The use of jet penetrators for movement in the lunar soil

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Abstract: *The possibility of using penetrators for researching the subsurface layers of the moon is considered. Possible options for launching such penetrators are indicated, from the way the launch is carried out depends on the depth of penetration into the regolith. It was found that when the propulsion system has less traction than the static resistance of the lunar soil, movement does not occur if the launch of the penetrator is accomplished from the surface with zero entry speed. The dependences are given that permit calculating with sufficient accuracy the penetrator mass, penetration depth and the resulting overloads. The depth of penetration of the inertial penetrator depends on its mass-dimensional qualities and the speed of entry into the soil, which is limited by the level of permissible overloads. The use of a solid fuel engine on the penetrator facilitates increasing the allowable speed of the penetrator into the ground by reducing the overloads acting on it, and thereby increasing the penetration depth.*

Key Words: *penetrator, moon, soil, regolith, penetration*

1. INTRODUCTION

To accomplish a number of scientific studies and practical works on the development of the Moon and other planets in order to deliver equipment and other loads to a certain depth, it is necessary to create devices capable of penetrating the sub-surface (regolith). The research of the moon will allow in the future to give answers to fundamental questions of terrestrial origin, the emergence of hydro and atmosphere, the evolutionary development of life. In addition, the moon is considered as an important point in the future energetics. According to various estimates, terrestrial sources of fossil fuels will not be able to cope with the growing needs of energy consumption and production by the middle of the 21st century. One of possible solutions of the problem is associated with the extraction and delivery of helium-3 to Earth [1]. Recent studies show that there are signs of ice at the lunar poles, which means that it can be possible to obtain efficient energy carriers such as hydrogen and oxygen. The availability of these resources allows us to consider the Moon as a fuel station for spacecraft exploring deep space, since the delivery of fuel from Earth is more energy-consuming. And the key role is played by the construction of lunar bases.

As a result, the solution of complex objectives for the study of the Moon, as well as the construction of bases and the organization of production requires performing drilling works to a depth of two to tens of meters. Machines and devices that are widely used for these works in Earth conditions are not suitable for space due to excessive mass-dimensional characteristics. Existing methods [2], [3] suggest movements in the soil that form a well, either by destroying the rock and then transporting it to the surface, or by compacting the soil particles. Mathematical modeling of thermal protection of motion in the ground is considered in works [4], [5], [6].

In this work, penetrators are considered that form a well by compaction and moving in the ground due to both kinetic energy and thrust of a solid propellant rocket engine. The purpose of this study is to assess the possibility of employing reactive penetrators for high-speed penetration into the regolith to a certain depth.

2. METHODOLOGY

The task of determining the optimal launch conditions for a penetrator with specified total, mass, and energy characteristics can be formulated as follows [7] .It is required to find such a set of parameters that set the position of the starting point of the jet penetrator, the moments of switching on and off the engine, the speed of the penetrator when entering the ground and at the time of the remote shutdown, as well as the overload acting on the penetrator, which, when fulfilling the disciplining conditions, linking the parameters and characteristics apparatus and trajectory, reversing the function of the depth of penetration to the maximum. And at the moment of remote activation, the penetrator has a certain speed of movement V_0.

Mathematically, this problem can be represented as follows: determine which H_3, t_{K1}, t_{K3}, V_{K1}, V_{K3}, fulfil the conditions $\varphi_I((H_3, t_{K1}, t_{K3}, V_{K1}, V_{K3}) = 0$, that turn the function $L = L$ (H_3, t_{K1}, t_{K3}, V_{K1}, V_{K3}) to a maximum.

The described problem can be solved with the help of the classical method of indeterminate Lagrange multipliers, when the Lagrange function is compiled separately for each penetration depth depending on the thrust ratio of the engine and the static resistance of the soil and is written in general form as follows:

$$F(H_3, t_{K1}, t_{K3}, V_{K1}, V_{K3}, \lambda_i) = L + \lambda_i \varphi_i (H_3, t_{K1}, t_{K3}, V_{K1}, V_{K3}) \tag{1}$$

For the case when the parameters and characteristics of the jet penetrator are defined, the mass of the structure is equal to the average value and the launch is performed from a fixed landing gear, this system of equations can be solved analytically, which means that the optimal conditions for launching the penetrator will be calculated. The established analytical expressions for determining the optimal launch conditions depend on the thrust ratio of the propulsion system and the static resistance of the soil.

