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Models of operation processes of bottom trawl under complex impact of abiotic, biotic and anthropogenic factors

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Abstract. In commercial fishing the bottom trawls are recognized as one of the most intensive tools for active use. Bottom trawls seriously impact the benthos in the fishing area. As a result of this impact, the suspended benthos forms extensive tail areas of sediments and dissolved nutrients. In addition, the movement of trawl doors on the ground, as well as the ground rope and cables increase the total resistance and wear of the bottom trawls. Consequently, these factors may cause the negative environmental effects, and lower the efficiency and safety of the bottom trawl system and its fishing operations, which can contribute to greater emissions of nitrogen oxides, sulfur oxides and greenhouse gases. At the initial stage of development of bottom trawl systems, the primary task is to draw up a list of operational requirements that the bottom trawl will satisfy. Generally, the list of these requirements includes functional requirements, i.e. a list of quantitative indicators of the fishing object to which the bottom trawl is directed, indicators of special fishing conditions and restrictions under which fishing is performed, indicators of environmental friendliness of fishing, energy costs, etc. Understanding these processes allows the development of performance requirements that bottom trawls can fully meet. Models of the operation processes of the bottom trawl complex have been developed, taking into account the complex influence of abiotic, biotic and anthropogenic factors, and the impact of the human factor on the control systems of the trawl complex. Within the framework of our research, a quantitative and a qualitative assessment of the physical impact of the above factors on the elements of bottom trawl systems used in the fishery.

Keywords: bottom trawl, abiotic factor, biotic factor, anthropogenic factor

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Научная статья

Модели процессов эксплуатации донного трала с учетом комплексного влияния абиотических, биотических и антропогенных факторов

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Аннотация. В промышленном рыболовстве донные тралы признаны как орудия рыболовства активного использования, наиболее интенсивно влияющие на экосистему. Донные тралы серьезно воздействуют на бентос, который обитает в районе промысла. В результате этого воздействия бентос во взвешенном состоянии образует обширные шлейфы из отложений и растворенных питательных веществ. Кроме того, движение траловых досок по грунту, а также грунтропа и кабелей увеличивает суммарное сопротивление донных тралов и износ этих деталей. Следовательно, могут возникнуть негативные последствия для окружающей среды с совокупным влиянием на эффективность и безаварийность донной траловой системы и промысловых операций с ней, что может увеличить выбросы оксидов азота, оксидов серы и парниковых газов. На первоначальном этапе разработки донных траловых систем первостепенной задачей является составление перечня эксплуатационных требований, которому донный трал должен будет удовлетворять. В общем случае список данных требований включает функциональные требования, т. е. перечень количественных показателей объекта лова, на который направлено действие донного трала, показателей особых условий промысла и ограничений, при которых выполняется лов, показателей экологичности лова, затрат энергии и др. Понимание данных процессов позволяет разработать такие эксплуатационные требования, которым донные тралы смогут полностью удовлетворять. Разработаны модели процессов эксплуатации донного тралового комплекса с учетом комплексного влияния абиотических, биотических и антропогенных факторов и воздействия человеческого фактора на системы управления тралового комплекса. В рамках проведенного нами исследования была выполнена количественная и качественная оценка физического воздействия указанных выше факторов на элементы донных траловых систем, используемых на промысле.

Ключевые слова: донный трал, абиотический фактор, биотический фактор, антропогенный фактор

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Introduction

The experts from the World Wildlife Fund (WWF) are convinced that in order to reduce the negative impact of bottom trawling on the marine ecosystem (both within and outside the EEZ) it is necessary to minimize the impact of trawls on bottom ecosystems (a comprehensive assessment of the impact on bottom communities, arranging the areas closed to bottom trawling, reducing the number of trawlers); develop and implement new systems of management and regulation of marine ecosystems [1]. If the bottom trawling process is carried out taking into account the ecosystem approach and meets the criteria of independent certification systems, the WWF will support such fishing. The general fishery policy of the world community is that fisheries are provided in terms of the ecosystem perspective and considering the environmental impact of bottom trawling. Therefore, for the rational and effective management of trawl fisheries it is necessary to quantitatively measure the effect of bottom trawls on the benthos of the reservoir [2-8]. To date, most studies and methodologies for assessing the impact of bottom trawls on benthos differ in the type and trawling equipment. In order to correctly design and operate bottom trawl systems with reduced impact on benthos, it is necessary to take into account their influence at the level of individual elements of the trawl system (trawl doors, trawl doors and cables) and at the level of individual components and types of sediments on the bottom of the reservoir (depth of movement of trawl doors, trawl and cables) shown in Fig. 1.

