SOIL MOTION ANALYSIS SYSTEM FOR EXAMINING WHEEL-SOIL SHEARING

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Though much research has been conducted regarding traction of tires in soft granular terrain, little empirical data exist on the motion of soil particles beneath a tire. A novel experimentation and analysis technique has been developed to enable investigation of terramechanics fundamentals in great detail. This technique, the Shear Interface Imaging Analysis Tool, provides visualization and analysis capability of soil motion at and below the wheel-soil interface. The method places a wheel (or other traction device) in granular soil up against a transparent sidewall. While driving or towing the tire, images are taken of the sub-surface soil, and are processed with optical flow software. Analysis of the resulting displacement field identifies clusters of soil motion and shear interfaces. Complexities in soil flow patterns greatly affect soil structure below the wheel and the resulting tractive capability. The Shear Interface Imaging Analysis Tool visualizes and helps analyze these complexities in richer detail than possible before, and allows for a deeper understanding of the physics behind wheel-terrain interaction. Results are presented for rigid wheels at various slip conditions, and various wheel configurations such as diameter, grouser spacing and compliance.

Keywords: terramechanics, rover, robotics, regolith, wheel

1 Introduction

The limitations posed by terrain during planetary surface exploration missions have created a need for continued development of traction devices for robotic vehicles. Targets of scientific interest exist in terrain that is frequently beyond the capability of all flown mobility platforms resulting in the loss of potential scientific return. Of specific challenge on the Moon and Mars are flat ground and slopes covered by loose, low strength regolith. Wheeled mobility systems can become entrenched in these terrains due to excessive slip and sinkage. With the continued exploration of planetary bodies, the study of wheel-soil behavior in loose, granular, material remains imperative for achieving future scientific discoveries. Methods available utilizing common terramechanics approaches do not achieve high fidelity. Difficulties are also presented with the analysis of most wheel designs, due to the complexities of interaction with the soil below.

The design of traction devices, such as wheels for planetary rovers, rarely involves the detailed analysis of the soil shearing and failure patterns. The stress applied to the soil mass is not only the result of external loading but also directly affected greatly by the operation of the wheel. The application of torque during rotation creates unique shearing patterns that vary widely in ability to support shear loading. The ‘shear interfaces’ are failure planes that develop in the soil below the region of interaction with the rim (Fig 1). Shear interfaces can indicate the soil failure mode, location, size and thus provide intuition about where load is being supported in the terrain. Geometry of the rim, presence of lugs, wheel stiffness, contact shape and many other properties have large effects on the shear interface during operation of a wheel. The performance of a traction device in loose, granular soil is ultimately governed by the soil properties and the shear failure that occurs. The shearing processes, shear failure types and flows determine how large a reaction load can be obtained to generate thrust and the type of motion resistances and their magnitude present leading to the net traction available.

For example, a rotating rigid wheel may induce a

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forward flow leading to losses. Furthermore, a small diameter rigid wheel may push sheared particles deep into the soil and then back up again in a “v”-like shape that follows the rim. In contrast, a foot pad utilized by vehicles with walking locomotion generates a significantly different mode of soil failure which has a shear interface extending well beyond the wheel contact region. The distinct modes of soil failure and flow processes occurring provide insight into the development of traction of these examples.

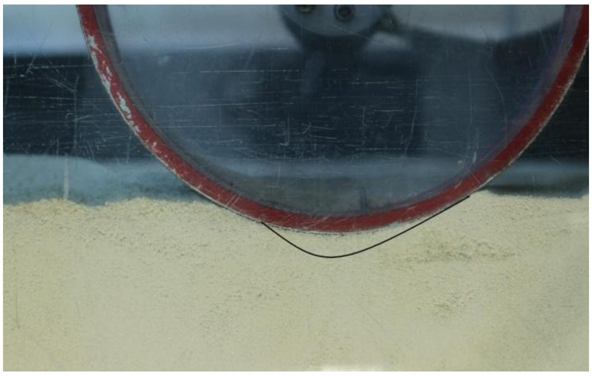

Fig 1: *Side cross-section view of wheel travelling over soil. Soil shears and is displaced below a wheel in operation. The shear interface is the extent of the zone within which maximum shearing occurs (drawn as line for example).*

The objective of this work is to (1) discuss the importance of the investigation of sub-surface soil shearing of traction devices in terramechanic evaluation, (2) introduce a system of analysis of the shear interface during physical testing of a specimen and (3) through examples, use the analysis system to discuss the effect wheel properties have on net traction.

