

Measurement and Prediction of Draft Force for a High-Speed Disk
Implement as a Function of Tillage Depth and Speed

By

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ABSTRACT

The increasing global demand for food production continues to drive the need for efficient and sustainable tillage systems. High-Speed Compact Disk (HSCD) implements have gained widespread use due to their ability to perform shallow tillage, manage crop residue, and enhance field productivity at higher operating speeds. However, the draft force and soil disturbance characteristics of these implements under varying field conditions remain insufficiently quantified. Existing predictive models for implement draft forces were primarily developed for traditional; low-speed implements and may not accurately represent the dynamic soil–tool interactions of modern HSCD equipment. In this study, field experiments were conducted using a Versatile HS180 Fury HSCD to measure draft force and soil disturbance under different tillage depths and operating speeds. Draft forces were measured using a calibrated load-cell system connected between the tractor and implement, while soil disturbance was assessed with soil surface roughness, residue incorporation, and cone index measurements. Field data were used to develop a draft force prediction equation through regression, and the prediction results were compared with those from existing equations. Results demonstrated that both tillage depth and operational speed had significant effects on draft force and soil disturbance. Draft force increased consistently with both parameters, ranging from approximately 6.5 kN at 25 mm depth and 10 km/h to 31 kN at 125 mm and 20 km/h. The regression model developed for draft force prediction showed a strong fit ($R^2 = 0.9837$) with minimal residual error (± 1700 N), confirming its capability to capture the interaction between tillage speed and depth. Comparison with the ASABE D497.7 equation indicated relative mean errors between -37% and 10%, all within the acceptable accuracy range of the standard. In addition, higher speeds and depths increased soil surface roughness and residue incorporation, reflecting more intensive soil engagement. These results underline the strong interdependence of mechanical power demand and soil disturbance parameters in high-speed tillage operations. This research provides valuable empirical data for validating and refining existing predictive models, supporting more accurate tractor–implement matching, and contributing to the development of efficient, sustainable high-speed tillage systems.

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LIST OF ACRONYMS

ASABE	American Society of Agricultural and Biosystems Engineers
HP	Horsepower
4WD	4 Wheel Drive
CFD	Computational Fluid Dynamics
CI	Cone Index
DB	Dry Basis
DEM	Discrete Element Method
DEM	Digital Elevation Model
FEE	Fundamental Equation of Earthmoving
Ha	Hectar
HSCD/HSD	High Speed Compact Disk
IR	Infrared
KM/H	Kilometers Per Hour
LiDAR	Light Detection and Ranging
MC	Moisture Content
MPH	Miles Per Hour
PTP	Portable Tillage Profiler
RI	Residue Incorporation
RMS	Root Mean Square
RMSH	Root Mean Square Height
RR	Random Roughness
SRF	Saleh Roughness Factor
SSR	Soil Surface Roughness
STIR	Soil Tillage Intensity Rating
VSA	Visual Soil Assessment

1 INTRODUCTION

Tillage has always been one of the most important operations in agriculture, shaping soil conditions for planting and ultimately influencing crop yields. The preparation of a proper seedbed improves seed-to-soil contact, root penetration, water infiltration, and nutrient availability. Over the centuries, tillage methods and tools have evolved from simple wooden sticks and animal-drawn plows to large, technologically advanced tractor-mounted implements. This evolution reflects ongoing efforts to reduce labor, improve efficiency, and optimize soil conditions while ensuring the long-term sustainability of agricultural land (Lal et al. 2007).

Among the wide range of tillage implements, disc-based systems have gained significant importance due to their versatility. Disc plows and disc harrows can be used in both primary and secondary tillage operations, providing the ability to cut through heavy residue, mix soil, and create an adequate seedbed. The concave shape and rolling action of discs reduce friction compared to moldboard plows and allow them to operate more effectively in diverse soil conditions. Modern high-speed compact disc (HSCD) implements are an evolution of these designs, intended to perform residue management and shallow soil disturbance at operational speeds nearly double those of conventional tools. The introduction of independent suspension systems, optimized disc angles, and depth control has allowed these implements to cover more area in less time, reducing operational costs while maintaining agronomic benefits (Smith 1955).

Despite their growing popularity, the scientific understanding of high-speed disc implements remains limited. Most of the established knowledge on soil–tool interactions, draft force requirements, and soil disturbance originates from studies of traditional tillage tools. Analytical and empirical models, such as McKyes’ earthmoving equation (McKyes 1985) and the ASABE draft force prediction equation (ASABE 2011), have served as valuable tools for estimating implement power needs. However, these models were largely developed for single tools or low-speed operations. Their accuracy under the higher speeds, dynamic interactions, and residue conditions typical of high-speed compact disc implements is uncertain. This knowledge gap creates practical challenges for both equipment manufacturers and farmers. Incorrect estimation of draft requirements may lead to inefficient tractor–implement matching, unnecessary fuel consumption, reduced field efficiency, or even structural failures of the equipment.

Another area of uncertainty concerns the combined effect of operational parameters such as speed and working depth on both draft force and soil disturbance. It is well established that deeper

and faster tillage increases power demand, but the interaction of these factors in high-speed operations, especially in terms of soil surface roughness, residue incorporation, and compaction, has not been sufficiently studied under field conditions. Furthermore, the balance between efficiency and sustainability adds complexity: while high-speed discs may reduce fuel use per hectare by increasing coverage rate, their impact on soil health and conservation outcomes requires careful evaluation.

Addressing these gaps requires experimental data collected under realistic field conditions. Controlled soil bin studies provide insights into the behavior of individual tools, but they cannot fully capture the interactions among multiple discs working simultaneously in variable soils with natural moisture and residue conditions. Field-based measurements of draft force, residue management, and soil disturbance are therefore essential for validating existing prediction equations and for guiding the design of future implements.

The present study investigates the draft force requirements of a high-speed disc implement at varying depths and operational speeds under field conditions. By comparing measured values with predictions from existing models, it seeks to evaluate their applicability to modern high-speed implements. In addition, the effects of operational parameters on soil disturbance indicators are examined to provide a more comprehensive understanding of the performance of high-speed compact disc tillage implement. The results are intended to assist in improving tractor–implement matching, reducing fuel use, and informing the design and management of equipment that supports both productivity and sustainable soil management.

2 LITERATURE REVIEW

2.1 History of Tillage

As human race started evolving from hunting gatherers society into agrarian society, it is become clear that one of the main factors that can affect the crop yield at the harvest time is the seedbed preparation. Early on, it was noticed that application of seeds on top of untreated soil will not provide the same results as incorporating the seeds into the soil. In addition, having the soil broken into smaller fractions allows the roots of plants to penetrate deeper and reach layers that contain more nutrients than the top layer. Due to the limited knowledge and lack of technologies, the early tools were extremely basic and were built from the most common material available, mostly wooden sticks and rocks (Lal et al. 2007; McKyes 1985).

As it is typical for humans to try and develop a way to ease the labor, so various tillage tools were designed. Starting with sticks that were used to dig and ending with implements that could be pulled by livestock. Roman plow is a great example of those implements. A development of an implement that inverted the soil, rather than scratching its surface was a significant innovation in tillage history.

In the Middle Ages the Roman plow evolved into moldboard plow. At first the farmer had to carry the plow by hand while the animal was pulling it, later wheels were added to the plow to ease the labor of the human and eventually a sit was added. Moldboard plow required less energy while improving the soil aeration. This led to increase of crop yields (Smith 1955). The effect of the newer implements was mostly noticed in the fertile areas of Northern Europe, where heavier soils required more robust tools to be efficiently cultivated.

In 1784, Thomas Jefferson designed the moldboard plow. In the U.S., Charles Newfold patented the design in 1796 and in the 1930s John Deere started marketing cast iron plow. The industrial revolution introduced steam-powered and later gas-powered tractors. Those tractors started replacing animal-drawn implements in the late 19th and early 20th centuries (Smith 1955). The transition to mechanised equipment revolutionized the way people cultivate the soil completely. It allowed farmers to increase efficiencies and farm larger areas. The first tractors were equipped by steel wheels, however the transition to rubber tires reduced the soil compaction while increasing the maneuverability of the early tractors.

The search for better farming tools in the mid 20th century, led to diversification of tillage implements designed for specific soil and crop condition. To address the soil compaction that was created by the heavier equipment traveling through the fields and the need to manage the residue led to the development of such tools as, disc harrows, chisel plows and subsoilers. Those implements allowed the farmers to tailor their tillage practices to the unique challenges of their fields. After the Dust Bowl of the 1930s there was a significant shift towards conservation tillage techniques, such as reduced tillage and no-till farming. Those techniques are better in preserving the soil structure, reducing fuel consumption and improving water retention (Lal 2009). The extensive studies performed on the conservation practices, showed significant improvements in organic matter content in the soil, soil biodiversity and overall productivity.

The latest technology developments such as GPS guidance, variable rate application and automated depth control, have transformed the tillage implements into highly sophisticated equipment. Those technologies allow the farmers to control tillage depth and intensity based on real-time field conditions, therefor improving efficiency of their operations with minimal impact to the environment (Gebhardt et al. 1985). To continue improving the operational efficiencies without compromising soil conservation high-speed tillage implements, such as vertical tillage and high-speed discs were developed. Some of the implements can be equipped with sophisticated sensors that can perform real time soil analysis, provide data on moisture content, compaction levels and nutrient availability. Those technologies allow precise decision making reducing the chances to over till and reduce the associated soil degradation.

The new developments in the tillage equipment were driven by the need to balance between productivity and sustainability. While conventional tillage techniques focused on soil inversion and weed control, the conservation tillage practices try to minimise soil disturbance to maintain soil health and reduce erosion. Artificial intelligence, robotics and advanced soil sensors are likely the next technologies that will be integrated into the tillage implements. The development of autonomous tractors and robotic tillage systems is already underway, promising to revolutionize field operations by reducing labor requirements and optimizing energy use. Moreover, the integration of machine learning algorithms into tillage planning can provide predictive insights, enabling proactive management of soil conditions based on historical and real-time data.

2.2 Tillage Practices and Tillage Implements

2.2.1 Types of Tillage

The tillage implements are generally categorised into two (2) groups, primary and secondary. This categorisation is based on the depth and the intensity of tillage the implements are designed to perform (Smith 1955).

Primary tillage, usually, performed after the harvest of previous crop and characterised by deeper and more aggressive soil disturbance. The main purposes of the primary tillage are, to loosen the soil and incorporate most of the crop residue and fertilizers into the tilled soil. Typical depth of primary tillage can vary between 150 to 900 mm depending on the desired soil conditions. This deeper tillage strives to increase drainage and soil aeration, incorporate residues to speed up their decomposition and reduce the spread of pest and diseases and reduce the soil compaction that may have been caused by previous agricultural practices or intense equipment traffic. Additional, secondary tillage is usually required after the primary tillage, since the surface after the primary tillage is usually rough and uneven (Smith 1955).

The primary tillage is followed by a shallower, less intensive operation which is called secondary tillage. The goals of the secondary tillage are to create finer seedbed suitable for planting, eliminate the weeds that might have germinated since the primary tillage and additional incorporation of crop residues. The goal of those operations is improving the quality of soil by breaking clods, leveling the soil surface and ideal conditions for seeding and germination. Additional role that the secondary tillage plays is in incorporating herbicides and other soil-applied fertilisers. After the secondary tillage the soil surface is usually more uniform, and smoother compared to the surface left after the primary tillage (Smith 1955).

2.2.2 Primary Tillage Implements

Plows have been designed for initial soil preparation and are essential as primary tillage implements. There are several types of plows that are used in primary tillage each with unique mechanism and applications (Smith 1955). Typical primary tillage implements include moldboard plow, disc plow, and chisel plow.

The moldboard plow (Figure 2.1) is widely used primary tillage implement known by its ability to completely invert the soil. Its components are, share – cuts the soil horizontally, a

moldboard – lifts and inverts the soil, a landside – provides stability against furrow wall and a frog that connects those parts to the plow beam. The plow leaves furrows, burying crop residue and weeds inverted soil. By burying deep, the weed seeds and pests, plowing could disturb the lifecycle of certain pests thus reducing their population. However, the intense tillage that is performed with moldboard plows has its drawbacks as well, it can create compacted layer (plow pan) just below the tilled area and it is increasing the chances of soil erosion due to lack of crop residue on the surface (Smith 1955).



Figure 2.1: Moldboard plow structure. 1 – Horizontal hitch, 2 – Beam, 3 – Braces, 4 – Handles, 5 – Moldboard

The use of moldboard plows in North America has reduced significantly after the dust bowls in the mid 1930s. Over-plowing the land and leaving the surface exposed to the winds was determined to be one of the main causes of the dust bowls (Devojee et al. 2020; Lal et al. 2007).

The disc plow (Figure 2.2) is constructed from one, or more concave steel discs that rotate as the implement is pulled through the soil. The rotation of the disc cuts and turns the soil to the side, although the soil inversion is not as intense as with moldboard plow. The rotation action of the discs allows the discs to penetrate through the soil and cut through heavy residue much more effectively without clogging, and this is the reason the disc plows are preferred in the hard or sticky soils, or in fields with significant amount of crop residue. The rotation also reduces the friction between the disc and the soil compared to the sliding action of the moldboard plow (Devojee et al. 2020; ISO/DIS 22494 2020).

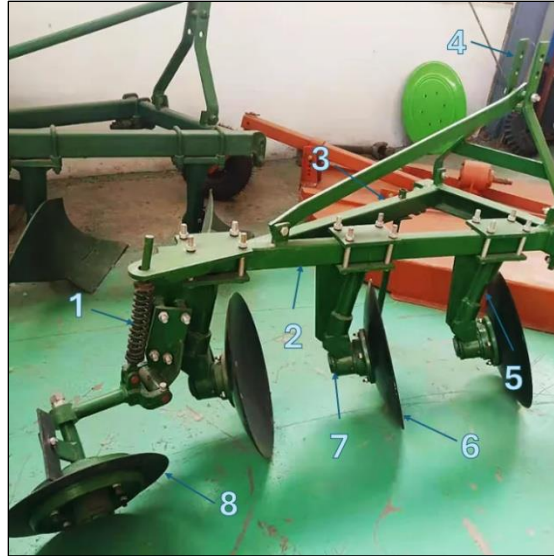


Figure 2.2: Structure of disc plow. 1 – Pressure spring, 2 – Beam, 3 – Frame, 4 – 3-point hitch, 5 – Shank, 6 – Concave disc, 7 – Bearing housing, 8 – Rear thrust wheel

Unlike the moldboard and disc plows, the chisel plow does not invert the soil, thus leaving majority of the residue on top of the soil. The chisel plow uses a series of tines or shanks with chisel-shaped points that are shuttering and loosen the soil as the tools are pulled through the soil. The fact that chisel plows leave most of the residue on the surface makes it one of the main implements in the conservation tillage systems since surface residue helps reducing the soil erosion caused by winds and running water, conserve soil moisture and improve soil organic overtime. Chisel plows allow to perform primary tillage while minimizing the soil disturbance. The surface after the chisel plows is usually rough and secondary tillage is required before seeding (Gachene and Kimaru 2018; Smith 1955).

2.2.3 Secondary Tillage Implements

The secondary tillage implements are used to refine the soil after primary tillage, prepare a suitable seedbed for planting operation and as weed control (Smith 1955). Typical secondary tillage implements include disc harrow, finger harrow, and cultivator harrow.

The structure of the disc harrows is usually including few sets of concave disc gangs, those discs are positioned in an angle to optimize soil cutting, crushing and mixing. The disc harrows are very effective in breaking the clods left by primary tillage operation, barring previous crop residues and creating desired seedbed for planting. The aggressiveness of the disc harrows can be controlled

by the depth and the angle of the disc gangs in relation to the travel direction, as well as speed of the tillage. In addition to the seedbed preparation disc harrows are often used for mechanical weed control (Srivastava et al. 2012; Devojee et al. 2020; Nalavade et al. 2010; Serrano et al. 2003; Smith 1955; Upadhyay and Raheman 2019).

Finger harrows are equipped with flexible, spring-like tines or fingers that lightly work the soil surface. Shallow cultivation is the primary function of finger harrows, those are very effective against very small, newly emerged weeds and breaking up surface crust without causing significant soil disturbance. The finger harrows offer a mechanical alternative to herbicides. They are also used for creating a very fine soil surface for planting small-seeded crops and improving seedling emergence by breaking surface crusts (Arvidsson and Hillerström 2010; Duerinckx et al. 2005; Godwin and Spoor 1977; Wheeler and Godwin 1996).

Cultivator harrows are generally referred to as cultivators, use a series of shanks with various types of sweeps, shovels or teeth to till the soil without inverting it. In row crops, such as corn, beans etc. the primary target of cultivator is mechanical weed control between the rows of growing crops, while minimizing disturbance to the crop plants themselves. Cultivators can be used for shallow tillage to improve soil aeration, water infiltration, incorporating fertilizer and even distribution of crop residue (Arvidsson and Hillerström 2010; Duerinckx et al. 2005; Godwin and Spoor 1977; He et al. 2023; Wheeler and Godwin 1996).

2.3 Disc Tillage and Disc Implement

Disc implements can be used for both primary tillage and secondary tillage. Disc implements for primary tillage (such as disc plows) often featured larger and heavier discs working at a greater depth compared with disc implements for secondary tillage (such as disc harrows). However, these disc implements have similar working principle.

2.3.1 Disc Implements: Working Principles

The contact between the soil and the concave tillage disc is the basic operating principal of disc tillage. While the implement is moving forward, the soil is being cut by each disc, a portion of the soil is lifted by the inner surface of the disc before dropping the loosen soil back on the field. This operation During this process the soil is loosened and aerated. The shape of the disc has huge effect on the process, the concavity of the discs enabling them to lift, brake to smaller fractions,

partially invert and displace the soil as the implement disc roll. The concavity of the discs can contribute to the down forces and can be varied depending on the soil type to optimise penetration and soil movement. For example, soils with different content of moisture and texture may require discs with different concavity for optimal performance (Smith 1955; Ucgul 2023).

The rolling motion of the discs reduces the friction with the soil, in comparison the moldboard plows which, invert the soil by cutting a furrow slice of soil and inverting it to one side through a sliding action. This rolling action, combined with lifting and throwing action of the soil due to the concave shape of the disc, allows disc implements to efficiently manipulate the soil. Potentially requiring lower draft forces compared to implements that rely only on dragging or inverting soil by sliding action (Ucgul 2023). Additional parameter that affects the efficiency of last year's crop residue cutting is the sharpness of the discs. Most of the disc manufacturers, such as Ingersoll (Hamilton, Canada), Metisa (Tímbo, Brazil), OFAS (Mussolente, Italy). are using boron steel to manufacture tillage discs. This gives the discs unique hardness and resistivity to wear while keeping the discs flexible to withstand impact from hard objects that could be encountered in the field.

Various forces are developed during the tillage operation, draft force, which is the horizontal force required to drag the implement through the soil. Vertical forces, that both push the implement out of the ground and suck in deeper into the ground, as well as side forces. The speed and depth of the tillage operation and the angles at which the discs are set have significant influence on the magnitude and direction of the above-mentioned forces. Additional contributors that play crucial role in determining the draft requirements of the tillage implements are the soil properties, such as soil type, moisture content and bulk density. Generally, studies have shown that draft force tends to increase with increasing operating speed and depth (Sahu and Raheman 2006a; Serrano et al. 2003; Smith 1955; Upadhyay and Raheman 2019).

To better understand and predict the forces involved in tillage operation and the resulting soil movement, the researchers often employ mathematical models and advanced simulation techniques. Using DEM (Discrete Element Method) with MBD (Multi-Body Dynamic) have been useful in simulating these complex interactions at a particle level, representing soil as compressible material with non-linear behavior. Tillage forces and soil movement can be analysed by those modeling considerations under various operational conditions, providing valuable insights for the design of more efficient and effective tillage implements. The understanding of those forces is

important for the optimization of tillage tools and field operation as those impact the fuel consumption (Ahmadi 2018; Mak et al. 2012; Sadek et al. 2021; Saunders et al. 2021).

In addition to preparation of seedbed, disc tillage has a major role in previous year crop residue management. Incorporation of residues into topsoil and mulching those residues helps to retain soil moisture and suppresses weed growth could be achieved using disc harrows. The main factors that could influence the extend of residue incorporation are disc angle, operating depth of the implement, operational speed and the moisture content of soil at the time of tillage. For corn, wheat and other crops that leave large amount of residue single pass with a disc implement may still have a significant amount of residue on top of the soil surface. This layer of the residue is very beneficial for erosion control. In conservation, especially, no-till seeding operations the disc angle shown a significant effect on cutting and dragging the residue. Bigger disc angles reduce the cutting effect of the residue and increase the dragging effect. Similarly, the depth of tillage influences the burial of the residue, in general the deeper tillage will result in greater degree of residue incorporation into soil (Srivastava et al. 2006; Klingberg and Weisenbeck 2011; Morttsonjr et al. 1993; Serrano et al. 2003; Zeng and Chen 2018). This ability to manage crop residues, by either incorporating them or leaving them on the surface, makes disc tillage a flexible approach that can be adapted to different farming systems and conservation goals.

2.3.2 Disc Tillage Implements: Structure and Components

Main structural components of the disc tillage implement that affect the effectiveness of tillage are the disc itself, the frame of the implement and the toolbar that the discs and other components are mounted to and bearings that allow the discs to rotate freely.

2.3.2.1 The Disc

2.3.2.1.1 Material and Dimensions

Carbon steel is commonly used for manufacturing discs for tillage implements, making those discs more affordable while providing strength and flexibility. However, for longer operational life and enhanced durability, boron steel is often used, particularly in more demanding operations. Such boron steel alloys, together with thermal treatment are often proprietary to disc manufacturers, provide increased hardness, which increases the ability of the disc to resist to wear from abrasive soils and crop residues, as well as the needed flexibility to withstand impact from the rocks and

other objects without fracturing. The diameter of the disc is a critical dimension that affects the performance of the tillage implement. The typical size of discs for disc plows is between 500 to 950 mm (20 to 38 in). The larger discs are generally used for wider cutting widths and deeper tillage operations as those discs are more effective in cutting through heavy residue. At the same time, smaller discs may exhibit better penetration in hard or compacted soil (Damanauskas et al. 2019; Godwin 2007; Hann and Giessibl 1998; Klingberg and Weisenbeck 2011; Gill et al. 1980; Zeng and Chen 2018). The thickness of the disc blade also contributes to its overall strength and resistance to bending or breakage under load.

2.3.2.1.2 Concave Shape

The concave or the spherical shape is a defining parameter of the discs used in tillage. The curvature is essential to the disc's ability to penetrate the soil, lift it and throw it to the side as the tillage implement moves forward. The degree of concavity plays critical role in determining the disc's interaction with soil. The down suction forces are strongly affected by the concavity of the discs, the more disc concave larger the suction forces (Srivastava et al. 2012; Smith 1955). This enhanced concavity facilitates a more pronounced lifting and inverting action, which can be beneficial for specific tillage goals such as burying weed seeds, incorporating cover crops, or managing non-wetting topsoil.

