A Theoretical Approach for Determining Irregularities of the Bottom of the Tillage Layer Caused by Horizontal Axis Rotary Tillers

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ABSTRACT

Horizontal axis rotary tillers produce irregularities in the tillage depth when they are inappropriately operated and constructed. In such cases, mixing and breaking of soil throughout the tillage layer is not uniform and some untilled ridges will remain at the bottom of the tillage layer. Available equations and methods are practically inadequate for determining the effect of design and operational characteristics on the height of the resultant ridges at the bottom of the tillage layer. In this study, a method based on the derived geometrical relationships between the rotary tiller operational parameters was developed to determine heights of ridges occurring at the bottom of the tillage layer. The ridge heights can be calculated for various combinations of blade peripheral speed, forward travel speed, rotor radius, and the number of blades on one side of a rotary tiller flange. This method allows for the investigation of effects of rotary tiller operational and constructional properties of horizontal axis rotary tillers on the ridge heights at the bottom of the tillage layers. The results obtained using this method show that the heights of ridges at the bottom of the tillage layer increase with increases in forward travel speed and decrease with increases in blade peripheral speed, rotor radius, and the number of blades on one side of a flange.

Keywords: Soil tillage, horizontal axis rotary tiller, tillage depth, ridge height, tillage layer irregularity, Turkey

1. INTRODUCTION

Tillage depth has an important effect on physical properties of the soil layer and power requirements of the tillage tool. Tillage depth is an important parameter in the design of tillage implements. For pull-type tillage implements, the ratio of tillage depth to tillage width, and for rotary tillers, the ratio of rotor diameter to tillage depth are considered in evaluating tillage performance (Grisso et al., 1996; McKyes and Maswaure, 1997; Taniguchi et al., 1999). For practical working conditions, the set tillage depth of rotary tillers is less than the rotor radius (Hendrick and Gill, 1971b).

The tillage depth of a pull-type tillage implement that has straight-cutting edges in a single horizontal plane is relatively constant. Rotary tillage implements that have tools rotating about a horizontal axis, however, cause irregularities in tillage depth even though a fixed depth setting is used. During the rotary soil-cutting process, some untilled ridges occur at the bottom of the tillage layer of soil. When these ridges are small, the depth of tillage is nearly uniform, and this typically is a desired condition (Gill and Hendrick, 1976; Yatsuk et al., 1981).

The paths of blade movement for rotary tillers form an uneven surface, typically in the form of ridges, beneath the loosened soil layer (Figure 1). The lower points of the intersections of the paths of subsequent blades on the same side of the flange influence the peaks of ridges at the bottom of the tillage layer. The height of these ridges is assumed to be the vertical distance of the peaks above the tangents to the trochoids, constructed through their lower points (Grinchuk and Matyashin, 1968; Saimbhi et al., 2004).