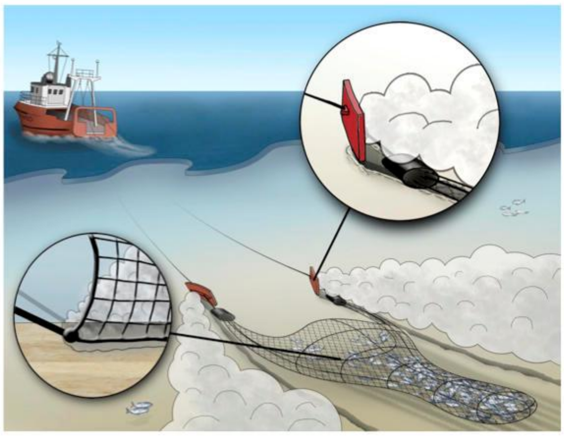


Fig. 1. Bottom trawl system

Bottom trawl system includes bottom trawl, trawl doors, ground rope, rigging, cable line, warps and control sensors.

The movement of trawl doors on the ground, crashing into it, as well as the ground rope and cables, increases the total resistance of bottom trawls and the wear of these parts. Consequently, there may be environmental implications as well as impacts on the efficiency and safety of the bottom trawl system and its fishing operations, which increases emissions of nitrogen oxides, sulfur oxides and greenhouse gases.

Formulation of the problem

An important component of the Strategy for the development of the fishery complex of the Russian Federation is the definition of a policy of sustainable fishing and its implementation through the promotion of competitive, environmentally sustainable and economically profitable fisheries. Indicators relating to the physical impact of bottom trawling on the benthos of the reservoir and to the influence on the habitat and integrity of the seabed will make a particular contribution to the development of sustainable fisheries. Bottom trawl fishing proposals are expected helpful to make decisions about permitted fishing activities. This will allow the fishing industry in the Russian Federation to prepare for and respond to future management measures, modify their bottom trawl systems, develop elements of bottom trawl systems with less impact on the benthos of the water body, and select the appropriate trawl fishing methods. Thus, constant access to fishing areas is provided and environmentally sustainable and economically profitable exploitation of bottom and near-bottom accumulations of aquatic organisms is ensured [9].

When considering any physical and biological systems (bottom trawl systems and fishing objects) it is advisable to distribute all variables that characterize the system or are related to it into three sets as objects of study (Fig. 2):

– input variables U_1, U_2, ..., U_m – characterizing external influences on system inputs;

– state variables X_1, X_2, ..., X_n – internal (intermediate) variables, the totality of which completely characterizes the properties of the system;

– output variables Y_1, Y_2, ..., Y_z, representing those reactions to external influences and those states of the system that are of interest to the researcher.

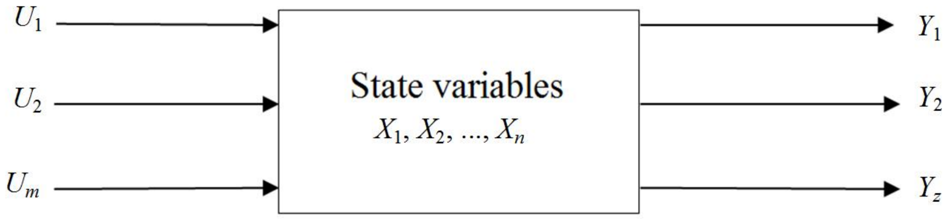
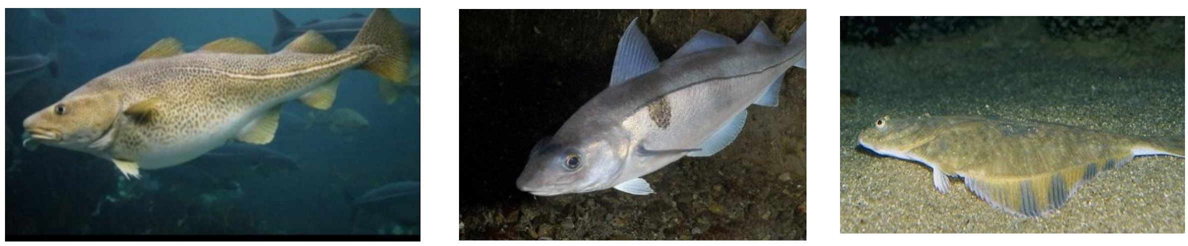


Fig. 2. Input, variable and output parameters of the system

Let us consider abiotic, biotic and anthropogenic factors of influence on the control systems of the trawl complex.

