A rationale of broach-plow’s parameters of the ridge-stepped ploughing of slopes

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Abstract. The aim of this study was to develop an improved technology for ridge-stepped ploughing of slopes and plow, which protects the soil from water erosion, improves the accumulation and preservation of soil moisture. The paper proposes an effective method for ridge-stepped ploughing of slopes, including the alternation of layer’s incomplete rotation with its full rotation within its furrow by 180° in combination with the band subsoil loosening. A technological model of a ridge-stepped ploughing with simultaneous subarable strip loosening was developed. The design of the developed plow for ridge-stepped ploughing is highlighted. During the study the followings were theoretically and experimentally established: with a longitudinal distance between the hulls of 50 cm, the required qualitative incomplete turnover of the layers with the lowest energy costs is provided with the following plow’s parameters of the odd hulls: plow length is 75 cm, plow width is 25 cm, stabilizing plate height is 15 cm, and the minimum distance from the ploughshare toe to the stabilizing plate is 25 cm.

1. Introduction

Worldwide, a sharp decrease in soil fertility occurs as a result of increased water erosion and its recovery is one of the very difficult and long-term global environmental problems [1-4]. In recent years, erosion has caused significant damage to Uzbekistan’s agriculture. Excessive tillage leads to the dissemination of wind and water erosion of soil. Water erosion mainly occurs on sloping lands. In Uzbekistan, more than 20.4% of arable land is located on the slopes with the steepness of 3 degrees or more. More than 85% of rainfed arable lands are subject to water erosion [5].

According to the review and literature analysis, agrotechnical techniques occupy a special place in the anti-erosion complex. The main anti-erosion requirement is the creation of such field surface and furrow bottom, which will be resistant to wind and water erosion, and provide the best conditions for plant development and yield formation.

Currently, in Uzbekistan, arable land is processed by traditional standard reversible moldboard plows. It is known that a plow sole is formed with annual ploughing with standard plows at the same depth in the subsurface layer, the density of which exceeds by 2 or more the arable layer density [6-11]. A great difference in densities on the slopes leads to a deterioration in the moisture imbibition by the lower subsurface soil layer. As a result, subsurface drainage occurs - water erosion on the slopes.
One of the promising ways of the main tillage is smooth ploughing using a new technology, which involves a full turn (1800) of soil layers and laying them in their own furrows [12, 13]. This method is carried out with frontal and linear-step plows. During the tillage of slopes soil by these plows, a bottom of furrow and an arable land surface are smooth. As a result, a soil’s ability to retain and accumulate rainwater deteriorates, resulting in water erosion.

One of the most important anti-erosion techniques of basic tillage is step ploughing contributing inland drain [2].

The aim of this study is to develop and substantiate an improved plow’s parameters for ridge-stepped ploughing based on a linear-step plow for smooth ploughing, protecting the soil from water erosion, improving the accumulation and preservation of slopes soil moisture.

2. Materials and Methods

The basic principles and methods of classical mechanics, mathematical analysis and statistics were used in this study.

Based on patent and research work [9], improved technology and design of a ridge-stepped plow based on a linear-stepped plow for smooth ploughing were developed (see Figure 1a).

![Figure 1. Plow’s constructive scheme for ridge-stepped ploughing (a) and furrow’s transverse profile after ploughing (b).](image)

A ridge-stepped plow consists of a frame 1, screw plow hulls 2 and 4, offset from each other. In this case, the odd hull 2 is equipped with a short broach-plow 3, and even hull 4 is equipped with a long broach-plow 5.

