Journal of Engineering and Applied Sciences 13 (Special Issue 8): 6505-6511, 2018
ISSN: 1816-949X

Mathematical Description of the Mechanical Erosion Process in Sloping Fields

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Abstract: The research is devoted to a mathematical description of the progress of mechanical soil erosion on sloping fields. The mechanical soil erosion means the movement of the soil down the slope by the working bodies of tilling and seeding machines. The dependence of mechanical erosion on the slope gradient, the parameters of the working body and the driving direction of the machine relative to the field horizontal is given. The obtained mathematical model allows to determine the permissible limits for changing the parameters of the working body and to indicate the optimal driving direction of the machine relative to the field horizontal. This model also shows that in order to preserve fertile soil in sloping fields it is necessary to combine the efforts of farm machinery developers to select the necessary parameters of working bodies for sloping fields and the efforts of farm workers to ensure the correct movement of the machine on the field to reduce mechanical erosion.

Key words: Slope gradient, mechanical erosion, A-hoe blade, one direction working body, sloping fields, necessary parameters

INTRODUCTION

In the agricultural lands of the South Urals (The Russian Federation), there is the so-called water erosion when rainfall or snow-melt waters flow down the field and flush the upper fertile soil layer away. The average annual soil loss is 1 mm.

But such humus losses are recovered by the decomposition of crop residues and root system of plants, since up to 18-21 tons of humus per hectare are formed annually. However, in sloping fields, in addition to water erosion, mechanical erosion also occurs as a type of soil degradation (Blednykh and Rakhimov, 2001).

Mechanical soil erosion is the soil movement down the slope by the working bodies of tilling and seeding machines. Mechanical erosion removes the fertile soil from the upper part of the slopes and greatly increases water erosion.

The study by Shvedas devoted to this problem shows that the considerable soil losses from mechanical erosion coincide in time with the beginning of the use of a mould board plough for tilling slopes. A large amount of experimental data on mechanical erosion is presented.

The theoretical and experimental study of mechanical soil erosion in sloping fields when plowing with mould board ploughs was carried out by Makarova (2010) and Makarova and Zatsarinny (2012). They considered the change in the angle of setting the ploughshare blade to the wall and the bottom of the furrow depending on the slope gradient and the driving direction of the machine. The study shows that soil displacement downward also depends on the range of soil throw from the mould board plough.

The research of Ruysschaert *et al*. (2006, 2007) shows that harvesting of such crops as sugar beet, potatoes, onions and carrots results in soil loss from arable land, since, the soil stuck to tubers and the balls of earth cannot be separated by a harvesting machine and the soil is carried from the field together with these harvested crops. These soil losses can be as considerable as the soil losses caused by water erosion processes (Ruysschaert *et al*., 2006, 2007).

In addition, Govers and Poesen (1998) indicate that even treading of goats and sheep can greatly facilitate the movement of soil fragments down the slope.

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Lobb (2008) points out that many technological operations lead to soil displacement. At the same time, soil cultivation is the most common of these activities (Lobb, 2008).

Guerra *et al*. (2017) note that soil erosion and mass movement (i.e., mechanical soil erosion) are two forms of land degradation and people play an important role in these geomorphological processes.

Muysen *et al*. (2002) prove that soil erosion occurs not only during the main tillage but also additional tillage contributes significantly to soil displacement and soil erosion.

Muysen *et al*. (2002) consider that the average distance of soil displacement depends not only on the slope gradient but also depends on the depth of tillage, speed and the direction of tillage.

Kosmas *et al*. (2001) point out that tilling the fields on an undulating land leads to the transportation of a large amount of soil from convex slopes (the upper part of the slopes). The application of the obtained empirical functions has shown that under existing climatic conditions and tillage methods, the area of unprofitable production areas will increase from 4.1-6.8% within 7 years.

Muysen *et al*. (1999) state that when the soil is initially friable, both the soil displacement downward and the movement speed become greater as the slope gradient increases.

According to Heckrath *et al*. (2006) the movement of the machine at an angle of 45° results in the tillage with the least erosion.

Blednykh and Rakhimov (2001) present the theoretical description of mechanical erosion and consider the process of mechanical erosion during the operation of A-hoe blades across the slope.

Purpose of research is to reduce mechanical soil erosion on sloping fields by improving technological and design parameters of tilling and seeding machines.