Abiotic factors include all the parameters of the surrounding water-air environment and the bottom of the reservoir that affect the bottom trawl system: depth of the fishing area and the associated water pressure; flow of water masses; wind power; excitement; air and water temperature; presence of ice salinity; transparency; nature and topography of the soil; etc. Abiotic factors are the input parameters of the *U* system (Fig. 2). Input effects *U* depend on many factors of the surrounding water-air environment and the bottom of the reservoir.

Biotic factors include all possible influences that aquatic organisms experience from the surrounding aquatic organisms. In other words, the effect of populations of fish or other organisms on the fishery stock. Restrictions can be imposed on bottom one-time fishing due to the presence of sea animals and birds in the area, a large number of valuable fish species juveniles in the distributed fish schools at the bottom of the reservoir, as well as the distribution of food objects. These factors include the behavior of fish – conditions that determine certain actions in order to survive and protect the offspring: movement speed (throwing, swimming); cluster density; distribution; reaction to stimuli; visibility range; migrations. Fig. 3 shows representatives of the bottom layers of the reservoirs.

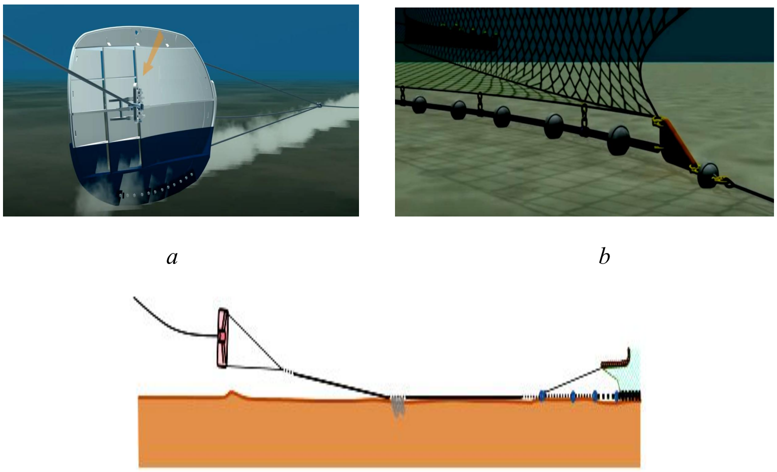


a *b* *c*

Fig. 3. Hydrobionts: *a* – fever; *b* – haddock; *c* – sea flounder

Biotic factors are the variable parameters of the *X* system (Fig. 2). Anthropogenic factors are factors caused by human impact on the benthos of a reservoir. Anthropogenic factors are input and variable parameters *U* and *X* (Fig. 2). The contact of bottom trawls with the seabed can lead to the penetration of elements of the bottom trawl system (trawl doors and ground rope) into the soil, lateral displacement of the benthos and a pressure field transmitted through the benthos (Fig. 4).

Fig. 5 presents a diagram of a bottom trawl system without sensors.



a *b* *c*

Fig. 4. Details of rigging the bottom trawl system that touch and cut into the bottom of a reservoir:
a – trawl door; *b* – ground rope; *c* – cable

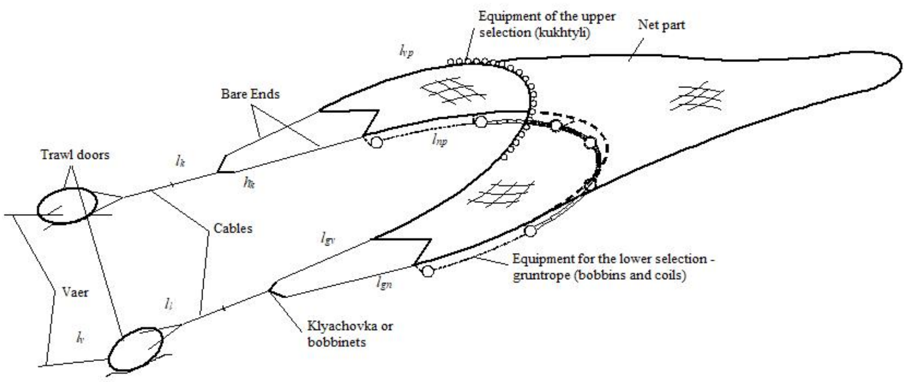


Fig. 5. Scheme of the bottom trawl system (without sensors)