2.3.2.1.3 Edge Types

There are two (2) main types of disc edges, notched (Figure 2.3a) and plain (smooth) (Figure 2.3b). Plain discs are typically used for leveling to soil surface and more effective in conditions that do not require heavy cutting. While the notched discs are providing a more aggressive cutting action better suited for working with heavy residue. The notched concave discs have an aggressive cutting edge that improves soil penetration in addition to the increased residue cutting operation. In addition to the standard notched or plain disc, specialised fluted discs (Figure 2.3c) have been developed and studied for their unique soil interaction (Zeng and Chen 2018). The of edge type allows the farmer to optimize their disc tillage implement for specific challenges and requirements of their field.



(a)



(b)



(c)

Figure 2.3: Different disc types. (a) Notched disc on Versatile implement, (b) Plain disc on Landoll implement, (c) Fluted discs on Will Richie implement

2.3.2.2 Frame and Toolbar

Implement frame provides the structural support for mounting the tillage tools, bearings and other operational components. Those frames can be designed as trailed implements, which are pulled behind the power unit (tractor) or as mounted implements which are attached to the tractors three-point hitch. The frames for the primary tillage that is used for breaking up virgin land or tilling

heavy compacted soil are designed particularly heavy as they must withstand the significant forces developed during the tillage operation. One of the most important elements of the frame is the toolbar, as the disc gangs, or the individual disc are mounted on the toolbar. Often the toolbars allow for adjustment of the disc spacing and the adjustment of the angle of the gangs relative to the direction of the travel. This flexibility is vital for adjusting the tillage implement for different soil conditions and various tasks (Smith 1955).

2.3.2.3 Bearing Assemblies

Additional critical component of disc implements are the bearings; those are allowing the free rotation of the tillage discs. Quality and reliability of the bearings can affect the performance, and the lifespan of the disc tillage implements. To reduce the need for regular maintenance and minimize the down time of the tillage implement, modern disc harrows often equipped with maintenance-free bearing components, which are sealed and lubricated for life. The agricultural bearing hubs are specially designed to securely mount the disc blades to the central shaft, in gang mounted implements or individual arm in individual mounted implements. These hubs are designed to withstand the demanding operating conditions of agricultural machinery, including high speeds in some applications, and they must be effectively sealed to prevent contamination from water, soil, dust, and other abrasive materials encountered in the field. Increased friction, wear and potential seizure could be caused by contamination in the bearing. Therefore, the design and quality of bearing assemblies are crucial for ensuring the efficient and durable operation of disc tillage implements.

2.3.2.4 Disc Mounting Configurations

There are two (2) main disc mounting configurations: individual disc mounting and gang mounting. And those significantly influence the performance and adaptability of the tillage implement to the field conditions.

In the individual disc mounting configuration each tillage tool is mounted to the implement's toolbar via its own arm or shank. This mounting allows each tillage tool to react individually to the changes in soil conditions. In fields with uneven terrain or significant soil irregularities, the individual mounting is particularly advantageous, as it helps to maintain a more consistent tillage depth across the width of the implement. Individual disc mounts are usually including spring mechanism or rubber shock absorbers. Those shock absorbers provide a degree of vertical

movement, allowing it to move up when hitting rocks, roots or other obstructions in the soil, reducing the chance of damaging the disc or the frame of the implement. Since each disc can exert its force directedly to the soil without being affected by adjacent discs this mounting method can improve the penetration of the discs in hard or compacted spots within the field.

2.3.2.4.1 Advantages of individual disc mountings

The main advantage of individual disc mounting lies in its ability to adapt to varying field surfaces. A more uniform tillage effect even on wavy ground, ensured by the continuous contact of the individual disc with the soil. This feature is especially important in precision agriculture where consistent soil preparation is vital for optimal germination of the crops.

The individual shock-absorbing mechanism provides a critical layer of protection for the implement. By allowing the discs to move around the obstacles, those shock-absorbing mechanism prevent extreme stress on the discs and the frame of the implement. Thus, reducing the frequency of repairs and extending the implements lifespan.

2.3.2.4.2 Disadvantages of individual disc mounting

Individual disc mounting systems are in general more complex and more expansive than the gang mounting systems. Due to the need to include the mounting with the shock-absorbing mechanism on each individual disc. In Figure 2.4 each disc requires an arm, arm cap, bearing assembly with at least 4 bolts, 4 rubber shock-absorbers. Achieving uniformed tillage depth with individual mounted discs could require a more complex setting then the gang-based system where multiple discs are controlled by a single axis. In some conditions, individual discs might not be as effective at leveling the soil surface compared to the combined action of a gang of discs.



Figure 2.4: Individual disc mounting on Amazone CATROS 03-2TX disc harrow with rubber shock absorbers

Gang mounting system is a system in which multiple tillage discs are mounted on a common axle or a shaft, forming a gang. Those gangs are then mounted to the implements toolbar which is connected to the frame. Offset and Tandem discs are the primary tillage implements that utilize the gang style mounting mechanism, with various configurations designed for specific purposes. The gangs on the single action disc harrow, arranged end to end at an angle, throwing soil in opposite directions. Tandem Disc harrows, known as double-action implements feature four (4) or more gangs arranged in an X providing multiple passes of discs over the soil in a single implement pass.

Gang mounting provides more rigid mounting compared to the individual mounting system, which could be especially advantageous in relatively level field conditions. Usually the angle of the gangs, relative to the travel direction could be adjusted, allowing the operator to change the aggressiveness of the implement, without the need to adjust each disc individually (Ahmadi 2018; Damanauskas et al. 2019; Serrano et al. 2003; Upadhyay and Raheman 2020).

2.3.2.4.3 Advantages of gang disc mounting

Gang mounting mechanism is significantly cheaper than the individual mounting mechanism, thus it is the more cost-effective option. The use of common axle for multiple discs reduces the number of parts required to mount the discs to the frame. For example, to mount seven discs on the gang will require only two bearing housing. The ability to adjust the gang angle provides

a convenient way to adjust the implements aggressiveness to match different soil types, residue levels or desired tillage intensities.

The different configurations of the gang-mounted implements (single, offset, tandem) demonstrate the versatility of this mounting method. Each configuration is engineered to achieve specific tillage outcomes and manage varying amounts of crop residue. Tandem discs, with their opposing gangs, are particularly effective at leveling the soil and creating a fine seedbed, while offset discs are better suited for primary tillage and cutting through heavy residue. These variations highlight the adaptability of the gang mounting concept to a wide range of agricultural practices.

2.3.2.4.4 Disadvantages of gang disc mounting

A significant limitation of gang-mounted systems (Figure 2.5) is their reduced ability to follow ground contours, which can lead to uneven tillage depth in wavy terrain. There is also an increased risk of plugging in situations with heavy crop residue, especially if the spacing between discs within the gang is insufficient to allow for the passage of the residue. Furthermore, when one disc in a gang encounters a large obstacle, it can affect the operation of the entire gang, potentially leading to inconsistent tillage or even implement damage.

Additional disadvantage of the gang-mounted units is complexity which is required when replacing a single damaged disc. This operation will require the farmer to disassemble the whole gang, replacing a single gang and then to reassemble the gang. This is much more complex than the individual mounted implements in which the farmer can simply remove the individual disk (Damanauskas et al. 2019; Serrano et al. 2003; Upadhyay and Raheman 2019).



Figure 2.5: SD550 offset disc by Versatile with gangs of notched discs

2.3.3 Influence of Disc Angles on Tillage Performance

There are two (2) primary angles that affect the performance of disc implements, disc (gang) angle and the tilt angle. The disc angle is the angle relative to the travel direction of the implement and the tilt angle is the angle between the plane of the disc's cutting edge and a vertical line (Malasli and Celik 2019).

2.3.3.1 Disc (gang) Angle

The disc angle could also be referred as the horizontal angle or in case of multiple discs mounted on a common shaft, the gang angle defined as the angle between the travel direction of the implement and the plane of the disc. Typical disc angle for disc harrows can vary between 15 to 35°. The width and the depth of the soil processed by each disc is strongly affected by the disc angle. Increasing the angle will end in wider cut and deeper penetration. For example, for stubble cultivation and the incorporation of crop residue into soil, a more aggressive disc angle is often recommended. On the other hand, for creating a finer soil bed smaller disc angle in the range of 15 to 20° is recommended (Malasli and Celik 2019; Zhang et al. 2024). Research has indicated a direct correlation between the disc angle and draft forces required to pull the tillage implement, as the disc angle increases the draft force tends to increase as well. This is due to a larger volume of soil being engaged by the disc at the more aggressive angles (Srivastava et al. 2012; Smith 1955).

The disc angle provides a basic way to control the intensity of soil disturbance and the volume of soil worked by the implement. By changing the disc angle, the farmers can adjust the tillage operation to the specific needs of their fields, whether it is breaking the hardpan, incorporating residue or create a fine seed bed (Malasli and Celik 2019; Serrano et al. 2003; Zhang et al. 2024).

Though the aggressive disc angle is required for certain tasks, it requires more energy, which increases the fuel consumption, or requires a bigger tractor. A trade-off between the desired soil finish and energy efficiency of the tillage operation should be considered by the farmers while setting up the implement.

2.3.3.2 Tilt (Vertical) Angle

The angle between the edge of the cutting edge of the disc and the vertical line is defined as the tilt angle. In disc implements this angle usually falls between 10 and 20°. It has been shown by

studies that the increased tilt angle reduces the ability of the disc to penetrate the soil, with some research indicating that the greatest plowing depths are achieved with lower tilt angles in combination with specific disc/gang angles (Srivastava et al. 2012; Smith 1955). In no-till seeding, the tilt angle of the openers, can affect how crop residue is handled affecting the amount of residue that is dragged or cut by the disc opener. Increasing the tilt angle in no-till seeders might help reducing the cross-sectional area of the furrow and the tilled soil. Contrarily to the trend with the disc angle, an increase in the tilt angle result in decrease in draft force required to pull the implement.

The tilt angle plays a critical role in determining the disc's entry into the soil and the shape of the resulting furrow. Adjusting this angle allows for optimization of penetration based on soil hardness, moisture content, and the presence of surface residue. This fine-tuning capability is essential for achieving the desired tillage depth and soil profile characteristics for different agricultural practices (Malasli and Celik 2019; Sadek et al. 2021; Wu and Chen 2024).

The inverse relationship observed between tilt angle and draft force, where increasing the tilt angle can reduce draft, suggests a complex interaction between the disc's vertical orientation and the forces required for soil movement. This phenomenon might be related to changes in the angle of attack of the disc relative to the soil, affecting how the soil is lifted and displaced. Understanding this relationship is important for maximizing tillage efficiency and minimizing energy consumption (Malasli and Celik 2019).

2.3.3.3 Interaction Effects

The combination of both the horizontal disc angle and the vertical tilt angle are crucial to optimal performance of disc tillage implement. These angle combinations could have a significant impact of the tractor, affecting parameters such as fuel consumption and the percentage of the wheel slippage. Farmers need to adjust these parameters in concert, considering the specific soil conditions, the type and amount of crop residue present, and the desired outcome of the tillage operation. The ideal combination of angles for one set of circumstances may not be optimal for another, highlighting the need for informed decision-making based on field-specific factors. By finding the right combination of angles for a given task and soil condition, farmers can minimize the energy required for tillage, leading to reduced operational costs and a more sustainable farming

practice. This emphasizes the role of precise implement adjustments in maximizing both tillage effectiveness and energy efficiency (Malasli and Celik 2019; Wu and Chen 2024).

2.3.4 High Speed Tillage

The transition to high-speed implements is driven by the need to increase the operational efficiencies in farming. Classic implements are usually operated at lower speeds. For example, classic offset or tandem disc are operated at speeds of 5 to 8 km/h. In contrast to the classic implements, high-speed implements are designed to maximum performance at 10 to 20 km/h, thus increasing the productivity of the implements and reducing the time the farmer needs to spend in the field tilling (Grisso et al. 2004). The performance of tillage implements is affected by several factors such as, design of the implement, soil properties, and the operational conditions, such as speed and depth of the tillage operation.

The modern-day high-speed discs are designed to be operated at higher speeds while keeping effective soil penetration. The main improvements include:

- Optimized disk angles and spacing: Modern high-speed disks are equipped with aggressive concave disks that facilitate better soil cutting and mixing while minimizing excessive power requirements (Godwin 2007).
- Suspension and vibration damping: Many high-speed discs feature independent disk suspension systems to improve stability and reduce vibration at high operating speeds, thereby enhancing soil penetration efficiency.
- Adjustable depth control: advanced high-speed disks allow for precise depth adjustments to optimize soil disturbance while preventing excessive draft force demands (Godwin 2007).

2.4 Draft Force in Tillage Operations

One of the main parameters that affects the performance of the high-speed tillage operations is draft force. Draft force is the horizontal total force required to pull soil engaged implement at given speed and the force is affected by the tillage depth, speed and by the tillage tools geometry (Godwin 2007). As the depth and the speed of tillage increases, the draft force needed to pull the implement increases as well. This is because the increased volume of affected soil and the more aggressive interaction between the tillage tools and soil (Godwin 2007). It is crucial to precisely

estimate and manage draft forces to optimize the performance of implements, reduce the fuel consumption of tractors, and ensure sustainable soil management practices.

Majority of the studies that were conducted on the relationship between the draft force and depth and speed of the tillage operation were performed with traditional implements (Sahu and Raheman 2006a; Serrano et al. 2003; Upadhyay and Raheman 2019). Those studies showed that the relation between the draft force and speed is not linear due to soil acceleration effect. However, those models may not account for the dynamic of high-speed implements.

Studies on high-speed discs in soil bins provide a valuable initial understanding of individual tool performance under controlled conditions, but they inherently have limitations compared to field testing. A key drawback is the inability to fully capture the complex interactions between multiple tillage tools and rows working together, either at the same time or one after another, in a real field. In actual farming, the way one tool affects the soil directly influences how subsequent tools perform, impacting things like how much power is needed, how the soil is moved, and how leftover plant material is handled – aspects often missed in isolated soil bin tests. Additionally, soil bins typically use simplified and uniform soil, lacking the natural variation in soil type, wetness, and structure found across a field, which can significantly change how tillage tools work. The complex processes of managing crop residue, including how it's cut, mixed into the soil, and buried by multiple passes of different tools, are also difficult to accurately simulate in soil bins. The limited size of soil bins can also create edge effects that alter how soil moves and how resistance is measured, making it different from open field conditions. Furthermore, short soil bin tests don't show the long-term effects of tillage on soil structure, the activity of living organisms in the soil, and other changes that happen over time. Simplified ways of looking at how the tools are pulled and the complete absence of weather elements like rain and temperature also make soil bin results different from what happens in a real field. Therefore, while soil bin research offers a basic understanding of how individual tools function, directly applying these findings to large-scale farming without considering these complex interactions and real-world factors can lead to inaccurate predictions and emphasizes the crucial need for testing tillage methods in actual field conditions

2.4.1.1 Universal Earth Moving Equation

Keeping the core principles of the simplified model McKyes (McKyes 1985; McKyes and Ali 1977; Patel et al. 2011) provided a specific formulation for the dimensionless N-factors. Those N-

factors are not constant, but complex functions of the soil friction angle ϕ , the soil-tool friction angle δ , the rake angle α and the soil failure wedge angle β .

A common practice in applying the McKyes equation involves determining the critical soil failure angle (β_{cr}) by identifying the value of β that minimizes the dimensionless factor N_γ . This approach is based on the principle that soil failure will occur along the path that requires the least amount of energy, which is often associated with minimizing the resistance component related to soil weight. The generalized form of the Fundamental Equation of Earthmoving (FEE) expresses the draft force (F) as a sum of components related to cohesion, soil weight, surcharge, and adhesion.

$$P = (\gamma g d^2 N_\gamma + c d N_c + q d N_q + c_a d N_a) w \quad (2.1)$$

where: P is the draft force [N], γ is unit weight of soil [kN/m³], d is depth of tillage [m], c is cohesion of soil [kPa], c_a is the soil metal to metal adhesion [N/m²], q is the surcharge pressure on the surface [kPa], N_γ , N_c , N_q and N_a are bearing capacity factors based on soil internal friction angle ϕ , w is width of the tool.

$$N_\gamma = \frac{\cot \alpha + \cot \beta}{2[\cos(\alpha + \beta) + \sin(\alpha + \beta) \cot(\beta + \phi)]} \quad (2.2)$$

$$N_c = \frac{[1 + \cot \beta_{cr} \cot(\beta_{cr} + \phi)]}{[\cos(\alpha + \delta) + \sin(\alpha + \delta) \cot(\beta_{cr} + \phi)]} \quad (2.3)$$

$$N_q = \frac{\cot \alpha + \cot \beta_{cr}}{[\cos(\alpha + \beta) + \sin(\alpha + \beta) \cot(\beta_{cr} + \phi)]} \quad (2.4)$$

$$N_a = \frac{[1 - \cot \alpha \cot(\beta_{cr} + \phi)]}{[\cos(\alpha + \delta) + \sin(\alpha + \delta) \cot(\beta_{cr} + \phi)]} \quad (2.5)$$

where α is the rake angle, β is soil failure wedge angle, δ is soil-tool friction angle, ϕ is the angle of soil-soil friction.

The McKyes Earth Moving equation is widely used to predict draft forces for various earthmoving and agricultural tillage tools. For example, it has been applied to estimate the draft forces of sweeps in loamy sand soil, providing a basis for calibrating numerical models such as the Discrete Element Method (DEM) (Mak and Chen 2014). It has also been used to predict the

horizontal force requirements of other farm implements. The core principles of the McKyes model have even been adapted to estimate excavation forces in lunar regolith, showing the broad applicability of its soil mechanics concepts. Additionally, the equation is often used as a benchmark to assess the accuracy and performance of more advanced draft force prediction methods, reinforcing its importance and continued relevance in the field (McKyes 1985; McKyes and Ali 1977; Patel et al. 2011).

2.4.1.2 ASABE Equations for Draft Force Prediction

The draft force equation for tillage tools presented in ASABE D497.7 standard (ASABE 2011) take an empirical form that includes a dimensionless soil texture adjustment factor (F_t) and several machine specific parameters.

The machine-specific parameters (A, B, and C) are determined through experimental testing for various categories of agricultural implements, highlighting the reliance on empirical data for these models. The ASABE Agricultural Machinery Management Data standard also provides valuable machinery management information, including typical values for implement power requirements, which are directly related to draft force (ASABE 2011).

The draft force prediction equations in the ASABE standard could be applied to a wide range of agricultural implements and soil conditions. The soil parameter (F_t) allows some differentiation based on the soil structure. The machine specific parameters (A, B and C) are correlate to different types of implements such as chisel plow, coulters and disc harrows, making the equation universal for estimating the draft forces of different machinery used for tillage operations. Previous study (Sadek et al. 2021) has evaluated the accuracy of ASABE predictions by comparing them with field measurements obtained under different soil types, including sandy loam and clay loam, and using various implements (ASABE 2011).

The accuracy of the ASABE draft force prediction equation has its limitations, and the results can vary based on specific conditions. One of the studies found that the error between the ASABE standard prediction and the actual draft force in sandy clay loam soil can exceed 30% (Roul et al. 2009). Those findings show that while ASABE draft forces predictions provide a useful general estimation of draft force, the accuracy can be influenced by specific soil properties, implement characteristics and operating parameters, sometimes forcing the use of alternative or more accurate methods.

2.4.2 Methods of Draft Force Measurement

Optimization of implement design, improving tractor efficiency and reducing fuel consumption during tillage operation would be impossible without precise draft force measurements. There are numerous methods to determine draft force, from empirical field measurements with the use of load cells to complex Computational Fluid Dynamics (CFD) simulation approaches. Below are few of the methods with advantages and limitation of each method.

2.4.2.1 Load Cell-Based Draft Force Measurement

The use of load cells for measuring draft force is widely spread in tillage research. The load cell is an instrument that converts mechanical force into electrical signal. The load cell usually mounted between the tractor and the tillage implement where draft force is being measured (Grisso et al. 2004).

A load cell-based system includes the following components:

1. Load cell sensor: Measures the draft force in real time.
2. Data acquisition system (das): Collects and records force readings.
3. Mounting frame: Ensures stable attachment between the tractor and implement.
4. Tractor-implement interface: Includes drawbar connections with adjustable heights for different tillage depths.

The Load Cell-Based System has several advantages as following:

- Provides direct and real-time force measurements.
- Highly accurate and widely used in research applications.
- Can be integrated with GPS and soil sensors for advanced analysis.

However, this system has some limitations:

- Requires precise calibration to ensure accuracy.
- Sensitive to tractor vibrations and implement oscillations.
- Costly equipment and specialized expertise are required.

Load Cell-Based System is suitable to measure draft forces of large-scale equipment that is typically pull-type equipment. In such measurements, a load-cell dynamometer is installed between the hitches of implement and tractor.

2.4.2.2 Three-Point Hitch Dynamometers

A three-point hitch dynamometer is installed on the tractor three-point hitch and designed to measure draft, vertical, and lateral forces acting on a tillage implement during tillage operations (Kushwaha and Linke 1996). Below are the advantages of this type of dynamometers:

- Measures multiple force components (draft, vertical, and lateral).
- Provides better insights into implement-soil interactions.
- Can be used for both mounted and semi-mounted implements.

This type of dynamometers is suitable for force measurements of small equipment that typically has three-point-hitch connection to tractors. In addition, the dynamometers have the following limitations:

- More complex setup compared to a simple drawbar load cell.
- Increased cost and calibration requirements.

2.5 Soil Disturbance Resulting from Tillage

Critical area of investigation and fundamental aspect of agricultural practices is soil disturbance, which is defines as any alteration to the soil physics, chemical or biological property (Wang et al. 2023). It is essential to understand and to quantify this disturbance for developing sustainable agricultural systems, optimizing tillage operations, predicting soil erosion and evaluating the agricultural machinery impact on the environment (Fizza et al. 2024).

2.5.1 Soil Surface Roughness

2.5.1.1 Definition and Importance

The vertical variation presents on the soil surface, at both macro and micro scale, are defined as soil surface roughness (SSR) (Alijani et al. 2022). It is vital factor affecting a multitude of environmental processes. For example, SSR plays a major role in microwave remote sensing, where it provides vital data for foil moisture estimation using electromagnetic surface scattering or

microwave radiative transfer models. The accuracy of soil moisture retrieval methods that rely on active and passive microwave remote sensing measurements is highly dependent on reliable SSR data. Some studies even showed that SSR can, sometimes, have greater impact on microwave signals than vegetation and soil moisture, especially in areas with bare soil (Alijani et al. 2022). Therefore, it is critical to obtain a reliable assessment of the SSR for various microwave sensing models used in applications like precision agriculture and environmental monitoring.

In addition to remote sensing, SSR is also an important parameter in surface hydrology, it can affect the ponding, runoff and infiltration. It can affect soil erosion rates, gas exchange between the atmosphere and the soil and the storage of water at the surface (Grundy et al. 2020). Root Mean square height (RMSH) is a statistical parameter that is usually used to describe SSR, the RMSH is the standard deviation of surface elevation and the correlation length, which represents the maximum distance over which correlation exists (Alijani et al. 2022).

It has been shown that different measurement methodologies applied to the same soil surface can provide a wide range of SSR values (Verhoest et al. 2008). This discrepancy emphasizes the complexity of characterizing SSR and highlights the challenges in comparing results across studies that use different measurement methods. The choice of the method and the parameterization of SSR can present a significant problem, particularly for applications like soil moisture retrieval where those parameters are vital inputs (Verhoest et al. 2008). The need for careful consideration of the measuring method and a clear understanding of its limitations for conducting research on soil surface is emphasized by this variability.

