Reliability and Efficiency of Tractive Force Generation by the Interlock Drive System

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Abstract

Tractors and other wheeled vehicles need considerable ballast to gain traction and have low tractive efficiency due to slip and tire flexing. The resulting soil degradation and energy cost are limiting factors which hinder intensification of mechanical field management. The interlock drive system overcomes these limitations through the use of articulated spikes which temporarily interlock with the soil to generate traction. Once inserted into the soil, relatively thin and short spikes provide sufficient motion resistance to pull implements through the soil, without the need for additional ballast.

To better understand the interaction of a spike with the soil, we conducted a number of experiments where we controlled the draft force and measured the resulting motion of the spike as it penetrates the soil and interlocks with it.

Results show that the interlock drive system can generate pull reliably even on wet soil, and that a pull/weight ratio of 2 and higher is possible. The tractive efficiency for a vehicle using the interlock drive system can reach a ratio as high as 0.96 for wet and 0.975 for dry soil, as calculated from the experimental results. Precise soil applications would benefit from a further improvement in the horizontal precision of soil penetration.

Keywords: interlock drive system, tractive efficiency, pull/weight ratio, precision agriculture

1. Introduction

1.1 Motivation

Tires and tracks need ballast to generate pull. When power is supplied to the tire without sufficient ballast, the tire slips, generating no or just little traction. As weight on the tire increases, the soil under the tire is compacted, the soil particles interlock until they can resist the forces of shear and friction, and the vehicle moves forward. Extensive data from the Nebraska Tractor Test Laboratory (NTTL) shows that optimal tractive efficiency is achieved at a pull/weight ratio of about 0.4 (Zoz and Grisso, 2003). Therefore, for every Newton N of draft which acts horizontally on the surface between tire and soil, the ballasted vehicle needs to apply 2.5 N of weight to the same surface. The combined force vector

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measures about 2.7 N for every N of draft and presses diagonally downwards into the soil at the rather steep angle of 68° from horizontal. Even at maximum tractive efficiency there is some slip, which shears the soil under the tire horizontally and increases the damage to the soil structure (Söhne, 1952).

Soil compaction has several undesirable effects. The soil under the tire is compressed into a continuous rut which can be a pathway for water erosion. The compacted soil has lost fertility due to reduced root penetration (Bengough et al., 2011), reduced soil aeration (Whalley et al., 1995), reduced water infiltration and reduced water storage (Ankeny et al.,1990), and due to erosion from excess runoff (Fullen, 1985). Compacted soil requires significantly more energy for weed control, seed bed preparation, incorporation of fertilizers, and breaking up of compacted layers below the top soil. That greatly increases machinery costs and energy consumption and leads to a cycle of bigger machinery to till soil which is compacted to increasing degree and depth (Håkansson and Reeder, 1994). Even though these problems have been studied and published for over 60 years, the available solutions offer only partial respite and never abandon the fundamental principle of locomotion by ballasted surface interaction. Tracks spread the weight over a longer section of the rut, which decreases the volume of compressed soil but shears the soil badly when steered (Hamza et al., 2005). Controlled traffic aims to limit compaction to permanent ruts in the field, sacrificing a significant portion of the soil in the process. No-till seeding can avoid some tractor traffic, but not all, while the associated dependency on herbicides leads to other problems like herbicide resistance and environmental degradation. There is a need for a tractive device that can generate traction while minimizing the load that causes soil compaction.

1.2 ***The interlock drive system***

The generation of traction on agricultural soil is also possible via the interlock drive system, which penetrates the ground at regular intervals with narrow articulated spikes from which it then pushes the vehicle horizontally over the ground (Bover, 2011), avoiding the vertical pressure of wheels which compacts the deeper soil horizon. This system can provide high tractive power for productive agriculture using lightweight construction and little energy consumption, as has been demonstrated by over 20 prototypes (Nannen ea., 2016)[†]. Regular perforation of a compacted soil layer by narrow spikes can significantly improve soil aeration, water infiltration, and root development, to the extent where the negative effects of compaction are largely overcome (Nambiar and Sands, 1992; Zhai and Horn, 2018). As the spikes first penetrate the soil and then remain stationary in the soil for several seconds, sensors attached to the spikes can measure important soil parameters such as penetration resistance, pH, and soil temperature and also extract soil samples for on-board electrochemical analysis (Bover, 2015).

One configuration which has evolved over a series of field trials connects a pair of two spikes, one behind the other, with a lever arm to a movable joint forward of the spikes as seen in Figure 1. When a backward oriented horizontal draft force is applied to such an articulated spike, the gravitational force acting on the articulated spike and the resistive force of the soil rotate the spike downwards and penetrates it into the soil. The resistive force of the soil increases with depth, and as soon as it equals the draft force, the spike is firmly anchored in the soil and provides a tractive force equal to the draft force. A forward force pulls the spike out of the soil with little effort.

[†] For extensive video documentation visit http://sedewa.com.

The spike as used here is made from 16 mm diameter rebar, has a backward and downward inclination of 45° from horizontal when out of the soil, and an inclination of up to 75° from horizontal when penetrating into the soil at a depth of up to 25 cm. In previous field trials in dry agricultural soil this spike routinely sustains a tractive force of 1000 N. If the draft force or penetration depth is increased further, the spike will eventually bend if not reinforced.

This configuration is self-regulating because the spike only penetrates the soil as deep as is needed to generate the required tractive force, minimizing the time and energy required to anchor the spike. It is passive in that it requires no actuators or control circuitry for the spikes to enter the soil, and its behavior is entirely controlled by the application of the draft force which the spike is meant to resist. This passive and self-regulated configuration allows for an exceedingly simple, robust and reliable implementation.

Devices that gain traction from a stationary connection with the ground typically use a push-pull configuration (Creager ea., 2015), where one part of the vehicle moves forward while the other part provides tractive force, see Figure 2 for a graphical exposition.

Many of the fundamental working principles of the interlock drive system are not yet properly described. This makes it difficult to design a machine for specific soil and operating conditions without adjustment and refitting in the field. The relationship between draft force, vehicle slip, penetration depth, horizontal motion of the spike, and tractive efficiency, as well as the dependency of these relationships on the level of compaction and moisture of the soil need to be properly understood in order to steer the vehicle, in order to apply sensors and tools with precision, and in order to optimize energy consumption. The remainder of this Article is as follows: The Materials and Methods section describes the specific implementation of the spikes, the experimental setup, and the measurements. Results are presented in Section 3 and discussed in Section 4. Section 5 concludes.

Figure 1. Left: Set of spikes with lever arm and movable joint, attached to the rear of a tillage tool. Right: Tillage device with one set of spikes and tillage tool in front of the main frame, and two sets of spikes and tillage tools on either side of the sliding frame. In the photo the device moves from left to right and the horizontal draft force acting on the spikes from the tillage tools is directed from right to left.

