Comparison of the Goryachkin Theory to Soil Flow on a Sweep

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Keywords
Soil dynamics, Velocity, Tillage

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
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COMPARISON OF THE GORYACHKIN THEORY TO SOIL FLOW ON A SWEEP

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ABSTRACT. The Goryachkin trihedral wedge theories describe soil flow over a surface resembling the wing of a sweep. The current study tested the Goryachkin crushing and lifting theories’ prediction of soil flow across a sweep by comparing with measurements from observed soil flow. Treatments included sweeps with three different rake angles (13.5, 16, and 44°) operated at three speeds (5, 7, and 9 km/h) and at two depths (50 and 100 mm). Flow direction was determined from scratch marks on the sweep surface.

In agreement with the Goryachkin theories, observed soil flow changed with rake angle, but not with speed or depth. In a manner opposite of that predicted by the theories, the ratio of vertical to lateral soil movement increased as rake angle increased. Most predicted values were outside of a 99% confidence interval of observed means. Soil flows on the sweep did not deviate appreciably (more than 5°) from a vertical plane parallel to the travel direction. The theories did not adequately predict observed soil flow on a sweep. Keywords: Soil dynamics, Velocity, Tillage.

Researchers have used passive earth pressure theory to model soil failure by simple inclined-plane tillage tools. Two-dimensional models (Söhne, 1956; Hettiaratchi et al., 1966) describe failure occurring in front of wide tools. Three-dimensional models (Hettiaratchi and Reece, 1967; Godwin and Spoor, 1977; McKyes and Ali, 1977; Perumpral et al., 1983; Swick and Perumpral, 1985) include soil failure outside of the tool’s travel path. Models commonly include forces of cohesion, friction, adhesion, and gravity. Dynamic forces are included in the models of Söhne (1956) and of Swick and Perumpral (1985).

The aforementioned models consider soil failure to occur when a shear plane forms and separates from the undisturbed soil the wedge of soil immediately in front of the tool. Hettiaratchi and O’Callaghan (1980) noted that classical soil mechanics’ focus on the instant of soil failure may be inappropriate in investigations of soil forces on the implement but is inappropriate in investigations of soil changes such as aggregate movement.

Kaburaki and Kisu (1959) predicted soil aggregate flow paths on a plane surface with cutting edge inclined to the travel direction. Their model was restricted to soil flow below the existing soil surface. They included a soil force that was assumed to act in a direction parallel to the travel path from the undisturbed soil ahead of the tool. In addition to this external soil force, gravitational force, normal tool force, and frictional force along the tool surface were included. The model predicts the direction of soil flow as a function of nose angle, rake angle, and soil-metal friction angle.

Kaburaki and Kisu (1959) limited the domain of their analysis to soil flow below the plane of the original soil surface. Their model predicts downward soil movement for commonly used sweep dimensions for a nose angle of 70° and a rake angle of 15° and thus does not explain commonly observed soil aggregate flow upward against the face of the sweep wing.

Kaburaki and Kisu (1959) reported data for a trihedral wedge displacing dry sand in a soil bin with a depth of 100 mm. The top edge of the wedge was at the same elevation as the sand surface during tillage. Wedge velocity was 1 m/s. Their data tend to refute their model for common sweep geometry. For a 70° nose angle and a 15° rake angle, the measured soil flow marks indicated upward movement at an angle of 40°, as measured above a horizontal plane and along the tool surface. As noted, despite its inclusion of additional soil and gravitational forces, the Kaburaki and Kisu (1959) model predicts downward soil flow in this situation.

Harrison (1990) developed a soil surface profile meter and used it to measure soil elevations above a tool surface during tillage. He found soil flow depth to change as soil flowed across a plane tool inclined to horizontal at 30° or at 45°.

GORYACHKIN THEORIES

Turn-of-the-century Russian tillage theorist V. P. Goryachkin (Goryachkin, 1968) developed three theories to explain soil flow over a plane inclined at two angles (one in a horizontal plane that the cutting edge
makes with the direction of travel and another in a vertical plane perpendicular to the tool’s cutting edge). These angles are shown in figure 1 as \( \theta \) and \( \gamma \), respectively. Goryachkin termed this plane surface a trihedral wedge.

The Goryachkin trihedral wedge theories (Goryachkin, 1968) of soil movement include both a normal force acting from the plane of the tool surface and a soil-metal frictional force. Goryachkin developed the three theories to describe situations of soil crushing, lifting, and shearing.