MATERIALS AND METHODS

The working body which has the form of a trihedral wedge (plough bottom, A-hoe blade, disc, etc.) displaces the soil across the driving direction of the machine. On the plain the soil displacement depends only on the parameters of the working body the angle y between the ploughshare blade and the driving direction and the angle ϵ between the surface of the working body and the parallel of the field surface passing through the ploughshare blade. Since, the soil displacement occurs symmetrically to the driving direction, there is no overall displacement of the soil.

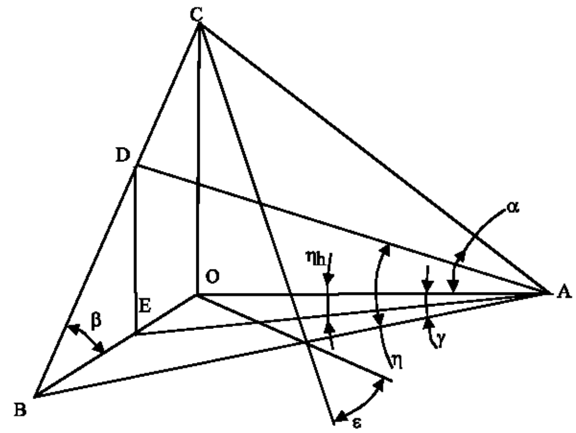

Fig. 1: Trajectory of soil displacement on the plain

When working on the plain, the soil moves along the working body of the tilling and seeding machine at an angle η between the ploughshare blade and the direction of the soil displacement along the wedge (Fig. 1) which is defined by the equation of Gyachev:

$$tg\eta = tg\gamma.\cos\varepsilon \quad (1)$$

The determination of soil movement is made by finding the angle η_h between the projection of the soil displacement trajectory in the horizontal plane and the driving direction of the working body:

$$tg\eta_h = \frac{tg\gamma - \cos\varepsilon.tg\eta}{1+\cos\varepsilon.tg\gamma.tg\eta} \quad (2)$$

The value of the soil displacement Δ_1 = OE Since, the soil displacement to the right and to the left will be the same, the overall displacement of the soil will not occur. The displacement Δ_1 affects only the width of open furrow. Accordingly, on the flat fields mechanical soil erosion does not occur due to the working bodies of tilling and seeding machines.

RESULTS AND DISCUSSION

On the slopes the soil displacement downwards will always be greater than the soil displacement upwards (Fig. 2) due to the changing parameters of the working body relative to the horizontal plane and due to additional lateral force Q = G•sin Ω(Ω, slope gradient), acting on the soil layer along the slope downwards. In this study, the technological parameters of the working body are the angles γ and ε which are formed at the cross-section of the trihedral wedge by a horizontal plane: γ_i, between the intersection of the working plane of the trihedral wedge

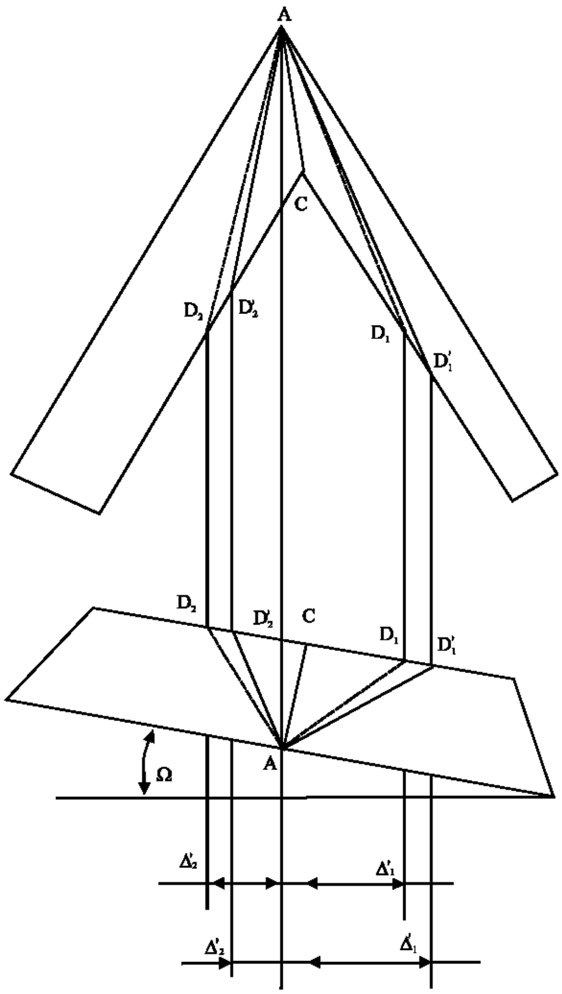

Fig. 2: Soil displacement on the slopes by A-hoe blades

with the horizontal plane and the direction of motion and ε_i between the working plane of the trihedral wedge and the horizontal plane.

