Theoretical study of forest fire extinguishing machine use

M A Gnusov*, M V Drapalyuk and D Yu Druchinin

Ministry of Science and Higher Education of the Russian Federation, Voronezh State University of Forestry and Technologies named after G.F. Morozov, 8 Timiryazeva Street, Voronezh 394087, Russian Federation

* E-mail: mgnusov@yandex.ru

Abstract. Nowadays, forest fires have become a serious problem for many countries. The world forestry suffers losses. This fact encourages scientists from different countries to actively engage in the development of new forest firefighting equipment, but the creation process is becoming more and more expensive. The simulation method has become increasingly used to increase the efficiency of the equipment creation. For a theoretical issue the simulation model of firefighting machine for extinguishing forest fires has been developed, which allows carrying out computational experiments on the forest fire unit functioning. The model implementation in the form of different computer experiments allows us to establish the influence of the structural and technological parameters of the forest fire machine on the efficiency of soil throwing during the forest fire extinguishing.

1. Introduction

The forest fund of the Russian Federation is under special control of governmental authorities, as the forest density in the country is more than 80 billion m³. This figure is reduced due to forest fires, which annually cover the country territory from 2 to 5 million hectares of valuable high-quality wood [1]. The problem becomes especially acute in the summer, as the weather conditions of recent years provoke drought and, as a result, a fire-hazardous situation for forestry. All forest fires lead to irreparable harm to the entire planet [2]. In recent years, the simulation has become increasingly relevant in world practice for the study of complex physical processes in various systems. It is advisable to use the finite element method. The modern computer models make it possible to conduct computational experiments as close as possible to real ones [3].

2. Materials and methods

The developed physical and mathematical simulation model allows us to study in more detail the process of soil cutting and throwing in a given direction and the required volume. This model makes it possible to describe the processes that affect the efficiency of forest fire origin extinguishing, and to study data on the unit movement and the interaction of working bodies with the working environment in the simulated space. It is necessary that the model allows working with high spatial resolution to correctly reproduce the movement of all soil particles of different sizes in order to estimate losses in the air [4]. This is necessary for the high adequacy of reproducing the direct interaction of the working surfaces of the machine with the soil during its throwing. The high computing capabilities of modern computers make it possible to create and use such models. In the framework of the finite element method, soil is represented as a combination of a large number (about $10^3$–$10^6$) of individual spherical elements. The sizes of the elements can be either the same to simplify the study, or different to avoid
adverse effects of the periodicity of element dense packing. All soil elements mechanically interact with a forest fire extinguishing machine [5]. While describing the mechanical behaviour of all the components to create the soil simulation environment, the particle dynamics method is used [6]. A large number of method variations are most often found for modeling a wide range of physical processes [7].

![Soil elements interacting with a forest fire extinguishing machine](image)

**Figure 1.** Representation in a model of a machine for extinguishing forest fires as a combination of elementary triangular surfaces and soil as a set of spherical elements (three projections).

### 2.1. Soil description in the model

During the particle dynamics method use, we assume that the development environment, namely the soil, consists of a large number of spherical elements with a diameter of 40 mm to 150 mm. When the balls interact with each other and the surfaces of the forest fire extinguishing machine, a viscous friction force and a dry friction force will occur (figure 2). The movement of elements is calculated according to the laws of classical dynamics.
As part of the simulation, three-dimensional Cartesian space is used along three axes x, y, z. In this case, the state of each individual element $E_i$ is denoted by six different variables: speed components $(v_{xi}, v_{yi}, v_{zi})$ and the coordinates of its center $(x_i, y_i, z_i)$.

