STUDY OF SOIL PROFILE OF A SINGLE SWEEP TOOL

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Written for presentation at the
CSAE/SCGR 2005 Meeting
Winnipeg, Manitoba
June 26 - 29, 2005

Abstract Soil profile of a single sweep was studied, and a soil profile model after tillage with a single sweep was mathematically improved. This model was based on a previous study of soil displacement. The parameters involved in this model were soil properties, tool geometry, and the depth and speed of tillage operation. The model parameters describing soil profile included the ridge height, furrow width, furrow depth, and the width of soil disturbance. The improved model was validated with the results from the soil bin experiments using a single 325-mm-wide sweep operated at the speeds of 5, 7.5, and 10 km/h. Results showed that the model had maximum error of 16% for all calculated dimensional parameters. Previous data conducted in a different soil bin with different soil were also used to validate the improved model. Results indicated that the maximum error of this improved model was reduced from previous error of 40% to 11%.
INTRODUCTION

Soil profile or soil redistribution after tillage operation has its importance in several aspects such as incorporating manure and crop residue, and protecting soil from erosion. The study of soil profile and soil redistribution by tillage has progressed slowly due to its complexity which involves many factors, such as soil types and properties, types of tillage tools and their operational parameters. Dowell et al. (1988) conducted study with sweeps and found that the ridge height and lateral distance increased with travel speed. Hanna et al. (1993) also indicated that higher speed and larger rake angle of sweep resulted in more soil movement creating higher ridges. Sharifat and Kushwaha (1999) studied soil lateral movement under different soil conditions with a sweep and a knife opener at speeds from 5 to 8 km/h. Different tools created different geometry of soil profiles. The parameters of soil profile were affected by tillage speed, soil bulk density, and soil moisture content. McKyes (1985) described results of soil disturbance study, and indicated that the shape, width and rake angle of tools strongly influence transporting and mixing of soil particles. Soil throwing to the sides of a tool varied with the square of tillage speed. Therefore, for tool design, it is imperative to develop physically based mathematical model and to quantitatively describe the soil profile after tillage operation.

Based on a mathematical model of soil displacement, Liu (2005) proposed a mathematical model of soil profile by tillage with a single sweep (Fig. 1). The soil profile was simplified as an isosceles triangle. Point C is the central point of right wing of the tool’s two wings. Point D is the average lateral displacement of soil. The parameters describing the soil profile include the furrow width \(2b_0\), the width of soil disturbance \(2b\), the ridge height \(h\), the furrow depth \(h+d_1\), and pile angle \(\phi\). The ridges will shift to a wider area with increasing tillage speed. This model worked well when tillage speed was 5 km/h; but, it resulted in error of 40% relative to the experimental results at tillage speed of 10 km/h. This was not acceptable.

The inadequacy is mainly caused by the assumption of isosceles triangle of a ridge. Sharifat and Kushwaha (1999) measured soil profile in a soil bin using the same sweep (McKay 50-12K) with the one used in this study. The results indicated that the soil profile could be simplified as an

![Figure 1. Geometric relations of soil redistribution after tillage operation with a sweep tool (d: tillage depth; w: tool width; e: average lateral soil displacement)](image-url)
isosceles triangle if the tillage speed is 5 km/h. However, experimental results indicated that the outer bottom angle $\phi_{out}$ was tending to be smaller than the inner angle with increasing tillage speed. Therefore, the goal of this study was to improve the model of soil profile after tillage operation with a sweep. The objectives of this study were:

1. To improve the mathematical model of the soil profile of a single sweep tool; and,
2. To validate the improved model with data from a soil bin experiment and previous study.

**EXPERIMENTAL STUDY**

*Material and Methods*

**Soil bin and tillage tool**

Experiment was conducted in an indoor soil bin located in the Department of Agricultural and Bioresource Engineering at the University of Saskatchewan. The maximum travel speed of the carriage was 16 km/h. The bin was filled with sandy loam soil to a 300 mm deep. Soil processing equipment includes a rotary tiller for loosening soil, a sheep-foot roller and a plain roller for packing soil. Tillage tool was a 325-mm wide sweep (McKay 50-12K) as shown in Fig. 2.

**Experimental design**

Experimental variable was tillage speed. The depth of operation was kept constant at 100 mm for every run. Three speeds, 5, 7.5, and 10 km/h were selected to get comparable results with data obtained in previous studies. Soil bulk density was maintained at 1280 kg/m$^3$, and the moisture content was 12%.