In Fig. 2 Δ'_1 and Δ'_2 'denote soil displacement without taking into account the lateral force. Together with the lateral force, the displacement of the soil upward by the upper wing decreases to Δ_2 and the soil displacement downward by the lower wing increases to Δ_1. The difference in displacement during machining leads to mechanical erosion of the soil, equal to:

$$\Delta = \Delta_1 - \Delta_2 \tag{3}$$

To avoid water erosion it is recommended to till the field across the slope but it is impossible to avoid soil movement along the slope. That is why, the working bodies together with the machine are tilted both across and along the driving direction of the machine. For this

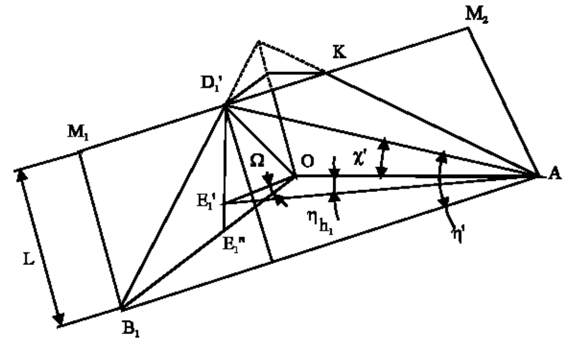

Fig. 3: Scheme for determining the soil displacement on slopes by the ploughshare

reason let us consider the driving direction of the machine both across and along the slope as well as at an angle to the slope (Rakhimov, 2005, 2013a, b).

The tilt of the working body across the driving direction of the machine is denoted by Ω_{acr} and the tilt of the working body along the driving direction is denoted by Ω_{al}.

The angles Ω_{acr} and Ω_{al} at the same slope gradient Ω depend on the driving direction of the machine relative to the horizontal of the field. Let us find these angles in relation of the angle θ to the driving direction and the field horizontal and to the slope gradient Ω. Let us consider the driving direction of the machine along the field horizontal with the fall of the soil layer to the right as zero direction and the angle θ as increasing clockwise. The tilt of the working body across the driving direction will be:

$$tg\Omega_{acr} = tg\Omega.\cos\theta \tag{4}$$

and the tilt of the working body along the driving direction will be:

$$tg\Omega_{al} = tg\Omega.\sin\theta \tag{5}$$

where, θ is the angle between the horizontal of the field and the driving direction of the machine, degree. When the machine moves at any angle θ, mechanical erosion is determined by the expression:

$$\Delta = |(\Delta_1 - \Delta_2).\cos\theta \tag{6}$$

Let us take the working body in the form of a ploughshare with a width L (Fig. 3). The ploughshare $AB_1M_1M_2$ is a part of the trihedral wedge. Soil displacement is defined as:

$$\Delta_1 = L.\frac{tg\eta_{h1}}{\cos\Omega.\sin\eta'.\cos\lambda'} \tag{7}$$

As can be seen to determine the soil displacements it is necessary to calculate the technological parameters of the working body the angles γ_i, ε_i and to know the width of the ploughshare L. We take the following symbols for these angles: γ_1 and ε_1 are the angles when the machine moves across the slope, degree; γ_2 and ε_2 are the angles when the machine moves along the slope, degree; $\gamma_{1,2}$ and $\varepsilon_{1,2}$ are the angles when the machine moves in any direction θ, degree. The calculation is made by the expressions:

$$\begin{aligned}
tg\gamma_1 &= tg\gamma.\frac{\sin\beta}{\sin(\beta \pm \Omega_{acr})} \\
tg\varepsilon_1 &= \frac{tg(\beta \pm \Omega_{acr})}{\cos\gamma_1} \\
tg\gamma_2 &= tg\gamma.\frac{\sin(\alpha + \Omega_{al})}{\sin\alpha} \\
tg\varepsilon_2 &= tg\varepsilon.\frac{tg(\alpha + \Omega_{al})}{tg\alpha}.\frac{\sin\gamma}{\sin\gamma_2} \\
tg\gamma_{1,2} &= tg\gamma.\frac{\sin\beta}{\sin(\beta \pm \Omega_{acr})}.\frac{\sin(\alpha + \Omega_{al})}{\sin\alpha} \\
tg\varepsilon_{1,2} &= tg(\beta \pm \Omega_{acr}).\frac{tg(\alpha + \Omega_{al})}{tg\alpha}.\frac{tg\gamma_1}{\sin\gamma_2}
\end{aligned} \quad (8)$$

where the angles α and β of the trihedral wedge are determined by the expressions $tg\alpha = tg\varepsilon\text{-}\sin\gamma$ and $tg\ \beta = tg\varepsilon\text{-}\cos\gamma$. The theoretical data obtained by the expressions (Eq. 8) correspond to the available calculated data of Makarova and Zatsarinny (2012). According to Makarova and Zatsarinny (2012). when the machine moves across the slope with the soil overturning down the slope, technological angles vary: γ_1 from 38-28° and ε_1 from 26-33° when the slope gradient changes from 0-9°. The calculations carried out by the expressions (Eq. 8) show that the angles vary within the range: γ_1 from 38-29.2° and ε_1 from 26-33.5°. The data of Makarova and Zatsarinny show that when the machine moves across the slope with the soil overturning up the slope, these angles vary: γ_1 from 38-53° and ε_1 from 26-22° but according to the expressions (8) the angles vary within the range: γ_1 from 38-53.4° and ε_1 from 26-20°. There is also a correlation between the behaviour of soil movement along the working body and the setting angle of the ploughshare to the furrow wall γ_1.

Depending on the driving direction of the machine due to the lateral force, the trajectory of the soil movement along the working body deviates which is defined as follows:

$$\frac{tg\gamma.\sin\varepsilon.\cos\xi.\sin\Omega.\cos\eta.\cos(\theta \mp \eta_h)}{\cos\varepsilon_{1,2}} \quad (9)$$

Where:

ξ = It is defined by the expression $tg\xi = tg\varepsilon.\cos(\gamma \mp \theta)$

η_1 = It is defined by the expression $tg\eta_1 = tg\gamma_{1,2}.\cos\varepsilon_{1,2}$

η'_{h1}, η' = These are defined by the expression

$$tg\eta_{h1} = \frac{tg\gamma_{1,2}\text{-}\cos\varepsilon_{1,2}.tg\eta'_1}{1 + \cos\varepsilon_{12}.tg\gamma_{1,2}.tg\eta_1'} \quad (10)$$
$$\eta_1' = \eta_1 \mp \delta, \eta_1 = \eta \mp \delta$$

The angle between the trajectory of the soil movement on the slope and the direction of motion of the working body χ' is calculated as follows:

$$tg\chi' = \frac{tg\chi}{\cos\delta} \quad (11)$$

where, χ is defined by the expression:

$$tg\chi = tg\gamma.\sin\varepsilon.\cos\eta \quad (12)$$

When the working body moves across the slope the soil displacement downwards by the lower wing of the A-hoe blade increases with the growing slope gradient and the soil displacement upwards by the upper wing decreases and when the gradient reaches the critical value Ω_{cr}, the soil also starts moving down the slope (Fig. 4). Experimental data were obtained by a specially designed instrument for determining the trajectory of the soil particles movement (Rakhimov, 2006). The soil displacement also depends on the parameters γ, ϵ and L.

The comparative statistical analysis shows that the theoretical data are adequate to the experimental data according to the Fisher criterion at the significance level of 5%.

