Strain state agrogenic soil under its interaction with a deep ripper

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Abstract. The cultivated soil environment changes its structure and is deformed; therefore, the considered model of the processes of interaction of the working body with soil remains understudied. The influence of soil criteria on the working body behavior can be taken into account through its density and tensile strength. To describe the movement of the soil near the leg during finite deformations, a plastic medium model proposed by academician Kh.A. Rakhmatulin and simplified equations obtained on the basis of the hypothesis of flat sections were used. When using the model of linearly elastic and compressible plastic medium, the resistance forces of the soil medium are determined when the legs of the subsoiler, presented in the form of a circular cone, move. It has been established that the magnitude of this force substantially depends on the type of contact conditions between the body and the soil, and its greatest value is achieved in the case of continuous motion. The dependence of the resistance force on time is obtained. According to the results of graph analytical studies, it is obvious that at the initial stage, while the contact area of the circular cone with the soil is variable, the resistance force depending on time changes according to a parabolic law, and then it remains constant. In the case of the movement of the subsoiler leg at a constant speed, it was found that, depending on the coefficient of internal friction and soil traction, a zone of increased soil density can form near the working body of the cultivator, where there is a significant increase in resistance force. With an increase in the angle of internal friction, a slight decrease in the resistance force is observed. The calculations were carried out based on the methods of mechanics of a deformable solid, soil mechanics, and were performed in the Maple-8 programming environment.

1. Introduction

The practice of cultivating agricultural land shows that more than 50% of the subsurface horizon is subjected to additional compaction by the operating elements of tillage tools, i.e. a “plow sole” is formed. In this regard, the roots of plants cannot go through the compacted soil layer (plow sole) and penetrate into the lower, wetter layers.

The prevention of the subsurface horizon compaction is important to ensure good functioning of soil and its ecological state, since the subsurface horizon compaction is almost a constant phenomenon; it reduces crop yield and increases the nutrients washing-out from soil [1].
As is known, one of the effective methods of soil loosening and “plow sole” destroying is mechanical cultivation to a depth of 50 cm using deep ripplers or chisel plows, widely used in foreign countries, such as the USA, Germany, Canada, Romania and Hungary. These countries occupy one of the leading places in the field of creating and producing special implements for deep soil loosening (subsoilers, kilifers, etc.).

According to the studies conducted by foreign scientists, it has been found that long-term rotation and tillage has a negative effect on the soil surface layer, and due to global climate change, water consumption in agriculture becomes more and more problematic. When loosening a dense subsoil layer to a depth of 60 cm due to water consumption, the permeability and moisture capacity of soil increases significantly, so, the side roots of plants develop better, and the crop is more complete [2].

In Central Asia, the studies by A Tukhtakuziev [3], T Rashidov [4], B Mardonov [5] and others are devoted to physical and mechanical properties of soil, taken into account when creating new and improving existing tillage machines. As a result of the studies, it was revealed that deep loosening of soil:

- creates conditions for "absorption", accumulation of significant reserves of moisture in soil and air, and its redistribution;
- improves the microclimate in soil;
- provides effective moisture-air exchange in a loosened layer;
- increases the number of active roots in the loosening zone;
- prevents erosion processes;
- due to compaction of soil, the resistance decreases at tractor and other implements passing, which leads to fuel and lubricants saving; the load on the implements is reduced;
- shows high weed control.

As a result of deep ripper operating element penetration into soil, a soil resistance force arises, the magnitude of which depends on the physical mechanical properties of soil and design features of the operating element of a deep ripper. The results of experimental data indicate the need to take into account the type of soil and its properties when creating new and improving existing tillage machines. Due to the fact that the soil has the least resistance to tension and torsion, it is recommended to cultivate soil by destroying the soil medium by tensile or torsional strain.

In [6], a working model of soil behavior was described at the border of arable and subsurface horizons using the discrete element method. The research results showed that the range of soil disturbance in the upper (shallow) layer was the widest one, followed by the less range of soil disturbance in the middle layer and then the range of soil disturbance in the deep layer. The resistance force of soil particles in the deep layer was the greatest, followed by the resistance force of soil particles in the middle layer and then in the shallow layer. The rate of soil particles motion in different places decreased with increasing distance between the arable and subsurface horizons. Relative error between the simulated and experimental values of soil friability and soil disturbance coefficient was 14.45% and 12.06%, respectively. Thus, the results of this research can be used to study the soil interaction with a cultivating point and to optimize the mechanisms of tillage machines.

