Interlocking Spikes for Extreme Mobility

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ABSTRACT

The interlock drive system generates traction by penetrating articulated spikes into the ground and by using the natural strength of the ground for traction. A fundamental problem of traction by interlocking spikes is how to penetrate the ground such that the spike will withstand the draft force. The theory of critical depth suggests that a high rake angle reduces soil fragmentation, while vehicle stability and demand for a high pull/weight ratio require a low thrust angle. To satisfy both requirements, we connect an interlocking spike with a high rake angle via a lever arm to a hinge close to the ground for a low thrust angle. The resulting friction of the spike with the soil increases the vertical penetration force during penetration. Experimental data shows that such a spike penetrates soil of a much higher penetration resistance than predicted from an analysis of the forces involved, possibly because the spike follows the path of least resistance. To better understand and improve the potential of interlocking spikes for mobility in extreme terrain, we need a comprehensive experimental analysis.

INTRODUCTION

Motivation. Tires generate traction on granular material through friction with and between the upper particles of the material. When a tire is powered without sufficient ballast, the particles under the tire flow backward rather than generate traction. As the normal force on the contact area increases, it compacts the ground under the tire (Söhne 1969), friction between the granular particles increases, the particles stop flowing backward and the vehicle moves forward. Extensive data from the Nebraska Tractor Test Laboratory shows that tires achieve an optimal tractive efficiency at a pull/weight ratio of ~ 0.4 on all soils and that between 20% to 55% of the energy available at the axle is lost on the interaction between tire and granular material (Zoz and Grisso 2003).

One alternative to force transmission by friction is an interlocking force transmission, used for example by rack railways where a cogwheel meshes with the rack rail. That an interlocking force transmission with granular material is possible is proven by a wide variety of ground anchors (Godwin and Wheeler 1996), fence stakes, and tent pegs, which withstand considerable lateral forces. When firmly penetrated into the ground, a fence stake requires neither ballast nor energy to withstand the lateral force. The question is how to penetrate an interlocking spike into the ground from a light moving vehicle without fragmenting the soil and without jeopardizing vehicle stability.

Table 1: List of symbols

α	rake angle, inclination from horizontal of the spike
β	thrust angle, inclination from horizontal of the line from hinge to spike tip
θ	angle between the thrust force F_t and the force F_n normal to the spike
δ	angle of soil-metal friction, e.g., ~ 20° on silty clay loam
μ	coefficient of soil-metal friction. $\mu = \tan\delta$, e.g., 0.36 for $\delta = 20°$
F_w	weight force at the tip of the spike, about 7 N in the present configuration
F_d	draft force, the independent variable
F_m	reactive force of the vehicle mass, $\|F_m\| = \|F_d\| \times \tan\beta$
F_t	the thrust from hinge to spike tip with magnitude $\sqrt{F_d^2 + F_m^2}$
F_n	component of F_t normal to the spike, $\|F_n\| = \|F_t\| \cos\theta$
F_r	reactive force of soil under pressure, $F_r = -F_n$
$\|F_t\| \sin\theta$	component of F_t parallel to the spike
$\|F_t\| \cos(\theta)\mu$	friction force opposing $\|F_t\| \sin\theta$
F_p	penetration force parallel to the spike. $\|F_p\| = \|F_t\| \sin\theta - \|F_t\| \cos(\theta)\,\mu$
F_v	vertical penetration force; vertical component of F_p. $\|F_v\| = \|F_p\| \times \sin\alpha$

THE INTERLOCK DRIVE SYSTEM

A key challenge when interlocking a spike with the ground is the correct application of force during penetration and extraction. Since the strength of granular material increases with depth (Taylor et al. 1966), most practical applications require a penetration depth at least as deep as the typical 10–20 cm of tent pegs. As anyone who has experience with tent pegs will know, penetration by vertical force can be difficult or even impossible, especially on stony ground, and extraction by vertical force can be difficult. Ship and land anchors often use lateral forces for penetration and extraction.