To study the shear interface of a wheel or other traction device, a model or test method must be used to observe the shearing of soil below the wheel within the soil mass. Minute details of the wheel rim geometry or mechanics of the wheel carcass have a profound effect on the shearing processes. Geometric parameters such as the commonly implemented wheel lug are often not incorporated into modeling techniques, thus inadequate results and misleading representations of the shearing processes are produced with most methods. In effort to directly investigate the soil shearing processes occurring due to wheel operation, a physical experimentation approach was taken for this body of work.

The development of a technique we call “shear interface imaging analysis” was undertaken in order to measure the location and characteristics of the shear failure planes in great detail. This method relies on the use of photographing the soil grains through a glass-walled box as a traction device operates. This technique has proven to produce accurate results and allowed for in-depth investigation of vehicle locomotion modes such as push-roll (inch-worming) for planetary surface vehicles [1]. This technique will be shown to be useful for investigation of more generalized parameters for wheels of vehicles in terrain environments of interest on the Moon and Mars. The study of the principles of traction are investigated from an experimental approach through soil failure analysis rather than bulk performance.

2 Shear Interface Imaging Analysis Technique

Previous efforts had been made to image the effect on soil due to travel with a wheel or other traction devices [2][3][4]. These researchers produced extensive results, but a very limited amount of that work can provide direct insight into the application of mobility in planetary environments. Previous terramechanics studies using subsurface soil imaging were primarily conducted for agricultural and military vehicles. The heavy weight of these vehicles and pneumatic type tires are generally not representative of planetary mobility systems, and the cohesive Earthen soils (clays and mud of interest to these studies) produce results greatly different in soil shearing processes from granular, cohesionless materials.

Much previous study was conducted using a “quasi-static” representation of the tread surface of a wheel. Results in this work show this does not produce shearing processes similar to that of a rolling wheel.

Prior methods of imaging relied on long exposure of film to indicate the shear interface. This produced low precision results that could only indicate whether soil was either moving or static; no other information could be measured. The shear interface imaging analysis technique described in this paper is founded from these previous works but now provides a method that is capable of recording many types of soil shearing information at high precision.

Other techniques for lower precision visualization of soil motion have included tracking tracer particles exposed to UV light [5], observing changes to a grid pattern of different-colored particles [6], and applying white light speckle autocorrelation to an arrangement of natural and colored sand grains [7].

2.1 Description of Technique: Hardware and Software

The experimental apparatus constructed to analyze the soil shearing below a wheel consists of a glass-walled soil bin filled with relevant regolith simulant, a traction device, an actuated horizontal axis of motion and a high-speed camera (Fig. 2). The wheel module (Fig. 3) of the imaging test bed is position or velocity controlled in coordination with the horizontal axis to create a commanded, constant slip as the wheel travels forward. A linear rail allows the wheel to translate freely in the vertical direction allowing for natural sinkage to occur.

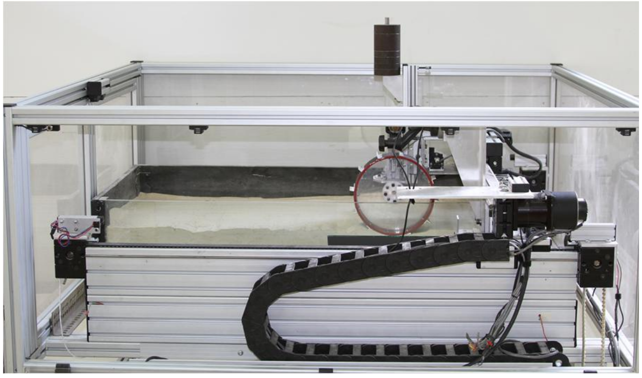

Fig 2: *Single Wheel Soil Imaging Testbed. Wheel travels from left to right with controlled slip along a belt-driven linear axis.*

This also allows for the transmission of a deadweight payload to be applied to the wheel. A 6-d.o.f. force/torque sensor is incorporated to measure the reaction loads in all directions. Sinkage is also measured via an optical encoder affixed to the vertical free linear axis. All telemetry; wheel angular velocity, travel velocity, slip, sinkage, load and power are logged simultaneously at 20Hz or higher.