When designing bottom trawl systems, there is always a specific list of performance requirements that bottom trawls must meet. In the general case, the list of requirements includes functional requirements, i. e. a list of quantitative indicators of the object of fishing, to which the action of the bottom trawl is directed, indicators of special fishing conditions and restrictions under which fishing is performed, environmental friendliness of fishing, energy costs, information costs, the value of forces etc. As part of the study, it is necessary to develop models of the operation processes of the bottom trawl complex, taking into account the complex influence of abiotic, biotic and anthropogenic factors, as well as the impact of the human factor on the control systems of the trawl complex. In particular, they include:

– determination of the depth to which the elements of the trawl system (trawl doors, trawl and cables) penetrate the seabed;

– development of predictive models of the physical impact of the elements of the trawl system (trawl doors, trawl and cables);

– determine which elements of the elements of the trawl system have the greatest impact on benthos;

– to determine the influence of the bottom trawl speed v on the soil-dynamic resistance of the elements of the trawl system (trawl boards, trawl and cables);

– prepare proposals for fishers on how to modify their bottom trawls to reduce the impact on the benthos of the reservoir.

Methods

It is possible to control the variable states X_1, X_2, …, X_n of the bottom trawl system by using the autotrawl system [10] to reduce the negative impact on the benthos of the reservoir, but in the absence of sensors for monitoring the bottom trawl system, control is only possible by means of regulating the speed of trawling and length of etched warps, taking into account the experience of the trawlmaster or a captain, trawl probe and sonar readings.

Biotic factors will be considered in the context of the research [11]. The swimming speed of a fish in water is proportional to the frequency and amplitude of its body and tail vibrations and fits into the framework of certain mathematical equations.

To describe the input anthropogenic factors affecting the control systems of the trawl complex there are demonstrated the main parameters of the mechanical properties of soils [12]. It is the mechanical properties of soils that are the basis for determining the output parameters of the bottom trawl system, designing bottom trawls and their elements. Soil characteristics are its features that depend on the composition and relationships between the components. The mechanical characteristics of soils are properties that manifest themselves when loads are applied to the soil. Characteristics serve as initial information and are of great importance for the study and prediction of trawling processes.

To calculate the deformations, the load that the soil can withstand and evaluate the indentation of the elements of the bottom trawl system, as well as the strength of the elements, it is necessary to have data on the mechanical properties of the exploited soils. The mechanical characteristics of soils are influenced by their composition, parameters of the physical state, as well as the features of their structure. The parameters of the physical state include:

– natural humidity (W) is the amount of water that is contained in the pores of the soil in its natural occurrence. This value is the most important natural characteristic of the physical and mechanical state of the soil, which determines the strength;

– soil density ($\rho_{\text{гр}}$) is directly proportional to soil cohesion, which increases with increasing density and affects water permeability;

– modulus of deformation (E) – the value of the forecast of subsidence of the soil. Reflects the response of soils to external load impacts.

For rocky soils, strength is evaluated by the ultimate value of compressive strength in one axis, and for non-rocky soils by their mechanical parameters. The following strength levels are distinguished; super strong – the value is more than 120 MPa; strong – more than 50 MPa, but less than 120 MPa; the average strength index is less than 50 MPa, but more than 15 MPa; low strength – less than 15 MPa, but more than 5 MPa; reduced strength – less than 5 MPa, but more than 3 MPa; reduced strength – less than 3 MPa, but more than 5 MPa; very low strength – less than 1.

Consider the schematization of the movement of the bottom trawl door on the ground (Fig. 5). The first studies in this direction were carried out by P. G. Grewe [13], who found that the soil resistance forces acting on the trawl door significantly exceed the forces of sliding friction and can reach values of the same order as hydrodynamic forces. The most complete data on the characteristics of trawl doors moving along the ground were obtained by V. L. Vedeneev [14, 15]. He also developed a method for calculating the forces of soil resistance acting on the board. This does not take into account the angle of attack, roll and trim.

