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Ripper foot movement in the ground, simulated compressible H.A.Rahmatulin's environment

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ABSTRACT: The article deals with the task of moving the ripper in a soil medium simulated by a plastically compressible medium proposed by Rakhmatulin. Where the soil under loading changes its density according to a certain law and, during unloading, it retains the density obtained during loading. Assuming the ripper with a thin body, the equation of the soil motion was compiled, where the "hypothesis of flat sections" proposed by Rakhmatulin and Ilyushin was used to solve a number of aerodynamic problems.

KEYWORDS: ripper, plastic medium, loading, unloading, thin body, flat section hypothesis.

I. INTRODUCTION

Establishing patterns of interaction of a solid body with the ground is of interest in questions of a projectile falling into the ground, landing an aircraft on the ground, driving piles and other tasks related to determining contact force (resistance) on the surface of the body. At the same time, difficulties arise in determining the movement of the ground, where its physicomechanical properties will play a significant role. Soils, as already noted, differ in structure, shape, packaging of solid particles, water and air content. The consequence of this is a large variety of soil mechanical properties under dynamic and static effects. This, in particular, explains the difficulties in practice for determining the laws of motion of solids in the soil environment.

In papers [1-2], experimental methods for studying the behavior of soils under static and dynamic effects were developed. Based on the analysis of the results of these studies, various models of soils with more or less general properties have been developed. This circumstance made it possible to achieve certain success in solving problems of the dynamics of bodies moving in a ground medium. The fundamentals of soil modeling are described in the monograph [1]. When considering applied soil, it is modeled as a multicomponent continuous medium, the motion of which is characterized as an ideal fluid or elastic (multicomponent) medium. Such a model can be used to describe the movement of water-saturated soils. For soils of low or medium humidity, i.e. consisting of solid particles and air inclusions, large shear and bulk irreversible deformations are significant. Such soils are usually considered as plastic compressible medium.

II. PROBLEM FORMULATION

With very large compressive loads (pressures), where the mean hydrostatic pressure is much higher than the shear stresses, soils can be considered as compressible fluid with reversible or irreversible volumetric deformation.

In this work, the model of "plastic gas" by academician Rakhmatulin [1] is used. According to this model, the soil during loading changes its density according to a certain law; during unloading, it preserves the density obtained during loading. In the future, simulate the soil plastic compressible medium. Consider the ripper legs in the form of a sharp wedge with the same two side faces in the form of a rectangle with an acute angle λ at the apex. The surface area of the foot will be equal to:

$$S_{лап} = h^2_{лап} \frac{tg\lambda}{\cos^2 \beta_{лап}},$$

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$h_{лап}$ is the height of the foot, $\beta_{лап}$ is the angle of inclination of the foot to the base. For the equation of motion of the surrounding wedge soil replace the wedge with the reduced circular cone with an area equal to $S_{кл}$. Denote by $h_{кон}$ and $2\beta_{кон}$ the height of the cone and the angle at the vertex, which should satisfy the equation:

$$\frac{\pi h^2_{кон} tg\beta_{кон}}{cos\beta_{кон}} = S_{лап}$$

In particular, if we take the heights of the foot and the cone equal to $h_{кл} = h_{кон} = h$, then for the angle ($\beta_{кон}$) we have the expression:

$$\beta_{кон} = \arcsin(\sqrt{p^2+1} - p),\ p = \frac{\pi \cos^2 \beta_{лап}}{2tg\lambda}$$

To compose the equation of motion of the soil, we use the "hypothesis of flat sections" proposed by Rakhmatulin and Ilyushin to solve a number of aerodynamic problems. According to this hypothesis, soil particles perform radial movements in a plane perpendicular to the axis of symmetry of a solid (cone). In this case, the problem of body motion is reduced to the study of the motion of a compressible plastic (granular) medium with cylindrical symmetry [2].

