

**Tire Performance Estimation Under Combined Slip and Empirical Parametrization of the
Tire Rut on Dry Sand**

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ABSTRACT

Applications like military, agriculture, and extra-planetary explorations require the successful navigation of vehicles across different types of terrain like soil, mud, and snow. As the properties of the terrain heavily influence the interaction with the tire, it is necessary to characterize the terrain from a tire performance and vehicle mobility perspective. Failure to properly understand the tire-terrain interaction can lead to undesirable conditions like loss of vehicle mobility due to excessive sinkage. As a result, it is essential to understand the tire terrain interaction between an off-road tire and a sandy terrain.

This study was done to assess the performance of tires in both pure slip (only traction and braking) and combined slip conditions (steering and acceleration). A single-wheel indoor test rig was used to conduct tests under different conditions and a force transducer was used to capture the forces and moments generated in the tire hub. In addition to this, the tire footprint was captured with the help of a light-based 3-D scanner. Key parameters were defined in the 3D scan, and these parameters were correlated to the input test conditions. Additionally, a grid of force sensors was made, and measurements of the normal force acting at a depth below the undisturbed terrain were taken. Inferences were made about the linear speed of the wheel and the length of the pressure bulb under the tire.

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General Audience Abstract

Several applications like military, extra-terrestrial exploration, and motor racing require vehicles to navigate off-road terrains like soil, snow, and ice. The tire interacts with these off-road terrains very differently from the way it interacts with the road. It is important to understand this interaction correctly as this interaction generates all the forces needed by a vehicle to perform various maneuvers like acceleration, braking, and turning. If not accounted for properly, there can be undesirable conditions like loss of vehicle mobility due to excessive sinkage in sand.

Tests were performed where an off-road tire ran on a non-cohesive, loose soil under different slip ratios, slip angles, and camber angles in an indoor test rig. The forces and moments acting on the tire during the tests were measured and its variation with input conditions was studied. A light-based 3D scanner was used to capture the tire rut profile on the soil after each test. The important parameters of the tire rut were defined and the variation of these parameters with input parameters were studied. Additionally, the stresses developed below the soil surface were measured with the help of a sensor grid, which was also used to verify the linear speed of the tire and infer the length of the zone inside the soil that is affected by the tire.

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Nomenclature

<u>Symbol</u>	<u>Name</u>	<u>Unit</u>
V_x	Longitudinal Speed of the rig	[m/s]
r_o	Wheel Rolling Radius	[m]
ω	Wheel Rotational Speed	[rad/s]
λ	Wavelength	[mm]
r	Maximum Rut depth	[mm]
V_p	Penetration Volume	[cc]
V_d	Displaced Volume	[cc]
F_x	Longitudinal Force	[N]
F_y	Lateral Force	[N]
M_x	Overturning Moment	[Nm]
M_z	Self-Aligning Torque	[Nm]
r_p	Differential Peak Height	[mm]
r_t	Total Rut Height	[mm]

Chapter 1: Introduction

1.1 Background and Motivation

There is a wide variety of applications that require vehicles to cross unconventional or off-road terrains like military, agriculture, mining, extra-terrestrial applications, racing sports and so on, which are becoming increasingly relevant with every passing day. The requirements of these vehicles are different as compared to that of on-road vehicles. For example, mobility and reliability are more important as compared to efficiency in military applications. Off-road terrain can be classified into different types of terrain like sandy loam, clay, ice, snow, vegetative terrain, lunar soil, etc. Each terrain behaves vastly differently under different parameters like moisture, compaction, etc. In addition, there is a higher level of uncertainty in these terrain properties as compared to regular roads, making the whole field very complex. As the properties of the terrain affect both the mobility and performance of tires, it is necessary to find an appropriate characterization of the terrain and study the correlation of the various terrain parameters with tire performance in different conditions, such as acceleration, braking, steering, etc. Without proper consideration, it may result in situations where the vehicle becomes trapped due to excessive sinkage, resulting in mission failure and the potential loss of property or life.

Terrains made up of fine sands which have low cohesion, pose problems generating sufficient traction to the tires to generate motion. It can also lead to high sinkage of the tire in the terrain, which can cause complete mobility loss. In addition to this, there is a deformation of the terrain surface, leading to the generation of tire ruts, which changes the landscape a lot and will have impacts on a pack of vehicles trying to follow a leading vehicle. This study proposes the use of 3D

scanners to capture the tire rut profile and correlate the parameters of the 3D scan to the suspension parameters of the tire and its performance.

1.2 Research Approach

The objective of this research is to conduct experimental tests on an off-road tire using a single wheel tester on loose sandy terrain. The force and moment acting on the tire hub will be measured and compared to the input conditions and then correlated with the different shapes and parameters obtained from 3D scans of the tire rut profile. The terrain will be instrumented to measure the forces exerted by the tire at a depth below the terrain surface.

1.3 Thesis Outline

Chapter 2 discusses the relevant literature concerning soil testing done in the past and reviews what parameters impact tire performance. Chapter 3 discusses the various equipment used in this study. Chapter 4 contains the methodology, while chapter 5 contains the post-processing. Results obtained from the forces and 3D scan output are discussed in Chapter 6. Chapter 7 discusses the soil instrumentation with force sensors and discusses the results obtained. Chapter 8 contains the inferences from the study. Chapter 9 concludes the whole study, highlights the novel contributions, and mentions future scope of this research.

Chapter 2: Literature Review

This chapter contains the summary of relevant literature that was reviewed for various aspects of the project.

2.1 Tire-soil interaction

All the tests performed in this research uses the SAE coordinate system shown in Figure 2.1. The measurements taken by the wheel force transducer are about the tire coordinate system.

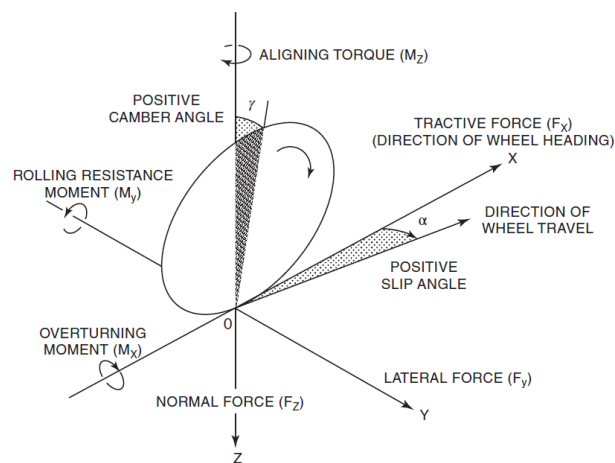


Figure 2.1. SAE coordinate system [2]

Given the distinct physics of tire-soil interaction compared to tire-road interaction, it is imperative to comprehend this interaction and define terms that offer a more precise explanation of the dynamics involved.

The total tire stiffness is the sum of the carcass stiffness and the inflation pressure. The terrain stiffness depends on the rigidity of the terrain. In on-road conditions, the road acts as a rigid surface and thus has very high stiffness. Off-road terrains like soil (e.g., sand) and snow are not rigid, and their stiffness depends on various properties like compaction, moisture, cohesion, internal friction angle, etc.

If the terrain stiffness is very high compared to the total tire stiffness, the tire will be in the elastic mode of operation. When in elastic mode, the tire will deform when it comes in contact with the terrain. If the total tire stiffness is very high compared to the terrain stiffness, the tire deformation is low and can be considered as a rigid member [1],[2]. However, other literatures see that the tire can have a non-zero deflection and operate in elastic mode even in such conditions. As it can be seen in Figure 2.2, unlike the flat contact patch observed in on-road conditions, the contact patch consists of an initial curved portion at the leading edge, followed by a flat portion, followed by a curved portion at the trailing edge [31].

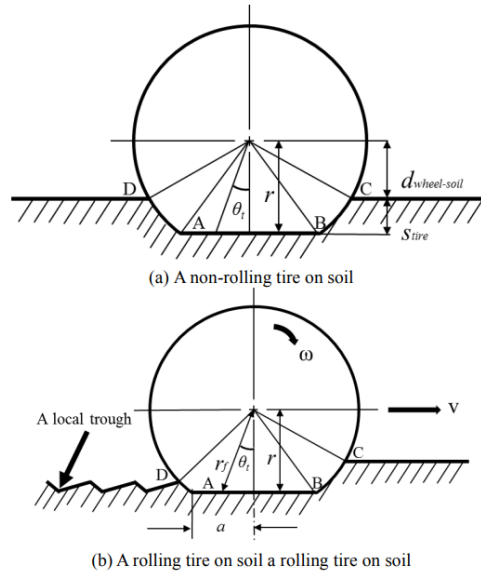


Figure 2.2 Tire Soil Interaction [31]

The tire leaves a rut after passing through a terrain, which is the plastic deformation of soil. The rut depth is defined as the vertical distance between the rut bottom and the undisturbed level of the terrain (before the tire passes over it).

Sinkage is defined as the distance between the lowest point of the terrain in the tire contact patch and the undisturbed level of the soil, when the terrain is still under pressure from the tire, when it is still passing over the terrain. Sinkage can be of two types: (1) Static sinkage, which is the

deformation of the terrain only due to normal load. (2) Slip sinkage, which is the additional sinkage that occurs when there is a slipping action between the tire and terrain.

The sinkage will be greater than the rut depth at the same point of soil due to the expansion of soil when it is unloaded. The expansion of the soil can be neglected if the soil is plastic and there is no elastic behavior [2]. The rut can also comprise the soil excavated from the leading edge of the tire which is then deposited to the trailing edge.

The radius of tire under unloaded condition (in air) is defined as the unloaded radius of the tire. The radius of the tire when it comes in contact with the terrain under static condition and is under a normal load is defined as the loaded radius. The effective rolling radius is defined as the ratio of the linear velocity of the wheel (longitudinal/forward speed) and the angular velocity of the wheel [3]. In other literatures, this is also referred to as the effective tire radius [4], effective radius or rolling radius [5]. This definition of effective rolling radius is valid in traction, braking and towing modes. The rolling radius is a special case of effective rolling radius, which is considered as the zero condition, and is used for calculation slip ratios. Different literatures define these zero conditions in two different ways: (1) self-propelled condition, (2) towed condition/free-rolling condition. In the self-propelled condition, torque is applied to the wheel to achieve zero drawbar pull. Literatures [6], [7] define rolling radius in this manner. In towed conditions, zero driving or braking torque is applied to the wheel to achieve free rolling. Literatures [2], [8] define rolling radius this way. For this dissertation, rolling radius was defined in the self-propelled condition and not in the towed condition.

To generate traction(acceleration) or braking, a differential is required between the tangential velocity of the tire treads and the ground velocity. It is due to this difference that force is acted

upon the wheel by the ground. This difference is quantified by the Slip ratio. Mathematically, slip ratio is defined as in Equation 2.1.

$$\text{Slip Ratio} = \left(1 - \frac{V_x}{r_o \omega}\right) \times 100\% \quad 2.1$$

where V_x is the longitudinal velocity in m/s, r_o is the rolling radius in m and ω is the angular velocity in rad/s. When there is a positive slip ratio, a positive driving torque is applied to wheel and a longitudinal tractive force is generated in the forward direction. This forward force is defined as the gross tractive force, which occurs from converting the axle torque to a longitudinal force [7]. In addition to this, forces are generated in the backward direction due to motion resistance, which is also known as rolling resistance [9]. The motion resistance can be classified into internal motion resistance and external motion resistance. The internal motion resistance occurs due to hysteresis of the tire rubber and energy dissipation [2]. The external motion resistance is due to compaction resistance and bulldozing resistance. Compaction resistance occurs due to the energy lost in increasing the bulk density of the soil and the bulldozing resistance is the resistance offered by the soil which accumulates in front of the tire when traversing through the terrain. The net tractive force (sometime referred to as tractive effort [2] or thrust force [11] or Drawbar pull (DP) [12] is the gross tractive force minus the motion resistance [10]. Tractive force can be determined by integrating the horizontal component of shear stress in the tire-contact patch [10]. The drawbar pull coefficient [13] is the ratio of DP to the dynamic tire load. The dynamic tire load can vary from the static tire load due to change in tire radius from loaded radius to effective radius during motion and effect of weight transfer during the run.

2.2 Soil properties and their measurement

The soil properties like grain size, moisture content, and compaction affect the performance of a tire while traversing through it. These are described with the help of parameters like bulk density, cone index (CI), remolding index (RI), cohesion and friction angle. Soil can be tested in the lab in accordance with certain standards to obtain these parameters. The CI is determined with the help of a penetration test. A cone penetrometer is inserted into the soil at a constant velocity to obtain the CI [24]. The cohesion and friction angle are determined from the results of multiple shear tests, selected based on the grain size and type of shearing. The triaxial shear test is the most used test. In addition to these tests, further tests are needed to obtain the pressure-sinkage and stress-shear displacement relations of the soil.

2.3 Experimental methods to measure tire-soil interaction.

Experimental tests performed for tire off-road tests in the past mainly focused on measuring the forces, moments, and deformations of terrain. The tests could be done either in the field or in lab environment [14],[15]. The tests can be done in towing mode, driving mode, or braking mode [8], [16]. The lab tests are performed in large bins containing the soil, while field tests are done on a selected outdoor area which is naturally available. The lab tests usually allow more control and show more repeatability in the terrain properties and tests outputs as techniques can be used for achieving the required parameter of the terrain like compaction and moisture, which are more difficult to control in the field. However, the lab tests limit the longitudinal speeds due to the space constraints that accompany the indoor lab tests. Most setups are equipped with wheel-force transducers to measure the force and moments acting on the wheel hub. Some transducers only measure some of the forces like normal load and longitudinal force while others can measure all the 6 forces and moments. A few setups are also equipped with sensors to measure additional

parameters like the tire sinkage and soil displacement. Few setups have arrangements with a plexiglass wall in the soil bin, which allows for capturing the shearing of the soil with high-speed cameras. Some tests have also deployed the use of pressure pads which can be used to capture the pressure distribution in tire-contact patch in low slip ratios. Attempts have also been made to instrument the tire itself, to measure more accurate data about the loaded and effective rolling radius, deflections and pressures. Wireless Internal Tire Sensors (WITS) comprised 8 optical sensors mounted along the circumference of the tire to achieve this [17]. Some studies have also attached pressure transducers to the tire tread to measure the normal stress at contact patch [19] and attaching three such sensors in different orientations could measure normal, lateral and longitudinal stresses [20],[21], which can be used to get stress as a function of angular position and location in contact patch. Image processing techniques have also been used to capture the real time rut depth with the help of two cameras, one mounted in front of the tire and other in the rear [18].

2.4 Inflation Pressure

Studies have been done on the combined effect of inflation pressure and normal load on different types of terrain and tires. Some lab tests performed in the past showed that an increase in inflation pressure led to decrease in the rolling resistance on clay loam, and the influence of the inflation pressure increased at higher loads [14], while other studies showed that the motion resistance first decreased and then increased with decrease of inflation pressure on sandy clay loam [22]. Another field test showed that decreasing the inflation pressure had significant improvement on the tractive performance in paddy field with stubble but had lesser effect on a concrete field and on rotary cultivated sandy loam [13].

2.5 3D scanning and footprint measurements

Various methods previously used for 3D scanning were compared by Talbot, et al [26]. One approach uses the phenomenon of photogrammetry, which captures images from different reference maps to obtain 3D coordinates of a surface. The resolution of the image affects the accuracy of the 3D footprint generated along with the color and texture of the terrain. LiDar (Light Detection and Ranging) technology utilizes light reflected from the source to measure the distance knowing the time taken between the emission of light and the sensing of light after reflection from the surface. This method can work in areas with low light, but the range depends on the instrument being used. Some studies have used Ultrasound to create a 3D map of the surface, however the larger wavelengths of sound lead to lower resolutions. Depth sensing cameras are more suitable for outdoor applications, as cameras can work for mobile applications. 3D scanners can be used to generate cloud point data of the surface, which can be exported to a CAD file. One study used time-lapse photography to capture the static footprint and the rut left behind by a rolling tire. The obtained 3D model was validated against a sand cone test and a 4%-7% error was found [27]. Farhadi et al [28] found a high correlation ($R=0.933$) between the contact volume and rolling resistance under various inflation pressures, normal load, and soil moisture. Ptak et al. [29] used 3D scanner to study the variation of contact patch in static condition with normal load and inflation pressure.

Chapter 3: Testing Equipment and Tools

3.1 Terramechanics Rig with WFT

The Terramechanics test rig used for this project is part of the Terramechanics, Multibody and Vehicle Systems (TMVS) Laboratory at Virginia Tech. It was made in 2008 and it was designed for conducting single wheel indoor tests that has capabilities to perform tests in controlled conditions. The rig has the capabilities to perform tests in different terrains like solid ground, soil, clay, ice, and snow. The test rig is illustrated in the Figure 3.1.



Figure 3.1. Test Rig at TMVS Lab, Virginia Tech

The test rig comprises a bed measuring 25 feet in length, 6 feet in width, and 4 feet in depth. The test rig is vertically divided into layers by C channels. This allows the use of a reduced terrain volume when excessive terrain depth is not required. The rig features a carriage assembly that moves longitudinally along its length. This movement is facilitated by a belt and pulley system, driven by an electric motor through a controller. To guide the carriage, a linear bearing is positioned on one side, while roller bearings on the other accommodate misalignments. The carriage consists of a fixed part and a moving part, with the latter having vertical freedom for wheel movement during testing. Guide rails and linear bearings enable this vertical motion. The wheel is mounted on a hub that is connected to a pneumatic clutch and hydraulic brake systems. Controlled wheel

rotation is facilitated by a second electric drive motor. The test rig is operated with the help of manual controller that has dedicated buttons for performing different functions. Figure 3.2 shows the controller.