We introduce the condition of not cutting the trawl door into the soil (minimum impact on the soil of the reservoir):

$$\omega \geq 90^{\circ},$$

where ω – angle between the force vectors F and G_d in the yOx plane,

$$T_o = \sqrt{F^2 + G_d^{\,2}}, \quad (1)$$

where T_0 – tension at the bottom of the warp; F – resultant forces; G_d – weight in water of the trawl door. According to the actions of forces (parallelogram rule),

$$F = \sqrt{T_o^{\,2} + G_d^{\,2} + 2T_oG_d\cos\varphi}, \quad (2)$$

where φ – angle between the force vectors T_0 and G_d in the yOx plane. The horizontal projection of the tension at the lowest point of the warp F is determined by the expression under ω = 90°:

$$F = \frac{R_{x\text{а}} - 2R_{x\text{в}}}{2},$$

where $R_{x\text{а}}$ – aggregate resistance of the trawl system; $R_{x\text{в}}$ – warp resistance.

Fig. 6 shows a schematic movement of the bottom trawl door on the ground.

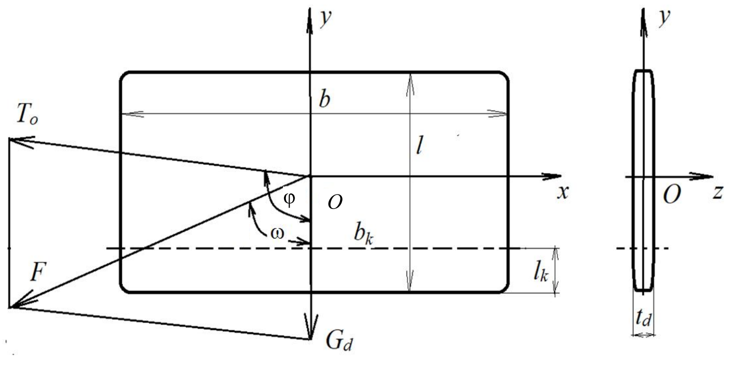


Fig. 6. Schematization of the movement of the bottom trawl door on the ground:
b – trawl door chord; l – sweep of the trawl door; t_d – trawl board thickness;
l_k – sediment of the soil (cutting the trawl door into the soil);
b_k – chord of soil settlement (cutting the trawl door into the soil); T_o – tension at the bottom of the warp;
G_d – is the weight in water of the trawl door; F – resultant forces; φ – is the angle between
the force vectors T_o and G_d in the yOx plane; ω – is the angle between the force vectors F and G_d in the yOx plane

Areas where the trawl door is cut into the ground along the *yOx* and *yOz* axes

$$\left.\begin{aligned} S_{kx} &= b_k t_d \\ S_{ky} &= l_k t_d \end{aligned}\right\}. \tag{3}$$

Let us write down the basic formulas for strength [16]

$$\sigma = \frac{\rho_{\text{гр}} v^2}{c_{\text{гр}} \varepsilon}; \tag{4}$$

$$E = \frac{\rho_{\text{гр}} v^2}{c_{\text{гр}} \varepsilon^2}, \tag{5}$$

where σ – soil strength; E – modulus of soil deformation (in the planes *yOx* and *yOz* E = const); v – trawling speed; $c_{\text{гр}}$ – coefficient taking into account the mechanical properties of the soil; ε – relative compression of the soil.

Mechanical characteristics of the soil in the *yOx* plane

$$\left.\begin{aligned} \sigma_y &= \varepsilon_y E_y \\ \sigma_x &= \varepsilon_x E_x \end{aligned}\right\};$$

$$\varepsilon_y = h/H,$$

where ε_y – is the relative compression of the soil along the *Oy* axis; E_y – soil deformation modulus along the *Oy* axis; E_x – soil deformation modulus along the *Ox* axis; $h = l_k$ – is the depth to which the element of the trawl system (trawl doors, trawl and cables) penetrates into the seabed; H is the thickness of the soil (benthos).

We write (4) as

$$\sigma_y = \frac{G_d}{S_{kx}} = \frac{\rho_{\text{гр}} v_y^2}{c_{\text{гр}} \varepsilon_y}; \tag{6}$$

$$\sigma_x = \frac{F}{S_{ky}} = \frac{\rho_{\text{гр}} v_x^2}{c_{\text{гр}} \varepsilon_x}, \tag{7}$$

where v_y is the rate of subsidence of the trawl door or other element of the trawl system into the ground; v_x – trawling speed; ε_x – relative soil compression along the *Ox* axis.