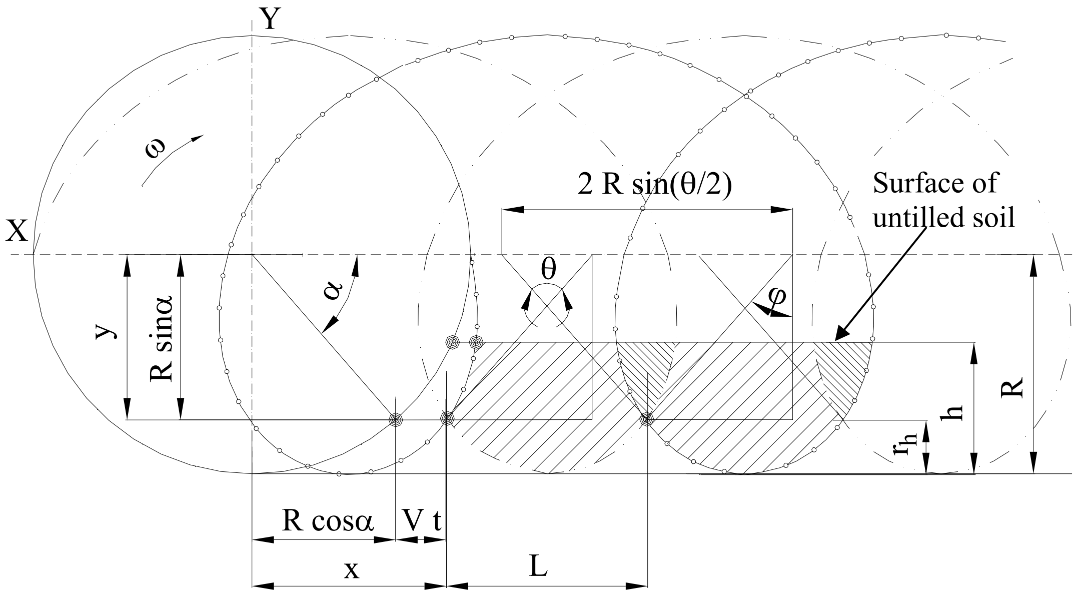

Figure 1. Side view showing geometric relationship among ridge height, rotor radius, tillage depth, longitudinal distance of any point on the blade path to the Y axis (x), and the tillage pitch (L), (Hendrick and Gill, 1971b). Direction of travel is from left to right.

The main factors affecting irregularities in the depth of rotary tillage can be separated into two sections based on constructional and operational parameters. The constructional parameters are the rotor radius and the number of blades on one side of a flange, and the operational parameters are forward speed, rotational speed of the rotor, and depth of tillage (Hendrick and Gill, 1971b; Hendrick and Gill, 1971c). The height of the ridges at the bottom of a rotary tilled furrow can be calculated using Equation (1).

$$h = R(1 - \sin\alpha) \quad (1)$$

where:

h = Tillage depth, mm

R = Radius of rotary tiller drum, mm

α = Angle in degrees measured about the tiller axis of rotation, between the cutting tip and the undisturbed soil surface (Figure 1).

Solving Equation (1) for α gives:

$$\alpha = \arcsin(1-\frac{h}{R}) \quad (2)$$

The blade of a rotary tiller executes a complex motion combining the rotary motion around the axis of the cutter drum and the forward motion due to the tractor forward velocity. This motion causes the end point of the blade to follow a trochoidal path (Bernacki et al., 1972). As the rotary tiller axis advances and the blades rotate, the successive paths result in a series of ridges that have a theoretical height of r_h. If the forward velocity is increased while rotor rotational speed is held constant, the height of the ridges can be as great as the tillage depth. To produce a smoother bottom of the tillage layer, however, the ridge height can be decreased by increasing the blade rotational speed while maintaining a constant forward velocity (Celik and Altikat, 2008). The height of ridges that are formed by successive soil slices shown in Figure 1 can be determined by the geometrical relationship between the parameters as follows (Hendrick and Gill, 1971a; Gill and Hendrick, 1976; Bok, 1965; Grinchuk and Matyashin, 1969; Blümel, 1986).

$$r_h = R(1-\cos\varphi) \quad (3)$$

$$\theta = 2\arccos(1-\frac{r_h}{R}) \quad (4)$$

where,

r_h = Theoretical height of the ridge, mm

φ = Angle between vertical and a straight line from the ridge to the centre axis of the rotor, degrees

θ = Angle between two successive rotor radius lines that intersect on the ridge point of the blade paths, degrees.

Hendrick and Gill **(**1971a) stated that α_2 can be found by Equation (5). But this expression cannot give a direct solution for α_2.

$$\frac{\pi}{z} = \lambda\sin\alpha_2 \pm \alpha_2 \quad (5)$$

where,

z = Number of blades on one side of a flange

λ = Ratio of blade peripheral speed to forward speed

α_2 = Angle between the vertical and a straight line from the ridge to the rotor axis of rotation.

The negative sign (-) is for blade forward and the positive sign (+) is for reverse rotation. Hendrick and Gill **(**1971a) produced some convenient diagrams showing relative height of ridges to the value of λ and z. All analyses here are for forward rotation of the rotor, which is the direction shown in figure 1 (Hendrick and Gill, 1971a)."