2.5.1.2 Contact Measurement Methods

2.5.1.2.1 Pin Profiler/Mesh Board

One of the most widely used methods for measuring the SSR is the pin profiler, or the mesh board (Alijani et al. 2022). The pin profiler method involves a series of pins, or a board with a grid that is placed on the soil surface and the height of the pins relative to the board is recorded (Thomsen et al. 2015a). The setup of this technique in the field is relatively simple, and it offers the capability of multiple 1-meter profiles to create a continuous profile, providing a more comprehensive evaluation of surface variations (Alijani et al. 2022).

However, there are few limitations associated with this method. The main disadvantage is that the physical contact of the pins with the soil surface can alter the micro topography being observed. This disturbance can be especially problematic while studying fragile or loose soil. In addition, the data collection problem can be very time consuming and labor intensive, when large fields must be measured. This method can be challenging in rough terrains or in fields with pronounced row soil structure created by cultivation, where maintaining consistent contact and obtaining accurate reading could be difficult (Alijani et al. 2022).

2.5.1.2.2 Chain Method

The chain method is relatively simple, fast and inexpensive for measuring surface relief (Gilley and Kottwitz 1995). The principle of this method is that a chain of given length will cover a shorter horizontal distance when placed on a rough surface compared to a smooth surface (Gilley and Kottwitz 1995). The reduction in the horizontal distance is directly related to the surface roughness. This method allows for the calculation of Saleh roughness factor (SFR), which provides a direct estimate of the surface roughness (Gilley and Kottwitz 1995). Measurements obtained by using other methods, like pin profiler can also be used to calculate SFR, allowing to relate different measures of roughness (Gilley and Kottwitz 1995). Although the chain method is very simple way to measure the SSR, its accuracy and level of detail might be less than more sophisticated methods.

2.5.1.3 Non-Contact Measurement Methods

2.5.1.3.1 Laser Scanning/LiDAR

Non-contact methods, such as laser scanning or LiDAR (Light Detection and ranging) can measure SSR over a wide area without physically disturbing the soil surface (Alijani et al. 2022). Those methods are especially valuable for remote or inaccessible locations where contact-based methods might be impractical (Alijani et al. 2022). Laser scanners work by emitting laser beams and measuring the time it takes for the reflected light to return to the sensor, allowing for the creation of a high-resolution three-dimensional model of the soil surface (Thomsen et al. 2015b). The 3D data can then be used to calculate various surface roughness parameters, including RMSH (Liu et al. 2022). In recent years the use of lasers scanners has become more common in soil surface studies

due to their ability to obtain detailed topographic data (Thomsen et al. 2015b). However, the cost of the laser scanning equipment might be a limiting factor in using the laser scanning methods in research applications (Liu et al. 2022).

2.5.1.3.2 Stereophotogrammetry/Digital Photogrammetry

Additional non-contact method that can provide high resolution three-dimensional datasets of the soil surface is stereophotogrammetry or digital photogrammetry (Grundy et al. 2020). This method requires taking multiple overlapping images of the soil surface from different directions and using special software to reconstruct a 3D model of the surface (Azizi et al. 2021). Using those 3D models a digital elevation models (DEMs) can be used to estimate various SSR parameters. To streamline the process of measuring SSR, automated photogrammetric methods have been developed making it more efficient approach. Stereophotogrammetry can be more cost-efficient method compared to the laser scanning especially with the advancements in digital imaging and processing capabilities (Azizi et al. 2021). However, there are many factors that can influence the results of photogrammetric measurements, such as lightning conditions or the precision of the camera calibrations.

2.5.1.3.3 Depth Cameras

A potentially simple and inexpensive alternative to the traditional methods for measuring soil surface roughness could be offered by the emergence of the depth camera technologies (Grundy et al. 2020). The principal of structured light is used by some depth cameras, a known light pattern is projected onto the soil surface, and the distortions in the pattern caused by the surface topography are analysed to reconstruct the 3D geometry (Grundy et al. 2020). A good accuracy and high precision in measuring soil surface elevation and parameters like random roughness could be achieved by those cameras (Grundy et al. 2020). The cameras, are usually, operate by emitting infrared (IR) pattern and using IR sensors together with visual light receiver to capture both IR and visible light information. Depth cameras can capture data at resolutions suitable for many SSR studies within specific range. In addition, there are software kits that will automate the image capture process, enabling to track changes in soil surface topography over time (Grundy et al. 2020). This accessibility and ease of use make depth cameras a promising tool for a wider range of research applications.

2.5.1.4 Analysis of Surface Roughness Data

To quantify the observed variations, statistical parameters are widely used in the analysis of SSR. Correlation length and root mean square height (RMSH) are usually calculated from the elevation data obtained by various measuring methods (Alijani et al. 2022). Additional processing steps are often required prior to calculating those parameters to remove the unwanted trends in the data (Verhoest et al. 2008). This process can be performed by several methodologies, including piecewise linear regressions, applying high-pass or moving average filters, or fitting and removing higher-order polynomials (Verhoest et al. 2008).

One of the most widely used parameters for quantifying the SSR is the Random Roughness (RR), which is defined as standard deviation of individual soil heights after the effects of slope and oriented tillage tool marks have been removed. This parameter provides a measure of the micro-topographic variability of the soil surface. Other parameters, such as the Saleh Roughness Factor derived from the chain method, offer alternative ways to characterize surface roughness based on different measurement principles (Gilley and Kottwitz 1995). The research objectives and the type of surface characteristics being investigated can affect the selection of appropriate roughness index. Different indexes may be more sensitive to different aspects of soil roughness and their relationship with other soil processes, such as water flow and erosion can vary (Thomsen et al. 2015b). Therefore, researchers must carefully consider the implications of their choice of roughness indices and be aware of the assumptions and limitations associated with each.

2.5.2 Soil Throw Distance

2.5.2.1 Definition and Significance

The extent to which soil particles are displaced, both horizontally and vertically, from their original position due to tillage or other activities that disturb the soil are referred as soil throw distance (Kucera 2020). Throw distance is a vital indicator of the tillage operation intensity and the degree of soil displacement achieved by different implements (Raper et al. 2004). Effectiveness of tillage in incorporating crop residue, loosening compact soil layers and preparing suitable seedbed can be significantly influenced by the distance that the soil is thrown. Furthermore, the extent of soil throw can be related to the potential for soil erosion, as greater displacement might leave the soil surface more vulnerable to wind and water forces (Kucera 2020). The spatial extent of soil disturbance caused by tillage is often defined and quantified by parameters such as maximum width of soil throw (Deshpande and Shirwal 2017). The distance the soil is thrown is directly related to the

energy imparted to the soil by the tillage implement and indicates the level of soil inversion and mixing, which are critical for various agricultural objectives (Deshpande and Shirwal 2017).

2.5.2.2 Measurement Methods

2.5.2.2.1 Portable Tillage Profiler (PTP)

A tool for quickly and accurately measuring both aboveground and belowground soil disruption caused by tillage have been developed and it is called portable tillage profiler (PTP) (Raper et al. 2004). The PTP usually built of a light aluminum frame that supports a laser distance sensor and a portable computer that controllers the sensor. A laser beam is projected by the laser sensor onto the soil surface, and the distance is calculated via triangulation, allowing the measurement of the soil surface elevation profile. The PTP can generate a detailed cross-sectional profile of the soil disruption, including the height of any thrown soil and the depth of the furrow by moving the laser sensor horizontally across the tilled area (Raper et al. 2004). Studies have shown the accuracy of PTP in measuring soil disruption, making them a valuable tool for quantifying the extent of soil throw and overall soil movement caused by different tillage implements. This is more automated and potentially less labor-intensive method compared to the traditional pin style profile meters, providing detailed and quantitative on soil displacement (Raper et al. 2004).

2.5.2.2.2 High-Speed Photography/Videography

The dynamic movement of soil particles during tillage operations can be captured by high-speed photography or videography (Zeng et al. 2023). The trajectory of individual soil particles can be tracked by analyzing the recorded images or the videos, allowing to measure the distance they are thrown from their original positions (Zeng et al. 2023). This method can provide valuable insights into the mechanics of soil disturbance, revealing how different tillage tool designs and operating speeds influence the pattern and extent of soil throw (Zeng et al. 2023). Both qualitative and quantitative understanding of the soil throw process are offered by visualizing soil movement in this mater, and it can be complimented by static measurements obtained from profile meters or other techniques (Zeng et al. 2023). Such dynamic analysis can be particularly useful for understanding the immediate effects of tillage implements on soil displacement.

2.5.2.3 Factors Influencing Soil Throw Distance

A combination of factors related to the tillage implement and the soil itself are influencing the distance that the soil is thrown during tillage operation (Deshpande and Shirwal 2017). The direction and the extend of the soil movement are determined by the shape and the geometry of the tillage tool, including its width tilt and disc angles. The speed and the depth of the tillage operation have significant effect on the amount of energy transferred to the soil and, consequently, the throw distance (Deshpande and Shirwal 2017). Different types of tillage implements are designed to achieve different degrees of soil throw based on specific purposes (Hanna et al. 1995). For example, a moldboard plow is intended to invert the soil, resulting in a significant vertical and lateral throw, while a chisel plow primarily aims to fracture the soil with less lateral displacement (Hanna et al. 1995). Soil conditions, such as soil texture, moisture content and bulk density also affect how the soil responds to forces applied by the tillage tool, influencing the distance and pattern of soil throw (Deshpande and Shirwal 2017).

2.5.2.4 Modeling Soil Throw

Discrete element methods (DEM) have proven itself as a powerful tool for soil-tool interactions simulation and predicting soil displacement, including the distance and pattern of soil throw (Alijani et al. 2022; Mak et al. 2012; Sadek et al. 2021; Saunders et al. 2021). Soil is represented as a collection of discrete particles that interact with each other and the tillage tool based on defined contact laws and material properties (Wang et al. 2023). The DEM models can be calibrated and validated by comparing the simulation results with experimental data obtained from soil bin or field measurements (Sadek et al. 2021; Saunders et al. 2021; Wang et al. 2023). DEM was used by researchers to compare the performance of different tillage tools, analysing both horizontal and vertical soil throw to optimise designs of different implement geometries and operating conditions, providing valuable insights into soil throw without the need for extensive physical experimentation. The ability to accurately model soil to tool interactions through DEM can significantly aid in the design and development of more efficient and effective tillage technologies.

2.5.3 Amount of Soil Disturbance

2.5.3.1 Volume Displacement Methods

It is possible to quantify the overall amount of soil disturbance caused by tillage or other activities by measuring the volume of soil that loosened, moved or inverted (Wang et al. 2023). There are few methods that are used to estimate this volume, depending on the scale and nature of

the disturbance. The depth-area method can be employed for relatively flat fields. In this method the area of tilled area is multiplied by the tillage depth to estimate the volume. For uneven or larger fields, the grid method provides a more precise approach. This involves setting up a grid over the tilled field and measuring the tillage depth at each grid point, which is then averaged to calculate the total volume.

While calculating the soil volume due to disturbance, it is important to consider the swell and compaction factors. Typically, soil increases in volume when it is tilled (swell). Profile meters can measure the cross-sectional area of the disturbed soil profile, and if the length of the tillage pass is known, this area can be multiplied by the length to estimate the volume of disturbed soil (Kumar et al. 2023). Accurate estimation of soil volume changes is critical for understanding the overall impact of tillage on soil structure and porosity (Alaoui et al. 2020).

2.5.3.2 Visual Assessment Techniques

Visual assessment methods provide fast and cheap way to evaluate the extent and nature of soil disturbance in the field (Shepherd et al. 2000). Visual Soil Assessment (VSA) is one of the methods, that involves observing and scoring various soil quality indicators, such as soil structure, compaction and tillage marks (Shepherd et al. 2000). VSA often utilizes field guides with photographs of different soil conditions to help in the assessment process (Ball and Munkholm 2015). This method can provide valuable qualitative information about the degree of soil disturbance and its potential impact on soil health.

Another assessment approach involves the Soil Tillage Intensity Rating (STIR), this is a method for evaluating tillage and planting systems based on factors such as speed, type and depth of tillage operation, and the percentage of surface soil disturbed (Kucera 2020). STIR assigns numerical values to different tillage practices, with higher values indicating greater soil disturbance (Kucera 2020). The rating considers both the area directly disturbed by the implement and the area affected by soil that is thrown or displaced (Kucera 2020). STIR provides a standardized way to compare the intensity of different tillage systems and their potential effects on soil properties. Visual assessment methods offer a practical means for farmers and researchers to quickly evaluate the impact of tillage practices and make informed management decisions (Shepherd et al. 2000).

2.5.4 Soil Bulk Density

2.5.4.1 Definition and Importance

The mass of dry soil per unit volume of soil, including the volume of solids and pores is defined as soil bulk density (Ball and Munkholm 2015). Soil bulk density is fundamental soil physical property that serves as a key indicator of soil compaction, aeration water infiltration capacity and the potential for root growth restriction (Ball and Munkholm 2015). Tillage can have temporary effect on soil bulk density by loosening the soil in the tilled layer, this usually causes a decrease in bulk density immediately after tillage (Ball and Munkholm 2015). However, settling and wheel traffic can lead to an increase in bulk density and potentially resulting in soil compaction (Ball and Munkholm 2015). Monitoring changes in soil bulk density before and after tillage is crucial for assessing the long-term effects of different tillage practices on soil physical health and their implications for crop yields and environmental sustainability (Altikat et al. 2024).

2.5.4.2 Standard Measurement Protocols

2.5.4.2.1 Soil Core Method

The core method is the most common protocol for measuring soil bulk density (Ball and Munkholm 2015). This method involves collecting a known volume of relatively undisturbed soil using cylindrical core sampler (Ball and Munkholm 2015). A metal cylinder of a known diameter and height is usually used as a sampler; it is carefully pushed into the soil until it reaches desired depth (Ball and Munkholm 2015). Once the core is extracted, the soil sample trimmed to a known volume (Hans 2023). The soil is then removed from the sampler and oven dried at 105°C for at least 24 hours to remove all moisture and weighted to determine the dry mass (Ball and Munkholm 2015; ISO/DIS 22494 2020). The bulk density is calculated by dividing the dry mass of the soil by the volume of the core. It is crucial to collect undisturbed samples to obtain accurate bulk density measurements, and this method may be challenging in soils with high gravel or rock content (Ball and Munkholm 2015).

2.5.4.2.2 Excavation Method

This method is usually used when the core method is difficult to apply, such as in soils with hi percentage of coarse fragments (Zhao et al. 2010). In this method a small hole of a known volume is dug, carefully collecting all the excavated soil, and then determining its oven-dry weight (Zhao et

al. 2010). The bulk density is then calculated by dividing the dry weight of the soil by the measured volume of the excavation (Zhao et al. 2010).

2.5.4.2.3 Other Methods

Other methods for measuring soil bulk density include the clod method, where the volume of a soil clod is determined by water displacement after coating it with paraffin wax, and the dry weight is then measured. Radiation methods, using nuclear gauges that emit gamma rays and measure their attenuation through the soil, can also be used to estimate bulk density, offering a non-destructive approach (Lichter and Costello 1994). However, radiation methods require specialized equipment and safety precautions.

2.5.4.3 Bulk Density Measurement Before and After Tillage

To assess the impact of tillage on soil bulk density, measurements should be taken at the same or representative locations within a field both before any tillage operations are performed and at specific time intervals after tillage (Ball and Munkholm 2015). The timing of the post-tillage measurements is important as bulk density can change over time due to settling and compaction (Ball and Munkholm 2015). It is essential to record the depth from which the samples are taken, the type of soil, and the specific tillage implement used to allow for meaningful comparisons (Abu-Hamdeh 2004). Comparing bulk density values obtained before and after different tillage operations provides a quantitative measure of how these operations alter soil structure and can help in determining optimal tillage strategies for maintaining or improving soil health (Altikat et al. 2024).

2.6 Research Gaps

High-speed disk (HSD) implements are designed to optimize field coverage and soil disturbance while minimizing operational time and fuel consumption. However, the draft force required to operate these implements under varying depths and speeds remains under-characterized, particularly in real field conditions. Existing models, such as those from ASABE and McKyes, were primarily developed for traditional tillage tools and may not accurately represent the complex interactions seen in high-speed operations.

In addition to draft force uncertainties, the quantification of soil disturbance resulting from high-speed tillage is not yet well established. Most existing research has focused on draft measurements or energy requirements, with comparatively limited attention given to soil condition parameters such as soil surface roughness, residue incorporation, and post-tillage compaction. The relationship between operational parameters (speed and depth) and the resulting soil disturbance has not been sufficiently studied under realistic field conditions, particularly for modern HSD designs that use independent disc suspensions and operate at higher speeds.

Another major gap exists in linking soil disturbance metrics with predictive draft models. Current empirical and analytical models describe the mechanical performance of the implement but seldom consider the agronomic consequences of soil disruption. Integrating soil disturbance measurements into predictive frameworks could provide a more comprehensive assessment of implement efficiency, combining mechanical power demand with soil conservation outcomes.

This study addresses these critical gaps by empirically measuring both draft force and soil disturbance indicators under controlled field conditions and by evaluating the applicability of established predictive models for HSD implements. The outcomes will support more accurate implement–tractor matching, reduce energy inefficiencies, and contribute to sustainable equipment design, ultimately enhancing productivity and environmental stewardship in modern farming systems.

2.7 Objectives

To bridge the gaps, one of the goals of this study was to evaluate the performance of a High-Speed Disc implement in field conditions. Another goal was to develop and verify a new equation for the prediction of draft forces required to pull High-Speed Disk implement. This will allow the farmers and the tillage manufacturers to predict the draft force needed to operate the equipment in optimal conditions based on number of disks installed on the implement, the tillage depth, and speed.

The specific objectives of this study were to:

- conduct a field experiment to investigate effects of working depth and speed on the draft forces and soil disturbance resulting from a high-speed disc harrow.

- use the field measurements to develop a prediction equation through regression for predicting the draft force required to pull a high-speed disk implement.
- compare the results in draft force between the prediction equation and the ASABE D497.7 standard equation (ASABE 2011).

3 METHODS AND MATERIALS

3.1 Equipment Description

3.1.1 Tillage Implement

The field experiment was conducted using a 5.5-m (18-foot) implement manufactured by Buhler Industries INC. (Winnipeg, Manitoba, Canada) and marketed under the brand name Fury. The implement was a high-speed disc harrow, designed as a primary tillage implement and its main function is to prepare seedbeds and incorporate crop residue into soil after harvest. The implement is constructed from four main assemblies: hitch, wings, center section, and finishing tool, as indicated in Figure 3.1. Wings are folded over the center section for transportation. The folding mechanism is controlled hydraulically from the tractor cabin and is performed in two (2) stages: center section folding and wing folding. Although there are several different options for the finishing tools, this implement was equipped with rubber packer finishing tools.

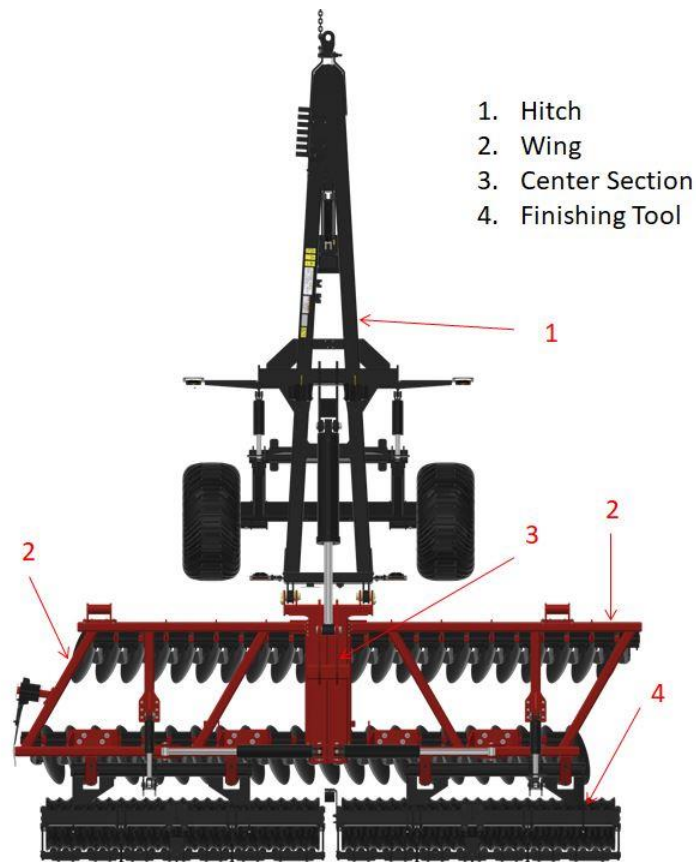


Figure 3.1: Fury high speed compact disc (HSCD) top view

3.1.1.1 Discs and Finishing Tools

The ground engaging tools, discs (Figure 3.2), are mounted on the frame in two (2) rows (front row and rear row) and designed to invert the soil in opposite direction to compensate for the lateral forces. Both the front and the rear disks are spaced 254 mm (10 inch) apart and a shift of 127 mm (5 inch) between the front and the rear rows makes the actual distance between the disk paths to be 127 mm.

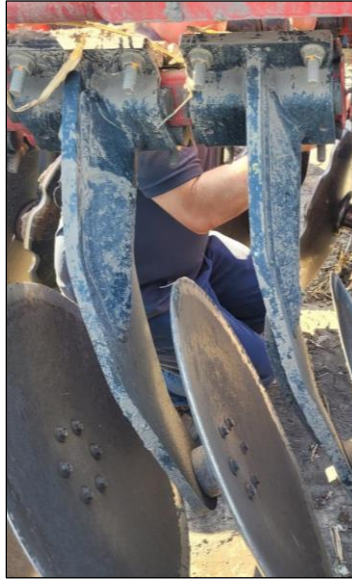


Figure 3.2: Tillage disk and arm

The disks are mounted to the disk arms using PEER EXTREME[®] bearing, and the disc arms are mounted to the gang beams. To prevent excessive vibrations and to allow the arms to react to the field irregularities, four (4) rubber isolators are installed between the disk arm and the gang beam.

The implement is designed to use either 560 mm (22 inch) or 610 mm (24 inch) discs, however for this study the 560 mm discs were selected. Due to the different nature of the mechanical interaction between the front and rear disk rows (front row engages undisturbed soil, while rear row engages soil inverted by front row), the orientation of the disks in relation to the travel direction is different between the front and the rear rows. While the tilt angle in both rows is set to 20°, the disk angle of the front row is set to 17°, while the disk angle of the rear row is set to 15° in opposite direction. The difference in the disc angle between the front row and the rear row

neutralize the lateral forces which may cause the implement slide sideways during the tillage operation and allow the implement to achieve uniform field finish with minimum ridging of the tilled soil.