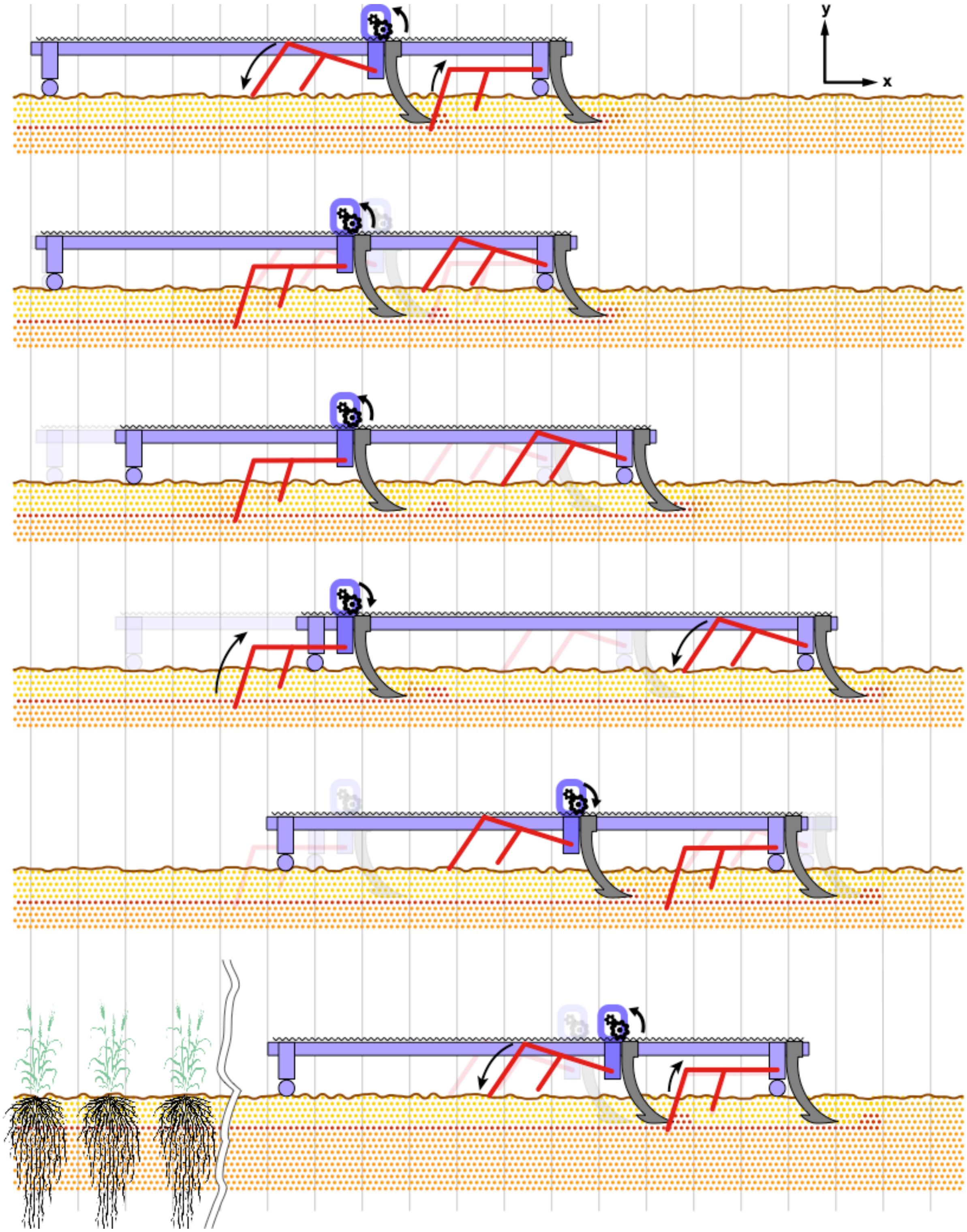

Figure 2: A full motion cycle of a push-pull device with an interlock drive system. Two alternating frames, each with a set of spikes and a tillage implement, move over the ground in a two-stroke cycle. When one spike is in the ground, the other frame moves forward, etc. Note how each frame slips backwards when penetrating the spike into the soil.

2. Material and methods

2.1 Experimental setup

To study how an articulated spike enters into soil in the passive, self-regulated manner described above, we attached a device with articulated spikes with a cable to a weight suspended from a system of pulleys, such that by manipulation of the weight a horizontal draft force could be applied at the joint in a controlled manner.

As can be seen in Figure 3, a pair of spikes was attached with a horizontal joint to a very simple device on rollers. A cable was attached on either side of the joint such that the center of the draft force from the cable would act on the device at the center of the joint. The cable was then led via a system of three pulleys to a hanging basked which was slowly filled with bricks of known weight. The cable and the pulleys translated the combined gravitational force of the basket and the bricks into a horizontal draft force acting on the joint. The combined mechanical efficiency of the pulleys was measured to be 0.77, such that every kg of weight in the basket should pull with a horizontal draft force of ~7.55 N at the joint. Each time the weight of the basket increases, the device on rollers is pulled towards the basket and the spikes rotate deeper into the soil until the resistive force of the soil halts further motion. To minimize the motion resistance of the device itself to a negligible level, the rollers rested on a smooth board which covered a section of the soil, while the spikes were in contact with the soil, see Figure 4.

