Forces Prediction of Underwater Soil Cutting by Excavating Robots

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ABSTRACT

The paper deals with the problem of forecasting forces, acting on operating devices (blades) of underwater excavating robots in the course of soil cutting, by means of mathematical simulation methods. To this end, the structure of soil underwater cutting process has been represented as three interacting subsystems: operating device, soil medium and water medium. The processes of cutting forces time variations have been formalized for the most probable types of chips formation. The approach under consideration simplifies significantly construction of generalized model for cutting processes and development of software for analysis. Simulating algorithm has been developed in block form, which allows determination of regularities for cutting forces variations, depending on the extent of acting factors influence. Computations error with regard to the basic parameters of the process hasn't exceeded 20 % as compared to that of experimental data.

Use of excavating robots is considered to be necessary for underwater soil excavation, particularly at large depths. So, special emphasis is to be placed on prediction of forces, acting on the blades of such machines in the course of soil cutting. Knowledge of their variation regularities under effect of various factors is required as well.

The processes of soil underwater cutting differ considerably from those typical of on-land surface ones. The factor mentioned should be taken into account, when analysing underwater machines loads. However, acquisition of initial data, required for the analysis, by means of experimental tests and trials of machines prototypes and even their models in underwater conditions proves to be rather complicated and expensive. On the other hand, some experimental data published may be regarded as particular cases. They don't provide the possibility for obtaining generalized refularities of soil underwater cutting processes. In this connection mathematical simulation methods are considered the most preferable for determination of soil underwater cutting forces.

To this end, the structure of soil underwater cutting process may be represented as three interacting subsystems: operating device (blade), soil medium and water medium (Fig.1).

The "soil medium" subsystem may be represented as two subsystems of lower level: "soil chip" and "soil mass" (Fig.2).

Taking into consideration the problems, connected with obtaining information on underwater soils characteristics, minimum amount of data on soil physical and mechanical properties, required for the analysis, has been assumed as sufficient for formalization of mathematical model for "soil medium " subsystem. Two indices selected have been taken as initial data: density, for example, according to the number of dynamic densimeter impacts C and soil moisture content ω .

Using earlier obtained correlations of soils parameters by the initial values of C and ω , the soil type, being characterized by the plasticity number W , may be derived from the following equation:

$$C = \frac{13W + 0,5}{\omega - 0,11} \quad (1)$$

By the number C and the plasticity number W and basing on static ratios soil specific cohesion (in MPa) may be defined as:

$$C_0 = 0,023WC \quad (2)$$

and soil volume weight as:

$$\Delta = 1,15 + 0,076C,\ t/m^3 \quad (3)$$

Shift angle ψ is defined by cutting angles γ and friction angles φ_1, φ_2 with the correction of hydrostatic pressure influence. Friction angles are defined as follows: angle φ_1 is calculated by Coulomb's law, when soil strength characteristics (C and C_0) are known; angle φ_2 is determined from the expression, proposed by Yu.A.Vetrov:

$$\varphi_2 = f_0 \frac{\ln \omega}{A} \quad (4)$$

where f_0 and A are coefficients, depending on the plasticity number.