Figure 3.2. Controller for operating the test rig.

The normal load on the wheel is applied through air springs. The load is controlled with the help of a proportional valve and a feedback circuit using NI Labview software. The minimum applicable load is constrained by the self-weight of the moving part of the carriage, set at 4000N. While lower loads can be applied using an offloading system, The maximum load that can be applied by the air springs is 8000N.

The rig allows testing under various slip ratios, toe angles, and camber. Slip ratio is adjusted independently by setting linear carriage speed and wheel rotational velocity, through the PicPro software. Toe and camber are set by using links of different lengths between carriage and wheel hub. The range of toe angle and camber angle is $\pm 30^\circ$ and $\pm 8^\circ$ respectively. Maximum limits may be influenced by wheel dimensions and the presence of partitions in the rig.

The rig is equipped with Kistler P650 system, a 6-axis Wheel Force Transducer that captures force and moment data. However, due to a problem in the calibration of this sensor, a new Wheel Force Transducer was used for this testing.

3.2 Modifications on Rig

3.2.1 MSC Wheel Force Transducer

The MSC LW12.8-45, supplied by Goodyear, was used as the wheel force transducer for capturing the three forces and the three moments in this test. With a maximum load capacity of 40kN in the longitudinal and vertical directions, and 26.7kN in the lateral direction, it utilizes strain gauges to collect data. The slip-ring based telemetry system facilitates the transfer of data to a data acquisition system, also provided by Goodyear. The setup can be seen in Figure 3.3.



Figure 3.3. MSC LW 12.8-45 sensor with data acquisition system

3.2.2 Partitioning of the test rig

For these tests, a partition was installed to create a 3 feet wide section within the rig, effectively restricting the amount of sand utilized. The partition can be seen in Figure 3.4. The achieved depth of the soil was 8 inches, and the length of the section was maintained at 25 feet. To ensure proper containment, a plastic sheet was positioned atop the C-channels in this region and securely taped to the rig, preventing soil from seeping into bottom layer from the top layer.



Figure 3.4. Partitioned Rig with soil on one side

3.3 Offloading System

As these tests required a lower normal load on the wheel than the self-weight of the carriage (4000N), an offloading system was implemented. Figure 3.5 shows the offloading system.



Figure 3.5. Offloading system

This involved the use of a cable-pulley system to suspend gym weights through a rod. The diameter of the cable was chosen based on the maximum expected load of the gym weights. A custom spacer was designed and manufactured to achieve the necessary clearance between the gym weights and the body of the rig and carriage. The cable length was carefully selected to minimize swaying of the weights during the initiation and stoppage of carriage movement. The weights were secured between the two cables to prevent sliding out of the rod.

3.4 Tire

The BKT AT 171 was selected as the tire for conducting tests. This is an off-road tire that is designed for mud-boggers. The tire has an overall diameter of 785 mm and section width of 211 mm. It has a rated load capacity of 450 kgs at an inflation pressure of 1.4 bar. To mount this tire onto the LW-12.8-45 system, a modified 16x6.5-inch rim was utilized. The tire can be seen in Figure 3.6.



Figure 3.6. BKT AT 171 tire.

3.5 Terrain selection and properties

For the testing of this tire, the need for fine dry sand led to the consideration of two available options in the lab: the lunar regolith simulant OPRUGRC1 and sandy loam. OPRUGRC1 was ultimately chosen as the terrain for the study due to its characteristics of low cohesion and small particle size, presenting a worst-case scenario for traction behavior. Another factor in favor of OPRUGRC1 was its existing presence in the test bed, along with the already established enclosures and safety precautions. This choice eliminated the necessity to transfer the soil into containers and refill the rig with a new soil type. The OPRUGRC1 soil used in this study was made by Off Planet Research LLC and provided to Virginia Tech by Goodyear.

This soil was based off GRC-1 simulant, which was created by Dr. Heather Ann Oravac [32]. The main constituent of the OPRUGRC1 is crystalline silica with very few traces of aluminum oxide and iron oxide. Appendix contains the Safety Data Sheet for this soil. The majority particle size is 2 mm but some of the particles are under 25 microns. The grain size distribution of GRC-1 can be seen in Figure 3.7. The specific gravity of the GRC-1 is 2.583 and its bulk density is between 1.6-1.89 g/cc. The angle of internal friction lies between 29.31°-48.16° and the cohesion in the range of 1 kPa, depending on the bulk density of the sample, from triaxial tests, at a strain rate of 0.5 percent of axial strain per minute.[32]

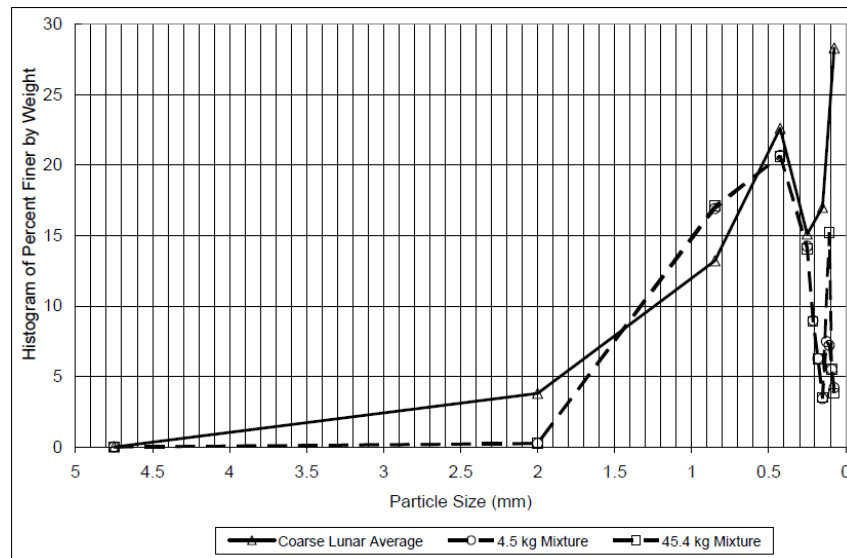


Figure 3.7. Particle size distribution of GRC-1.[32]

3.6 Terrain Preparation and compaction measurement system

To perform tests that were repetitive in nature, it was necessary to achieve consistent compaction of the soil every time the test was performed. This was done by using a shovel and leveller. A hammer and roller system were also available, but were not required for this project, as no compaction was done on the soil while preparing it.



Figure 3.8. Shovel and leveller used for soil preparation.

Soil compaction was assessed using a Cone Penetrometer Test (CPT). The CPT measured the force needed to steadily advance the cone of the penetrometer to a predetermined depth at a constant velocity of 2 cm/s. This penetration resistance was measured by the strain gauge present inside the penetrometer. For this study, measurements were taken up to a depth of 100 mm. It is important to note that there is some operator dependency in this process, as the CPT was manually pushed into soil, making it difficult to maintain a consistent velocity while insertion. The cone penetrometer used for these tests is the Humboldt HS-4210 Digital Static Cone Penetrometer [29], which can be seen in Figure 3.9.



Figure 3.9. Humboldt HS-4210 Digital Static Cone Penetrometer

3.7 3D scanner

For capturing the tire footprint left after each test, a 3D scanner was employed. Figure 3.10 shows the Einstar Shining 3D, which was used for this. This structured white light-based handheld 3D

scanner was chosen due to its excellent depth accuracy of 0.1 mm and sufficient stability, ensuring accurate capture of footprint data even when used in a handheld manner.



Figure 3.10. Einstar Shining 3D Scanner

3.8 Enclosures and safety precautions

In the preceding project, GRC-1 was employed for conducting traction testing. The same soil was retained inside the rig for the current project due to its suitability for the planned studies and the readiness of the terrain in the rig. However, since the terrain comprises 99% crystalline silica, which is hazardous when inhaled in high concentrations, the Environmental Health and Safety department at Virginia Tech suggested specific safety measures. The following preventive actions were implemented during the previous testing were continued for this project.

The first hazard was the spread of airborne silica to surrounding equipment and individuals working around the area. This was eliminated by building a safety enclosure with the help of General Motors by putting up wooden structures which were used as anchors to cover the surrounding space of the rig with a plastic enclosure. Figure 3.11 displays the enclosure built.



Figure 3.11. Enclosure around the test rig

To ensure the safety of personnel within the enclosure, Powered-Air Purifying Respirators (PAPR) were employed. Additionally, Tyvek suits, shoe covers, and hand gloves were used to prevent silica from settling on clothing and to avoid skin irritation. To minimize the concentration of silica in the air, a negative air machine was incorporated into enclosure, taking care to disperse it in an open area.



Figure 3.12. Safety Equipment used. (a) PAPR (b) Negative air machine (c) Tyvek suits

The Environmental Health and Safety department conducted air quality monitoring during the process of emptying the sand into the rig, which was anticipated to be the activity that will generate maximum air borne silica. The results indicated silica concentrations of $480 \mu\text{g}/\text{m}^3$ near the rig and $85 \mu\text{g}/\text{m}^3$ near the negative air machine. Given that the Permissible Exposure Limit (PEL) set by OSHA is $25 \mu\text{g}/\text{m}^3$, it underscored the necessity for PAPR usage as per the initial assessment. Subsequent monitoring was done throughout the duration of the project under various conditions

to make sure that the air outside the enclosure is not contaminated and to determine filter change interval of PAPR.

Chapter 4: Methodology

This chapter covers the various steps undertaken as a part of this testing.

4.1 Design of Experiment

This subsection outlines the conducted tests and the reasoning behind their selection. The testing process followed a phased approach, with insights from each phase informing the decisions for subsequent tests. This iterative methodology allowed for a systematic and informed progression of the testing procedures.

The initial testing phase focused on pure traction tests, i.e. at zero slip angle and zero camber. The objective of these tests was to obtain the traction behavior of the tire with varying slip ratio.

Initially, tests were conducted at a normal load of 4000N. Table 4.1 lists these tests. However, anomalies (discussed in section 6.1.1.1) were observed at higher slip ratios, prompting an investigation into potential causes. It was hypothesized that the observed unnatural behavior might be attributed to the presence of boundary effects due to high sinkage at this load.

Table 4.1 DOE of phase 1 tests

Normal Load(N)	Inflation Pressure(psi)	Slip Ratios (%)
4000	20	-65,-60,-40,-25,-15,-5,0,5,10,20,25,30,40,45,50,60,65

To eliminate the effects of boundary conditions, the subsequent phase of tests was performed at a reduced normal load of 2000N. This lower load addressed the concerns related to higher sinkage and thus facilitated testing at elevated slip ratios. Consequently, further tests were carried out at this adjusted normal load. Table 4.2 lists the tests that were performed as a part of this phase.

Table 4.2. DOE of phase 2 tests

Normal Load(N)	Inflation Pressure(psi)	Slip Ratios (%)
2000	20	-65,-60,-40,-25,-15,-5,0,5,10,20,25,30,40,45,50,60,65

The next testing phase was conducted to examine the performance of the tire in combined slip conditions, i.e. a combination of slip ratios, slip angles, and camber angles. Considering that the behavior of slip ratios had been previously quantified in the initial phase of tests, a decision was made to limit the variation to three slip ratios. However, for slip angles and camber angles, a more comprehensive approach was taken, with five camber angles and four slip angles selected for this phase of testing. The detailed list of tests performed in this phase is presented in Table 4.3. All tests were repeated twice to ensure the correctness of data.

Table 4.3. DOE of phase 3 tests

Normal Load(N)	Pressure(psi)	Slip Ratio (%)	Slip Angle(deg)	Camber(deg)
2000	20	0,20,50	0,6,10,20	-4,-2,0,2,4

4.2 Terrain preparation

The first step in preparation of the terrain involves shoveling. The shovel was used to manually remove any stress history and compaction in the soil due to previous tests. Figure 4.1 shows the terrain after shoveling.



Figure 4.1. Terrain after shoveling.

Following the shoveling step, the next step of soil preparation entails using a leveler to achieve a smooth surface with a repeatable terrain depth. Holes were drilled on the leveler to facilitate attachment to the rig to achieve the required terrain depth in the test bed. Subsequently, it was securely mounted on the rig using nuts and bolts, and its forward movement was facilitated by the forward motion of the test rig. This process ensured the creation of a consistently smooth and leveled surface with repeatable terrain depth and compaction. Figure 4.2 shows the levelled terrain.



Figure 4.2. Levelled terrain.

4.3 Terrain compaction measurement

After the terrain was prepared, the compaction of the terrain was measured with the help of Humboldt HS-4210 Digital Static Cone Penetrometer. The least count of the penetrometer is 1 lbf. The penetration resistance measured was used to calculate the cone penetrometer gradient, which

is obtained by dividing the penetration resistance by the depth. This gradient can be used as an indication of the soil bulk density, and hence the soil compaction.

Measurements were taken at 10 points that were spread along the length and width of the prepared terrain. Table 4.4 lists the values of the measured cone penetrometer gradient.

Table 4.4 Cone Penetrometer Gradient values

	Penetrometer Gradient (kPa/mm)											
Depth(mm)	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9	Point 10	Average	SD
0-40	0.74	0	0.74	0	0.74	0.74	0	0.74	0	0.74	0.44	0.36
40-60	1.49	1.49	2.97	1.49	2.97	1.49	2.97	4.46	1.49	4.46	2.53	1.16
60-80	2.97	1.49	2.97	4.46	4.46	2.97	4.46	2.97	4.46	2.97	3.42	0.95
80-100	2.97	1.49	5.95	7.43	4.46	1.49	7.43	4.46	7.43	2.97	4.61	2.25

As it can be seen from Table 4.4, the compaction of soil is quite low. Maximum value of penetration resistance was measured to be around 297 kPa, which is approximately taken as lower level of compaction by Rui [10]. Also, the compaction is not uniform throughout the depth of the soil and higher values of penetration resistance and gradients are obtained at the bottom.

4.4 Test Rig setup

This subsection explains how the different parameters were set before each test.

4.4.1 Normal Load

Two different normal loads were applied in these tests. For the 4000N normal load, the offloading system was not utilized; instead, the self-weight of the carriage itself was sufficient to achieve the required normal load.

In the case of the 2000N normal load, the offloading system came into play. After some trial and error, it was determined that hanging gym weights of 900 lbs provided the desired normal load of 2000N.

Notably, no normal load controller was employed to observe changes in the vertical force (F_z) during the run. The weights were added before the commencement of tests with a normal load of 2000N and remained unchanged for all subsequent tests.

4.4.2 Slip Ratio

4.4.2.1 Linear Speed of the carriage

Consistency was maintained in the linear speed of the carriage, set at 0.5 kmph, throughout all the tests conducted in this study. This speed was then converted into ladder units using the designated conversion factor in the PicPro software, and the corresponding values were entered into the software for accurate test execution. Table 4.5 lists the conversion factors used.

Table 4.5 True units to Ladder units' conversion table.

	True units	Ladder units
Longitudinal speed	1 cm/s	34515.9285 LU/min
Wheel motor speed	1 rad/s	572957.7684 LU/min

4.4.2.2 Estimating zero condition and rolling radius

The initial step involved determining the rolling radius(r_o) of the wheel at each normal load. This was achieved through a trial-and-error process, wherein the test was repeated with different values of wheel speed(ω), and by keeping the longitudinal speed(V_x) constant. Following each trial, the data recorded by the force hub was processed to examine the value of longitudinal force(F_x) in the run. The wheel speed corresponding to the condition where the value of F_x was closest to 0 was selected as the zero condition, with the wheel speed ultimately set at 0.38 rad/s. The rolling radius at this normal load was calculated at this condition by using Equation 4.1.

$$r_o = \frac{V_x}{\omega} \text{ (In Free Rolling condition)} \quad 4.1$$

where r_o is the rolling radius in m, V_x is the longitudinal velocity in m/s, and ω is the angular velocity in rad/s. The rolling radius obtained was 14.35 in.

4.4.2.3 Setting wheel speed and slip ratio.

As per the slip ratio that was selected for each run, the wheel speed was calculated using Equation 4.2.

$$\omega = \frac{V_x}{r_o \times (1 - 0.01 \times \text{Slip Ratio})} \quad 4.2$$

Like the linear speed, this wheel speed was then converted into Ladder units as per Table 4.5 and was entered into the PicPro software.

Thus, by setting both the carriage speed and wheel speed relative to each other, the required slip ratio was set.

4.4.3 Slip Angle

The slip angle was set with the help of links of specific length that were available in the lab. Prior to each test, the links for specific slip angles were mounted on the rig to achieve the required slip angle.

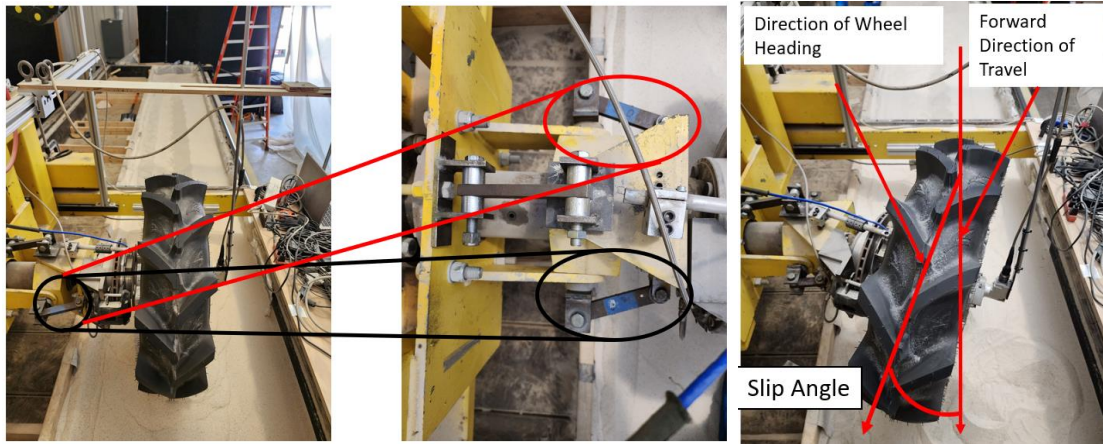


Figure 4.3. Links used to adjust slip angle.

