The effects of vibration on viscoplastic dispersion medium by the example of lake sapropels

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Abstract. The paper is devoted to the study of the possible behavior of the sapropel layer under the influence of the vibration mechanism from the standpoint of the analysis of mathematical models of the dynamics of multiphase rheological media under the influence of vibration (amplitude, frequency). The results of the analysis showed that there are different variants of the behavior of particles entering into a multiphase system; changing the amplitude and frequency of oscillations one can produce various effects that are necessary to obtain the material.

Keywords. Sapropel, viscoplastic disperse medium, rheological models, pulp, vibration effect, hydromechanical method, lake.

Introduction

Sapropel is a natural formation, the accumulation of which is accompanied by a negative phenomenon - a reduction, and then the death of water bodies. This process is beginning to take on a swift character. At present, it can already be noted that modern lakes are silted by 50%. In many places, the siltation process has become irreversible. These phenomena negatively affect the general condition of aquatic ecosystems and territories adjacent to them. For example, in the Yaroslavl region, there are 17 lakes containing sapropel, some of them are currently in disastrous condition due to the powerful deposits of sapropel.

As a result of siltation processes, water bodies lose their role as sources of water, fisheries and recreation sites, their hydrological regime worsens and, as a result, vegetation changes, soils turn into swamp and saline, etc.

The development of sapropel deposits of silted sapropel lakes is an urgent task today. The solution to this problem is dictated not only by a shortage of sources of organic fertilizers, but also by the need to restore dying lakes for economic and other purposes.

Methods

A hydromechanical method is widely used for cleaning lakes from sapropels, which is characterized by high productivity and low labor intensity. One of the promising areas of using this method is the extraction of sapropel of plastic consistency, i.e. in a state of natural moisture without diluting it with water. There are various types of working equipment for dredgers that allow this process to be carried out. One of the most modern ones is vibration rippers, which can reduce the viscosity of sapropel and reduce the energy intensity of the processes of extraction and transportation of sapropel.

Sapropels are among the complex dispersed systems. The effect of vibration on dispersed systems can be divided into two phases. In the first phase, structural bonds are destroyed with a decrease in viscosity. In the second phase, particles are moved following the effect of vibration. The intensity of
vibration leads to volumetric and isotropic destruction of the spatial structure [10,11]. The viscosity of sapropel in static conditions differs from viscosity under dynamic effects. The viscosity of sapropel depends on the time of vibration processing, physical and mechanical properties, frequency and amplitude of vibration exposure. When the vibration effect is removed, the properties of the dispersed system are restored. Mathematical modeling of the process of the behavior of dispersed medium under unsteady conditions is necessary to intensify the process of destruction of an array of sapropel deposits and the proper design of soil sampling devices for dredgers, taking into account the rheological properties of sapropel. Let us consider some approaches to modeling such systems.

Research

To study the possible behavior of the sapropel layer under the influence of the vibration mechanism, the analysis of mathematical models of the dynamics of multiphase rheological media under the influence of vibration is of interest.

In nature, there are almost no perfectly elastic materials. The behavior of all materials depends on the time, the loading speed and the magnitude of the applied loads. Usually, there are no dependencies, describing the ratio of physical parameters for such materials and loading schemes, and the expressions obtained on the basis of experimental results are used in practical problems.

The identification and study of the mechanisms of the emergence of various forms of motion of multiphase medium under periodic influences is the subject of direction in the dynamics of multiphase medium (the theory of nonlinear vibrations and the stability of motion of multiphase medium). Its basics are most fully described in [1, 2, 12]. Vibrational impacts generate not only oscillatory, but also unilaterally directed movements of the components of the medium [1, 2, 3]. Besides, the effects determine the appearance in the volume occupied by the multiphase medium of the equilibrium positions of the elements of finely dispersed phases and their stability.

In real conditions, a multiphase medium is always under the influence of some external forces of non-vibrational nature, for example, gravitational ones. The mode of motion of the medium during vibrational influences determines the relationship between these quantities and the values of the latter are determined by the amplitudes and frequencies of the external periodic influences. To create powerful vibrational force fields, resonant effects can be used, allowing even with minor external influences to create vibrational forces that are comparable in magnitude or always superior to external forces of different nature. By selecting rational influences in a certain way, one can strengthen and weaken the effect of vibrational forces. Thus, technological processes occurring under the influence of external forces of a vibrational nature can be significantly intensified. In addition, the specific properties of vibrational forces (heterogeneity of distribution in the volume of the medium, the ability to control by changing vibrational effects, the selective effect on the motion of individual elements of multiphase media) open up great opportunities for creating completely new technological processes [2, 4, 13].

One of the simplest models [1] is the motion of a spherical particle of mass $M$ in a liquid $\xi(t)$ vibrating according to the law. If the particle is completely carried away by the medium, then the force $m\ddot{x}$ acts on it, where $m$ is the mass of the medium in the volume equal to the volume of the particle. When the particle $x(t)$ moves, other than the medium’s motion, some of the latter (the added mass $m_0$) moves with the particle. Therefore, the equation of motion of the particle has the following form:

$$M\ddot{x} = m\ddot{x} - m_0(\ddot{x} - \ddot{\xi})$$

(1)

Integrating the law of motion under the conditions $t = 0, x = 0$, we obtain

$$x(t) = \frac{m + m_0}{M + m_0}\xi(t)$$

We consider the particle to be spherical, and then the added mass for a ball of radius $r$ [5] is:

$$m_0 = \frac{2}{3}\pi\rho r^3,$$

where $\rho$ is the density of the added mass of the medium.