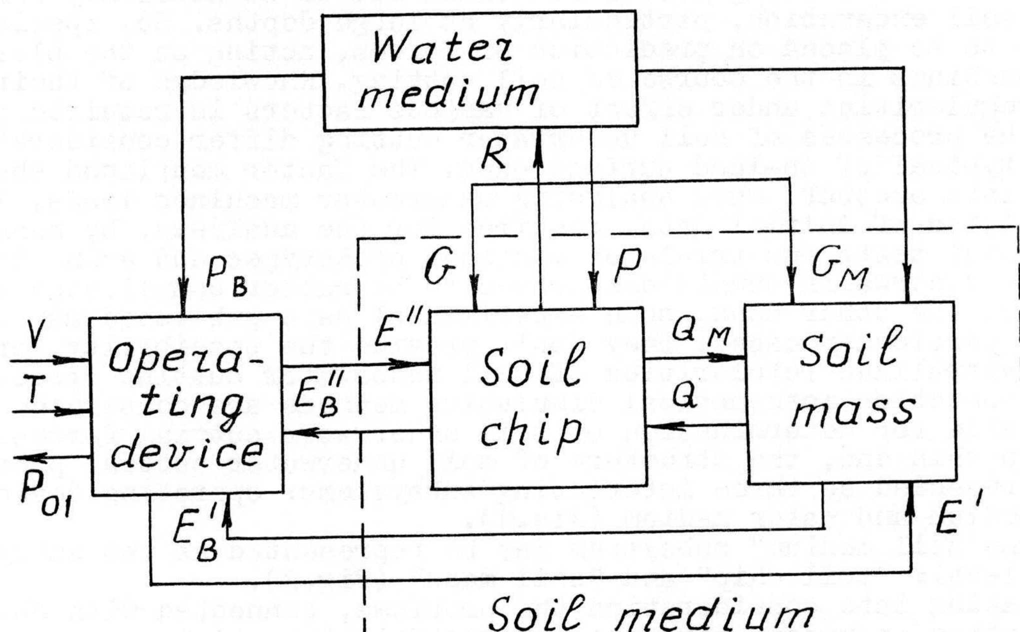

Figure 1. Structural model for the system "operating device" - "soil medium" - "water medium":
$E'(E'_B)$ and $E''(E''_B)$ are forces of operating device interaction with soil; Q (Q_M) are forces of soil chip interaction with soil mass; G and G_M are forces of gravity; P, P_B and P_M are hydrostatic pressure; R is buoyancy force; T is tractive force; P_{01} is tangent component of soil cutting force; v is cutting speed.