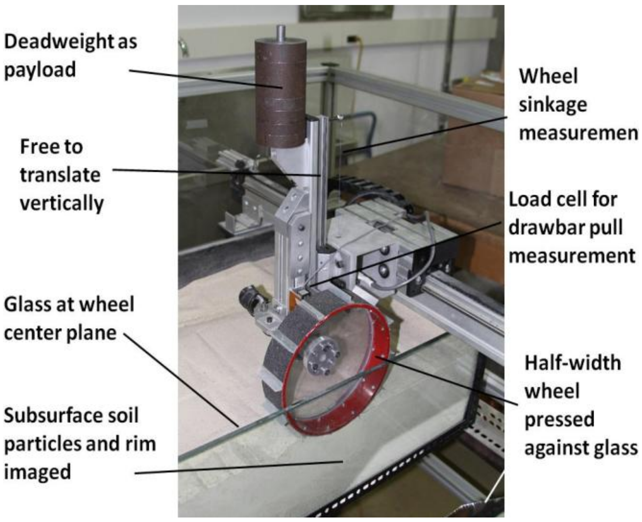

Fig 3: *Wheel module, carraige (travel axis) and glass-walled soil bin. A 12"x8" coss-section of soil below the wheel is imaged with a highspeed camera.*

The wheel for all shear imaging analysis expriments is pressed against a sheet of tempered glass that extends the depth of the soil bin. Of importance is the use of a wheel of half the width of the actual specimen of interest and the appliction of half the payload weight. This setup simulates a full wheel under unconstrained conditions, assuming that the unconstrained wheel has a plane of symmetry at it's centerline. The accuracy of this representation relies on having relatively low shearing resitance between the wheel and glass boundary. This is achieved by the use of tempered glass with a high hardness surface and by the low pressure of the soil particle against the glass wall.

The shearing analysis requires the ability to track soil motion. A digital SLR camera with a 50mm macro lens is used to image the wheel-soil interface, logging frames simultaniously with the rest of the telemetry. A frame rate of 8 frames-per-second is used and is sufficiently fast for the slow speeds of wheel travel applied (1.5inch/second). The camera is mounted perpendicular to the soil bin glass wall and travels with the wheel in the horizontal direction as the carraige moves. For most wheel specimens (9in to 20in diameter) a 12in wide by 8in high (soil depth) patch of soil is framed and able to capture the complete shear interface produced by the wheel in the regolith simulants that were used. External halogen flood lights at a high angle normal to the glass are utilized to illuminate the soil particles.

Image processing comprises of optical flow and clustering techniques. An overview of the process described herein is presented in Figure 4. The optical flow algorithm [8] tracks displacement of soil regions relative to a prior frame and calculates a motion vector at each pixel. Initial clustering separates each image into "soil" and "not soil" regions. Additional processing and output is continued only for "soil" regions. The magnitude of flow at each pixel of the soil regions is calculated from the optical flow vector fields. Soil flow is clustered into "significant" and "insignificant" magnitudes of motion. No explicit threshold is used to demarcate these clusters, but rather automatically adaptive clustering is used. The shear interface is derived from the boundary between significant and insignificant motions. Soil flow direction is calculated from the optical flow vector fields, for soil regions exhibiting significant soil flow. Soil flow in any direction (360 degrees) is visualized, and an additional boundary is identified at points where the soil transitions between forward and rear flow. Figure 5 is a sample output of the process, showing soil flow magnitude, shear interface between significant and insignificant flow, soil flow direction (within region of significant flow), and boundary between forward and rear flow.

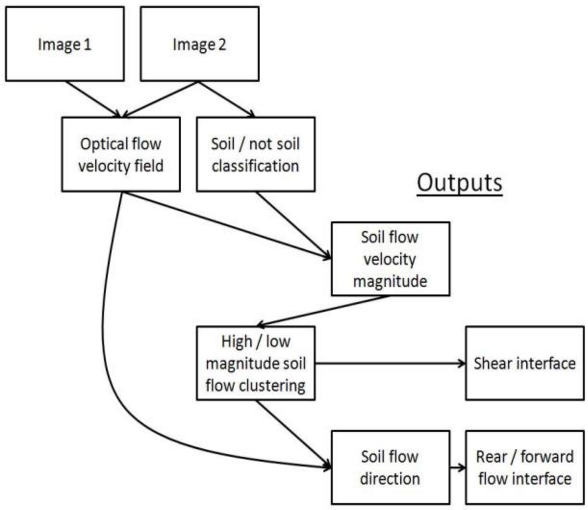

Fig 4: *Proccessing steps for image analysis to producesoil flow and shear interface output plots.*