Soil profile was measured after tool operation. Figure 3 shows the main parameters used for validating the model. Five sections along the direction of tool travel were randomly selected as replications. The parameters of soil profile, namely $B$, $B_0$, $H$ were determined using average value of left and right profiles. The bottom angle ($\phi_1$) was determined with linear regression of all measured points between $C$ and $F$ (Fig. 3).

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**Figure 3. Geometric parameters used to determine soil profile after tillage**

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**Fig. 2 A 325-mm wide sweep (McKay 50-12K) used in this study**
Results and Discussion

The soil profiles of five replications are shown in Fig. 4 to 6. Soil profile changed with increasing tillage speed; however, the ridge height slightly decreased. The increase in speed resulted in more soil being tossed away thus increasing the furrow depth. Hence, furrow became wider. The furrow width ($b_0$) and the width of soil distribution ($b$) were significantly increased with increasing tillage speed (Table 1). The slope angle of the furrow ($\phi_1$) was significantly decreased when tillage speed increased to 7.5 km/h, but it did not differ with that at the speed of 10 km/h. The slope gradient of soil outside the furrow was decreased when tillage speed increased, and it was smaller than that of furrow slope. All these indicated that the ridges were tending to be flattened at higher tillage speed.

![Figure 4](image1.png)

Figure 4. Measured soil profile of a single sweep operated at 100 mm deep and 5 km/h speed

![Figure 5](image2.png)

Figure 5. Measured soil profile of a single sweep operated at 100 mm deep and 7.5 km/h speed

![Figure 6](image3.png)

Figure 6. Measured soil profile of a single sweep operated at 100 mm deep and 10 km/h speed
Table 1 Some parameters measured from the experiment

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>B₀ (mm)</th>
<th>B (mm)</th>
<th>H (mm)</th>
<th>ϕ₁ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 km/h</td>
<td>172 (13.3*) a⁷</td>
<td>388 (21.8) a</td>
<td>62.9 (8.3) a</td>
<td>24.4 (1.3) a</td>
</tr>
<tr>
<td>7.5 km/h</td>
<td>214 (20.1) b</td>
<td>472 (21.4) b</td>
<td>54.4 (4.3) a</td>
<td>18.4 (2.1) b</td>
</tr>
<tr>
<td>10 km/h</td>
<td>250 (24.5) c</td>
<td>564 (38.3) c</td>
<td>58.2 (12.4) a</td>
<td>18.5 (2.4) b</td>
</tr>
</tbody>
</table>

* Standard deviation of ten replications; # The same letters followed the measured results in the same column show no significant difference were detected by ANOVA Duncan test at significant level of 0.05

MODEL DEVELOPMENT

Modeling the Soil Profile of a Single Sweep

The mathematical model of soil displacement developed in previous study (Liu, 2005) provided a method of calculating soil displacement as soil moving in three phases: forced, projectile, and rolling and sliding. The process of soil redistribution by a sweep was considered different with that in the previous model described in Fig. 1. Soil clods were dropped at location F (Fig. 7), and then roll and/or slide. However, soil rolling and sliding was not always equal for all soil clods during a ridge formation. At the beginning, ground surface was flat and smooth; soil clods would roll or slide easily. Soil rolling and sliding distance was reduced on the rough surface. Accordingly, average displacement of the top soil, which was inverted as the bottom layer of a ridge, included full range of rolling and sliding distance but did not have rolling and sliding at the top of a ridge. Soil rolling and sliding were considered as linearly distributed between the top and bottom of a ridge. The rolling and sliding formed area FSG (Fig. 2).

The furrow formed between the two ridges, thus the two ridges were symmetrical to the furrow centre (i.e. tool centre). The ridge shown in Fig. 2 has two bottom angles: ϕ₁ and ϕ₂. Angle ϕ₁ indicates the angle of the furrow slope while angle ϕ₂ is the slope to the end surface. The parameters describing the soil profile include the furrow width (2B₀), the width of soil disturbance (2B), the ridge height (H), and the furrow depth (H+D₁).

![Figure 7. Improved geometric relations of soil profile after tillage operation with a sweep tool (r: average lateral displacement of soil rolling/sliding)](image-url)
Hypotheses

An assumption was made that the soil volume increased by tillage operation with the sweep. Assuming that the soil mass in the tool region \( OO_0O_bQ_bQ \) consists of a number of cubes with the edge length of \( a \) (Fig. 3). After the tool passed, these cubes are randomly redistributed, and each cube occupies a space of a ball with the diameter of \( \sqrt{2}a \). All the cubes are rearranged as a stack of balls. The spaces between the balls are eliminated. Each cube occupies an extra space. Thus, the redistribution of these soil cubes results in an expansion of soil volume. The extra area occupied by each square is:

\[
\Delta A_0 = \left( \frac{\pi}{2} - 1 \right) a^2
\]  

Therefore, the total area expended is:

\[
\Delta A = \left( \frac{\pi}{4} - \frac{1}{2} \right) wd
\]  

where \( w \) is tool width; \( d \) is tillage depth.

