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PARAMETRIC METHOD APPLICABLE IN ASSESSING BREAKOUT FORCE AND TIME FOR LIFTING SLENDER BODIES FROM SEABED

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ABSTRACT

The article presents a parametric method applicable in assessing the suction force of a slender body to the seabed, and prognosing the body extrication time. Along with the body weight in water, the information on the suction force is essential for assessing the force needed to lift the object from the seabed. Based on the Foda theory and the resulting integral equation, which relates the maximum suction force with basic parameters of the issue of concern, the parametric method has been developed which can be widely applied in engineering practice of lifting objects. A set of discrete values of parameters selected from the range of typical values for engineering practice was the basis for developing algebraic formulas approximating the integral Foda equation for slender bodies. The included results of tests present the variability of suction force characteristics and the envelopes of maximum forces needed to extricate the body from the seabed.

Keywords: lifting objects from the seabed, breakout force, force needed to extricate the object from the seabed

INTRODUCTION

The engineering practice in lifting objects from the seabed, such as a sunken shipwreck, a submarine, of a ballast anchor, for instance, reveals that the force needed to extricate the object from the seabed can be a multiple of its weight in water. The knowledge of this phenomenon and physical relations which describe it, along with the ability to predict the force, speed, and time needed to extricate the object from the seabed, is a useful tool in both preparing the recovery procedure and selecting necessary instrumentation.

The empirical observations quoted in [4] and [10], and experimental tests reported in [1] and [2] for instance, give the evidence that the phenomenon of object sucking to the seabed results from local pressure differences appearing in water and in the porous seabed soil when the object is extricated from the seabed.

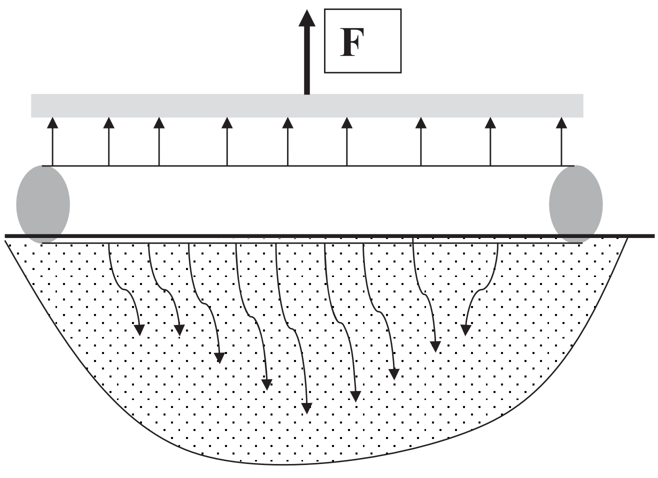

Fig. 1 Conceptual sketch of the phenomenon of slender body extrication from porous seabed

The shape of the contact surface between the body and seabed is frequently slender and elongated, with the contact length much larger than width. This is the case of a sunken shipwreck, a pipeline laid on the sea bottom, or a submarine resting on the seabed. Preparing a relevant lifting procedure requires determining the force needed to extricate the body from the seabed and predicting the time duration of the entire operation. The shape of the body/seabed contact surface affects considerably the exact value of the acting suction force. The pressure distribution on this surface is different in the case of a slender body than for an axisymmetric object, due to different ratios between surface circumference and area, and different volumes of water inflowing over the edge to the space under the body during the pressure balancing process when the body is extricated from the seabed.

Due to specific geometric configuration, methods to determine the extrication force for axisymmetric objects, such as [3], [5], [9], and [10], for instance, are of very limited use for prognosing the suction force for a slender body. The elongated shape of the body requires a method which will take into account specific boundary conditions for this type of body/seabed contact surface. This requirement is considered in the Foda theory [3].

PURPOSE AND SCOPE

Methods to determine forces needed to lift an object resting on the seabed are either simple and based on empirical data, at the same time neglecting important aspects of the phenomenon, or take into account many essential parameters at the expense of higher complication of the mathematical model, for instance [3], [4], [9], and [12], with resulting difficulties in assessing parameters important in engineering practice.

The cognitive purpose of the study presented in this article was assessing and testing the characteristics of forces generated during extrication of a slender body from the seabed. These forces are related with the phenomenon of water suction from porous seabed structure during body extrication, with the resulting pressure drop in seabed structure pores. The study was based on the analytical theory formulated by Foda [3] for slender bodies.