Creager et al. (2012) have shown that a push-pull device with independently articulated pairs of wheels can double the pull/weight ratio, presumably because braked wheels have higher static friction. Bover (2011) discovered that a push-pull device with frames that move independently along a common axis can use the resulting lateral forces to penetrate interlocking spikes into the ground and extract them from the ground. While the device by Creager et al. brakes one set of tires to provide traction for the other set of non-braked tires, the device by Bover has articulated spikes attached to each frame that penetrate the ground to provide traction for the other non-interlocking frame. When the device pushes a frame backward, the spikes of that frame penetrate the ground until they withstand the draft and provide traction for the other frame which the device simultaneously pushes forward, pulling the spikes of the other frame out of the ground. This interlock drive system can generate considerable tractive forces in steep, rocky, soft and wet terrain (Nannen et al. 2016, 2017, 2019).

Lesson from an early design. Figure 1 shows an early design by Bover from 2010 for soil tillage. It has two diagonal spikes attached to the rear frame to the left and two diagonal spikes attached to the front frame to the right. Both frames have vertical feet with soil cultivators for weed control beneath the soil surface. A central pair of bars connects the two frames. An electric motor at the rear frame drives a cogwheel that meshes with a motorcycle chain welded to the upper central bar. By reversing the direction of the motor, the device contracts and extends in an alternating motion pattern, such that either the front or the rear spikes penetrate the ground, inhibit the motion of their frame, and provide traction for the other frame.

Figure 1: early design of interlocking spikes. The vehicle moves from left to right.

The spikes in Figure 1 are straight hollow steel bars with a robust width of 8 cm, each connected to a hinge, such that they rotate into the ground under backward pressure. The rake angle α of the front spikes is 30° from horizontal when out of the soil and 40° at a penetration depth of 20 cm. The thrust force F_t from the hinge that pushes a spike into the soil aligns with the spike, such that its inclination β from horizontal is equal to α. The horizontal component of F_t is the draft F_d of the soil cultivators, and its vertical component is the reactive force F_m of the vehicle mass. F_m has the same magnitude as the vertical component $|F_d| \times \tan\beta$ of the moment force about the tip of the spike which lifts the vehicle at the articulation, except that F_m cannot exceed the vehicle mass or the vehicle will flip over. Because the vertical penetration force increases with the draft force, this design is self-regulating: the spikes only penetrate the ground as deep as needed to withstand the draft. See Table 1 for a list of symbols.

During evaluation in the field, this early design revealed significant drawbacks: the spikes had difficulties penetrating the ground, lacking vertical penetration force; when the spikes did penetrate, they often fragmented the soil and broke free again; when the spikes did anchor and $|F_d| \times \tan\beta$ exceeded the vehicle weight at the hinge, the moment force about the tip of the spike would flip the vehicle over.

The importance of narrowness and a high rake angle. A narrow spike minimizes penetration resistance at its tip and friction as its sides. A narrow spike at a high rake angle also minimizes fragmentation of the soil because of the effect spike width and rake angle have on critical depth. The theory of critical depth states that there are two distinct modes of soil failure along a spike which is pulled laterally through the soil and that these two modes are vertically separated at a critical depth that depends on soil conditions, spike width, and rake angle (Zelenin 1950; Kostritsy 1956; O’Callaghan and McCullan 1965; Hettiaratchi 1965; Godwin and Spoor 1977).

Above the critical depth, the soil experiences either shear or tensile failure. Shear failure occurs at high rake angles and low shear strength, while tensile failure occurs at low rake angles and high soil strength (Aluko and Seig 2000). With shear failure, the lateral force acting on the spike breaks away a wedge of soil and lifts it until the wedge breaks and is pushed aside. With tensile failure, also called brittle failure, the soil is first fragmented and then pushed up, either forward or sideways. In either case, the soil in front of the spike loses its strength. Once fragmented, the inertia of the material pushed up and aside is the only force resisting the spike. See Figure 2 for an illustration.