Let the cone begin to move according to the law. Consider an arbitrary section of the cone ($L_1 = L(t_1)$ ($0 < L_1 < L(t)$) we assume that at the point of contact of the vertex of the cone of this section ($t = t_1$), a cylindrical compression wave occurs in the ground at the moment (), and at the time point ($t > t_1$) the boundary of the field of disturbed soil motion will be limited by the radii of the cylindrical wave $r = r_*(t)$ and $r = tg\beta\ L(t)$, which is the intersection line of the surface of the cone with the plane under consideration.

III. SOLUTION METHOD

We assume that the density of the soil changes only at the front of a cylindrical wave is determined by the intensity of this wave and therefore the density of the soil in the perturbation region is only a function of the coordinate r and does not depend on time t. We take r for the Lagrangian coordinate and write the equations of motion and continuity in cylindrical coordinates in an arbitrary section $L = L_1$:

$L = L_1$

$$\rho_0 r \frac{\partial^2 u}{\partial t^2} = (r+u)\frac{\partial \sigma_r}{\partial r} + (\sigma_r - \sigma_\theta)\frac{\partial}{\partial r}(r+u), \tag{1}$$

$$\frac{1}{2}\frac{\partial}{\partial r}(r+u)^2 = \frac{\rho_0}{\rho} r, \tag{2}$$

r is -the initial distance of particles from the axis of the cone, $u = u(r,t)$ - displacement of the soil particle at this distance, t - time, ρ_0 and ρ are the initial and current density of the soil in the disturbed region $L_1 < r < r_*(t)$, σ_r and σ_θ are radial and tangential stresses.Since the soil is modeled by plastic (bulk) medium, the stresses satisfy the Prandtl plasticity condition [3]:

$$\sigma_r - \sigma_\theta = \tau_0 + \mu(\sigma_r + \sigma_\theta) \tag{3}$$

where $\tau_0 = 2k\cos\theta$ and $\mu = \sin\theta$, k - grip, θ - the angle of internal friction.

Eliminating the stress from equation (1) we bring it to the form:

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$$\nu\sigma_r \frac{\partial(r+u)}{\partial r} + (r+u)\frac{\partial \sigma_r}{\partial r} = \rho_0 r \frac{\partial^2 u}{\partial t^2} - \frac{\tau_0}{1+\mu}\frac{\partial}{\partial r}(r+u) \,. \tag{4}$$

Here $\nu = 2\mu/(1+\mu)$

Multiply both sides of equation (4) by functions $(r+u)^{\nu-1}$ and integrate with respect to the Lagrangian variable r

$$(r+u)^\nu \sigma_r(r,t) = \rho_0 \int_0^r (r+u)^{\nu-1} r \frac{\partial^2 u}{\partial t^2} dr - \frac{\tau_0}{1+\mu}\frac{(r+u)^\nu - R^\nu}{\nu} + R^\nu \sigma_r(0,t)\,, \tag{5}$$

where $R = tg\beta L(t)$ is the radius of the internal boundary of the perturbed region in the Lagrangian variable $r = 0$ at an arbitrary time.

We denote by $\sigma_r^* = \sigma_r(r_*,t)$ the stress at the front of a cylindrical wave, where the movement of particles is zero. Then equality (5) on the front $r = r_*(t)$ is written in the form:

$$r_*^\nu \sigma_r^* = \rho_0 \int_0^{r_*} (r+u)^{\nu-1} r \frac{\partial^2 u}{\partial t^2} dr - \frac{\tau_0}{1+\mu}\frac{r_*^{\ \nu} - R^\nu}{\nu} + R^\nu \sigma_r(0,t) \tag{6}$$

Subtracting (6) from (5), we get:

$$(r+u)^\nu \sigma_r(r,t) - r_*^\nu \sigma_r^* = -\rho_0 \int_r^{r_*} (r+u)^{\nu-1} r \frac{\partial^2 u}{\partial t^2} dr + \frac{\tau_0}{1+\mu}\frac{r_*^{\ \nu} - (r+u)^\nu}{\nu} \tag{7}$$