Thus, the previously developed technological schemes for soil cultivation and corresponding designs of operating elements of a deep ripper in conditions of unlocked soil cutting, experimental methods for studying soil behavior under static and dynamic effects, as well as the proposed soil models using the discrete element method [7 – 9], allowed to achieve certain success in solving the problems of the dynamics of bodies moving in soil medium.

However, the models of soil medium under its interaction with the operating elements of a deep ripper, the dynamic phenomena in soil and cultivator units in the process of loading by variable tractive force have not been sufficiently studied; and there is no scientifically based methods for assessing the stress state of strained nodes of the deep ripper units interacting with soil medium. The above problems are relevant and require the development of analytical and numerical methods for studying the dynamics of the deep ripper operating elements when it moves in soil modeled by an elastic and compressible
plastic medium and requires the assessment of its load, which is necessary for a further reduction in energy consumption and improvement of operating quality of tillage machines.

In this work, on the basis of previous studies, the key factors that affect the stress-strain state of soil medium are identified, the soil resistance forces are determined using the selected soil model, and thereby the law of motion of the deep ripper operating element in soil medium is established.

2. Description of design and key parameters of the working process of deep ripper operating elements
Special deep rippers are used to loosen the subsurface horizon since it presents an energy-intensive technological process.

Figs. 1 and 2 show a side view of operating element of a deep ripper and the scheme of an experimental design of a deep ripper [3].

A deep ripper consists of a frame 7 (Fig. 2) and fixed on it (sequentially and terrace-like) central 3 and side 1 operating elements, and supporting wheels 6. The central operating element of the implement is made in the form of a rack with a ripping element (chisel), made in the form a horizontal dihedral wedge with a horizontally transverse cutting edge, and the side operating elements are made in the form of one-sided left and right vertical ripping plates (wedges) installed at angle \( \beta \) to the direction of motion (Fig. 1).

Consider the technological process of the implement operation, Figure 2. The central operating element of the deep ripper located first in the direction of motion loosens the soil at a set depth and forms loosened zone 4. Next, the side operating elements loosen the soil and form loosened zones 2 and 5. The side operating elements deform the soil in the direction of weakened bonds, that is, towards the zone loosened by the previous operating element. Thus, soil destruction occurs along the lines of the weakest bonds, that is, where the soil strength is minimal. This leads to a reduction in energy consumption for tillage at deep loosening.

3. Models of the process of cultivating machine operating elements interaction with soil medium
During the motion of a tillage machine in soil medium, the soil is deformed and a time-varying interaction force (the resistance force) arises on the contact surface of processing elements and the moving part of surrounding medium. The magnitude of the interaction force primarily depends on dynamic structure of soil, which undergoes constant changes due to a wide spectrum of biotic and abiotic factors, such as bioturbation and mechanical disturbance of soil, considered in [10], and structural features of processing machine. The parameters of power capability of machines are determined by the nature of machine operating elements interaction with the processed soil medium. Therefore, in theoretical terms, the choice of an interaction model of soil medium with operating elements of the
processing machine is of particular importance. In [11], an exact solution was obtained for one-dimensional Riemann problem of elasticity and plasticity, used to validate the reliability of a method for solving problems of a compressible fluid of complex geometry in a solid region, when studying the reaction of various structural regions. When solving applied problems of soil interaction with rigid body, soil is most often modeled as a multicomponent continuous medium; its motion is characterized as an ideal fluid or an elastic (multicomponent) medium. Such a model can be used to describe the motion of water-saturated soils [15, 16]. For soils of low or medium humidity, that is, the ones consisting of solid particles and air inclusions, the presence of large volume irreversible strains and shear strains is significant. Such soils are usually regarded as a plastic compressible medium.

Figure 3. Scheme of a deep ripper cultivating point motion in soil

As is known, the three-dimensional theory of elasticity is used for structural modeling of a cylindrical shell [17]. Based on this, assume that at the point of contact of the cone vertex of this section at time \( t=t_1 \), a cylindrical compression wave is initiated in soil, and at time \( t>t_1 \), the boundary of the region of disturbed ground motion is limited by the radius of cylindrical wave \( r=r^* (t) \) and the radius \( r=L(t)\tan \beta \) that is the line of intersection of cone surface with the plane under consideration.

