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Theoretical substantiation of the influence of parameters on the quality and energy performance of a slope-type plug-type softener

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Abstract: Bentleg furrow openers can significantly reduce soil disturbance and reaction forces relative to conventional narrow point openers used in no-tillage farming. The effect of bentleg opener geometry on soil disturbance and reaction forces in a cohesive soil was assessed in a virtual soil bin using the discrete element method.Furrow size was found to be more dependent on shank lateral offset and side leg bend angle than side leg forward angle. Though side leg forward angles >90° reduce particle displacement and will work better in fields with stones and roots, they also considerably increase draught and penetration resistance. A low rake angled foot minimises soil reaction forces and drives soil loosening. Reducing foot height and interaction of the vertical shank with soil particles minimises surface soil displacement. These results have expanded the understanding of bentleg opener mechanics and are in close agreement with those reported for sandy soils. Therefore, similar criteria can be followed to optimise bentleg opener design for different soil types.

Keywords: narrow point opener, No-tillage sowing, soil disturbance, soil reaction forces, vertosol.

The main indicators of no-tillage furrow opener performance include soil disturbance and reaction forces. Low soil disturbance reduces soil movement out of furrows and retains adequate quantities of crop residue cover on the soil surface. This, in turn, helps to conserve water within the seed zone, control soil temperature, and discourage weed growth. It also ensures adequate seed coverage and seed-soil contact for improved germination, seedling emergence, early crop stand, and yield potential. Low soil disturbance mainly implies the ability to open a furrow of size just enough for the seed being sown and the ability to contain soil movement within the furrow. This ensures that loosened soil particles or aggregates can easily fall back into the furrow to cover seed without, or with minimum, extra mechanical effort. Thus, the main parameters used to measure soil 65 disturbance include furrow cross sectional area, furrow width, displacement of loosened soil particles, spill over distance, furrow backfill, and ridge height as defined in Fig. 1.

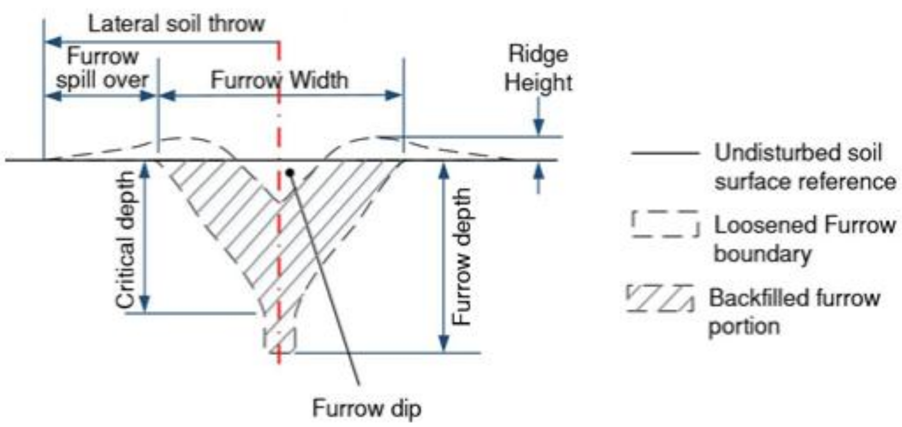

Fig. 1: Cross section of soil surface and furrow profile showing soil disturbance parameters from a typical narrow tine soil cutting tool.

Of these soil disturbance parameters, lateral soil throw, spill over distance, and furrow backfill are of particular importance. Lateral soil throw measures the distance through which loosened particles are thrown laterally from the centre of the furrow. Spill over distance provides a more practically relevant measure of lateral soil throw. It shows how far soil particles are throw laterally beyond the furrow banks and are, thus, not readily available for backfilling or seed covering. Furrow backfill refers to the percentage of the volume of a furrow that is refilled with loosened soil particles after an opener has passed through it. When excessive lateral soil throw occurs, furrow backfill is reduced. Excessive lateral soil throw also results in soil stepping which causes inconsistent seed covering and seeding depth, and toxicity problems when surface soil laden with pre-emergence herbicides is thrown to cover seeds in adjacent furrows. Previous studies have highlighted the ability of bent leg soil cutting tools, both as deep conservation tillage tools and no-tillage furrow openers, to reduce soil disturbance and soil reaction forces. The discrete element method (DEM) has been used to assess the effect of soil tillage tool and furrow opener geometric features on performance, achieving results that closely agree with experimental outcomes. It has been used to accurately predict soil surface and furrow profiles after tillage, from which soil disturbance parameters such as furrow width, cross-sectional area, backfill, and depth, and lateral soil throw, spill over distance, ridge height, and critical depth are determined. It has also been used to predict both draught and vertical forces. Barr et al used DEM to analyse the effect of bentleg opener geometric features on performance. The DEM studies referenced above focused overwhelmingly on cohesionless and less cohesive soils with cohesive strength ranging from 0 to 36 kPa. The objective of this study was to assess the effect of varying bentleg opener geometric features on soil disturbance and reaction forces in cohesive soil using the DEM.

