Theoretical substantiation of low-frequency shock-contact impact as a way to increase the efficiency of ultrasonic drilling of extraterrestrial soil

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Abstract. A physical and mathematical model of ultrasonic destruction and deformation of solid soil has been developed, taking into account the presence of additional influences (low-frequency impact, rotational). The numerical implementation of the model is carried out in the form of a computer program for calculating the process of deformation and destruction of the soil. The presented results of calculations proved the possibility of additionally increasing the efficiency of ultrasonic drilling by more than 2.5 times due to the imposition of low-frequency shock-contact action.

1 Statement of the problem

To study the structure, mechanisms of origin, evolution of space objects and the possibility of their colonization, it is necessary to provide:

1) accelerated fixing of landing modules on objects with low gravity and unknown soil composition;
2) revealing the composition and properties of the soil at various depths.

To date, soil research is carried out either by optical methods (mainly by photographing and analyzing the photographs obtained), or by mechanical sampling of soil.

Optical methods make it possible to study the soil only at the surface and do not make it possible to reveal the composition and properties of the soil at finite depths.

However, to understand the mechanisms of origin and evolution of space objects; to detect the presence of traces of water, organic substances, minerals, metals or energy carriers in order to maintain the vital activity of colonies in the event of global catastrophes on Earth or for the purpose of a more profound study of deep space, it is obviously necessary to investigate the soil at considerable depths.

Since the 60s-70s of the last century, a method of mechanical drilling for fixing the landing module and mechanical sampling of extraterrestrial soil has been known, which consists in screw drilling the soil of a space object to a certain depth for fixing, sampling

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and further delivery of the selected samples to Earth. For example, in 1976, the Soviet station Luna-24 carried out mechanical drilling to a depth of 2.25 m, which led to the discovery of water in the lunar soil, and the development of mechanical drilling devices of the National Astronautics and Space Administration (NASA) is also known ([1] and reports NASA - Planetary Drilling and Resources at the Moon and Mars – NASA; Deep Drill Core. Frozen samples; Synopsis of Deep Lunar Drill Strings // Lunar Sample Compendium, 2007).

However, mechanical drilling also has several disadvantages:

- impossibility of drilling on objects with low gravity for fixing of landing modules to asteroids (due to inertial forces preventing drilling, which exceed gravitational forces);
- high degree of soil heating due to friction forces. Heating is capable of leading to evaporation, sublimation of traces of water and ice, volatile and other useful substances;
- the impossibility of obtaining information about the properties and composition of the soil in real time without the costly delivery of soil samples to the Earth for a detailed study.

In addition, mechanical drilling does not even make it possible to make a preliminary assessment of the structure and composition of the soil in real time, it does not allow preliminary identification of the type of the drilled soil. This is necessary to determine whether further deeper studies of the soil in a given zone of a space object are expedient or not. A preliminary assessment of the type, structure, and composition of soil in real time is especially relevant in the study of distant objects, since aircraft for long-range interplanetary missions have limited energy resources, which do not allow delivering huge volumes of soil from various zones of a space object to Earth.

This implies the relevance of research and development of the physical principles of soil drilling, which provide not only energy-efficient drilling of soil with minimal heating and fast drilling at objects with low gravity, but also soil feedback with a drilling device to ensure the most effective impact on soils of various properties.

Over the past 20–30 years, along with the mechanical method of drilling, the ultrasonic method of drilling the soil of extraterrestrial objects has been successfully developed (the first developments in the physical principles and devices for ultrasonic dimensional processing of solid materials present on Earth date back to the 50s of the last century) [2-5]. The essence of the ultrasonic drilling method is the impact of high-frequency mechanical vibrations (frequency 20...44 kHz) or combined impact (high-frequency vibrations + pseudo-rotation + (optionally) low-frequency impact) on the soil. Vibrations lead to the destruction of the soil. The main feature of such an impact is that the ultrasonic emitter of piezoelectric type, which oscillates, is sensitive to changes in the acoustic properties of the soil.

This provides soil feedback with the emitter and allows a preliminary assessment of the properties of the soil. In addition, this makes it possible to determine the presence of contact between the landing module and the surface of a space object in real time. Information about the presence of contact with the surface of the object will allow more rational use of fuel resources when controlling the main engines of the landing module.