Ridge heights can be calculated by Equations (3) or (4), when either φ or θ are known. Some equations given in this study to calculate the ridge heights made by rotary tiller blades include an unknown angular parameter. These angles depend on many factors such as the blade rotational speed, forward speed, rotor radius, and the number of blades mounted on one side of each flange. These equations are not adequate for determining the actual height of ridges. Soil shear causes the actual heights of ridges to be less than theoretical heights. For the average soil, the actual height of ridges is half of the theoretical height (Bok, 1965).

The objectives of this study were;
-To propose a new approach on the derived geometrical relationships for determining heights of ridges formed in the bottom of the tillage layer by horizontal axis rotary tillers.
-To determine the effects of various combinations of forward speed, rotor rotational speed, rotor radius, and the number of blades on one side of a flange on ridge heights.

2. THEORETICAL CONSIDERATIONS

Rotary tiller blade paths and the ridges formed were geometrically analyzed to determine the ridge height. The longitudinal distance from any point on the blade path to the Y axis is designated as x. This distance, x, depends on the tillage pitch, L (fig. 1), the longitudinal distance between corresponding points of successive blade paths (Hendrick, 1971), and the number of blades on one side of a flange, z. The following expressions for x were geometrically determined from drawings obtained using a program developed in the AutoLISP programming language (Celik and Altikat, 2004) and run in the AutoCAD computer-aided design program (AutoDesk, Inc., San Rafael, California, USA).

$$x = L - \frac{1}{4}L \qquad (z=1), \qquad (6)$$

$$x = L \qquad (z=2), \qquad (7)$$

$$x = L + \frac{1}{4}L \qquad (z=3), \qquad (8)$$

$$x = L + \frac{1}{2}L \qquad (z=4), \qquad (9)$$

The longitudinal spacing of the ridges, which is the tillage pitch, is calculated by Equation (9) (Bernacki, 1962).

$$L = \frac{60\,V}{n\,z} \qquad (10)$$

where,
V = Forward speed, m/s
n = Rotor rotational speed, rpm.

The calculated x values using Equations (6) through (9) for each z, are also equal to x found using Equations (11) and (12). These equations which describe a point on the trochoidal path of an individual blade are (Blümel, 1986; Hendrick and Gill, 1978);

$$x = R\cos(\omega t) + V t \tag{11}$$

$$y = R\sin(\omega t) \tag{12}$$

where,

y = Vertical distance of any point on the blade path to the X axis, mm
$\alpha = \omega t$ = Angular rotation of rotor in time t, degrees
ω = Angular velocity of the rotor, rad/s.

In Equations (11) and (12), the only unknown parameter is t, the time for the rotor to rotate through angle, α. To calculate values of t, a program was written using the Maple 4 mathematics computer program (Waterloo Maple Inc., Waterloo, Ontario, Canada). By running this program, t was found for any x value. If we use the t values in Equation (11), the value of y can be determined. There is a geometric relation among r_h, y, and R (Figure 1). According to this relation, the theoretical ridge height, (r_h) can be calculated as follows,

$$r_h = R - y \tag{13}$$

The above expressions provide for an analysis to determine the effects of the parameters on the ridge height. Therefore, the ridge heights were calculated, using the above relationship for 10 levels of rotor rotational speed (90, 140, 190, 240, 290, 340, 390, 440, 490, and 540 rpm), 10 levels of forward speed (0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, and 2.75 m/s), five rotor radii (150, 200, 250, 300, and 350 mm) and four different numbers of blades on one side of a flange (1, 2, 3, and 4). Regression analysis was used to determine equations describing the ridge height as functions of forward speed, rotor rotational speed, and number of blades on one side of a flange. Although this is a theoretical study, regression was used to attain relatively simple equations describing effects of these variables on ridge height.

