition $Sn_{\Theta} = Sn$ is preserved, then the plane of separation of water from the air should move downwards in parallel, as shown in Fig. 4.2.4.2.

Assume that UT - is the height of the air volume after the corresponding adjustments of the plane separating water and air are made

$$y_1' = \frac{UT}{\sin\Theta}\ ; \qquad y_2` = \frac{b}{2\cos\Theta}$$



Фиг. 4.2.4.2.

The pressure of the air volume in a direction parallel to the inclined water plane does not create a moment of equalizing force. In the vertical direction with respect to the inclined water plane at a time when the composite force of the air volume pressure is related to the actual buoyancy, the magnitude of the forces does not change, but the point of action moves to the left and the composite force PO creates a moment of equalization force Mk2 relative to the center of gravity G.

The moment of the equalizing force created by the air volume pressure:

$$Mк2 = - P_{\Theta}.(l_1 + l_2) =$$

$$= - p.L.b.[hg.\ \sin\Theta + \frac{1}{2}(\frac{b}{2\cos\Theta} - \frac{UT}{\sin\Theta})] \quad 4.2.4.8.$$

The moment of the equalizing force:

$$Mк = Mк1 + Mк2 =$$

$$= Mk1 - p.L.b.[hg.\sin\Theta + \frac{1}{2}(\frac{b}{2\cos\Theta} - \frac{UT}{\sin\Theta})] \quad 4.2.4.9.$$

As far as in the determination of Mk, Mk2 participates with a negative sign (worsens the moment of the equalizing force), then when the air flows out of the air volume Mk will increase sharply and will lead to the leveling of the caisson with already increased draft T. This is one of the specifics of the stability of the new type of floating caisson.

Since the outboard no longer produces a hydrostatic effect, when calculating the hydrostatic moment of the equalizing force at this stage it is only necessary to calculate the buoyancy of the submerged board and the submerged volume of the caisson's body multiplied by the arm of the force along the central longitudinal line, i.e. to calculate the moment of hydrostatic positive force.

IV.3. Model hydrodynamic tests of floating caisson type pneumatic construction

The model studies were performed at the Institute of Hydro and Aerodynamics, Varna in the section "Resistance in ship movement". The aim of the research is to establish some basic hydrodynamic properties (stability, resistance, seaworthiness, etc.) of a floating caisson type pneumatic construction with a dynamic principle of support, necessary for its transportation from the place of production to the place of installation as part of a specific hydro facility.

For this purpose, the following tests have been done:

- rolling;
- towing tests on still water;
- seaworthy tests.

IV.3.2. Towing tests on still water

IV.3.2.1. Experiment set up

The experiment was carried out in the deep-water basin of IHA by means of the regular towing trolley and towing installation. The air volume inside the model is created and maintained by means of a standard "vacuum-pressure" system. A special system has been implemented to measure the pressure in the air volume.

The point of application of the towing force is selected on the upper wall of the model, corresponding to the presumed point of reduction of the towing forces of the natural object.

The tests were performed for immersion T = 0.55m.

IV.3.2.2. Results from still water towing tests

The results of the towing tests are given in Table 4.3.2.2.1

L_{wl} = 1,580 m - length of the caisson; Scale 1:16
B = 0,775 m - width of the caisson; t° of the water – 14°
T_b = 0,550 m - draft of the caisson; $\nu = 1{,}169633.10^{-6}$ m²/sek
T_a = 0,550 m - immersion of the caisson; ρ = 101,88 kg.sek²/m⁴
S = 2,801 m² - area of the waterline; C_d – resistance coefficient;
W = 129 m³ - water volume in the basin; Rn – Rejnold's num.;
Vm – towing speed; Ψ – running trim angle;
Fn - Froude's number; P_{bb} – air volume pressure
R_{tm} – towing resistance