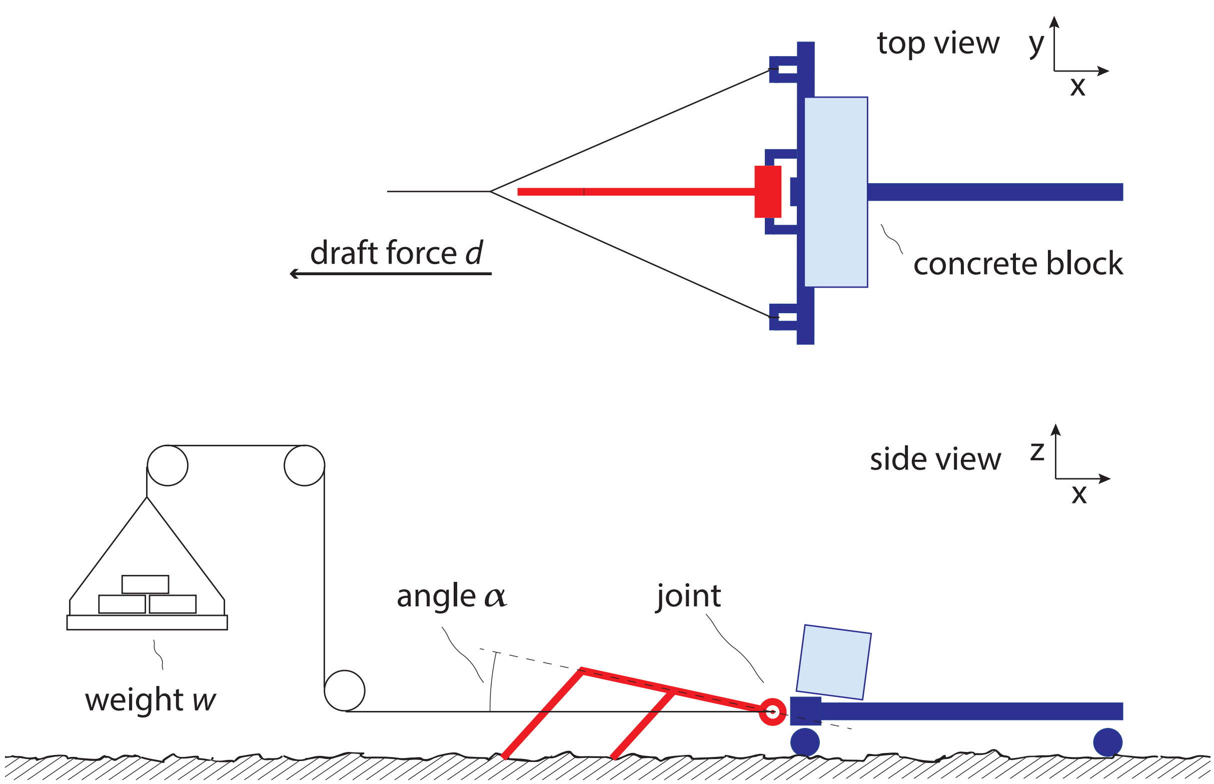

Figure 3: The experimental setup consists of a set of three pulleys which transfer the gravitational force from the weight w to the device such that the draft force d acting on the device is centered at the hinge and that the direction of the draft force is horizontal at the hinge.

Figure 4: The actual experiment, here in a pumpkin field after harvest, in wet soil. The basket with bricks to the left is attached to a cable, which pulls the device on the right. Note the concrete block on top of the device, without which the device would rotate about the tip of the spike in the soil.

The longer of the two spikes had a diameter of 16 mm while the shorter one had a diameter of 12 mm. The angle between the spikes and the arm is 59.2°. The arm itself measured 380 mm from the joint to the long tine and the long tine was 290 mm long. The tip of the long tine was 584 mm from the joint. The total weight of the device is 4 kg, of which the spikes weigh 1.6 kg. A pull at the joint creates a rotational moment about the tip of the spike which would tip the very light device over. To counter this rotational moment and to stabilize the device, we placed a 15 kg concrete block on top of the joint as a counterweight.

2.2 Measurements

We increased the draft force in increments of 38 N, up to 500 N. For every increase in weight we measured the slip s as the distance by which the device moved horizontally at the joint and the angle of inclination α from horizontal of the lever arm that connects the spikes to the joint, see Figure 5 and Table 1 for an explanation of all symbols.

Table 1: List of symbols

d	draft force in N, the independent variable,
c	cycle expansion length of the vehicle in m, typically between 1 m and 4 m,
s	slip or horizontal displacement of the device in mm, measured directly,
α	angle of inclination from horizontal of the lever arm that connects the spikes to the joint,
p	penetration depth in mm of the tip of the long spike, calculated from α**,**
h	horizontal displacement of the tip of the spike in mm, calculated from s and α,
w	work or energy expenditure of penetration in J, calculated from d and s**,**
b	weight force at tip of spike, 6.8 N in the present configuration,
μ	coefficient of friction, ~0.3 on silty clay,
t	tractive efficiency as a ratio.

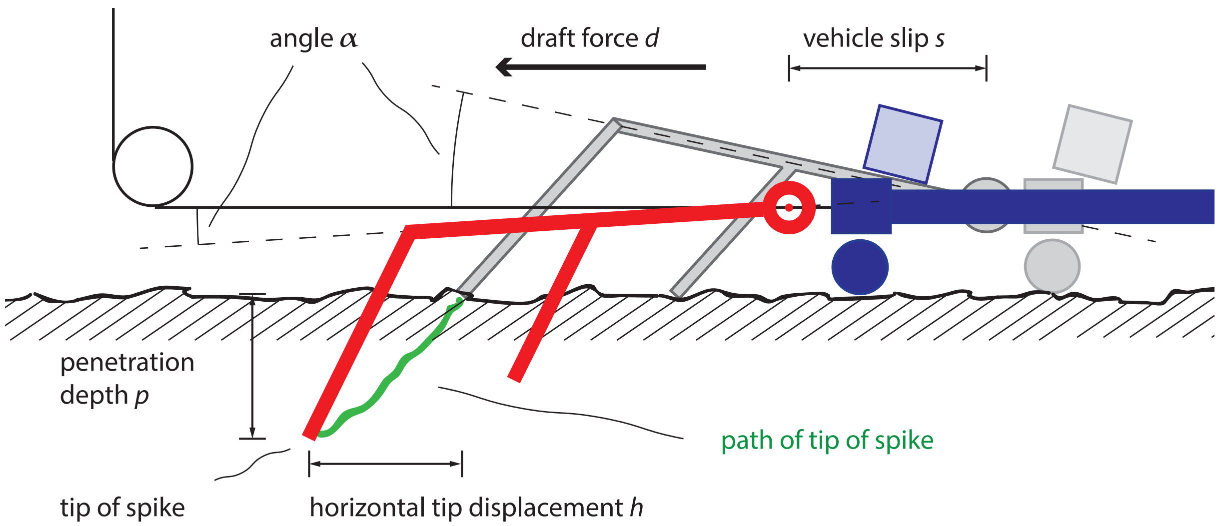

Figure 5: As the draft force *d* increases, the spikes are pressed deeper into the soil. The horizontal motion *s* of the devices is measured at the joint and the angle **α** is measured at the arm of the spikes.

After each increment of weight, it took typically 1–5 seconds (slower for wet soil) for the spike to settle deeper into the soil. We allowed for a further 15–30 seconds before measuring s and α. The penetration depth p can be calculated directly from α as follows:

$$p = 110\,mm - 584\,mm * sin(25.2° - \alpha), \tag{1}$$

where 110 mm is the height of the axis of the joint over the soil, 584 mm is the distance between the axis of the joint and the tip of the spike, and 25.2° is the angle of inclination from horizontal of the line from the axis of the joint to the tip of the spike when the lever arm is horizontal.