Soil displacement and mechanical soil erosion vary depending on the driving direction of the machine relative to the field horizontal (Fig. 5). The maximum soil displacement by the lower wing of the working body (Δ_1) occurs when the machine moves at an angle θ 45, ..., 70° to the field horizontal, depending on the design angles of the working body which is explained by the superposition of the forward pitch Ω_{al} and the sideways pitch Ω_{acr} of

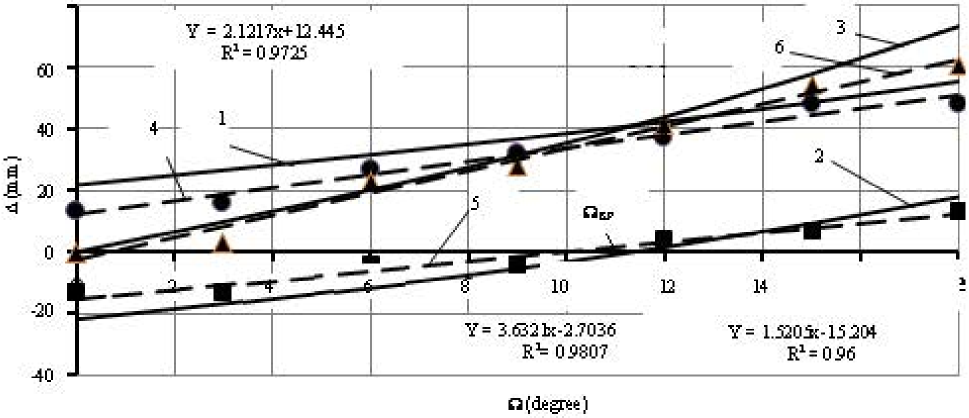

Fig. 4: Dependency of soil displacements Δ_1 and Δ_2 and mechanical erosion Δ (during the operation of a ploughshare with the width L = 100 mm and the angles γ = 50°, ϵ = 30°) on the slope gradient Ω when moving across the slope. 1-3 theoretical data Δ_1, Δ_2 and Δ and 4-6-experimental data Δ_1, Δ_2 and Δ

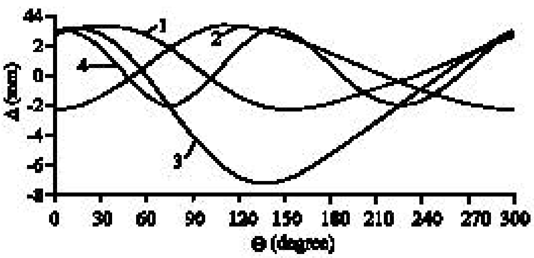

Fig. 5: Dependency of soil displacements by the A-hoe blade and mechanical erosion on the driving direction θ on the slope (6° slope, γ = 60°, ϵ = 20°): 1) Soil displacement by the lower wingΔ_1; 2) Soil displacement by the upper wingΔ; 3) Overall Soil displacement Δ_2 and 4) Mechanical erosionΔ

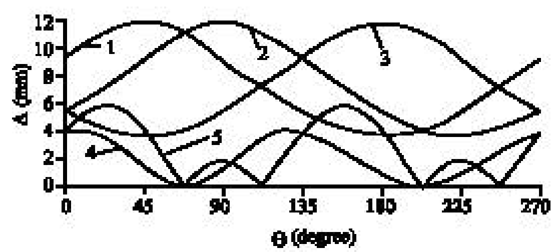

Fig. 6: Dependencies of soil displacements and mechanical erosion when operating with an A-hoe blade and a one direction working body on the driving direction of the machine θ (6° slope, γ = 32.5° and ϵ = 26°): 1) Soil displacement down the slope; 2) Soil displacement upward by Δ_2 the upper wing of the A-hoe blade; 3) Soil displacement upwards by a one directionworking body $\Delta 2_{one\text{-}direction}$; 4) Mechanical soil erosion when tilling withA-hoe blade and 5) Mechanical soil erosion when operating with the one direction working body

the working body. The minimum mechanical erosion for the A-hoe blades occurs when the machine moves at the angles θ=90±35° and θ=270±35° and the maximum values are reached when the machine moves at the angles θ=15±15° and θ=165±15°.

Special attention should be paid to the process of tillage by one direction working bodies such as plough bottoms. The peculiarity of the process is that the soil movement upwards (Δ_2) occurs when the tool moves in the opposite direction (θ+180°). This leads to a change in mechanical erosion (Fig. 6).

For one direction working bodies, the minimum values of mechanical erosion are observed when the machine moves at the angles θ=120±40° and θ=300±40° to the horizontal and the maximum values at the angles θ=30±15° and θ=210±15°. As can be seen from Fig. 6. the maximum mechanical erosion when operating with the one direction working bodies is 1.5 times greater than with A-hoe blades. In any driving direction of the machine θ an angle increase ϵ leads to an increase in mechanical erosion (Fig. 7).