We write (5) as

$$E_y = \frac{\rho_{\text{гр}} v_y^2}{c_{\text{гр}} \varepsilon_y^2}; \tag{8}$$

$$E_x = \frac{\rho_{\text{гр}} v_x^2}{c_{\text{гр}} \varepsilon_x^2}, \tag{9}$$

since $E_y = E_x$, then from (8) and (9) we get

$$\frac{v_y}{v_x} = \frac{\varepsilon_y}{\varepsilon_x}. \tag{10}$$

From the equations (6) and (7) we obtain, taking into account (3),

$$\frac{\sigma_y}{\sigma_x} = \frac{G_d S_{ky}}{F S_{kx}} = \frac{h}{b_k}\frac{G_d}{F} = \frac{\varepsilon_x v_y^2}{\varepsilon_y v_x^2}. \tag{11}$$

From (11) we find h taking into account (10)

$$h = b_k \frac{F}{G_d}\frac{\varepsilon_x v_y^2}{\varepsilon_y v_x^2} = b_k \frac{F}{G_d}\frac{v_y}{v_x} = b_k \frac{F}{G_d}\frac{\varepsilon_y}{\varepsilon_x}. \tag{12}$$

Based on (11), we obtain

$$\frac{\sigma_y}{\sigma_x} = \frac{\varepsilon_y}{\varepsilon_x} = \frac{v_y}{v_x}. \tag{13}$$

Relations (13) characterize the strength properties of the reservoir soil. Based on the equations (1) and (2) we obtain the value of the angle φ:

$$\varphi = \arccos\left(-\frac{G_d}{T_o}\right).$$

Poisson's ratio μ for the soil of the reservoir along the axes *Oy* and *Ox*

$$\left.\begin{aligned} \mu_y &= \left(1 - \sqrt{\frac{1}{1+\varepsilon_y}}\right)\frac{1}{\varepsilon_y} \\ \mu_x &= \left(1 - \sqrt{\frac{1}{1+\varepsilon_x}}\right)\frac{1}{\varepsilon_x} \end{aligned}\right\},$$

where μ_y – is Poisson's ratio along the *Oy* axis; μ_x – Poisson's ratio along the *Ox* axis.

In the absence of experimental data, the values of the Poisson's ratio can be taken according to 5.4.7.5 of GOST 12248-96: for coarse clastic soils it is 0.27; for sand is from 0.30 to 0.35 depending on the density; for sandy loam is from 0.30 to 0.35 depending on the density; for loams is from 0.35 to 0.37, depending on the density; for hard clay is from 0.20 to 0.30 depending on the density for semi-hard clay is from 0.30 to 0.38 depending on the density; for hard plastic clay is from 0.38 to 0.45 depending on the density; for soft plastic clay is from 0.38 to 0.45 depending on the density; for flowable clay is from 0.38 to 0.45, depending on the density. In accordance with experimental studies [16], a plot of Poisson's ratio for model loams and sandy loams depending on soil moisture was obtained (see Fig. 7).

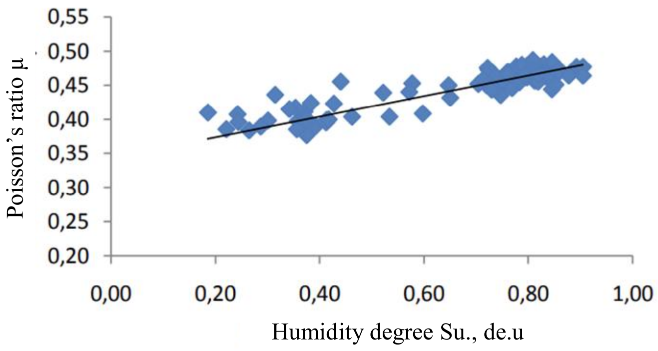


Fig. 7. Relationship between the Poisson ratio and the degree of moisture content of loams and sandy loams

The value of ε_y directly depends on h, whose value is the main factor affecting the benthos of the reservoir. This means that if

$$h \le h_д , \tag{14}$$

where $h_д$ is the allowable depth to which an element of the trawl system (trawl doors, trawl and cables) can penetrate the seabed, provided that the precautionary principle is observed.

The value $h_д$ is determined experimentally for each area where bottom trawling is carried out. Thus, a deviation from the fulfillment of condition (14) will affect the threat of causing serious or irreversible damage to the benthos of the reservoir where bottom trawl systems are operated. For rocky rocks, condition (14) is satisfied. With a known value of Poisson's ratio $\mu_н$ for soils, it is not difficult to determine the value of relative deformation ε_y; also, with a known value of benthos thickness H, it is possible to determine the value of h.