The formulated practical goal consisted in developing a useful method to determine parameters of lifting a slender body from the seabed. This method was expected to have a form of a simple mathematical model with accuracy comparable with theoretical methods, and thus be easily applicable in engineering practice. The presented method refers to objects with elongated shapes, when the length of the object/seabed contact is larger than its width. The determined extrication force is the force value per unit length of object/seabed contact.

The applicability of the method is limited by the range of the assumed parameters of the examined phenomenon, including the shape and dimensions of the lifted body, the extrication speed, as well as the degree of saturation and elasticity of the seabed structure. The values of these parameters affect considerably the final values of extrication force and time.

Beside the extrication force, when assessing the total force needed to lift an object from the seabed, the object weight in water should also be determined. However, this is a separate issue going beyond the scope of the present study. Its detailed description can be found in [7], among other publications. The prognostic value of the Foda theory, which can predict the appearance of a breakout phenomenon, well-known from practice, was the motivation for the present attempt to bring the theory closer to practical applications.

REVIEW OF CURRENT KNOWLEDGE ON THE SUBJECT

The force needed to extricate a body from the seabed can be assessed using empirical relations, such as the Poinc formula [7], for instance, which defines the relation between the force needed to extricate the object from the seabed and the weight of the object in water – depending on the type of seabed soil. In the Poinc formula, the suction force only depends on the type of seabed and the object weight in water, which is a major simplification, as both practical experience and performed experiments show that the in-depth structure of the seabed, as well as the speed and time of extrication, affect considerably the required final value of the extrication force and are mutually dependent.

It results from the laboratory tests performed by Basinski [1], [2] that the extrication force – directed opposite to the suction force – can reach a large value, which is also confirmed by reports from excavation works [8], [11]. Basinski examined objects with circular shapes and diameters of up to 30 cm, at different soil grain sizes. The phenomenon of object extrication from granular soil during the suction force action phase was explained by Basinski as follows. The applied external lifting force reduces the pressure under the rigid body base with respect to the surrounding hydrostatic pressure. The distribution of pressure drop under the object base is non-uniform when the object rests freely on the soil surface, and is uniform when it is embedded into the soil. The pressure drop caused by the object motion propagates into the soil, and the created pressure gradient initiates the flow of water in soil pores.

At object edges, the pressure difference makes that the water flows faster under the object base, as a result of which the soil becomes more liquefied and is washed out. The water flow generates relatively large forces of inertia of the accelerated water masses and friction forces between water particles moving up and soil grains, all this leading to the reduction of soil cohesion and lifting up of part of soil grains. With the increasing gap between the rigid body base and the soil, the resistance of motion in the gap decreases and the amount of water flowing through it increases.

Theoretical analyses of this phenomenon are based on the concept of boundary layer in porous medium. It is assumed that in direct vicinity of the seabed surface, the dynamics of motion of the water filling the soil pores differs from that inside the soil. This assumption is justified by the fact that the value of the suction force depends on the speed of extricating the object from the seabed, as well as on the type and cohesion of the soil, the saturation degree, the geometry and dimensions of the object, and the depth of object embedment into the soil.

When analysing pressure changes in relation with the speed of body extrication from the seabed, Sawicki [9], [11], [12], three phases of the extrication phenomenon can be named. In the first phase, which lasts until the stability loss of the soil structure skeleton, the breakout force is mainly composed of adhesive and cohesive forces acting on the contact surface between the extricated body and the soil. In the second phase, which starts when the soil stability is lost, the dominating force is the resistance of the water flowing through the soil, while in the third phase – the resistance of the water flowing through the gap between the object and the seabed.

Foda [3] has proposed mathematical models of object extrication from seabed for both axisymmetric and slender bodies. After adopting a number of simplifying assumptions, he developed equations describing the pressure drop between the seabed structure and the extricated object during object motion initiation. Making use of Biot's theory about properties of flows in porous-elastic bodies and the Darcy's law, the author derived formulas describing the resultant force of object suction to the bottom of water reservoir. The obtained solutions referred to axisymmetric objects (with vertical symmetry axis) and slender bodies. The Foda theory and the resulting solutions reveal good prognostic properties. Among other aspects, they can predict the so-called breakout phenomenon, well-known from practice, which consists in the appearance of maximal breaking force after some time from the beginning of object detachment from the seabed, after which soil liquidation and fast decrease of sucking force take place. A detailed analysis of assumptions made and results obtained by Foda [4] was done by Mei et al. [7] who raised the issue of specific assumptions in the model describing the soil structure and the shape of the object/soil contact surface.