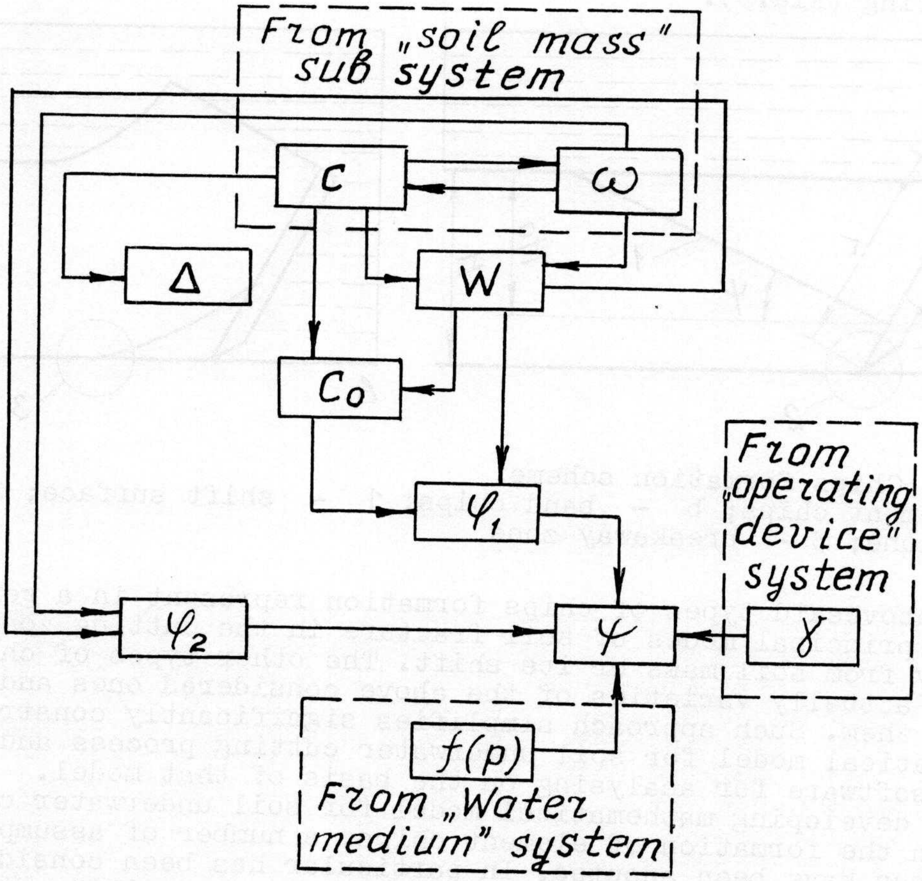

Figure 2. Structural model for subsystem "soil medium": W is plasticity number; C is density according to the number of densimeter impacts; C_0 is specific cohesion; ψ is shift angle; φ_1 is angle of soil internal friction; φ_2 is angle of soil friction against steel; γ is cutting angle; Δ is soil volume weight.

Mathematical simulation of soil underwater cutting processes requires formalization of periodicity for soil cutting forces variations.

Current value of cutting force (tangent component) within time scale t may be generally represented as the following expression:

$$P_{01}(t) = \frac{(P_{max} - P_{min}) \cdot t}{\tau} + P_{min} . \qquad (5)$$

Periodicity of cutting forces variation depends mainly on periodicity of chip elements separation, i.e. on the period τ, which is the function of the cutting speed v, the cutting angle γ and the depth of soil shift zone H_0 (Fig.3):

$$\tau = \frac{2H_0 \varepsilon}{v \cdot \sin\gamma \cdot \cos\gamma} , \qquad (6),$$

where ε is coefficient of proportionality, $0 < \varepsilon < 1$.

As the observations showed, the process of band or element chips formation appeared to be the most probable in the course of soil underwater cutting (Fig.3).

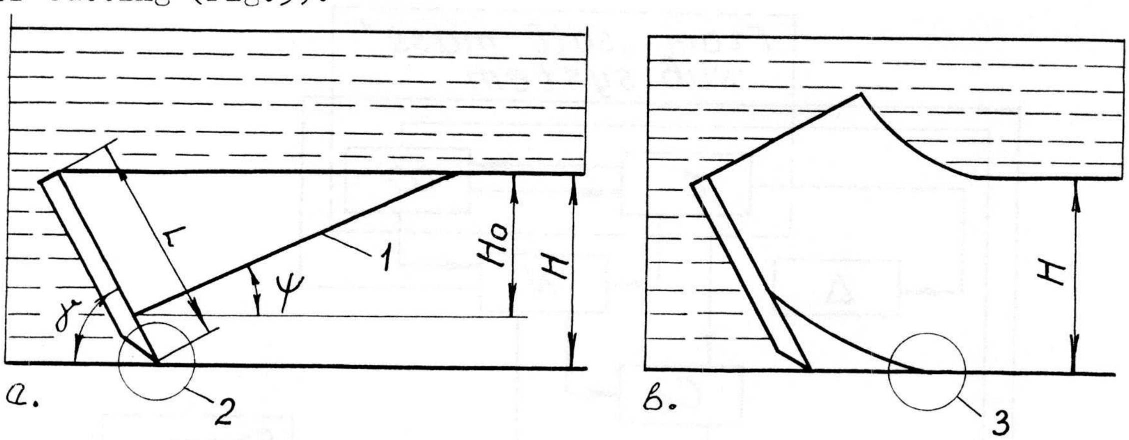

Figure 3. Chips formation scheme
a - element chips; b - band chips; 1 - shift surface; 2 - compression zone; 3 - breakaway zone

The abovesaid types of chips formation represent in a generalized form two principal modes of soil fracture in the cutting zone: stratum breakaway from soil mass or its shift. The other types of chips formation are actually varieties of the above considered ones and are refered to them. Such approach simplifies significantly construction of a mathematical model for soil underwater cutting process and development of software for analysing on the basis of that model.

When developing mathematical model for soil underwater cutting process with the formation of element chips, a number of assumptions and limitations have been adopted. In particular has been considered the process of the so-called "pure cutting", when the cutting depth H and the length of blade front face L have the relationship as: $H = L \sin\gamma$ (plane problem).