Assume that the soil density changes only at the front of the cylindrical wave and is determined by the intensity of this wave. Therefore, the soil density in the disturbance region is a function of coordinate \( r \) and does not depend on time \( t \). We take \( r \) for the Lagrangian coordinate and write the equation of motion and continuity in cylindrical coordinates in an arbitrary section \( L=L_1 \):

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

where \( r \) is the initial distance of the particles from the cone axis, \( u=u(r,t) \) is the displacement of a soil particle at this distance, \( t \) is time, \( \rho_0 \) and \( \rho \) are the initial and current densities of soil in the disturbed region \( L_1<r<r^*(t) \), \( \sigma_r \) and \( \sigma_\theta \) are the radial and tangential stresses. Since the soil is modeled by a plastic (loose) medium, the stresses satisfy the Prandtl plasticity condition:

\[
\sigma_r - \sigma_\theta = \tau_0 + \mu (\sigma_r + \sigma_\theta),
\]

where \( \tau_0 = 2k \cdot \cos \theta \) and \( \mu = \sin \theta \), \( k \) is the cohesion, \( \theta \) is the angle of internal friction.

Excluding stresses \( \sigma_\theta \) from equation (1), reduce it to the form:

\[
\nu \sigma_r \frac{\partial (r+u)}{\partial r} + (r+u) \frac{\partial \sigma_r}{\partial r} = \rho_0 r \frac{\partial^2 u}{\partial t^2} - \frac{\tau_0}{1+\mu} \frac{\partial (r+u)}{\partial r}.
\]

Here \( \nu = \frac{2\mu}{(1+\mu)} \). We multiply both sides of equation (4) by function \( (r+u)^{\nu-1} \) and integrate over the Lagrangian variable \( r \):

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

where \( R = \nu_0 \cdot \tan \beta \) is the radius of the inner boundary of the disturbed region at the Lagrangian variable \( r = 0 \) at an arbitrary moment in time.
Denote by $\sigma_r^* = \sigma_r(r, t)$ the stress at the front of cylindrical wave $r = r_0(t)$, where the particle displacement is zero. Then equality (5) at the front $r = r_0(t)$ is written in the form:

$$n^r \sigma_r^* = \rho_0 \int_0^r (r + u)^{\nu-1} r \frac{\partial^2 u}{\partial t^2} dr + \frac{\tau_0 - r_0^v - R^v}{v} + R^v \sigma_r(0, t).$$

(6)

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

$$(r + u)^v \sigma_r(r, t) - n^r \sigma_r^* = -\rho_0 \int_0^r (r + u)^{\nu-1} r \frac{\partial^2 u}{\partial t^2} dr + \frac{\tau_0 - r_0^v - (r + u)^v}{v}.$$  

(7)

Given the independence of density on time in the disturbed region, we integrate the continuity equation (2):

$$(r + u)^2 = 2\psi(r) + R^2(t),$$

(8)

where $\psi(r) = \int_0^r \rho_0 \rho(r) r dr$.

Knowing that $u = 0$ at the wave front $r = r_0(t)$, from (8) we have:

$$r_0^2 = 2\psi(r_0) + R^2(t),$$

(9)

where:

$$\psi(r_0) = \int_0^{r_0} b(r) r dr, \quad b = \rho_0 / \rho(r)$$

At a constant velocity of the cone we have $L = v_0 t \cdot (R = v_0 t \cdot r_0 \beta)$, then according to the well-known law $\rho = \rho(r)$, from formula (9), we can state the law of displacement of the front of a cylindrical wave $r = r_0(t)$.

Differentiating (8) over time, we find the velocity and acceleration of soil particles in the disturbance region $L_1 < r < L_4(t)$:

$$\frac{\partial u}{\partial t} = \frac{R \cdot \dot{R}}{\sqrt{2\psi(r) + R^2(t)}},$$

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

(10)

where $R = v_0 t \cdot r_0 \beta$, $\dot{R} = v_0 t \cdot \beta$, $\ddot{R} = 0$.