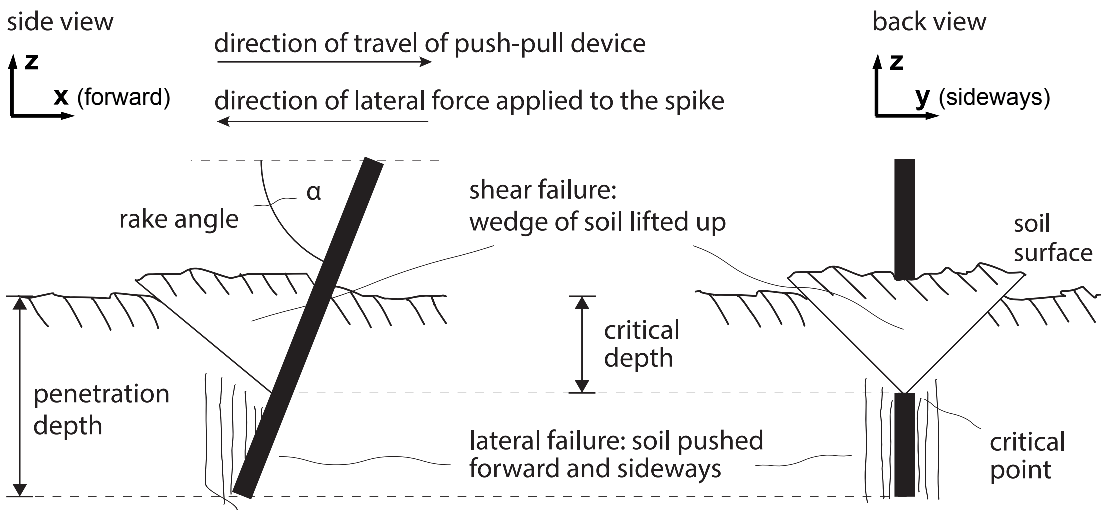

Figure 2: different regimes of soil failure above and below the critical depth.

Below the critical depth, the lateral force acting on the spike compresses the soil against which it pushes, until it creates a plastic flow around the spike. The soil is not fragmented but molded and homogenized, and even though the soil in the immediate neighborhood of the spike may lose its structure and strength, reactive pressure on the spike is maintained by the intact soil structure against which the homogenized soil presses. Because it is the area below the critical point that sustains pressure, an interlocking contact with the soil requires a critical depth close to the surface. The cited literature shows that, for given soil conditions, the narrower the spike and the higher its rake angle, the closer the critical depth is to the surface. Also, the critical depth is closer to the surface in uncompacted than in compacted soil.

The importance of a lever arm and a hinge close to the ground. An interlocking spike should be narrow and have a high rake angle to avoid soil fragmentation. However, the destabilizing moment force that lifts the vehicle increases with the angle β of the thrust force F_t from the hinge to the tip of the spike. At $\beta = 65°$, vehicle weight at the hinge should exceed at least 2.5 times the draft to prevent the vehicle from flipping over. For a lightweight vehicle that is supposed to pull twice its weight, β should not exceed 25°. The solution is a design with distinct rake and thrust angles. Bover (2011) achieves this by connecting a spike with a rake angle $\alpha > 45°$ to a lever arm, and by connecting this lever arm to an articulation (a hinge) as close to the ground as possible for a low thrust angle β.

Figure 3 shows a current design of the interlock drive system. It attaches narrow spikes made from 16 mm rebar to a lever arm which it connects to a hinge close to the ground, backward of each frame. The spikes incline backward at a rake angle $\alpha = 45°$ from horizontal when sliding over the ground. When the spikes penetrate the ground, they rotate about the hinge, such that $\alpha = 65°$ at a penetration depth of 20 cm. The thrust angle is $\beta = 10°$ when the spike is out of the ground and $\beta = 30°$ at a penetration depth of 20 cm. According to Godwin and Spoor (1977), the critical depth of spikes with such width and rake angles ranges from 5 to 12 cm.

Figure 3: Push-pull bulldozer with interlocking spikes. Motion is from left to right.

A motorcycle chain is welded to the central bar which connects the two push-pull frames. An electric motor connected to the rear frame to the left drives a cogwheel that meshes with the motorcycle chain and pulls the two frames together and pushes them apart in an alternating motion pattern. The rear frame has two undriven wheels for ground clearance and two large double spikes with lever arms painted in red. The front frame to the right has a single undriven wheel for ground clearance, a plate to push soil, and small spikes with lever arms, half-hidden behind the central bar and painted in red. When the motor pushes a frame backward, the spikes of that frame penetrate the ground. When the motor moves a frame forward, it pulls its spikes out of the ground.