Materials and methods: Key geometric features of the bentleg furrow opener were varied to determine their effect on opener performance. These features were namely: side leg bend angle (β), cutting edge chamfer angle (γ), elbow radius (r), foot height (h), foot rake angle (α), shank lateral offset (L), side leg forward angle (δ), and tine thickness (t) (Figure 2). These geometry parameters were varied as shown in Table 1. Shank lateral offset, side leg bend angle, and side leg forward angle were varied to investigate the interaction of the side leg and shank with soil particles. Varying shank offset distance from the foot was aimed at revealing the effect of the shank on the displacement of loosened soil. Cutting edge chamfer angle, elbow radius, and tine thickness were varied with the aim of streamlining the opener design to assess their impact on soil movement and reaction forces. By varying foot height from 0 to 40 mm, the effect of the absence or presence of a foot on performance was also examined. For straight tine openers, rake angle has significant impact on soil loosening and reaction forces. Thus, different foot rake angles were used to ascertain how they affect soil loosening and reaction forces of a bentleg opener. The side leg forward angle, together with the cutting edge chamfer angle, determine the lift angle (λ) of the side leg (Fig. 2b). This combination acts as a pseudo-rake-angle, especially for footless bentleg openers and drives soil loosening. Using different side leg forward angles helped assess the effect of lift angle on soil loosening and reaction forces of a footless bentleg opener.

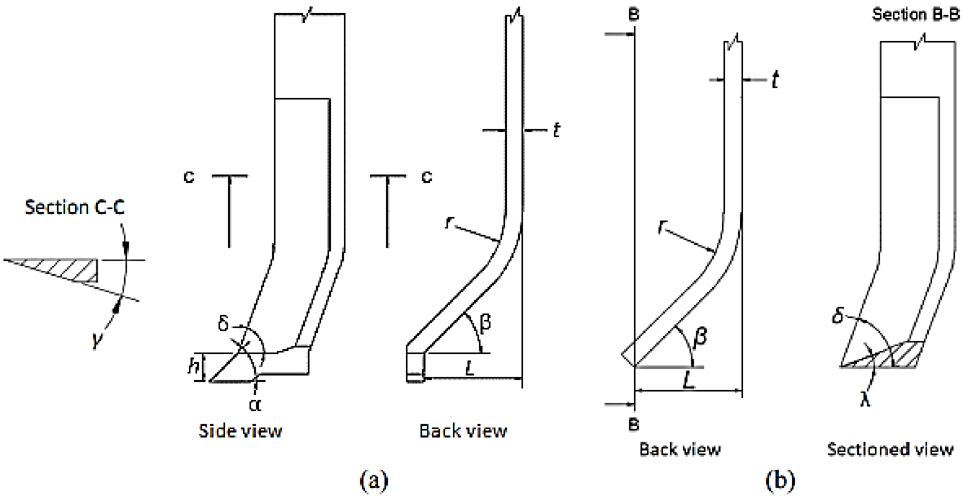

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Fig. 2: Details of the bentleg opener geometry (a) with a foot and (b) without a foot: β = side leg bend angle, γ = cutting edge chamfer angle, r = (arched) elbow radius, h = foot height, α = foot rake angle, L = shank lateral offset, δ = side leg forward angle, λ = lift angle, and t = tine thickness.

All simulations were run using an operating speed and depth of 8 km h-1 and 100 mm, respectively. Operating speed of 8 km h-1 represents the maximum recommended speed used for conventional narrow point openers. The 100 mm operating depth was selected to cover a range of placement depths for different seeds and fertilizer and under-seed soil loosening.

