Soil Cutting by a Chisel Plough with Self-Oscillations: Process Analysis

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Abstract. The paper presents the results of analytical studies. It describes the basics of modeling the chisel plough and soil interaction; it further analyzes the hypothesis of how soil is deformed. To reduce the draught of the implement, the authors propose using elastic cutter mounts to induce self-oscillations. The paper derives the amplitude of such oscillations expressed in terms of the cutter tilt angle \( \alpha(t) \) and the moment of all forces acting on the cutter on the soil side.

1. Introduction

To model the soil cutting process by systematic analysis of experimental materials and literature overview, the authors hereof consider the following soil deformation hypothesis:

- when a system of forces is applied to a soil layer, it causes relatively small deformations compliant with Hooke's law [1] i.e. with linear elasticity laws;
- as these deformations increase, they compact the soil, and the internal stresses rise enough to break the bonds between soil particles. As a result, soil fractures or a viscoplastic flow emerges;
- bond-breaking is associated with the accumulated elastic energy being converted into kinetic energy (acceleration and overcoming the adhesive and friction forces).

To model the interactions in the elastic strain area, the following assumptions were made:

1) normal and tangential stresses in soil are linear functions of the shear;
2) normal and tangential stresses on the sliding surfaces comply with Mohr-Coulomb’s law [1,2,3]:

\[
\tau = C_0 + f \cdot \sigma,
\]

where \( \tau \) is the tangential stress; \( \sigma \) is the normal stress;
\( C_0 \) is the soil adhesion coefficient; \( f \) is the soil-soil friction coefficient.

When the elastic forces hit the limits, two processes occur in the soil: a soil block breaks away due to critical normal stress, and a viscoplastic flow emerges when the tangential stress becomes critical.

To break away a soil layer, normal stresses need to reach values sufficient to produce a clean breakaway work, which is proportional to the adhesion coefficient multiplied by the surface area of the expected fracture and layer lift (e.g. work sufficient to overcome the gravity associated with the higher soil layers).

When the cutters are working below the critical cutting depth, normal stresses are not enough
to overcome the gravity of the higher soil layers, which is why tangential stresses are the first to hit the critical mark. This induces a viscoplastic flow.

Since cutting above the critical depth induces shearing, it is only logical to assume that elastic deformation and fracturing are two processes separated in time. In other words, draught has a periodic component.

The amplitude of draught oscillations is proportional to the soil adhesion coefficient multiplied by the fracture surface area.

Thus, normal and tangential stresses near the implement-soil interface first grow linearly as the implement moves through the soil. When the soil stresses hit the critical value, fracturing begins. This causes normal and tangential stresses to quickly drop, whereby elastic energy is converted into kinetic energy, i.e. the motion energy of the shorn soil block that is further considered herein a solid. These processes are periodic and have an occurrence frequency $\Delta t$.

The pulsating stress components are proportional to the fracture surface area while the constant components are proportional to the volume of the shorn soil block (gravity and friction forces).

As the chisel implement moves further, it destructs, loosens, and pushes the soil it faces sideward. Where affected by the viscoplastic flow, soil becomes somewhat denser and moves partly upwards and partly to the sides.

Soil buildup increases the draught, as the soil-soil friction coefficient is several times the soil-metal friction coefficient.

To reduce specific draught, the authors hereof propose chisel plough design that features self-oscillation.

This design equips the cutter with elastic elements [4] that induce self-oscillation to prevent soil buildup and increase the shearing depth.

2. Theory

When the implement equipped with an elastic fastener moves through soil, the following phases alternate: the elastic element shrinks, and the soil stress rises; then the element extends back after a soil block has been shorn, and the soil stress decreases. Phase I ends when the stress upon the cutting edge of the implement becomes sufficient for fracturing. Once shorn, the fracture surface will comply with Mohr-Coulomb’s requirement.

As the implement moves through the soil, it destroys the soil in a process similar to chipping [5, 6]. Assume that the shorn block has the shape shown in Figure 1, the accuracy of which is sufficient for practical use.