In the upper photo of Figure 3, the motor has pulled the rear frame forward. Its large spikes are out of the soil. In the lower photo, the motor has reversed direction. It has pushed the rear frame backward and penetrated the large spikes into the ground. Once the spikes withstand the draft, the plate attached to the front frame to the right pushes the accumulated soil forward, acting as a bulldozer. For a video of this bulldozer and other implementations see http://sedewa.com/Xtreme.html.

A lever arm adds vertical penetration force. A lever arm connected to a hinge close to the ground reduces the destabilizing moment force, which increases the pull/weight ratio. We tested the articulated spikes of Figure 3 with a very light vehicle on dry compacted soil with a cone penetration resistance of 4.8 MPa in the upper 5 cm. We need a vertical force of ~ 965 to penetrate a 16 mm cone 5 cm deep into such soil, penetrometer style. The vehicle mass at the hinge provided a vertical force of 170 N and the mass of the spike provided another 7 N. When pulled laterally, the articulated spike penetrated to a depth of over 5 cm every single time we tried. How does the lateral pull overcome a penetrometer resistance of 965 N?

Here the lever arm is important. In the early design, the thrust vector F_t from the hinge to the tip aligned with the spike. This reduced the friction between the soil and the spike to a minimum, since the angle θ between the thrust vector and the normal to the spike was 90° (We ignore adhesion and soil elasticity). With a lever arm, F_t is no longer aligned with the spike. We have $\theta = 90° - (\alpha - \beta)$ with $\alpha > \beta$. The resulting friction between the spike and the soil produces a penetration force F_p that aligns with the spike, see Figure 4. Note that $|F_p| = |F_t| \sin\theta - |F_t|\cos(\theta)\mu$.

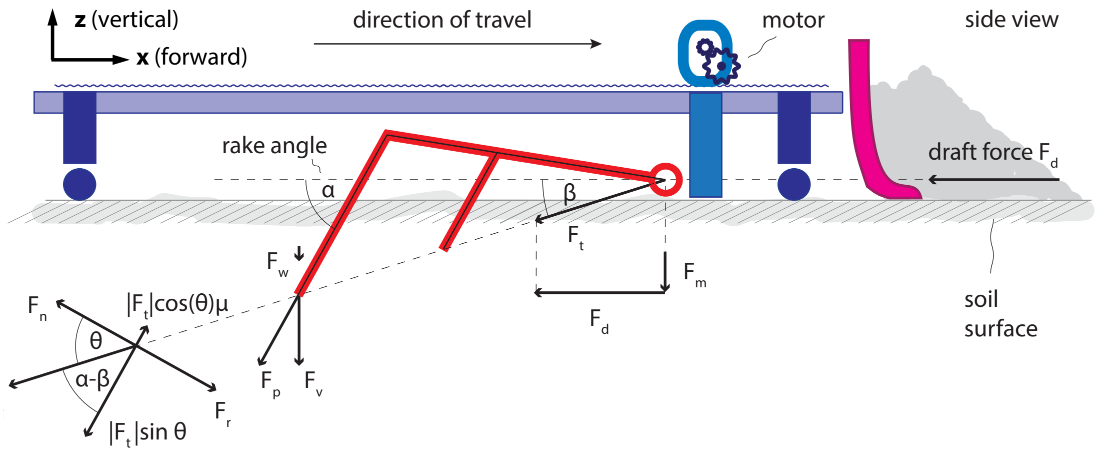

Figure 4: Forces acting on an interlocking spike with a lever arm.

Both the magnitude of the reactive force F_m of the vehicle mass and the vertical component F_v of the new penetration vector F_p are trigonometric functions of the draft force F_d. While the magnitude of F_m is equal to $|F_d| \tan\beta$, the magnitude of F_v is equal to $|F_d| \sqrt{1 + \tan^2\beta}\,(\sin\theta - \mu\cos\theta)\sin\alpha$, where $\mu = \tan\delta$, and where $\theta = 90° - (\alpha - \beta)$ is constant for the spike design in Figure 3.