The velocity of soil particles at the wave front is determined from the first expression (10), where it is assumed that $r = r_4(t)$:

$$u_s = \frac{R \dot{R}}{\sqrt{2\psi(r_0) + R^2(t)}} = \frac{R \dot{R}}{r_0}.$$  

(11)

To determine stress $\sigma_r = \sigma_r^*$ at the wave front, the law of mass conservation and the momentum theorem [14] are used:

$$\rho_0 D = \rho(D - u_s),$$

(12)

$$\rho_0 Du_s = -\sigma_r^* - p_a,$$

(13)

where $D$ is the velocity of cylindrical wave front, $p_a$ is the pressure ahead of compression wave. From (12) and (13) we find the wave velocity $D$ and stress $\sigma_r^*$:

$$D = \frac{u_s}{1 - b(r_0)}, \quad \sigma_r^* = -\frac{\rho_0 u_s^2}{1 - b(r_0)} - p_a.$$
Substituting into (7), the particle acceleration and expression \( \sigma_r^* \) from (12) and (13), respectively, we find the stress in the disturbed region:

\[
(r + u)^2 \sigma_r = \rho_0 (R_R + R^2) \left\{ \frac{dr}{r^2[2\psi(r) + R(t)]^{1-v/2}} - \rho_0 (R_R)^2 \left\{ \frac{dr}{r[2\psi(r) + R(t)]^{2-v/2}} + \frac{\rho_0}{1 - b(r)} \frac{(R_R)^2}{r e^{-v}} + \frac{\tau_0}{1 + \mu} [r^v - (r + u)^v] + p_a r^v. \right. \right\} 
\] (14)

Substituting expression (8) into formula (14), we can state the spatial-time stress distribution in the disturbance region, where it is necessary to consider as known the experimentally determined function \( \psi(r) \). If to consider the process of wave propagation in a short period of time, we can assume that the soil density behind the wave front is constant and equal to \( p = \rho_1 = \text{const} \). Assuming that \( r = 0, u = R(t) \), we obtain an explicit expression for stress \( p = -\sigma_r \), on the cone surface:

\[
p - p_a = E \left[ \frac{\rho_0 \cdot \phi(v, b_1) \cdot xtg^2 \beta}{b_1} + L^2 \frac{\rho_0 \cdot tg^2 \beta}{b_1 (v - 2)} [(v - 2) \cdot \phi(v, b_1) + b_1 (v - 2) \cdot a^{v/2} - a^{v/2-1} + 1] + \phi(v, b_1) \left[ v \cdot p_a + \frac{\tau_0}{(1 + \mu)} \right], \right. \right\] (15)

where \( b_1 = \rho_0 / \rho_1 \), \( x = L - L_1 \), \( \phi(v, b_1) = (a^{v/2} - 1) / v \), \( a = 1/(1 - b_1) \).

Using the known values of stresses \( \sigma_y, \sigma_0 \) (9) – (12) and pressure \( p \) from formula (15) on the surface of the body, and integrating them, we can find the contact force of soil medium and body interaction.

4. Determination of tractive force of body motion at a constant velocity

The value of the contact force of interaction (the resistance force), as noted above, depends on the chosen model of soil medium and body configuration. Let us find the expression of this force in the case of body motion in the form of a circular cone in a compressible plastic medium. Then the total resistance force acting on the cone surface is calculated using the integral (\( \mu_0 \) is the coefficient of friction between the cone surface and soil):

\[
F = 2\pi (\sin \beta + \mu_0 \cos \beta) \int_0^H (p - p_a) xtg \beta \sqrt{1 + xtg^2 \beta} \, dx
\]

Substitute the pressure expression from (15) and perform the integration, then, with \( R = H \cdot xtg \beta \), we obtain:

\[
F = \pi (1 + \mu_0 xtg \beta) \left( A + B \rho_0 H^2 + \phi_0 C \cdot H \cdot H^2 xtg^2 \beta, \right)
\] (16)

where:

\[
A = \left[ p_a + \frac{\tau_0}{v(1 + \mu)} (a^{v/2} - 1) \cos^4 \beta \right],
\]

\[
B = \frac{1}{4b_1 (v - 2)} \left[ \frac{v - 2}{v} (a^{v/2} - 1 + b_1 (v - 2) a^{v/2} - (a^{v/2-1} - 1)) \cos^2 \beta \sin^2 2\beta, \right.
\]

\[
C = \frac{1}{6b_1 v} (a^{v/2} - 1) \cos^2 \beta \sin^2 2\beta, \quad a = 1/(1 - b_1)
\]

In the case of a cone moving at a constant velocity, we have \( H = v_0 t \), \( \dot{H} = v_0 \), \( \dot{H} = 0 \). Then formula (16) takes the form:

\[
F = \pi (1 + \mu_0 qtg \beta) \left( A + 0.5B \rho_0 H^2 \right. v_0 \cdot vtg^2 \beta \cdot 2. \right)
\] (17)