![Figure 1. Soil shearing diagram.](image-url)
Calculate the breakaway surface area:

\[ S = S_1 + 2(S_2 + S_3); \]  

where \( S_1 = S(F, D, D^1, F^1) = q \cdot H / \sin(\beta), \)
\( S_2 = S(F, D, C) = \sqrt{(p(p-x)(p-y)(p-z))}, \)
\( S_3 = S(B, C, F, G) = r \sqrt{(d^2 + H^2)}, \)

where \( x = H / \sin(\beta), \)
\( y = \sqrt{(d^2 + (b-c)^2)}, \)
\( z = \sqrt{(d^2 + c^2 + H^2)}. \)

To unambiguously describe the shape of a shorn soil block, one needs to set the following parameters: \( H, d, c, q, \) and the angles \( \alpha, \beta, \gamma. \)

Loose soil volume:

\[ V = V_1 + 2(V_2 + V_3) + V_4 + 2 \cdot V_s; \]  

where \( V_1 = H(s) \cdot b(s) \cdot q/2, \)
\( H(s) = H - \sin(\alpha), \)
\( b(s) = H(s) \cdot \cot(\beta), \)
\( V_2 = H(s) \cdot b(s) \cdot d/6, \)
\( V_3 = H(s) \cdot d \cdot r/2, \)
\( V_4 = H(s) \cdot a(s) \cdot d/6, \)
\( V_5 = H(s) \cdot a(s) \cdot q/2, \)
\( a(s) = H(s) \cdot \cot(\alpha). \)

Calculate the volume of the shorn soil layer:

\[ V' = S \cdot r \cdot \sin(\beta). \]  

As the implement is symmetrical relative to its vertical plane \((Z = 0),\) all the forces acting on the implement and on the soil can be reduced to a coplanar system of forces acting in this plane.

Consider the constrain of the equilibrium of the coplanar forces acting on the soil block AQE in Figure 2 (loose soil supported by the implement):

\( \vec{F}_\alpha = F_\alpha \hat{n}_\alpha \) is the pressure the implement exerts on the block AQE;

\( \vec{F}_\beta = F_\beta \hat{n}_\beta \) is the pressure soil exerts on the block AQE;

\( \overrightarrow{p} = \rho g V \) is the weight of the block AQE;

\( \overrightarrow{p'} = \rho g V', \) \( g = 9.8 \, m/s^2 \)

![Figure 2. Diagram of the coplanar force system.](image-url)

The equilibrium equation is written as:

\[ F_\alpha \hat{n}_\alpha + k_\alpha F_\alpha \tau_\alpha + F_\beta \hat{n}_\beta + k_\beta F_\beta \tau_\beta + P(0,1) = (0,0), \]

where \( k_\alpha \) is the soil-steel friction coefficient, \( k_\beta \) is the soil-soil (loose and block) friction coefficient.

By solving the equations to find \( F_\alpha \) and \( F_\beta, \) find:

\[ F_\alpha = \frac{P \left( \sin(\beta) + k_\beta \sin(\beta) \right)}{\left( \cos(\alpha) - k_\alpha \sin(\alpha) \right) \left( \sin(\beta) + k_\beta \cos(\beta) \right) + \left( \cos(\beta) - k_\beta \sin(\beta) \right) \left( \sin(\alpha) + k_\alpha \cos(\alpha) \right)} \]
\[
F_a = \frac{P(\sin(\alpha) + k_a \sin(\alpha))}{(\cos(\alpha) - k_a \sin(\alpha))(\sin(\beta) + k_\beta \cos(\beta)) + (\cos(\beta) - k_\beta \sin(\beta))(\sin(\alpha) + k_a \cos(\alpha))}
\]

If the values \(H, c, p, q, \alpha, \gamma\) are assumed to be constants in the neighborhood of some values picked to be in line with experimental data, the shearing angle \(\rho\) can be found by force minimization \(F_a(\vec{n}_a + k_\alpha \vec{e}_a) + F_a'(\vec{n}_a + k_\alpha \vec{e}_a)\).