The vertical penetration force F_v will exceed the reactive mass force F_m as long as θ exceeds the angle δ of soil-metal friction. For example, at an initial rake angle $\alpha = 45°$, an initial thrust angle $\beta = 10°$, and an angle of soil-metal friction $\delta = 20°$, the magnitude of the reactive mass force is 17% of the draft force, while the magnitude of the vertical component of the resulting penetration force is 44% of the draft force. Even at a high soil-metal friction angle of $\delta = 30°$, the vertical component is still 35% of the draft force. While facilitating a high pull/weight ratio and a comparatively high rake angle, the lever arm also more than doubles the vertical penetration force compared to what the earlier design would have achieved at such a low thrust angle.

Another advantage of the lever arm is that it allows the addition of a second spike, as shown in Figures 3 and 4. While the second spike will not penetrate as deep into the soil as the larger spike, we found that it is of great help during the initial penetration of soil with a duricrust surface, possibly because of the inhomogeneous nature of the soil.

Optimal spike design. Numerical analysis shows that for all combinations of soil-metal friction δ and thrust angle β, with $0 \leq \delta \leq 45°$ and $10° \leq \beta \leq 30°$, we maximize the vertical penetration force F_v for rake angles $35° \leq \alpha \leq 55°$, with 45° being the value that will work best for the largest number of combinations. For any combination of δ and β, the rake angle that maximizes F_v also maximizes the ratio F_v / F_r.

Since the difference $\alpha - \beta$ is constant in the spike design in Figure 3, the angle $\theta = 90° - (\alpha - \beta)$ is also constant. Numerical analysis shows that independent of the soil-metal angle of friction δ, we maximize the vertical penetration force F_v if we keep $\alpha - \beta$ in the range $15° < \alpha - \beta < 35°$, that $\alpha - \beta = 30°$ is optimal for $\beta = 10°$, and that $\alpha - \beta = 15°$ is optimal for $\beta = 30°$.

We conclude that there is a tradeoff between demand for vehicle stability and a high pull/weight ratio (which calls for a low thrust angle β), firm anchoring in the soil (which requires a high rake angle α), and a high vertical penetration force F_v, especially during initial penetration (which calls for a rake angle $\alpha \approx 45°$ and a difference $\alpha - \beta \approx 30°$). Our field trials have favored an initial rake angle of 45° which increases up to 65° during penetration, a thrust angle which we try to keep below 30° during penetration, and a spike design with a difference $\alpha - \beta = 35°$.

EXPERIMENTAL VALIDATION

To verify the penetration ability of spikes with the above characteristics, we conducted a series of controlled field trials on agricultural land in Vilafranca de Bonany, Spain, a silty clay loam with 6% gravel and stones by weight. We investigated three different compaction levels: compact (headland compacted by tractor), firm (after manual harvest and with a duricrust surface) and tilled (five days after being tilled with a turn plow). We measured cone penetration resistance in the upper 10 cm with a hand penetrometer, which averaged 6 MPa, 3.9 MPa, and 960 kPa respectively for the three compaction levels. The soil was dry after four months without rain and six weeks after the last application of drip irrigation on the firm soil. The soil for each compaction level would not stick and would not deform but break and pulverize under pressure.

During penetration, we increased the draft in increments of about 38 N up to 500 N while we carefully measured the motion of the spike in the soil. Every time we increased the draft, the spike would penetrate deeper into the soil until the reactive force of the soil pressing against the spike equaled the draft force. For each increment, we recorded both the horizontal and the vertical motion of the spike in the soil. For each compaction level, we repeated the test three times at different locations in undisturbed soil and averaged the results. We confirmed visually that the spike did not fragment the soil such that it would break free, as happened with the earlier design. For a detailed description of the experimental setup, see Nannen et al. (2019).