Given the last expression, we can write:
\[ x(t) = \frac{3\rho}{2\rho_m + \rho} \zeta(t), \]  
(2)

where \( \rho_m \) is the medium density.

From equation (2) it follows that the relative motion depends on the density ratio and does not depend on the particle size.

The equation (1) does not take into account resistance to motion and gravity. If we take them into account, then the equation (1) has the form:

\[ M(\ddot{x} + g) = m(\ddot{\xi} + g) - m_0(\ddot{x} - \ddot{\xi}) + F, \]

(3)

where \( g \) is the acceleration of gravity;

\( F \) is resistance to motion.

In the case of a purely viscous resistance \( F = F(\dot{x} - \dot{\xi}) \) for \( M > m \), the particle immerses, and it floats up for \( M < m \).

Fundamentally different dependencies may appear if the resistance force has the nature of dry friction (which is observed in the natural sapropel layer [6]):

\[ F = \begin{cases} 
-f_+ \text{ for } \dot{x} > \dot{\xi}; \\
-f_- \text{ for } \dot{x} < \dot{\xi}.
\end{cases} \]

It was found that the resistance to emersion \( \dot{x} > \dot{\xi} \) is less than when the particle is immersed, i.e. \( f_- > f_+ \). When dry friction forces are present, the particle will move together with the medium \( (x \equiv \xi) \) until:

\[-f_+ \leq (M - m)(\ddot{x} + g) \leq f_- \]

(4)

If equality (4), the mixture will behave like a solid mass. If at least at some points in time the inequality is violated, the picture of the motion becomes more complicated, and mutual displacement (the effect of fluidization) is observed.

Particles are lighter than the medium \( (M < m) \); if fluidization in the case of symmetric vibrations is presented, they will certainly float up. A more complex picture is observed if the particles are heavier than the medium. If the largest amplitude value of the accelerations of symmetric oscillations is large enough to break inequality (4), then not only immersion, but also surfacing particles heavier than the medium is possible.

The latter is a consequence of the difference in the resistance forces to emersion and immersion, and this difference should be quite large. The level of vibration is significantly affected. So, the same particle can both float up and sink at different accelerations.

Rheological models are widely used to describe various media. The behavior of the medium is described using a different combination of elastic, viscous and plastic characteristics [7, 14].

Sapropel is a rather complex medium, and its behavior can be described using the elastic-viscous-plastic model of Bingham or Shvedov [7] (Fig. 1). In this case, the elastic properties of sapropel are modeled by the elastic component \( K_1 \), and the viscous ones are modeled using the elements of viscous resistance \( h_b \) and \( h_{sh} \). The resistance forces of dry friction are taken into account using the coefficient \( K_2 \). In the Shvedov model (Fig. 1b), an additional elastic component \( K_2 \) is used, which allows taking into account temporary changes in the viscous properties.

However, the properties of sapropel vary quite significantly depending on the mechanical composition, humidity, consistency, etc. So, for example, the sapropels of Lake Nero in the Yaroslavl region lose all connectivity and acquire a creamy consistency at humidity over 90%. Solidification of sapropel colloids occurs at humidity about 60% [8]. If humidity is changed from 86% to 80%, its viscous properties also change: the coefficient of viscosity for Shvedova is changed from 0, 4 to 24,5 \( P_s \), and according to Bingham - from 0,2 to 8,6 \( P_s \) [9].
A sharp change in the viscosity of the pulp occurs with increasing concentration of sapropel. So, with an increase in concentration from 1% to 2%, an increase in viscosity from 1 \( P_3 \) to 5.5 \( P_3 \), and with an increase in concentration up to 3%, the viscosity increases to 21.3 \( P_3 \) [8].

The rheological characteristics strongly depend on the type of sapropel, its particle-size distribution and deformation rate.

An analysis of the data [10] shows that with a pulp consistency of < 30 g/l, the dynamic viscosity coefficient practically does not change for all types of sapropel within the deformation rate from \( 2.8 \cdot 10^3 \) to \( 8.3 \cdot 10^3 \) s\(^{-1}\). Moreover, the dynamic viscosity decreases with increasing ash content.

Sapropel pulp is characterized by a wide change in rheological characteristics. An even more complex change in rheological properties occurs in natural sapropels. In addition, these properties are practically unexplored.

The upper layer of sapropel (100 ... 50 mm) in its natural state has a flowing character and humidity more than 90%. It acquires a stronger structure, and its humidity decreases with an increase in the thickness of the sapropel layer [10]. The rheological characteristics also change. These changes have to be taken into account when drawing up mathematical models describing the behavior of the sapropel layer. Moreover, the parameters of the rheological characteristics should be determined from the experiment in each case.

**Conclusions**

1. The dynamics of multiphase rheological systems under the influence of vibration is determined by both the vibration parameters (amplitude, frequency of exposure) and the physical characteristics of the components included in the multiphase system. By changing these parameters, one can obtain various behaviors of the particles that make up the system.
2. The effects described above can be obtained only when the vibrational forces exceed the external forces acting on the particles.
3. When using descriptive mathematical models to study the behavior of sapropel under the influence of vibration, it is necessary to know and take into account the properties of the latter and, in particular, the bonds between individual particles.

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