Considering now the independence of density from time in a perturbed domain, we integrate the continuity equation (2):

$$(r+u)^2 = 2\psi(r) + R^2(t) \tag{8}$$

Where $\psi = \int_0^r \frac{\rho_0}{\rho(r)} r dr$

At the wave front $r = r_*(t)$ we have $u = 0$, therefore from (8) we have:

$$r_*^2 = 2\psi(r_*) + R^2(t)\,,\ \psi(r_*) = \int_0^{r_*} b(r) r dr\,,\ b = \rho_0/\rho(r) \tag{9}$$

With a known law $\rho = \rho(r)$, from the formula (9) it is possible to establish the law of movement of the front of a cylindrical wave $r = r_*(t)$.

Differentiating (8) over time, we find the velocity and acceleration of soil particles in the perturbation region $L_1 < r < r_*(t)$:

$$\frac{\partial u}{\partial t} = \frac{R\dot{R}}{\sqrt{2\psi(r) + R^2(t)}}\,,\ \frac{\partial^2 u}{\partial t^2} = \frac{\dot{R}^2 + R\ddot{R}}{\sqrt{2\psi(r) + R^2(t)}} - \frac{R^2\dot{R}^2}{[2\psi(r) + R^2(t)]^{3/2}}\,, \tag{10}$$

The speed of soil particles at the wave front is determined from the first expression (10), where you should assume $r = r_*(t)$:

$$\dot{u}_* = \frac{R\dot{R}}{\sqrt{2\psi(r_*) + R^2(t)}} = \frac{R\dot{R}}{r_*} \tag{11}$$

To determine the stress at the wave front $\sigma_r = \sigma_r^*$, we use the law of conservation of mass and the theorem on the amount of motion [2]:

$$\rho_0 D = \rho(D - \dot{u}_*) \tag{12}$$

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$$\rho_0 D\dot{u}_* = -\sigma_r^* - p_a \tag{13}$$

Where D is a frontal velocity of a cylindrical wave, p_a is pressure ahead of the compression wave. From (12) and (13) we find the wave velocity D and stress σ_r^* :

$$D = \frac{\dot{u}_*}{1-b(r_*)}, \sigma_r^* = -\frac{\rho_0 \dot{u}_*^2}{1-b(r_*)} - p_a \tag{13}$$

Supplying the acceleration of particles and the expression σ_r^*, respectively, from (10) and (13) to (7), we find the voltage in the perturbed region:

$$(r+u)^\nu \sigma_r = \rho_0 (R\ddot{R} + \dot{R}^2)\int_r^{r_*} \frac{rdr}{[2\psi(r)+R(t)]^{1-\nu/2}} - \rho_0 (R\dot{R})^2 \int_r^{r_*} \frac{rdr}{[2\psi(r)+R(t)]^{2-\nu/2}} + \frac{\rho_0}{1-b(r_*)}\frac{(R\dot{R})^2}{r_*^{2-\nu}} +$$

$$+\frac{\tau_0}{1+\mu}[r_*^\nu - (r+u)^\nu] + p_a r_*^\nu \tag{14}$$

Substituting the expression $r+u$ from (8) in formula (14), we can establish the spatial – temporal distribution of stress in the perturbation region, where it is necessary to consider a known experimentally determined function $\psi(r)$. If we consider the process of wave propagation over a small period of time, then we can assume the density of the soil behind the wave front is constant and equal to $\rho = \rho_1 = const$. Assuming $r = 0, u = R(t)$ we obtain an explicit expression for the stress $p = -\sigma_r$ on the surface of the cone:

$$p - p_a = \ddot{L}\frac{\rho_0 \varphi(\nu, b_1) x tg^2\beta}{b_1} + \dot{L}^2 \frac{\rho_0 tg^2\beta}{b_1(\nu-2)}[(\nu-2)\varphi(\nu,b_1) + b_1(\nu-2)a^{\nu/2} - a^{\nu/2-1} + 1] +$$

$$+\varphi(\nu,b_1)[\nu p_a + \tau_0/(1+\mu)] \tag{15}$$

Where $b_1 = \rho_0/\rho_1$, $x = L - L_1$, $\varphi(\nu,b_1) = (a^{\nu/2}-1)/\nu$, $a = 1/(1-b_1)$.