The effect of key bentleg opener geometric features on performance was evaluated by simulating the operation of the openers in a virtual soil bin using DEM. The virtual soil bin was filled with spherical particles of nominal radius 5 mm assembled to mimic a soil bed.

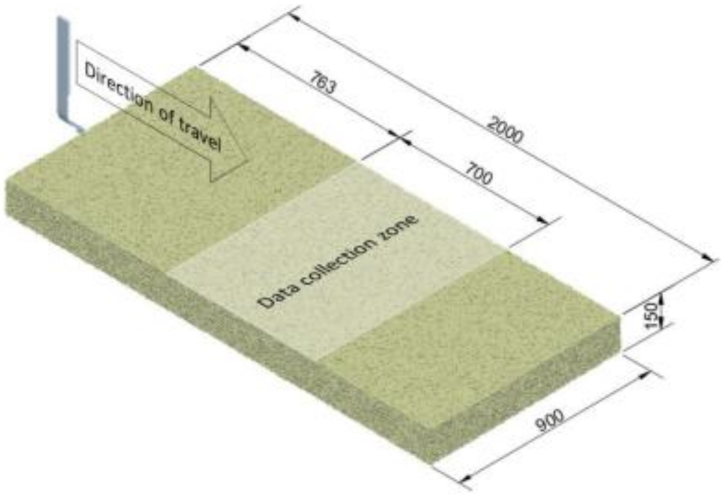

Fig. 3: Description of virtual soil bin (all dimensions are in mm).

Determination of loosened furrow boundary Particle displacement analysis was employed to predict furrow profile. This analysis is capable of capturing the actual patterns and magnitudes of particle displacement in all directions, from which furrow boundary could be determined, using an appropriate criterion. This approach has been reported to produce accurate predictions of furrow profiles and furrow cross-sectional area, furrow width, and critical depth with relative errors ranging from 1% to 19%. The coordinate (xyz) points of each particle within the data collection zone were obtained before and immediately after tillage and used to calculate their respective particle displacement in the forward (Δx), lateral (Δy), and vertical (Δz) directions. Result immediately after particle loosening (before the particle settled), was used to provide a clearer distinction between displaced and unmoved particles. Resultant displacement was calculated as

$$\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}.$$

The particle location before tillage and resultant displacement data were converted to a contour matrix using the meshgrid function with linear interpolation. The cross-section of the bin was meshed into several square grids of size 4×4 mm, and the data were averaged over the 700 mm length of the data collection zone. The criterion for determining the boundary between loosened and undisturbed particles was established based on the fact that the minimum particle displacement caused directly by an opener occurs with particles just adjacent to the bottom part of the opener.This minimum particle displacement was traced up the profile to produce loosened furrow boundary as shown in the contour plot in Fig. 4.

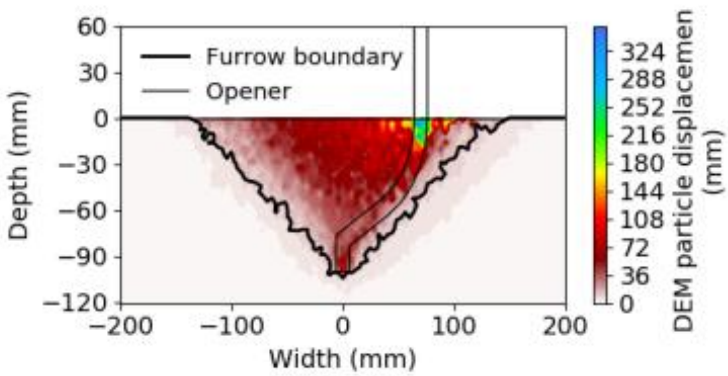

Fig. 4: Definition of furrow boundary in the particle displacement analysis.

Determination of surface profile Surface profile after tillage was determined using the actual coordinate (xyz) points of all particles located at the surface of the bin within the data collection zone after the particles had settled. These data were averaged over the length (700 mm) of the data collection zone, which helped to account for variability along the furrow direction. Surface particles' coordinate points extracted from the simulation define locations of the particles' centroids. Thus, an upward offset of 5 mm was used (Fig. 5) to account for particle radius and to capture the top surface profile as is done in practice.