The equations of element movement are based on Newton’s second law:

$$m_i \frac{d^2 x_i}{dt^2} = \sum_{j=1}^{N_{ij}} \left\{ \begin{array}{ll}
\frac{d_i + d_j}{2} - r_{ij} \left( \frac{x_i - x_j}{r_{ij}} \right) + \left( C v_{xi} - v_{xj} \right) \left( r_{ij} - \alpha_a \frac{d_i + d_j}{2} \right), & r_{ij} < \alpha_L \frac{d_i + d_j}{2} ; \\
0, & r_{ij} \geq \alpha_L \frac{d_i + d_j}{2} ;
\end{array} \right. $$

$$m_i \frac{d^2 y_i}{dt^2} = \sum_{j=1}^{N_{ij}} \left\{ \begin{array}{ll}
\frac{d_i + d_j}{2} - r_{ij} \left( \frac{y_i - y_j}{r_{ij}} \right) + \left( C v_{yi} - v_{yj} \right) \left( r_{ij} - \alpha_a \frac{d_i + d_j}{2} \right), & r_{ij} < \alpha_L \frac{d_i + d_j}{2} ; \\
0, & r_{ij} \geq \alpha_L \frac{d_i + d_j}{2} ;
\end{array} \right. $$

$$m_i \frac{d^2 z_i}{dt^2} = \sum_{j=1}^{N_{ij}} \left\{ \begin{array}{ll}
\frac{d_i + d_j}{2} - r_{ij} \left( \frac{z_i - z_j}{r_{ij}} \right) + \left( C v_{zi} - v_{zj} \right) \left( r_{ij} - \alpha_a \frac{d_i + d_j}{2} \right), & r_{ij} < \alpha_L \frac{d_i + d_j}{2} ; \\
0, & r_{ij} \geq \alpha_L \frac{d_i + d_j}{2} ;
\end{array} \right. $$

Figure 2. Forces that occur when two soil elements come into contact with each other (a), as well as between the soil element and the surface of the machine (b): $F^y$ - elastic forces; $F^c$ - dry friction forces; $F^b$ - viscous friction.
where $i$ – item number; $N_{ab}$ – number of elements; $m_i$ – element mass; $t$ – time; $j$ – item number, possibly in contact with the $i$ element; $c_{ij}$ – stiffness coefficient of interaction of elements $i$ and $j$ (calculated through elastic moduli); $k^{ij}_{\alpha}$ and $k^{ij}_{\beta}$ – dry friction coefficients of elements $i$ and $j$ one about the other; $d_i$ – diameter $i$ element; $r_{ij}$ – distance between centers of elements $i$ and $j$; $\alpha_0$ – coefficient of restriction of interaction between elements (selected from the range 1.0...1.1 and allows you to set the connectivity or «stickiness» of the soil); $N_P$ – number of elementary soil thrower surfaces; $c_{i-P}$, $k^{C}_{i-P}$ and $k^{B}_{i-P}$ – stiffness factors, dry and viscous friction during the interaction of the element $i$ with surface $j$; $r_{i-P}$ – distance from center $i$ element before $j$ surface; $x_i,y_i,z_i$ – Cartesian coordinates of the projection point of the center of the element $i$ to the surface $j$; $v_{xi},v_{yi},v_{zi}$ – center speed components $j$ elementary surface; $[..]_t$ – vector module; $g$ – acceleration of gravity.

The elastic force in the simulated physical and mathematical model is indicated in the role of the normal reaction force applied between the parts of the cultivated soil, which describes the repulsion of the elements from each other, if it comes into contact - if the distance between the elements $r_{ij}$ will be less $(d_i + d_j)/2$. The distance $r_{ij}$ between the element centers is calculated through the coordinates of the centers by the Pythagorean theorem: $r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}$.

The efficiency evaluation of the soil throwing process will be the result of solving a system of differential levels of the second order for the function $x_i(t)$, $y_i(t)$, $z_i(t)$, which will describe the trajectories of the movement of soil elements in the developed space. In the model, when moving large fragments, for example, such as large clods, its rotation is taken into account and described automatically, but the rotation of smaller elements around their centers is not taken into account, since this practically does not introduce an error into the overall result.