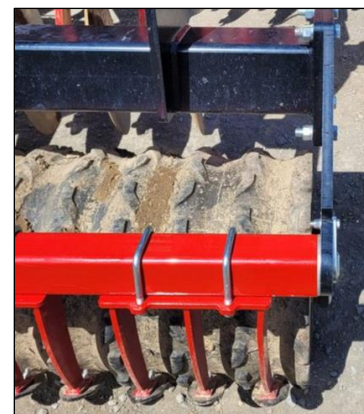
There are three (3) typical finishing tools used with high-speed discs, cage roller, spring packer, and rubber packer. Cage (steel) roller (Figure 3.3a) is used to break clods of soil left by the disc operation and is very popular for implements used for primary tillage. Spring packer (Figure 3.3b) is designed for use in sticky soil. As the packer rotates the springs are hitting the stoppers and start vibrating. The vibration prevents the soils to stick to the packer thus keeping it clean. Rubber packer (Figure 3.3c) provides smoother field finish than the standard cage roller and compacts the top layer of soil to reserve the soil moisture. Rubber packer is used in implements that might be used for spring tillage. For this study a rubber roller made by a Otico INC. (Chalmaison, France),



(a)



(b)



(c)

with a diameter of 545 mm was used.

Figure 3.3: Finishing tools used on High-Speed tillage implements. (a) Cage (steel) roller, (b) Spring roller, (c) Rubber semi pneumatic roller

3.1.1.2 Working Depth and Speed Control

The implement weight is carried by the front wheels and the rear finishing tools; therefore, the working depth is controlled by limiting the stroke of the hydraulic cylinders that control height of the transport wheels and the finishing tools. The cylinders are connected to rockshafts that, by changing the angles, controls the height of the wheels and the finishing tools of the implement.

Thus, controlling the depth at which the ground engaging tools (discs) can penetrate the soil. The implement designated working depths can vary from 25 mm (1 inch) to 125 mm (5 inch).

A set of steel plates (Figure 3.4) is installed on the rod of the hydraulic cylinders of the centre section of the implement and on the left cylinder of the finishing tool. By engaging the plates, the equipment operator is expected to limit the stroke of the hydraulic cylinder, preventing it from fully retracting, and thus, controlling the depth of the implement. The numbers of the required plates are determined by the disc diameter and are set based on the operational instructions of the implement.



Figure 3.4: Depth stop plates on the hitch of HSCD implement

In addition to depth control, ground speed during the tillage operation is also a critical parameter. Speed control is managed by the tractor operator and is adjusted according to the desired tillage intensity, soil conditions and residue incorporation requirements. Maintaining a consistent and appropriate speed ensures uniform soil disturbance, optimal draft force, and prevents excessive implement bounce or depth variation, particularly in uneven field conditions.

3.1.2 Power Unit

A Versatile™ 4WD (Winnipeg, Canada) articulated tractor with 610 HP (Figure 3.5) was chosen to pull the implement for the experiment. The tractor can provide up to 610 horsepower at the draw bar and can reach maximum speed of 40 km/h. It is powered by Cummins X15 engine (15

L engine) and TA22 powershift transmission manufactured by Caterpillar™. Although the tillage implement is designed for Category IV drawbar, the tractor is equipped with category V drawbar.



Figure 3.5: Tractor (Versatile 610, 610 hp) used to pull the tillage implement in the experiment

3.2 Field Experiment

3.2.1 Experimental Site Description

The field experiment was conducted on October 15, 2024, starting at 10 am and concluded at 4 pm. The chosen field is located at the RM of Kronsthal, Manitoba at the precise GPS coordinates 49°01'28.5"N 97°43'49.2"W (location on map Figure 3.6). The total field size was 6.25 ha offering sufficient room to perform the experiments under controlled and consistent conditions.

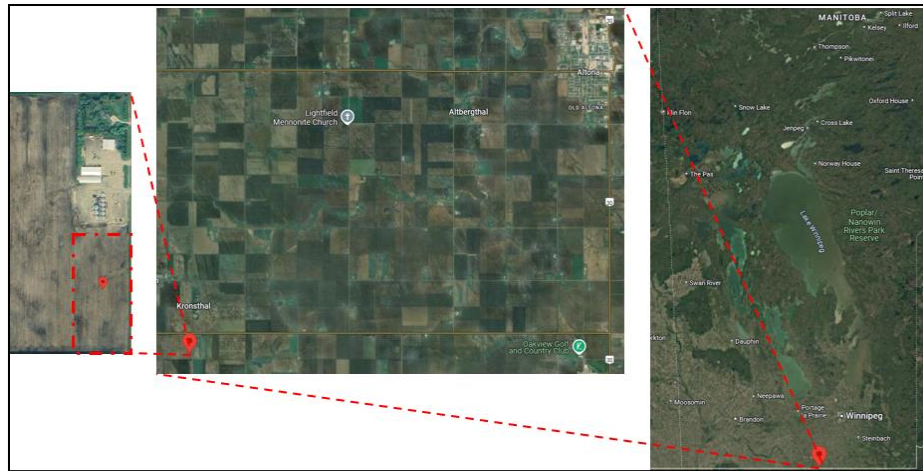


Figure 3.6: Test field location

The experiment was carried out in the field following the harvest of wheat, which produced an average grain yield of 6.72 tons per hectare. During the previous spring, prior to seeding, the field was prepared using a field cultivator and a packer to optimize soil conditions. In the previous growing season, the field had been utilized for corn production, yielding 9.5 tons of grain per hectare, after which a disk ripper was employed for soil management. A summary of the 2-year history of the field is available in Table 3-1.

Table 3-1: History of the tested field

Activity	Description	Season
Field experiment	Disk plow on wheat stubble	Fall 2024
Crop 2024	Wheat at 6.72 tons/ha	Fall 2024
Secondary tillage	Cultivator and pack	Spring 2024
Primary tillage	Disk ripper	Fall 2023
Crop 2023	Corn at 9.5 tons/ha	Fall 2023
Secondary tillage	Cultivator and pack	Spring 2023
Primary tillage	Disk ripper	Fall 2022

3.2.2 Experimental Design and Procedure

3.2.2.1 Experimental Design

The field experiment had a completely randomised block design. To understand the effects of speed and depth of an implement on the draft forces and soil disturbance, the experimental factors were chosen to be tillage depth and tillage speed. The experimental treatments were the

combinations of three target tillage depths: 25, 75, and 125 mm and two target tillage speeds: 10 and 20 km/h. Each treatment was repeated four (4) times, making it a total of 24 tests.

To reduce the effect of the field elevation, the block and tillage direction were chosen to be perpendicular to the change in elevation, and the four (4) data sets were collected while traveling in parallel but opposite directions. Sets one (1) and three (3) were conducted from north to south while sets two (2) and four (4) were conducted from south to north. The six (6) different treatments were assigned designation numbers from 1 to 6 and using the Excel software were randomised into 4 blocks. The field plot layout is summarised in Figure 3.7.

FIELD PLOT LAYOUT											
North											
Block 1 			Block 2 			Block 3 			Block 4 		
Tillage direction 	Plot 1 Speed = 10 km/h Depth = 75 mm	Tillage direction 	Plot 7 Speed = 10 km/h Depth = 25 mm	Tillage direction 	Plot 13 Speed = 20 km/h Depth = 75 mm	Tillage direction 	Plot 19 Speed = 20 km/h Depth = 25 mm				
	Plot 2 Speed = 20 km/h Depth = 125 mm		Plot 8 Speed = 10 km/h Depth = 125 mm		Plot 14 Speed = 10 km/h Depth = 75 mm		Plot 20 Speed = 20 km/h Depth = 75 mm				
	Plot 3 Speed = 10 km/h Depth = 25 mm		Plot 9 Speed = 20 km/h Depth = 25 mm		Plot 15 Speed = 10 km/h Depth = 25 mm		Plot 21 Speed = 20 km/h Depth = 125 mm				
	Plot 4 Speed = 20 km/h Depth = 75 mm		Plot 10 Speed = 20 km/h Depth = 75 mm		Plot 16 Speed = 10 km/h Depth = 125 mm		Plot 22 Speed = 10 km/h Depth = 25 mm				
	Plot 5 Speed = 10 km/h Depth = 125 mm		Plot 11 Speed = 20 km/h Depth = 125 mm		Plot 17 Speed = 20 km/h Depth = 25 mm		Plot 23 Speed = 10 km/h Depth = 75 mm				
	Plot 6 Speed = 20 km/h Depth = 25 mm		Plot 12 Speed = 10 km/h Depth = 75 mm		Plot 18 Speed = 20 km/h Depth = 125 mm		Plot 24 Speed = 10 km/h Depth = 125 mm				
South											

Figure 3.7: Field plot layout

3.2.2.2 Tillage Depth and Speed Setting

To verify the actual tillage depth, measurement was taken for each target depth setting using a measuring tape. The penetration depth was calculated by subtracting the distance from the top of the disc to the soil surface from the disc diameter (Figure 3.8). For each plot, the number of shims was adjusted to set the implement to the desired depth. For discs with a diameter of 560 mm that are used for the experiment, twelve (12) shims correspond to 25 mm tillage depth, seven (7) shims correspond to 75 mm tillage depth, and two (2) shims correspond to 125mm tillage depth. Once it was verified that the number of shims at a given depth setting corresponded to the desired depth, it was not necessary to repeat the measurement for each plot since the number of shims that control the depth of the implement would not change.

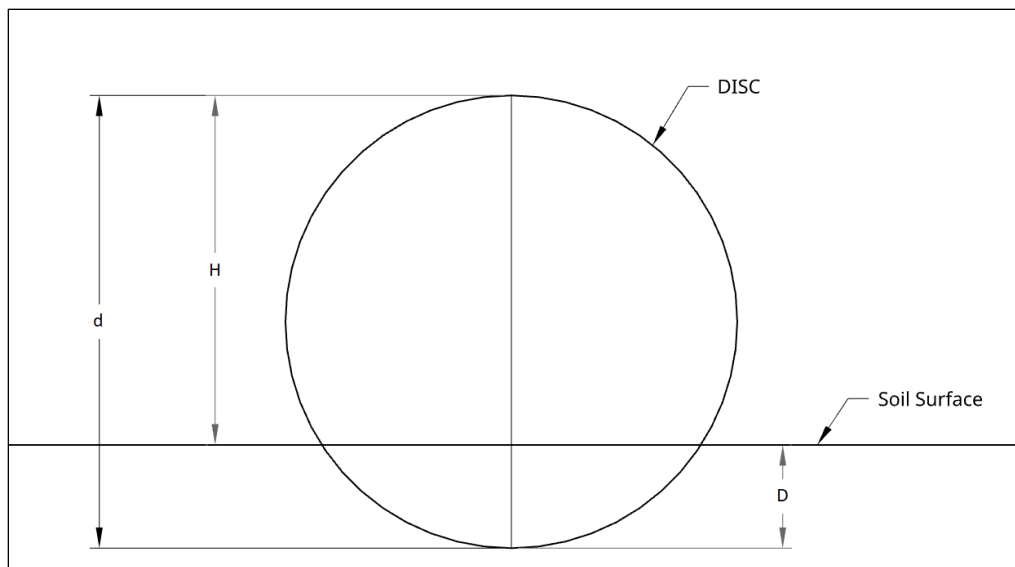


Figure 3.8: Measurement of the tillage depth, where d is the disc diameter, H is the distance from soil surface to top of the disc, D is tillage depth.

The operating speed of the tractor was established using a GPS-based speedometer (John Deere StarFire™ 6000) to ensure accurate and consistent travel speed measurements. During each tillage operation, the tractor operator adjusted the throttle and gear selection to maintain the target ground speed as indicated by the GPS unit installed in the cab. The StarFire™ 6000 receiver

provided real-time measurements of true forward velocity relative to the ground surface with sub-meter accuracy.

This method was adopted to eliminate the influence of wheel slippage on speed determination. Conventional wheel-speed sensors estimate travel speed based on tire rotation, which can lead to overestimation when traction losses occur under varying soil conditions or draft loads. By relying on GPS-based speed readings, the effects of wheel slip were excluded from the calculation of draft forces. Consequently, the recorded draft data corresponded to the actual ground travel speed of the tractor rather than its theoretical wheel speed, thereby enhancing the accuracy and reliability of draft force measurements across the different tillage depth and speed treatments.

3.2.3 Field Measurements

3.2.3.1 Initial Soil Moisture Content

Prior to conducting the experiments, twenty (20) random samples of soil were collected from the tested field using a core sampler (Figure 3.9) with a diameter of 20 mm and a height of 300 mm. The soil samples were collected into plastic bags, and the bags were marked with the sample number and transported to a lab. Where the soil moisture content was measured following the gravimetric oven dry method as per the standards (ASTM D2216, 2019). The method consists of four main steps, weighting a wet sample, drying in oven at 110 °C for 24-48 hour, reweighting the soil sample after the drying process and calculating the moisture content (dry basis).



Figure 3.9: Core sampler used to collect the soil samples

The moisture content data was organized into Table 9-1: Moisture content calculations shown in APPENDIX B. For the drying process, each sample was transferred from the plastic bag,

in which it was collected in the field, into a container. Before the transfer, the container was weighted, and the weight of each individual container was recorded in the table. After the transfer of the sampled soil into the container, the container with the soil was weighted again and recorded in the table. The weight of the wet soil was calculated by subtracting the weight of the container from the weight of the sample in the container. The weight process was repeated after drying the samples. Once the weight of the wet and dry soil was calculated, the moisture content was calculated using the following equation:

$$MC = \frac{W_W - W_D}{W_D} 100 \quad (3.1)$$

where MC is moisture content [% d.b], W_w is wet soil weight [gr], W_D is dry soil weight [gr].

The bulk density of the sampled soil was calculated by the equation:

$$BD = \frac{W_D}{1000S} \quad (3.2)$$

where BD is bulk density in [kg/m³], W_D is dry soil weight [gr] and S is soil sampler volume [m³].

3.2.3.2 Draft Force

An Interface Force™ load cell (model #1232F8N, Interface, Scottsdale, Arizona, USA) with 44,500 kN capacity, was used to collect the draft forces. The load cell in Figure 3.10 was mounted between the hitches of the tractor, and the tillage implement as shown in Figure 3.11.



Figure 3.10: Load cell used to collect the draft force data



Figure 3.11: Load cell connection to the power unit and the implement

Using the Somat Data Acquisition Device (e-DAQ) system in Figure 3.12 connected to the load cell and the tractor CAN network, the following data was recorded: draft force, engine RPM, engine HP, speed and GPS coordinates, on a computer using Catman data acquisition software. Since the measured tractor speed does not accommodate the slippage affect, the GPS data was used to confirm the actual speed of the tractor with the tillage implement.

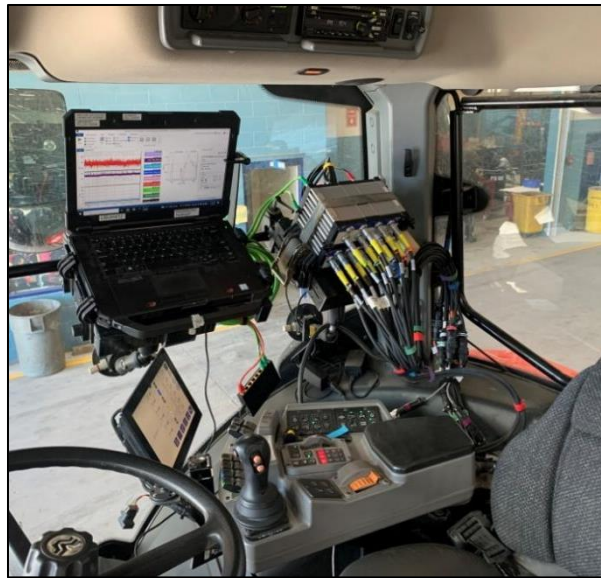


Figure 3.12: Somat data acquisition and logging computer

Each measurement was conducted in a plot with the length of 100 meters to allow the tractor to reach the operational speed and collect force data over a measurement distance of several

meters. Then, the force data were average over the measurement distance, the average forces are presented. During the experiment, a total of twenty-four (24) data sets were recorded.

A limiting factor of the selected measuring method (load cell with not rigid connection to the implement) is the fact that it does not take in an account the lateral (side to side) or the vertical (up and down) forces that might have contribution to the measurement of the forces with the load cell.

3.2.3.3 Soil Cone Index

The soil cone index was measured using a hand penetrometer (Royal Eijkelkamp, 615SA, Nijverheidsstraat, Netherlands) (Figure 3.13a) with a cone (Figure 3.13b) with base area and rod diameter of 333 mm^2 and 10 mm respectively. Using a load cell (Figure 3.13c) with capacity of 1,000 N, the penetrometer measures the force required to penetrate the soil to certain depth. A reflective plate (Figure 3.13d) allows penetrometer to measure and record the distance from the soil surface, which allows to build a compaction profile in cone index vs. soil depth.

To analyse the effect of the high-speed tillage implement on the cone index of the soil, an initial twenty (20) measurements were performed. The initial results obtained before tillage, were later used as reference for the cone index results obtained after tillage.



(a)



(b)



(c)



(d)

Figure 3.13: Instrument for cone index measurements. (a) Monitor, (b) Cone, (c) Load cell, (d) Reflector plate at use

After completing the tillage operation, four (4) additional measurements per plot were conducted. The measurements were taken up to the depth of 800 mm in increments of 10 mm. Although the data was collected to the depth of 800 mm for the analysis only the data to the tillage depth was used. To compare the results at different depths, the averages of the top 130 mm were calculated, and the results are shown in Table 12-1 in APPENDIX E.

3.2.3.4 Soil Surface Roughness

To measure soil surface roughness (SSR), the linked-chain method (Jester and Klik 2005) was used. Initially, twenty (20) measurements were collected at random locations and orientations of the field prior to the tillage operation. the initial roughness indicators were compared with those measured after the tillage operation. The samples were collected by laying a chain (Figure 3.14) on one (1) meter of soil. Due to the soil roughness, the length of the chain will be longer than 1 meter. The difference of the chain length in relation to 1-meter was then calculated in percentage and this is the soil surface roughness indicator.



Figure 3.14: Soil surface roughness measurement using the chain method

3.2.3.5 Residue Incorporation

The residue incorporation was measured using image feature descriptors (Owen et al. 2020). Pictures of a wooden frame with dimensions of 600 mm x 600 mm placed on the ground were taken (Figure 3.15a). For initial residue conditions, 20 measurements were performed at random locations of the field before tillage. After tillage, a total of four (4) measurements of residue incorporation per plot were performed. The pictures were cropped (Figure 3.15b) only to include the image within the frame and resized to 600 x 600 pixels. Using a MatLab version R2024a software, the pictures were converted to black (soil) and white (residue) image (Figure 3.15c) and the ratio white to black pixels was calculated using the equation:

$$RI = 100 - \frac{100P_b}{P_a} \quad (3.3)$$

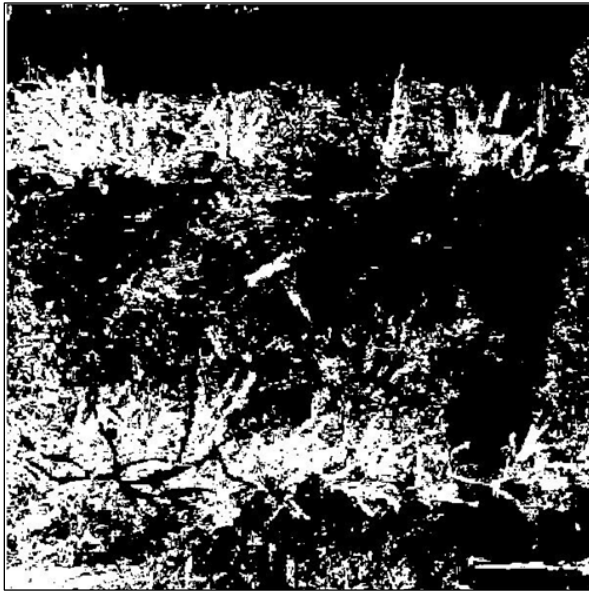
where RI is residue incorporation [%], P_b is the count of pixels in initial measurement before tillage and P_a is the count of pixels after the tillage.



(a)



(b)



(c)

Figure 3.15: Residue incorporation measurement. (a) Collection of the data, (b) Image cropped to 600 by 600 pixels (c) Cropped image converted to black and white

3.2.4 Data Analysis

A General Linear Model (GLM) and Analysis of Variance (ANOVA) were performed utilizing the ‘*car*’ package in the R statistical software (RStudio), to assess the effect of the speed and tillage depth on the draft force, cone index, soil surface roughness, and surface residue incorporation. Duncan’s multiple range test was performed in the same software for pairwise

comparisons of factor levels and their interaction effects. A significance level of $P < 0.05$ was chosen. When interaction effects were significant, simple effects were presented. Otherwise, main effects were presented.

3.3 Draft Force Prediction

3.3.1 Development of a Prediction Equation

To establish the relationship between draft force (F) of the High-Speed Disc implement and tillage depth (D) and tillage speed (S), a multiple regression analysis was performed with F being dependent variable, D and S being independent variables. Data for regression analysis was from the experiment in which draft forces were measured under varying combinations of tillage depth and tillage speed. The regression model included the main effects of D and S as well as their interaction term $D*S$, which was retained due to its potential significance in explaining the combined influence of the two variables. The general form of the fitted model was:

$$F = aD + bS + cDS \quad (3.4)$$

where F is draft force of High-Speed Disc implement [N], D is working depth [cm], S is operating speed [km/h], and a , b , and c are regression coefficients. The predicted draft force, F , is zero, when both D and S are zero. When the equation is used to predict draft force, the following conditions apply: if $S=0$, F must be zero, and if $D=0$, S must be zero.

The regression analysis was performed using the R statistical software (RStudio) version 2025.05.1 build 513. The model adequacy was assessed using the coefficient of determination (R^2) to evaluate the proportion of variance explained by the model.

3.3.2 Validation of the Prediction Equation

The draft force results predicted using equation (3.4) were compared to the calculated results using the ASABE D497.7 (ASABE 2011) standard equation for tillage tools operated at shallow depths. The accuracy of draft-force estimation using this equation is limited, with reported errors of up to $\pm 50\%$, indicating that the ASABE equation provides an approximation rather than a precise prediction (Sadek et al. 2021). The equation has a general format as following:

$$F = f_i[A + B(S) + C(S)^2]WD \quad (3.5)$$

where F is tillage implement draft [N], f is a dimensionless soil texture adjustment parameter, A , B , and C are machine-specific parameters, S is operating speed [km/h], W is machine width [m] or number of rows or tools, D is tillage depth [cm] for major tools, D is 1 (dimensionless) for minor tillage tools and seeding implements.

The soil texture adjustment factor in equation (2.5), f_s , is categorized into three levels: fine, medium, and coarse textures. Machine parameter A primarily reflects soil strength, while B and C are speed-related coefficients influenced by soil bulk density. These parameters remain constant for a given implement type.

The implement used for draft force measurements in this study consisted of two types of tillage equipment: a high-speed disc (excluding finishing tools) and finishing rollers. Consequently, the total draft force should consist of two components: the draft generated by the high-speed disc and the draft generated by the finishing rollers. Thus, the total draft force of the implement was estimated as following:

$$F_t = F_{disc} + F_{roller} \quad (3.6)$$

where F_t is the total draft force [N], F_{disc} is the draft force of the tandem disc plow [N], and F_{roller} is the draft force of finishing rollers [N].

Both F_{disc} and F_{roller} were estimated using the general equation (3.5). The ASABE Standards provide tabulated values for both soil- and machine-specific parameters for various implements. For the tandem disc plow, the ASABE machine parameters for tandem disc for primary tillage were used. The machine-specific parameters are $A = 309$, $B = 16$, and $C = 0$, while the soil adjustment factors are $f_1 = 1.0$ for fine-textured soils, $f_2 = 0.88$ for medium-textured soils, and $f_3 = 0.78$ for coarse-textured soils. The accuracy of draft-force estimation using this equation is ± 45 . For the finishing tools (rubber rollers), the ASABE machine parameters for roller packer were used. The machine-specific parameters are $A = 600$, $B = 0$, and $C = 0$, with soil adjustment factors f_1 , f_2 , and $f_3 = 1$ and a similar accuracy of approximately $\pm 50\%$.