Crushing theory assumes that absolute soil motion is normal to the tool surface. Soil initially at point O in figure 1 has absolute motion along normal ON to point N on the trihedral surface. Relative soil motion on the trihedral tool surface (ABC) is parallel to flow path AN.

Lifting theory assumes no shape change for the two-dimensional soil slice in contact with the tool, i.e., the relative positions of soil aggregates within the soil slice remain the same. In figure 2, soil initially at point O in figure 1 has absolute motion along normal ON to point N on the trihedral surface. Relative soil motion on the trihedral tool surface (ABC) is parallel to flow path AN.

Soil shearing theory assumes that soil motion is parallel to planes of shear failure in the soil. Flow path depends on the angle of soil shear failure.

The Goryachkin model does not include forces in undisturbed soil reacting on the wedge of soil being moved. Later, two-dimensional models for wide tools (Söhne, 1956; Reece, 1965; Hettiaratchi et al., 1966) and three-dimensional models for narrow tools (Hettiaratchi and Reece, 1967; Godwin and Spoor, 1977; McKyes and Ali, 1977; Perumpral et al., 1983) all included such forces. The Goryachkin model includes a soil-metal frictional force as a linear function of the normal force, but neglects the effect of soil-metal adhesive force.

Because soil shearing theory predicts soil movement along soil shear planes, flow path varies with those soil and tool parameters affecting shear plane angle. Further analyses of the Goryachkin crushing and lifting theories were conducted to determine the soil flow path AN and to project the soil flow path on to the yz and xz planes.

Soil crushing movement is analyzed in figure 3. Triangle COD is constructed perpendicular to cutting edge AB and through point O. Line NO, constructed perpendicular to CD and through O, is the line of absolute soil motion for soil crushing. Vertical line EN is constructed with point E on the xz plane and line EF is constructed parallel to the x axis. Note that DO = AOsin\( \theta \), NO = DOsin\( \gamma \), EN = NOcos\( \gamma \), EO = NOsin\( \gamma \), EF = EOsin\( \theta \), and FO = EOcos\( \theta \).

The path of relative motion AN projected on to the yz plane creates an angle \( \chi \) with the z axis where \( \chi = \tan^{-1}(EN/FO) \). Substituting the above relationships:

\[
\chi = \tan^{-1} \left( \frac{1}{\tan \gamma \cos \theta} \right)
\]
equal to the magnitude of tool velocity (segment AO, fig. 2) and for crushing theory can be considered to be the product of the magnitude of tool velocity and the ratio of AN to AO. From figure 3, the ratio AN/AO equals \((1 - \sin^2 \theta \sin^2 \gamma)^{0.5}\). The Goryachkin velocities for soil aggregate crushing are expressed by equations 5 and 6 and for soil aggregate lifting by equations 7 and 8:

\[
V_{yc} = V(1 - \sin^2 \theta \sin^2 \gamma)^{0.5} (\sin \theta \sin \gamma \cos \gamma) \\
V_{ze} = V(1 - \sin^2 \theta \sin^2 \gamma)^{0.5} (\sin \theta \cos \theta \sin^2 \gamma) \\
V_{yl} = V \sin \theta \sin \gamma \\
V_{zl} = V \sin \theta \cos \theta (1 - \cos \gamma)
\]

where

- \(V\) = travel speed
- \(2\theta\) = nose angle
- \(\gamma\) = rake angle

In similar fashion the relative velocity of soil with respect to the tool in the travel direction \(V_x\) is predicted by equation 9 for crushing and 10 for lifting:

\[
V_{xc} = V(1 - \sin^2 \theta \sin^2 \gamma)^{1.5} \\
V_{xl} = V(\sin^2 \theta \cos \gamma + \cos^2 \theta)
\]

Both theories predict the relative velocity of soil with respect to the tool in the travel direction \(V_x\) to be less than tool speed \(V\) in equations 9 and 10.

The theory was originally developed to model soil movement on a moldboard plow. A sweep in its simplest form may be considered a plane-cutting surface angled in two directions.

Commercially available sweeps in use for cultivation had nose angles between 65° and 70°, but different crown heights. First order partial derivatives of equations 5 through 8 with respect to \(\theta\) and \(\gamma\) can be used to find the theories' predicted effects of nose angle and rake angle on soil acceleration in the \(y\) and \(z\) directions. To test the Goryachkin theories, rake angles were chosen with large differences in predicted \(V_y\) and \(V_z\) and with tool geometry similar to that commonly used in practice. Commercially available low and medium crown sweeps were used with rake angles of 13.5° and 16°, respectively, as well as a geometrically similar sweep with 44° rake angle.