During the computer program experiments, the elements move inside the simulated box, shown in figure 3, described in the shape of a rectangle and having dimensions $L_X \times L_Y \times L_Z$. In the course of the experiment, the spherical elements with a center of gravity are deposited on the lower wall of the rectangle, which simulates the zero-reference point, forming a random stacking on top of each other at the highest stacking density [8-9]. The shake algorithm is used for this. The machine moving along the $OY$ direction, interacting with disks and rotors with soil elements, removes it from the soil layer and makes it move along a ballistic trajectory. In this case, the characteristic groove is formed behind the machine, which is close to the real objects being created in its configuration [10-13]. To trace the trajectory of the elements being thrown, one of the walls of the parallelepiped must remain open (figure 3). The soil elements after throwing can move along close to parabolic trajectories until it comes into contact with the soil deposition plane located at the soil level.
During the experiments, if the elements of the development environment, namely the soil, touch the closed walls of the modeling loop, the following conditions are considered: \( x_i < 0 \), \( y_i < 0 \), \( y_i > L_Y \), \( z_i < 0 \), \( z_i > L_Z \). For example, if during the experiment the condition \( y_i > L_Y \), then in this case the coordinate assigned a value \( y_i = L_Y - (y_i - L_Y) \), and in this case, the speed of the element in the OY direction changes sign: \( v_{yi} = -v_{yi} \). When the balls are reflected from the walls of the parallelepiped, the element will lose part of the energy, which is described by adapted formulas (1).

The adequacy of the model depends on the diameter of the soil \( d_{sh} \). The accuracy of the representation in the soil model depends on the diameter of the spherical elements \( d_{sh} \), since the soil is finely dispersed, therefore, it should be as small as possible. The number of spherical elements \( N_{sh} \), required to display the assigned soil volume \( V_g \), will increase according to cubic law with a decrease \( d_{sh} \). Although today the capabilities of modern computers can significantly reduce the time frame for calculating models, increasing the number of spherical particles will lead to an increase in the number of equations and, consequently, significantly increase the calculation time. For example, if you reduce the diameter of each sphere by half, the time will increase by almost eight times. Therefore, it is worthwhile to focus on saving time and on the capabilities of computer technology, the optimal diameter, which allows without loss of quality and accuracy of the program to describe the soil, without increasing the time spent on each experiment, is approximately 70 mm. In this case, the total content of the model elements will be approximately equal to 10,000 pcs.

At the end of the preparation of the simulation environment (soil), the element interaction is determined. The process consists of the stage of filling a two-dimensional array \( K(i, j) \), in which each individual cell is individually indicated can take several values. If the elements \( i \) and \( j \) are at a distance \( r_{ij} < d_{sh} + d_{sh} \), in this case the cell takes the value «true», and if the value is the opposite, then «false». During the simulation experiment, at each integration step for each coupled pair \( i-j \), it is checked whether it is divided into the same condition, and if the condition is not satisfied, the array \( K(i, j) \) the value is false. In the case of friable soil (sandy soil) modeling, all soil elements are considered unconnected.

In order for the model to fully correspond to reality, it is necessary not only to correctly describe the soil, but also to accurately reproduce the complex geometry of all combined working bodies of the machine to extinguish forest fires, with a description of the general contact interaction. In the framework of the finite element approach, epy surfaces of complex shape are usually replaced by a large number of flat figures [14]. The working bodies of the machine are presented in the form of elementary figures, in particular, in the finite element method these are triangles. Such a description makes it easy to dock them together and reproduce the complex surfaces of the working bodies that
come into contact with the soil. The surface representation in the form of a set of triangles is very convenient and will allow you to optimize the shape and geometric arrangement by changing the sizes of elementary triangles, which describe the working bodies of the unit.

The triangle in three-dimensional space is defined by the coordinates of its three vertices $T_i(x_{i1}, y_{i1}, z_{i1}), T_{i2}(x_{i2}, y_{i2}, z_{i2}), T_{i3}(x_{i3}, y_{i3}, z_{i3})$, where $T$ – designation of the vertex point of the triangle; $i$ – triangle number; indices 1, 2, or 3 mean the vertex number for the $i$ triangle. In the framework of the mathematical description on the calculation schemes, the indexing of triangles is presented in this format. For the formation of complex surfaces, triangles are joined together on any edge: for adjacent triangles, two vertices coincide (e.g., $T_{71} = T_{81}, T_{72} = T_{82}$). If the triangles are not joined along some ribs, these ribs act, for example, as cutting edges of rotors and disks.