The expanded area is distributed in the “pile” area \( EFG \). That is, the expanded area plus area \( OCE \) are equal to the area of \( EFG \).

Analytical Model

According to the simplified ridges, geometric relationships of various parameters used in the model shown in Fig. 7 are derived as follows:

\[
B_0 = \frac{w}{4} + \text{forced + projectile}
\]  

\[
H = \frac{1}{2} \left( \sqrt{(2B_0 + r)^2 + (2\pi - 4)wd \cot \varphi_1 + 4B_0^2} - (2B_0 + r) \right) \tan \varphi_1
\]  

\[
D_1 = B_0 \tan \varphi_1 - H
\]
\[ B = B_0 + H \cot \varphi_1 + r \quad (6) \]

\[ \varphi_2 = \tan^{-1}\left( \frac{H}{H \cot \varphi_{in} + r} \right) \quad (7) \]

The parameter \( B \) (width of the soil ridge) is the most important one in describing the soil distribution by tillage, and \( 2B \) will be the total width of soil disturbance. The model included operational parameters of tillage (depth and speed) and geometric parameters of the tool. Soil property parameter (soil failure angle) was included in the calculation of soil displacement. The final format of this model does not include the dimension of the soil clod although it was in the hypothesis.

**MODEL VALIDATION**

*Validation Using the Soil Bin Experimental Results*

Based on the calculation of soil lateral displacement including three phases of soil moving, the soil profile of a single 325-mm-wide sweep was then calculated. Measured bottom angles (\( \varphi_1 \)) listed in Table 1 were used as inputs of the model calculation. Primary parameters of soil profile are given in Table 2 to compare with measured values.

Experimental results showed that the width of soil distribution significantly increased with increasing tillage speed. The measured ridge height tended to decrease when tillage speed increases, but there was no significant difference detected. The calculated height also tends to decrease with increase in tillage speed. The comparison showed that the model of soil profile of a single sweep correctly predicted the width of soil distribution (\( 2B \)), and its relative error was 14% or lower for the three speeds of 5, 7.5 and 10 km/h. Calculated ridge height \( H \) and furrow width \( B_0 \) had maximum error of 10% and 3% respectively. For the depth parameter \( D_1 \), the maximum relative error of 16% occurred at tillage speed of 5 km/h. The changes of soil profile at different tillage speed were determined using the model and were found to be the same as measured in the soil bin tests. It could be concluded that the soil profile model worked well in the speed range of 5 to 10 km/h.

*Validation Using Previous Experimental Data*

The model described in Fig. 1 was validated with the tests conducted in the soil bin located in the Department of Biosystems Engineering at the University of Manitoba (Liu, 2005). The soil in that bin was loamy (fine) sand. These results were also used to validate the proposed model in this study. The parameters of soil profile were recalculated according to the soil and its conditions (16.3% moisture content and 1250 kg/m\(^3\) bulk density). Calculated and experimental results are listed in Table 3. The slope angle (\( \varphi_1 \)) of the furrow was not available. The slope angle of soil ridges of 25° was used as \( \varphi_1 \) in the calculation for all three tillage speeds. The comparison indicated that the maximum error in the three parameters of soil profile was 11% for all three tillage speeds compared to the previous error of 40%. This indicates that the proposed model would also be suitable for these soil conditions.
Table 2 Comparison of calculated and measured parameters of soil profile of a single 325-mm-wide sweep in the soil bin. Soil: (coarse) sandy loam, tillage depth: 100 mm

<table>
<thead>
<tr>
<th>Tillage speed (km/h)</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>B (mm)</td>
<td>Measured (Standard deviation*)</td>
<td>388 (22)</td>
<td>472 (21)</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>334</td>
<td>419</td>
</tr>
<tr>
<td></td>
<td>Relative error (%)</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>H (mm)</td>
<td>Measured (Standard deviation)</td>
<td>63 (8)</td>
<td>54 (4)</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>61</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>Relative error (%)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>B₀ (mm)</td>
<td>Measured (Standard deviation)</td>
<td>172 (13)</td>
<td>214 (20)</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>168</td>
<td>208</td>
</tr>
<tr>
<td></td>
<td>Relative error (%)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>D₁ (mm)</td>
<td>Measured (Standard deviation)</td>
<td>13.6 (2)</td>
<td>18.6 (3)</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>11.4</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td>Relative error (%)</td>
<td>16</td>
<td>9</td>
</tr>
</tbody>
</table>

* Measured results were calculated from five replicates for D₁. Ten replications for other parameters.
# The same letters followed the measured results in the same row show no significant difference were detected by ANOVA with Duncan test at significant level of 0.05.