Other common variables related to sweep movement through the soil are speed and depth. Although the Goryachkin model does not consider these variables, they should be included in evaluations of a model's validity for describing soil flow during tillage.

Although the Goryachkin theories are nearly a century old, the authors could find no field test of their ability to describe soil flow. If crushing or lifting theories are able to predict soil flow, they would be useful in designing sweeps to change soil microtopography.

**OBJECTIVES**

The objectives of researchers were to:

- Use the Goryachkin crushing and lifting theories to predict soil flow across a cultivator sweep.
Table 1. Description and dimensions of experimental sweeps (see fig. 5)

<table>
<thead>
<tr>
<th>Sweep Description</th>
<th>Edge Rake Angle</th>
<th>Sweep Rake Angle</th>
<th>Sweep Nose Angle</th>
<th>Wing Width Front</th>
<th>Wing Width Rear</th>
<th>Wing Lift Front</th>
<th>Wing Lift Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Crown Type</td>
<td>ω</td>
<td>γ</td>
<td>θ</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(degrees)</td>
<td>(degrees)</td>
<td>(degrees)</td>
<td>(mm)</td>
<td>(mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>HL16-5</td>
<td>Low</td>
<td>18</td>
<td>13.5</td>
<td>67</td>
<td>83</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>25</td>
<td>16</td>
<td>68</td>
<td>83</td>
<td>70</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>54</td>
<td>44</td>
<td>67</td>
<td>86</td>
<td>73</td>
<td>60</td>
</tr>
</tbody>
</table>

produced from different formulations and colors of paint although some were more easily visible in different soil conditions (Hanna, 1991). Two sweeps set at a 4° pitch and at 760-mm spacing were operated for a distance of 15 m in each experimental plot. Four different paint formulations — lacquer, enamel, acrylic, and automotive upholstery — were used on four sweep wings in each plot to obtain a reliable set of scratch marks on the painted surface. The small amount of paint remaining after tillage indicated that soil flow paths predominantly occurred on a metal rather than painted tool surface near the end of each plot.

Scratch angles on sweeps were photographed after tillage. Parallax in reading the angles from the photographs was avoided by calibration of measurements with photographs of known angles. Scratch angles were projected on both the xz (plane including sweep cutting edges) and yz planes by the method shown in figure 6. Single scratch angle measurements from each of two wings were averaged for each experimental plot.

Scratch angle measurements for all tool types were compared with Goryachkin's predicted values by means of a t-test (Steel and Torrie, 1980).

Results and Discussion

Predicted (χ, μ, ν, and ψ) and measured soil flow angles are given in tables 3 and 4.

The model correctly predicted little flow variation in the lateral (z) direction (angles μ and ψ), with most of the flow being vertically upward (angles χ and ν).

The confidence interval of the mean of each factor level indicated soil flowing over the tool at a small acute angle, i.e., between 0° to 5°, with travel direction as viewed from

Table 2. Soil conditions in experimental blocks at the time of experimental measurements

<table>
<thead>
<tr>
<th>Block</th>
<th>Soil Type</th>
<th>Depth (mm)</th>
<th>Soil Moisture (Mg/Mg)</th>
<th>Soil Bulk Density (Mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Canisteo</td>
<td>0-50</td>
<td>0.212</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50-100</td>
<td>0.283</td>
<td>1.63</td>
</tr>
<tr>
<td>2</td>
<td>Canisteo</td>
<td>0-50</td>
<td>0.191</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50-100</td>
<td>0.267</td>
<td>1.50</td>
</tr>
<tr>
<td>3</td>
<td>Canisteo</td>
<td>0-50</td>
<td>0.164</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50-100</td>
<td>0.195</td>
<td>1.67</td>
</tr>
<tr>
<td>4</td>
<td>Clarion</td>
<td>0-50</td>
<td>0.093</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50-100</td>
<td>0.136</td>
<td>1.87</td>
</tr>
<tr>
<td>5</td>
<td>Clarion</td>
<td>0-50</td>
<td>0.116</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50-100</td>
<td>0.151</td>
<td>1.73</td>
</tr>
</tbody>
</table>
soil (=A0) equals speed, YVLB = (speed)/—!—sina, ZVLB = (speed)tana

By assuming amount of soil on wing reaches a constant value, X velocity of component of
8. BN = Y velocity component = YVLB
7. BO = Z velocity component = ZVLB
6. ZBAO = a = scratch angle
5. AN is scratch mark
4. ZCAO = 9 = 1/2 nose angle of sweep
3. ZBCN = rake angle,
2. Plane AON is trihedral wedge
1. X axis parallel to travel path with positive X in direction of tool motion