Cutting force P_{max} corresponds to the moment of soil limiting stressed state before shift, while cutting force P_{min} conforms to the moment, ensued immediatedly after shift.

Then cutting force for element chips formation is expressed as:

$$P_{01}^{a} = (E' + E'') \cdot \sin(\gamma + \varphi_2) - P_B \cdot \sin\gamma \; ; \qquad (7)$$

$$P_B = p \cdot \frac{H}{\sin\gamma} \cdot B \, ,$$

where p is hydrostatic pressure, MPa ; B is blade width.

Rorce $E''(E''_B)$ (see Fig.1) is obtained from equilibrium condition of forces, acting on "soil chip". At the moment of shift we have P_{max} and

$$E''_{max} = \frac{F \sin(\varphi_1 + \psi) + S \cos\varphi_1}{\sin(\gamma + \varphi_1 + \varphi_2 + \psi)} \qquad (8)$$

where soil cohesion force $S = \dfrac{C_0 \cdot H_0 B}{\sin\psi}$, F is the sum of hydrostatic pressure, gravitational and buoyancy forces, acting on soil chip elements.

After shift at $S=0$ we have E''_{min} and P_{min}. In the soil compression zone there acts the force as:

$$E' = \frac{\sigma (H - H_0) B}{2 \sin\gamma \cos\varphi_2}, \tag{9}$$

where stress is expressed as:

$$\sigma = \frac{2E''_{max} \cos\varphi_2 \sin\gamma}{H_0 B} - P. \tag{10}$$

When developing mathematical model for soil underwater cutting process with the formation of band chips, the soil stratum is assumed as continuous solid body, which length corresponds to that of the blade's front face (see Fig.3).

The blade getting into contact with soil mass and reaching limiting state, stratum breaking off from the soil mass and its lifting by the blade take place. Elasticity force of the stratum being by an order greater as compared to cohesion forces, advance of chip separation (breaking off) from the soil mass occurs. The size of this separation zone depends mainly on the soil strength (specific cohesion C_0), on cutting angle γ, friction angle φ_2 and plasticity number W.

Here, as it is in the case of element chips formation, the blade is in equilibrium under the effect of base machine active forces, hydrostatic pressure, acting on the blade's back face, and soil chips load. In such a case $E'(E'_B)=0$, and force $E''(E''_B)$ is determined by hydrostatic pressure on the chip basic surface P and its end face, by normal pressure from breaking off resistance N_1, bending N_2, force of gravity N_3 and buoyancy force N_4 of soil chip, as well as friction forces, corresponding to them.

The process has been considered under conditions of "pure cutting", which is similar to the former model with element chips formation. Tangent component of soil underwater cutting force for band chips formation is obtained from the following equation:

$$P_{01}^{b} = \left\{ \left[P + N_1 + N_2 + N_3 - N_4 \right] (1 + tg\varphi_2) - P_B \right\} \sin\gamma. \tag{11}$$

Figure 4 shows simulating algorithm for analysis of soil underwater cutting force. It has been plotted in block form on the basis of the above considered models for chips formation process. Block I is for input of initial data and conditions. Block II is designed for computation of cutting minimum force P_{min}. Block III provides computation of soil cutting maximum force for element chips formation. Block IV is designed for computation of cutting force for band chips formation. Maximum values of forces obtained for two types of chips formation are compared in Block V. If P_{max} of element chip is less than P_{01}^{b} of the band one, then calculations are performed using channel Z_1. If P_{max} of element chip is more than P_{01}^{b} of band chip, then channel Z_2 is used. And the last Block VI is designed for results recording and processing.

On the basis of the proposed algorithm for analysis of cutting forces there has been developed a program for computations. Output data of the program are mean and maximum cutting resistance for element chips formation and maximum cutting resistance for band chips formation. Computations error with regard to basic parameters doesn't exceed 15-20 %.