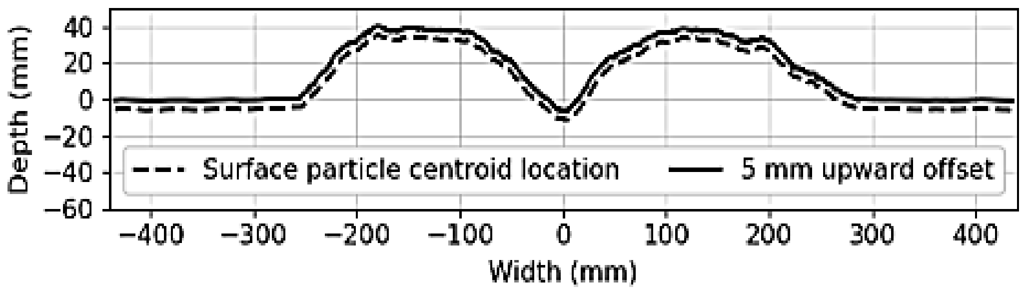

Fig. 5: Plot showing offsetting of surface particle centroid location to account for particle

Soil disturbance parameters and soil reaction forces from the surface and furrow profiles after tillage, soil disturbance parameters were determined. Soil disturbance parameters analysed in this study are defined in Fig. 1, namely: furrow cross sectional area, furrow width, lateral soil throw, and ridge height. Furrow cross-sectional area was calculated using the trapezium rule. Draught and vertical forces were determined within the data collection zone. Downward vertical force that assists penetration is designated positive while upward vertical force that resists penetration is designated negative.

Results and discussion: Interaction of side leg and shank with soil .Shank lateral offset Figure 6a reveals that shank lateral offset (L) affected soil failure boundary on both sides of the openers. All the openers had a foot rake angle of 45° and hence, they all caused crescent failure. Increasing shank offset to the right of the foot reduced the impact of the shank on loose soil and increased the distance particles had to cover to fall outside the furrowAn increase in upward reaction force against the opener could have consequently increased the frictional force on the lower side of the side leg, thereby causing an increase in draught force. The association of reduced draught and vertical forces with an offset shank has been reported in previous studies. The bentleg opener encountered a downward (positive) vertical force, which acted to assist penetration, in the field experiment on the same soil and conditions modelled in this work . Thus, the DEM prediction of an upward (negative) vertical force for the bentleg openers in this study, which was also reported by Aikins et al is in contrast with experimental result. This disagreement could be attributed mainly to the DEM particles being larger than real soil particles as explained by Aikins et al.

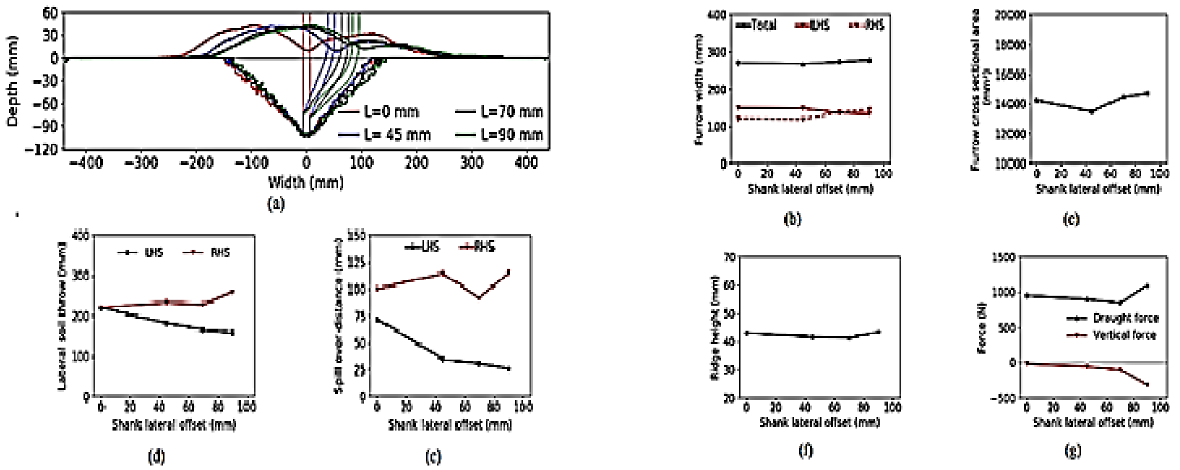

Fig. 6: Effect of shank lateral offset (L) on: (a) loosened furrow profile, (b) furrow width, (c) furrow cross-sectional area, (d) lateral soil throw, (e) spill over distance, (f) ridge height, and (g) draught and vertical forces (negative vertical force indicates the opener encountered an upward force from the soil). LHS means left hand side and RHS means right hand side.