The horizontal displacement h of the tip of the spike is calculated from s and α as follows:

$$h = s + 584\,mm * cos(25.2° - \alpha) - 574\,mm, \tag{2}$$

where 574 mm is the horizontal distance of the tip from the joint when resting on the soil, and 584 mm and 25.2° are the same values as mentioned before.

Energy expenditure can be calculated from the work done by the weight pulling at the cable as follows: for every increment $i \in [0..n]$ in weight, let us denote the resulting draft force as d_i, the cumulative slip as s_i, and the cumulative work as w_i. At $i = 0$ we have $d_0 = 0$ N, $s_0 = 0$ mm, and $w_0 = 0$ J. For every increment i we calculate the additional work $\Delta w_i = w_i - w_{i-1}$ which is needed to anchor the spike deep enough to counter the corresponding draft force d_i by multiplying d_i with the increase in slip $\Delta s_i = s_i - s_{i-1}$. Integration over Δw_i gives us the cumulative work $w(d_n)$:

$$w(d_n) = \sum_{i=1}^{n} d_i * (s_i - s_{i-1}). \tag{3}$$

Once anchored into the soil, spikes do not require any further energy input to provide tractive force. The energy cost to pull the spike out of the soil the weight force b at the tip of the spike times the penetration depth, i.e., $b * p(d_n)$.

The calculation of tractive efficiency t_{tires} for tires takes advantage of the fact that all forces act continuously on the soil and tire. Following Zoz and Grisso (2003), t_{tires} can be calculated as the ratio of drawbar force F_{draft} divided by axle torque F_{axle}, where the difference between drawbar force and axle torque is accounted for by the mechanical loss F_{loss} due to tire-soil interaction and tire flexing:

$$t_{tires} = \frac{F_{draft}}{F_{axle}} = \frac{F_{draft}}{F_{draft} + F_{loss}}. \quad (4)$$

By contrast, the discrete motion pattern of a push-pull device with an interlock drive system performs work $w(d)$ at regular intervals to anchor the spike, where d is the same drawbar or draft force F_{draft} as in the case of tires. To calculate the equivalent of F_{loss} for the interlock drive system we need to divide $w(d) + b * p(d)$ by the length of the penetration interval. This length depends on the cycle expansion length c (which is the difference between maximal and minimal expansion length of the push-pull device) minus the draft dependent slip $s(d)$ by which the vehicle slides backwards at the beginning of each expansion and each contraction of the push-pull device, twice per motion cycle. E.g., if $c = 1$ m and $s(d) = 0.1$ m, then the interval length is 1 m – 2 * 0.1 m = 0.8 m. We can calculate

$$F_{penetration\ loss} = \frac{w(d) + b * p(d)}{c - 2 * s(d)}. \quad (5)$$

In the simplest configuration the spike also needs to be dragged over the soil to the next location where it is penetrated into the soil[‡]. This work is equal to the weight force b times the coefficient of kinetic friction μ times the distance $c - s(d)$, i.e., the cycle expansion length minus the draft dependent slip. The complete loss function is

$$F_{loss} = \frac{w(d) + b * p(d) + b * \mu * (c - s(d))}{c - 2 * s(d)}. \quad (6)$$

By combining formula (4) and (6) we can now calculate the draft dependent tractive efficiency $t(d)$ of a push-pull device with an interlock drive system as:

$$t(d) = \frac{d}{F_{axle}} = \frac{d}{d + \frac{w(d) + b * p(d) + \mu * b * \left(c - s(d)\right)}{c - 2 * s(d)}}. \quad (7)$$

[‡] The cost of dragging the spike over the soil can be eliminated by lifting the spike.

2.3 Measurement environment

The experiments were done on silty clay loam in Vilafranca de Bonany, Spain. In total three different compaction levels of soil were investigated: compact, medium and loose soil. Each compaction level was investigated in dry and wet conditions, resulting in six different soil variations. The compact soil was the compacted headland of a vegetable field which has been compacted by a 4 t tractor. The medium soil was a field where the seed bed had been prepared by a 4 t tractor six months beforehand, and where the crops had been harvested by hand three weeks earlier. The loose soil was the same agricultural soil five days after primary tillage.

The dry condition was the condition of the soil in October after four months without rain and six weeks after the last application of the drip irrigation system. The soil for each compaction level would not stick and would not deform but break and pulverize under pressure. For the wet condition, for each of the three compaction levels an area of 1.0 m by 0.5 m was enclosed by a little earthen dam, and over the course of two hours an amount of 100 liter of water was poured into the enclosure in increments of about four liters at a time and allowed to slowly infiltrate. During infiltration, the water column on top of the soil had a height of between zero and two cm. After this treatment, the soil for each compaction level would feel almost liquid to the touch and accumulate as a sticky smeary mass on the spikes and the tools.

For each of the six soil variations, the experiment was repeated three times and results were averaged. This resulted in a total of 18 trials.

2.4 Data analysis

To analyze the results obtained in the trials, the following procedure was applied: For every trial, about ten data points were collected, 30 data points for the three trials of each soil variation. When wanting to plot e.g. average work against penetration depth for a given soil variation, the three data points for penetration depth would not align. In order to obtain an average, we first interpolated energy expenditure against penetration depth to obtain a continuous line for each trial, and then averaged over the three lines, discarding any value which was not supported by all three trials. In other words, the line showing the average would be as long as the shortest of the three lines representing the individual trials. In order to make it easier to distinguish between the soil variations, we plotted additional markers ('x', 'o', etc.) in regular intervals on the lines. These markers do not indicate specific data points, they merely aid the visual identification of each soil variation.

3. Results

3.1 General observation

The rotational moment about the tip of the spike in the soil depends on the draft force, the length of the lever arm connecting the spike to the joint, and the depth of the tip in the soil. In one trial with wet loose soil the highest draft force that could be safely applied was 367 N. In the other trials the maximal draft force ranged from 415 N to 520 N.

The variable of this experiment is the draft force *d* and Figure 6 plots the values of device slip *s* and penetration depth *p* against draft force *d*. Note the almost linear relation between draft and slip as well as between draft and penetration depth for values of draft > 100 N. The initial deviation is probably due to a combination of top soil conditions, the pointed shape of the tip of the spike, and the weight of the spike, even though the gravitational force acting on the tip of the spike was only 6.8 N.
The response of both slip and penetration depth to changes in draft clearly depends on soil conditions: Both slip and penetration depth increase for softer soil, penetration depth increases significantly for wet soil (hence a larger rotational moment and earlier termination of the trials), while there appears to be less slip in wet soil than in dry soil.