Some surfaces perform rotational and translational movement (rotor, spherical disks, auger drum), some surfaces (protective casing and soil pipe) are only translational.

2.2. General introduction of the forest fire extinguishing machine

The model considers a single-row machine to extinguish forest fires (or half of a two-row machine). The simulated forest fire extinguishing machine consists of four main parts: a rotor, a protective casing that passes into the soil pipe, a spherical disk with cutouts, and a screw drum. Figure 4 presents the basic geometric parameters of the mutual layout of the main parts of the machine to extinguish forest fires. The layout center of the forest fire extinguishing machine in the $CG$ - model coincided with the assumed location of the center of gravity of the machine. Figure 4 shows the location of the key points of the components of a forest fire extinguishing machine using soil: $CR$ – rotor, $CP$ – protective casing, connected to the soil pipe, $CD$ – spherical disk equipped with a cutting edge with semicircular cutouts, $CB$ – auger drum. The location of the key points is chosen so that the mathematical expressions describing the parts of the forest fire extinguishing machine using soil can be composed in the simplest way.

![Figure 4. Basic layout parameters of the forest fire extinguishing machine.](image)

3. Conclusions

The physical and mathematical model and computer program have been developed for carrying out computational experiments on soil throwing by a machine, which allow us to study the influence of structural and technological parameters of the machine, as well as the properties of the soil on the performance indicators of soil throwing.
Acknowledgments
The reported study was funded by RFBR, project number 19-38-60041.

References
[1] Bartenev IM, Druchinin D Yu and Gnusov M A 2012 On the question of fighting forest fires with soil Forestry engineering journal 8 97-101
[2] Baburkin P O, Komarov P V, Hizhniak S D and Pakhomov P M 2015 Modeling the gelation process in a cysteine-silver solution by the method of dissipative particle dynamics Colloid journal 77 572-81
[3] Belotserkovsky O M and Davydov Yu M 1982 The method of large particles in gas dynamics Science 392
[4] Voznesensky A S 2011 Computer methods in scientific research. Part 2 Computer modeling of physical objects and processes of mining production 107
[5] Grigoryev Y N, Vshivkov V A and Fedoruk M P 2004 Particle-in-cell numerical simulation Novosibirsk: Publishing House SB RAS 360
[6] Drapalyuk M V, Stupnikov D S, Druchinin D Yu and Pozdnyakov E V 2019 Forest fires: methods and means for their suppression IOP Conf. Series: Earth and Environmental Science 226
[7] Efimova N B 2010 Ensuring fire safety as a factor of increasing the stability of a low-forest region Problems and prospects for the development of land reclamion and forestry in the Southern Federal District: materials of international scientific training conference. The 90th anniversary of higher forest education in the Don pp 241-5
[8] Zaliznyak V E 2006 Fundamentals of Computational Physics. Part 2. Introduction to particle methods Regular and chaotic dynamics 156
[9] Kryvtsov A M and Kryvtsova N V 2002 Particle method and its use in the mechanics of a deformable solid Far Eastern Mathematical Journal of the Far Eastern Branch of the Russian Academy of Sciences 3 254-76
[10] Español P 1995 Hydrodynamics from Dissipative Particle Dynamics Phys. Rev. E. 52 1734-42
[11] Hoover W G 1983 Atomistic Nonequilibrium Computer Simulations Physica A 118 111-22
[12] Hockney R, Eastwood J 1987 Particle Numerical Modeling World 638
[13] Kryvtsov A M and Kryvtsova N V 2002 Particle method and its use in the mechanics of a deformable solid Far Eastern Mathematical Journal of the Far Eastern Branch of the Russian Academy of Sciences 3 254-76
[14] Jakob C and Konietzky H 2012 Particle Methods An Overview Freiberg 24