A change in resistance force on time according to law (17) takes place up to the moment \( t = t_0 = v_0 / h_{\text{cont}} \). At \( t \geq t_0 \) the resistance force is constant and equal to:
\[ F = F_0 = \pi (1 + \mu_0 \cotg \beta) \left( A + 0.5 B \rho_0 h_0^2 \right) t \cotg \beta. \]  

(18)

Figs. 4 and 5 (for curves 1, 2, 3, 4, 5 at \( h_0 = 0.2 \), \( b_1 = 0.4 \), \( b_2 = 0.6 \), \( b_3 = 0.8 \) respectively) show graphs of dependence of the resistance force on time for various values of the ratio \( b_1 = \rho_0/\rho_1 \). In calculations the following values are taken: \( \lambda_{lap} = 10^9 \), \( \beta_{lap} = 10^4 \), \( k = 50000 \ N/m^2 \), \( \theta = 30^\circ \), \( \rho_0 = 2000 \ kg/m^3 \), \( v_0 = 2.777 \ m/s \) (10 km/h), \( \mu_0 = 0.2 \), \( h_{lap} = h_{const} = 0.2 \ m \).

As seen from the graphs at the initial stage, while the cone-soil contact area is variable, the resistance force depends on time according to a parabolic law, and then it remains constant. An increase in ratio \( b_1 = \rho_0/\rho_1 \), which corresponds to a more compacted state of soil behind the front of a cylindrical wave, leads to a significant increase in resistance force. Figure 5 shows similar dependences in the case of modeling soil as an ideal-plastic medium, i.e. \( \mu = 0 \) (\( \theta = 0 \)).

It can be seen that the absence of an angle of internal friction of soil for the case under consideration leads to about 1.2 - 1.3 time increase in the value of soil resistance forces.

The total resistance force acting on the cone surface is calculated using the integral (\( \mu_0 \) - coefficient of friction between the cone surface and soil):

\[ F = 2 \pi (\sin \beta + \mu_0 \cos \beta) \left( p - p_a \right) t \cotg \beta \sqrt{1 + \cotg^2 \beta} dx. \]

Substituting the pressure expression from (15) and performing the integration, with \( R = L \cdot \cotg \beta \), we obtain:

\[ F = \pi (1 + \mu_0 \cotg \beta) \left( A + B \rho_0 h_0^2 + \rho_0 C \cdot \hat{h} \cdot \hat{L} \right) h^2 , \]  

(19)

where:

\[ A = \pi \cdot \cotg^2 \beta \cdot \left[ p_a + \frac{\tau_0}{\sqrt{1 + \mu}} \right], \]

\[ B = \frac{\pi \cdot \cotg^4 \beta}{b_1 (\nu - 2)} \left[ \frac{v - 2}{\nu} \cdot (a^{\nu/2} - 1) \left( b_1 (\nu - 2) a^{\nu/2} - (a^{\nu/2} - 1) \right) + b_1 (\nu - 2) a^{\nu/2} - (a^{\nu/2} - 1) \right], \]

\[ C = \frac{\pi \cdot \cotg^4 \beta}{3b_1 \nu} (a^{\nu/2} - 1), \]

\( a = 1/(1-b_1) \).

In the case of a cone moving at a constant velocity, we have \( L = v_0 \), \( \hat{L} = v_0 \), \( \hat{L} = 0 \). Then the formula (17) takes the form:
\[ F = (1 + \mu \cot \beta) (A + B \cdot \rho_0 v_0^2) h^2. \]  

(20)

Figs. 6 and 7 (for curves 1, 2, 3, 4 at \( \mu = 0, \mu = 0.5, \mu = 0.7, \mu = 0.9 \)) show graphs of changes in the resistance force depending on \( b_1 (b_1 = \rho_0 / \rho_1) \) for two values of angle \( \lambda \) and for different values of soil parameter \( \mu = \sin \theta \). In calculations the following values are taken: \( \beta_{lap} = 20^\circ, \ k = 50000 \text{ N/m}^2, \ \rho_0 = 2000 \text{ kg/m}^3, \ v_0 = 2.777 \text{ m/s (10 km/h)}, \ \mu_0 = 0.2, \ h_{lap} = h_{const} = 0.2 \text{ m}. \)

As seen from the graphs, with an increase in ratio \( b_1 = \rho_0 / \rho_1 \), which corresponds to a more compacted state of soil behind the front of a cylindrical wave, the resistance force \( F \) significantly increases. On the other hand, an increase in the angle of internal friction \( \theta \) leads to a certain decrease in resistance force.