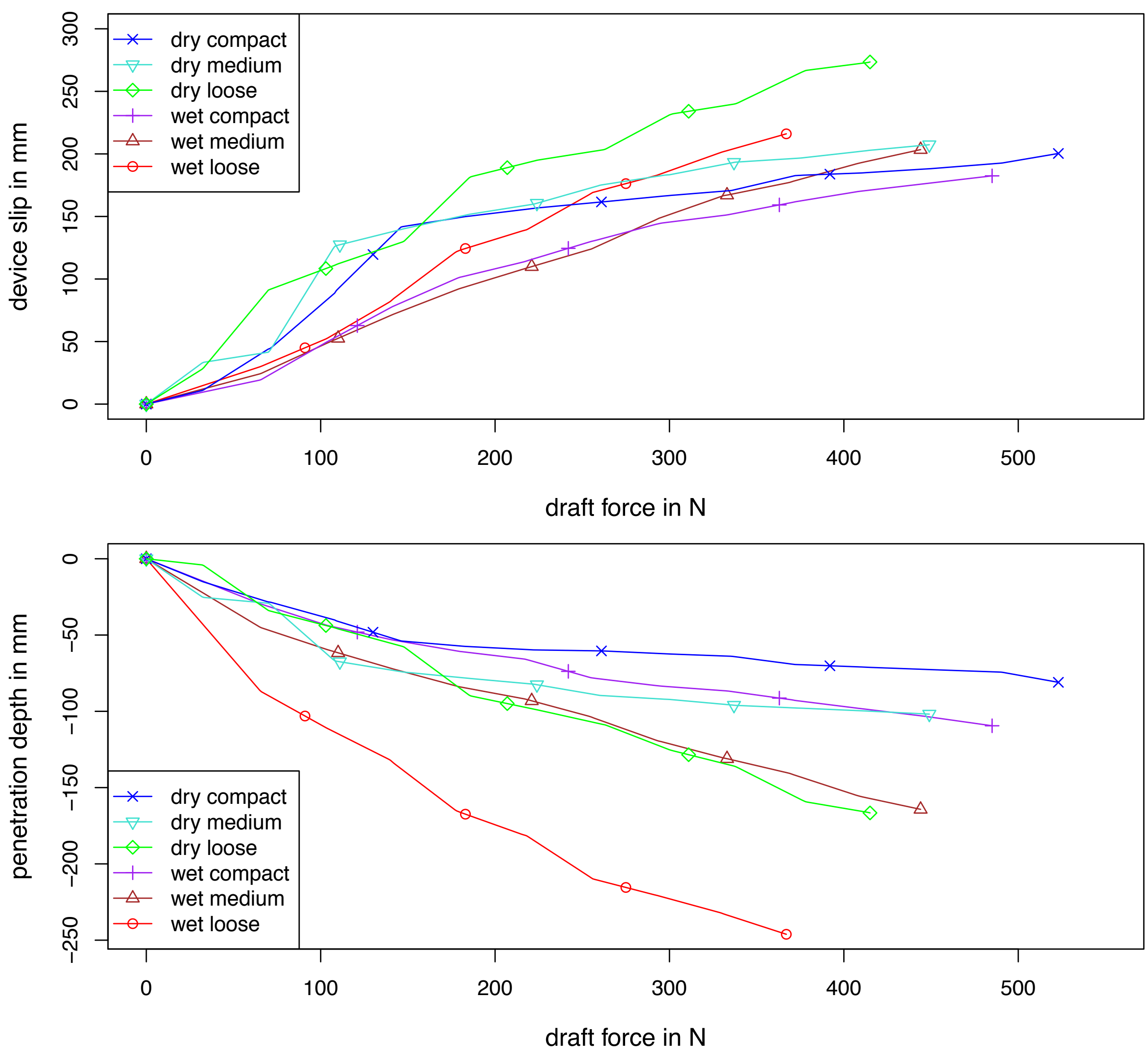

Figure 6: The top graph shows device slip in mm and the bottom graph shows penetration depth in mm as a function of draft force.

3.2 Soil perforation

In some applications it can be desirable to control the depth of the spike, for example in order to give extra stability to subsequent vehicle operations, or in order to improve soil aeration, water infiltration, and root penetration. Depth control can be achieved by controlling the number of spikes used to counter a given draft force or by controlling the depth of a tillage implement. Figure 7 shows the energy cost of penetrating the soil to a certain depth. While three trials per soil variation do not justify a proper statistical analysis, a simple comparison of the top and bottom graphs of Figure 7 seems to indicate that penetration depth of an articulated spike growths as the square root of the energy cost. The energy cost of penetration depth seems to increase significantly with both the level of dryness and compaction of the soil.