The boundary on the left-hand side of the furrow was similar for all the side leg bend angles (Fig. 7a). This was because only the 45° rake angled foot (which was the same for the side leg bend angles) was responsible for soil failure on that side without any effect by the side leg. The boundary on the RHS, however, became wider with decreasing side leg bend angle (β). As side leg bend angle decreased from 60° to 30°, the elbow (transition between the side leg and the vertical offset shank) got deeper into the soil. This widened the furrow throughout its depth, and the furrow width was greatest for β=30°, followed by 45°, then 60°. This was because the side leg became more horizontal at low bend angles and vice versa. A more horizontal side leg increases the effective underside surface area of the opener, which results in higher resistance to penetration.

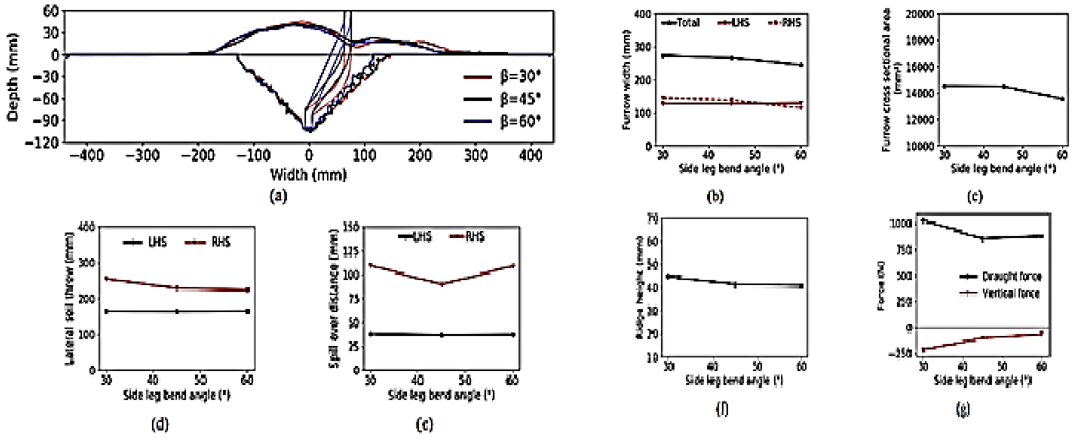

Fig.7: Effect of side leg bend angle (β) on: (a) loosened furrow profile, (b) furrow width, (c) furrow cross-sectional area, (d) lateral soil throw, (e) spill over distance, (f) ridge height, and (g) draught and vertical forces (negative vertical force indicates the opener encountered an upward force from the soil). LHS means left hand side and RHS means right hand side.

Figure 8 presents the side and rear views of bentleg opener with varying side leg forward angles. Figure 9a reveals that furrows skewed slightly toward the left with increasing side leg forward angle. However, results presented in Figs. 9b and 9c reveal that side leg forward angle (δ) had minimal impact on actual furrow parameters.

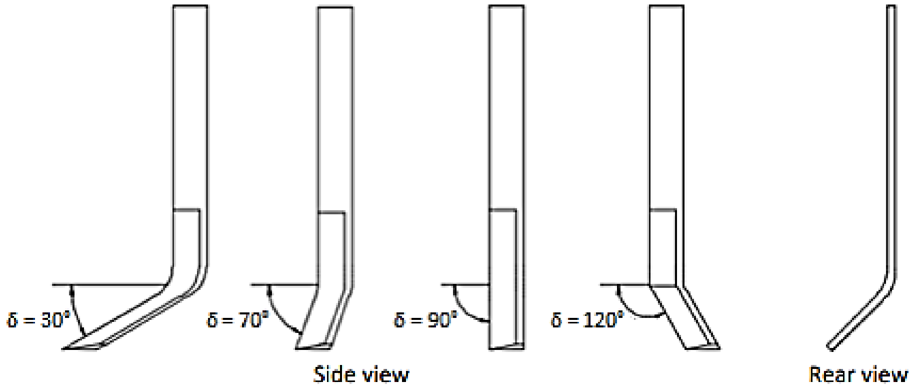

Fig. 8: Bentleg opener with side leg forward angle (δ) varying from 30° to 120°.