2.2 Processed Results

The soil shearing plots generated during a single wheel experiment are used to identify the effect wheel parameters and design features have on performance. During operation of the wheel, traction is generated to produce thrust and ultimately travel. The net thrust, often referred to as drawbar pull [9], is the most widely used metric for tractive capability in soft soil. Other metrics, such as Power Number [10] are also used to assess the useful amount of work generated for a given energy input. These performance metrics are quantified by measuring external reaction loads and energy input. Although these metrics are critical for evaluation, there is little information provided that aids in investigation of the underlying principles that determine the metrics values. Observing the soil shearing planes allows for qualitative analysis of how soil structure develops and reacts thrust loads.

The shear interface is indicative of the soil failure process and type. Analysis of this and the flows present within the soil can aid with design of traction devices and study of terramechnic fundamentals. Figure 5 shows the processed results of a single wheel shear interace imaging analysis experiment. The Flow Velocity Magnitude and Flow Direction plots are used to analyze the wheel. These plots show processes typically present for a wheel operating in loose, cohensioless soil (at 20% steady-state slip for Fig. 5).

The flow velocity magnitude plot uses the optical flow velocity field measured between image pairs and clustering methods for classification to display the soil flow speed. These plots (Fig. 5, top) scale from dark blue (stationary soil) to red (representing the soil flowing at maximum speed,V_{max}). This type of plot allows for the evaluation of the soil flow due to shearing. The shear interface is a key indicator of the means by which the wheel produces traction. This term, for purposes of this study, is defined as the region (line or band like in shape) where soil transitions from measured shear displacement (flowing) to near static (not flowing).

The Flow Direction plot (Fig. 5, bottom) displays the direction of soil particle shearing as measured by the flow velocity field. The multi-colored wheel is the legend that maps color to direction with respect to the wheel coordinate frame. 'Dark blue' indicates soil particles moving completely horizontal in the left hand direction, opposite the direction of wheel travel. The direction of shearing aids in determining what type of soil failure process occurs, design feature that may contribute to the failure and the identification of

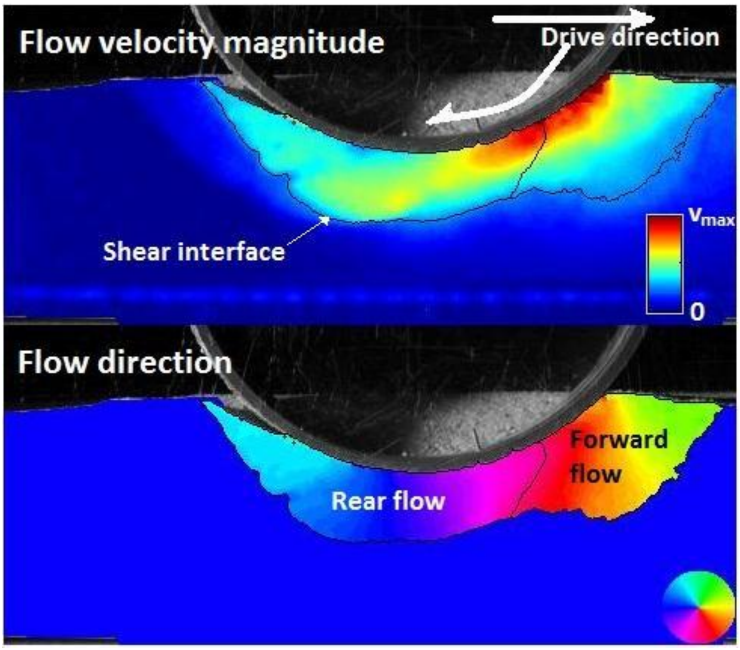

Fig 5: *Shear Interface Imaging plots. Plots show soil flow magnitude (top) and direction (bottom). Magnitude is plotted from dark blue (stationary soil) to red (representing the soil flowing at highest speed). Direction (within the shear interface) is plotted representing 360^o as shown in the legend.*

mulitple flows, such as resistive types at the wheel front. The seperation of two flows (Fig. 5, bottom), as detected by the developed analysis software, allows for the identification of forward flows and the measurement of the location of point of maximum shear stress along the rim. This occurs at the intersection of the wheel rim and flow separation point.