The total resistance force acting on the surface of the cone is calculated using the integral (μ_0 - coefficient of friction between the soil and the surface of the cone):

$$F = 2\pi(\sin\beta + \mu_0\cos\beta)\int_0^h (p-p_a) x tg\beta\sqrt{1+tg^2\beta})dx$$

Substitute the expression of pressure from (15) and perform the integration, then taking into account $R = Ltg\beta$, we obtain:

$$F = (1+\mu_0 ctg\beta)\,(A + B\rho_0\dot{L}^2 + \rho_0 Ch\ddot{L})h^2 \tag{16}$$

Where

$$A = \pi tg^2\beta[p_a + \frac{\tau_0}{\nu(1+\mu)}](a^{\nu/2}-1),\ C = \frac{\pi tg^4\beta}{3b_1\nu}(a^{\nu/2}-1),\ a = 1/(1-b_1)$$

$$B = \frac{\pi tg^4\beta}{b_1(\nu-2)}\left[\frac{\nu-2}{\nu}(a^{\nu/2}-1) + b_1(\nu-2)a^{\nu/2} - (a^{\nu/2-1}-1)\right].$$

The equation of motion of a cone (body) with mass m under the action of an external force $P_0(t)$ is written in the form:

$$m\ddot{L} = -F + P_0(t)$$

or taking into account (16) we bring to the form:

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$$[m+m_{np}(h)]\ddot{L} = -(1+\mu_0 ctg\beta)(A+B\rho_0\dot{L}^2)h^2 + P_0(t) \tag{17}$$

Where $m_{np}(h) = (1+\mu_0 ctg\beta)\rho_0 Ch^3$ - attached ground mass.

Equation (17) with the action of an arbitrary force is integrated numerically with the initial conditions $L=0$ and $\dot{L}=0$ at $t=0$. Consider the case:

$P_0(t) = P_{00} = const$

Assuming $\dot{L}^2 = y(L)$, $p_0 = 2P_{00}/[m+m_{np}(h)]$, from equation (17) we bring to the form:

$$y' + ay = -b + p_0 \tag{18}$$

Let the foot begins to move with a zero initial speed, i.e. believe $y=0$ at $L=0$. To overcome the resistance force of the soil, as can be seen from the equation, it should be assumed $\ddot{L}>0$ that it is necessary to apply a force satisfying the condition $P_{00} > P^* = A(1+\mu_0 ctg\beta)h^2$.

IV. ANALYSIS OF THE RESULTS

Figure 1 shows the dependence of the limiting force on the ratio $b_1 = \rho_0/\rho_1$ for different values of the parameter $\mu = \sin\theta$. The maximum and minimum values of this force for the selected parameters will be equal $P^*_{\min} = 2.6H$ at $b_1 = 0.1$, $\mu = 0.9$ and $P^*_{\max} = 241H$ at $b_1 = 0.9$, $\mu = 0.$.

It can be seen that for loosened soil (small values of the ratio $b_1 = \rho_0/\rho_1$ or large values of the parameter μ), the movement of the foot begins at insignificant values of force $P_{00} \approx 2.6H$.