Given:
1. X axis parallel to travel path with positive X in direction of tool motion
2. Plane ACN is trihedral wedge (i.e. sweep wing)
3. BCN = rake angle, γ
4. CCAO = 8 = 1/2 nose angle of sweep
5. AN is scratch mark
6. CBAO = a = scratch angle
7. BO = Z velocity component = ZVLB
8. BN = Y velocity component = YVLB

By assuming amount of soil on wing reaches a constant value, X velocity of component
of soil (=AO) equals speed. YVLB = (speed) (1/cosa) sina, ZVLB = (speed)tana

Figure 6-Soil aggregate flow paths from scratch angles.

above the tool. As predicted by the Goryachkin model, no statistically significant differences in flow path occurred when different speeds or depths are compared (table 4).

The model correctly predicted some flow differences due to rake angle. Flow paths projected onto the yz plane showed a difference between all three low, medium, and high crown sweeps (α = 0.05). All values predicted by the lifting theory and crushing theory values predicted for the low and high crown sweeps, however, are outside the 99% confidence interval. Both theories predicted increased lateral flow for steeper rake angles, whereas the trend of measured values was in the opposite direction. Neither theory correctly predicts the trend of a significant increase in the flow path’s ratio of vertical to lateral direction for steeper rake angles.

Comparing equations 1 and 3 for χ and v it can be shown that lifting theory predicts greater vertical movement than crushing theory for rake angles between 0° and 180°. Values predicted by the crushing theory were closer to the range of observed means for low and medium crown sweeps and values predicted by the lifting theory were closer to observed means for the high crown sweep.

Table 3. Comparison of experimentally observed scratch angle with angle predicted by Goryachkin model for each tool (confidence limits constructed with Student’s t analysis)

<table>
<thead>
<tr>
<th>Tool Crown</th>
<th>Predicted by Goryachkin Model</th>
<th>Measured from Scratch Path</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95% Conf. Limits</td>
<td>99% Conf. Limits</td>
</tr>
<tr>
<td></td>
<td>Angle of Soil Flow (degrees)</td>
<td></td>
</tr>
<tr>
<td>PROJECTED ON XZ PLANE</td>
<td>Low†</td>
<td>1.46‡</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE**</td>
<td>Low†</td>
<td>78.68††</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE**</td>
<td>Medium</td>
<td>76.63</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE**</td>
<td>High#</td>
<td>14.59</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE**</td>
<td>High#</td>
<td>51.16</td>
</tr>
</tbody>
</table>

As noted in table 1, the commercial sweeps used were not simple inclined planes but had a small section of increased rake angle at the cutting edge. The unknown effect of this change in rake angle may have been

Table 4. Experimental means and confidence intervals for scratch angle as affected by speed and depth (confidence limits constructed with Student’s t analysis)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Exp. Mean</th>
<th>Low</th>
<th>High</th>
<th>95% Conf. Limits</th>
<th>99% Conf. Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROJECTED ON XZ PLANE</td>
<td>Low†</td>
<td>2.61</td>
<td>1.75</td>
<td>3.47</td>
<td>1.47</td>
</tr>
<tr>
<td>PROJECTED ON XZ PLANE</td>
<td>Medium</td>
<td>2.37</td>
<td>1.51</td>
<td>3.23</td>
<td>1.22</td>
</tr>
<tr>
<td>PROJECTED ON XZ PLANE</td>
<td>High#</td>
<td>2.70</td>
<td>1.84</td>
<td>3.56</td>
<td>1.56</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE†</td>
<td>Low†</td>
<td>74.93</td>
<td>71.05</td>
<td>78.80</td>
<td>69.77</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE†</td>
<td>Medium</td>
<td>75.45</td>
<td>71.56</td>
<td>79.31</td>
<td>70.28</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE†</td>
<td>High#</td>
<td>75.54</td>
<td>71.67</td>
<td>79.42</td>
<td>70.39</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE†</td>
<td>High#</td>
<td>76.15</td>
<td>72.98</td>
<td>79.31</td>
<td>71.94</td>
</tr>
<tr>
<td>PROJECTED ON YZ PLANE†</td>
<td>High#</td>
<td>74.45</td>
<td>71.29</td>
<td>77.62</td>
<td>70.42</td>
</tr>
</tbody>
</table>

* The xz plane includes sweep cutting edges and is inclined by a sweep pitch of 4° in this experiment with a horizontal plane.
† The yz plane is formed by rotating xz plane 90° about horizontal line in xz plane.
‡ Angle predicted by crushing theory in xz plane is µ.
§ Angle predicted by lifting theory in xz plane is ψ.
¶ 16° rake angle.
# 44° rake angle.
** The yz plane is formed by rotating xz plane 90° about horizontal line in xz plane.
†† Angle predicted by crushing theory in y plane is χ.
‡‡ Angle predicted by lifting theory in y plane is ν.
responsible for some of the discrepancy between predictions and data collected.

