STUDY OF EFFICIENCY OF SOIL-THROWER AND FIRE-BREAK MAJER ON THE BASIS OF MATHEMATIC SIMULATION

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ABSTRACT

Introduction. Combating forest fires is one of the most pressing problems of forestry. Increase in the number of fires is associated with global climate change on our planet. At present, requirements to the level of forest protection have increased. Therefore, it is necessary to increase the amount of firefighting equipment in forests and increase material resources of forest fire services. The article presents a mathematical model of interaction between working bodies of soil-thrower and soil. This mathematical model enables to investigate the efficiency of the machine on the basis of computer experiments. The task of the research is to conduct a multifactor theoretical study of the processes of formation of soil flow, its movement in the air and impact on the edge of forest fire using the created model. Materials and methods. Development of highly detailed simulation model is based on modern mathematical methods focused on the use of high-performance computing equipment. A modern SPH-method (Smoothed Particle Hydrodynamics) has been used to simulate soil and air environment, within which environments are divided into a multitude (from 10,000 - 100,000) of individual spherical elements interacting with each other and moving according to the laws of classical mechanics and aerodynamics. Results of research. A mathematical model of a machine for extinguishing forest fires has been obtained. It enables to choose optimal parameters of soil-thrower working bodies. It allows reducing time and costs for design and technological work on the production of soil-thrower. Discussion and conclusions. A computer program has been developed. The computer program enables to investigate the influence of the main parameters of soil and soil-thrower on productivity, quality and power consumption. This program is written in the programming language Object Pascal in the Borland Delphi environment.

Key words: fire suppression, forest fire, simulation, soil, soil-throwing.
1. INTRODUCTION

Forests are important part of the ecosystem and play a significant role to preserve and maintain the environment. The main hazard is the forest fires because its consequences are terrible in nature. Therefore, there is a need to detect fire and extinguish before it spreads to destroy the resources [1]. The forest fire spreading is a complex process affected by multi-factors. Understanding the relationships between these multi-factors and the forest fire spreading trend is vital to predicting the fire spreading promptly and accurately to make the strategy in extinguishing the forest fire [2-11].

A fire soil-thrower and fire-breaking maker has been developed for extinguishing forest fires and laying fire lines (Fig. 1).

![Assembled representation of soil-thrower and fire-breaking maker](image)

1 – frame; 2 – header support; 3 – screw; 4 – ripper; 5 – concave disks; 6 and 7 – miller-thrower; 8 – gear case; 10 – hydraulic motor; 11 – remote hydraulic cylinder for soil-thrower control; 19 – yaw axis of soil-throwers; 12 – butt pans; 16 – shaft drive; 17 – gear set; 18 – belt-drive; 13 – ripper shank; 14 – safety spring of ripper; 15 – knife

**Figure 1** Assembled representation of soil-thrower and fire-breaking maker
2. MATERIALS AND METHODS

Mathematic simulation has been used for developing a fire-soil-thrower and fire-breaking maker. It is intended to clarify the features of soil-thrower in various modes and to determine optimal design and technological parameters. Simulation is based on the particle dynamics method [12, 13]. In modeling, forest soil is represented by a set (about 6000) of spherical elements (with a diameter of about 7 cm). These elements interact with each other and with working surfaces of the machine: a rotor, a disk, etc. The model takes into account only the right half of soil-thrower.

Mechanical motion of soil element is described on the basis of Newton's second law:

\[
\begin{align*}
    m_i \frac{d^2 x_i}{dt^2} &= \sum_{j \neq i} \left( F_{ij}^x + F_{ji}^x \right) + \sum_{k=1}^{N_g} \left( F_{ik}^x + F_{ki}^x \right) - m_i g, \\
    m_i \frac{d^2 y_i}{dt^2} &= \sum_{j \neq i} \left( F_{ij}^y + F_{ji}^y \right) + \sum_{k=1}^{N_g} \left( F_{ik}^y + F_{ki}^y \right) - m_i g, \\
    m_i \frac{d^2 z_i}{dt^2} &= \sum_{j \neq i} \left( F_{ij}^z + F_{ji}^z \right) + \sum_{k=1}^{N_g} \left( F_{ik}^z + F_{ki}^z \right) - m_i g,
\end{align*}
\]

(1)

Where \( m_i \) – element mass; \( t \) – time; \( N_E \) – number of elements; \( N_S \) – number of elementary surfaces; \( F_{ij}^{x/y/z} \) – components of elasticity force acting between the elements, and proportional to the introduction of elements into each other; \( F_{ij}^{B/x/y/z} \) – components of viscous frictional force between elements proportional to the difference in velocities of elements; \( F_{ik}^{x/y/z} \) – components of elastic forces and viscous friction when element \( i \) interacts with an elementary surface \( k \); \( g \) – gravitational acceleration.