Assume that the force \(F_a\) is distributed linearly along the implement, while the force \(F_a'\) is contained in the cutting edge of the implement; the moment of these forces relative to the rotation point 0 can be written as:

\[
M(\vec{F}) = \frac{2H}{3\sin(\alpha)} F_a' + \frac{H}{\sin(\alpha)} F_a
\]

Let us now analyze what is happening to the soil in front of the implement. Phase I: soil in front of the implement, the soil-implement reaction peaks. Transition to Phase II (soil deformation) results in fracturing and shearing a block of soil, whereby the soil reaction to the implement drops dramatically. Phase II: due to lesser soil resistance, the implement will move forward faster, while the shorn soil block will move up and forward at minimum friction. Thus, when an elastic fastener-equipped chisel plough moves, it produces two fundamentally different phases: shrinking and extension of the elastic element [7, 8, 11, 12].

The chisel plough cutter in Figure 3 is elastically mounted (1) onto the tine at Point 0. There is another, stiffer elastic element 2. Thus, being exposed to a variable load, the cutter will be forced into self-oscillating at some frequency and amplitude.

As the elastic fastener-equipped chisel plough moves, it produces two fundamentally different phases: shrinking and extension of the elastic element.

Figure 3. Diagram of an elastic cutter-equipped chisel plough implement: 1 is the first elastic element, 2 is the second elastic element.

Let us now introduce a system of coordinates bound to the cutter, see Figure 4. Let the onset be at the point, around which the cutter can turn. The X-axis is pointing in the implement travel direction. The Y-axis is pointing downwards. The Z-axis is perpendicular to the plane of this drawing.
Let the implement be moving at the speed \(v(t) = (v(t), 0, 0)\) relative to the soil. The cutter is exposed to the variable soil reaction force, which causes it to deviate by an angle \(\alpha(t)\). The position of a point on the cutter can be written as follows:

\[
\begin{align*}
x(s) &= s \cos(\alpha) \\
y(s) &= -s \sin(\alpha) \\
z(s) &= 0
\end{align*}
\]

In this chisel plough-bound coordinate system, different points on the cutter will have different speeds.

\[
\vec{\omega}(t) = \left(\vec{v}(t), 0, 0\right)
\]

Since the coordinate system itself is moving along the soil at \(v(t) = (v(t), 0, 0)\), the absolute speed of a point can be written as

\[
\vec{U} = \vec{V}(t) + \vec{\omega}(t) = \left(\vec{v}(t) - s \cdot \vec{\alpha}'(t) \cdot \sin \alpha(t), -s \cdot \vec{\alpha}'(t) \cdot \cos \alpha(t), 0\right)
\]

Assume that the elastic forces emerging in the cutter-tine fasteners comply with Hooke’s law. In this case, the following ratios link together the cutter tilt angle \(\alpha(t)\) and the moment of all the forces acting on the cutter on the soil side as found in relation to the coordinate onset:

\[
\begin{align*}
\alpha(t) - \alpha_1 &= \frac{1}{C_1} \cdot M(F), \text{ при } M(F) \leq (\alpha_2 - \alpha_1) \cdot C_1 \\
\alpha(t) - \alpha_2 &= \frac{1}{C_1 + C_2} \cdot \left[ M(F) - \frac{\alpha_2 - \alpha_1}{C_1} \right], \text{ при } M(F) \geq (\alpha_2 - \alpha_1) \cdot C_1
\end{align*}
\]

where \(C_1\) is the stiffness coefficient of the first element, \(C_2\) is the stiffness coefficient of the second element, \(\alpha_1\) is the cutter tilt angle in its initial state (unstressed), \(\alpha_2\) is the tilt angle, at which the second elastic element is activated, \(M(F)\) is the moment of rotation.

The elastic properties of the system, and thus the amplitude of the cutter’s self-oscillations will depend on the stiffness coefficients of the elastic elements, as well as on the geometric dimensions of the suspension [9]. To find the stiffness and other properties of the elastic elements, rely on the agricultural and technical conditions of using the implement; [10, 13] use the appropriate material strength formulas. A properly configured suspension will reduce the draught by swaying the system.

3. Conclusions
This paper presents a hypothesis of how soil deforms, which is used to theoretically prove that the draught can be reduced by using an implement equipped with elastic elements that induce self-oscillations; the paper further examines the vibration effects the implement exerts on the shorn soil block. It also presents the cutter tilt angle as a function of the moment of all the forces acting on the cutter on the soil side; this helps optimize the structural design of the elastic fasteners used to mount the tillage implements.
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