4.4.4 Camber

Like the approach taken for slip angle, the camber was also adjusted using links of specific lengths. These links were mounted on the rig before each run to achieve the desired camber for the upcoming test.

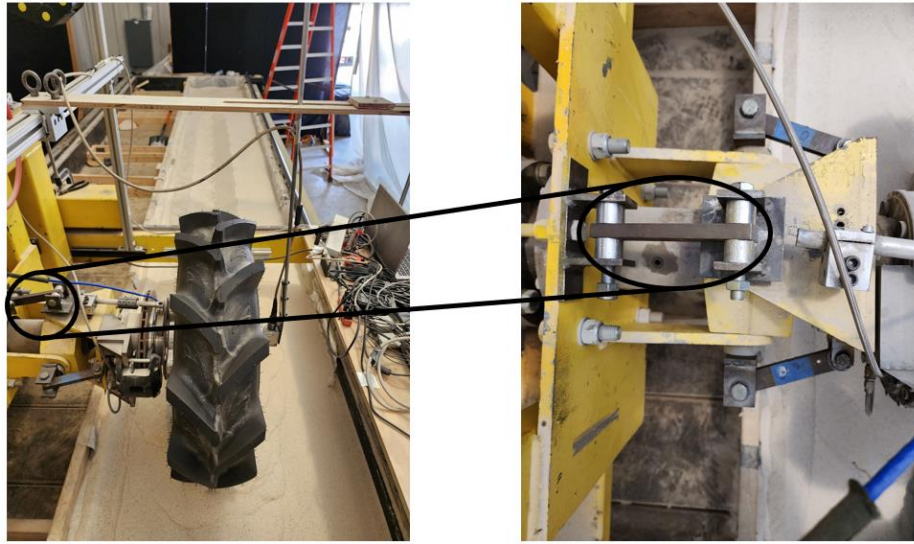


Figure 4.4. Link to adjust camber angle.

4.4.5 Force Hub Calibration

Before the test is started, care needs to be taken that the hub is calibrated. As the WFT works well in dynamic conditions, the calibration is done by spinning the wheel in air, turning on the data recording in laptop and allowing it to run for around 30 seconds. The wheel spinning and data recording was then stopped. This was to be done every time the force hub was powered on, and not before every test.

4.4.6 Testing and force hub data recording

Upon completion of terrain preparation, test rig setup, and wheel force transducer calibration, the actual test could commence. The carriage was initially brought to the starting point with the wheel suspended in the air. Subsequently, the wheel was manually lowered using a wrench and the belt system, shown in Figure 4.5. Once the wheel was lowered, data recording with the force hub was initiated through the software.



Figure 4.5. Wheel lowering mechanism.

Following this, the rig was activated using the remote controller, engaging both the linear and wheel motors to propel the wheel forward. Upon reaching the end of the rig, the remote controller was utilized to bring the rig to a stop, and the data recording was ceased in the software. The wheel was then raised using the wrench.

It's noteworthy that the start and stop of the rig, as well as data recording, were handled independently, a factor accounted for during the post-processing stage.

4.4.7 3D scanning

Following the completion of a run and the collection of force and moment data, the tire footprint was obtained by connecting the 3D scanner to a laptop to capture the tire rut. The Ex-star software facilitated the capture of 3D scan data. The 3D scanner had to be calibrated only once at the start of the project, using the calibration kit provided.

A portion of the rig where the wheel speed had stabilized was selected for capturing the 3D scan. Once the 3D scanner had been brought to its start position, data capturing was initiated using the software. The 3D scanner was then manually moved over this fixed portion at an approximately constant speed to capture the tire footprint, after which data capture was turned off. Special

attention was given to scanning the wooden partition of the rig, which served as a reference for alignment during post-processing.

The data was captured in the form of point cloud data, which was then converted into a mesh with a setting of 10,000 nodes. Subsequently, it was exported as an .stl file (Stereolithography file format) into CAD software.

Chapter 5: Data Processing

5.1 Force hub data

The data collected during the run was exported from the MSC LW12.8-45 as a .mat file to be processed in MATLAB.

The unprocessed data can be divided into four sections: (i) Stationary part before the run (A in Fig. 5.1), (ii) Transient portion when the wheel and carriage speed increases from rest to its set values (B in Fig. 5.1), (iii) The steady state portion of the run (C in Fig. 5.1), (iv) The transient portion and stationary portion after the test rig is stopped (D in Fig. 5.1).

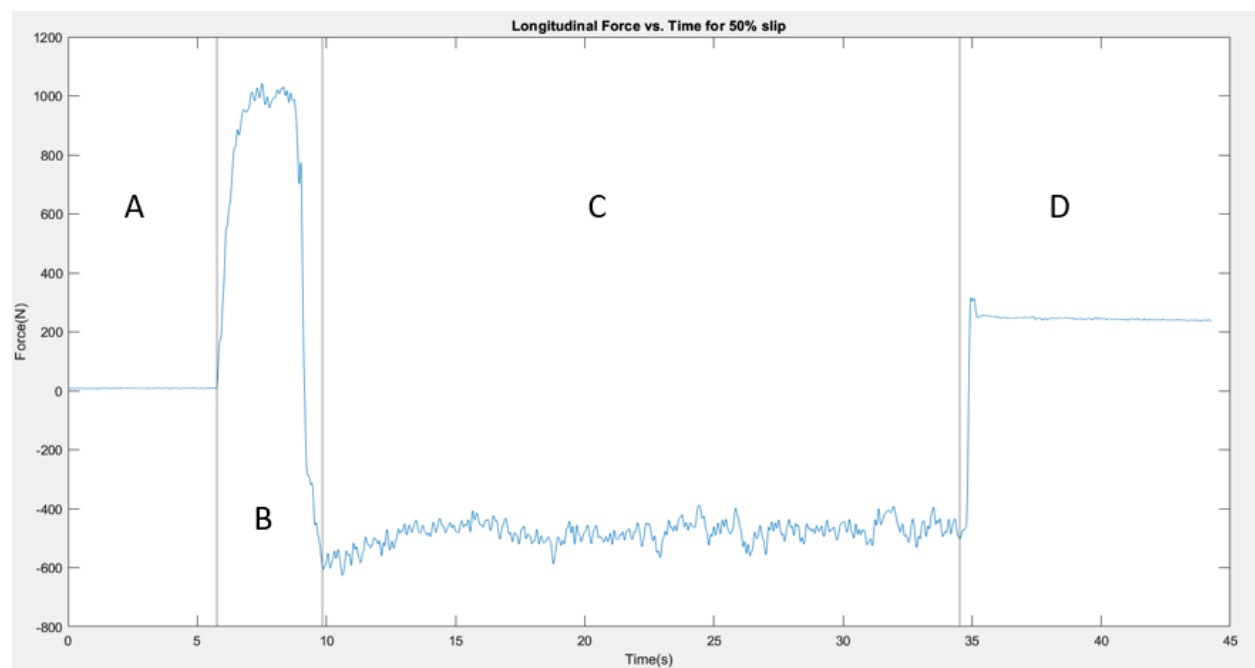


Figure 5.1. Plot of Longitudinal Force vs time for 50% slip ratio.

A segment from the steady-state portion of the run was extracted and utilized for data analysis. An FFT was performed on the data with a sampling frequency of 1000 Hz to identify the presence of any noise. Subsequently, a second-order Chebyshev filter with a cutoff frequency of 20 Hz was employed to eliminate noise.

The data was then converted from mV to N using a calibration factor supplied with the force hub. Offsets were subsequently incorporated to accommodate the weight of the force hub. Once this was done, the average forces and moments in the 6 DOF were taken as the output of each run.

5.2 3D scan data

It is to be noted that all the 3D scans were manually post-processed one by one. The STL file generated from the 3D scan software is imported into a 3D CAD software as a mesh model. Using the built in features of the CAD software, the mesh model is first converted into a surface model. The surface is then aligned with the three principal planes using the reference of the partition which was captured in the scan. The undeformed terrain level is identified by creating a plane 74 mm below the top surface of the partition. The value of 74 mm was obtained from conducting measurements in the actual test rig.

Once the ground has been established, a rectangle of appropriate size was generated and used to create extrusions from the undisturbed terrain level to the surface of the final profile of the terrain in both upward and downward directions. These generated volumes represent the volume of soil that was displaced/deposited in the different regions of the tire rut. Different parameters were then defined and extracted from each run, which were the final output from 3D scans.

Chapter 6: Results and Discussions

6.1 Pure Longitudinal slip tests

6.1.1 Drawbar pull results

6.1.1.1 Tests at Normal Loads of 4000N.

The initial set of tests were done at a rated load of the tire (4000N). The figure below shows the variation of drawbar pull coefficient with slip ratio. Drawbar pull coefficient is defined as the ratio of drawbar pull to the normal load on the wheel. The dots represent the average of two runs and the curve represents an interpolation of the points in the form of a fourth order polynomial. The standard deviation is represented by the red bars.

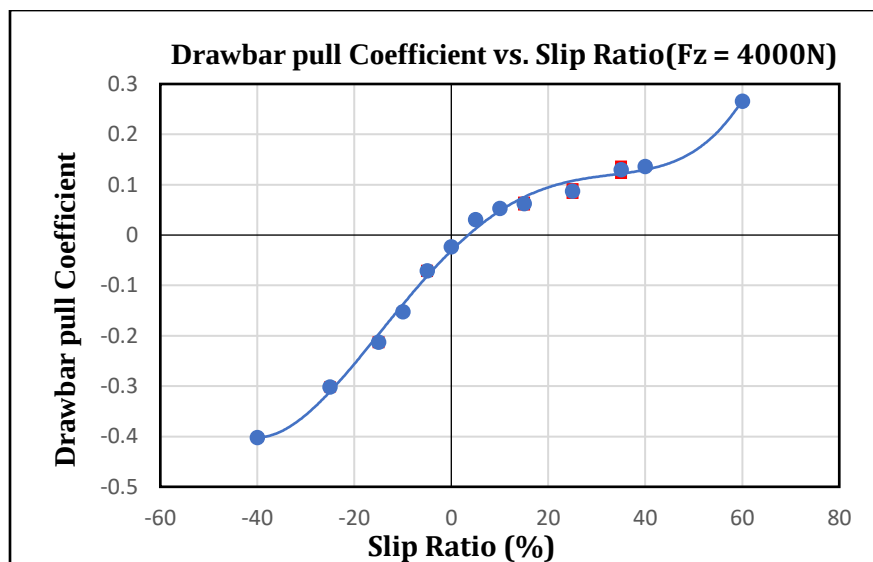


Figure 6.1. Variation of Drawbar pull coefficient with slip ratio at normal load of 4000N in pure slip condition.

It can be seen from Figure 6.1 that there is a sudden increase in the drawbar pull coefficient at high slip ratio of 60%. This was unexpected, as the drawbar pull coefficient typically plateaus at higher slip ratios. It was speculated that the reason for this could be the high sinkage of the tire into the soil, due to which the tire was getting too close to the C-channels on the rig, leading to boundary

effects. The consensus is that the undisturbed soil bed must be at least 5 times the overall sinkage of the tire. As this was not observed, it was decided that further tests should be conducted at lower normal loads.

6.1.1.2 Tests at Normal Loads of 2000N.

The next set of sets were conducted at a normal load of 2000N. The figure below shows the variation of drawbar pull coefficient with slip ratio.

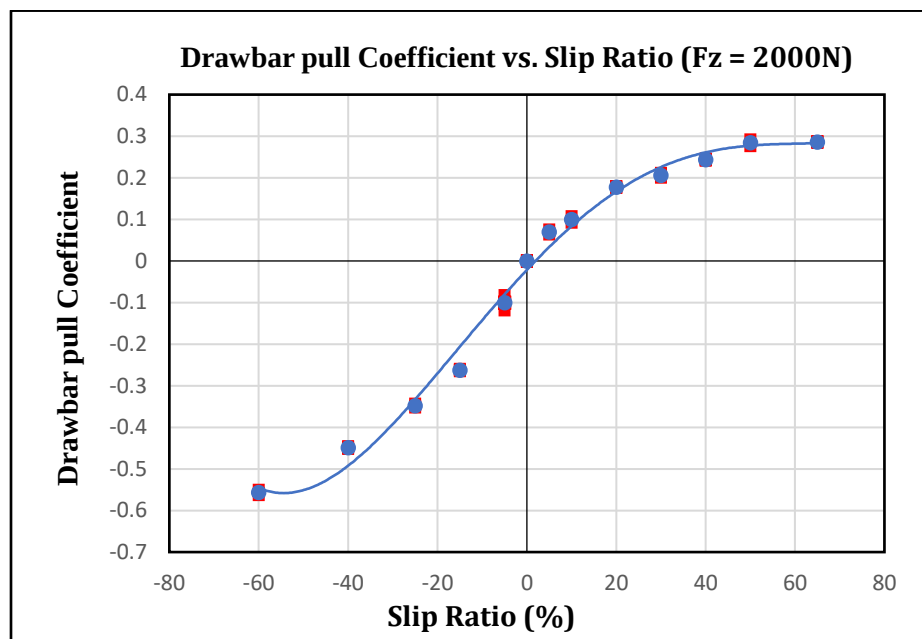


Figure 6.2. Variation of Drawbar pull coefficient with slip ratio at normal load of 2000N in pure slip condition.

As evident from Figure 6.2, there is a plateau in the higher slip ratio region, aligning more closely with expectations. The obtained sinkage is also within an acceptable range, confirming the existence of boundary effects in the prior set of tests.

Notably, the drawbar pull coefficient exhibits higher values during braking (negative slip ratios) compared to acceleration (positive slip values). In positive slip ratios, the tangential velocity of the treads is greater than the longitudinal velocity of the wheel center, due to which the soil is thrown

back. This excavation of soil from the front of the tire to the rear of the tire prevents buildup of soil in front of the tire. However, this does not occur in the braking, because the tangential velocity of the treads is less than the longitudinal velocity of the wheel center, which prevents the excavation of soil in the center. This leads to build up in front of the tire, generating an additional resistive force in the negative x direction. This additional resistive force leads to higher magnitudes of drawbar pull coefficient in braking zone than in traction zone.

6.1.2 3D scan results

All the scans shown below are for normal loads of 2000N.

In the front view, the shape of the rut left behind by the tire is V-shaped, with peaks on either side forming shoulders, and the maximum rut depth occurring at the center, creating a valley. The height of the two peaks is similar when there is no slip angle or camber. The following parameters were defined in the 3D scan of tire footprint, which are displayed in Figure 6.3.

1. Wavelength (λ) is defined as the distance between two consecutive lug imprints.
2. Maximum rut depth (r) is defined as the vertical distance of the lowest point in the tire rut from the undisturbed terrain.
3. Penetration Volume (V_p) is defined as the net volume of soil displaced in the center of tire rut due to the penetration of tire into the terrain.
4. Displaced Volume (V_d) is defined as the volume of the soil displaced laterally from the center and deposited along the shoulder of the rut.

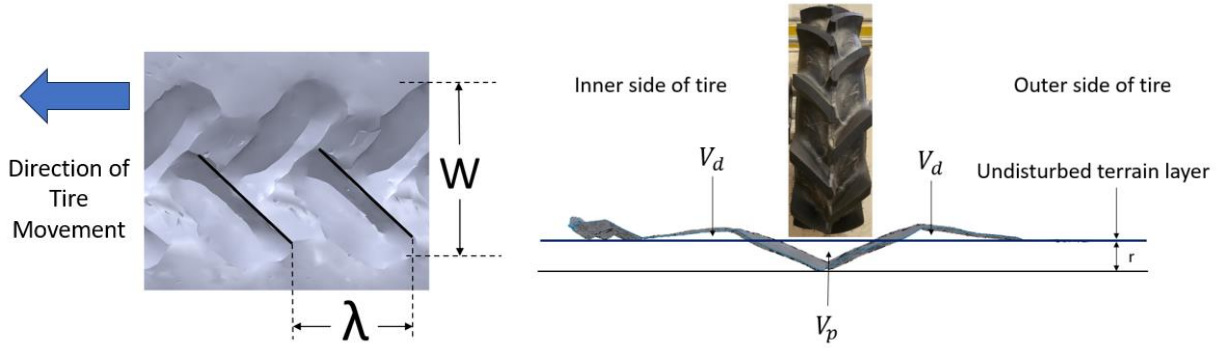


Figure 6.3. Parameters defined in 3D scan for pure slip tests.[30]

The penetration volume is enclosed by undeformed terrain plane and the deformed soil profile and lies below the undisturbed terrain level. This gives the difference between the volume of tire which penetrated the terrain and the volume of terrain that was deposited along the center of tire rut. The displaced volume is enclosed by the undeformed terrain plane and the deformed soil profile and lies above the undisturbed terrain level. This represents the volume of soil that was displaced by the tire and was deposited laterally. Figure 6.4 shows the 3D scans of the rut obtained in positive slip ratios placed side by side.