The analysis process used to study the soil behaviour of a wheel specimen is primarily qualitative for the time being. As an example of this process, the experimentation and analysis of the wheel shown in Fig. 5 will be described. The single wheel imaging testbed is prepared with GRC-1 lunar soil simulant [11] before each test run. This simulant was design for vehicle mobility experimentation, producable in mass quanitity by use of commercially available grades of sand. The soil is loosened to a state of lowest relative density and slighty compacted by use of a drop tamper to produce repeatable soil properties. The wheel speciment shown in Fig. 5 is rigid, 9in diameter by 2.2in wide (4.5in effective width), with the rim covered by course grain sandpaper. A 22lb payload is applied in the vertical direction (44lb effective payload). All experiments are analyized at steady-state response of the soil and reaction loads (although some time varying but periodic). The test run begins at static sinkage and then travels under a controlled slip rate for approximately five wheel diameters in distance. All rigid wheels (rough rim and lugged rim) tested quickly entered steady-state sinkage, reaction loading and soil shearing behaviour within the first wheel revolution. For all plots shown, unless otherwise indicated, the average values where calculated over the steady-state period of the experiment test run. The testbed controls the wheel slip while mainting a wheel tangential rim speed of 1.5inch/second by varying horizontal travel (carraige) speed. Most experiments, such as shown in Fig. 5, are evaluated at 20% slip. Generally, wheel peak performance in loose, granular soil occurs between 10-30% slip and as such, 20% was chosen as a point of study for most evaluations.

The plots generated by the example experiment just described provide useful information. It is immediatlely evident by what process the soil fails at the shear interface and the primary source of loss of traction. The shape of the shear interface and the point at which it originates at the rim and reaches the soil surface behind the wheel indicate a forced type failure due to wheel rotation (non-ground type failure). This is further supported by the direction of the flow at the shear interface. For this wheel, the soil shearing direction is near vertical at the front of the wheel and returns to the surface behind the wheel at a near vertical upward direction. These types of behaviours are typical of small diameter rigid wheels with mid-range performance where siginificant slip induced sinkage (slip-sinkage) is present. This leads to a high entrance angle of the soil-rim forward contact region. Additionally, the combination of sinkage at the rim leading edge and the downward direction of soil flow results in a forward resistive flow that is a mechanism for motion resistance. These types of observable, qualitative observations of soil behaviour under a wheel rim are valuable in understanding terramechanic fundamentals and the function of a specific wheel design.

The focus of this paper is to introduce the technique of improved shear interface imaging analysis. An overview of the investigation of common wheel design features and resulting soil behaviour through examples of experiments conducted will be utilized in the following section in effort to shed light on this technique.

3 Parametric Analysis

There is a set of important parameters commonly decided upon in the design of a wheel for planetary surface systems. Choices between rigid or compliant rims, tread surface parameters such as rough or lugged, and wheel geometry such as diameter. These all have significant results on the soil behaviour during operation of the vehicle and its traction performance. The study of the effect of some of these parameters was conducted and preliminary results are shared.

To study the development of net thrust produced by rigid wheels, soil shearing was investigated over a range of slip ratios, and over changes in wheel diameter, tread surface, and locomotion mode. The approach was to conduct a preliminary survey of design features that have effect on performance and attempt to associate soil shearing behaviour with gains or losses. The degree of wheel slippage affects not only the net thrust produced but also what state of soil behaviour the wheel produces. Figure 6 shows the net thrust-slip curve for a 9in diameter (2.25in wide) rigid wheel with a sand- paper like tread with a 10kg payload applied.