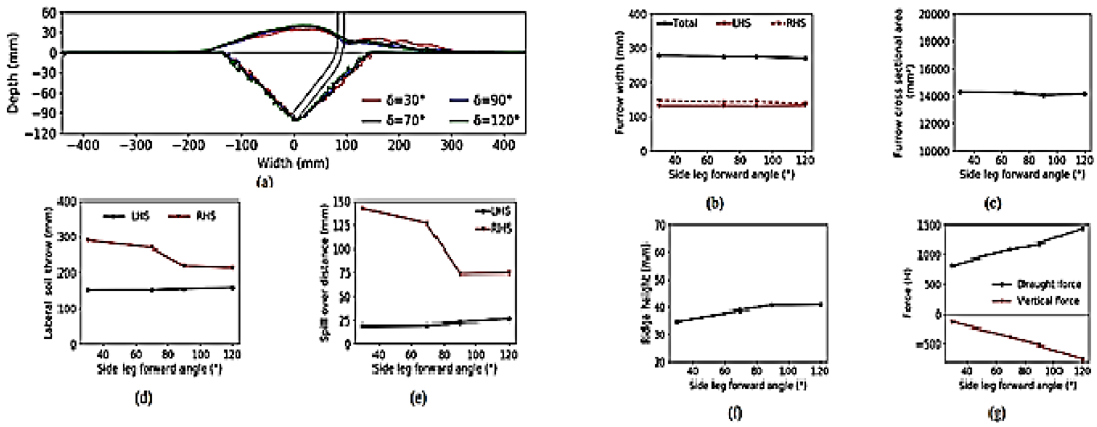

Fig. 9: Effect of side leg forward (δ) angle on: (a) loosened furrow profile, (b) furrow width, (c) furrow cross-sectional area, (d) lateral soil throw, (e) spill over distance, (f) ridge height, and (g) draught and vertical forces (negative vertical force indicates the opener encountered an upward force from the soil).

LHS means left hand side and RHS means right hand side. The greater RHS lateral soil throw and pulverisation resulted in the lowest ridge height for δ=30°, which increased as δ increased to 120°. Ridge height increased by 6 mm (18%) from 35 mm for δ=30° to δ=120° (Fig. 9f).

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Effect of streamlining on performance: The 45° rake angled foot was the only driver of soil failure for the left-hand side of the openers. Therefore, soil failure boundary on the left-hand side followed a similar path for all shank chamfer angles (γ) (Fig. 10a). Soil failure on the right-hand side, however, varied slightly with shank chamfer angle. As a result, RHS half furrow width varied by -4%, -3%, and 1% for γ= 30°, 60°, and 90° (blunt), respectively, in comparison to γ=17° (Fig. 10b). The fluctuation could, thus, be attributed to the generally low vertical forces and the larger than real soil particle sizes used in the simulations. Overall, cutting edge chamfer angles as low as practical are recommended for low soil disturbance and low soil reaction forces.