CONCEPT AND RESULTS OF THE STUDY

COGNITIVE ASPECT

The prognostic value of the Foda method [4] has justified initiating a systematic simulation study to develop an approximation model based method with much simpler mathematical structure than the original integral Foda equations, Eq. (1) or Eq. (2). This method could be easily applicable in engineering practice. Promising results of application of original Foda equations for practical calculations have been reported in [8], while experiments designed to verify the Foda theory have been conducted by Liu [4]. Unfortunately, the results of those experiments were only presented as an internal report and are not widely available.

The Foda theory is based on the assumption that the seabed soil has a porous structure and consists of linearly elastic (porous) skeleton with small channels filled with water. When the object starts moving, the water is sucked from these channels and flows into the space between the seabed and the object bottom. The seabed structure is modelled as a porous body filled with compressible liquid, the properties of which are defined by the volumetric pore fluid's bulk modulus β with values depending on the saturation degree of the pores. The elasticity of the porous body is given by its shear modulus G; the value of which decides about the time of beginning of porous structure destruction caused by pressure drop [13]. The other important parameter is the seabed soil porosity coefficient n, which was assumed constant.

According to the Foda theory [4], for the motion with nonuniform extrication speed, the force F with which a slender body is sucked to the seabed soil is given by Abel's differential-integral equation:

$$F(t) = 2 \cdot b \cdot \alpha \cdot \int_0^t \left[1 - \frac{\tanh(f_o \cdot b)}{f_o \cdot b} \right] \cdot \left(\frac{d\Delta}{d\tau} \right) \frac{d\tau}{(t-\tau)^{1/2}} \quad (1)$$

For body extrication with uniform speed w, the time-history of the extrication force $F(t)$ related to the length of body adherence trace is given by the integral equation:

$$F(t) = 2 \cdot b \cdot \alpha \cdot w \cdot \int_0^t \left[1 - \frac{\tanh(f_o \cdot b)}{f_o \cdot b} \right] \cdot \frac{d\tau}{(t-\tau)^{1/2}} \quad (2)$$

$$\alpha = \frac{1+m}{m} \cdot \left[\frac{\frac{G}{k}}{\pi \cdot m \cdot (1 - 2 \cdot \nu) + \frac{\pi \cdot (1 - 2 \cdot \nu)}{2 \cdot (1-\nu)}} \right]^{\frac{1}{2}} \quad (3)$$

The following symbols are used in the above equations:

$$f_o = \left(\frac{6 \cdot \mu}{\alpha \cdot w^3} \right)^{\frac{1}{2}} \cdot t^{-\frac{7}{4}}; \quad m = \frac{n \cdot G}{(1 - 2 \cdot \nu) \cdot \beta}; \; k = \frac{\beta}{\gamma} \quad (4)$$

Nomenclature and adopted values of parameters:

	time;
w	speed;
b	half beam of the object;
Δ	displacement distance;
β	pore fluid's bulk modulus,
$G = 10^7$ N/m^2	shear modulus of seabed soil;
$k = 10^{-10}$ m^{3}s/kg	soil permeability coefficient;
$n = 0.3$	soil porosity coefficient;
$\mu = 1.325$t/(m·s)	water viscosity;

$\gamma = 10^4\ \mathrm{N/m^3}$ specific weight of water;

$m = 0.9$ ratio of solid skeleton elasticity to fluid elasticity;

$\nu = 0.333$ Poisson's ratio of solid-fluid system;

The following ranges of parameters were considered interesting from the point of view of engineering practice and used in the study:

– set of object widths (base beams):

$$B \in \{1.00\ \mathrm{m},\ 5.00\ \mathrm{m},\ 10.00\ \mathrm{m}\};$$

– set of uniform extrication speeds:

$$w \in \{10^{-3}\mathrm{m/s},\ 10^{-4}\mathrm{m/s},\ 10^{-5}\mathrm{m/s},\ 10^{-6}\mathrm{m/s}\};$$