3. FINDING THE MAXIMUM DEPTH OF PENETRATION

There are three options for launching this kind of penetrators [8]. The first option is dropping the penetrator from the landing module, which has a certain speed. In this case, the penetration into the soil happens by inertia due to the kinetic energy of the penetrator.

The second option is launching a jet penetrator from the landing module located on the lunar surface. In this case, the motion of the penetrator in the ground happens due to the thrust of the rocket engine of solid fuel. The third option is a combination of the first two and is accomplished by dropping the penetrator from the landing module has a certain speed. The inclusion of the engine is done on the site of motion of the penetrator by inertia. In this case, the penetration into the lunar soil is performed both due to the kinetic energy of the penetrator, and due to the thrust of the rocket engine of solid fuel.

Clearly, depending on how the penetrator is launched, its depth of penetration into the regolith will be different [9]. In particular, if the thrust of the propulsion system is less than the static resistance, then when the penetrator is started up with a zero entry speed, movement in the lunar soil will not occur. On the other hand, a viable option to use the penetrator's kinetic energy available on the landing site requires consideration of the strength of its structure due to the high level of shock overload acting at the moment the penetrator enters the lunar soil [10], [11], [12] .Moreover, when analyzing the use of inertial or penetrator equipped with a propulsion system, a comparison should be made for the same values of their overall mass characteristics, which are represented in this research by the outer diameter of the penetrator (D_H = 0.2 m); the mass of the load (M_{PN} = 10 kg), the total (full) mass of the penetrator (M_P = 20 kg) and the range of maximum permissible overloads:

$$n_X = 5000 \div 10{,}000$$

The equation of motion of the penetrator with a working propulsion in the regolith (without taking into account the force of gravity) can be written as follows:

$$m\frac{dV}{dt} = R - F, \tag{2}$$

where m is the current mass of the penetrator; R – engine thrust; F – soil resistance force; V and t – the speed and time of movement of the penetrator.

As we know [13] the resistance force of the soil during the motion of the penetrator with velocity V can be determined by the dependence in the form

$$F = F_0 + BV^2, \tag{3}$$

$$F_0 = \pi\frac{D_{\text{н}}{}^2}{4} F_{0UD}; \tag{4}$$

$$B = \frac{\pi}{4} D_{\text{Н}}^2 C_x \frac{\rho_r}{2}, \tag{5}$$

where F_{0UD} – is specific static resistance of the soil, value of which for some soils are shown in table 1; ρ_G – density of the soil; C_X – soil resistance coefficient, depending on the ratio of the velocity of the penetrator to the speed of sound of the soil.

If the speed of sound V_s is small enough compared to the speed of movement V, then C_X becomes almost constant. With $\frac{V}{V_s} \approx 1$ value of C_X can change strongly with small changes in the speed of movement. Finally, when $\frac{V}{V_s} \geq 1$ C_X value can be considered constant at changes in the velocity V intervals small compared to V_S. In addition, C_X in some measure depends on the Reynolds number. Calculations according to the formula (3-5) give relatively good results, but for practical purpose it is necessary to determine the resistance coefficient experimentally.

Table 1. – The value of specific frontal resistance for some types of soils

N/ n	Soil name	F_{0SP}, MPa
1	Loam and clay	6 ÷ 8
2	Silty loam and peat	2.5 ÷ 4
3	Loam with pebbles	> 10
4	Loose sand	2.5 ÷ 5
5	Medium density sand	5 ÷ 10
6	Dense sand	10 ÷ 20
7	Very dense sand	> 20
8	Soft clay, peat, mound	<1,0

9	Weak limestone	6 ÷ 8
10	Dry dense clay	40 ÷ 50

The order of magnitude C_X can be evaluated by representing the soil with the "plastic gas" model proposed by A.Ya. Sagomonyan [13], [14].