It should be noted that draft forces estimated by the ASABE equations include both functional draft (soil and crop resistance) and rolling resistance of the implement. Likewise, the measured draft forces for the high-speed compact disc (HSCD) implement in this study also included both components—the draft from the discs and the rolling resistance from the transport

wheels—ensuring valid comparability between the experimental results and those derived from the ASABE equations.

4 RESULTS AND DISCUSSION

4.1 Experimental Results

4.1.1 Actual Tillage Depths and Tillage Speeds

Tillage depths were measured only during initial machine depth setting. All verification measurements confirmed the accuracy of these settings. Therefore, actual tillage depths were not monitored during the tests. The average speed and standard deviation for each treatment were calculated and summarized in Table 4-1.

Table 4-1: Average speed and standard deviation (STDEV) of each treatment

Treatment	Average Speed (km/h)	STDEV (km/h)
D1S1	9.64	0.09
D2S1	9.64	0.07
D3S1	9.58	0.06
D1S2	19.60	0.20
D2S2	18.96	0.67
D3S2	18.28	0.48

The data indicate that the actual speeds were very close to the target speeds of 10 and 20 km/h. The standard deviation was low, indicating low speed variation. The deviations from the targeted speeds might have been affected by the following factors: inaccuracy of the tractor instrumentation in comparison to the GPS data and reduced air pressure in the tires which have caused a decrease in the radius of the tractor wheels. Another factor could be that the operator of the tractor was trying not to exceed the desired speed and kept the tractor at constant speed.

In the setup of the target speed of 20 km/h (S2) with tillage depths of 75 mm (D2) and 125 mm (D3), the actual speed exhibited some increased variability in comparison to other treatments. This lack of speed stability might have been caused by the bouncing of the tractor either due to the rough field conditions or due to slippage of the wheels caused by the increased draft forces. Another possible explanation is that some of the discs encountered an obstruction, leading to the implement dragging soil rather than tilling it effectively. As the speed increased, the obstruction may have been cleared due to the centrifugal force generated by the rotating discs. A result of such occasion could be seen in Figure 4.1. However, the actual speeds were only slightly lower than the target speeds, which are normal in such field applications.



Figure 4.1: Disc harrow dragging soil instead of effectively tilling it

4.1.2 Initial Field Conditions

At the time of field experiment, the average soil moisture content was 25.4% dry basis (DB) with standard deviation of 2.2%. This indicates that the moisture content was reasonably uniform across the measured field with only minor variation. Such uniformity is very advantageous for measuring draft forces as it minimizes the effects of major changes in soil conditions due to moisture differences. The average bulk density was 1241.1 kg/m^3 with standard deviation of 61.5 kg/m^3 , implying moderate variability.

4.1.3 Draft Force

The draft force data was averaged over the stable section of a test run and shown in Table 8-1 of APPENDIX A. During the data processing it was noticed that the draft force for the test at 20 km/h and 75 mm depth showed abnormal results. The graphs for the test in replications A and C show no variation in draft force with changes in speed. Thus, it can be concluded that the soil was not properly tilled during these tests but instead was merely dragged. This likely resulted in distorted draft force measurements. As a result, these data points were identified as abnormal data and excluded from further analysis.

To compare the means of multiple groups of draft force, a Duncan's multiple range test was performed on the data, and the results are presented in Table 4-2. The effect of tillage depth and speed on draft force was highly significant, as P value is smaller than 0.05. This means that changes

in tillage depth or speed caused statistically significant differences in the draft force required. Also, the interaction between speed and depth is statistically significant, indicating that the effect of speed on draft force depends on the tillage depth, and vice versa. In other words, the influence of one factor is not independent of the other.

Table 4-2: Individual and interaction effect of tillage speed and depth on draft force (two-way ANOVA)

Source of Variation	DF	F value	P-value
Speed	1	577.987	3.68283E-12
Depth	2	1583.950	2.97894E-16
Speed x Depth	2	6.684	0.01007935

Since there was a significant interaction between tillage depth and speed, their combined effects are presented (Figure 4.2). Draft force increased significantly with both tillage depth and operating speed. At each speed level, draft force rose sharply as depth increased from D1 to D3, reflecting greater soil resistance at larger engagement volumes (Sahu and Rahman 2006b; Serrano et al. 2003). Similarly, increasing speed from S1 to S2 led to higher draft forces at all depths, likely due to increased inertial effects and soil acceleration. The interaction between speed and depth was also significant ($p = 0.0101$), indicating that the effect of speed on draft force became more pronounced at greater tillage depths. Overall, the highest draft force (approximately 31 kN) occurred at the combination of S2D3, while the lowest (approximately 7 kN) was observed at S1D1.

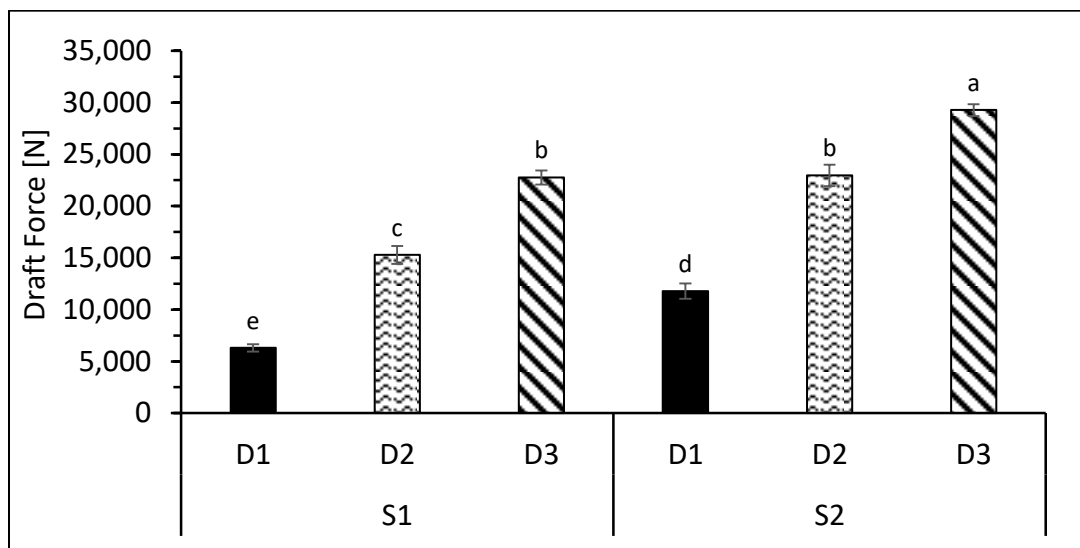


Figure 4.2: Draft forces as affected by tillage depth (D) and tillage speed (S). D1 = 25 mm, D2 = 75 mm, D3 = 125 mm, S1 = 10 km/h, D2 = 20 km/h

4.1.4 Soil Surface Roughness

The measurement results of the soil surface roughness were summarised into a Table 10-1 in APPENDIX C. A Duncan's multiple range test was performed on the data, and the results are presented in Table 4-3. The analysis showed that while there is no significant dependency of the soil surface roughness parameter on the depth of the tillage, there is a significant dependency on the speed at which the tillage is performed ($P=0.001$). This effect did not depend on the tillage depth as the effect of its interaction with tillage depth was not significant.

Table 4-3: Main and interaction effect of tillage speed and depth on soil surface roughness (two-way ANOVA)

Source of Variation	DF	F value	P-value
Speed	1	14.63411	0.00123
Depth	2	0.79989	0.46471
Speed x Depth	2	1.12067	0.34777

The original soil surface roughness before tillage was 6% with standard deviation 2, that was at the same statistical level as those tilled plots (Figure 4.3a). This suggests that within the tested range, increasing the working depth did not substantially alter the roughness of the soil surface. In contrast, tillage speed had a noticeable influence on surface roughness (Herodowicz-Mleczak et al. 2022; Martinez-Agirre et al. 2016). The highest roughness value (approximately 9%) was observed at speed S1 (Figure 4.3b), which was significantly greater than that at S2 (approximately 6%). These results imply that moderate speed (S1) generated more soil disturbance and clod formation on the surface, whereas higher speed (S2) tended to smooth the surface, possibly due to increased soil fragmentation and redistribution. Overall, while depth did not have a measurable effect, tillage speed showed a significant impact on soil surface roughness, suggesting that operating speed plays a more critical role than depth in determining post-tillage surface condition.

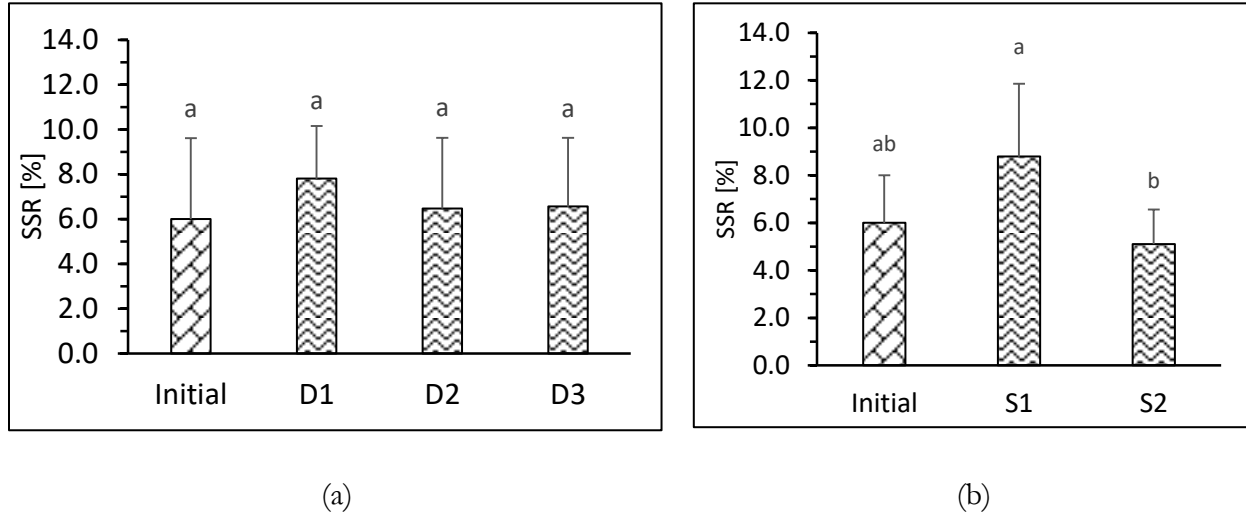


Figure 4.3: Soil surface roughness (SSR). (a) Tillage depth, D1 = 25 mm, D2 = 75 mm, D3 = 125 mm, (b) Tillage speed, S1 = 10 km/h, D2 = 20 km/h

4.1.5 Residue Incorporation

During the image analysis of residue coverage, limitations of the selected image analysis approach were discovered. Due to the sunny conditions, on most of the pictures the exposed soil (Figure 4.4a) was recognised by the software as being the same color as the residue or the shadowed pieces of residue were not recognized as it is seen on Figure 4.4b and thus significantly affected the results of the test.



Figure 4.4: Residue pictures. (a) Cropped natural light image, (b) Black and white image, missing significant areas with not incorporated residue

Residue incorporation (RI) percentage data was organised in Table 11-1 in APPENDIX D and a Duncan's multiple range test was performed on the data, and the results are presented in Table 4-4. The results of the two-way ANOVA show that neither tillage speed nor tillage depth had a statistically significant effect on the roughness index (RI). The F-values for speed ($F = 1.31$, $p = 0.27$) and depth ($F = 0.18$, $p = 0.83$) were both low, indicating minimal variation in RI among the treatment levels. Similarly, the interaction between speed and depth was not significant ($F = 0.17$, $p = 0.84$), suggesting that the combined influence of these two factors did not produce any measurable effect on soil surface roughness. These findings imply that within the tested range of operating speeds and tillage depths, the roughness index remained relatively stable and was not sensitive to changes in tillage operational parameters. The lack of significant effects may be attributed to the soil's inherent structural stability, moisture condition, or the limited variation among treatment levels. Overall, the results indicate that both tillage speed and depth had negligible influence on RI, suggesting that residue incorporation were largely uniform under the experimental conditions which is in contradiction with Hanna et al. (1995) and Klingberg and Weisenbeck (2011).

Table 4-4: Individual and Interaction effect of tillage speed and depth on residue incorporation (two-way ANOVA)

Source of Variation	DF	F value	P-value
Speed	1	1.30836	0.270619
Depth	2	0.18284	0.834734
Speed x Depth	2	0.17061	0.844761

The individual effect graph was constructed based on the results of the Duncan's Multiple Range Test. The results indicate that there were no significant differences in RI among the various tillage depths (D1-D3) Figure 4.5a or speeds (S1-S2) Figure 4.5b. The mean RI values remained relatively consistent, ranging from approximately 82% to 87% across all treatments. This suggests that within the tested operational range, neither tillage depth (25, 75, and 125 mm) nor operating speed (10 and 20 km/h) had a measurable effect on the residue incorporation. The minimal variation observed may be attributed to uniform surface residue incorporation, consistent implement design, and similar soil disturbance patterns at different speeds and depths. Overall, the results indicate that the residue incorporation remained the same statistically, regardless of tillage intensity, implying that the residue incorporation were largely unaffected by the tested operating conditions.

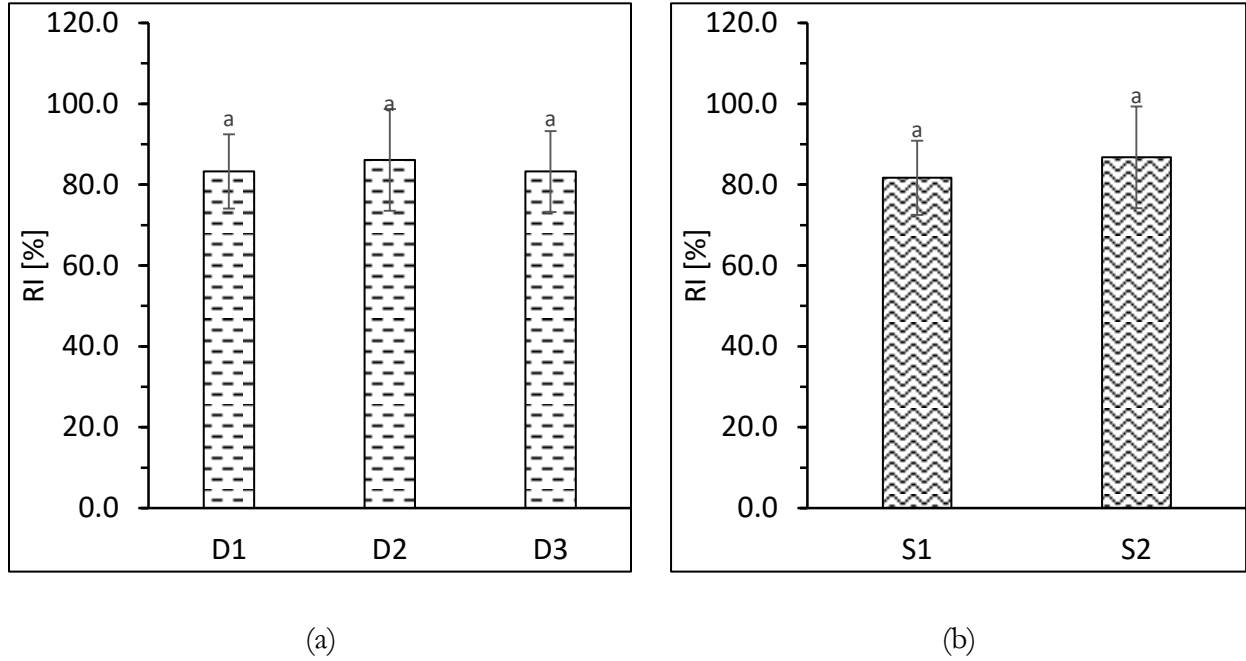


Figure 4.5: Residue incorporation (RI). (a) Tillage depth, D1 = 25 mm, D2 = 75 mm, D3 = 125 mm, (b) Tillage speed, S1 = 10 km/h, S2 = 20 km/h

4.1.6 Cone Index

The results of the initial 20 measurements of the cone index before tillage were plotted in Figure 4.6. As expected, the compaction of the soil increases in the soil depth profile. There was a rapid increase up to the depth of 150 mm and then it gradually increased with data points being more scattered. This represents a typical cone index profile where lower cone index is observed in the tilled soil layer. Roughly, the data fit a polynomial trend with a coefficient of determination (R^2) of 0.62.

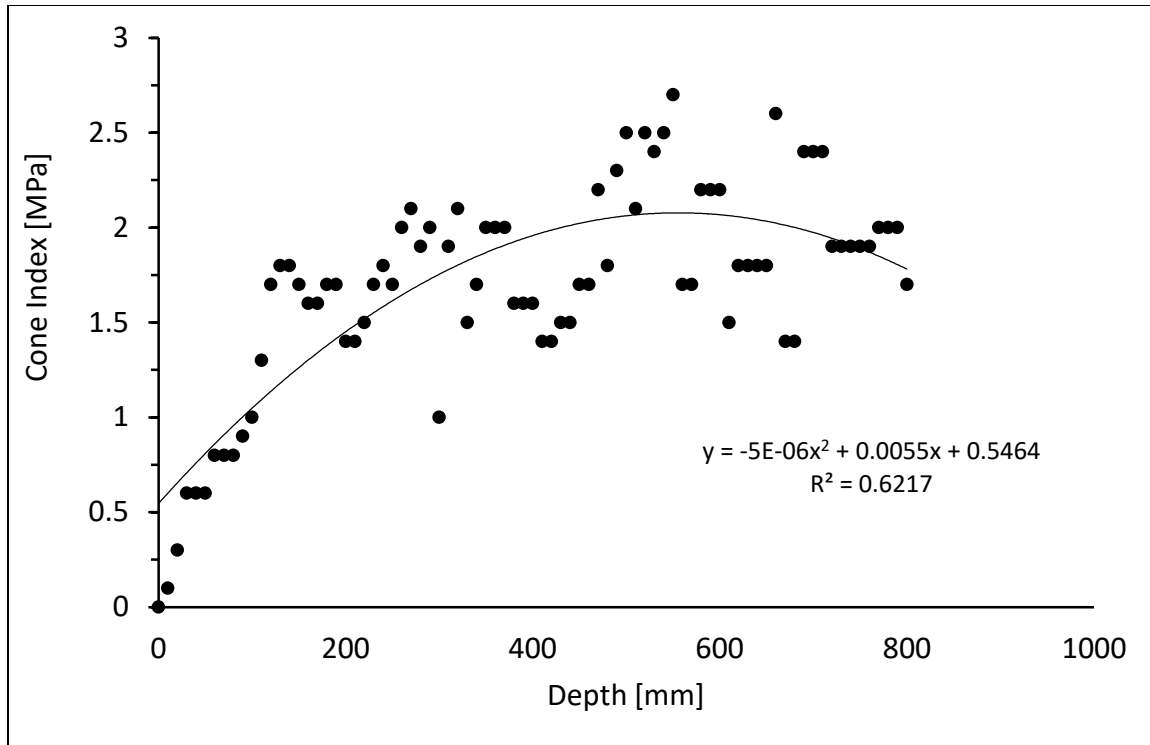


Figure 4.6: Average of cone indices of initial soil profile before tillage

The cone index data collection is performed in a very manual method and could be affected by the speed it is being pushed into the soil or the angle of the measuring apparatus to the reflective plate. Based on Figure 14.1 in APPENDIX G the following data points were excluded from the calculations since they showed abnormal results: replication A treatment S1D1, replication B treatment S1D3 and S2D2 and replication C treatment S1D2 and S2D3. ANOVA analysis results are presented in Table 4-5. There is a significant dependency of the results on the tillage depth and the combination of the tillage depth and speed, however there is no significant dependency on the tillage speed. The interaction effect graph was constructed based on the results of the Duncan's Multiple Range Test Figure 4.7.

Table 4-5: Main and interaction effects of tillage speed and depth on cone index (two-way ANOVA)

Source of Variation	DF	F value	Pr (>F)
Speed	1	0.4633	0.508038
Depth	2	11.3740	0.001395
Speed x Depth	4	26.37301	3.631e-6

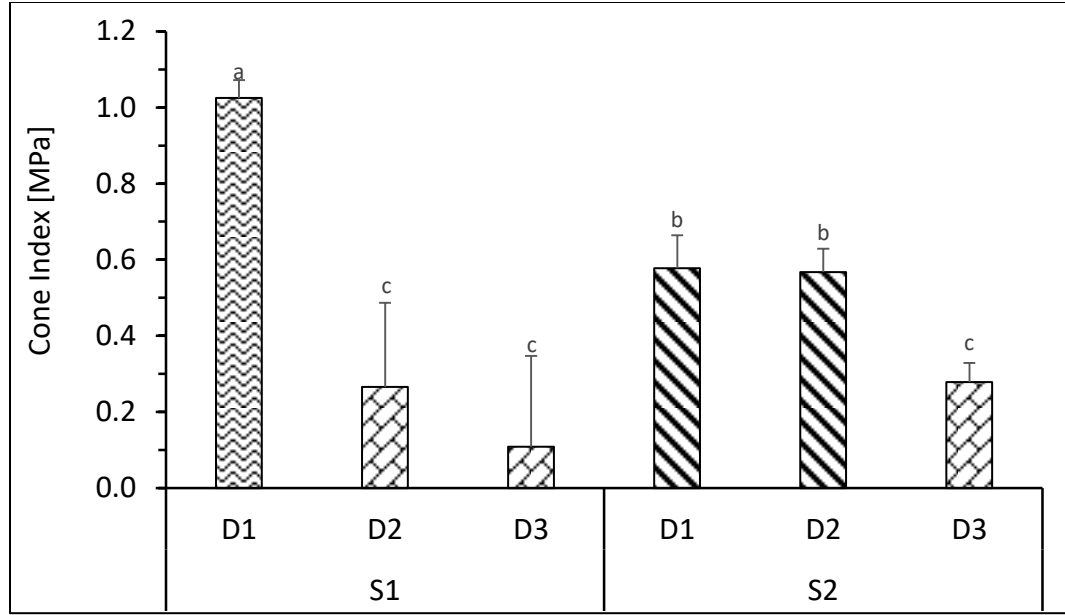


Figure 4.7: Average soil cone index (CI) for the 0–130 mm depth range under different tillage treatments. Tillage depth: D1 = 25 mm, D2 = 75 mm, D3 = 125 mm; Tillage speed: S1 = 10 km/h, S2 = 20 km/h

The lowest cone index was recorded at S1D3 and was statistically similar to the treatments S1D2 and S2D3. This indicates that operating at higher depths under both lower and higher speed conditions generally resulted in reduced soil strength, suggesting more effective soil loosening. The subsequent group of cone index values was observed at S2D1 and S2D2, which did not differ significantly from each other, implying comparable levels of soil compaction within these treatments. The highest cone index was measured at S1D1, representing the condition with the least soil disturbance and, consequently, the lowest impact of the tillage operation on soil loosening. Those observations are concurrent with Chen et al. (2005).