– set of pore fluid's bulk moduli [12];

$$\beta \in \{10^7\ \mathrm{N/m^2};\ 10^9\ \mathrm{N/m^2}\};$$

For different combinations of parameters from the above sets, solutions to Eq. (2) were obtained using numerical methods, thus giving a set of discrete values of suction force $F(t)$ and gap size $d(t)$:

– $F_i(t) = f(B_i, w_i, \beta_i, t)$;

– $d_i(t) = f(B_i, w_i, \beta_i, t)$;

Graphic representations of the obtained results are given in Fig. 2, Fig. 3 and Fig. 4. In the diagrams, red lines refer to speed $w = 10^{-3}\mathrm{m/s}$, blue lines to $w = 10^{-4}\mathrm{m/s}$, green lines to $w = 10^{-5}\mathrm{m/s}$, and claret lines to $w = 10^{-6}\mathrm{m/s}$. Changes of the presented force characteristics range over several orders of magnitude, therefore these representations are shown in graphs with log scales.

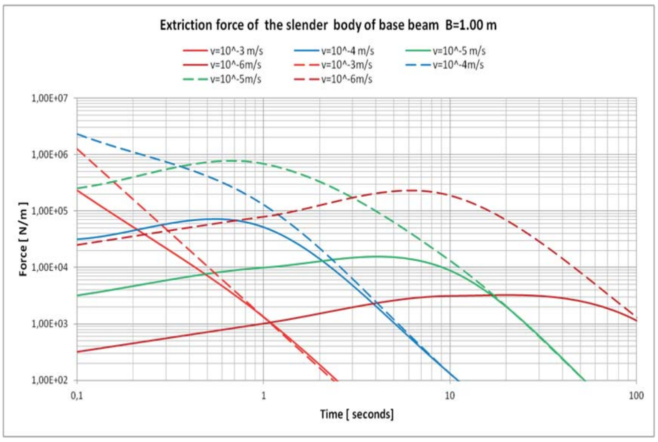

Fig. 2. Extrication force characteristics for $B = 1\ \mathrm{m}$; $\beta = 10^7\ N/m^2$ and $\beta = 10^9\ N/m^2$

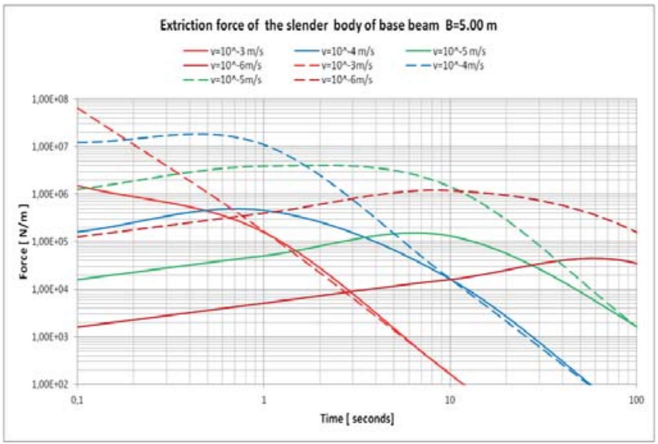

Fig. 3. Extrication force characteristics for $B = 5\ \mathrm{m}$; $\beta = 10^7\ N/m^2$ and $\beta = 10^9\ N/m^2$

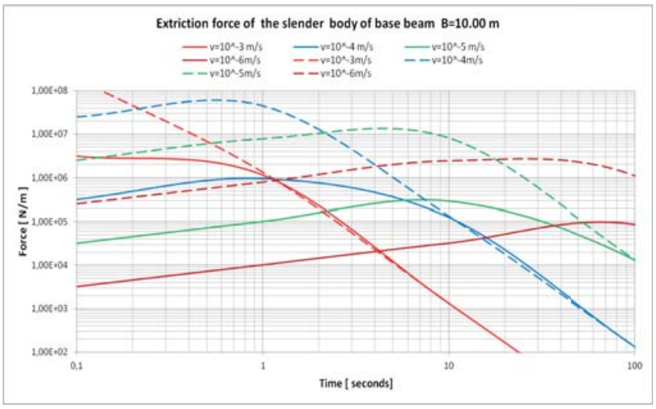

Fig. 4. Extrication force characteristics for $B = 10\ \mathrm{m}$ $\beta = 10^7\ N/m^2$ and $\beta = 10^9\ N/m^2$