Neighboring elements of soil are considered interconnected before simulation. Both repulsive force when introducing elements into each other, and force of attraction when removing elements from each other act between the elements. This condition enables to take into account the initial connectivity of the soil and its fragmentation under the influence of soil-thrower in the model:

\[
\begin{align*}
    F_{ij}^y &= \begin{cases} 
    c(d_E - r_{ij})(\xi_i - \xi_j)/r_{ij}, & r_{ij} < d_E + d_M \sigma_{ij}; \\
    0, & r_{ij} > d_E + d_M \sigma_{ij},
    \end{cases} \\
    F_{ij}^z &= \begin{cases} 
    0, & \sigma_{ij} \leq 0; \\
    0, & \sigma_{ij} > 0.
    \end{cases}
\end{align*}
\]

(2)

where \( \xi \) – generalized coordinate designation (x, y or z); \( c \) – stiffness coefficient; \( r_{ij} \) – distance between the centers of the elements; \( d_M \) – limiting distance between the elements up to which attracting forces act on the elements; \( \sigma_{ij} \) – connectivity coefficient of elements.

At removing related items at a certain critical distance, "connectivity" is turned off (\( \sigma_{ij} \) takes "0" value instead of "1"). Subsequently, only repulsive forces act between the elements. This approach enables to adequately set friable, moist soils, reproduce the cohesion of upper part of soil by plants of lower tier of forest and roots.

Before the simulation begins, random, dense packing of the elements in space area in the form of rectangular parallelepiped with dimensions \( L_X \times L_Y \times a \) (respectively width, length, height) is created (Fig. 2). The upper layers of the elements (dark in Fig. 2) represent the ground cover in the model. The lower layers of the elements are loosely connected soil, meant to extinguish fires. The machine moves in \( OY \) direction and interacts with soil elements,
screw, discs, rotors and butt pans. As a result, a stream of soil is formed, moving along a parabolic trajectory.

Significant computational complexity is associated with calculation of forces impacting soil elements from machine’s working surfaces. These forces lead to deformation, fragmentation of soil, give velocity to the fragments of soil. In parallel, calculation of inverse forces acting on the working surfaces of the soil-thrower is made. According to them, soil-thrower power consumption is calculated. Calculation of interaction of soil elements and working surfaces of soil-thrower is based on a preliminary definition of element introduction into surface. For this we use the apparatus of analytic geometry.

Finite element approach is used to transfer spatial configuration of working surfaces to the model. Surfaces of complex shape are replaced by a large number of planar figures in it [14, 15]. In this case, the surfaces are represented as a set of a large number of triangles, since the triangles are easily joined together.

Further it is described in more detail how the working surfaces have been divided into triangles. The coordinates of the vertices of triangles are denoted by \( T_{i1}(x_{i1}, y_{i1}, z_{i1}) \), \( T_{i2}(x_{i2}, y_{i2}, z_{i2}) \), \( T_{i3}(x_{i3}, y_{i3}, z_{i3}) \), where \( i \) – triangle number; indices \( i1 \), \( i2 \) and \( i3 \) denote numbers of vertices. The working surfaces are preferably not closed. After the triangles are joined, free ribs remain. This ribs act as cutting edges of screw, disc and rotor, and point-vertices.