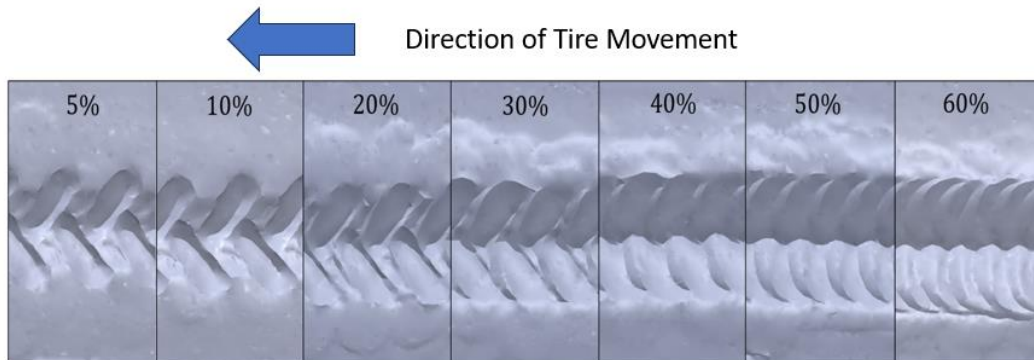


Figure 6.4. Tire rut profile with increasing slip ratios(traction) [30]

At lower slip ratios, the lug pattern of the tire can be clearly recognized in the rut. As the slip ratios are increased, the distance between the consecutive lug pattern keeps decreasing and the lug pattern starts blending in with the wave pattern.

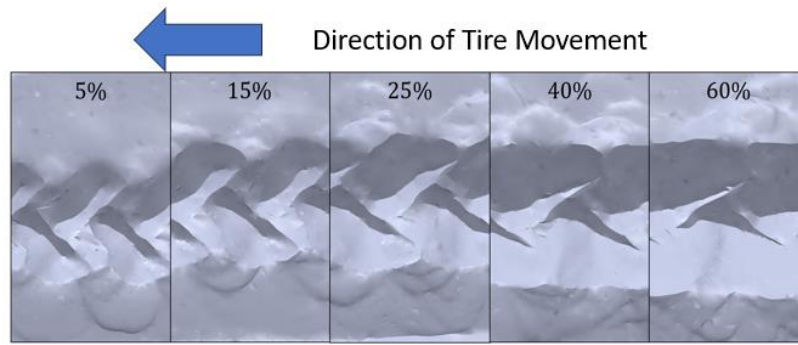


Figure 6.5. Tire rut profile with increasing slip ratios(braking) [30]

Figure 6.5 shows the 3D scans of the rut in negative slip ratios. While the wavelength reduces with an increase in slip ratio in traction region, the wavelength increases with as slip ratios become more negative in braking. The pattern elongates as slip ratios become more negative making it increasingly challenging to identify. Also, shear failure zones are more prominent in braking as compared to traction as is evident with the semicircular depositions of soil near the shoulders of the rut.

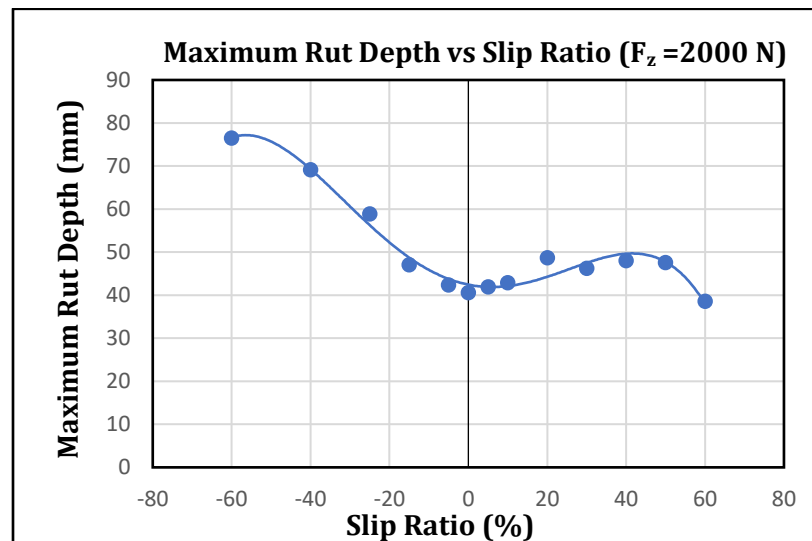


Figure 6.6. Variation of Maximum Rut Depth with slip ratio at normal load of 2000N in pure slip condition [30]

Figure 6.6 shows the plot of maximum rut depth to the slip ratio. It can be seen that the rut depth is higher in the negative slip region. This correlates to higher sinkage of tire, which in turn

contributes to a greater bulldozing effect in braking, resulting in higher values of F_x as observed previously.

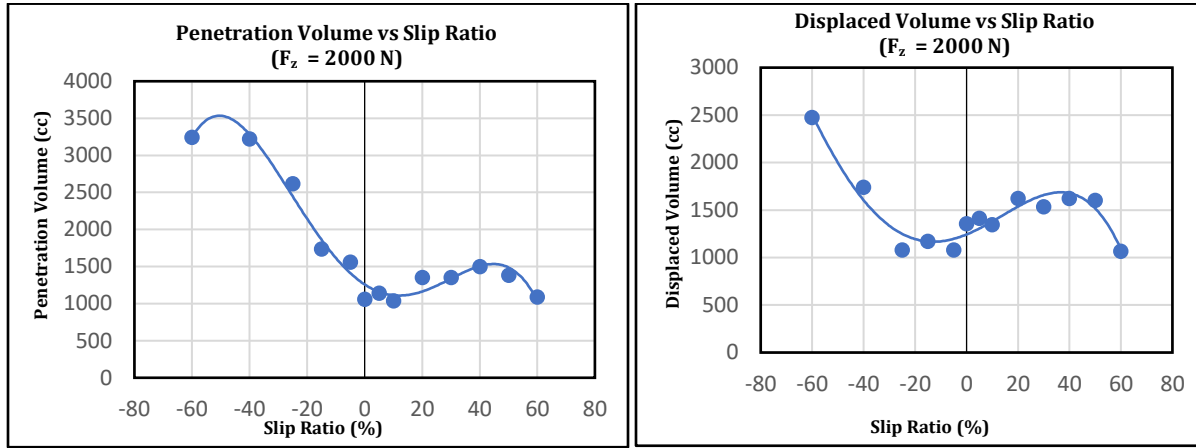


Figure 6.7. Variation of (a) Penetration Volume and (b) Displaced Volume with slip ratio at normal load of 2000N in pure slip condition [30]

Figure 6.7 illustrates the variation of penetration and displaced volumes with slip ratio. It is evident that they follow a similar trend to the maximum rut depth. In braking, the lugs try to push the soil forward, i.e. bulldoze the soil, causing it to accumulate in front of the leading lug. Subsequently, this soil is displaced along the sidewall of the tire, resulting in a greater volume of soil in the rut shoulder. In traction, the leading lug attempts to pull the soil back, leading to soil excavation rather than bulldozing. This excavation causes the soil to be displaced from the leading lug to the trailing lugs, resulting in less lateral displacement of soil and more soil deposition along the center of the rut rather than the rut shoulder. This explains why the displaced and penetration volumes are higher in braking than in traction.

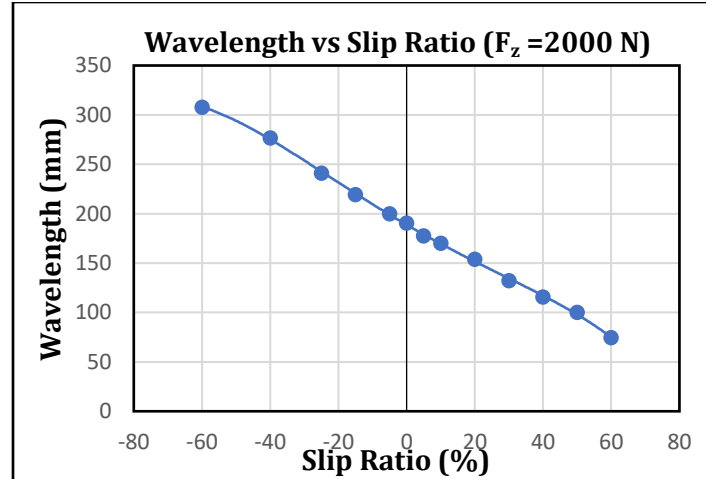


Figure 6.8. Variation of Wavelength with slip ratio at normal load of 2000N in pure slip condition [30]

Figure 6.8 shows the variation of wavelength with slip ratio. It can be seen that there is a high inverse proportionality between the wavelength and slip ratio. As the slip ratio increases, the lug pattern moves closer, and form ripples in the rut. This was also observed in [31], where this was termed “Ripple effect”. This occurs because the tip of the shear failure zone spreads to the surface of soil, which results in the deposition of soil in layers along the center of the rut. In this case, the shear failure zones are more evident in lower slip ratios along the rut shoulder due to taller lugs of the off-road tire used.

6.2 Combined slip tests

In this phase, tests were performed under a combination of slip ratios, slip angles, and camber. The variations of all the forces and moments across the wheel hub concerning slip ratio, slip angles, and camber were examined, and the key trends and insights are summarized. Additional parameters were introduced in the 3D scans and their variations with the input parameters were studied.

6.2.1 Variation of force and moments with input parameters

6.2.1.1 Drawbar Pull

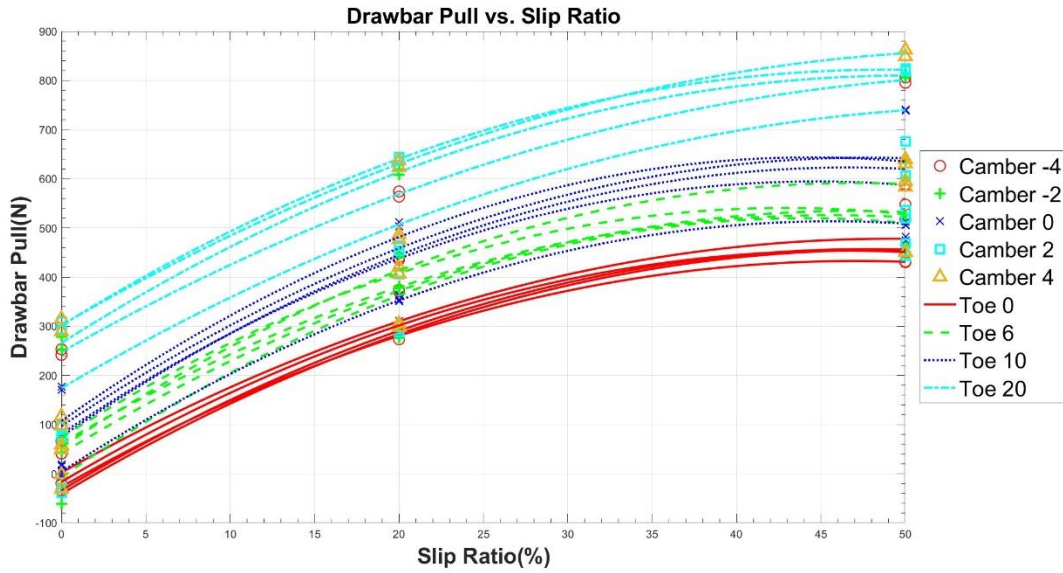


Figure 6.9. Variation of longitudinal force with slip ratio under constant slip angle and camber

Figure 6.9 shows the variation of the longitudinal force with respect to slip ratio, at constant slip angle and camber. It can be seen from the graph that the longitudinal force increases consistently with slip ratio as expected at all slip angles and camber. Though the values change, the overall trend is not affected due to the introduction of slip angles and camber.

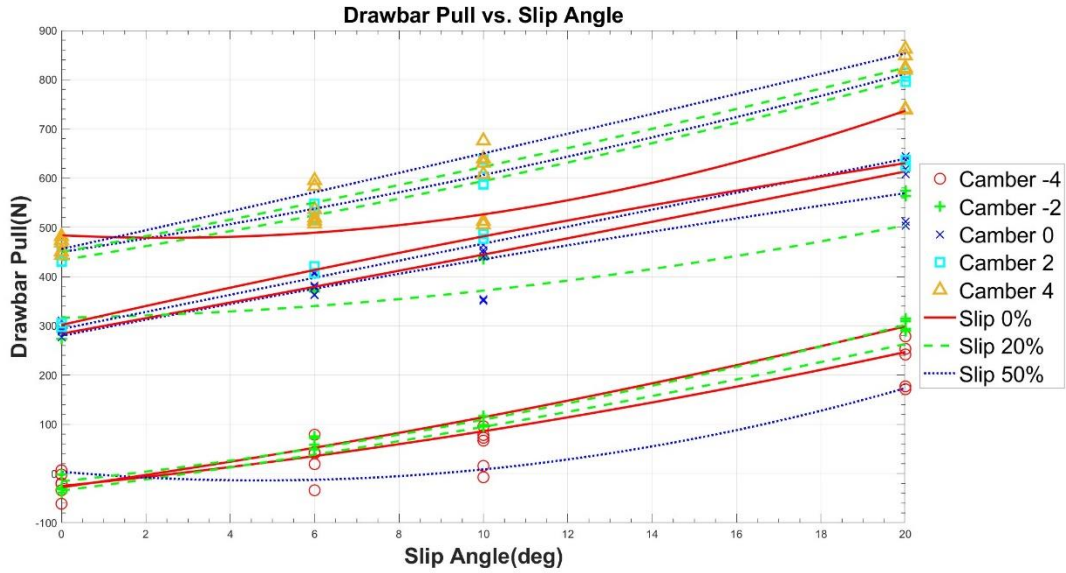


Figure 6.10. Variation of longitudinal force with slip angle under constant slip ratio and camber.

The Figure 6.10 depicts the variation of longitudinal force with slip angle at a constant slip ratio and camber. Surprisingly, there is an increase in the longitudinal force with respect to the slip angle. This result was unexpected, as the slip angle is typically anticipated to influence only the lateral force and not the longitudinal force. Nevertheless, the consistent increase across all slip ratios and camber levels indicates the existence of a phenomenon causing this unexpected behavior.

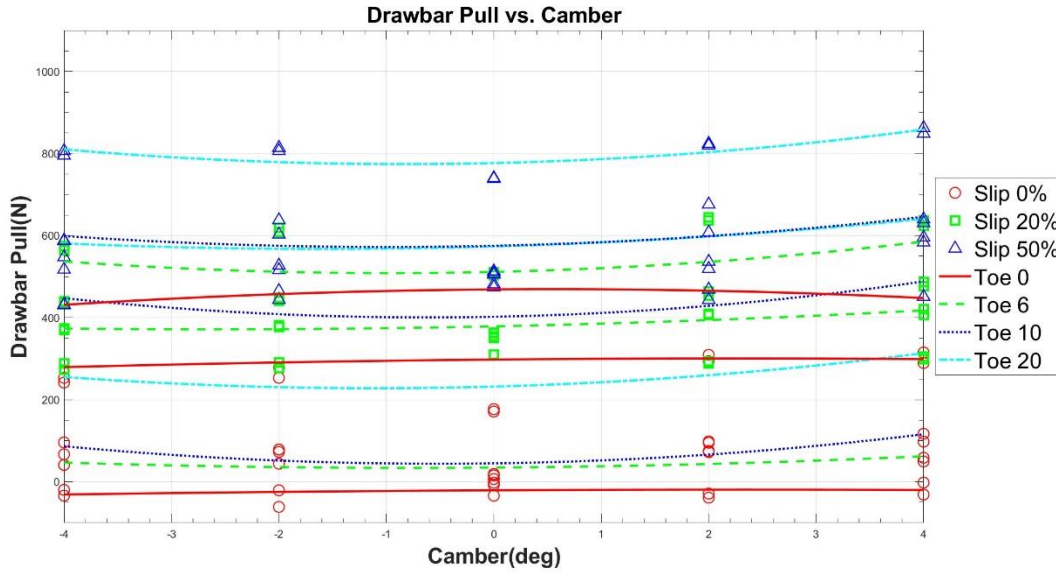


Figure 6.11. Variation of longitudinal force with slip angle under constant slip angle and slip ratio.

The Figure 6.11 shows the variation of the longitudinal force with respect to camber at constant slip ratio and slip angle. There is a small increase at both positive and negative cambers, but the increase is marginal. Overall, there is very little effect of camber on the longitudinal force.