Solid lines in Fig. 2, Fig. 3 and Fig. 4 represent suction force characteristics expressed as functions of object extrication time and refer to the case when the volumetric water's bulk modulus in the porous structure is equal to $\beta = 10^7\ \mathrm{N/m^2}$, which corresponds to saturation degree of 99%. The suction force increases with the increasing extrication speed. In each case, its maximum value, often referred to as the "*breakout force*" $F_{\max}$, can occur either at the beginning of body motion, or after the "*breakout time*" T_{break}. The former case takes place at higher extrication speeds (here: $w = 10^{-3}$ m/s), while at lower speeds, (here: $w = 10^{-6}$ m/s) the maximum force appears later.

Dashed lines in the graphs represent the extrication forces when the volumetric water's bulk modulus in the porous structure is $\beta = 10^9\ \mathrm{N/m^2}$, which corresponds to saturation degree of 100%. The increase of the saturation degree from 99% ($\beta = 10^7\ \mathrm{N/m^2}$) to 100% results in the increase of the extrication force $F_{\max}$ by as much as two orders of magnitude.

It results from both the Foda theory, and the performed simulations that after the appearance of the maximum value $F_{\max}$, the suction force clearly decreases, due to the destruction of the porous structure and loss of its stability expressed by the shear modulus $G = 10^7 \text{ N/m}^2$, which corresponds to the seabed being a mixture of sand and silt [13]. The pressure drop-caused destruction of the seabed skeleton structure means its fluidisation and the beginning of intensive extrication motion. The performed simulations have revealed that this beginning time depends on both the extrication speed w and the G/β ratio, expressed by the parameter m in Eq. (4).

A practical conclusion from the obtained results is that the object excavation should be preceded by detailed examination of the saturation degree of the seabed structure [9], which is an essential condition for correct prognosis of the force needed to lift the object from the seabed.

PARAMETRIC METHOD

The maximum value of the suction force (the "*breakout force*") $F_{\max}$, and the breakout time T_{break}, after which this force occurs depend on object dimensions and the extrication speed. The values of these two quantities were determined from the equation being the precondition for the existence of extremum of suction force characteristic:

$$\frac{dF(t)}{dt} = 2 \cdot b \cdot \alpha \cdot \frac{d}{dt}\left\{ w \cdot \int_0^t \left[1 - \frac{\tanh(f_o \cdot b)}{f_o \cdot b} \right] \cdot \frac{d\tau}{(t-\tau)^{1/2}} \right\} = 0 \quad \textbf{(5)}$$

The solutions to Eq. (5), obtained in the form of sets of discrete extreme values:

- $T_{breaki} = f(B_i, w_i, \beta_i)$;
- $F_{\max i} = f(B_i, w_i, \beta_i, T_{break\,i})$;

were approximated with continuous functions of simple mathematical form, convenient for practical calculations. The adopted measure of accuracy of a given approximation was the sum of squares of relative mean errors. After testing selected approximation formulas, the following results were obtained.

For $\beta = 10^7 \text{ N/m}^2$, the best approximation of the breakout force $\mathrm{F}_{\max}$ characteristic is given by the relation:

$$approx\,\mathrm{F}_{\max} = 331 \cdot w^{0.57} \cdot \left(B^{0.142} - \ 0.041\right)^{8.76} \quad \textbf{(6)}$$

For $\beta = 10^9 \text{ N/m}^2$, the best $\mathrm{F}_{\max}$ approximation is given by:

$$approx\,\mathrm{F}_{\max} = 7665 \cdot w^{0.6} \cdot \left(B^{1.22} - \ 1.38 \cdot w + 0.57\right)^{1.16} \quad \textbf{(7)}$$

For $\beta = 10^7 \text{ N/m}^2$, the best approximation of the breakout time $T_{\max}$ characteristic is given by the relation:

$$approxT_{break} = 0.087 \cdot w^{-0.86} \cdot B^{0.564} \quad \textbf{(8)}$$

For $\beta = 10^9 \text{ N/m}^2$, the best $T_{\max}$ approximation is given by:

$$approxT_{break} = 0.024 \cdot w^{-0.86} \cdot \left(B^{0.81} + 2.5 \cdot w + 0,045\right)^{0.72} \quad \textbf{(9)}$$

In Eq. 6÷9, the extrication speed w is expressed in [mm/s], and object width (base beam) B in [m]. The obtained breakout force $approx\,\mathrm{F}_{\max}$ is given in [kN/m], and the breakout time T_{break} in [s].