In particular, for a cylindrical solid body with a conical head, an expression for determining the coefficient can be found by the formula (3-5) in the form

$$B = \frac{\pi}{4} D_{\text{н}}^2 C_x x \sin\beta \frac{\rho_0}{(v-0)b_1}\left[\frac{v-2}{v}\left(a^{\frac{v}{2}}-1\right)+b_1(v-2)a^{\frac{v}{2}}-(a^{\frac{v}{2}-1}-1)\right] \quad (6)$$

where $a = \frac{1}{1-b_1}$; $b_1 = \frac{\rho_0}{\rho}$; $x = 1+\mu_0 ctg\beta$; $v = \frac{2\mu}{1+\mu}$; $\mu = \sin\varphi$; μ_0 is the ratio of sliding friction, equal to ~ 0.3 for steel along the ground; b_1 – the ratio of the densities in front and behind the shock wave in the soil, equal (at high speeds of movement) to ~ 0.6; $\beta = 30°$ - is the angle of the semi-solution of the penetrator head cone; φ is the angle of internal friction of the soil, equal to ~ 30° for soil of average density.

By putting the values of the characteristics of the soil of medium density to the formula (7) and comparing it with the expression (3-5), we obtain the value $C_X = 1.7$ Soil drag ratio [15], [16], [17] depends on the parameter $\theta = V\sqrt{\frac{\rho_H}{\tau_s}}$, where ρ_G is the density of the soil; $\tau_S = 0.2 \div 0.8$ MPa – is soil strength on shear.

When speed is low, the resistance ratio of the soil strongly depends on V and considerably exceeds $C_X = 1$, and when speed is high ($\frac{\tau_\tau}{\rho_\Gamma V^2} \ll 1$) practically does not depend on the speed and approaches the constant value $C_X = 0.8$. Integrating equation (1) at $R = 0$ (engine thrust is absent), we find the depth of penetration of the module into the lunar soil by inertia

$$L = \frac{4\text{M}_P}{\pi C_x \rho_H D_{\text{н}}^2}\ln\left(1+\frac{B V_{\text{вх}}{}^2}{F_0}\right) \quad (7)$$

In addition to the obtained dependence (7), to determine the penetration depth by inertia, in the first approximation, we can use the Berezansky formula [18], obtained experimentally for the penetration of artillery shells into various obstacles

$$L = \lambda K_P \frac{M_P}{D_{\text{н}}^2} V_{\text{BX}}, \quad (8)$$

where $\lambda = 1 \div 1.5$ – when the elongation of the head part from 1.5 to 2.5; M_P – the mass of penetrating module in kg; D_N – the diameter of the module in m; V_{BX} – the speed of entry of the module into the barrier (soil) in m/ s; K_P – the coefficient characterizing the properties of the obstacles, determined empirically and some values of which are presented in Table 2.

Table 2. – The value of the ratio KP with the penetration of the shell into some obstacles

N / n	Obstacle	$K_P \cdot 10^6$
1	Loose earth, soft clay	10
2	Dense earth, ordinary soil	5.5
3	Dense clay, wet sand	5
4	Soft soil, clay with sand	4.5
5	Sandstone, limestone	3
6	Masonry	2.5
7	Concrete	1,3
8	Reinforced concrete	0.9

Figure 1 shows the dependences of the module penetration depth into various obstacles for different values of the module penetration speed into the obstacle (soil).