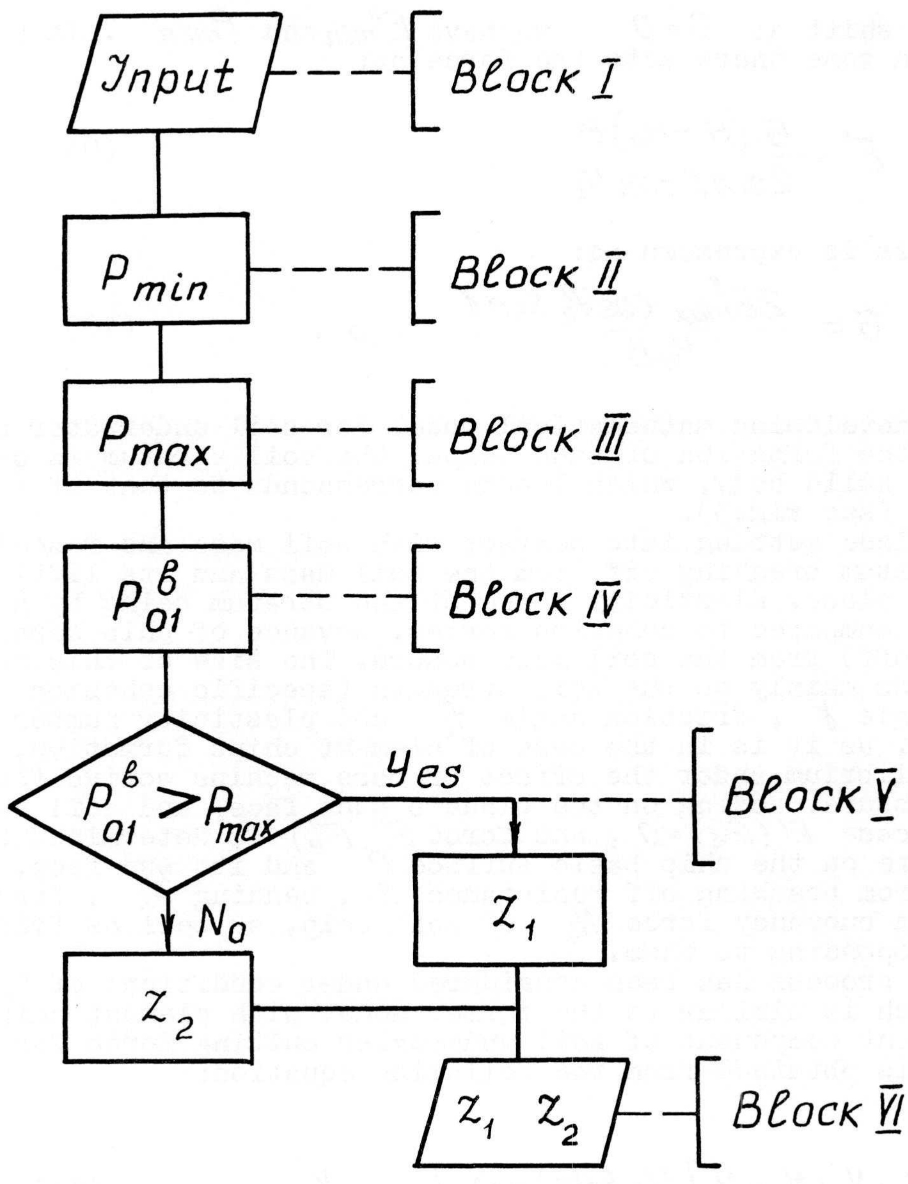

Figure 4. Scheme of simulating algorithm for analysis of tangent component of soil underwater cutting force

Computer-plotted graphs for cutting forces variations in real time, forecasting operating loads in the course of soil underwater cutting at prescribed combination of acting factors are shown in Figure 5.

Simulating algorithms presented and their software are recommended to be used for prediction of soil cutting forces, when designing excavating robots and equipment for application in underwater conditions.