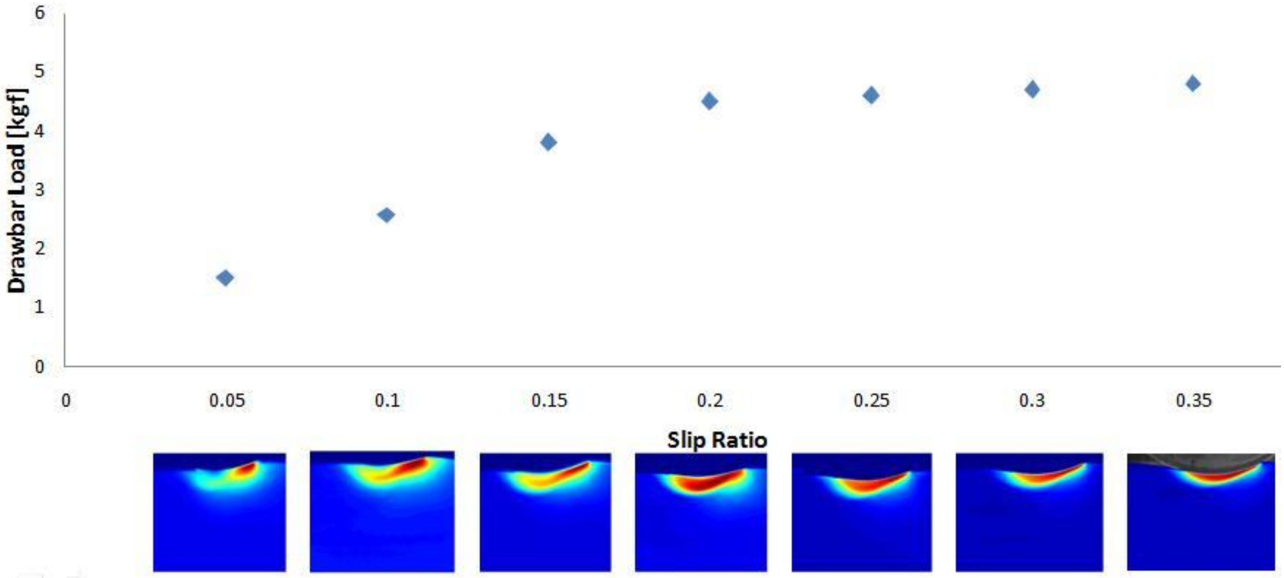

Fig 6: *Drawbar-Slip curve with corresponding soil flow magnitude plots at 5% slip intervals (see value above inset plots). Distinct changes in soil shearing behavior at key slip (0.2) and load points are observed.*

The shape of the curve is typical of most wheels in loose soils relevant to planetary vehicles.
There are distinct changes of the soil behaviour at key points of the drawbar-slip curve. Three important observations can be made: (1) The shear interface size and shape does not change much between 0.05 and 0.20 slip ratio although the drawbar pull produced quadrupled. (2) From 0.05 to 0.20 slip ratio, the soil shearing proces within the shear interface transitions from a broad gradient of shearing to a region with near zero gradient within (moving as a whole) and sharp gradient at the shear interface. (3) Lastly, above 0.20 slip ratio, the forward flow appears to diminish while the shearing zone (region within shear interface) begins to reduce in depth. There are a number of hypotheses that can be made from these observations. First, the shear interface shape and location may primarily be governed not by the applied drawbar pull load but by the shearing induced by the rotation of the rim. This is evident since even at low slip and low load (0.05 slip and lower), the extent of the soil is similar to that at 0.20 slip ratio. Therfore, it may not be the horizontal thrust loads that produce the soil failure but rather the tangential stress created along the rim due to torque applied by actuation. The second important hypothesis is that the knee in the drawbar-slip curve (at 0.20 slip in this example) may occur when the soil shearing is fully developed within the shear interface. I.e. Gains in net thrust by increased slip diminish when the soil begins to move through the shear interface as a single mass, and is therefore excavated from the ground.

To investigate the effect of the rotating rim on the generation of thrust, a study comparing push-roll locomotion to rolling locomotion was conducted. Push-roll like locomotion (use of walking and rolling wheels) has been demonstrated to produce high net thrust for increased locomotion capability [1]. Utilizing shear interface imaging analysis, it is shown that the soil failure type of a walking wheel was different from a rigid rolling wheel (Fig. 7). This figure shows the "general failure" mode created by a walking wheel. This type of soil failure, due to the minute degree of shearing required, is able to produce multiple times the thrust of a rolling rigid wheel.