Soil seemed to make only small lateral deviations (in the z direction) as it flowed over the tool at the soil tool interface. Most of the tool's influence seemed to be in lifting soil. This may have been caused by constant soil mass flow rate in the travel (x) direction and the resisting force of undisturbed soil in a lateral (z) direction.

Flow continuity in the travel direction dictated that after the tool was initially filled with soil, it processed a certain amount of soil per unit of time. This amount of soil must have equaled the amount of soil flowing onto the tool (with random variations). If the amount of soil leaving the tool was not equal to that entering it, either soil would have continually built up in front of the tool or the mass of soil on the tool would have continually decreased.

Continuity required that the average soil mass flowrate in the travel direction with respect to the tool must have been a constant. This mass flowrate equaled the product of initial cross-sectional area of the soil slice in the yz plane, pre-tillage soil density, and tool speed. It was assumed in estimating the magnitude of observed soil velocity that the cross-sectional area of the soil slice in the yz plane and soil density did not change as soil flowed over the tool so that the magnitude of velocity with respect to the tool in the travel direction must have been greater than tool speed. A constant soil mass flowrate over the tool might have been responsible for a soil velocity component in the travel direction at least equal to tool speed.

Goryachkin's crushing and lifting theories assume a reduction in soil aggregate speed in the travel direction, as line segment AN is shorter when measured along the x axis than is line segment AO in figures 1 and 2. Assuming soil mass flowrate across the tool in the travel direction to be a constant, a reduced velocity in the travel direction assumed by either theory implies either an increase in cross-sectional depth normal to the tool surface or the velocity of soil flow with respect to the tool in the travel direction must have been greater than tool speed. A constant soil mass flowrate over the tool might have been responsible for a soil velocity component in the travel direction at least equal to tool speed.

Harrison (1990) found soil flow depth to decrease as soil flowed across a plane tool inclined at 30° or at 45°. If the cross-sectional area of the soil slice decreased as indicated by Harrison's observations, then either soil density must have increased on the tool surface or the velocity of soil flow with respect to the tool in the travel direction must have been greater than tool speed. A constant soil mass flowrate over the tool might have been responsible for a soil velocity component in the travel direction at least equal to tool speed.

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Flow continuity in the travel direction dictated that after the tool was initially filled with soil, it processed a certain amount of soil per unit of time. This amount of soil must have equaled the amount of soil flowing onto the tool (with random variations). If the amount of soil leaving the tool was not equal to that entering it, either soil would have continually built up in front of the tool or the mass of soil on the tool would have continually decreased.

Continuity required that the average soil mass flowrate in the travel direction with respect to the tool must have been a constant. This mass flowrate equaled the product of initial cross-sectional area of the soil slice in the yz plane, pre-tillage soil density, and tool speed. It was assumed in estimating the magnitude of observed soil velocity that the cross-sectional area of the soil slice in the yz plane and soil density did not change as soil flowed over the tool so that the magnitude of velocity with respect to the tool in the travel direction must have been greater than tool speed. A constant soil mass flowrate over the tool might have been responsible for a soil velocity component in the travel direction at least equal to tool speed.

Goryachkin's crushing and lifting theories assume a reduction in soil aggregate speed in the travel direction, as line segment AN is shorter when measured along the x axis than is line segment AO in figures 1 and 2. Assuming soil mass flowrate across the tool in the travel direction to be a constant, a reduced velocity in the travel direction assumed by either theory implies either an increase in cross-sectional depth normal to the tool surface or the velocity of soil flow with respect to the tool in the travel direction must have been greater than tool speed. A constant soil mass flowrate over the tool might have been responsible for a soil velocity component in the travel direction at least equal to tool speed.

Harrison (1990) found soil flow depth to decrease as soil flowed across a plane tool inclined at 30° or at 45°. If the cross-sectional area of the soil slice decreased as indicated by Harrison's observations, then either soil density must have increased on the tool surface or the velocity of soil flow with respect to the tool in the travel direction must have been greater than tool speed. A constant soil mass flowrate over the tool might have been responsible for a soil velocity component in the travel direction at least equal to tool speed.

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