Let us represent the aggregate resistance of the trawl system in the following form:

$$R_{ха} = 2R_{хв} + 2R_{xd} + 2R_{xk} + R_{xo} + R_{xc},$$

where R_{xd} – is the drag of the trawl door ($R_{xd} = R_{xdг} + R_{xdгр}$, where $R_{xdг}$ is the hydrodynamic drag of the trawl door; $R_{xdгр}$ – is the soil dynamic resistance of the trawl door); R_{xk} – cable resistance ($R_{xk} = R_{xkг} + R_{xгтр}$, where $R_{xгт}$ – cable hydrodynamic resistance, $R_{xk} = 0$; $R_{xkгр}$ – cable soil-dynamic resistance); R_{xo} – is the tooling resistance ($R_{xo} = R_{xoг} + R_{xoгр}$, where $R_{xoг}$ – is the hydrodynamic resistance of the tooling; $R_{xoгр}$ – is the soil-dynamic resistance of the tooling) [17].

Movement on the ground of a cable, cable, reel, reel, trawl board or other element of the trawl system is associated with the influence of both the characteristics and characteristics of the soil of the reservoir (soil connectivity, soil density, etc.). An important value that affects the trawling process is the towing speed of the bottom trawl system v.

The value of soil-dynamic resistance of the cable is determined by the expression

$$R_{xkгр} = f_k G_k = f_k q_k l_k ,$$

where f_k – soil-dynamic friction coefficient of the cable; G_k – cable weight in water; q_k – weight in water of one meter of cable; l_k – cable length.

The value of the soil-dynamic friction coefficient of the cable at $f_k \le 1$ indicates that it does not cut into the benthos, only sliding along the ground occurs [18]. Let us consider the process of movement and cutting into the benthos of a cable and a section of soft ground rope in the form of a cable. The process can be considered if the angle of attack of the cable is $0° \le \alpha \le 90°$, the ratio is $25.0 \le q_k / d_k \le 300.0$ N/m^2, where d_k is a cable diameter. The value of the soil-dynamic coefficient of friction of the cable f_k at $q_k / d_k = 300$ N/m^2 and $\alpha = 90°$ reaches the value $f_k = 6$-8, this indicates that at high pressure on the ground and the value of the angle of attack of the cable (cable section) $\alpha = 90°$ the cable is immersed in ground and is towed in the ground, and not on its surface.

The ratio q_k / d_k can be represented as

$$q_k / d_k = \sigma_y ,$$

then expressions (12) and (13) are valid for the cables.

In general, the formula for calculating the soil-dynamic coefficient of cable friction f_k for the conditions: $25.0 \le q_k / d_k \le 300.0$ N/m^2 and $0° \le \alpha \le 90°$ turns into the expression:

$$f_k = e^{0.001\frac{q_k}{d_k}(0.6-5v)} \left(0.023\frac{q_k}{d_k} + 0.33\right) e^{-\left(0.0023\frac{q_k}{d_k}-0.005\right)\left(\frac{\pi}{2}-\alpha\right)^{3.5}} ,$$

where v is the towing speed in m/s.

In accordance with the results of mathematical modeling of the process of cable movement and cutting into benthos, it is proposed to use a cable of different ratios along the length q_k / d_k, taking into account its angle of attack α in the process of bottom trawling. It is important to note that in this case it is advisable to use the parameters of the chain line, the shape of which is the lower line of the bottom trawl [19]. The bottom trawl speed v has a positive effect on the soil-dynamic resistance of the cable, that is, the value of the soil-dynamic coefficient decreases with an increase in the speed of trawling v and cutting into the ground does not occur, but the cable parameters q_k / d_k and α must be taken into account in combination. So, to reduce the cutting of the bottom seine edges, it is advisable to reduce the length of the sagging part, in order thereby to reduce the area of the seabed lost for fishing. The length of the sagging part is the smaller, the heavier the edge. But heavy ropes cut into the ground more strongly, increasing the tension of the edges during hauling. To avoid this, in practice, the cuts are completed from several pieces of ropes of different weights, and the ropes at the net bag should have the smallest weight, and as they approach the ship, the weight of the ropes increases. In this case, the sagging part of the edge of the bottom seine may consist of ropes having different weights in the water. We shall proceed accordingly assembling the central part of the lower headline from the cable with its pressure on the ground $q_k / d_k \rightarrow$ min, the middle part of the half of the ground rope $q_k / d_k \rightarrow$ medium and in the approach to the ends of the lower headline (at the junction of the bare ends) $q_k / d_k \rightarrow$ max, taking into account q_k / d_k value of the bare ends. Thus, the minimum impact of the cables will be on the benthos, provided that the pressure on the soil is minimal, while its deepening characteristic remains.