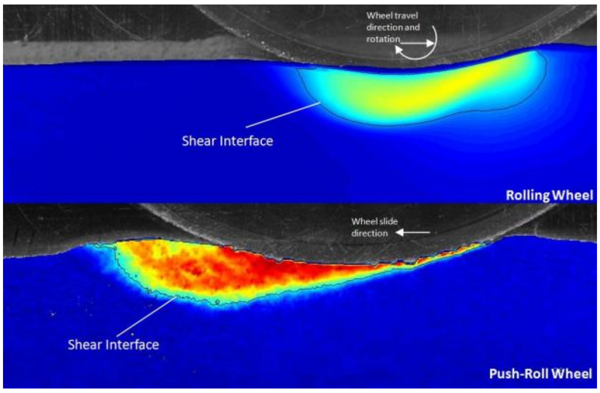

Fig 7: *Shear interface analysis comparing rolling wheel to push-roll locomotion (walking wheel). "Ground type failure" of the soil is observed for the walking wheel, identifying a source of tractive gains.*

The diameter of a wheel has a profound effect on the behavior of the soil shearing and the resulting tractive performance. An experiment comparing a 9" diameter rigid wheel to a 16" diameter rigid wheel of equal width, payload and slip is shown in Figure 7. The result ing tractive performance using the drawbar pull metric measured a 33% increase in traction for the larger diameter wheel. The behavior of the soil shearing is also observably different.

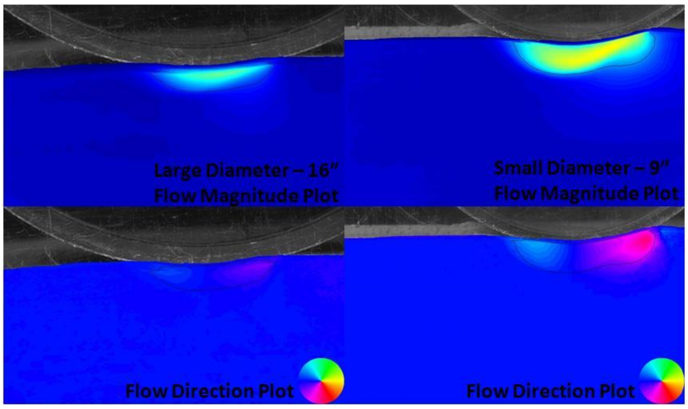

Fig 8: *Variation of shear interface with change in wheel diameter. Soil flow magnitude for both diameter wheels are equally scaled. The large wheel shows nearly horizontal flow compared to large changes in flow direction (down then up) under the small wheel.*

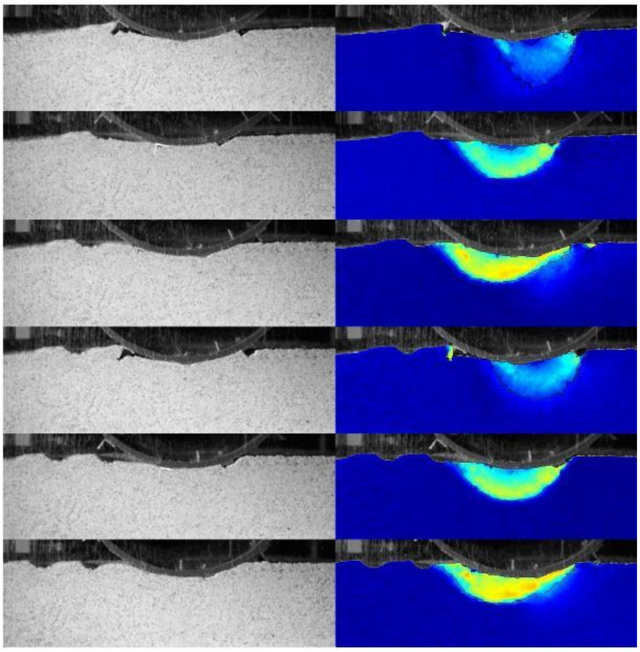

Fig 9: *Timelapse images of soil sheared by a wheel with lugs. The shearing is dominated by the leading lug, and exhibits distinct periodic soil motion as each new lug rotates into the soil.*

The large diameter wheel lacks an observable forward flow and the soil shearing is in a near horizontal direction. Lowered resistive flows may contribute to the increase in measured net thrust. The more unified flow in the direction of travel (horizontal) may also account for the increased net thrust. Overall the larger diameter wheel allows for greater net thrust and at the same time requires less disturbance of the ground below. The lower shearing magnitude is also evident for the large diameter wheel.