4.2 Equation for Draft Force Prediction

4.2.1 Prediction Equation

A multiple regression analysis was conducted to quantify the effects of tillage depth and tillage speed on draft force. The term of depth and speed interaction is included in the equation, as the interaction effect was statistically significant as shown in Table 4-2. The fitted regression model with R^2 value 0.9837 was:

$$F = 377.5755S + 119.7288D + 3.1032(DS) \quad (4.1)$$

where F is the draft force of the High-Speed Disc implement [N], D is tillage depth [mm], and S is tillage speed [km/h].

The draft force predicted by equation (4.1) includes the draft forces from soil engaging tools (discs and rollers) and the rolling resistance of wheels of the implement. There are some conditions for using the regression model. These conditions are when implement is not moving, i.e. $S=0$, the F is zero. When $D=0$, S must be zero.

The model represents the draft force arising from soil engagement as a function of tillage depth and operating speed. Both tillage depth and tillage speed had positive coefficients, suggesting that increasing either parameter leads to higher draft force which is similar to the conclusions made by similar studies (Godwin and O'Dogherty 2007; Sadek et al. 2021). The interaction term was also positive, indicating that the combined effect of greater tillage depth and higher tillage speed further amplifies draft force.

Diagnostic checks included the plot of predicted versus observed values (Figure 4.8) that compares measured draft forces with those estimated by the regression model. Each blue point represents an experimental observation, while the blue dashed line indicates the 1:1 reference line (perfect agreement between predicted and observed values). The points lie close to the reference line, demonstrating that the regression model provides a strong approximation of draft force across the tested ranges of tillage depth and speed. There are some minor deviations. At lower draft force values (6,000-7,000 N), predictions slightly overestimate the observed data. At intermediate values (22,000-23,000 N), the model slightly underestimates the draft force. At the highest draft force values (29,000-30,000 N), predictions are slightly above the 1:1 line. Despite these minor discrepancies, the overall trend shows strong alignment, with an R^2 value of 0.9837. This confirms that the model captures the combined influence of tillage depth and tillage speed effectively.

The residual plot (Figure 4.9) shows the distribution of residuals (differences between observed and predicted draft forces) against predicted values. Ideally, residuals should be randomly scattered around the horizontal zero line without forming a distinct trend or systematic pattern. In this case, the residuals appear relatively evenly distributed above and below the zero line, suggesting no strong systematic bias in the model. Most residuals fall within ± 500 N, which is small relative to the overall draft force range (6,000-30,000 N). One slightly larger residual (+1600 N) is observed,

but it does not indicate a consistent pattern. The residuals do not display curvature or increasing spread with larger predicted values, implying that both linearity and homoscedasticity assumptions are reasonably satisfied. Overall, the residual analysis confirms that the regression model adequately represents the relationship between tillage depth, tillage speed, and draft force. The absence of systematic bias supports the reliability of the model predictions across the tested range of conditions.

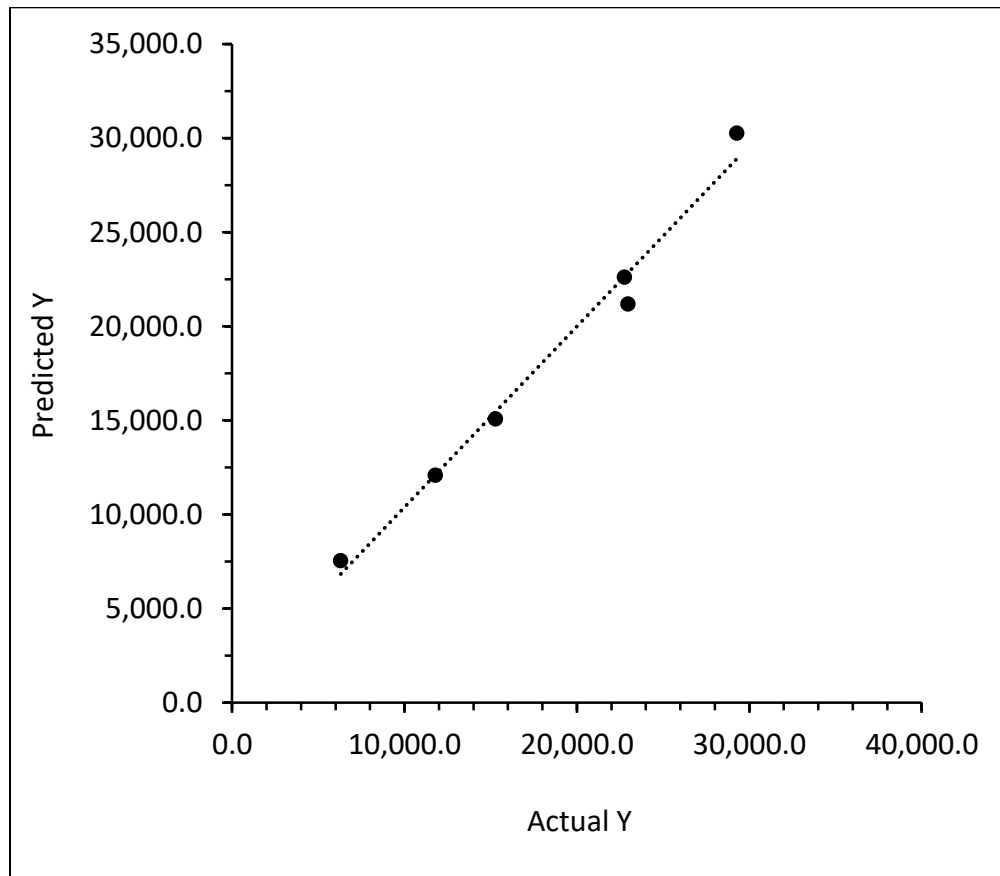


Figure 4.8: The 1:1 line for predicted vs actual draft force values

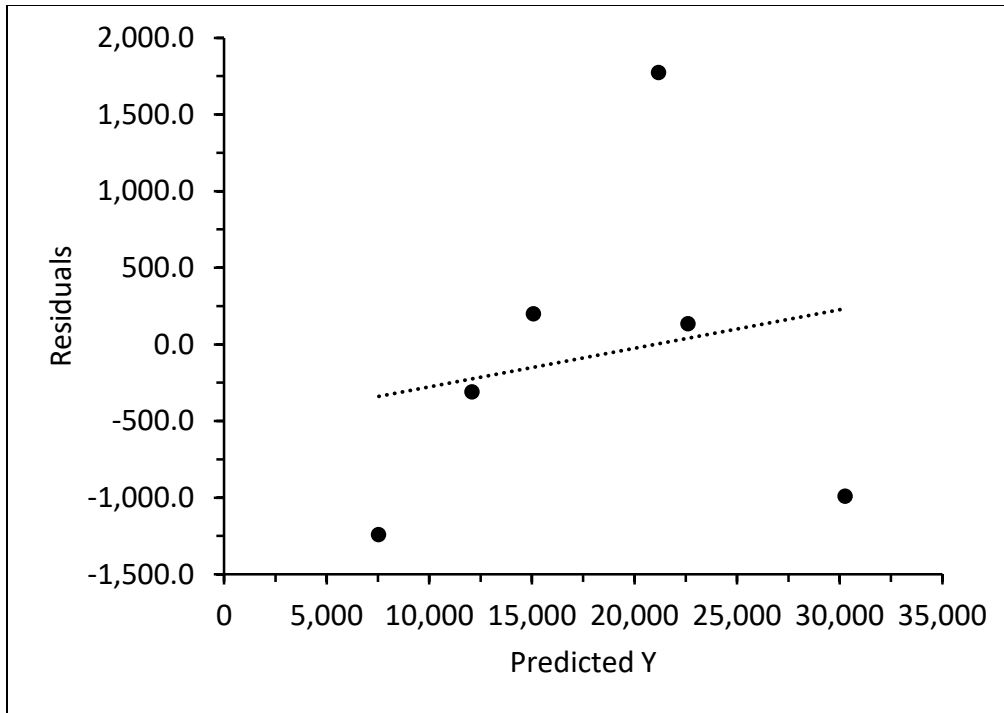


Figure 4.9: Residual plot of predicted draft forces

4.2.2 Comparisons in draft force between the regression equation and ASABE equation

To evaluate the accuracy of the prediction equation, the predicted draft force results were compared with values estimated using the ASABE equation (Equation 2.3). With the soil texture adjustment factor and the values of machine-specific parameters mentioned in the method section, draft forces were calculated for different tillage depths and speeds. Results, together with the results from the prediction equation, are shown in Table 4-2.

The relative mean error was computed to assess the agreement. Overall, the comparison revealed that the level of agreement varied with both tillage depth and tillage speed with no particular trends. The lowest relative error was observed at the S2D3 treatment (-37%), whereas the highest relative error was observed at S2D1 treatment (+10%). These relative errors were within the range of accuracy (50%) of the ASABE equation (ASABE 2011).

As tillage depth increased, the draft force rose substantially at all speeds, reflecting the larger soil volume engaged by the discs and the higher soil-metal frictional resistance. However, the magnitude of increase was greater at higher tillage speeds, demonstrating that the combined effect of

speed and depth was multiplicative rather than additive. At higher speeds, the momentum of soil displacement and the rate of soil acceleration contributed additional dynamic resistance, amplifying the draft requirement beyond what would be expected from depth alone.

Conversely, at shallower depths, the influence of speed was less pronounced, as soil engagement was confined primarily to the surface layer and crop residue. This pattern agrees with previous findings by (Sahu and Raheman 2006) and (Serrano et al. 2003), who observed nonlinear increases in draft with simultaneous rises in speed and depth. The agreement between tillage speed and depth observed in this study emphasizes that both parameters must be considered jointly in predictive modeling. Including their interaction term in regression analysis improved the model's accuracy, aligning predicted values more closely with measured field data and better reflecting the actual operating behavior of high-speed disc implements under variable field conditions.

Table 4-6: Relative mean error comparison of draft forces between the prediction equation and ASABE equation values

Speed [km/h]	Depth [mm]	Draft force from Regression equation [N]	Total draft force calculated from ASABE equation [N]	Relative mean error [%]
10	25	7544.1	8974.9	-19
10	75	15080.6	20324.7	-35
10	125	22617.1	31674.5	-40
20	25	12094.9	10910.9	10
20	75	21181.4	26132.7	-23
20	125	30267.9	41354.5	-37

Furthermore, the combined influence of tillage speed and depth was also reflected in soil disturbance parameters. At higher depths and speeds, soil surface roughness and residue incorporation increased notably, indicating a more aggressive soil engagement and enhanced mixing effect. Similarly, cone index measurements taken after tillage showed a reduction in surface compaction at moderate speeds, but a tendency toward greater subsurface disturbance at higher speeds and depths. These findings demonstrate that the mechanical and agronomic responses of the soil are closely linked through the same operational parameters that govern draft force, reinforcing the need for integrated evaluation of both power demand and soil condition when assessing the performance of high-speed tillage implements.

5 CONCLUSION

In this study, the performance of a high-speed disc implement was evaluated in a field experiment for its draft forces and soil disturbance characteristics. An empirical equation for predicting draft force of the disc implement was developed using the experimental data. The prediction results were compared with those from the ASABE equation for estimating draft force to evaluate the accuracy of the prediction equation. The following conclusion was drawn.

There was consistent and significant increase in draft force as the speed, and the depth of the tillage increases. This is caused by the fact that at higher depth and speeds, the discs engaged larger volume of soil, resulting in greater resistance. The data confirmed that the interaction effect of tillage depth and speed was significant. Tillage depth had no significant effect on the soil surface roughness. However, speed did have a significant impact: the soil roughness at 10 km/h was significantly higher than at 20 km/h. These findings point out that operating speed plays a more critical role than depth in determining surface roughness under high-speed tillage, which has practical implications for seedbed preparation and erosion control strategies. Interestingly, no significant difference in soil surface roughness was found between tilled and untilled plots, suggesting that the surface structure after tillage remained within a similar range of variability as the native field condition, or that measurement sensitivity was limited under field variability. No treatment differences were observed in regard to the effect of the tillage depth or speed on the amount of the material incorporated by the tillage operation. However, the results of the material incorporation were significantly affected by the measuring method and should not be considered as reliable. The speed of the tillage has no significant effect on the soil cone index, while the depth of the tillage and the interaction of speed and depth have a significant effect. The deeper the tillage the lower the cone index. This confirms that the high-speed disc implement could reduce soil compactions within its working depth. The soil cone index results provided consistent support for the draft force trends observed, reinforcing that increased draft requirements at greater depths were indeed associated with higher soil cone indices. When compared with the ASABE equation, the prediction equation achieved good agreement, with relative mean errors ranging from -40% to +10.%. However, the relative mean error range of the ASABE standard equation could be as high as 50%. This highlights the need for further verification of the prediction equation.

The findings of this study confirmed that tillage speed or/and depth significantly impact draft force, soil disturbance, and residue incorporation. The proposed model for draft predictions

not only enhances predictive accuracy for power requirements of implement but also provides a useful framework for evaluating tillage performance in high-speed applications. Additionally, the detailed analysis of soil disturbance metrics such as soil surface roughness, soil cone index, and residue incorporation contributes to a broader understanding of the agronomic impacts of high-speed disc tillage. This research provides empirical evidence for better equipment selection, improved power matching between implement and tractor, and the development of more efficient draft prediction models.

This study had several limitations. The field experiments were conducted for a given soil type in one year. The experiment tested only three tillage depths and two operating speeds, which were representative of typical field operation but did not capture the full operational range of high-speed disk implements. The draft force prediction equation was validated by the ASABE equation that was developed for approximation only. The findings from this study must be interpreted within the context of the outlined limitations. Addressing these constraints in future research, through multi-location and multi-year trials, expanded implement operating ranges, and the inclusion of a larger data set for empirical model development, is needed.

6 RECOMENDATION FOR FUTURE RESEARCH

Building upon the findings and limitations of this research, several opportunities exist to expand and deepen the understanding of draft force dynamics and soil interaction characteristics for high-speed tillage implements. The following recommendations are proposed to guide future investigations:

Future studies should include a broader range of tillage depths and operating speeds to capture non-linearities in draft force behavior, especially under extreme conditions. Intermediate values (e.g., 12 km/h or 14 cm depth) would allow for the development of more detailed response surfaces and potentially reveal critical thresholds or inflection points in soil-tool interaction. To improve the generalizability of draft force prediction models, future research should incorporate multi-location trials across various soil textures (e.g., clay, sandy loam, silty clay), compaction levels, and moisture conditions. This would allow for the development of soil-type-specific draft force models or machine learning tools trained on a broader dataset. Future research should aim to build more robust and universally applicable models for draft force prediction. Expanding experimental scope and leveraging modern modeling tools will play a vital role in advancing the design and management of high-efficiency tillage systems.

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8 APPENDIX A

Table 8-1: Average draft force measurements, raw data

Plot #	Configuration #	Replication	Speed [km/h]	Depth [mm]	Draft Force [N]
1	3	A	10	75	16534.19
2	6	A	20	125	29130.96
3	1	A	10	25	6548.28
4	5	A	20	75	
5	3	A	10	125	23404.44
6	4	A	20	25	12415.30
7	1	B	10	25	6305.55
8	3	B	10	125	22102.79
9	4	B	20	25	11737.64
10	5	B	20	75	22226.40
11	6	B	20	125	28713.28
12	3	B	10	75	14695.81
13	5	C	20	75	
14	2	C	10	75	14714.16
15	1	C	10	25	5805.07
16	3	C	10	125	23258.51
17	4	C	20	25	12209.58
18	6	C	20	125	30072.29
19	4	D	20	25	10775.54
20	5	D	20	75	23682.55
21	6	D	20	125	29191.05
22	1	D	10	25	6547.08
23	2	D	10	75	15174.68
24	3	D	10	125	22240.00
C			10	25	5674.90
C			10	75	17024.70
C			10	125	28374.50
C			20	25	7610.90
C			20	75	22832.70
C			20	125	38054.50

9 APPENDIX B

Table 9-1: Moisture content calculations, raw data

Sample Number	Container Weight [gr]	Initial Container + soil Weight [gr]	Final Container + soil Weight [gr]	Wet soil Weight [gr]	Dry Soil Weight [gr]	Moisture Content [%]	Bulk Density [kg/m ³]
1	16.0	163.3	130.6	147.3	114.6	28.53	1215.45
2	15.9	161.2	133.1	145.3	117.2	23.98	1243.03
3	15.7	159.7	127.6	144	111.9	28.69	1186.82
4	15.9	160.8	132.7	144.9	116.8	24.06	1238.79
5	16.1	161.6	132.7	145.5	116.6	24.79	1236.67
6	15.6	159.1	125.8	143.5	110.2	30.22	1168.79
7	15.7	163.3	134.8	147.6	119.1	23.93	1263.18
8	16.0	159.5	128.6	143.5	112.6	27.44	1194.24
9	15.7	165.6	137.1	149.9	121.4	23.48	1287.58
10	16.1	171.5	139.7	155.4	123.6	25.73	1310.91
11	16.2	161.4	133.1	145.2	116.9	24.21	1239.85
12	15.9	163.0	132.3	147.1	116.4	26.37	1234.55
13	15.7	168.0	134.8	152.3	119.1	27.88	1263.18
14	16.2	154.5	125.2	138.3	109	26.88	1156.06
15	15.8	170.7	141.1	154.9	125.3	23.62	1328.94
16	16.6	170.3	141.3	153.7	124.7	23.26	1322.58
17	16.0	170.3	140.4	154.3	124.4	24.04	1319.39
18	16.0	143.4	119.2	127.4	103.2	23.45	1094.55
19	16.0	159.6	131.1	143.6	115.1	24.76	1220.76
20	16.0	166.1	138.3	150.1	122.3	22.73	1297.12

10 APPENDIX C

Table 10-1: Soil surface roughness, raw data

Plot #	Configuration #	Replication	Speed [km/h]	Depth [mm]	SSR [%]
1	3	A	10	75	8.375
2	6	A	20	125	5.775
3	1	A	10	25	12.800
4	5	A	20	75	3.000
5	3	A	10	125	14.150
6	4	A	20	25	3.600
7	1	B	10	25	10.950
8	3	B	10	125	5.275
9	4	B	20	25	3.200
10	5	B	20	75	5.675
11	6	B	20	125	3.900
12	3	B	10	75	7.825
13	5	C	20	75	4.850
14	2	C	10	75	10.475
15	1	C	10	25	11.075
16	3	C	10	125	6.225
17	4	C	20	25	7.800
18	6	C	20	125	5.300
19	4	D	20	25	5.225
20	5	D	20	75	6.400
21	6	D	20	125	6.500
22	1	D	10	25	7.800
23	2	D	10	75	5.150
24	3	D	10	125	5.375
25		i	0	0	5.000
26		i	0	0	5.000
27		i	0	0	9.000
28		i	0	0	5.000

11 APPENDIX D

Table 11-1: Measurements of the residue incorporation, raw data

Plot #	Configuration #	Replication	Speed [km/h]	Depth [mm]	Residue Incorporation [%]
1	3	A	10	75	94.3704
2	6	A	20	125	78.1443
3	1	A	10	25	90.9367
4	5	A	20	75	96.2654
5	3	A	10	125	85.0103
6	4	A	20	25	95.8058
7	1	B	10	25	71.8755
8	3	B	10	125	75.8976
9	4	B	20	25	82.1160
10	5	B	20	75	97.5563
11	6	B	20	125	94.6731
12	3	B	10	75	98.0120
13	5	C	20	75	85.5008
14	2	C	10	75	64.5828
15	1	C	10	25	80.6811
16	3	C	10	125	66.4988
17	4	C	20	25	89.7520
18	6	C	20	125	96.2808
19	4	D	20	25	69.4842
20	5	D	20	75	74.5375
21	6	D	20	125	80.6179
22	1	D	10	25	85.4628
23	2	D	10	75	77.9029
24	3	D	10	125	88.9385

12 APPENDIX E

Table 12-1: Cone index data, raw data (excluding outliers)

Plot #	Configuration #	Replication	Speed [km/h]	Depth [mm]	CI [MPa]
3	1	A	10	25	0.48929
1	2	A	10	75	0.29286
5	3	A	10	125	0.06190
6	4	A	20	25	0.40714
4	5	A	20	75	0.48333
2	6	A	20	125	0.28571
7	1	B	10	25	1.03929
12	2	B	10	75	0.19524
8	3	B	10	125	0.43571
9	4	B	20	25	0.59643
10	5	B	20	75	0.21190
11	6	B	20	125	0.34524
15	1	C	10	25	0.93214
14	2	C	10	75	0.62679
16	3	C	10	125	0.16190
17	4	C	20	25	0.67857
13	5	C	20	75	0.61429
18	6	C	20	125	0.01905
22	1	D	10	25	1.10357
23	2	D	10	75	0.30952
24	3	D	10	125	0.10238
19	4	D	20	25	0.62857
20	5	D	20	75	0.60476
21	6	D	20	125	0.20476
i			0	0	0.80714
i			0	0	1.15000
i			0	0	0.72143
i			0	0	0.65000
i			0	0	0.78571
i			0	0	0.81429