A specialty of the proposed technology is that a complete turnover of the layers alternates with an incomplete turnover of the layers at 1800 within its own furrow [8]. At the same time, ridges are formed on the surface of arable land, and at the bottom of the furrow - steps (Figure 1b), which contribute to the retention and accumulation of rainwater and prevents the occurrence of water erosion. When the turnover of the layer is reversed to 1800, the hull 4, first independently, and then, in cooperation with the broach-plow 5, turns the layer without displacing its center of gravity, placing it within its own furrow. In case of incomplete turnover, the turnover of the layer is carried out without displacement and with the displacement of its center of gravity. In this case, the hull 2 and the short broach-plow 3 interact to such a turn of the layer, at which a stable position of the turning layer must be ensured, a further turn of the layer is carried out by the hull without broach-plow’s interaction. In this case, the layer turns at an angle of at least 1350.

To implement the proposed technology, the odd hull 2 must perform an incomplete turnover of the layer, which must be wrapped so that a moisture-holding ridge is formed on the surface of arable land, but an open furrow should not form between the wrapped layers. Incomplete rotation of the layer can be carried out in the following known ways: turnover of the layer with the displacement of its center of gravity in the transverse direction; turnover of the layer without lateral displacement of the center of gravity.

It is known that when the layer is reversed with a transverse displacement of its center of gravity, an open furrow is formed with a width equal to the width (b + a), where b and a are the width and thickness
of the layer, which does not satisfy the required condition. A flat surface is formed when the layer is rotated 180° without lateral displacement of its center of gravity, after the working hull passes [9-10]. Therefore, a combination of layer turnover with and without displacement of its center of gravity in the transverse direction is proposed for the implementation of incomplete layer rotation. This technology can be implemented in the following way: initially, the layer turnover is from 0 to π / 2 without lateral displacement of the center of gravity, based on the edge D (see Figure 2a); a subsequent turnover of the layer without transverse displacement of the center of gravity from π / 2 to (π / 2 + j), while the layer leans on the C2 edge (see Figure 2b), the rotation of the layer with transverse displacement of its center of gravity from (π / 2 + j) to (π – δ), leaning on the edge C3 (see Figure 2b). Here j is the angle between the diagonal of the layer cross section and its base, and δ is the inclination angle of the rolled-off layer.

With the proposed method, the action line of gravity G of the layer passes at a sufficient distance S from the support point C3 (see Figure 2c), which ensures the stability of the laid layer. At the same time, ridge with the height h is formed on the surface of arable land.

\[
\delta = \arctg \frac{2a}{b}, \quad h = \sqrt{a^2 + b^2} \sin(j + \delta) - a, \quad B_a = \frac{b}{2} - a \sin\delta. \quad (1)
\]

When a=25 cm and b=50 cm, a layer inclination angle is δ=45°, a ridge height is 27.85 cm, and an open furrow width is B_a=7.3 cm, which fully meets the requirements of the water retaining surface of the field [1, 2].

3. Results

A technological process quality of the layer’s turnover by the proposed plow’s hull depends largely on the broach-plow’s location relative to the main hull, as well as on its design parameters. A broach-plow is attached to the main ploughshare of the hull (see Figure 3) in the stepped plow for ridge-stepped ploughing. It consists of a stabilizing plate 2 with a bracket, a short ploughshare 3 and wing 4. A broach-plow’s ploughshare 3 is welded to the stabilizing plate 2. The wing 4 is attached to a stabilizing plate’s bracket.

![Figure 3. Schematic patterns of a mutually located broach-plow and plow hull.](image)
The following expressions were obtained to determine the greatest distance from the plowshare toe to a stabilizing plate \( l_1 \) and a stabilizing plate length \( l_{sp} \) of the broach-plow [6]:

\[
l_1 = 0.5 b_p \cot \gamma, \quad l_{sp} = 0.5 b_p \cot \gamma \frac{s}{\sin \gamma}.
\]  

(2)

A hull’s total traction resistance with broach-plow consists of hull and broach-plow’s resistance.

\[ R_i = R_K + R_z = K a b + R_z, \]