6.2.1.2 Lateral Force

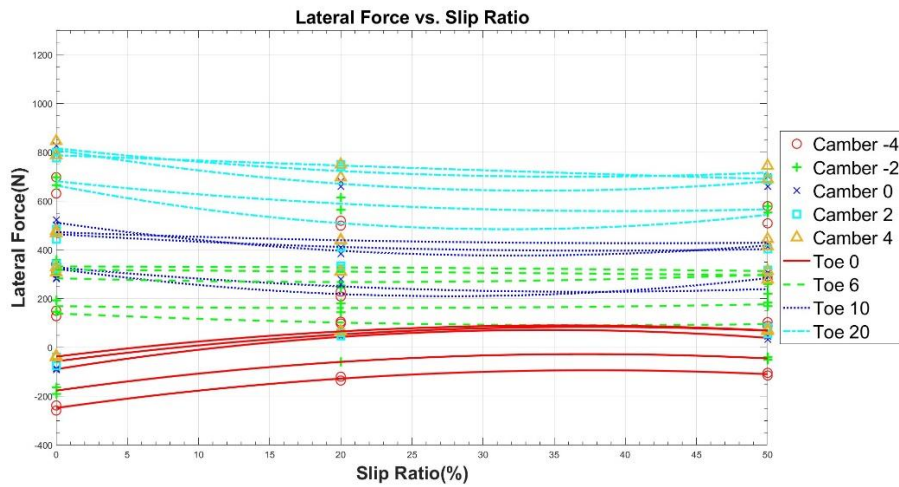


Figure 6.12. Variation of lateral force with slip ratio under constant slip angle and camber

Figure 6.12 illustrates the variation of lateral force with respect to slip ratio at a constant slip angle and camber. It is observed that there is a marginal decrease in lateral force with an increase in slip ratio. However, there is no significant impact of slip ratio on the lateral force, which is in accordance with expectation.

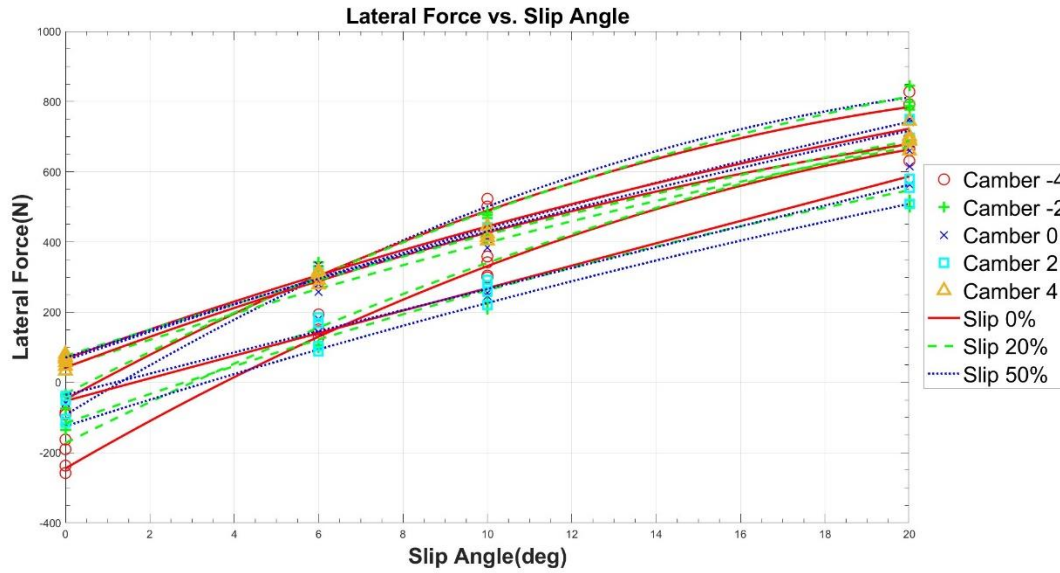


Figure 6.13. Variation of lateral force with slip angle under constant slip ratio and camber

Figure 6.13 shows the variation of the lateral force with respect to slip angle at constant slip ratio and camber. As expected, there is an increase in lateral force.

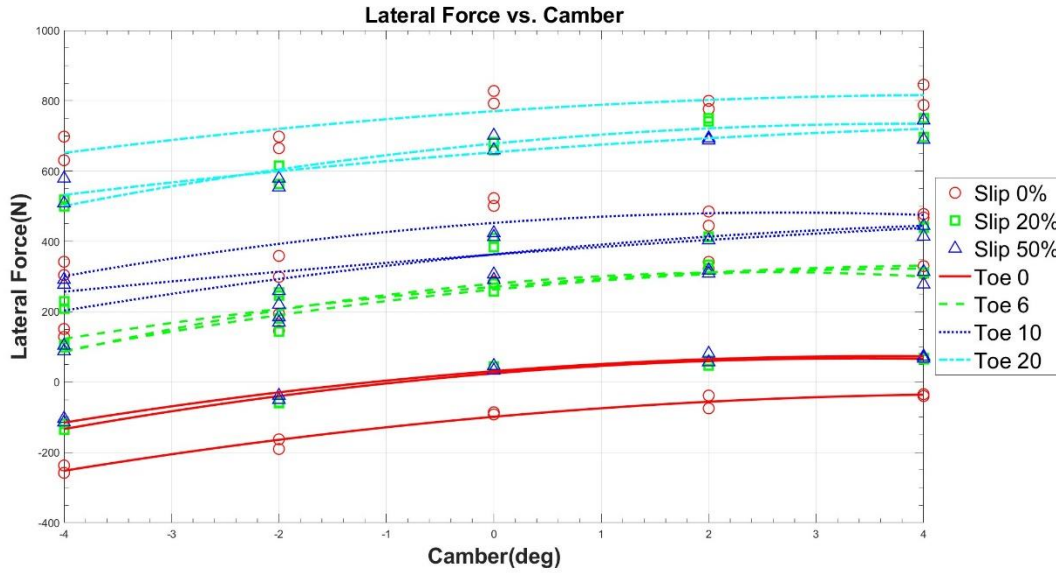


Figure 6.14. Variation of lateral force with camber under constant slip ratio and slip angle.

Figure 6.14 illustrates the variation of lateral force concerning camber at a constant slip ratio and slip angle. A slight increase in lateral force is observed as the transition is made from negative camber to positive camber. However, the magnitude of the increase is not as significant as that observed with the slip angle.

6.2.1.3 Overturning Moment

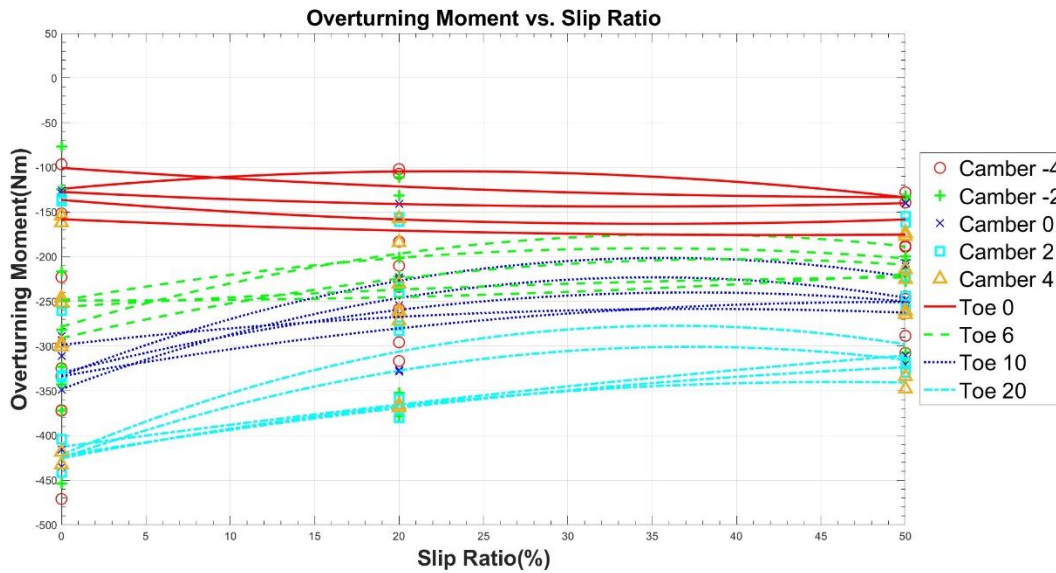


Figure 6.15. Variation of overturning moment with slip ratio under constant slip angle and camber.

Figure 6.15 shows the variation of the overturning moment with respect to slip ratio at constant slip angle and camber. There is a decrease in the overturning moment at higher toe angles, but it remains fairly constant for the lower toe angles.

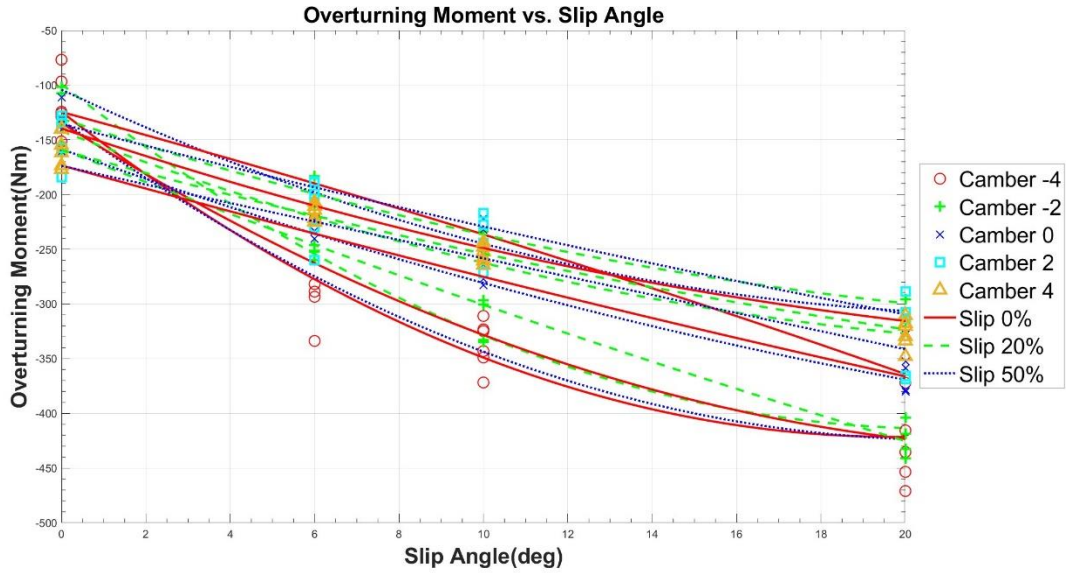


Figure 6.16. Variation of overturning moment with slip angle under constant slip ratio and camber.

Figure 6.16 illustrates the variation of the overturning moment with respect to slip angle at a constant slip ratio and camber. As expected, the graph indicates an increase in the overturning moment with slip angle.

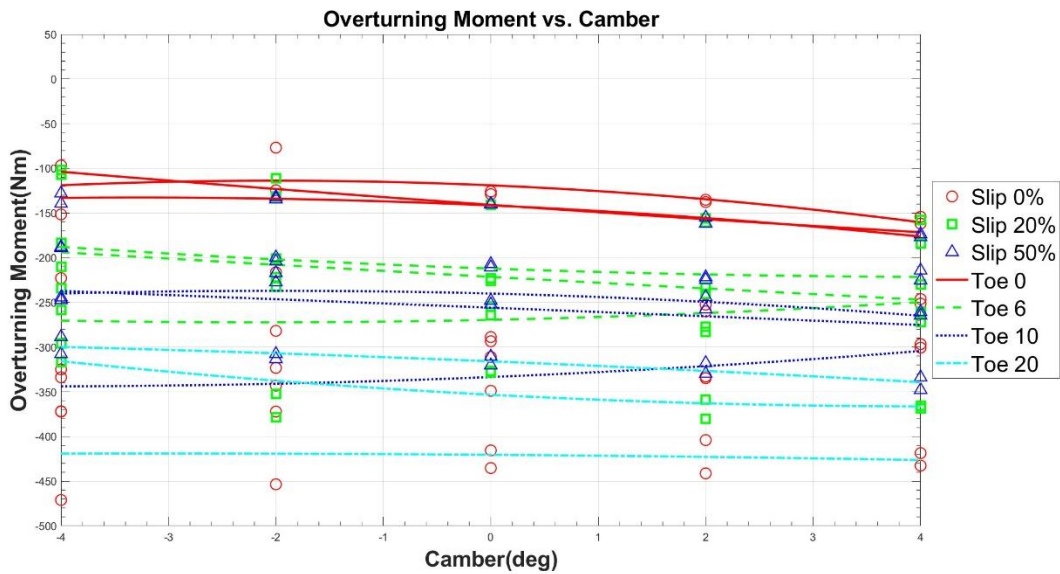


Figure 6.17 Variation of overturning moment with camber under constant slip ratio and slip angle.

Figure 6.17 shows the variation of the overturning moment with respect to camber at constant slip ratio and slip angle. As can be seen from the graph, there is no major effect of camber on the overturning moment.

6.2.1.4 Self-Aligning Torque

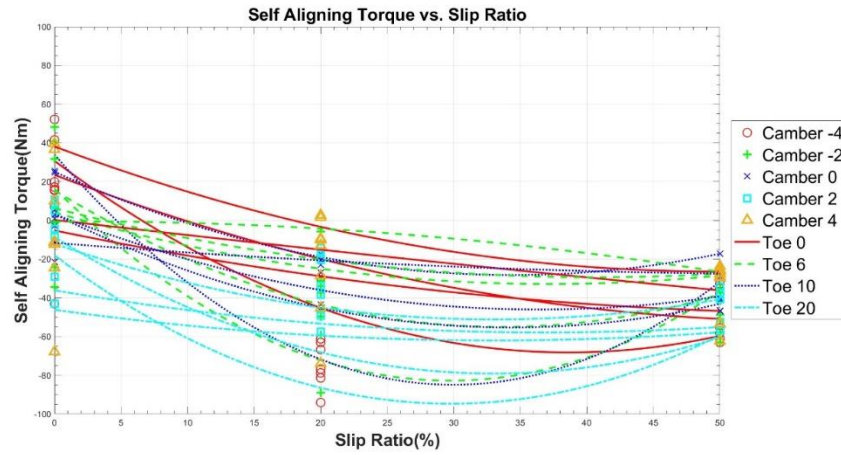


Figure 6.18 Variation of self-aligning torque with slip ratio under constant camber and slip angle.

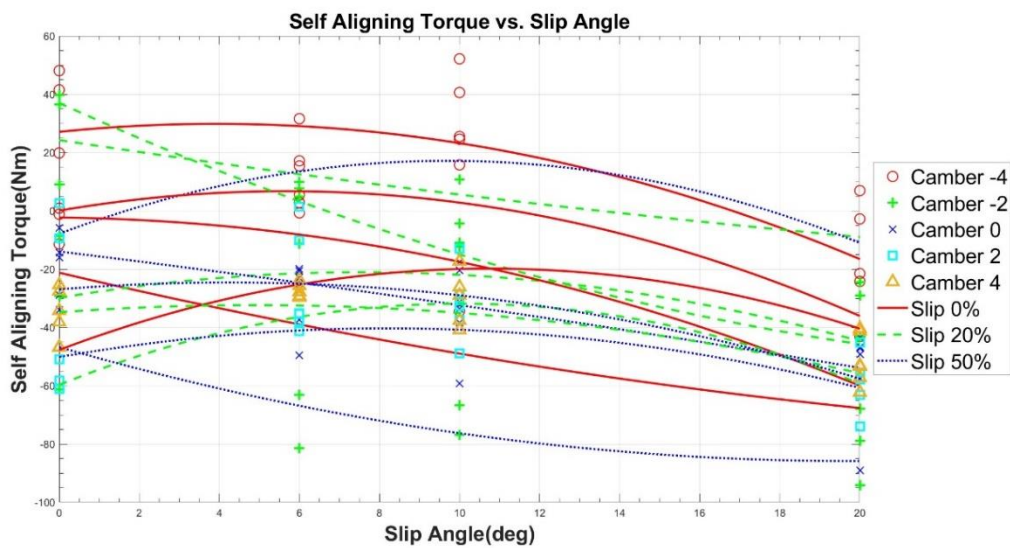


Figure 6.19. Variation of self-aligning torque with slip angle under constant camber and slip ratio.

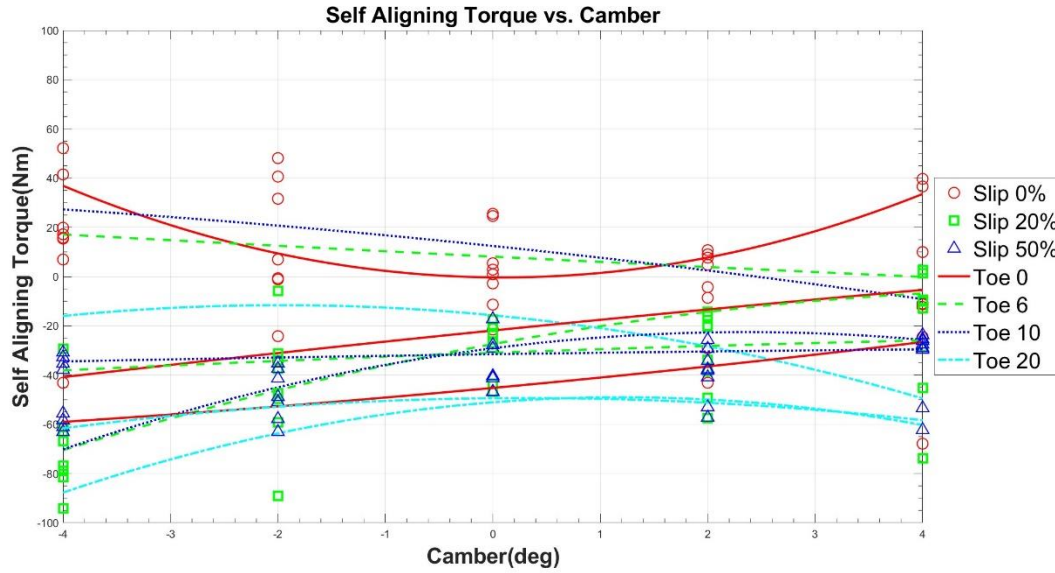


Figure 6.20. Variation of self-aligning torque with camber under constant slip ratio and slip angle.