Vm [m/s]	Fn --	Rtm [kg]	$C_d.10^2$	$Rn.10^6$	Ψ [grad]	P_{bb} [kg/ m²]
0,2066	0,0525	0,598	0,1898	0,279	0,80	315,5
0,3022	0,0768	1,295	0,4111	0,408	1,55	315,5
0,4017	0,1020	2,347	0,7451	0,543	2,6	315,5
0,5011	0,1273	3,682	1,1689	0,677	3,95	315,5
0,5990	0,1522	5,787	1,8371	0,809	5,40	315,5
0,2495	0,0634	0,962	0,3054	0,337	1,15	315,5
0,3499	0,0889	1,799	0,5711	0,473	2,00	315,5
0,4487	0,1140	3,069	0,9743	0,606	3,20	315,5
0,5513	0,1401	4,696	1,4908	0,745	4,65	315,5
0,6496	0,1650	6,977	2,2149	0,877	6,30	315,5
0,2831	0,0719	1,198	0,3803	0,382	1,40	315,5
0,3291	0,0836	1,624	0,5155	0,445	1,80	315,5

Table 4.3.2.2.1. Towing tests on still water.

IV.3.4. Results of seaworthy tests

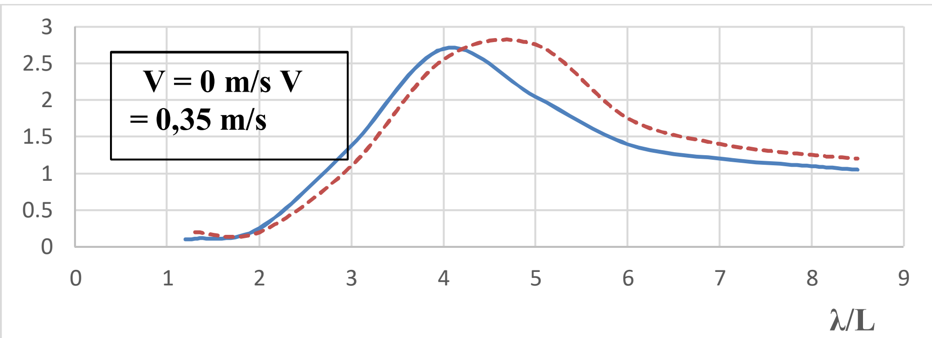


Fig. 4.3.4.2 presents the amplitude-frequency characteristics (frequency response) of vertical oscillation with and without

movement. The maximum of the curve at V = 0 m / s coincides with the period of free vertical oscillations. There is a certain dephasing of the maximum at V = 0.35 m / s, which is due to the replacement of the wave frequency with the frequency of strike at sail.

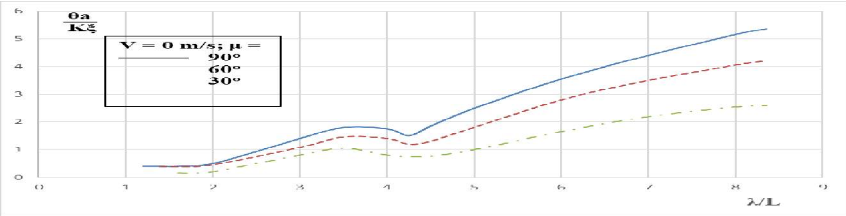


Fig. 4.3.4.4. Assessment for on-board oscillation

According to the physical notions of the process, it is greatest at μ = 90 °. The small peak at λ / L ≈ 4 corresponds to the maximum of the vertical oscillation.