3. RESULTS AND DISCUSSION

Effects of forward speed, rotor rotational speed, and number blades on one side of a flange, on ridge height, are shown in Figure 2. As shown in the figure, relatively high forward speed, few blades on one side of a flange, and low rotor rotational speed can cause the ridge height to be as great as the tillage depth. In this case, untilled ridges occurred in the tillage layer. Low forward speed, high rotor rotational speed and many blades on one side of a flange produce a tillage layer with a nearly ridge-free bottom.

The effects of the parameters on ridge height are shown graphically in Figures 3, 4, and 5, which are based on Equations (6) through (9). Ridge height decreased as rotor radius increased (Figure 3a) and as the number of blades on one side of a flange increased (Figure 3b). There is a significant linear relationship between ridge height and forward speed (Figure 4a) and an exponential relationship between blade peripheral speed and ridge height (Figure 4b). Ridge height increases as forward speed increases and as blade peripheral speed decreases.

Tillage pitch is affected by forward speed and the number of blades on one side of a flange. As tillage pitch increases, ridge height increases exponentially (Figure 5a). Ridge height increases as the ratio of blade peripheral speed to forward speed decreases (Figure 5b).

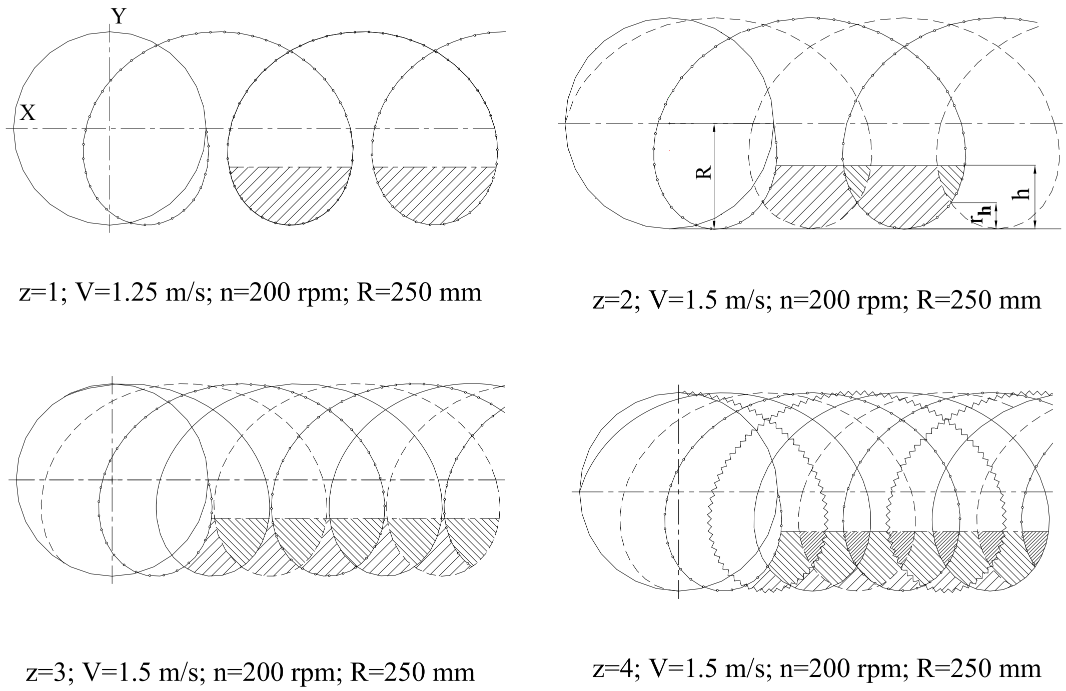

Figure 2. Side view showing ridges occurring at the bottom of the tillage layer as affected by the number of blades on one side of a flange (z), forward speed (V), and rotor rotational speed (n). Direction of travel is from left to right.