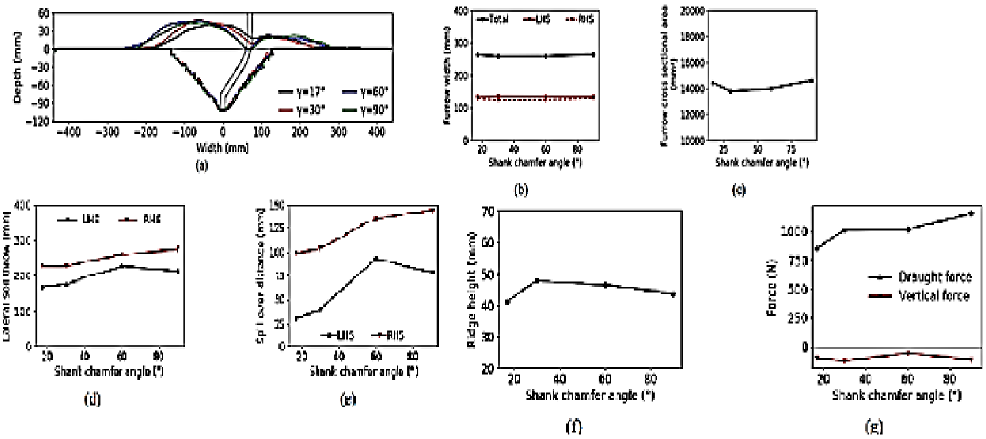

Fig. 10: Effect of shank chamfer angle (γ) on: (a) loosened furrow profile, (b) furrow cross-sectional area, (c) furrow width, (d) lateral soil throw, (e) spill over distance, (f) ridge height, and (g) draught and vertical forces (negative vertical force indicates the opener encountered an upward force from the soil). LHS means left hand side and RHS means right hand side.

For the openers with different elbow radii, all other geometric features of the bentleg opener responsible for soil loosening and lateral soil throw were the same. Therefore, it can be seen from Fig. 11a that surface and furrow profiles for all elbow radii followed very similar path, except the dip where the shank sticks out of the soil. This implies that furrow

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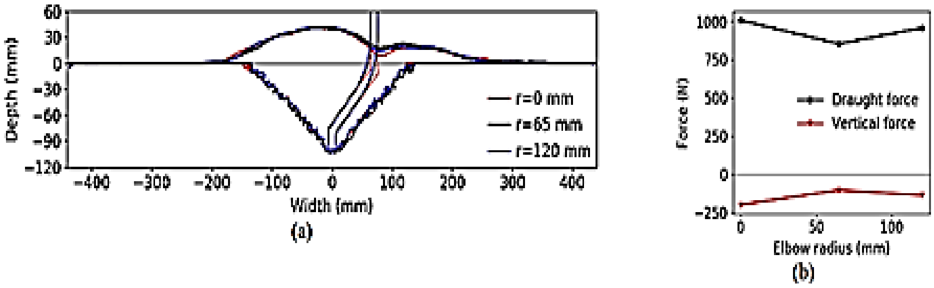
cross-sectional area, furrow width, lateral soil throw, spill over distance, and ridge height were similar for all elbow radii. The only clear difference was that the angled elbow (r = 0 mm) caused a deeper dip. This reveals that angled elbows, especially when located below the soil surface, are likely to cause greater furrow emptying and, thus, arched elbows are recommended. This confirms the finding of Barr et al for cohesionless or low cohesive (sandy) soil. Typically, furrow openers that cause greater soil movement require higher draught and vertical forces. Accordingly, the bentleg opener with angled elbow, which caused greater particle movement, also required greater draught and vertical forces.



Increasing tine thickness resulted in an increase in all furrow parameters, particle movement, and reaction forces on the opener (Fig. 12).

These results are in keeping with classical understanding from empirical soil mechanics studies.

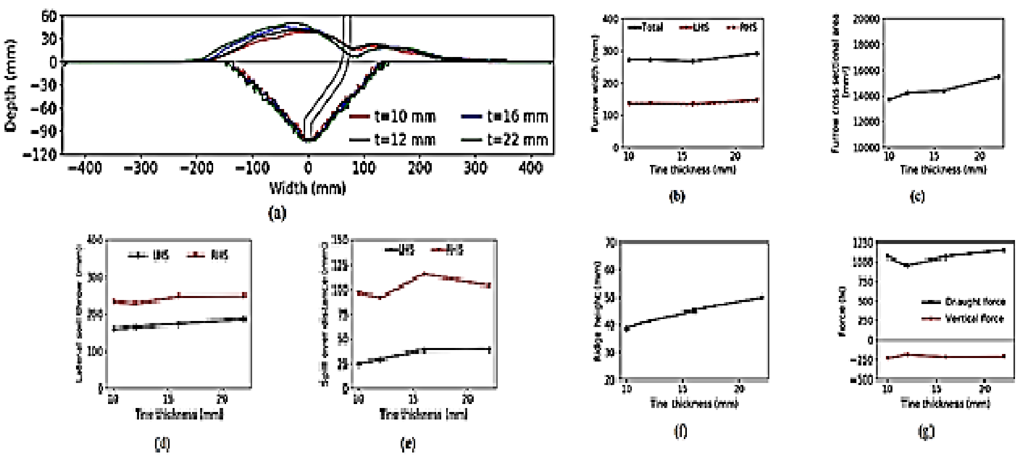


Fig. 12: Effect of tine thickness (t) on: (a) loosened furrow profile, (b) furrow width, (c) furrow cross sectional area, (d) lateral soil throw, (e) spill over distance, (f) ridge height, and (g) draught and vertical forces (negative vertical force indicates the opener encountered an upward force from the soil). LHS means left hand side and RHS means right hand side.