A broach-plow’s traction resistance consists of the plowshare resistance, a stabilizing plate and broach-plow’s wing [6], e.g.:

\[
R_b = b_p (1 + f \cos \gamma \left( \sigma \delta + \frac{pl_p}{\sin \beta_p} \right) + f \rho_1 h_p^2 + \\
+ \left( \frac{pl_1}{\sin \beta_1} + \sigma \delta \right) (1 + f \cos \alpha_c) h_p + \\
+ f \rho_1 (l_{sp} h_p - \frac{h_p^2}{2} \cot \alpha_c) + k f_1 h_m b_w,
\]

(3)

where \( \sigma \) – temporary soil resistance to plowshare blade tipping, Pa; \( \delta \) – blade thickness, m; \( p \) – specific soil pressure on the plowshare’s facet, Pa; \( t_p \) – broach-plow’s plowshare thickness, m; \( \beta_p \) – broach-plow’s plowshare sharpening angle, gr; \( \rho_1 \) – specific pressure of soil on plowshare’s surface, Pa; \( b_p \) – width of broach-plow’s plowshare, m; \( \alpha_c \) – plate’s blade inclination angle to the bottom of the furrows in the longitudinal-vertical platan, gr; \( f \) – soil friction coefficient on steel; \( \beta_1 \) – layer sharpening angle, gr; \( t_l \) – layer thickness, m; \( \rho_1 \) – specific pressure during the collapse of the lateral face of the layer, Pa; \( k \) – specific resistance of soil, Pa; \( f_1 \) – internal friction coefficient; \( h_m \) – middle wing height, m; \( b_w \) – wing width in the horizontal platan, m.

The resulting analytical expression allows us to determine the traction resistance of the broach-plow depending on its design parameters and the physical and mechanical properties of the soil.

The length of broach-plow and the longitudinal distance between the hulls with short and long broach-plows are the main parameters affecting the quality of ploughing for smooth-step ploughing.

A short broach-plow length is determined by the following expression:

\[
L_z = \frac{L (\pi - \delta)}{\pi},
\]

(4)

where \( L \) - layer length with its turnover on \( \pi - \delta \).

Following expression 4, a short broach-plow’s length should be within 73.8-79 cm with \( L = 95 \) cm, \( \delta = 30-40^\circ \).

To identify the rational length of the broach-plow, experimental broach-plows of 25, 50, 75, and 93 cm were designed, and the longitudinal distance between the hulls \( L_z \) of the plow was changed by moving the hull attachment brackets along the longitudinal beams of the frame and fixed at 10; 30; 50 and 70 cm.

Experimental results showed (see Figure 4) that with an increase in the distance between the hulls \( L_k \) from 0 to 0.5 m, a traction resistance decreases intensively. With a further increase in \( L_k \), a traction resistance of plow decreases slightly. With an increase in \( L_k \), the degree of seeding of plant residues and the plow stroke stability were improved. Based on the above, a minimum longitudinal distance between the hulls should be 0.5 m.
The results of experimental studies showed (see Figure 5) that the length of broach-plow has the main influence on the layer turnover and the profile of arable land. When hull worked without a broach-plow, the layer was superimposed on the neighboring layer, and an open furrow (dedeepening) is formed on the left side with a width of 31.6 cm, a depth of 19.8 cm and a ridge height of 14.1 cm, and at the same time there was a shortage of layer. With an increase in the broach-plow length to \( L_z = 50 \text{ cm} \), a shortage of layer was also observed. A deepening was formed with a width of 23.6 cm, a depth of 12.8 cm, and a ridge height of 17.5 cm. A reliable technological process of layer turnover was carried out with a broach-plow length of \( L_z = 75 \text{ cm} \). The depth of deepening is small - 5.6 cm, the height of the ridges is 12.5 cm.

As a result of experimental studies, the following optimal parameters were established: the broach-plow length of the odd hull is 75 cm and the even hull is 93 cm; a longitudinal distance between hulls \( L_k = 50 \text{ cm} \).