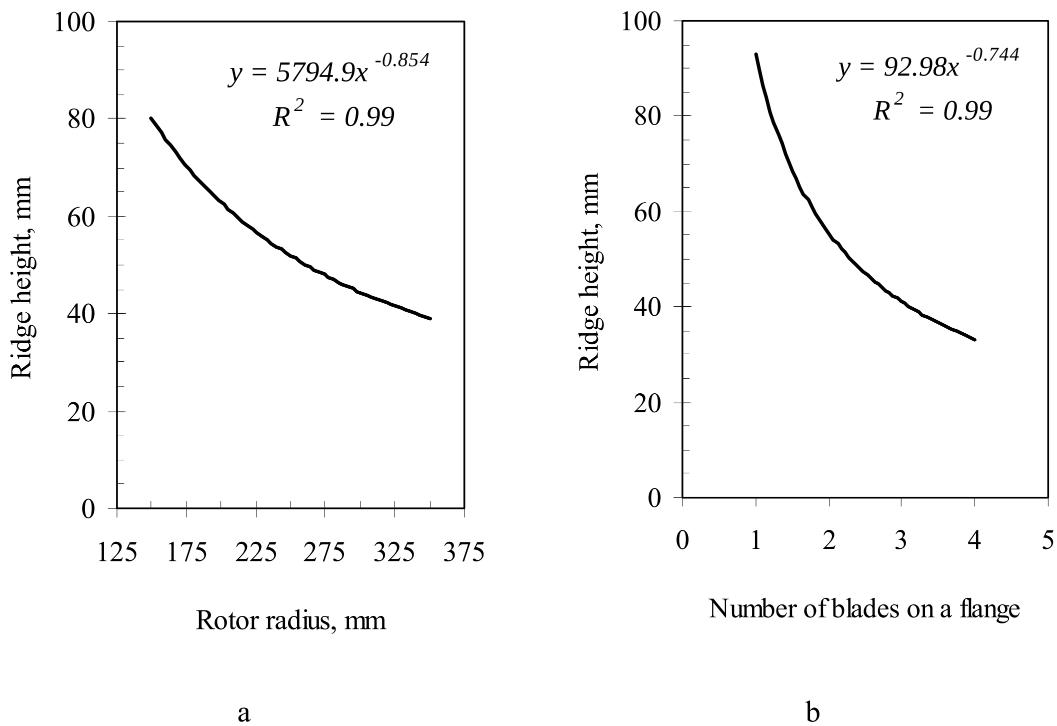

Figure 3. (a) Effect of rotor radius on ridge height;
(b) Effect of number blades on one side of a flange on ridge height.