Lugs, also called grousers, are often employed in wheel designs for planetary rovers. The affect of soil shearing should be studied when analyzing lugs. Figure 9 shows the periodic nature of soil shearing due to individual lug effects. It appears that the lug at the front of the wheel entering the soil has the most dominant effect on the shear interface. The load may not be shared amongst all lugs in contact with the soil, but primarily by the lug at the front of the wheel. Experiments with very close spaced lugs were also conducted and showed similar results but with periodicity proportional to spacing. As the optical flow algorithm utilizes overlapping image pairs, high fidelity movies of the lug shearing effects can be utilized to observe individual lugs interacting with soil as the rim rotates. For comparative study of tread design and optimization, the shear interface imaging technique may be a powerful tool.

Compliant wheels may provide large gains in performance for future surface exploration missions. Drawbar pull testing of individual wheels and full vehicles with compliant wheels have shown high tractive and energy performance. The study of the effect on soil behaviour in the generation of thrust is essential.

Experiments were conducted using a 9in diameter by 4in wide compliant wheel with sandpaper-like tread. The compressible foam material used in construction of the wheel did not produce uniform contact pressure as a pneumatic tire could, but a flat contact length was achieved.

Many observable differences between the rigid wheel and compliant were present in Figure 10. The direction of the soil displacement is nearly horizontal. This may occur due to the extraordinary low sinkage and the flat shape of the contact along the length of the deformed rim.

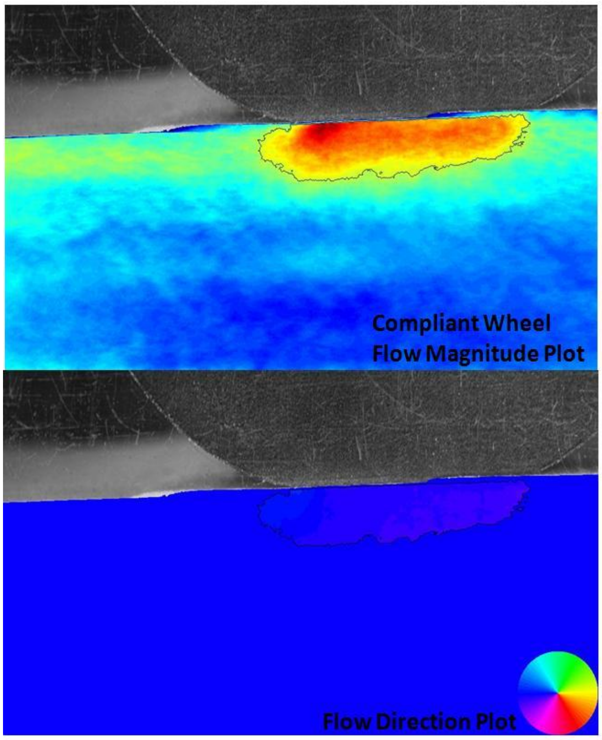

Fig 10: *Compliant wheel shearing analysis showing low sinkage, no forward flow,low shearing magnitude and completely horizontal motion of soil displacement (may all be within compaction process)*

It should be noted that the soil flow magnitude shown in Fig 10, though shown in full relative scale up to maximum speed as always, is actually an order of magnitude lower than with the rigid wheel. As such, the soil shearing was so low, it appeared to be within the compaction regime of the soil simulant (as initial state was relatively loose). This limited study illustrates the importance of study the specific shear interface and soil behaviour of a compliant wheel design when designing for high performance wheels. An understanding of how the observed behaviour of the wheel-soil system affects performance will aid in developing more capable traction systems.

4 Conclusion

A technique for studying wheel-soil behaviour and analyzing shear interfaces was developed and demonstrated. The technique can aid in design of high performance systems and increase the knowledge of terramechanics for wheels in soft soils. Examples investigating common wheel design parameters show a wide variation of shearing behaviour that is intimately linked to traction performance.

The technique has been used for detailed quantitative observation of:

- distinct changes in soil shearing behaviour at key slip and load points
- distinct failure modes beneath rolling and pushed wheels
- variations in soil flow magnitude and direction between wheels of varying diameter and compliance
- discrete periodic soil motions induced by lugs

The state of maturity of the measurement tool (software and hardware) is high enough that it can now used by designers of mobility platforms for soft soils. Additionally, the technique provides the benefit of a different perspective on terramechanics fundamentals.

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