The rotor in the model consists of eight triangles (Fig. 3, a), a disk - of 24 triangles (Fig. 3, b), a butt pan - of 6 or 8 triangles (Fig. 3, c). The surface of a screw drum consists of a cylindrical surface and a set of triangles. They form a screw surface (Fig. 3, d). To simulate rotation of the rotor, coordinates of the base points 3-10 of the rotor are changed with the passage of time \( t \):
\[ x_1 = x_{CR}; \quad y_1 = y_{CR} + \frac{B_B}{2}; \quad z_1 = z_{CR}; \]

\[ x_2 = x_{CR}; \quad y_2 = y_{CR} - \frac{B_B}{2}; \quad z_2 = z_{CR}; \]

\[ x_{3+2i} = x_{CR} + R_r \cos \left( \omega p t + i \frac{\pi}{2} \right); \quad y_{3+2i} = y_{CR} + \frac{B_B}{2}; \quad z_{3+2i} = z_{CR} + R_r \sin \left( \omega p t + i \frac{\pi}{2} \right); \]

\[ x_{4+2i} = x_{CR} + R_r \cos \left( \omega p t + i \frac{\pi}{2} \right); \quad y_{4+2i} = y_{CR} - \frac{B_B}{2}; \quad z_{4+2i} = z_{CR} + R_r \sin \left( \omega p t + i \frac{\pi}{2} \right); \]

where \((x_{CR}, y_{CR}, z_{CR})\) – rotor center coordinates; \(B_B\) – blade width of the rotor; \(R_r\) – rotor radius.

**Figure 3** Representation of the model as a set of elementary triangles of rotor (a), spherical disk (b), butt pan (c), screw drum (d, e). Indices of base points and elementary triangles are shown.
Triangles are drawn up on the basis of main points \( P_i \), moving in space. Interaction with soil elements is calculated for them later: \( T_1(P_1, P_3, P_4); T_2(P_1, P_2, P_4); T_3(P_1, P_5, P_6); T_4(P_1, P_2, P_6); T_5(P_1, P_7, P_8); T_6(P_1, P_2, P_8); T_7(P_1, P_9, P_{10}); T_8(P_1, P_2, P_{10}) \). Placement of the base points of the disk in the space is as follows. The coordinates of the disc center (point \( P_{21} \)) are:

\[
x_{21} = x_C; \quad y_{21} = y_C; \quad z_{21} = z_C.
\]

Coordinates of points of a small circle with numbers from 22 to 29 are calculated by the formulas:

\[
x_i = x_U + \frac{1}{3} \left( r_{C\phi} - \sqrt{r_{C\phi}^2 - R^2_{D}} \right);
y_i = y_U + \sqrt{r_{C\phi}^2 - \left( r_{C\phi} - \frac{1}{3} \left( r_{C\phi} - \sqrt{r_{C\phi}^2 - R^2_{D}} \right) \right) \cos \left( \omega_D t + (i-22) \frac{\pi}{4} \right)};
z_i = z_U + \sqrt{r_{C\phi}^2 - \left( r_{C\phi} - \frac{1}{3} \left( r_{C\phi} - \sqrt{r_{C\phi}^2 - R^2_{D}} \right) \right) \sin \left( \omega_D t + (i-22) \frac{\pi}{4} \right)},
\]

where \( R_D \) and \( R_{SPH} \) – disc and sphericity radii; \( \omega_D \) – disk rotational speed. Coordinates of points of the big circle with numbers from 30 to 37 are calculated as follows.

\[
x_i = x_C + R_{SPH} \cos \left( \frac{\pi}{4} \right);
y_i = y_C + R_D \cos \left( \omega_D t + (i-30) \frac{\pi}{4} \right);
z_i = z_C + R_D \sin \left( \omega_D t + (i-30) \frac{\pi}{4} \right).
\]

After its advanced setting, disc is installed, first, by the angle \( \beta \) with respect to the vertical plane, then by the angle of attack \( \alpha \) with respect to the direction of movement. The following coordinate transformation is performed to rotate the disk through an angle \( \beta \) relative to the vertical plane.

\[
r = \sqrt{(x_i - x_C)^2 + (y_i - y_C)^2};
\]

\[
\phi = \begin{cases} 
\arctan \frac{z_i - z_C}{x_i - x_C}, & x_i - x_C \geq 0; \\
\arctan \frac{z_i - z_C}{x_i - x_C} + 180^\circ, & x_i - x_C < 0;
\end{cases}
\]

\[
x_{i2} = x_C + r \cos(\phi + \beta);
y_{i2} = y_C;
z_{i2} = z_C + r \sin(\phi + \beta).
\]

Where \( r \) and \( \phi \) – polar coordinates of base points in the coordinate system associated with disc center; \( (x_i, y_i, z_i) \) and \( (x_{i2}, y_{i2}, z_{i2}) \) – coordinates of the base point \( P_i \) before and after transformation of rotation about \( OY \) axis.