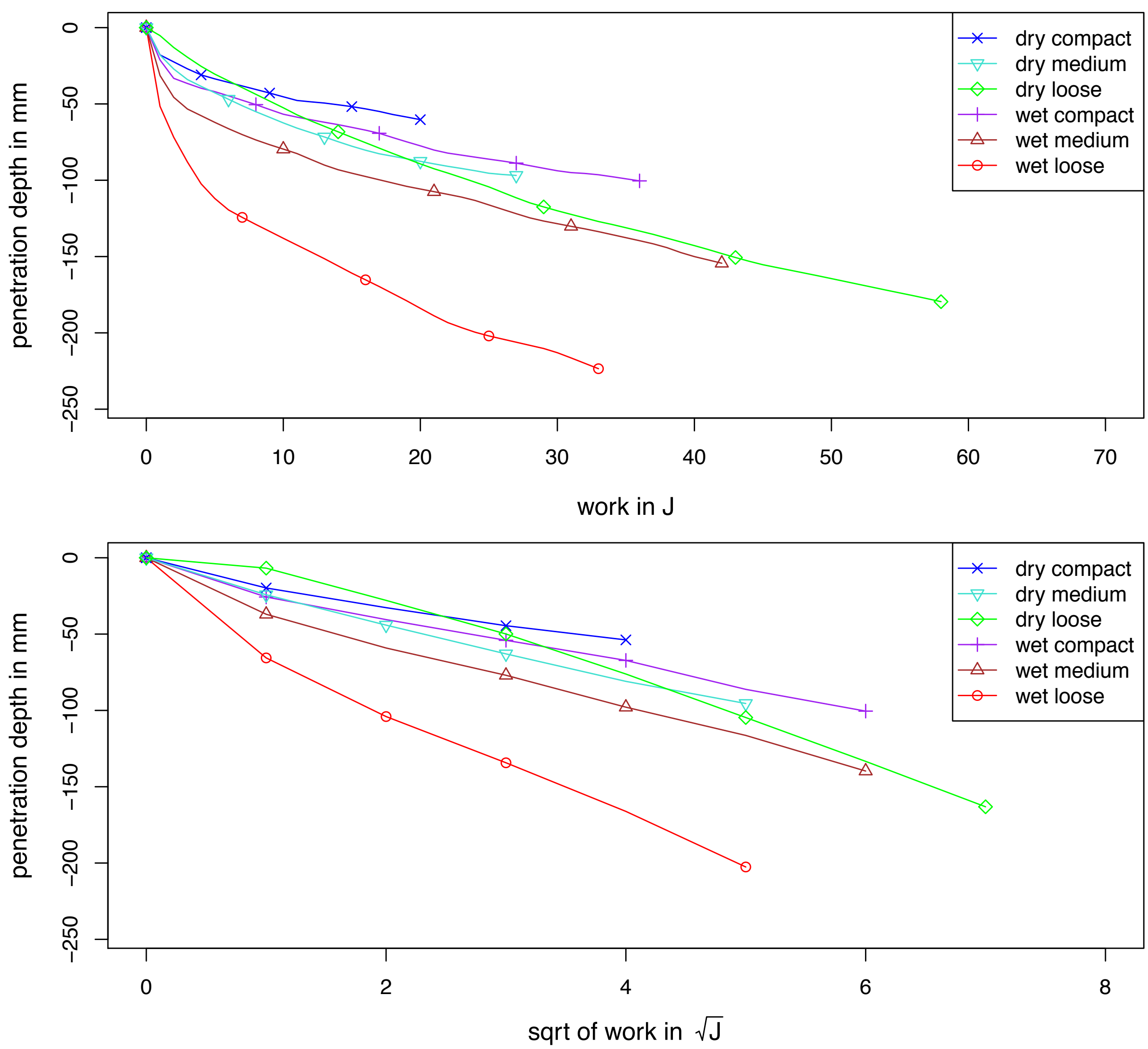

Figure 7: The top graph plots penetration depth in mm against work in J. The bottom graph plots penetration depth as a function of the square root of work in $\sqrt{J}$.

Figure 8 shows the path of the tip of the spike through the soil and the area through which the spike sweeps during penetration. We observe a significant initial effect for soft and for wet soil, which is likely due to the weight of the spike. After the initial effect the paths are largely linear but with different slope. Overall, the paths vary widely with soil conditions. Note how the spikes do not leave a narrow hole in the soil. Instead, the area of disturbed soil has the shape of a wedge.

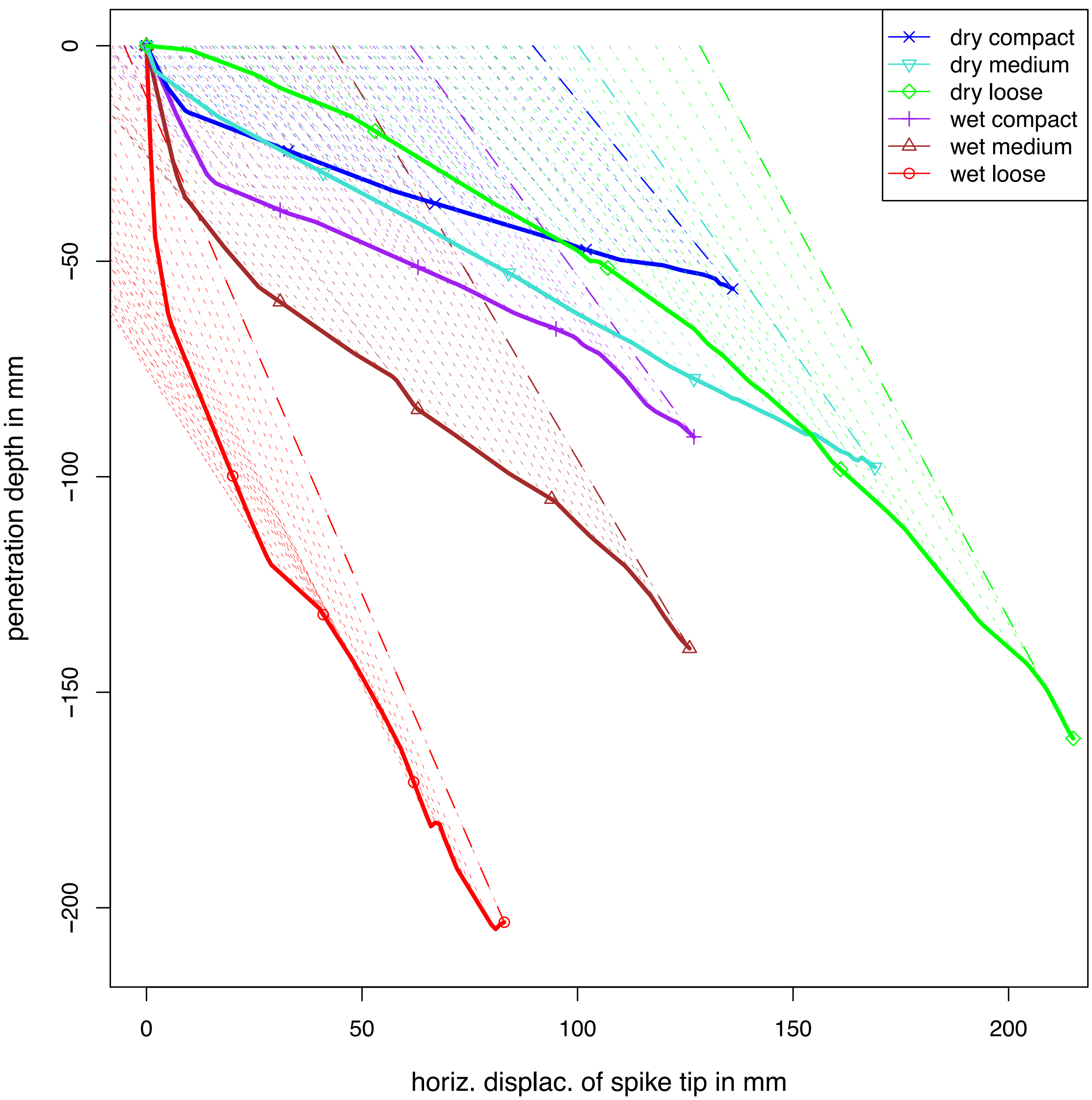

Figure 8: This is a visualization of the trajectory of the tip of the spike in the soil. The solid lines plot penetration depth against horizontal dip displacement, effectively plotting the path of the tip of the spike through the soil. The dashed lines plot the position of the spike when the tip of the spike follows the solid lines. The area of the dashed lines visualizes the area of soil through which the spike has swept.