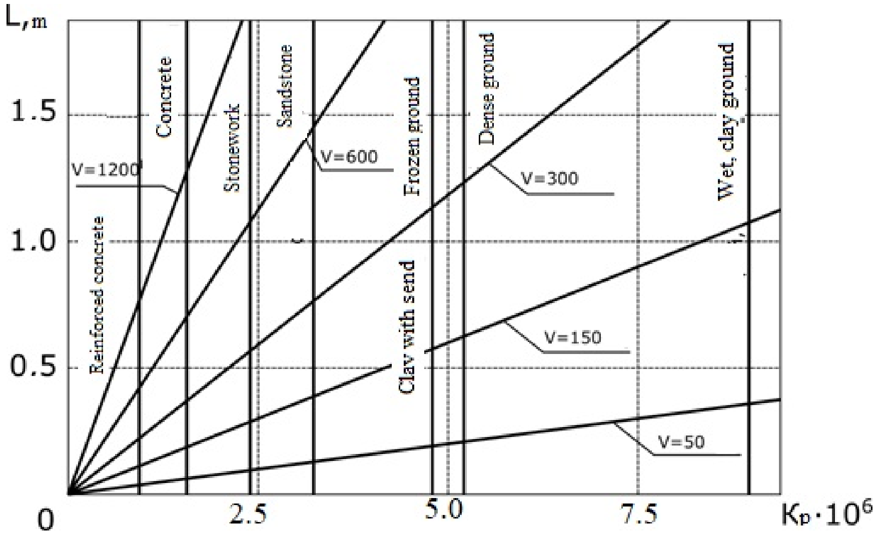

Fig. 1 – The dependence of the penetration depth of the module into various obstacles for different values of the velocity of the module

Regarding the penetration depth of the module by inertia, it should be noted that at present there are several empirical formulas that allow to calculate this characteristic with sufficient accuracy for preliminary analysis. In addition to formula (8), in the literature we can find dependencies of the same type suggested by Valle, Vuitch, Zabudski, Nobile, Perez, Petri, and other researchers [19], [20]. There is no fundamental difference between all these formulas, and the external differences reflect only the individual approach of each author to the solution of the problem.

4. FINDING ACTING OVERLOADS

When analyzing possible external loads, it is easy to see that the greatest of them are the loads when the penetrator enters the ground. In this regard, it is precisely the moment of the module penetration into the ground that is taken as calculated to determine the minimum permissible wall thickness of the construction. It was experimentally found that the magnitude of the overload n_X acting on the inertial penetrator depends on the depth of penetration [21]. In this case, when the penetrator is deepened by approximately the length of the head part, the overload reaches the maximum. On the rest of the path, the overload gradually decreases to zero.

The dangerous section of the penetrator for reliability calculation should be sought at the time when it is affected by the greatest inertial overload, i.e. active forces are at maximum. Formally, any equatorial section can be considered as a dangerous section. Nonetheless, taking into account the fact that the deformations of the sections in the barrier are limited by the resistance of the medium itself, which takes on part of the load, it should be assumed that the true dangerous section will be at the point where the conical part changes into the cylindrical one. Definitely, the calculated case for determining the overload in the dangerous section is the case when the defining processes of the penetrator body are the stresses caused by the action of the inertial forces of the structure located above the dangerous section. In this case, the penetrator is considered as a rigid cylindrical shell, compressed by a longitudinal force, for which the compression stress σ $_X$ is found by the formula:

$$\sigma_x = \frac{P_{\text{м}} n_X}{\frac{\pi}{4}(D_{\text{н}}^2 - d_{\text{в}}^2)} = \frac{\sigma_{\text{c}g}}{\varepsilon}, \tag{9}$$

where $P_{\text{м}} n_x$- is inertial load of the body of the penetrator, located above the dangerous section; $2\sigma = (D - d_{\text{в}})$- penetrator wall thickness; σ_{SJ} – is material compressive strength; ε – is safety margin; (σ_{LF} = 600 MPa); M_K – is the body weight above a dangerous section (in the first approximation $P_{\text{м}} = \text{М}_{\Pi} g$).

From formula (10) by solving the quadratic equation, we get the formula for determining the minimum allowable wall thickness

$$\delta_{min} = \frac{D_{\text{H}}}{2} - \sqrt{\frac{D_{\text{H}}^2}{4} - \frac{P_{\text{м}} n_X \varepsilon}{\pi \sigma_{\text{C}g}}}, \tag{10}$$

An approximate calculation of the maximum overload can perform by using a kinetic energy, which is expended only to overcome the resistance of the medium to the module penetration. In this case, the energy balance is found as:

$$\frac{\text{М}_{\text{п}} V_{\text{вх}}^2}{2} = A_{sopr}, \tag{11}$$

where A_{sopr} is the total work of the medium resistance forces. In the first approximation, we can assume that as the penetrator deepens, the resistance force varies linearly from F_{max} to zero, i.e.:

$$A_{sopr} = \frac{1}{2} F_{\max} L = \frac{1}{2} \text{М}_P n_X g L, \tag{12}$$

where $F_{\max} = \text{М}_{\text{п}} n_X g$; L – is the module penetration depth. From expressions (11) and (12) we find:

$$n_X = \frac{V_{\text{вх}}^2}{gL}, \tag{13}$$

Placing in (13) the depth of penetration, determined by the formula (7), we will get:

$$n_X = \frac{V_{\text{вх}} D_{\text{н}}^2}{\lambda \text{К}_P \text{М}_P g} \tag{14}$$