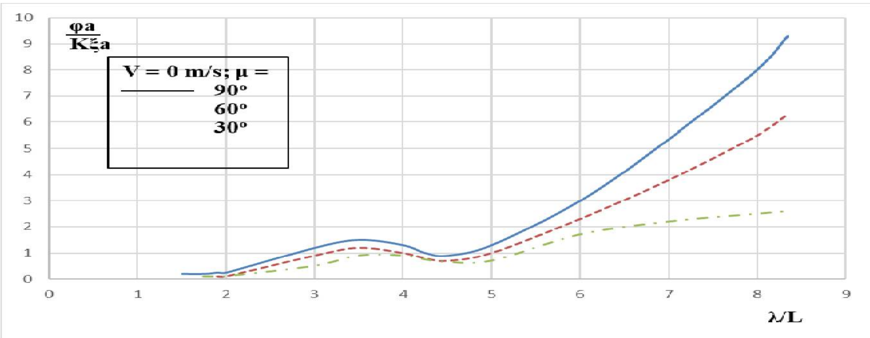
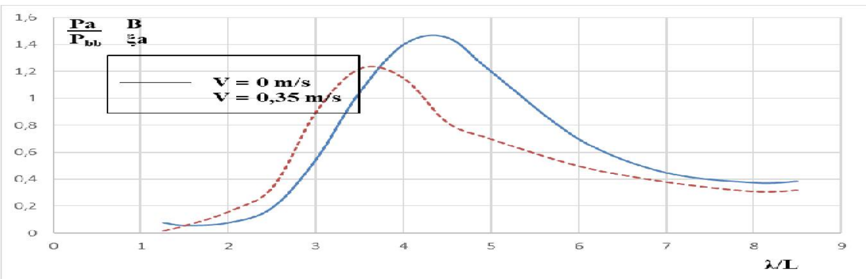


Fig. 4.3.4.6. The change in the frequency response of the keel oscillation by changing the angle of strike with the wave.



Фиг. 4.3.4.8.

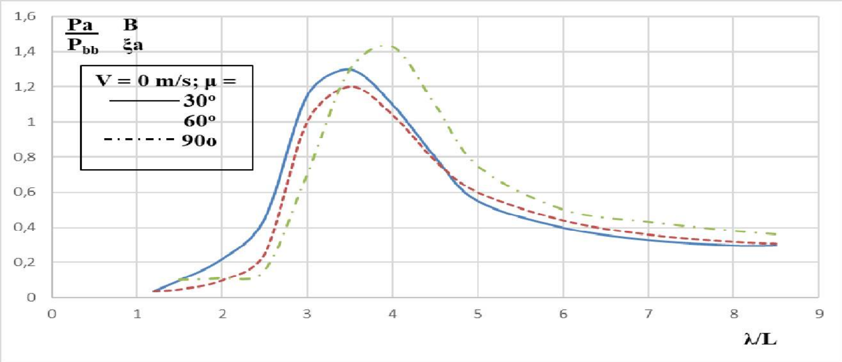


Fig. 4.3.4.9.

Figures 4.3.4.8 and 4.3.4.9 show the dimensionless pressure pulsations in the air volume at different wavelengths. From Fig.4.3.4.8 it can be seen that they are larger at motion (V = 0.35 m / s) than without motion, and from Fig.4.3.4.9 that they are larger at μ = 90°, which corresponds to vertical oscillation. The maximum of the curves also corresponds to the maximum of the vertical oscillation. In total RA / PBB <5%, and decreases at long waves.

CONCLUSIONS AND RECOMMENDATIONS

Avoiding the use of floating cranes with high lifting capacity, reducing the underwater work and eliminating the costly bottom preparation for the hydro construction of port facilities from large structural units are prerequisites for the implementation of the floating caisson type pneumatic construction.

The practical use of the new type of floating caisson will contribute to its inclusion in the interdepartmental unification of the types of industrial structures and details. This will allow the implementation of one of the most economical and universal structures in hydro engineering. The requirement for unification must be combined with the specifics of the construction of facilities in certain special conditions, in which some caisson facilities will be unique and will require individual design solutions and methods of construction. Examples of this have been discussed in detail in Chapter III.

It has been proven that the methods and requirements for the sizing of the floating caisson type pneumatic structure do not differ from those set out in and for the giant massif. The solution of problems in the field of earth mechanics in the interaction of a new type of caisson with marine sediments does not differ from the provided detailed examples for large diameter piles (sinking wells).