3.3 Horizontal control for precision applications

In order to precisely measure soil conditions at the seed or seedling, or precisely fertilize a seed or seedling, the motion of the spike should be measured and controlled to within the cm-range not only in the vertical but also in the horizontal direction. Figure 6 bottom has already shown that a spike that can resist a draft force of 350 N will have penetrated the soil to a depth of between 50 and 250 mm, depending on soil conditions. Figure 9 top shows that in order to counter a draft force of 350 N the tip of the spike will have moved horizontally between 100 and 200 mm. Up to 200 N the relationship between draft and horizontal tip motion appears to be non-linear and highly dependent on soil conditions, which makes it a weak candidate to either predict or to control horizontal tip motion. However, Figure 9 bottom indicates that device slip should be an excellent linear predictor of horizontal tip motion that is largely independent of soil conditions except for wet loose soil.

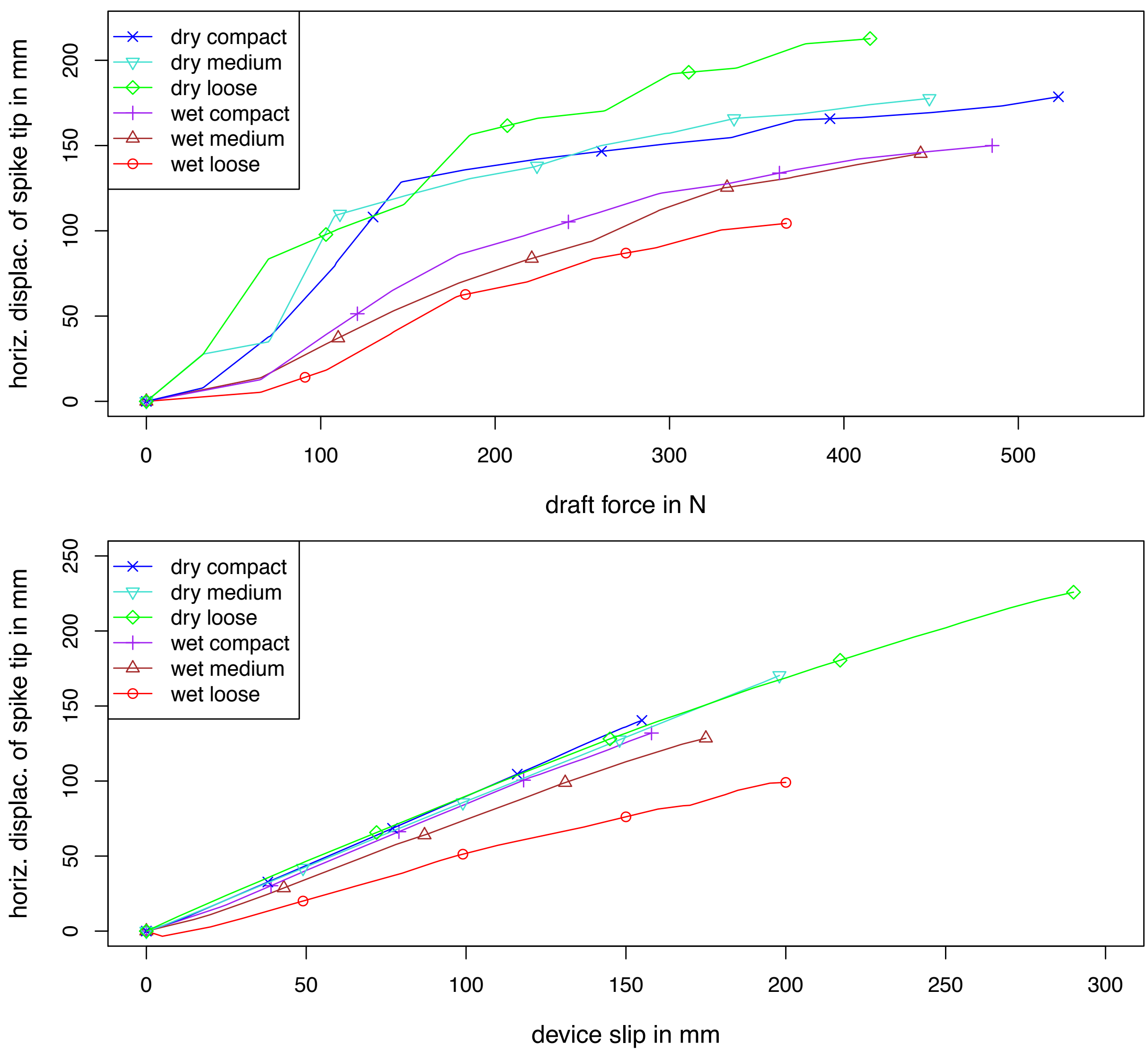

Figure 9: The graph at the top plots the horizontal displacement of the tip of the spike against the draft force. The bottom graph plots horizontal tip displacement against device slip.

3.4 Tractive efficiency

Figure 10 shows the tractive efficiency ratio as calculated from experimental results for push-pull vehicles with cycle expansion lengths c = 1 m and c = 4 m. These are expansion lengths which we have used for field applications like weed control and seed bed preparation. As can be expected, tractive efficiency is better for longer vehicles. Also, tractive efficiency is about twice as good on compact soil as on loose soil. Interestingly, there is no dramatic effect of soil moisture on tractive efficiency. Note however that while on wet soil and on loose dry soil the tractive efficiency decreases as the draft increases, on dry medium and dry compact soil the tractive efficiency seems to reach a minimum at 100 N and 150 N respectively, after which it first increases slightly with increasing draft up to about 200 N and 300 N respectively and then remains constant with further increases in draft.