DISCUSSION

The model of the soil profile of a single sweep was developed and validated with two sets of soil bin experimental results. The model included the speed and depth of tool operation, but the validation was completed at a constant depth only.

One application of this model is straw burial. If the purpose of tillage operation was only to bury all the straw, it could be completed by adjusting the tool spacing to 2B. To partially bury straw, the tool spacing could be arranged between w and 2B depending on the amount of straw to be kept on the soil surface.

The slope angle of a furrow was used as a parameter in model calculation. This angle could be affected by tillage speed. The validation in the first Section of model validation used measured values, which were different for three tillage speeds. The validation in the second Section of model validation, however, a pile angle of soil was employed to calculate those parameters of soil
profile. How to determine the angle ($\varphi_1$) as an input in model calculation is a remaining question. The suggested solution is to study the impact of tillage speed on the angle ($\varphi_1$) under different soils and soil conditions.

Table 3 Comparison of calculated and measured (Liu, 2005) parameters of soil profile of a single 325-mm-wide sweep in the soil bin. Soil: loamy (fine) sand, tillage depth: 100 mm

<table>
<thead>
<tr>
<th>Tillage speed (km/h)</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>357.9 $a$ #</td>
<td>411.9 $b$</td>
<td>488.3 $c$</td>
</tr>
<tr>
<td>(Standard deviation*)</td>
<td>(31.4)</td>
<td>(14.2)</td>
<td>(18.0)</td>
</tr>
<tr>
<td>Predicted</td>
<td>319.5</td>
<td>395.4</td>
<td>489.4</td>
</tr>
<tr>
<td>Relative error (%)</td>
<td>10.7</td>
<td>4.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$B$ (mm)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>74.6 $a$</td>
<td>69.3 $a$</td>
<td>68.6 $a$</td>
</tr>
<tr>
<td>(Standard deviation)</td>
<td>(10.2)</td>
<td>(11.6)</td>
<td>(41.5)</td>
</tr>
<tr>
<td>Predicted</td>
<td>71.8</td>
<td>72.8</td>
<td>75.3</td>
</tr>
<tr>
<td>Relative error (%)</td>
<td>3.8</td>
<td>5.1</td>
<td>9.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$H$ (mm)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>172.0 $a$</td>
<td>221.9 $b$</td>
<td>257.8 $b$</td>
</tr>
<tr>
<td>(Standard deviation)</td>
<td>(2.1)</td>
<td>(13.2)</td>
<td>(10.8)</td>
</tr>
<tr>
<td>Predicted</td>
<td>169.1</td>
<td>210.5</td>
<td>254.7</td>
</tr>
<tr>
<td>Relative error (%)</td>
<td>1.7</td>
<td>5.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

* All measured results were calculated from six replicates.
# The same letters followed the measured results in the same row show no significant difference were detected by ANOVA with Duncan test at significant level of 0.1.

**CONCLUSIONS**

Soil profile of a single sweep was studied and an improved mathematical mode for soil distribution was proposed. The main conclusions of this study are as follows:

a. Experimental results indicated that furrow width increased with increasing tillage speed, but the ridge height decreased slightly. The total width of soil disturbance significantly increased with increased tillage speed. The slope gradient of furrow was reduced at higher tillage speed, and the furrow slope was always larger than that of the slope of the end surface.

b. The mathematical model of soil profile after tillage with a single sweep was improved by modifying the process of forming soil ridges. Soil rolling and sliding changed the geometry of the soil ridge from an isosceles triangle to a triangle with a larger bottom angle at the furrow side.

c. The improved model was validated with a test conducted in a soil bin filled with coarse sandy loam soil, and the calculated soil profile was very close to that tested for tillage speeds of 5, 7.5, and 10 km/h. The maximum relative error of all dimensional parameters in this model
was 16%. The improved model was also validated with previous data obtained from a different soil bin with loamy (fine) sand soil. The maximum relative error was reduced to 11% from previous error of 40%.

ACKNOWLEDGEMENT

We thank the Natural Sciences and Engineering Research Council of Canada for financial support.

REFERENCES