The open furrow width varies according to the slope gradient Ω, the parameters of the working body γ, ϵ and L and the driving direction of the machine θ. If the ploughshare width L and the angle ϵ increase and the angle γ decreases as the slope gradient increases, an open furrow size increases. The open furrow has a minimum value when the machine moves up the slope (θ = 270°) and a maximum value when it moves down the slope (θ = 90°) (Fig. 8).

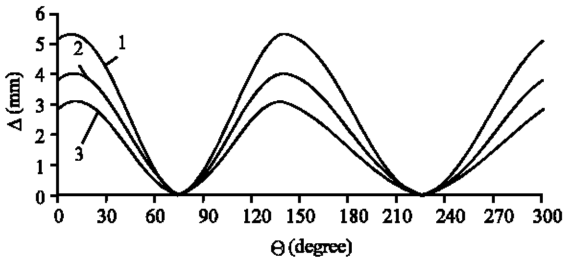

Fig. 7: Dependence of mechanical erosion Δ at the angle γ = 32.5° and different values of the angle ε on the driving direction of the machine θ; 1) ε = 26° and 2) ε = 22° and 3) ε = 18°

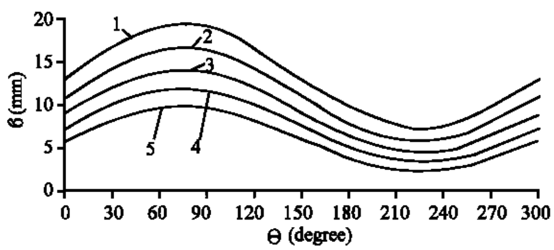

Fig. 8: Dependency of the open furrow width $б_1$ on the driving direction of the machine θ on the 6° slope at the angle γ = 32.5° and different values of the angle ε; 1) ε = 26°; 2) ε = 24°; 3) ε = 22°; 4) ε = 20°; 5) ε = 18°

Thus, to reduce mechanical soil erosion it is necessary to select the appropriate parameters of the working body as well as the driving direction of the machine. If there is no threat of water erosion soil cultivation should be carried out with A-hoe blades at the angle θ = 90±35° and with the use of one direction working bodies at the angle θ =120±40°.

The results obtained can be explained by the concept of Makarova and Zatsarinny (2012). According to this authors working bodies have different parameters depending on the direction of movement when working on slopes. Therefore, they will have different agrotechnical and energy performance indicators as well as a different mechanical soil movement down the slope.

The developed mathematical model of the mechanical soil erosion process on sloping fields has shown that together with water erosion there is also mechanical erosion that arises from the movement of soil down the slope by the working bodies of tilling and seeding machines. This movement depends both on the parameters of the working bodies and the driving direction of the machine on the field. Thus, to preserve fertile soil in sloping fields it is necessary to unite the efforts of farm machinery developers who must select the right parameters of working bodies and farm workers who must ensure the correct movement of the machine on the field to reduce mechanical erosion.

CONCLUSION

Mechanical soil erosion on the slopes occurs even with the use of symmetrical working bodies in the form of a trihedral wedge. Mechanical soil erosion on the slopes occurs during the work of tilling and seeding machines due to asymmetric soil displacement up and down the slope by the working body and depends on the slope gradient, technological and design parameters of the working body and the driving direction of the machine. Calculations have shown that the maximum soil displacement by the lower wing of the working body ($Δ_1$) occurs when the machine moves at the angle θ = 45÷70° to the field horizontal. The minimum mechanical soil erosion occurs when the machine moves at the angle 90±35° to the horizontal of the field when operating with A-hoe blades and at the angle 120±40° when operating with one direction working bodies. It is desirable to avoid the driving direction of the machine θ≈0, ..., 70° when there is maximum mechanical erosion when operating with one direction working bodies (plough bottoms) which exceeds mechanical erosion by 1.5 times when moving on the field horizontal.

When operating with A-hoe blades, the open furrow width increases as the ploughshare width L and the angles γ, ε increase too. On a 6° slope the open furrow width changes three times according to the driving direction of the machine. The minimum width of the furrow will be when the machine moves up the slope and the maximum width when the machine moves down the slope.

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