Figure 5 shows how deep the spike penetrates the soil for a given vertical penetration force F_v. The spike has a diameter of 16 mm and a cross-sectional area of 201 mm^2. By multiplying this area with the cone penetration resistance of 960 kPa, we predicted that the spike needs a vertical force F_v of ~ 190 N to penetrate the tilled soil to a depth of 10 cm. Figure 5 shows that the spike penetrated the upper 10 cm with a vertical penetration force $F_v \approx 125$ N. We predicted from the cone penetration resistance of 3.9 MPa that the spike needs a vertical force of ~ 780 N to penetrate the firm soil to a depth of 10 cm. Figure 5 shows that the spike only needed 230 N to do so.

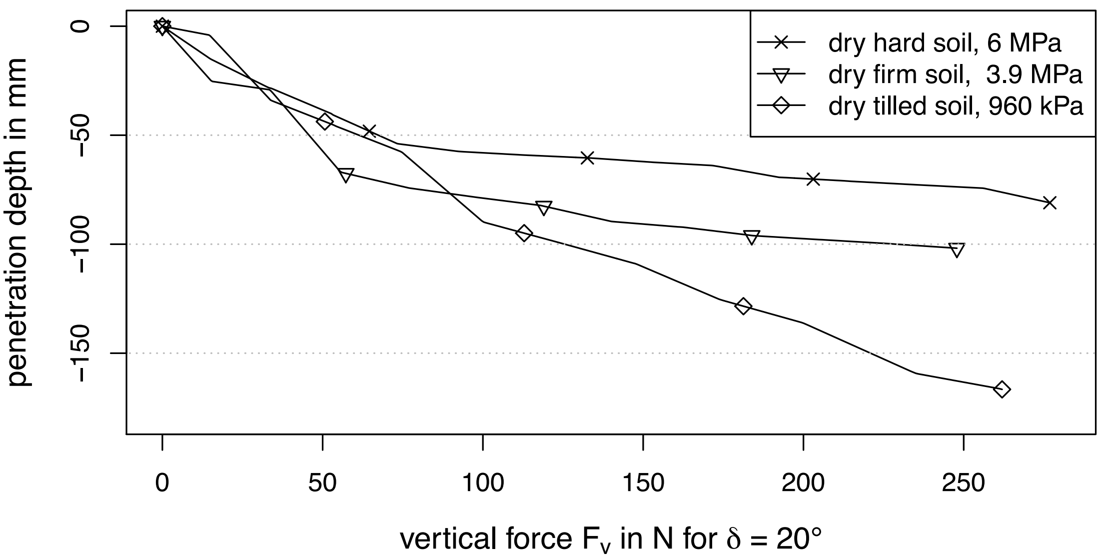

Figure 5: Penetration depth as a function of the vertical force F_v.

With the limited lateral force applied in the experiment, the spike never penetrated the hard soil to a depth of 10 cm. The penetration resistance in the upper 5 cm of the hard soil was 4.8 MPa, from which we predicted that we need a vertical force of ~ 965 N to penetrate to this depth. Figure 5 shows that on average the spike needed a vertical penetration force $F_v \approx 70$ N to penetrate the hard soil to a depth of 5 cm, a difference of an order of magnitude. To confirm the general observation described here, we conducted many additional trials with a similar setup but with less detailed measurements. Every single time the spike penetrated the soil with comparatively little force. How is this possible?

Path of least resistance. The answer to this mystery may be that natural soil is highly heterogeneous and that the tip of the articulated spike is free to follow the path of least resistance. Unlike a penetrometer that has to push gravel and stones out of a fixed vertical path, an articulated interlocking spike is free to move sideways or penetrate deeper into the ground. Figure 6 plots the path of the tip of the spike in the ground for each of the three trials of each compaction level, nine paths in total. It shows that there is significant variation in the precise path that the tip of the spike takes during each trial, and that the spike changes direction during penetration. Such changes of direction might prevent the accumulation of compacted material in front of the tip of the spike or bypass such compacted material when it has accumulated. An interlocking spike will either slide over any broken rock that prevents depth penetration or, if the rock does not move and does not allow the spike to slide over it, the spike can use the resistance of such a rock for traction.