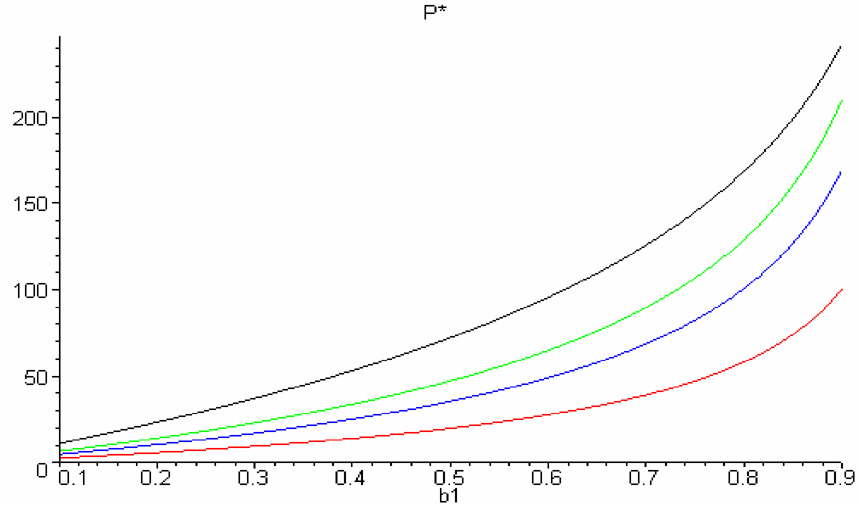

Fig.1. Dependence of the limiting force $P^*(H)$ on the ratio $b_1 = \rho_0/\rho_1$ for different values of the parameter $\mu = \sin\theta$: black - $\mu = 0$, green- $\mu = 0.5$, blue- $\mu = 0.7$, red- $\mu = 0.9$

Integrating equations (18) with the initial condition $y=0$ for $L=0$, we get:

$$y = \frac{dL}{dt} = v_* \sqrt{1-\exp(-aL)} \tag{19}$$

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Where $v_* = \sqrt{\dfrac{p_0 - b}{a}}$ maximum speed of the foot, achieved at $t \to \infty$.

Figure 2 shows the dependence of the limiting velocity v_* $(м/c)$ on the ratio $b_1 = \rho_0 / \rho_1$ for $P_{00} = 50H$ different values of the parameter $\mu = \sin\theta$. Analysis of the curves shows that for the selected value of the force P_{00}, the movement of the foot is realized for limited values of the parameters b_1 and μ, and it has the highest limiting speed at small values of the ratio $b_1 = \rho_0 / \rho_1$. It can be seen that a significant effect of the parameter is found for large values of the ratio $b_1 = \rho_0 / \rho_1$.

As the value grows P_{00}, the realizable motion region for the parameters b_1 and will μ also increase.

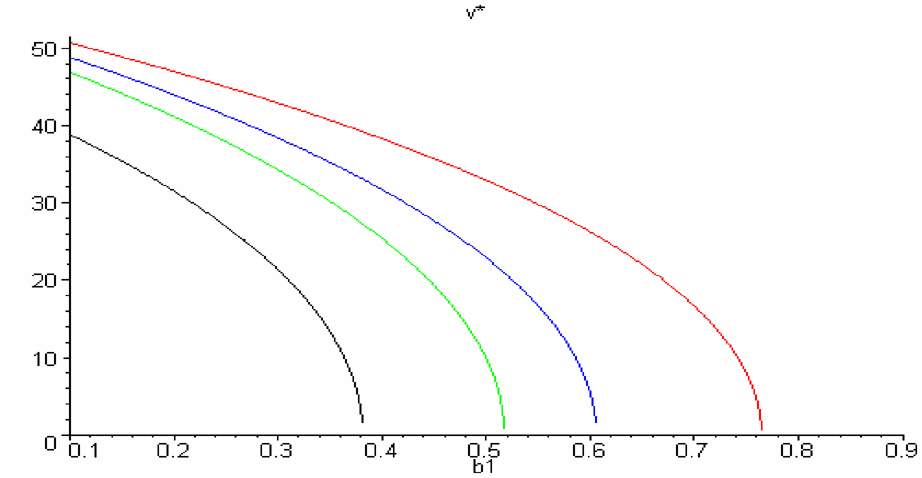

Fig.2. Dependence of the limiting velocity v^* $(м/c)$ on the ratio $b_1 = \rho_0 / \rho_1$ for different values of the parameter $\mu = \sin\theta$: black - $\mu = 0$, green- $\mu = 0.5$, blue- $\mu = 0.7$, red- $\mu = 0.9$

We integrate equation (19) with the initial condition $L = 0$ at $t = 0$, then we get:

$$L = \frac{1}{a}\ln\left[\frac{[1+\exp(v_* at)]^2}{4\exp(v_* at)}\right]$$

In fig. 3 shows the graphs of the movement of the foot $L(м)$ mass $m = 5кг$ with time for three values of the parameter μ and different values of the ratio $b_1 = \rho_0 / \rho_1$ under the action of a constant force $P_{00} = 50H$.