Fig. 8 shows a diagram of a composite ground rope in the form of a cable (steel cable, Hercules cable, etc.).

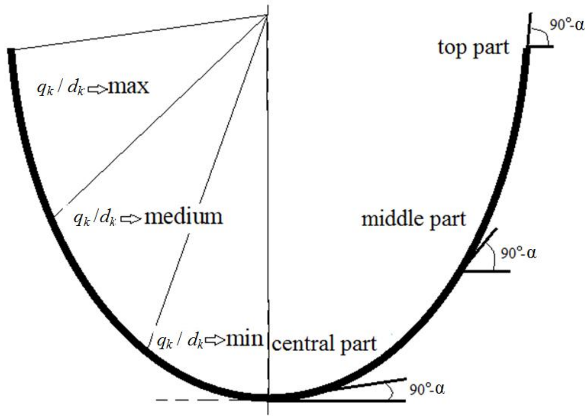


Fig. 8. Scheme of a composite ground rope in the form of a cable

The movement of trawl reels on the ground was studied by G. E. Bidenko [12, 20, 21]. From the results obtained by him, it follows that almost all the spools of the ground trawl do not roll over the ground, but slide along its surface. This nature of the movement is explained by the fact that when the bobbin axis deviates from the normal to the direction of movement by only 2-3°, its rotation stops. In addition, in the process of movement, significant friction forces arise in the bushings of the bobbins and between the bobbins, which also prevent their rotation. By analogy with the movement of a cable, let us imagine the movement of bobbins under the condition of $25.0 \leq G_r / D_r \leq 300.0$ N/m^2, where G_r is the weight of the reel in water; D_r – bobbin diameter. The compression of the soil by the bobbin occurs at significant pressures $G_r / D_r \leq 300.0$ N/m^2.

The ratio G_r / D_r can be represented as

$$G_r / D_r = \sigma_y ,$$

then, expressions (12) and (13) are valid for the bobbins.

Conclusion

In the course of the study, theoretical and experimental data of the Russian and foreign scientists on the effect of cutting into the ground of trawl doors and bottom trawls were analyzed. In the course of the study there have been obtained:

– models of the operation processes of the bottom trawl complex, taking into account the complex influence of abiotic, biotic and anthropogenic factors, and the impact of the human factor on the control systems of the trawl complex;

– theoretical calculations relating the mechanical properties of soils, the characteristics of the elements of the trawl system (trawl doors, trawl and cables), as well as the hydrodynamics of the movement of the trawl system;

– dependence of the depth to which the elements of the trawl system (trawl doors, trawl and cables) penetrate the seabed;

– predictive models of the physical impact of the elements of the trawl system (trawl doors, trawl and cables);

– influence of bottom trawl trawl speed v on the mechanical properties of soils and soil-dynamic resistance of trawl system elements (trawl doors, trawl and cables);

– the influence of the mechanical properties of the reservoir soils on the soil-dynamic resistance of the elements of the trawl system (trawl boards, trawl and cables).

The research revealed:

– soil-dynamic resistance of trawl doors increases as its weight increases;

– the angle of attack, roll and trim of the trawl door affects the soil dynamic resistance, since the coefficient that takes into account the energy for discarding the soil layer depends on the shape of the blade and the properties of the soil;

– the ground-dynamic resistance of the ground-rope parts increases as their weight increases;

– soil-dynamic resistance of the fixed parts of the ground rope is greater than the rolling resistance;

– the dependence of the soil-dynamic resistance coefficient of their cables on elongation, cutting into the ground and the angle of attack and details of the ground rope was obtained;

– the fixed rigging of bottom trawl systems may penetrate the seabed to a lesser depth when they are towed at higher speeds, but when they are rolling there is no such dependence.

Based on mathematical models (12) and (13), it is possible to minimize the impact of the anthropogenic factor on the benthos of the reservoir.

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