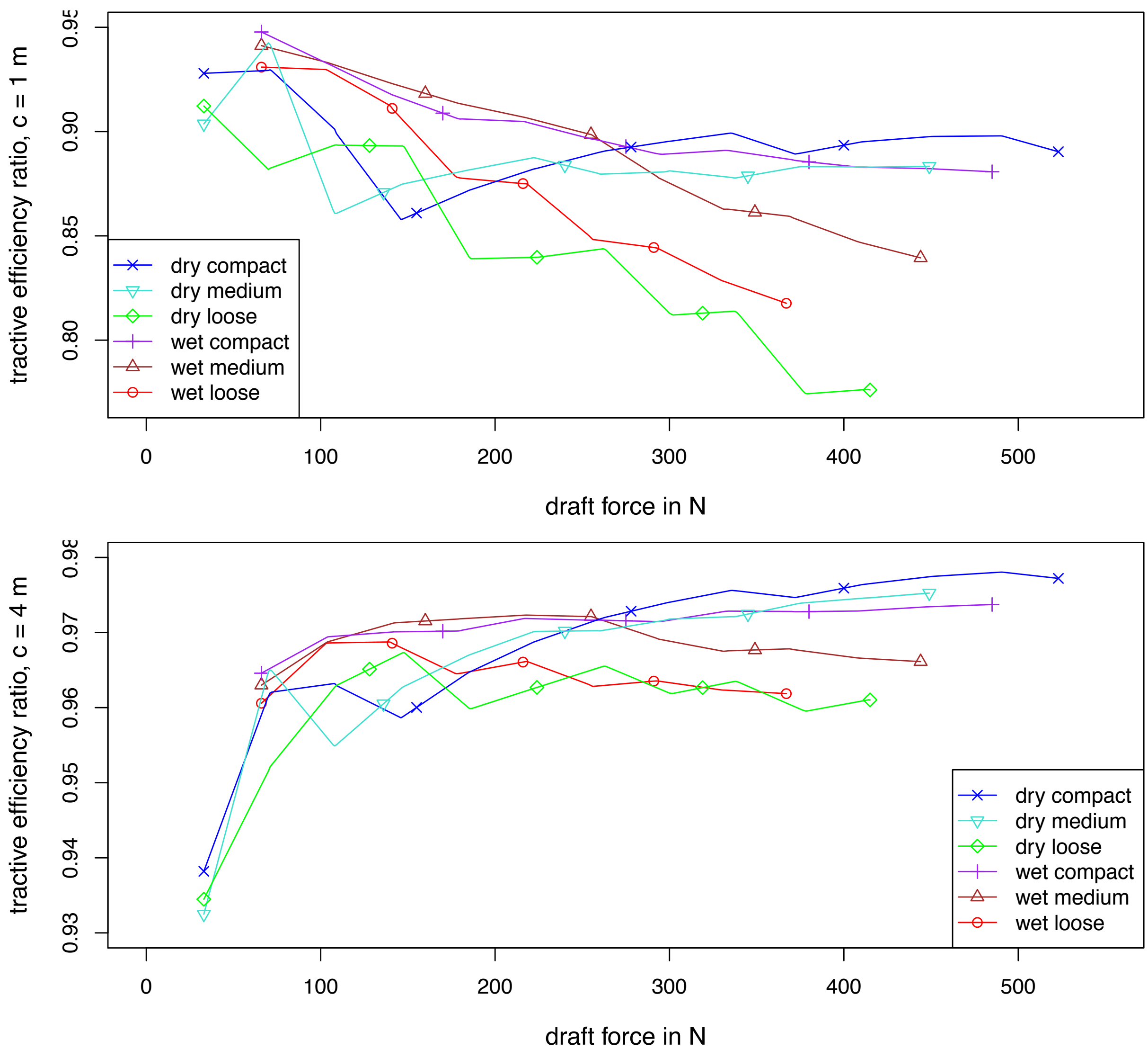

Figure 10: Tractive efficiency as a function of draft force. The upper graph shows tractive efficiency for a device with cycle expansion length *c* = 1 m, the lower graph for *c* = 4 m.

4. Discussion

The high tractive force which can be achieved with relatively short and thin spikes and the reliability and robustness of their application still surprises. The results partly explain this reliability: whenever the soil is too soft or too wet to hold the spike, the spike will penetrate deeper into the soil just as fast as it slips sideways. And while wet soil which is in immediate contact with the spike seems to give way quickly, the rest of the surrounding soil structure seems to remain intact and provide the required tractive force. Because the spikes penetrate quicker into wet soil, slip actually decreases in wet soil.

The total weight of the device with spike and concrete block was 19 kg = 186 N, which sustained a draft force of between 367 and 520 N depending on soil conditions. This is equivalent to a pull/weight ratio of between 2.0 and 2.8, much more than the pull/weight ratio of 0.4 that is typically achieved for tired vehicles. Since the weight is not needed to overcome the forces of shear and friction in the soil, but to counter the rotational moment of the spike, the same can be achieved by extending the length of the lever arm or by using the dynamic weight transfer between tillage tools and spikes. In other words, while the interlock drive system cannot possibly have a pull/weight ratio that is zero, its pull/weight ratio is not a meaningful indicator for possible negative effects on soil health.

The close to linear dependence of slip and penetration depth on draft suggests that these two can form a good predictor of soil strength.

The amount of energy needed to penetrate the soil to a given depth appears to be quadratic in depth for all soil variations. This has to be expected if soil strength increases linearly with depth. Much agricultural soil has been compacted to a depth of 50 cm or more. To perforate compacted soil efficiently to such a depth, the shape and articulation of the spike would require significant reinforcement.

Precision applications require vertical and horizontal accuracy in the cm-range. The current configuration seems to allow a precise measurement of penetration depth and horizontal tip displacement. However, the path of the tip of the spike in the soil is non-linear and it is not clear how the depth and horizontal position of a passive self-regulating spike can be controlled simultaneously. Since most of the non-linearity can be observed during the initial penetration (< 5 mm depth and < 100 N draft) a more precise placement of the spike might be achieved by further study and control of this initial penetration.

Besides the straight cylindrical spikes used in the current trials, we have also found that curved and flat spikes work well, with and without a lever arm. Perhaps some of these geometrical alternatives gives better control over the penetration path.

The tractive efficiency ratio of the interlock drive system depends mostly on vehicle geometry, in particular the cycle expansion length. For a vehicle with a 4 m cycle expansion length it is between 0.96 and 0.975, which is very high. On loose and wet soil the tractive efficiency also depends somewhat on the distribution of draft force over the number of spikes: Less force per spike increase the tractive efficiency. On medium and hard dry soil however, the opposite is true: once draft per spike is higher than 150 N, fewer spikes increase the tractive efficiency. By adding additional factors like tool width and mechanical efficiency of the drive train, the calculation of tractive efficiency can be expanded to calculate the field capacity and the energy cost a push-pull device with interlock drive system.

With a gravitational force of 6.8 N at the tip of the spike the cost of pulling it out of the soil is 1.7 J at 250 mm penetration depth. The coefficient of kinetic friction is ~0.3 on silty clay loam and so the cost of dragging the spike over the ground is 2 J for every meter of the cycle expansion length. Both terms are insignificant compared to the 30–60 J needed to penetrate the spikes for a draft force of 500 N. Further improvements of the tractive efficiency should focus on optimizing the energy cost of penetration.

5. Conclusion and further work

The results show that narrow articulated spikes can reliably generate a strong tractive force regardless of soil conditions. The pull/weight ratio and the tractive efficiency can be significantly better than for tired tractors. Spikes perforate the soil in the shape of a wedge. It would be of interest if such a shape has the same benefits to soil aeration, water infiltration and root penetration as the artificial channels studied in (Nambiar and Sands, 1992; Zhai and Horn, 2018). The precise placement of sensors and fertilizers would benefit from a further improvement in the horizontal precision of soil penetration.

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