Information about the presence of contact and soil properties also makes it possible to choose the optimal drilling modes that ensure the maximum speed of fixing the landing module on the surface of a small celestial body. And also this information is useful for further study of the structure, evolution and origin of a space object.

To date, a model of the influence of soil properties on the impedance characteristics of an ultrasonic emitter is known, described in [6]. The model made it possible to develop a method for determining the impedance characteristics of the emitter. However, this model does not consider the issue of soil destruction.
The models of soil destruction given in publications [7, 8] are based on empirical data, do not consider the mechanism of the process of crack development in the soil during drilling, and do not take into account the heterogeneous structure of the soil.

The crack development in a heterogeneous solid material was numerically studied in [9, 10]. However, the force impact, which is of a pulsed nature, which takes place during ultrasonic drilling, was not considered.

The proposed model for the crack development in the soil, taking into account the heterogeneity of its structure and the impulsive nature of the force action, is in the next section.

2 Model of crack development in soil under shock-contact ultrasonic impact

The proposed model for the crack development in the soil is based on the following assumptions:

1. Point contact of the ultrasonic emitter with the soil.
2. The force effect from the emitter is carried out perpendicular to the soil surface.
3. The process of crack development is rather slow compared to the oscillatory speed of the ultrasonic emitter (the change in the length of the crack for 1 period of ultrasonic vibrations is much less than the displacement amplitude of the ultrasonic emitter and the soil surface).
4. The crack is flat and the position of the crack plane is determined by the preferred orientation of the symmetry axis of each defect in the soil.
5. The stress intensity factor at the crack tip is determined according to the following expression $K = C \sigma a$, where $\sigma$ is the absolute value of the stress tensor projection onto the normal vector to the soil surface, Pa; $a$ is the most probable radius of a defect in the soil, m; $C$ is a constant coefficient determined empirically.
6. Macroscopic mechanical properties of the soil weakly depend on the length of the crack.

A schematic representation of ultrasonic drilling of the soil is shown in Figure 1.

![Fig. 1. Schematic representation of the process of ultrasonic drilling of soil.](image-url)
Since the macroscopic mechanical properties of the soil weakly depend on the length of the crack, and the process of crack development is rather slow compared to oscillatory processes in the ultrasonic emitter, the equations described in [6] are used to calculate the emitter vibrations.

In turn, the calculation of crack development is described by the model of growth and coalescence of defects, first proposed by K.B. Broberg [9] and subsequently developed by the team of the Institute of Physical and Technical Problems of the North, Siberian Branch, Russian Academy of Sciences (Yakutsk, Russian Federation).

The calculations were carried out at an ultrasonic emitter oscillation frequency of 22 kHz and an oscillation amplitude of the emitter (in the absence of contact with the soil of 50 μm). The calculations were carried out taking into account the pseudo-rotary motion in order to exclude the compaction of drilling waste.

Figure 2 shows the dynamics of the process of crack development over time under ultrasonic action with the absence of low-frequency impacts.

![Crack foundation](image)

Fig. 2. Development of a crack in the soil during ultrasonic drilling with pseudo-rotary motion.

Further, Figure 3 shows the dynamics of crack development when additional low-frequency impacts are applied. Low-frequency impacts are created using a free mass of 0.1
kg, which collides with the plane of the input end of the concentrating link of the ultrasonic emitter. The crack development dynamics is presented on the same scale as in Figure 2.

![Fig. 3. Development of a crack in the soil during ultrasonic drilling with pseudo-rotary motion.](image)

It has been established that the imposition of additional low-frequency impacts leads to a reduction in the time of crack propagation by more than 2.5 times with the same crack length.

### 3 Conclusion

A physical and mathematical model of ultrasonic destruction and deformation of solid soil has been developed, taking into account the presence of additional influences (low-frequency impact, rotational). The numerical implementation of the model is carried out in the form of a computer program for calculating the process of deformation and destruction of the soil. The presented results of calculations proved the possibility of additionally increasing the efficiency of ultrasonic drilling by more than 2.5 times due to the imposition of low-frequency shock-contact impact.

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