This result is in contrast to the findings of Barr et al who observed higher soil reaction forces with the introduction of a foot. The lower penetration resistance of the 40 mm foot than the 20 mm foot could be attributed to the greater surface area of the leading face than that of the 20 mm foot. Thus, 40 mm foot height experienced greater downward vertical force.

Increasing foot rake angle narrowed both the LHS and RHS boundaries of the furrow (Fig. 14a).

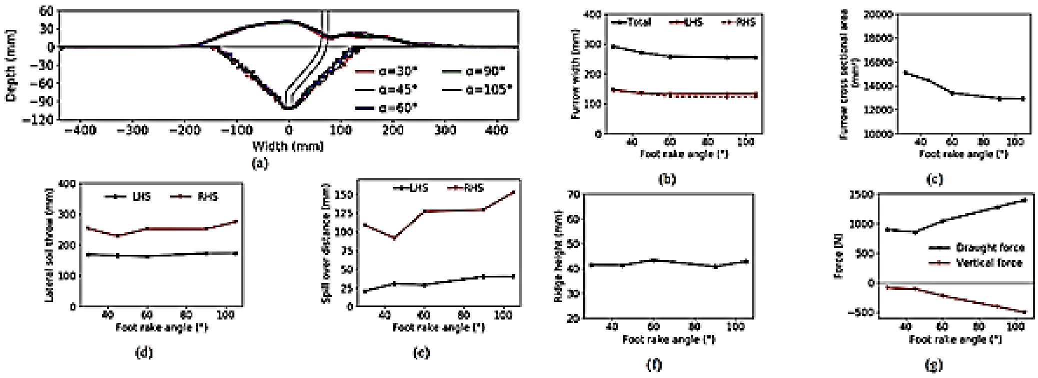


Fig. 14: Effect of foot rake angle (α) on: (a) loosened furrow profile, (b) furrow width, (c) furrow cross-sectional area, (d) lateral soil throw, (e) spill over distance, (f) ridge height, and (g) draught and vertical forces (negative vertical force indicates the opener encountered an upward force from the soil). LHS means left hand side and RHS means right hand side.

It can be seen from Fig. 14g that draught and resistance to penetration of the openers increased with increasing foot rake angle (α). Draught was N at α=30° and increased by

56% to α=105°. Vertical upward force, which acted to resist opener penetration, increased by five times the value at α=30°. All these results, except for lateral, spill over distance, soil throw and ridge height, followed well established trends of the effect of opener rake angle in the literature. This reveals that foot rake angle is a major factor that drives soil loosening and determines soil reaction forces, while the shank is mainly responsible for particle movement at the soil surface.

Conclusions: This study involved discrete element method (DEM) simulation and analyses of bentleg opener geometry effect on performance in cohesive soil (Black Vertosol). The results provide insight into how bentleg opener design can be optimised for such soils. The following conclusions and recommendations are made:

1. At 100 mm operating depth, bentleg opener with 70 mm shank lateral offset, 20 mm foot height, and 45° foot rake angle showed potential to best minimise particle movement and soil reaction forces.

2. With same shank lateral offset distance, a side leg with bend angle greater than 45° that transitions to the vertical shank across the surface reference line can be used to minimise both soil disturbance and reaction forces.

3. Furrow size is more dependent on shank lateral offset and side leg bend angle than side leg forward angle. Though side leg forward angles greater than 90° caused less particle displacement and will improve breakout performance in fields with obstacles such as stones and roots, they resulted in considerably high draught and penetration resistance.

4. Cutting edge chamfer angles as low as practical are recommended for low soil disturbance and low soil reaction forces.

The findings derived from this work on cohesive soil agree with observations reported in previous studies on sandy soil, indicating similar criteria can be adopted in optimising bentleg furrow opener design for different soils in a friable state. Further research needsto be conducted to assess the effects of operating speed and depth on bentleg opener performance

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