Graphic representation of the approximated breakout force $approx\,\mathrm{F}_{\max}$ is shown in Fig. 5,

- solid lines represent envelopes of base beam-dependent maximal forces $F_{\max}$ for $\beta = 10^7 \text{ N/m}^2$;
- dashed lines represent envelopes of base beam-dependent maximal forces $F_{\max}$ for $\beta = 10^9 \text{ N/m}^2$;
- dotted lines represent the breakout time T_{break} of occurrence of the breakout force $F_{\max}$ when $\beta = 10^7 \text{ N/m}^2$.

Fig. 5 Characteristics of breakout force $F_{\max}$ and corresponding breakout time $T_{\max}$

SAMPLE METHOD APPLICATION

The breakout force $F_{\max}$ and the breakout time T_{break} are to be assessed for the case of rectangular plate extricated from the seabed. The plate/seabed contact dimensions are: width $B = 2.40$ m and length $L = 10.00$ m. The assumed extrication speed is $w = 0.001$mm/s, while the pore fluid's bulk modulus β takes the values of $\beta = 10^7 \text{ N/m}^2$ and $\beta = 10^9 \text{ N/m}^2$.

For $\beta = 10^7 \text{ N/m}^2$:

$$\mathrm{F}_{\max} = L \cdot \left[331 \cdot w^{0.57} \cdot \left(B^{0.142} - 0.041\right)^{8.76} \right] =$$

$$= 10 \cdot \left[331 \cdot 0.001^{0.57} \cdot \left(2.4^{0.142} - 0.041\right)^{8.76} \right] \cong 140 \text{ kN}$$

This maximum suction force will occur after time T_{break}:

$$approxT_{break} = 0.087 \cdot w^{-0.86} \cdot B^{0.564} = 0.087 \cdot 0.001^{-0.86} \cdot 2.4^{0.564} \cong 55 \text{ s}$$

For $\beta = 10^9\ \mathrm{N/m^2}$:

$$F_{\max} = L \cdot \left[7665 \cdot w^{0.6} \cdot \left(B^{1.22} - 1.38 \cdot w + 0.57 \right)^{1.16} \right] =$$

$$= 10 \cdot \left[7665 \cdot 0.001^{0.6} \cdot \left(2.4^{1.22} - 1.38 \cdot 0.001 + 0.57 \right)^{1.16} \right] \cong 5150\ \mathrm{kN}$$

This maximum suction force will occur after time T_{break}:

$$approxT_{break} = 0.024 \cdot w^{-0.86} \cdot \left(B^{0.81} + 2.5 \cdot w + 0.045 \right)^{0.72} =$$

$$= 0.024 \cdot 0.001^{-0.86} \cdot \left(2.4^{0.81} + 2.5 \cdot 0.001 + 0.045 \right)^{0.72} \cong 2\ \mathrm{s}$$

The presented method has been developed based on the relations resulting from the theoretical description of the examined phenomenon. This approach is justified by the fact that building upon the results of experiments performed in laboratory conditions with small objects, such as [2] for instance, i.e. at a large scale with respect to real objects, faces certain difficulties, as the laws of similitude for this phenomenon have not been well-defined yet.

The reported results of simulations can make a basis for working out a programme of laboratory experimental tests to define the laws of similitude controlling the body extrication phenomenon, while practical applicability of the presented method consists in fact that these calculations can be performed using a simple calculator.

SUMMARY

The issue discussed in the article reflects the need for research to improve the technology of lifting objects from seabed. This issue gains in importance when considering the ecological threat caused by progressive plating degradation of shipwrecks sunk during World War I and II. A large number of these shipwrecks rest on the bottom of the Baltic Sea. Their tanks contain both oil derivatives and lethal chemicals, all creating an "ecological bomb", especially dangerous for such a small water region as the Baltic Sea. The problem of counteracting this threat is a serious technological challenge for the Baltic coastal states.

The present method to calculate forces needed to lift objects resting on the seabed fills a gap between methods based on simple empirical relations, such as those proposed in [7], and complicated formulas taking into consideration basic theoretical relations, presented, for instance, in [3] and [9].

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