To set the disk at the angle of attack \( \alpha \) relative to the \( OZ \) axis, the same is done by converting coordinates of the base points. Mutual arrangement in the space of working surfaces of soil-thrower is made taking into account a lot of geometrical parameters (Fig. 4). Thus, placement of the rotor center \( (x_{CR}, y_{CR}, z_{CR}) \) and disc center \( (x_C, y_C, z_C) \) in space is produced, respectively, by the formulas:
where $B_r$ – distance between centers of rotors; $y_M$ – current coordinate of the machine along the longitudinal axis; $R_r$ and $R_D$ – radii of the rotor and disk, respectively; $a_R$ и $a_D$ – required depths of the rotor and disc respectively; $B_D$ – the distance between the hinges in which the levers of the discs are fastened; $L_D$ – length of the disk mounting lever; $\phi_{AD}$ – angle of disc installation.

First, mutual placement in the space of working surfaces takes place. At each integration step, spatial arrangement of the machine as a whole is set, which is relative to fixed coordinate system. For most computer experiments, soil-thrower moves uniformly and rectilinearly along the OY axis. Y coordinates of triangles vertices of working surfaces are calculated by the formula:

$$y_{ij} = y_{0ij} + v \cdot t,$$

where $y_{0ij}$ – Y component of vertex $j$ of triangle $i$ at the initial moment of time; $v$ – soil-thrower speed; $t$ – current time.

Figure 4 Basic geometric parameters of soil-thrower

At the initial time, soil-thrower is artificially lifted above the surface. This is necessary to exclude appearance of high accelerations of soil elements due to instantly appeared working
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surfaces. With the beginning of simulation, soil-thrower gradually penetrates into the soil. For a period of time \( t_{pen} \), disk and the rotor, initially touching the ground surface, must reach a predetermined depth \( a_p \) and \( a_D \). For this, the coordinates \( z_{ij} \) of the vertices of the triangles of the working surfaces vary linearly, up to \( t = t_{pen} \): \[ z_{ij} = z_{0ij} - a \cdot t / t_{pen}, \quad (10) \]

Where \( z_{0ij} \) – vertical coordinates of the vertices of triangles at the initial moment of time

Forces between elements and working surfaces are calculated analogously to the forces between the elements: in the elastic-viscous approximation. This is necessary to preserve the universality of the model. When calculating the forces at each step of numerical integration, the contact of each element with each triangle is checked. In case of contact, value of introduction \( r_{int} \) of an element into the plane of a given triangle is calculated. Further, elastic force is calculated on the basis of \( r_{int} \) by a formula, which is similar to (2).

From the point of view of mathematical analysis, the model developed is a system of a set of second-order differential equations with essentially discontinuous free terms. Modified Euler-Cauchy method has high efficiency in solving such systems [15]. This method has been used in this work.

Computer program "The program for simulation of fire soil-thrower and fire-breaking maker" in the language of Object Pascal has been specially developed to implement the developed mathematical apparatus. Borland Delphi 7 has been used as a programming environment.

To assess the effectiveness of soil-thrower in different modes of operation, four performance indicators have been calculated:

1) content of ground cover in the flow of soil:

\[ p_n = \frac{\sum_{i=1}^{N_\mathcal{G}} \left\{ \begin{array}{ll} 1, & x_i > L_X; \\ 0, & x_i \leq L_X; \\ 1, & x_i = 2; \\ \end{array} \right. \}
\]

\[ \sum_{i=1}^{N_\mathcal{G}} \left\{ \begin{array}{ll} 1, & x_i > L_X; \\ 0, & x_i \leq L_X; \\ \end{array} \right. \]

\[ \frac{x_i - L_X}{t_{CE}}, \quad (11) \]

where \( \tau_i \) – element type (1 – soil; 2 – ground cover); curly and square brackets in logical conditions mean, respectively, simultaneous fulfillment of the conditions and fulfillment of one of the conditions;

2) soil-thrower performance:

\[ p = \frac{m_S}{t_{CE}}, \quad (12) \]