13 APPENDIX F

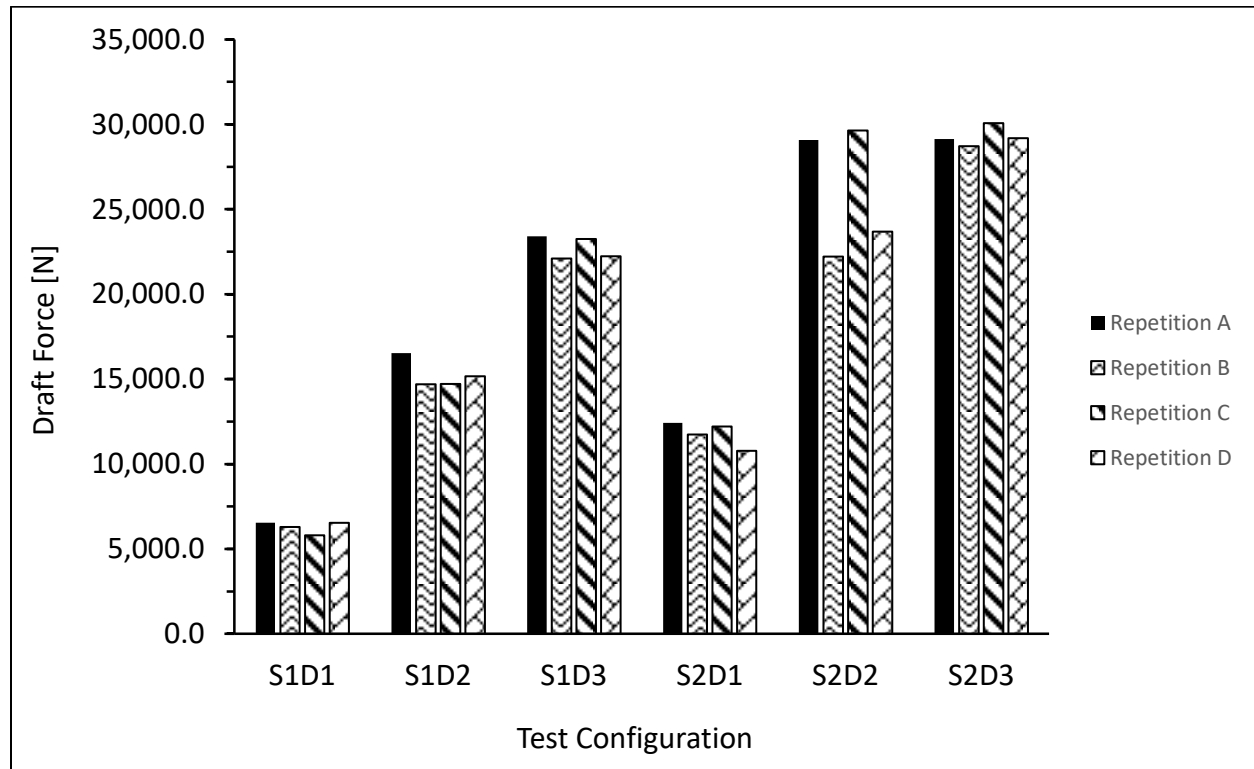


Figure 13.1: Average of raw draft forces per test

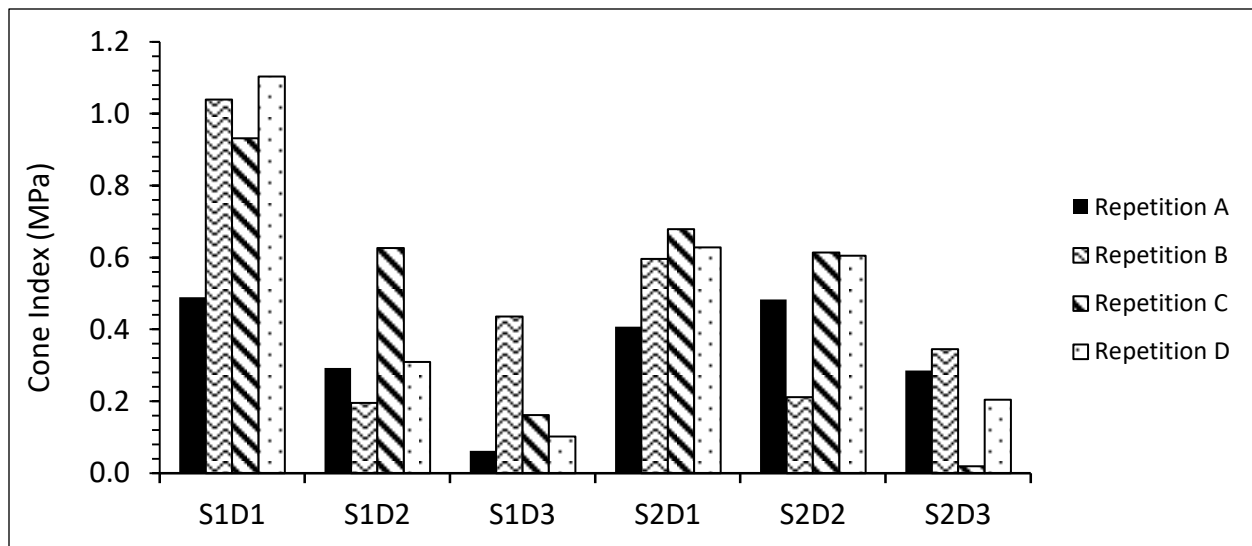


Figure 14.1: Average value of raw cone index data per test

15 APPENDIX H

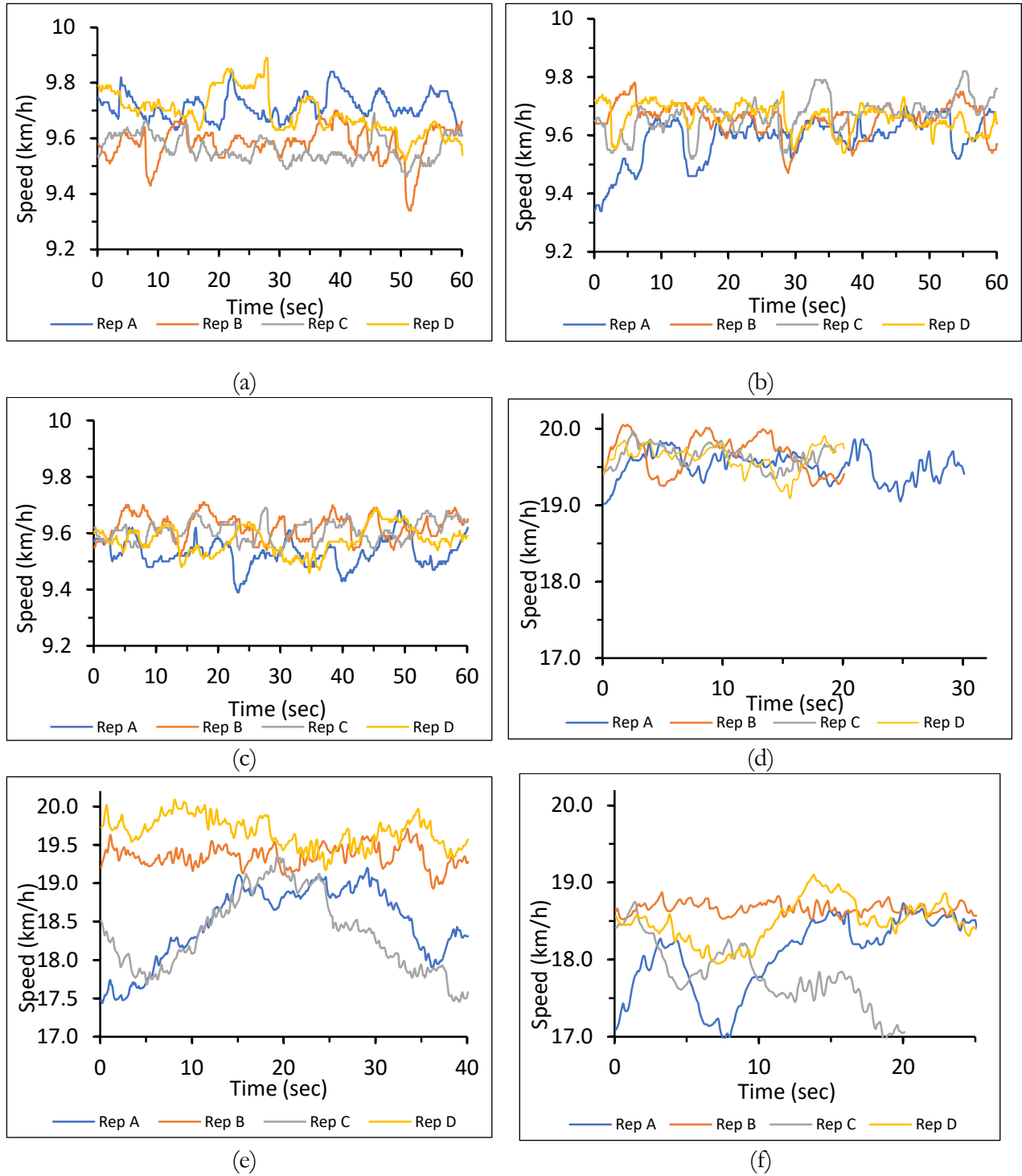
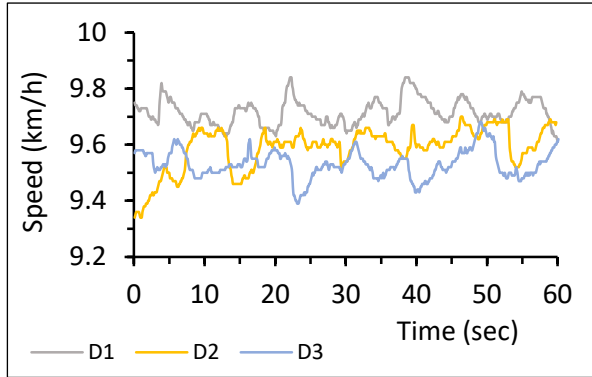
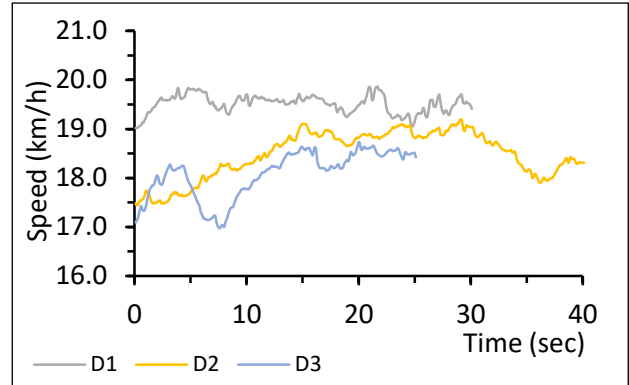


Figure 15.1: Actual tillage speed during the test. (a) D1S1, (b) D2S1, (c) D3S1, (d) D1S2, (e) D2S2, (f) D3S2

16 APPENDIX I

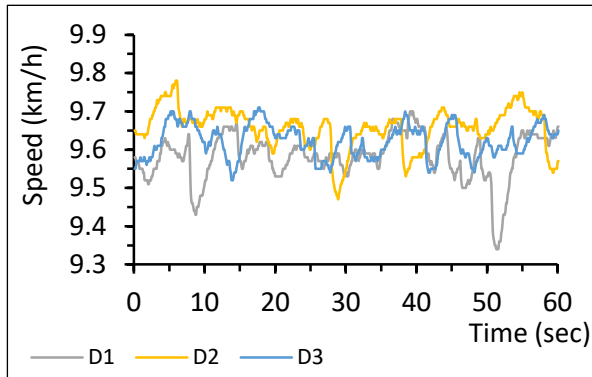


(a)

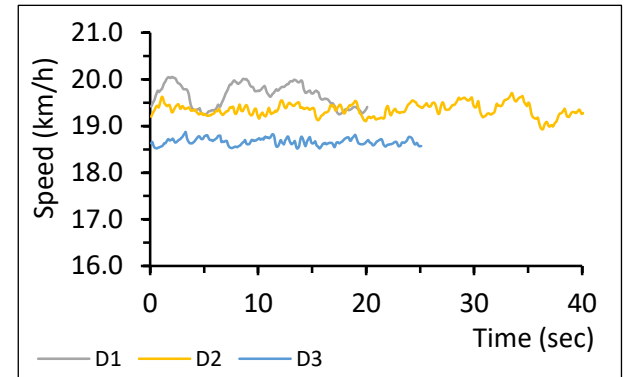


(b)

Figure 16.1: Speed comparison for replicate A. (a) 10 km/h, (b) 20 km/h

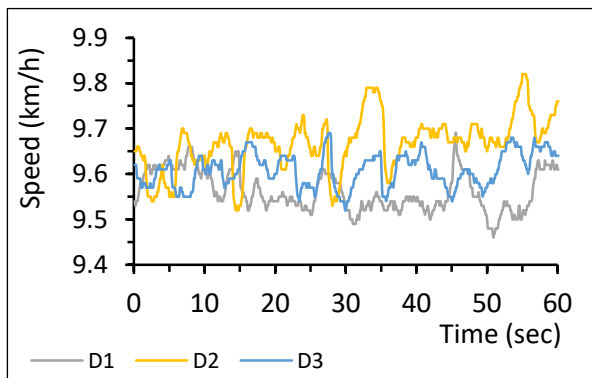


(a)

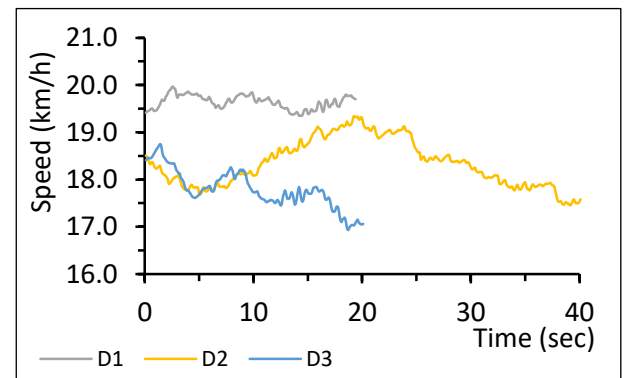


(b)

Figure 16.2: Speed comparison for replicate B. (a) 10 km/h, (b) 20 km/h

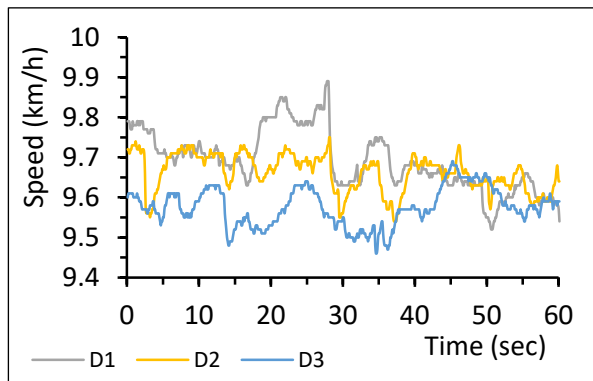


(a)

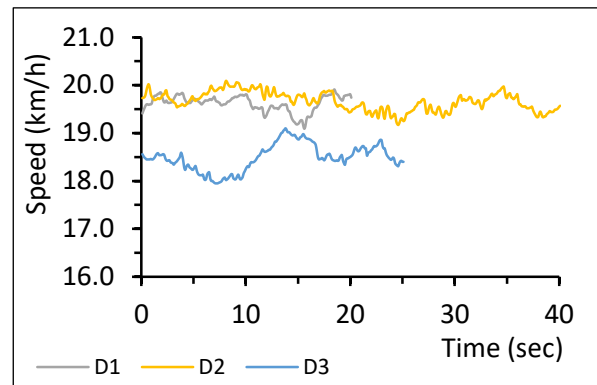


(b)

Figure 16.3: Speed comparison for replicate C. (a) 10 km/h, (b) 20 km/h



(a)



(b)

Figure 16.4: Speed comparison for replicate D. (a) 10 km/h, (b) 20 km/h

17 APPENDIX J

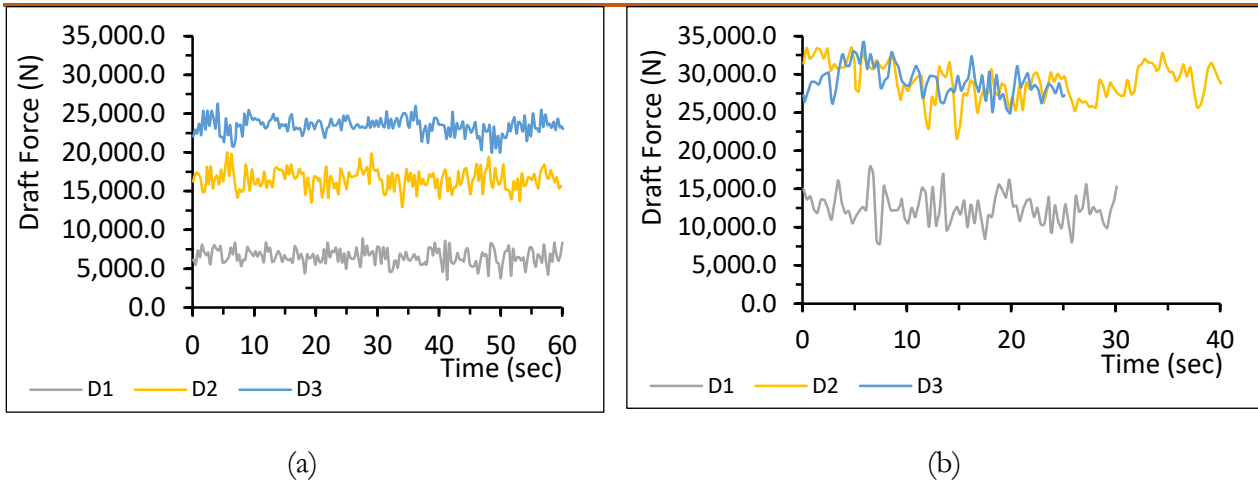


Figure 17.1: Draft force stability per test for replicate A. (a) 10 km/h, (b) 20 km/h

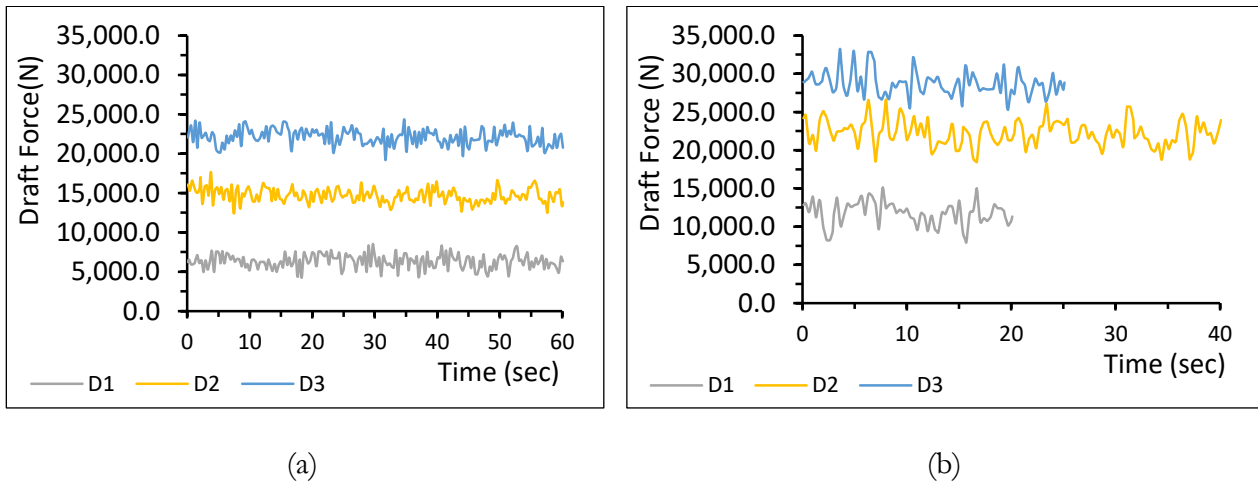


Figure 17.2: Draft force stability per test for replicate B. (a) 10 km/h, (b) 20 km/h

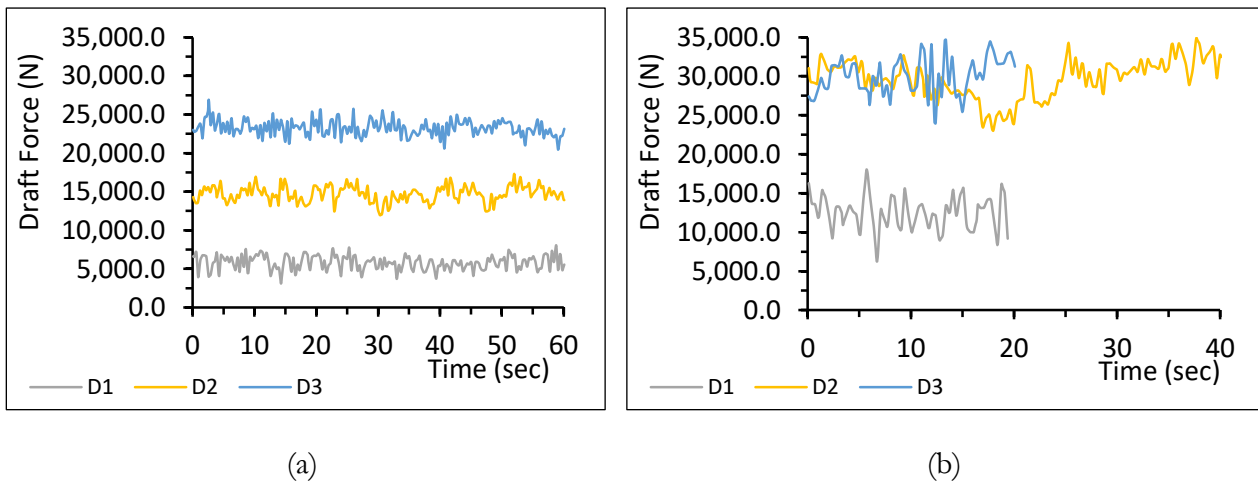


Figure 17.3: Draft force stability per test for replicate C. (a) 10 km/h, (b) 20 km/h

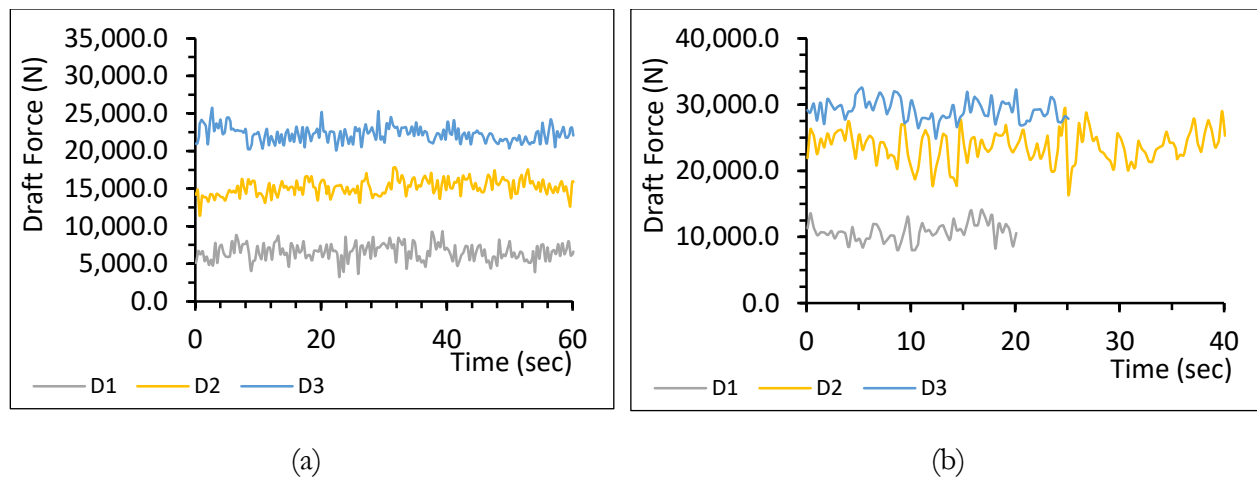
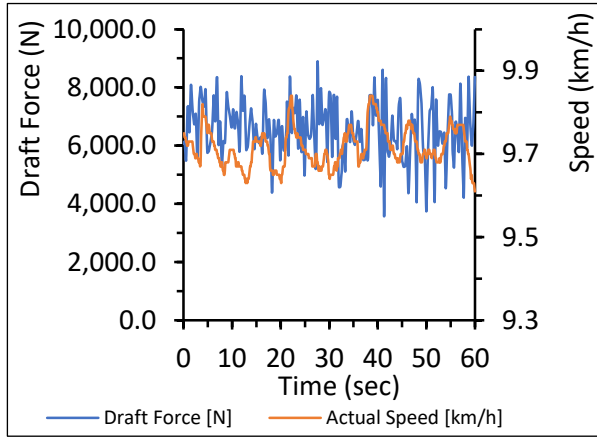
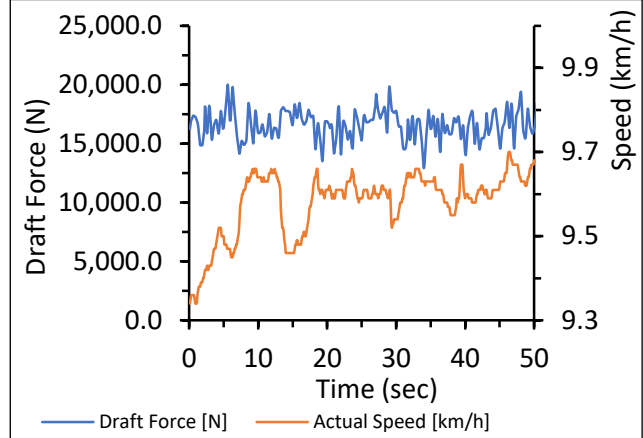