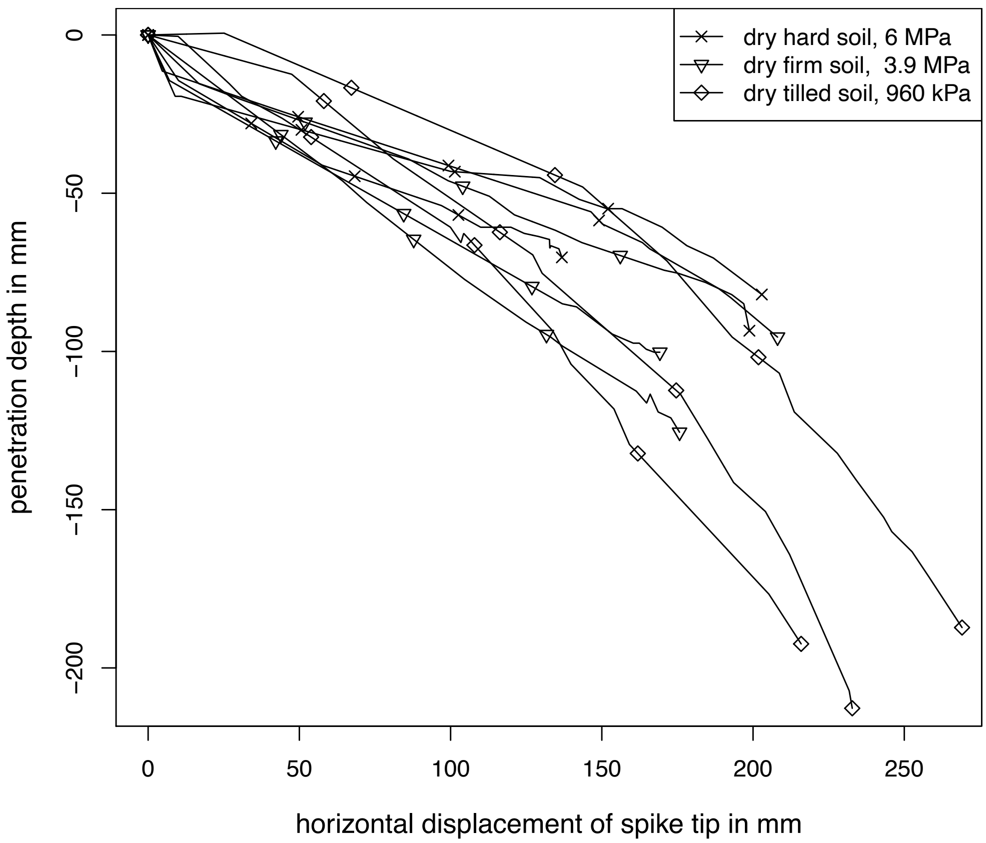

Figure 6: Visualization of the path of the tip of the spike in the soil.

CONCLUSION

The interlock drive system emerged from an iterative process where we identified and overcame obstacles through empirical evaluation and modification of prototypes in the field. An early design showed that spikes with identical rake and thrust angles have difficulties penetrating the ground, fragment the soil, and flip the vehicle over. Vehicle stability and a high pull/weight ratio require a low thrust angle, while a high rake angle minimizes soil fragmentation, as per the theory of critical depth. We solve this problem by connecting a spike with high rake angle via a lever arm to a hinge close to the ground for a low thrust angle. The lever arm also increases the vertical penetration force through a favorable friction angle, especially during initial penetration, and allows the addition of a second smaller spike, which eases initial penetration.

Our field trials show that the spikes not only penetrate the soil to a depth where they withstand the draft but that they penetrate the soil to a greater depth than predicted from cone penetration resistance. The vertical force needed to penetrate a spike to a given depth increases with cone penetration resistance and the rate of increase of the required vertical force is far lower than that of the cone penetration resistance. The experimental data showed a significant amount of variation in the path taken by the tip of the spike. Natural soil is highly heterogeneous, and the articulated spike is free to follow the path of least resistance during penetration, which may explain at least part of the discrepancy between the predicted and the observed penetration force. We conclude that these are only exploratory trials. We need to study the distribution of forces in the soil and their effect on soil strength during and after penetration to better understand, improve, and control how the spikes interlock with the soil and to predict the tractive force they generate under different field conditions.

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