Where \( m_S \) – total mass of soil thrown for the entire computer experiment; \( t_{CE} \) – computer experiment time;

3) average throwing range:

\[ L_{aver} = \frac{x_{aver} - L_X}{2} = \frac{1}{2} \frac{\sum_{i=1}^{N_E} \left\{ \begin{array}{ll} x_i, & x_i > L_X; \\ 0, & x_i \leq L_X; \\ \end{array} \right. - L_X}{\sum_{i=1}^{N_E} \left\{ \begin{array}{ll} 1, & x_i > L_X; \\ 0, & x_i \leq L_X; \\ \end{array} \right.}, \quad (13) \]
Where \( x_{\text{aver}} \) — averaged for all the elements thrown by soil-thrower coordinate \( x \);

4) soil-thrower energy input:

\[
N = \frac{A}{t_{CE}} = \frac{1}{t_{CE}} \left( \int_0^{t_{CE}} \omega_R M_{\text{tot},R}(t) dt + \int_0^{t_{CE}} \omega_{Dr} M_{\text{tot},Dr}(t) dt \right).
\]  

Where \( A \) — work of forces on the part of elements. It impedes rotation of rotor and screw drum during the entire time of computer experiment; \( \omega_R \) and \( \omega_{Dr} \) — angular velocity of rotor and screw drum, respectively; \( M_{\text{tot},R}(t) \) and \( M_{\text{tot},Dr}(t) \) — total moments of interaction forces between soil elements and elementary surfaces of rotor and screw drum, respectively.

3. RESULTS OF RESEARCH

The developed model has enough versatility. It enables to investigate the influence of dozens of structural, technological parameters of soil-thrower, as well as soil parameters. In view of the limited volume of the article, only one of the main parameters for a given machine - the rotational speed of a screw drum - has been considered \( f_D \). In the framework of this series of computer experiments, the parameter \( f_D \) (which is connected with mentioned above angular velocity by the expression \( \omega_D = 2\pi f_D \)) has been changed from 0 to 6 rev/s in steps of 1 rev/s (Fig. 5).

The increase in the speed of rotation of screw drum has a favorable effect on the decrease of ground cover content \( p_c \) in the flow of soil. At frequencies above 3.5 rev/s, \( p_c \) value becomes less than 10% (Fig. 5, a). However, an excessive increase in \( f_D \) has a negative effect on productivity (Fig. 5, b) and the range of soil throwing (Fig. 5, c). The case of a high speed of screw rotation and the usual speed of step motion of soil-thrower has been considered. In this case, screw shifts laterally not only the ground cover, but also a significant proportion of the ground. This soil is intended for throwing. As a result, it leads to excessive penetration of the machine as a whole. Because of this, rotor directs a considerable part of the soil into the wall of penetration. This results in a sharp drop in performance. The performance is calculated by the volume of thrown soil and average range of soil throwing. Maximum performance and range have been achieved in \( f_D \) range from 2 to 4.5 rev/s.

![Figure 5](http://www.iaeme.com/IJMET/index.asp)

**Figure 5** The effect of screw drum rotational speed \( f_D \) on the share \( p_c \) of ground cover in the ground flow, performance \( P \), average throwing distance \( L_{\text{aver}} \) and power consumption \( N \).
Power consumption is high at low $f_D$. This is due to the fact that rotor rotation is complicated by a dense coherent ground cover. In this case, ground cover is almost not displaced by the screw drum. A minimum of power consumption in the range $f_D$ from 1.5 to 3 rev/s has been found. It is associated with the optimal ratio of angular velocity of rotation of screw drum and speed of the machine. At high values of $f_D$ the power is reduced. This is due to the fact that screw drum reliably removes soil cover and rotor carries loosely bound soil.

4. DISCUSSION AND CONCLUSIONS
Let's summarize the conclusions on all performance indicators. Optimum speed of screw drum rotation at the range of 3.0 -3.5 rev/s can be recommended. In this range, the ground cover in the ground flow is less than 15%, the productivity is more than 40 kg/s, average earthing range is more than 11 m, and power consumption is less than 11 kW.

Thus, a mathematical model of fire-soil-thrower and fire-breaking maker has been developed. A computer program implementing it has been developed. Computer program enables to investigate the effect of basic parameters of soil and soil-thrower on the performance, quality and power consumption of the latter one.

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