From the analysis of the curves obtained it follows that the speed of the foot with time increases quickly reaches the limit value, and then the foot moves at a constant speed. At small values of the parameter μ, the movement of the foot is realized only for smaller values of the ratio $b_1 = \rho_0 / \rho_1$ (Fig. 3a), which corresponds to a looser soil. With the growth of the soil relatedness parameter μ $(\mu > 0.5)$, the movement of the foot can be realized for all values of the ratio $b_1 = \rho_0 / \rho_1$ (Fig. 3b)

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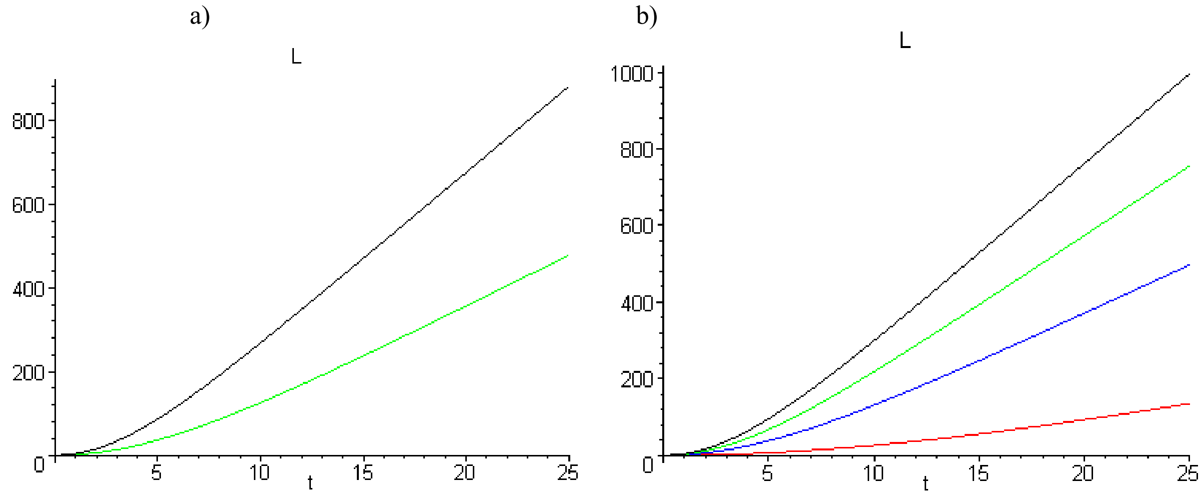

Fig.3. Dependence of the movement of the foot L $(м)$ on time t (s) with $\mu = 0.1$ (a), $\mu = 0.5$ (b) and various values of the relation $b_1 = \rho_0 / \rho_1$: black - $b_1 = 0.1$, green- $b_1 = 0.3$, blue- $b_1 = 0.4$, red- $b_1 = 0.5$

V CONCLUSION

1. It is shown that for the selected value of the force P_{00}, the movement of the paw is realized for limited values of the parameters b_1 and μ, and it has the highest speed limit at small values of the ratio $b_1 = \rho_0 / \rho_1$. As the value grows P_{00}, the realizable motion region for the parameters b_1 and μ will also increase.
2. It has been established that with the growth of time, the speed of the foot quickly reaches the limiting value, and for small values of the soil relatedness parameter μ, the movement of the foot is realized only for small values of the ratio $b_1 = \rho_0 / \rho_1$, which corresponds to a looser soil. With the growth of this parameter $(\mu > 0.5)$, the movement of the foot can be realized for all values of the relation $b_1 = \rho_0 / \rho_1$.

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