Figure 6.18, Figure 6.19 and Figure 6.20 depict the variation of the self-aligning torque with slip ratio, slip angle, and camber, respectively. The magnitude of self-aligning torque increases with both slip ratio and slip angle. It can also be seen that the self-aligning torque magnitude decreases as we move from negative camber to positive in the presence of a slip ratio and slip angle, while the magnitude increases with both positive and negative camber at zero slip ratio and slip angle.

As F_z corresponds to the normal load on the tire and M_y corresponds to the applied torques to the wheel, these parameters were not plotted.

6.2.2 Variation of 3D scan parameters with input parameters

With the introduction of slip angle and camber, it was observed that there were significant changes to the rut profile of the displaced terrain. As a result, it was necessary to introduce new terms in order to correctly quantify the various parameters.

The figure shows the front view of the 3D scan of the deformed terrain.

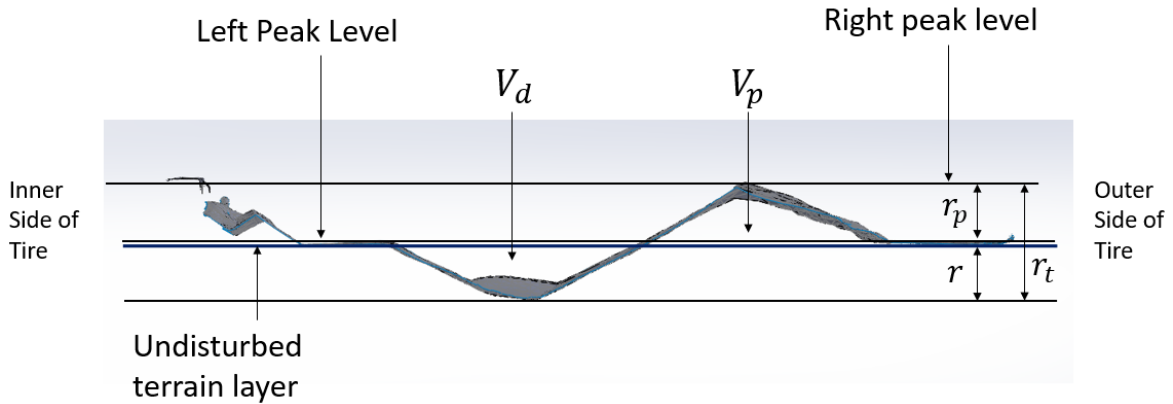


Figure 6.21. Additional parameters defined in 3D scan for combined slip tests.

Along with the previously defined terms, the following new terms were defined:

1. Differential peak height (r_p) is defined as the vertical distance between the leading (left) and trailing (right) peaks.
2. Total Rut height (r_t) is defined as the vertical distance from the highest peak to the lowest point on the rut profile.

As it can be seen from Figure 6.21, it can be seen that the peaks generated with the introduction of slip angle are now of different heights. This is different from scans taken at zero slip angle and camber. The following figure shows the 3D scans of rut obtained with order of increasing slip angle.

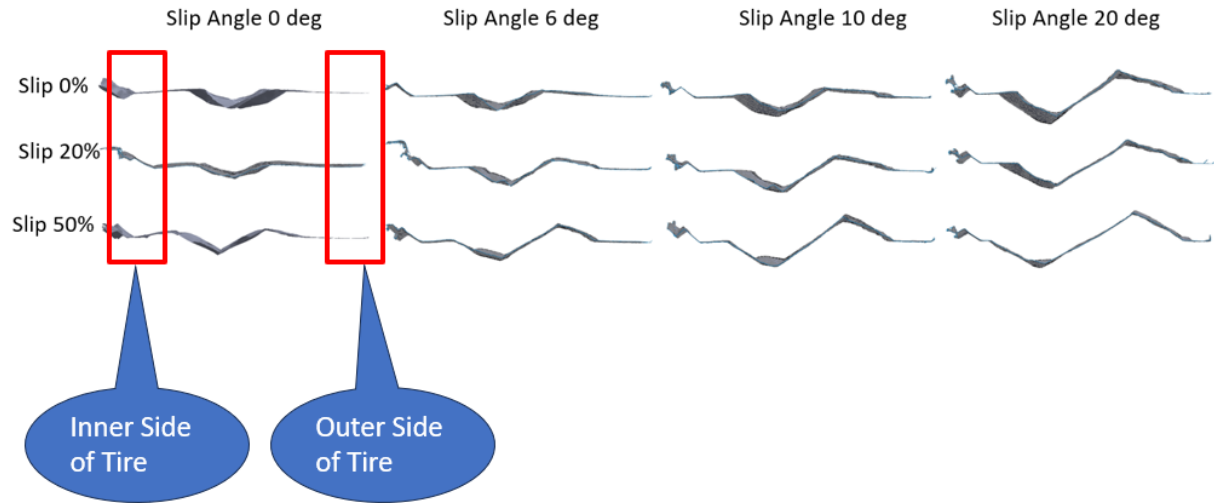


Figure 6.22. 3D scans of tire rut for zero camber tests

As it can be seen in Figure 6.22, the difference in the heights of the left and right peaks increase as we increase the slip angle. Also, the increase is more prominent in the higher slip ratios. In some cases, the left peak is very small, or completely vanishes at high slip angles. This occurs because the excavated soil is deposited entirely on only one side.

6.2.2.1 Variation of maximum rut depth with input parameters

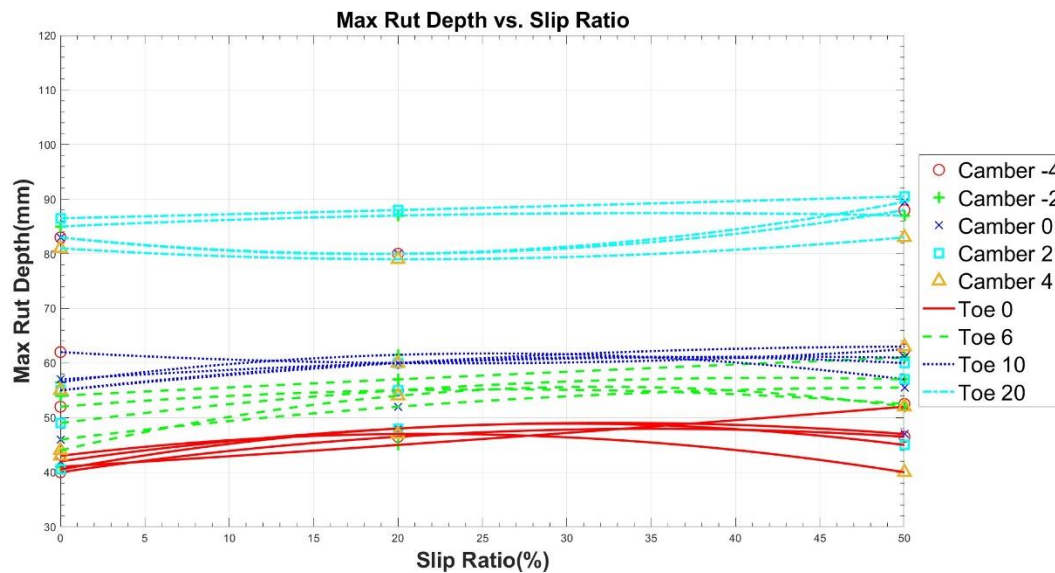


Figure 6.23. Variation of maximum rut depth with slip ratio under constant slip angle and camber.

Figure 6.23 show the variation of maximum rut depth with slip ratio. A slight increase can be seen as the slip ratio increases from 0% to 20% and a decrease can be observed from 20% to 50%. This is similar to what was obtained in tests with pure slip. However, better correlation can be obtained with more tests.

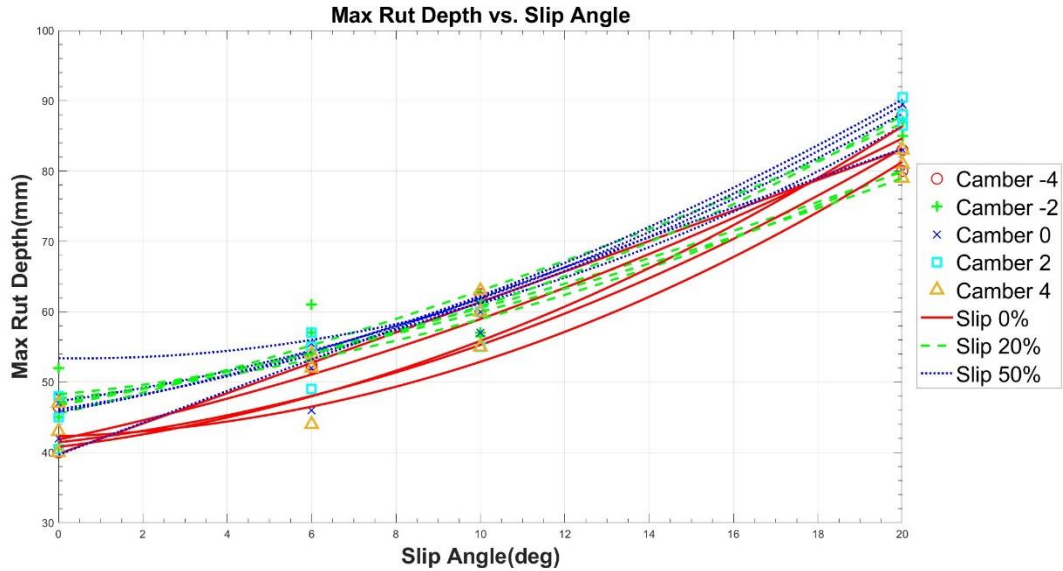


Figure 6.24. Variation of maximum rut depth with slip angle under constant slip ratio and camber.

Figure 6.24 shows the variation of maximum rut depth with slip angle. It can be seen that there is a clear increase with slip angle. It is crucial to note that this does not necessarily indicate an increase in tire sinkage. When the slip angle is zero, the soil is excavated by the leading lug and deposited in the center of the rut as the trailing edge is in the center of the rut. However, with an increase in slip angle, the excavated soil is deposited along the shoulder of the rut, as the trailing edge is now at an angle with respect to the travel direction. Consequently, the amount of soil deposited along the center of the rut decreases, leading to greater rut depths.

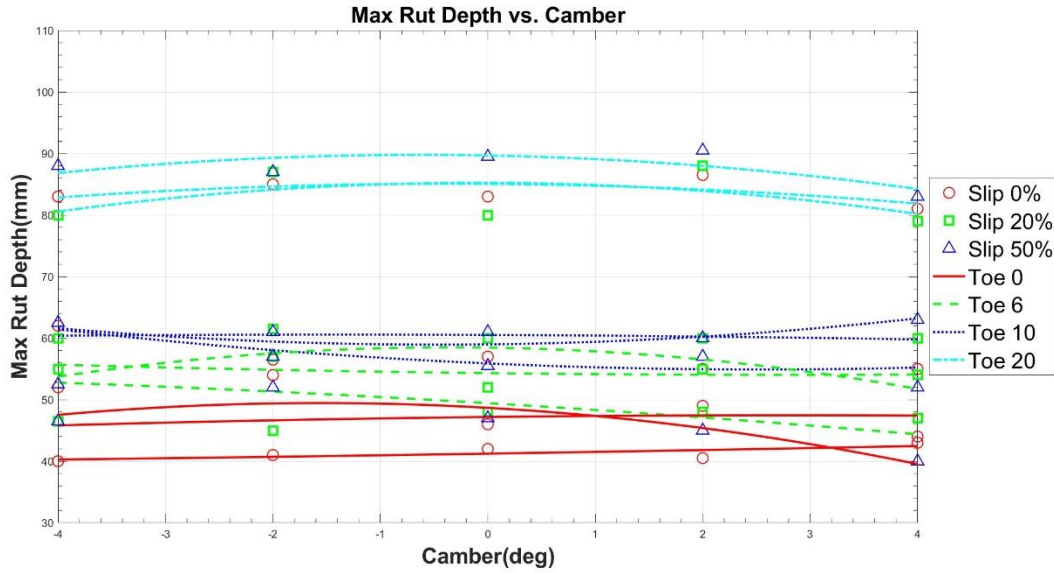


Figure 6.25. Variation of maximum rut depth with camber under constant slip ratio and slip angle.

Figure 6.25 shows the variation of maximum rut depth with slip angle. It can be seen that there is no major influence of camber on the maximum rut depth.

6.2.2.2 Variation of displaced and penetration volumes with input parameters

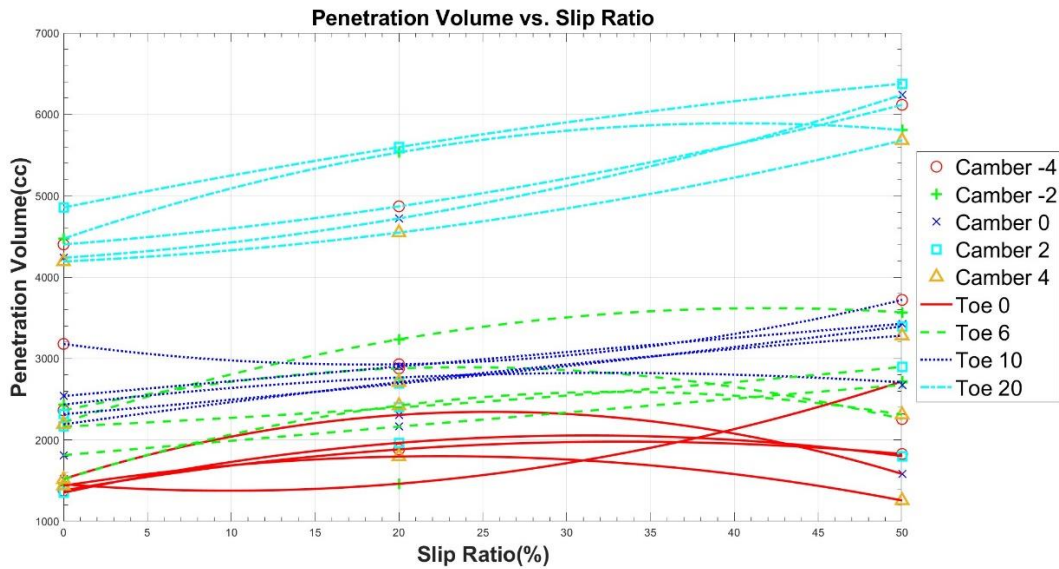


Figure 6.26 Variation of penetration volume with slip ratio under constant slip angle and camber

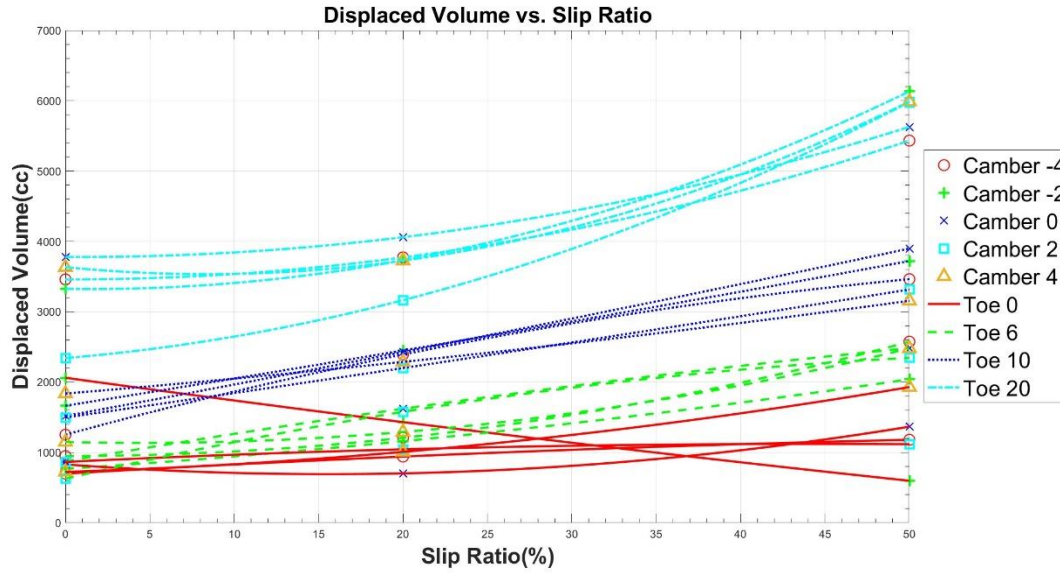


Figure 6.27. Variation of displaced volume with slip ratio under constant slip angle and camber

Figure 6.27 and Figure 6.27 show the variation of displaced and penetration volumes with slip ratio. The trends are similar to what was observed with maximum rut depth. It is to be noted that the trend is more consistent with maximum rut depth as compared to the volumes.