Based on the results from theoretical and experimental studies, the following designs of plow’s prototypes for smooth-plowed ploughing were designed: 1 - a double-hulled plow with hulls with different rack heights; 2 - a double-hulled plow with two submersible tillers mounted on hulls with the same height; 3 - the same plow with one subsoiler mounted on the even hull with a long broach-plow. A short broach-plow was installed on the odd hull of these plows. At the same time, a subsoiler with an inclined rack “paraplau” type was installed on the plow for loosening of subarable horizon.

The results of experimental studies conducted on prototypes of plows showed that they are not significantly different in basic quality indicators. After their passage, a ridge surface and stepped bottom of the furrow are formed. The greatest ridge surface of arable land is obtained when the plow operated with hulls of different heights. However, this reduces the depth and degree of embedding plant residues compared with other options. This is obviously due to the fact that with an increase in the depth processing, a layer turnover is worsening in an even hull. It was established that the plow with subsoilers of the “paraplau” type, installed behind even hulls, has advantages compared with the first and second options in terms of traction resistance, respectively by 11.88% and 7.9%, in terms of stability and metal content.
A plow with one subsoiler installed behind the hull with long broach-plows produces a strip loosening of subarable horizon (see Figure 6). A strip width loosened by the subsoiler is $b_s=34.3-36.4$ cm. The distance between the loosening strips is $l=100$ cm.

![Figure 6. A typical profilogram of a field’s transverse profile processed by a plow with a subsoiler installed behind an even hull: 1 - line of the field surface before the plow pass; 2 - line of arable land after the plow passage; 3 - the bottom line of the furrow.](image)

4. Discussions
The main soil cultivation problems of slopes have been reviewed in many published scientific works [2, 15-19]. Aleksandryan et al. [2] analyzed a layer turnover with a traditional plow during the tillage. Nagorny [14], Makarova [15] and Rakhimov [16] studied soil movement patterns on the slopes of the working hulls of soil-cultivating units. Nagorny [14] substantiated the technological parameters and means of mechanization for soil slotting and two-tier processing. A two-tiered PNY-4-40 plow has been developed for ploughing to a depth of 14-18 cm of the upper layer with turning a layer and loosening to a depth of up to 35 cm of the lower layer without turning a layer. Rustamov [17] recommended the use of tiller-free tillage with flat cutters and heavy harrows (BDT-3,0) with alternation of traditional dump tillage to a depth of 20-22 cm [14] in the mountainous bagarny zone conditions of Uzbekistan prone to water erosion, in order to protect the rainfed dark gray soils from water erosion, to maintain a humus deficit-free balance and the main plant nutrients. A periodic use in the crop rotation system of the following tier tillage is recognized as perspective by Ukrainian scientist [18]: two-tier ploughing, blade-flat-cut, dump-chisel, and flat-cut chisel processings. Pazova [18] developed a combined unit for drainage and flat-cutting of sloping soils, performing simultaneously several technological operations in a single pass. Krasnoshekov and Spirin [19] recommended a post-harvest slotting soil cleavage in order to prevent water runoff and soil flushing on sloping plots. All these studies are aimed at improving the traditional technologies and technical means of tillage, which does not meet the modern requirements of agricultural production. These shortcomings can be eliminated by developing plows, based on a promising new technology of non-furrow ploughing.

5. Conclusions
An effective method for ridge-stepped ploughing of slopes is the alternation of incomplete layer turnover with full rotation within its 1800 furrow in combination with strip subsoil loosening.

A relative position of the hulls and subsoilers, hulls and broach-plow and stability of the plow movement showed that the rational plow’s design for ridge-stepped ploughing is a stepped diagram with alternating equally-sized hulls with short and long broach-plows and subsoilers installed behind even hulls. With a longitudinal distance between the hulls of 0.5 m, a required qualitative incomplete turnover of the layers with the lowest energy costs is provided with the following broach-plow’s parameters of the odd hulls: broach-plow length and width are 75 cm and 25 cm, a stabilizing plate height is 15 cm, and the minimum distance is 25 cm.
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