Setting the maximum permissible level of overloads for the penetrator n_X, from expression (14) we obtain the formula for determining the maximum speed of module penetration into the ground by inertia.

$$V_{en}^{add} = \frac{n_X{}^{add} g \text{М}_l \lambda \text{К}_l}{D_{\text{н}}^2} \tag{15}$$

Fig. 2 shows the dependence of the maximum speed of entry of the penetrator into different grounds for some values of the maximum permissible overload.

We should note that the results of calculations for determining the penetration depths and admissible velocities of module penetration into grounds [22] by inertia, that can be done by formulas (7), (8) and (15) coincide with sufficient accuracy for engineering practice.

This circumstance allows us to state that when calculating penetration depth of a penetrator with running engine, it is reasonable to use the expression (3-5) when determining the resistance of the lunar soil.

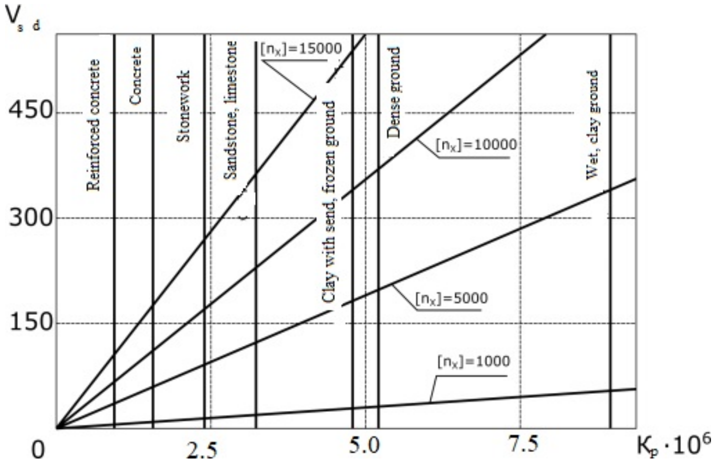

Fig. 2 – The dependence of the maximum speed of entry of the penetrator in various obstacles for some permissible overloads

Analysis of the equation of motion (1) indicates that when the penetrator enters the lunar soil with the propulsion system turned on ($R > 0$), the negative overload from the resistance of the regolith is compensated for by the engine (in particular, when $R = F$, it will be zero). From the above we can make conclusion that for a given value of the maximum permissible overloads acting on the penetrator, turning on the propulsion system at a certain point in time, to obtain a greater penetration depth, it is possible to increase the permissible speed of entry into the lunar soil.

In addition, when using a penetrator with a rocket engine of solid fuel, it is possible to achieve greater depths of penetration into the regolith with a significantly lower level of overload. In the case when the penetrator is launched from the lunar surface with a zero entry speed into the regolith [21], the engine thrust must be greater than the static resistance of the medium (otherwise movement in the lunar soil will not occur).

From the theory of designing jet apparatus for movement in the ground [7] we know that to achieve the maximum penetration depth at a given energy cost in the form of a mass of solid fuel, it is necessary that the thrust of the rocket engine should be twice the static resistance of the medium, i.e. $R = 2\,F_0$. In this case, from equation (1) we can see that the optimal speed of movement of the penetrator can be determined by the formula:

$$V_{opt} = \sqrt{\frac{2F_{0ud}}{C_x \rho_{\text{т}}}} \tag{16}$$

5. CALCULATION OF THE REQUIRED MASS OF SOLID FUEL

In works [7], [8], [21], a relationship was obtained between the required mass of solid fuel, well parameters, environmental characteristics and penetrator in the case of launching a penetrator with zero entry speed into the ground. This dependence has the this form:

$$\text{M}_{\text{т}} = \frac{L D_{\text{н}}^2 \sqrt{2 C_x \rho_{\text{т}} F_{0ud}}}{4 I_{ed}}, \tag{17}$$

where, except for the mentioned values M_T – the required mass of fuel to achieve the depth L; I_{ED} – a single impulse of solid fuel, which determines the amount of thrust of a solid-fuel engine when burning 1 kg of fuel. As we know [23], [24] that for solid fuel engines

$$R = I_{ed} S_{hor} U_{hor} \quad (18)$$

where ρ_T, S_{hor}, U_{hor} – are density, burning surface and burning rate of solid fuel, respectively.

Table 3 depicts the main results of calculations of the required mass of fuel for penetrators of different diameters to a depth equal to one hundred calibers. From this table 3, in particular, we can see that for penetration of the module with a diameter of D_H = 0.2 m to a depth of L = 20 m, a mass of solid fuel is required, equal to M_T = 40.9 kg, i.e. at M_T = 1 kg, it is possible to form a well of a given diameter with a depth of L = 0.5 m.

Calculating the strength conditions of the rocket engine design [18], the mass of the fuel can be only half the mass of the loaded engine. With other things being equal for inertial and reactive penetrators, according to the given in this study information, the mass of fuel can be M_T = 5 kg, which allows for such a device to penetrate to a depth of L = 2.5 m when it starts at zero ground entry speed, or increase by 2.5 m the depth of penetration when discharged from the nozzle of the penetrator with the maximum speed of entry into the regolith.

Table 3 – The results of calculations of the characteristics of penetrators of different diameters

Characteristic	Penetrator diameter		
	0.2	0.06	0.025
L, m	20	6	2.5
F_{0SP}, MPa	7		
ρ_g, kg/ m^3	1800		
cx	1		
I_U, m·s/ kg	2500		
U_{HOR}, m/ s	0.7		
V_{opt}, m/ s	88		
R, kN	440	39.5	6.9
T s	23	0.07	0.03
M_T, kg	40.9	1.1	0.08
ρ_T, kg/ m^3	1600		
S_{HOR}, m^2	0.157	0.014	0,0024
S_M , m^2	0.0314	$2.8 * 10^{-3}$	$0.5 * 10^{-3}$

6. CONCLUSIONS

1. For researching the subsurface layers of the Moon and other planets of the solar system, it is recommended to use inertial penetrators, dropped from the landing module at the site of its descent from the planet's orbit and using the kinetic energy available to penetrate into the ground. The depth of penetration depends on the mass-dimensional characteristics of the penetrator and the velocity of its entry into the ground, which is limited by the level of permissible overloads. For an inertial penetrator with a mass of M_P = 20 kg and a diameter D_H = 0,2m with a level of permissible overloads n_X = 5000 ÷ 10,000 at its entrance into the planetary ground ($K_P = 5.5 \times 10^{-6}$) range V_{BX} = 195 ÷ 390 m/ s, and the depth of penetration into the ground under surface will be L = 0.9 ÷ 1.8.

2. The use of a solid fuel engine on the penetrator facilitates increasing the allowable speed of the penetrator into the ground by reducing the overloads acting on it, and thereby increasing the penetration depth. For example, for a penetrator with a mass of M_P = 20 kg considered as an example, the presence of an engine with a mass of fuel M_T = 5 kg allows to

increase the allowable entry velocity and penetration depth of the module into the ground by 1.5 ÷ 2 times.

3. When organizing the module penetration process in such a way that the thrust of a solid-fuel engine is two times bigger than the static resistance of the ground, the module penetration depth can be significantly increased. In this case, it is possible to launch a penetrator with a zero entry velocity into the ground. For the example considered in this work, each kilogram of fuel provides an increase in the penetrator depth by 0.5 meters.

4. If at the moment of entry of the penetrator into the ground we can provide engine thrust directed to the direction of movement of the penetrator and equal in magnitude to force the ground resistance, the overload acting on the load to be equal to zero. This circumstance permits, using explosive-jet solid-fuel engines, to create high-speed inertial penetrators for deep penetration, providing an acceptable level of actual overloads.

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