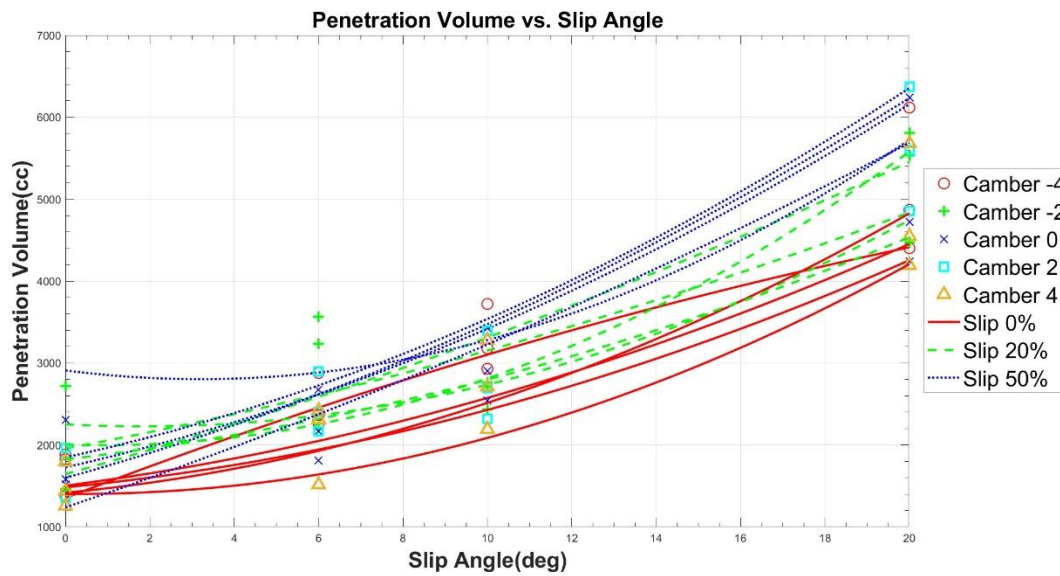


Figure 6.28 Variation of penetration volume with slip angle under constant slip ratio and camber.

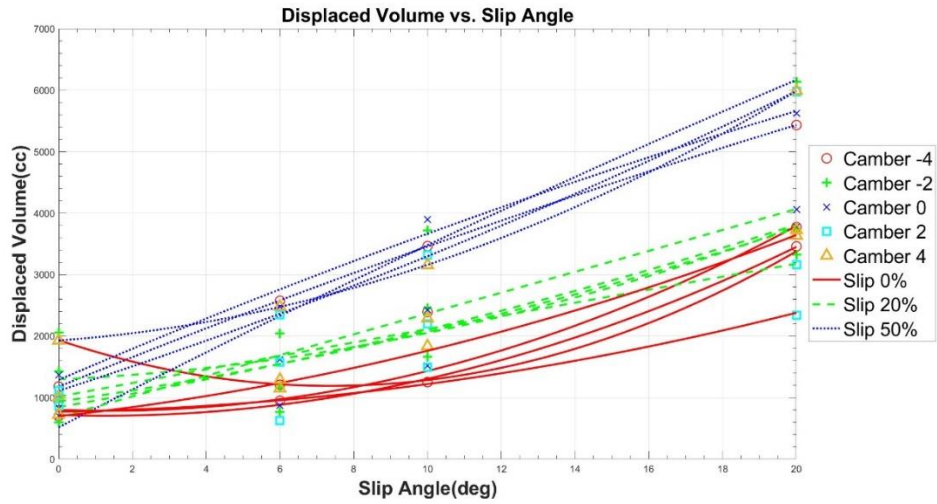


Figure 6.29. Variation of displaced volume with slip angle under constant slip ratio and camber.

Figure 6.28 and Figure 6.29 show the variation of parameters with slip angle. Similar to maximum rut depth, it can be seen that there is a clear increase with slip angle.

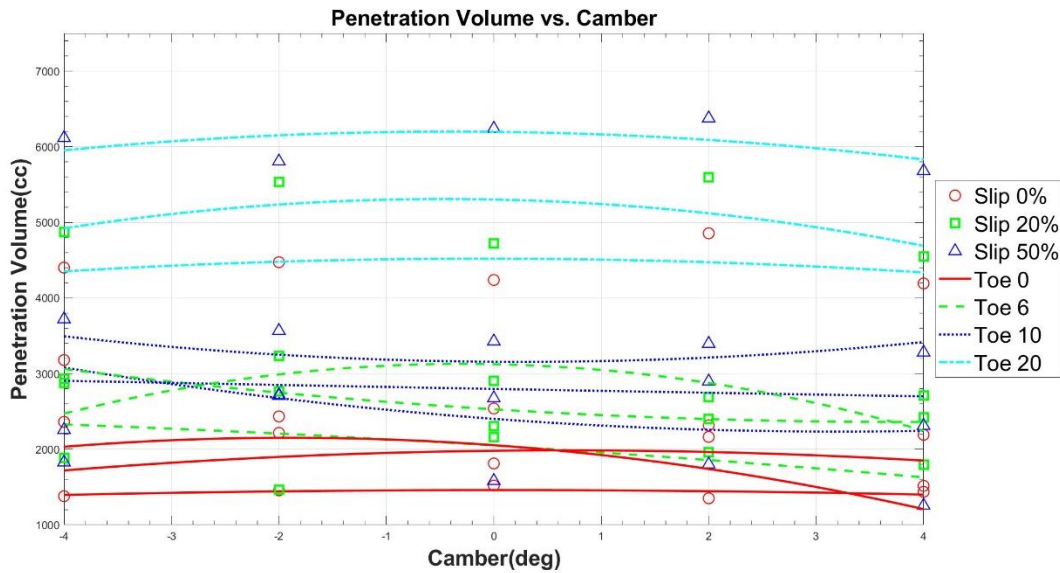


Figure 6.30 Variation of penetration volume with camber under constant slip ratio and slip angle.

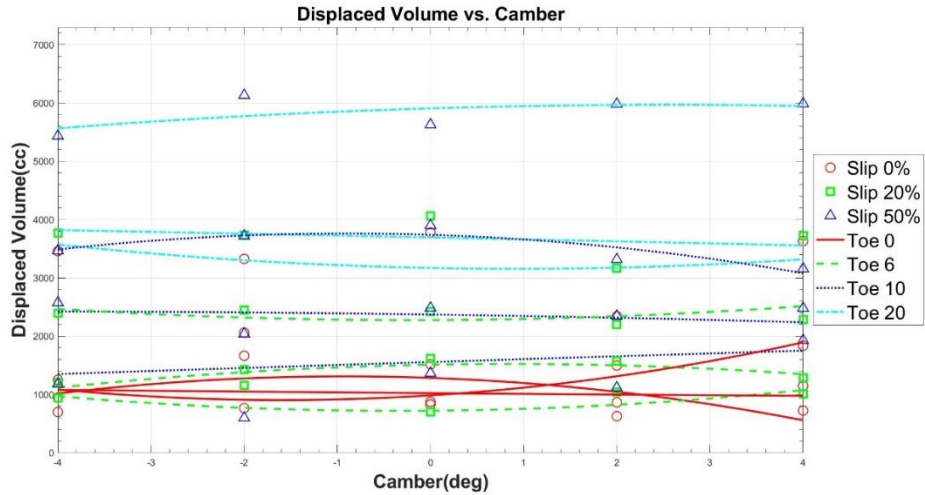


Figure 6.31. Variation of displaced volume with camber under constant slip ratio and slip angle.

Figure 6.30 and Figure 6.31 show the variation of penetration volumes and displaced volumes with camber. It can be seen that there is no major influence of camber on the maximum rut depth.

6.2.2.3 Variation of differential peak height with input parameters

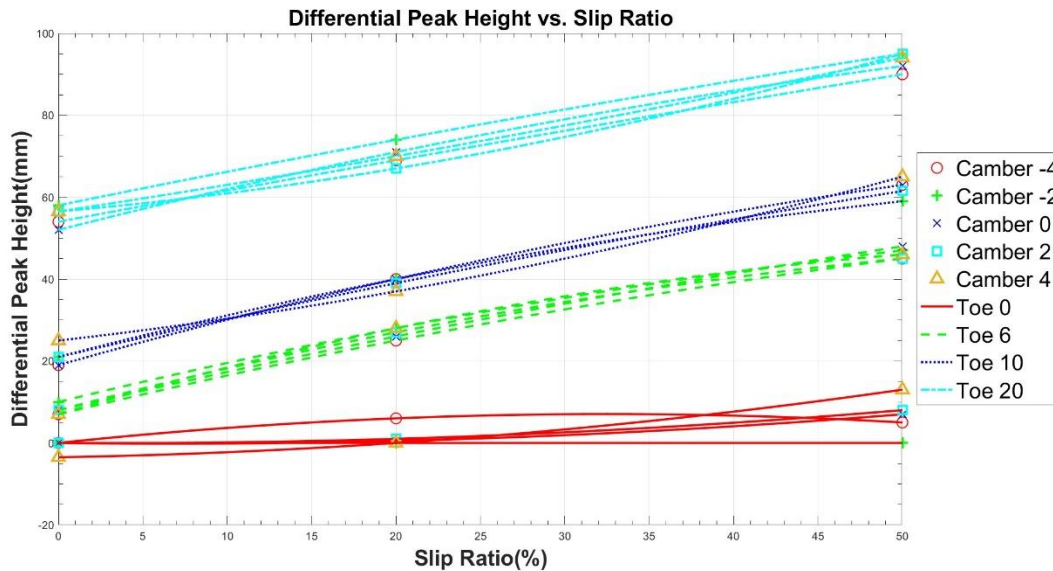


Figure 6.32. Variation of differential peak height with slip ratio under constant slip angle and camber

Figure 6.32 shows the variation of differential peak height with slip ratio. At zero slip angle, there is no effect of the slip ratio on the differential peak height. However, as slip angle is introduced, a

positive correlation between the differential peak height and slip ratio can be observed. This is expected as in the presence of slip angle, higher slip ratios will excavate more soil and thus deposit more soil in the rut shoulder, leading to higher peak heights.

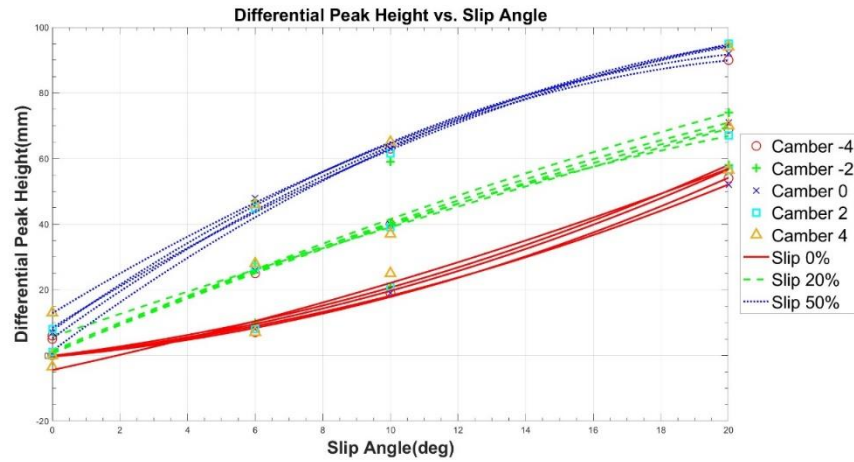


Figure 6.33. Variation of differential peak height with slip angle under constant slip ratio and camber

Figure 6.33 shows the variation of differential peak height with slip angle. Once again, a clear and consistent correlation can be observed of the differential peak height with slip angle. Also, the curves for each slip ratio lie very close to each other and can be grouped together.

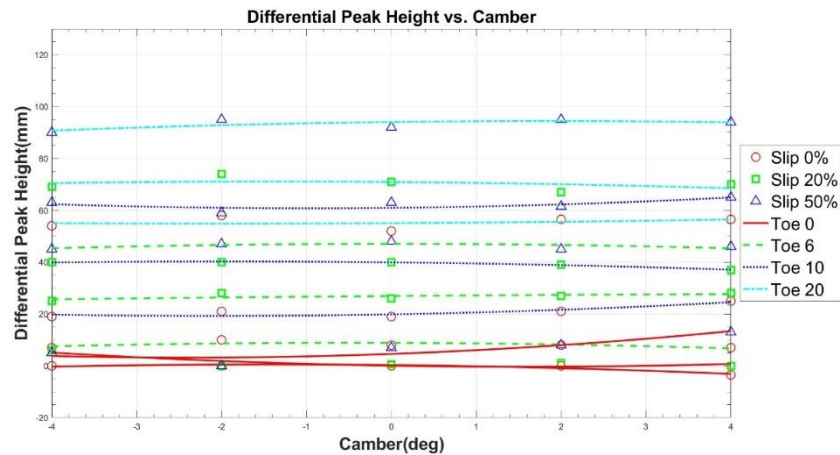


Figure 6.34. Variation of differential peak height with camber under constant slip ratio and slip angle.

Figure 6.34 shows the variation of differential peak height with camber. There is no major influence of camber on the differential peak height.

6.2.2.4 Variation of total rut height with input parameters

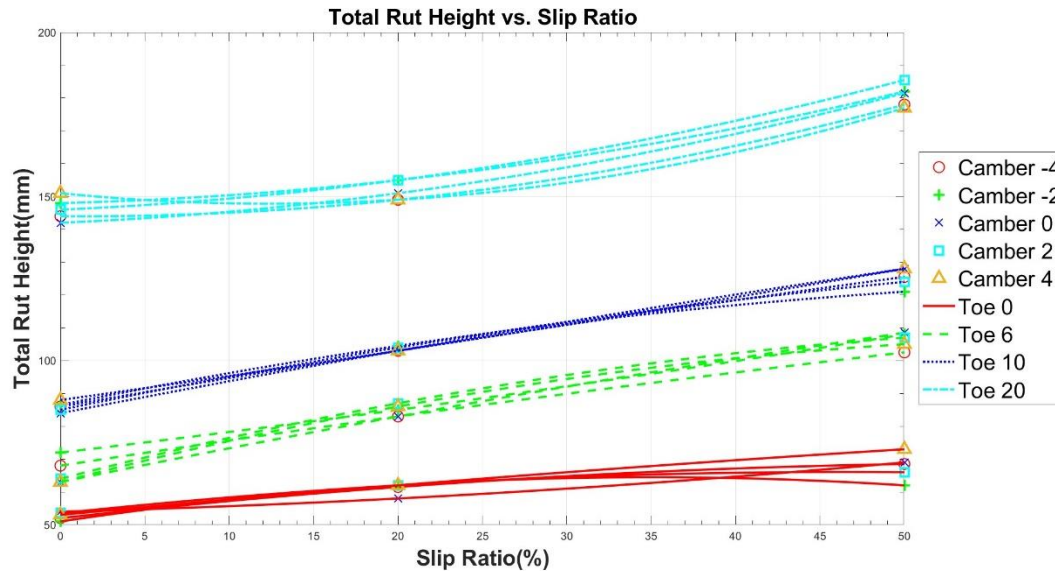


Figure 6.35. Variation of total rut height with slip ratio under constant slip angle and camber

Figure 6.35 shows the variation of the total rut height with slip ratio. As expected, the increase is small at lower slip angles and higher with slip angle. At slip angles of 6 degree and 20 degrees, the increase is almost linear. However, at slip angle of 20 degrees, the increase is parabolic. This suggests that the nature of rate of increase of total rut is linear at lower slip angles but is parabolic at higher slip angles.

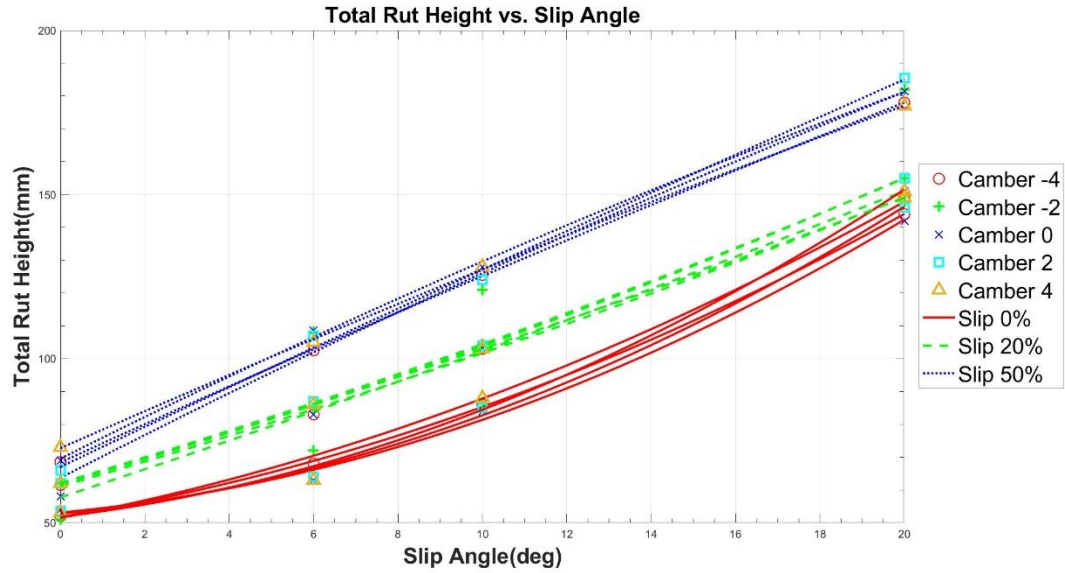


Figure 6.36. Variation of total rut height with slip angle under constant slip ratio and camber

Figure 6.36 shows the variation of the total rut height with slip angle. In this case, it can be seen the nature of the curve is quadratic at slower slip ratios but becomes linear at higher slip ratios.