5. Conclusions

To describe the dynamics of cultivated soil, the models of linearly elastic and compressible plastic medium are used. When using the model of linearly elastic and compressible plastic medium, the resistance forces of soil medium are determined when the cultivating points of a deep ripper, in the form of a narrow wedge and a circular cone, are moving in it. It has been stated that the magnitude of this force substantially depends on the type of contact conditions between the body and soil, and its greatest value is reached in the case of continuous motion.

The dependence of the resistance force on time is obtained. According to the results of graphical-analytical studies, it is clear that at the initial stage, while the circular cone - soil contact area is variable, the resistance force depending on time changes according to a parabolic law, and then it remains constant. In the case of a cultivating point motion at a constant velocity, it was found that, depending on the coefficient of internal friction and soil cohesion, a zone of increased soil density could be formed near the operating element of the cultivator, where there is a significant increase in resistance force. With an increase in the angle of internal friction, a slight decrease in the resistance force is observed.

References

[1] Thorsøe M H 2015 Maintaining Trust and Credibility in a Continuously Evolving Organic Food System J. Agric. Environ. Ethics 28 767–87

[2] Kuang N, Tan D, Li H, Gou Q, Li Q and Han H 2020 Effects of subsoiling before winter wheat on water consumption characteristics and yield of summer maize on the North China Plain Agric. Water Manag. 227 105786

[3] Tukhtakuziev A 2019 Ensuring the Uniformity of Tillage Depth Agric. Mach. Technol. 13 34–8

[4] Rashidov T R, Yuldashev T and Bekmirzaev D A 2018 Seismodynamics of Underground Pipelines with Arbitrary Direction of Seismic Loading Soil Mech. Found. Eng. 55 243–8
[5] Mardonov B 1976 Effect of water-saturated elastic porous layers on intensity of seismic waves Soil Mech. Found. Eng. 13 221–4
[6] Hang C, Huang Y and Zhu R 2017 Analysis of the movement behaviour of soil between subsoilers based on the discrete element method J. Terramechanics 74 35–43
[7] Ucgul M, Fielke J M and Saunders C 2014 Three-dimensional discrete element modelling of tillage: Determination of a suitable contact model and parameters for a cohesionless soil Biosyst. Eng. 121 105–17
[8] Ucgul M, Fielke J M and Saunders C 2014 3D DEM tillage simulation: Validation of a hysteretic spring (plastic) contact model for a sweep tool operating in a cohesionless soil Soil Tillage Res. 144 220–7
[9] Ucgul M, Fielke J M and Saunders C 2015 Three-dimensional discrete element modelling (DEM) of tillage: Accounting for soil cohesion and adhesion Biosyst. Eng. 129 298–306
[10] Diel J, Vogel H-J and Schlüter S 2019 Impact of wetting and drying cycles on soil structure dynamics Geoderma 345 63–71
[11] Feng Z W, Kaboudian A, Rong J L and Khoo B C 2017 The simulation of compressible multi-fluid multi-solid interactions using the modified ghost method Comput. Fluids 154 12–26
[12] Da Costa Mattos H S, Teixeira L P and Martins-Costa M L 2018 Analysis of small temperature oscillation in a deformable solid matrix containing a spherical cavity filled with a compressible liquid – Analytical solutions for damage initiation induced by pore pressure variation Int. J. Eng. Sci. 129 1–20
[13] Teodosio B, Baduge K S K and Mendis P 2020 Simulating reactive soil and substructure interaction using a simplified hydro-mechanical finite element model dependent on soil saturation, suction and moisture-swelling relationship Comput. Geotech. 119 103359
[14] Rakhmatulin K A 1958 On the propagation of elastic-plastic waves owing to combined loading J. Appl. Math. Mech. 22 1079–88
[15] Rashidov T R and Nishonov N A 2016 Seismic Behavior of Underground Polymer Piping with Variable Interaction Coefficients Soil Mech. Found. Eng. 53 196–201
[16] Rashidov T R and Bekmirzaev D A 2015 Seismodynamics of Pipelines Interacting with the Soil Soil Mech. Found. Eng. 52 149–54
[17] Qu Y, Zhang W, Peng Z and Meng G 2019 Nonlinear structural and acoustic responses of three-dimensional elastic cylindrical shells with internal mass-spring systems Appl. Acoust. 149 143–55