The static stability of the proposed model of floating caisson type pneumo - structure is insufficient. In order to ensure satisfactory static stability of the caisson it is recommended, when immersed at T> 0.5 m. (around the operating level) to reduce the center of gravity of the caisson by about 15%.

The required power of the tug hook, when towing the caisson at a speed of 3 kns, is 180 hp. (subject to the practical absence of waves and wind).

The results of the seaworthy tests refer to the realized configuration of geometric, kinematic and dynamic parameters. Any changes of these parameters will require additional experimental checks.

The results for the angular oscillations show that relatively small amplitudes of waves cause large amplitudes of oscillation. Therefore, the transportation of the natural object must be carried out at small sea waves.

The pressure fluctuations in the air volume during sea rocking do not exceed 5% from the initial value.

AUTHOR'S CLAIMS

1. A new type of caisson is proposed - a floating pneumatic structure, which is a novelty in hydro engineering construction and has no analogue in the world hydro-technical theory and practice. The structure is applicable in hydro-engineering for the construction of gravitational facilities subjected to high loads in aquatic environment, on virtually any type of ground in shallow and deep water areas. It was protected by a patent (Caisson - invention with copyright № 44643 / 08.07.1985, patented in Bulgaria with patent № 1147, the Netherlands with patent № 8 701 423, France with patent № 2 616 464,

Finland with patent № 890047, Singapore (China) with patent № 89100199.9 and Russia with patent № 7774529/03).

2. A method had been developed for the installation of a caisson pneumatic structure (invention with copyright certificate № 91624, 1990), in which by means of back pressure / vacuum / in selected or all working closed only from above and in contact with the ground medium chambers of caisson, the main contour of the caisson is incised to the desired or limit value into the ground. With a balance and long-term action of the raised and retained water volume, the ground base under the main contour of the caisson is consolidated and with vertical loads significantly exceeding the operational ones, the ground base under the main contour of the caisson is pre-stressed, if subsequent filling with another filler is further intended. The method for pre-driving of a bottomless caisson and tensioning the ground base is a novelty in hydro engineering construction and such a method is not known in the world hydro engineering theory and practice.
3. The working parameters of the project have been validated by a specially planned experiment of a floating caisson type pneumatic construction in order to establish some basic hydrodynamic properties (stability, resistance, seaworthiness, etc.) of a floating caisson with a dynamic principle of support, which are necessary during its transportation from the place of production to the place of installation to a certain hydro facility.
4. As a result of model studies of caisson pneumatic construction at a certain configuration of geometric, kinematic and dynamic parameters, conclusions and recommendations are made regarding: static stability, the required power of the tug hook and the state of the sea when towing the caisson.
5. Recommendations have been made to ensure achievement of desired structural characteristics and requirements have been set for the insulation and airtightness of the reinforced concrete, while the structure should be fully implemented in accordance with the changing external temperature and constant impact of aggressive sea water.

Publications related to the thesis

1. Georgiev G., Floating Caisson Type Pneumo-Structure, Proceedings of the Union of Scientists – Varna, Series “Marine sciences”, 2017, ISSN 1314-3379, pp. 53-58 (in Bulgarian)
2. Georgiev G., Method for Preliminary Incision, Leveling of Floating Caisson Type Pneumo-Structure and Pre-stressing of the Ground Base, Proceedings of the Union of Scientists – Varna, Series “Marine sciences (Oceanology)”, 2018, ISSN 1314-3379, pp. 19-25 (in Bulgarian)
3. Palazov A., Georgiev G., Donev V., Pneumo-structures for gravitational hydrotechnical construction, Sustainable Development and Innovations in Marine Technologies – Georgiev & Guedes Soares (eds), © 2020 Taylor & Francis Group, London, ISBN 978-0-367-40951-7, pp. 579-584
4. Georgiev G., Air-Impermeability of Reinforced Concrete Floating Caisson Type Pneumo-Structure, "Science in Service of Society 2017" - Conference of the Union of Scientists – Varna, Varna, October 2019 (in Bulgarian)