Figure 17.4: Draft force stability per test for replicate D. (a) 10 km/h, (b) 20 km/h

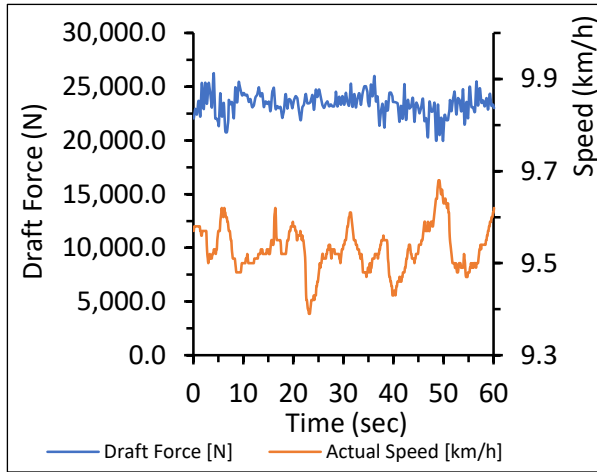
18 APPENDIX K



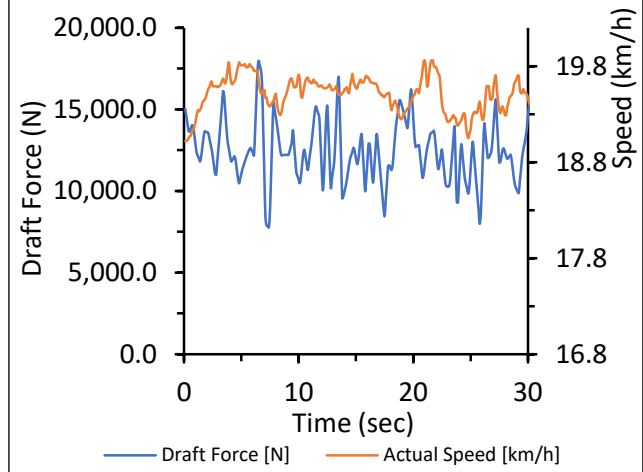
(a)



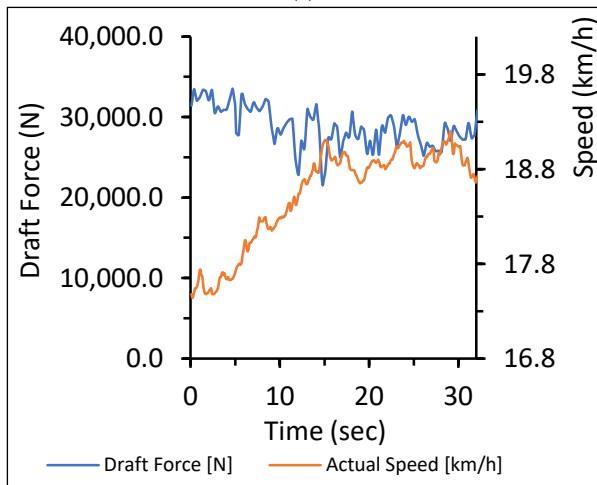
(b)



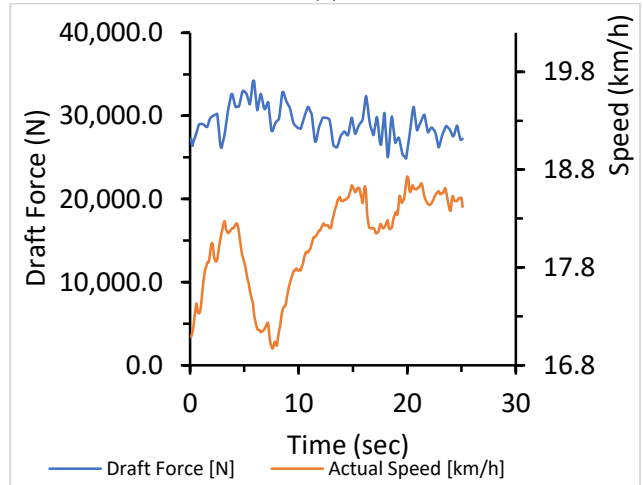
(c)



(d)

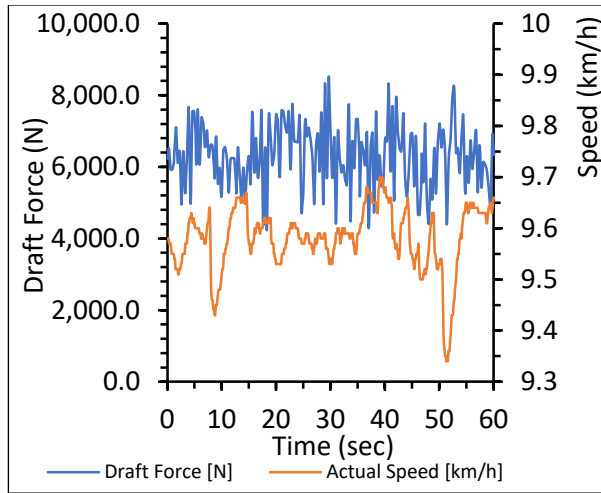


(e)

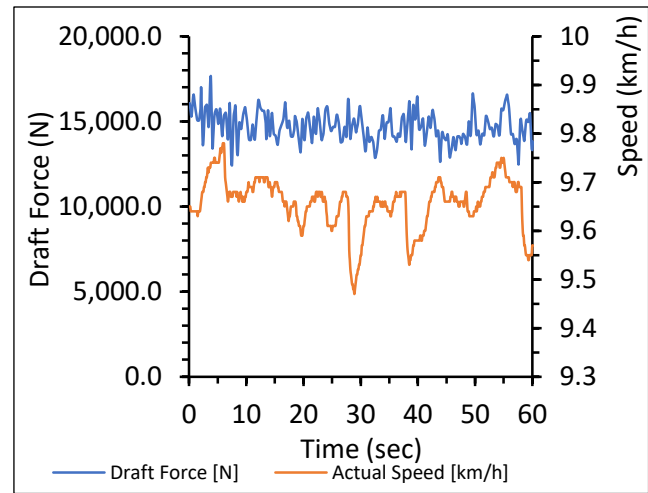


(f)

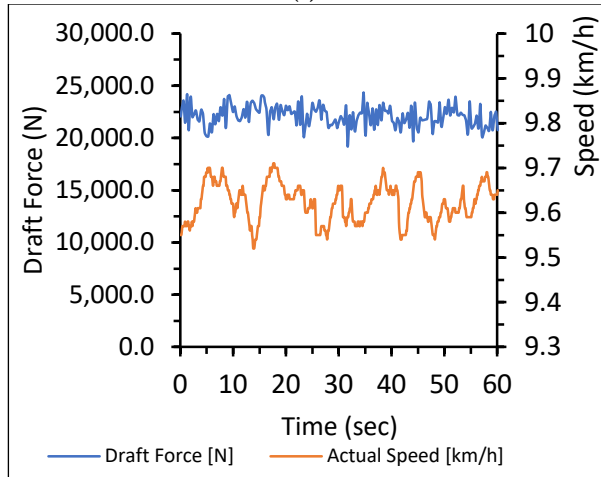
Figure 18.1: Draft force and speed fluctuations during replicate A. (a) S1D1, (b) S1D2, (c) S1D3, (d) S2D1, (e) S2D2, (f) S2D3



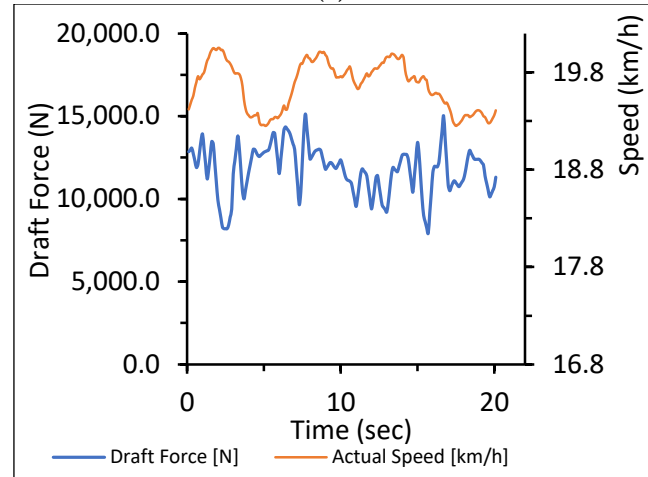
(a)



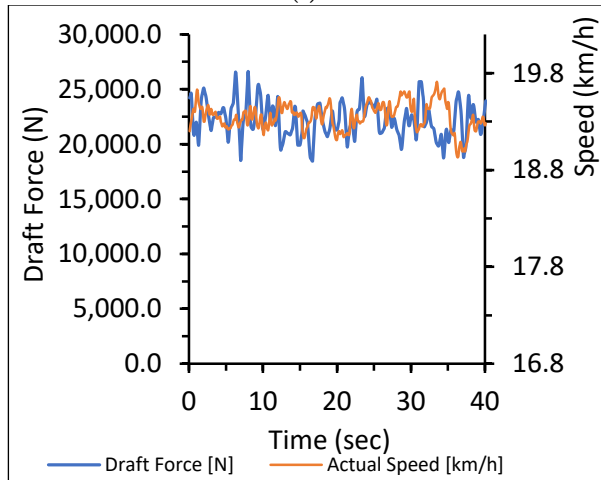
(b)



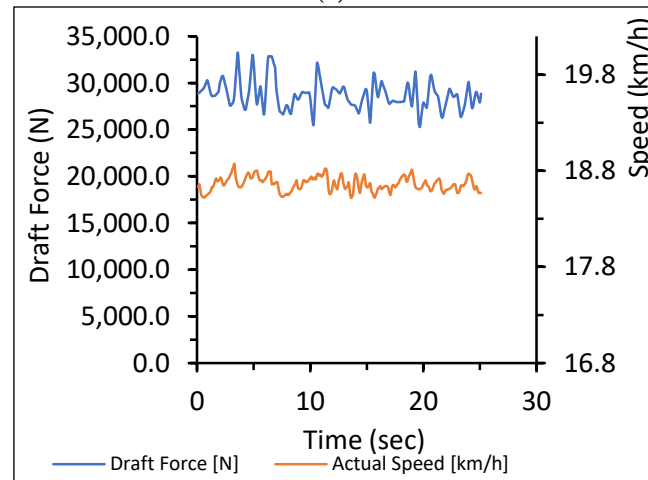
(c)



(d)

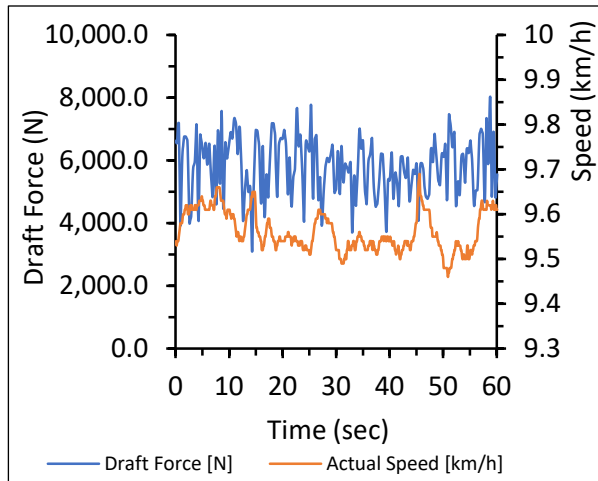


(e)

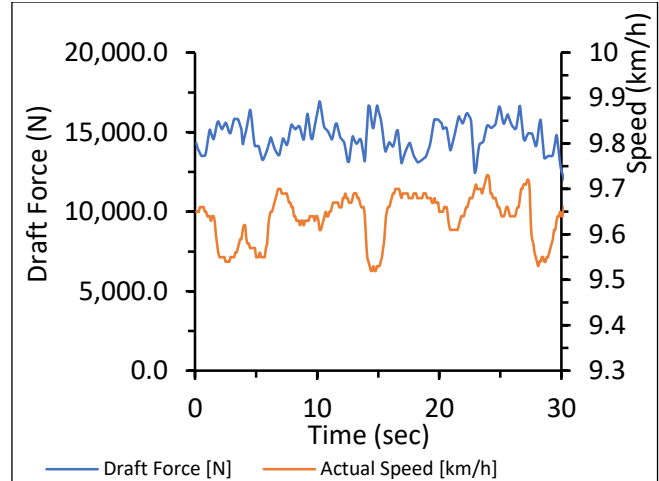


(f)

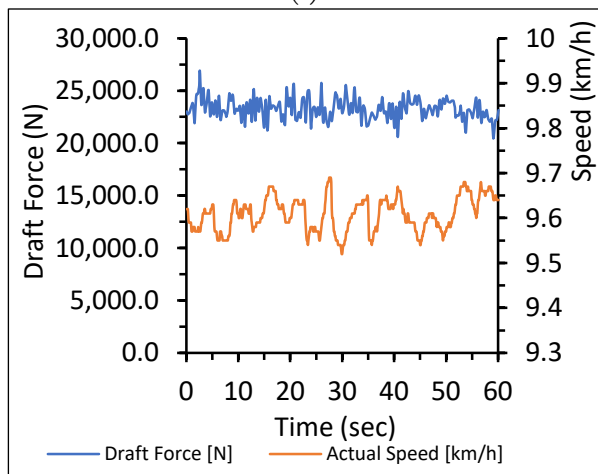
Figure 18.2: Draft force and speed fluctuations during replicate B. (a) S1D1, (b) S1D2, (c) S1D3, (d) S2D1, (e) S2D2, (f) S2D3



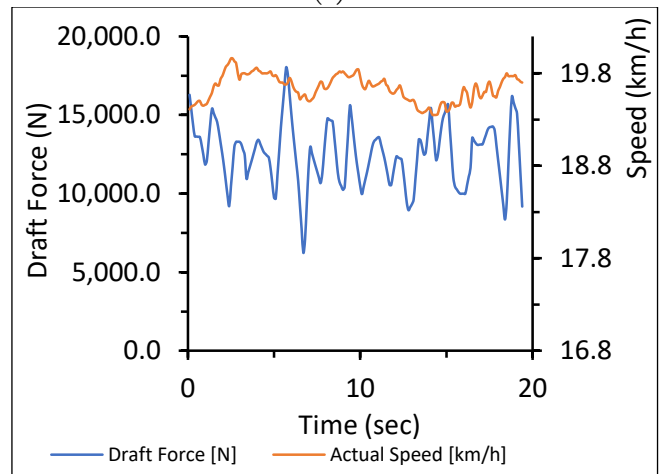
(a)



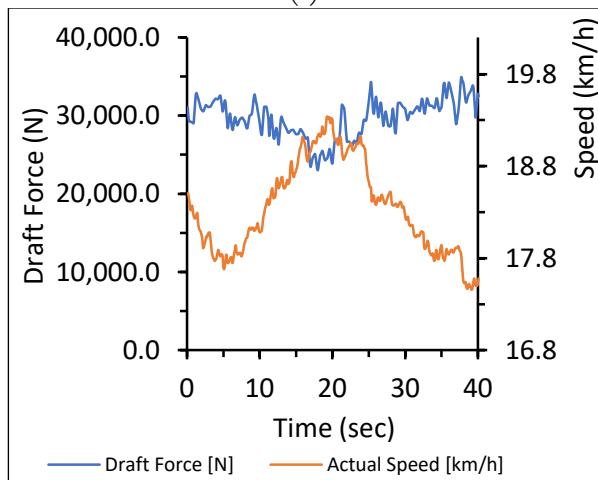
(b)



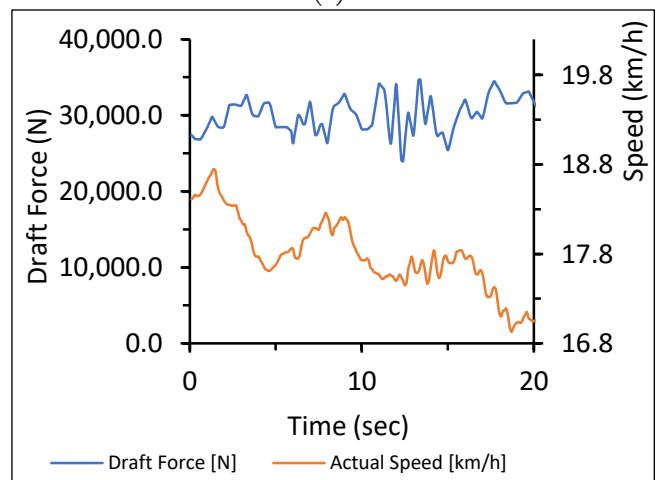
(c)



(d)

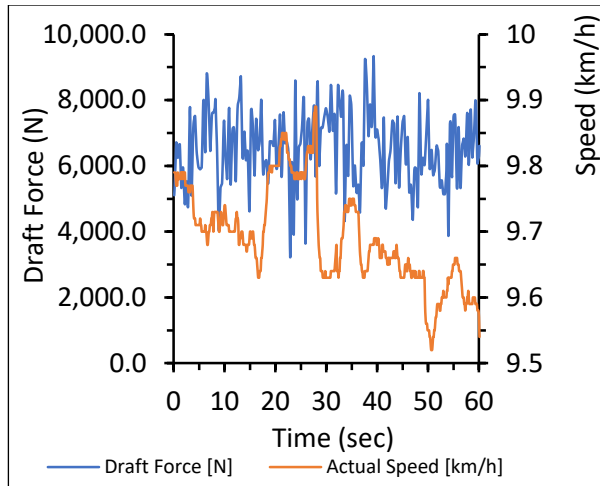


(e)

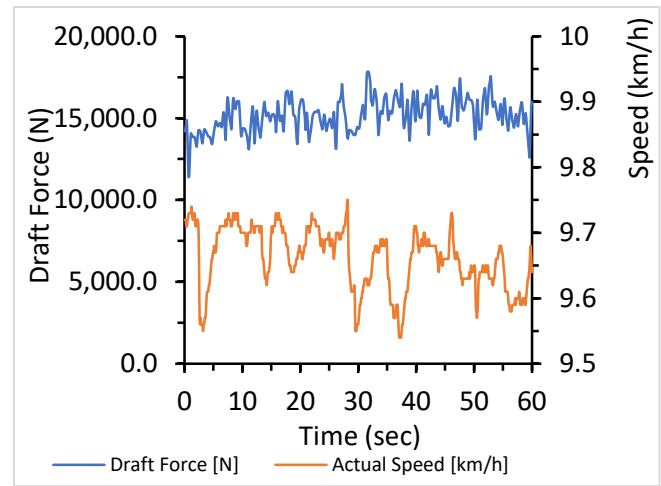


(f)

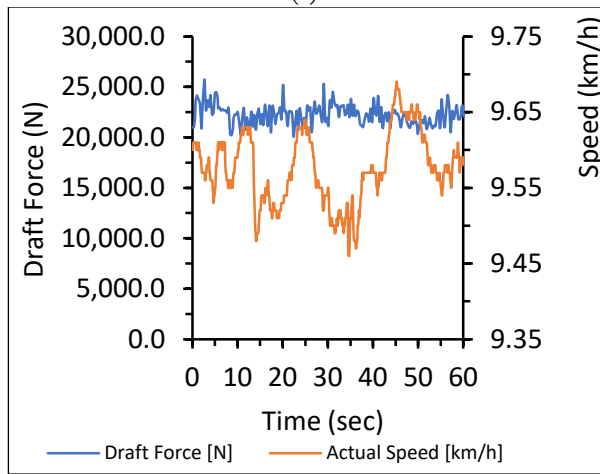
Figure 18.3: Draft force and speed fluctuations during replicate C. (a) S1D1, (b) S1D2, (c) S1D3, (d) S2D1, (e) S2D2, (f) S2D3



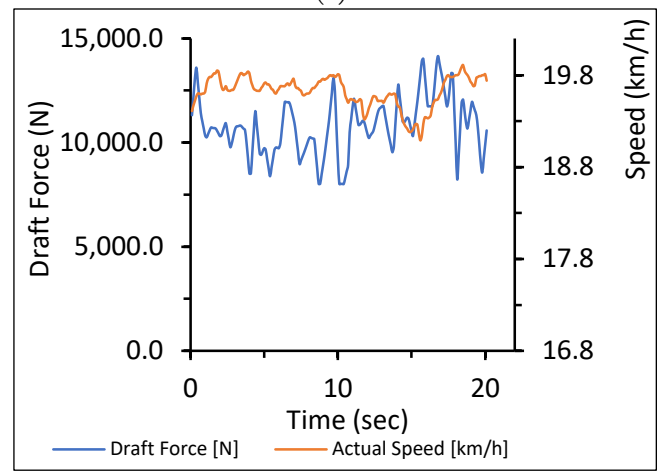
(a)



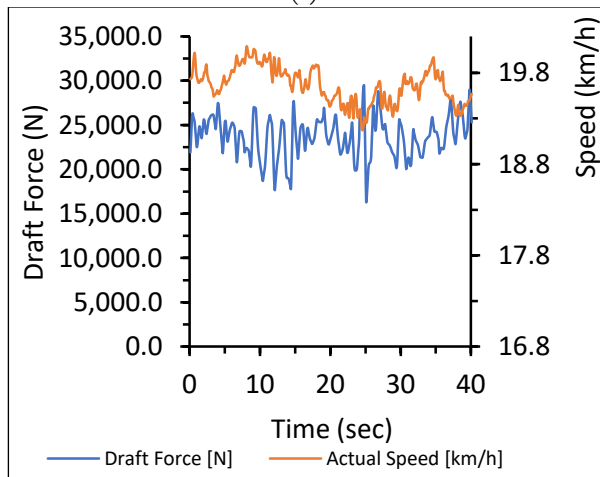
(b)



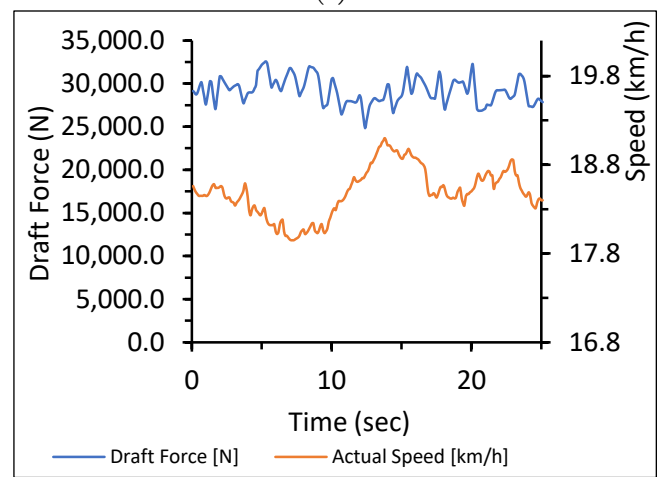
(c)



(d)



(e)



(f)

Figure 18.4: Draft force and speed fluctuations during replicate A. (a) S1D1, (b) S1D2, (c) S1D3, (d) S2D1, (e) S2D2, (f) S2D3