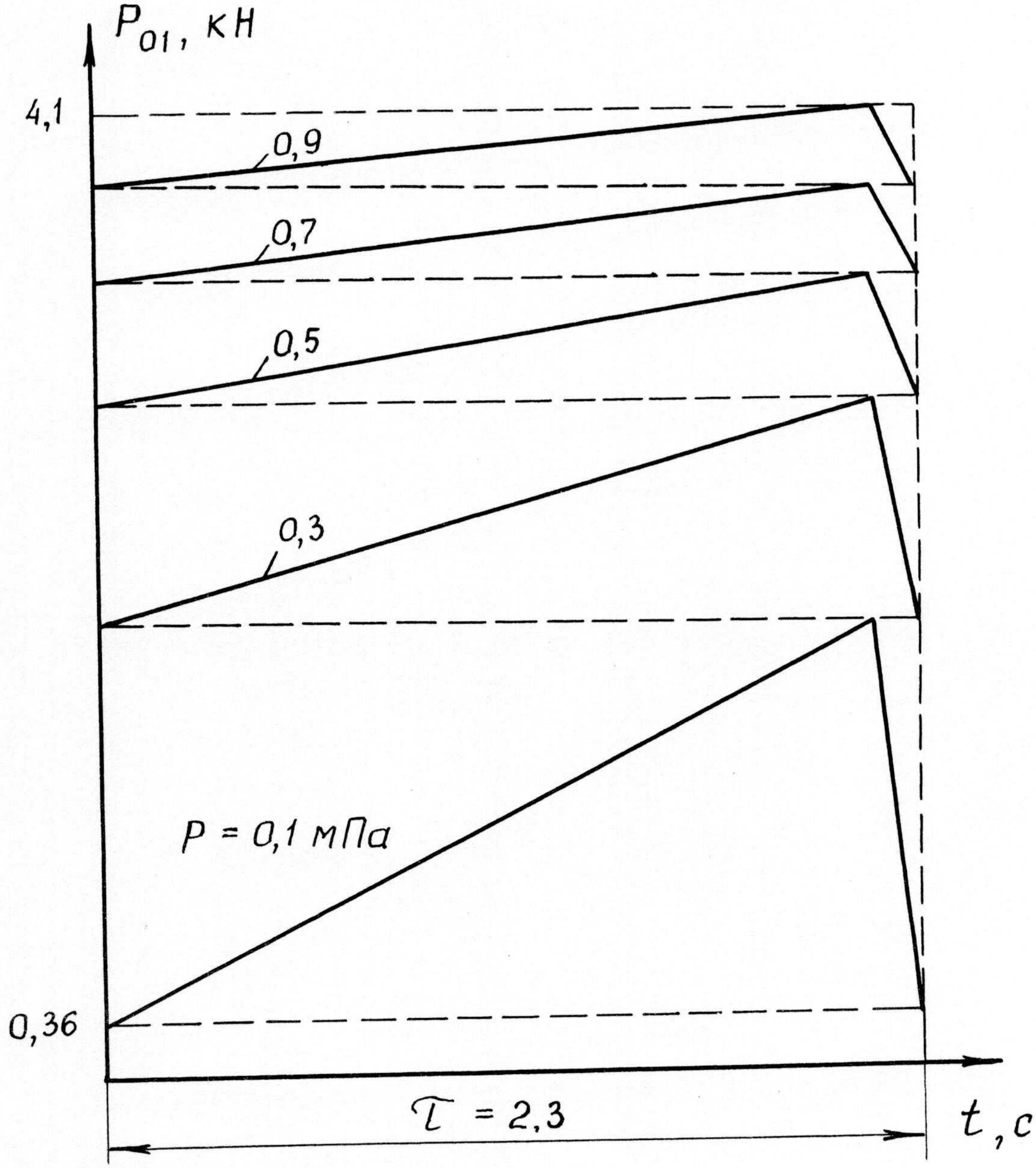

Figure 5. Graphs for soil cutting forces variation for element chips formation, plotted at $\varphi_1 = 29°$, $\varphi_2 = 21°$, $\gamma = 70°$, $H = 7.5$ cm, $C_0 = 0.057$ MPa.