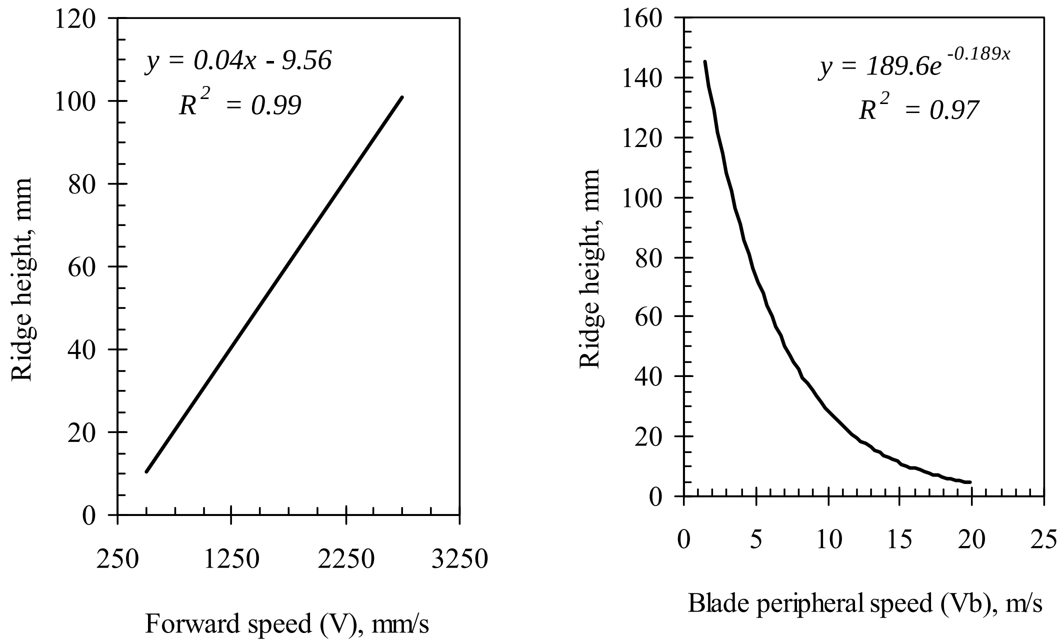

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Figure 4. (a) Effect of forward speed on ridge height;
(b) Effect of blade peripheral speed on ridge height.

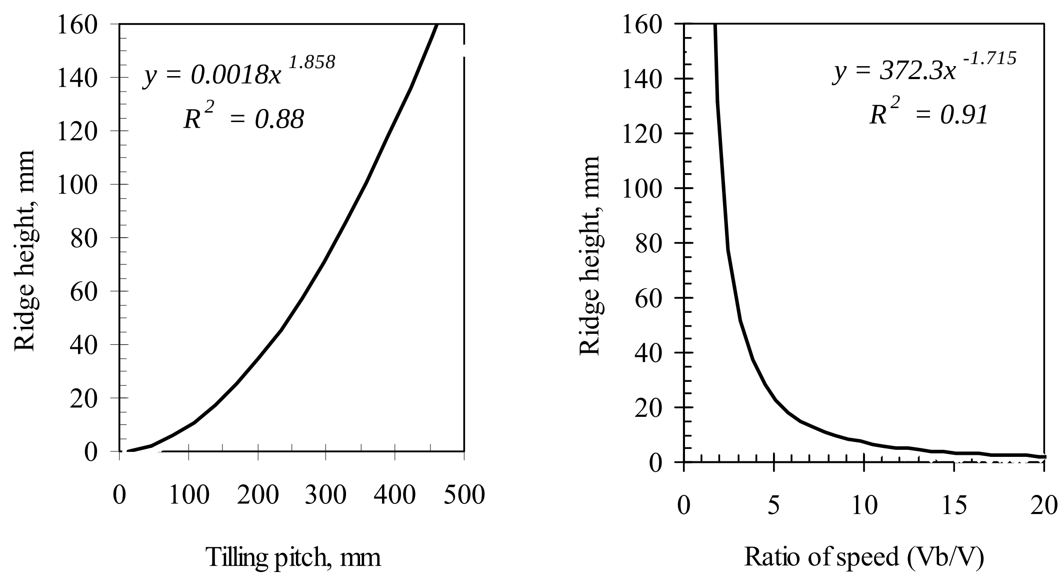

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Figure 5. (a) Effect of tillage pitch on ridge height;
(b) Effect of ratio of blade peripheral speed to forward speed on ridge height.

4. CONCLUSIONS

To determine the effective depth of tillage it is important to determine the height of ridges occurring in the bottom of the tillage layer of soil. When the ridge height is small, the depth of tillage is nearly uniform, and this is a desired condition for crop growth and for avoiding excessive power requirements of equipment. A combination of low forward speed, high rotor rotational speed and many blades on one side of a flange produce a tillage layer with a nearly ridge-free bottom.

In this study a new approach was developed for determining heights of ridges formed in the bottom of the tillage layer by horizontal axis rotary tillers. By using this approach, the effects of various combinations of forward speed, rotor rotational speed, rotor radius, and the number of blades on one side of a flange on ridge heights was determined.

The heights of ridges formed by a horizontal axis rotary tiller were found to increase with increases in forward speed and tillage pitch, and to decrease with increases in blade peripheral speed, rotor radius, number of blades on one side of a flange, and ratio of blade peripheral speed to forward speed. There is a significant linear relationship between ridge height and forward speed and an exponential relationship between blade peripheral speed and ridge height. As tillage pitch increases, ridge height increases exponentially. Ridge height increases as the ratio of blade peripheral speed to forward speed decreases. As operational parameters, greater blade peripheral speed and lower forward speed are the most convenient options.

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