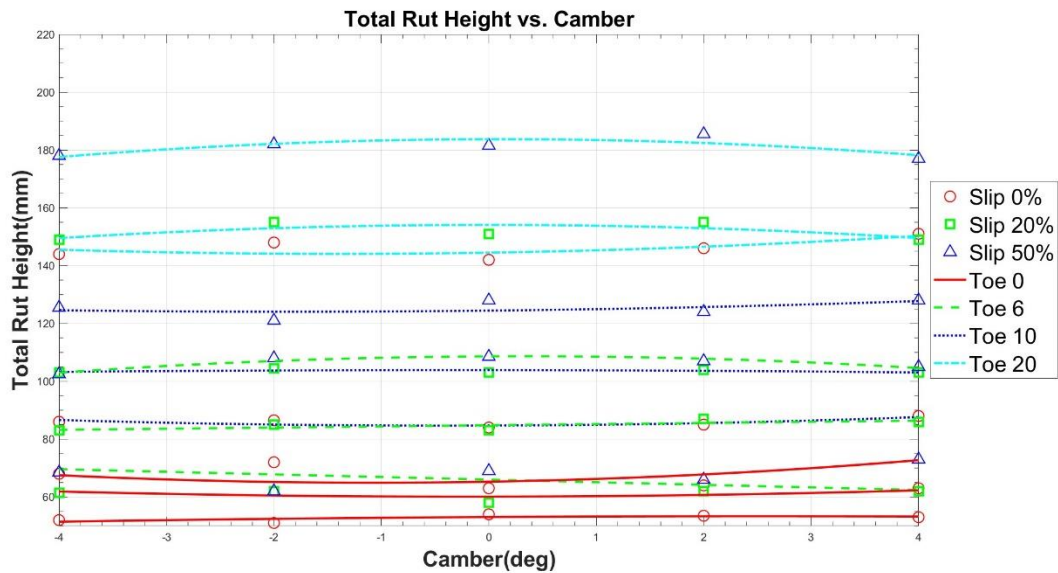


Figure 6.37. Variation of total rut height with camber under constant slip ratio and slip angle.

Figure 6.37 shows the variation of total rut height with camber. It can be seen that there is no major influence of camber on the total rut height.

Chapter 7: Soil Instrumentation testing and results

This chapter contains details about the instrumentation of soil with sensors and the results of the tests performed.

As the tire passes over the soil, it exerts forces on the soil. As soil is a type of deformable terrain, these forces compact the soil and generate normal stresses not only at the surface, but also upto a certain depth. Developing an understanding of these stresses helps better understand the mechanism of tire-soil traction. Pressure pads are available in the market that can be inserted into the soil to measure the contact patch distribution. However, the act of inserting a pad inside the soil affects the reactions on the tire and will affect the measurements. This method attempts to resolve this problem by creating a grid of sensors on a flexible material like cardboard that will have minimum interactions with the soil and still collect data regarding forces acting at a depth in the soil.

7.1 Measurement System and Calibration

In order to measure the normal forces inside the soil, Tekscan FlexiForce A401 sensors were used. These are very thin sensors with a sensing area of 1 inch and a thickness of 0.203 mm. A grid of 15 sensors were made using these sensors which could measure the normal force at 15 different points in the same horizontal level. To filter the data from these sensors and process them, the DI-2108-P was used as the DAQ system. MSP-430 boards were used to provide a constant 5V supply to these sensors. Figure 7.1 shows the equipment used.



Figure 7.1 Sensors and DAQ systems used.

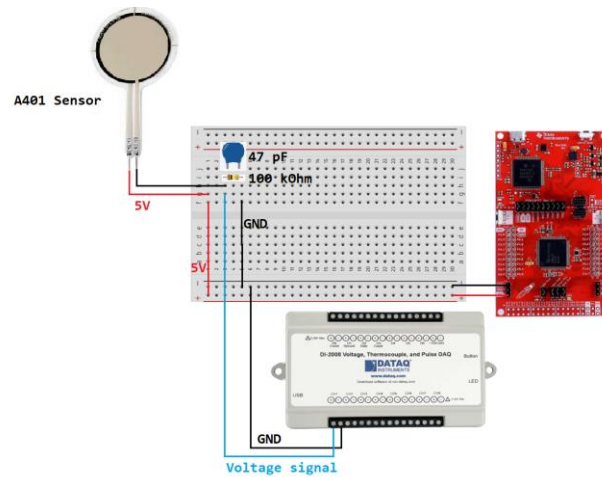


Figure 7.2 Circuit made for A401 sensors.

Figure 7.2 shows the circuit that was made in order to measure the data from the sensor. A 47pF capacitor and 100 kΩ resistor was used for the filter. The DAQ was connected to the laptop through USB and data was processed in the WinDAQ program which was provided with the DAQ system. Each sensor was calibrated by applying known loads through calibrated weights on a flat table. Each sensor was individually calibrated, and a unique calibration factor was found for each sensor, which was used to convert the sensor readings to force values. Figure 7.3 shows the calibration setup and the calibration graph for sensor 1. Figure 7.4 shows the setup for calibrating all the sensors.

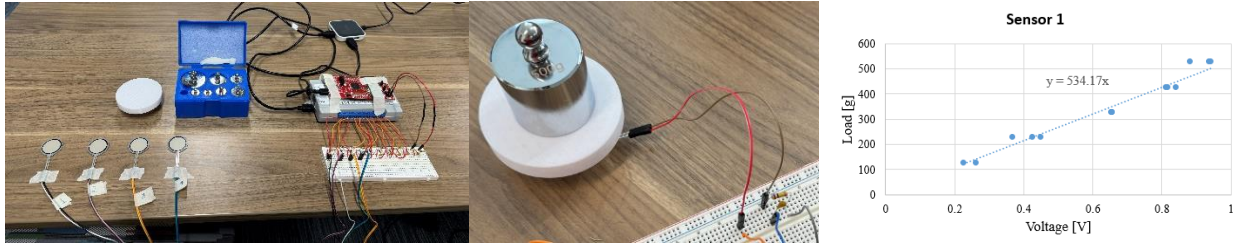


Figure 7.3 Calibration setup and curve for sensor 1.

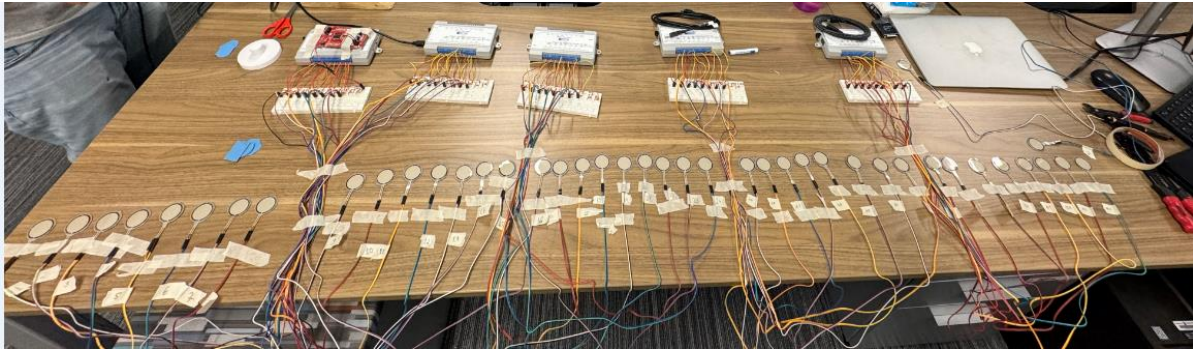


Figure 7.4 Calibration of individual sensors.

7.2 Testing

The entire DAQ system with breadboards and MSPs were organized and taped onto a cardboard to transport it to the rig. This setup was kept on the other side of the partition where there was no soil, while the sensor grid was inserted into the soil. Figure 7.5 shows the DAQ setup and Figure 7.6 shows the sensor grid assembly.

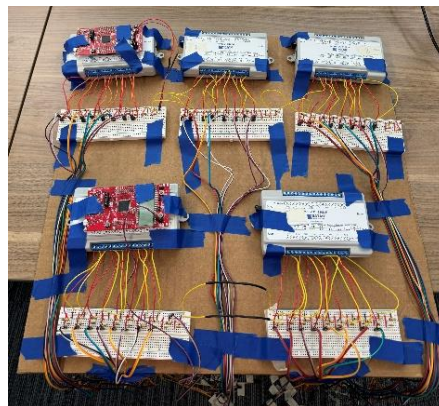


Figure 7.5 DAQ setup.

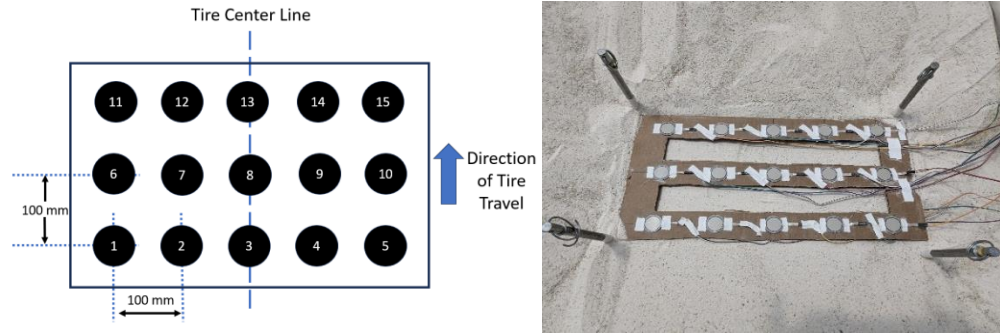


Figure 7.6 (a) Schematic of Sensor grid setup, (b) Sensor grid in soil with locating pins.

The soil was manually shoveled to remove any stress history from previous tests. Then, the soil was removed to achieve a depth of 2 in. The depth of the soil was controlled with the help of some pins with markings which were inserted into the soil. The leveling had to be done manually without the leveler, as only 2in of soil was available and the leveler was made for 8in of soil. After the leveling was done, the sensor grid was placed on top of the leveled surface. The sensor grid was placed at the same section of the test rig with the help of markings on the rig to achieve consistency in the readings. Once the sensor was placed, the pins were removed and soil and carefully shoveled on top of the grid to achieve 8 in of soil. After this, the leveler was used to achieve a smooth surface. The test rig was then setup as per section 4.4 and tests were conducted.

As it can be seen from the schematic of sensor grid, the sensors are arranged in 5 layers laterally and 3 layers longitudinally. The tire will first pass over sensors 1-5, then over 6-10 and finally over 11-15 run each run. Also, the grid was arranged in a way that the center of the tire runs over sensors 3, 8 and 13.

7.3 Preliminary Results and inferences

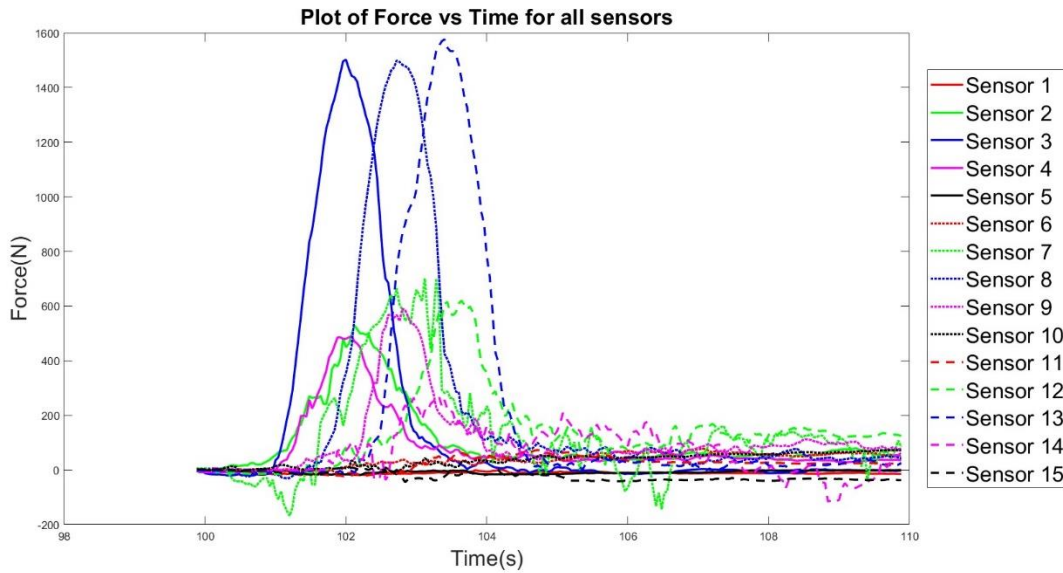


Figure 7.7 Plot of all sensors for slip ratio 20%

Figure 7.7 shows the output for all the 15 sensors when a slip ratio of 20% was applied. Maximum values of force occur in sensors 3, 8 and 13 which are directly below the tire. Also, sensors 2, 7 and 12 on the immediate left of the tire center line and sensors 4, 6 and 14 which are on the immediate right of the tire center also show some force values, but they are lower than the sensors that are directly below the tire. All the sensors that are on the periphery record very low force values. The shifted peaks of the sensors 3, 8 and 13 occur as tire moves over the sensor in this order.

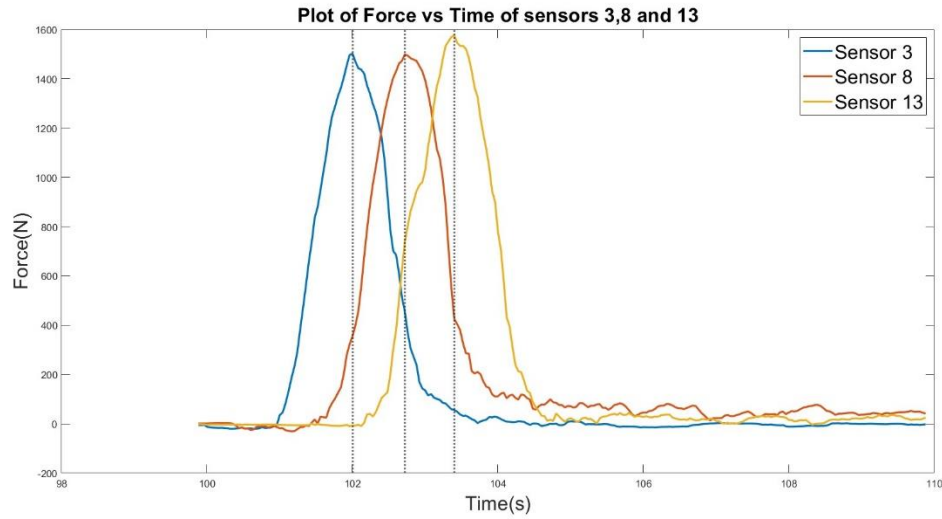


Figure 7.8 Plot of sensors 3,8 and 13 for speed estimation.

Figure 7.8 shows plots of sensors 3, 8 and 13. It can be assumed that each sensor measures maximum force when it is directly under the point of the tire where the contact pressure is maximum. By measuring the time stamp at which the maximum values occur, it is possible to calculate the time taken for the tire to move from sensor 3 to sensor 8. As we know the distance between the two sensors, the linear speed of the wheel can be calculated. The average speed in this case was found to be 0.56 kmph, which is close approximate to the speed which was set in the run (0.5 kmph), thus validating the data provided by the sensor.

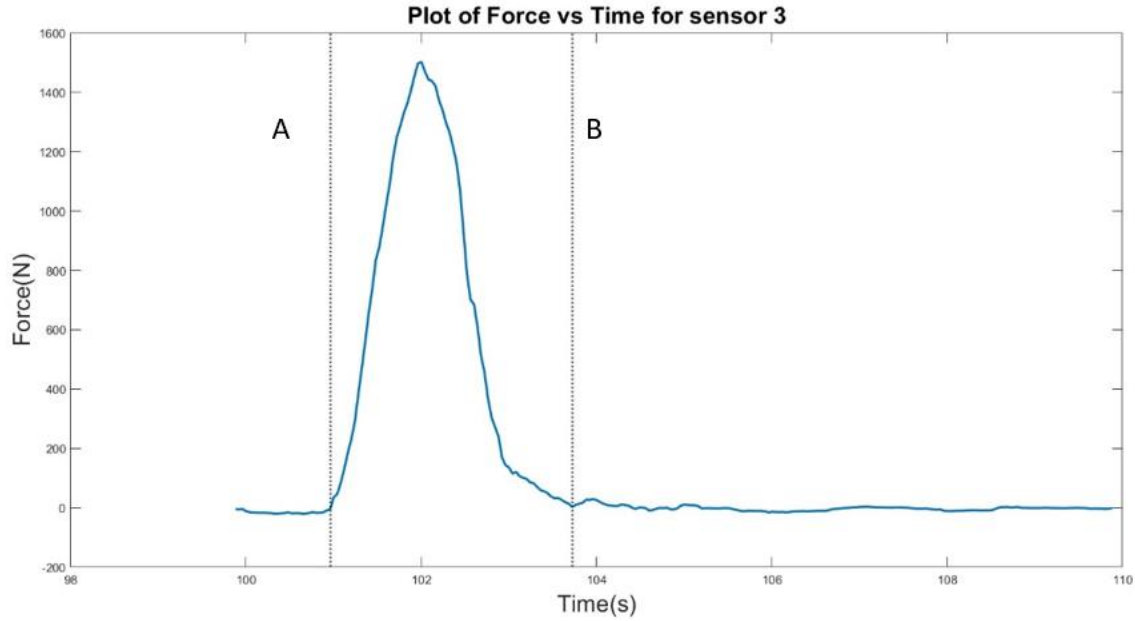


Figure 7.9 Plot of Force of Time for sensor 3.

Figure 7.9 shows the variation of force with time for sensor 3. At point A, the sensor starts measuring an increase in force and the sensor force becomes constant at point B. It can be said that the sensor feels the effect of the tire between points A and B. By multiplying this time difference with the linear speed of the wheel, the length of the pressure bulb which is affected by the tire can be estimated at this depth, which can be seen in Figure 7.10. It was found to be 0.394 m in this case.

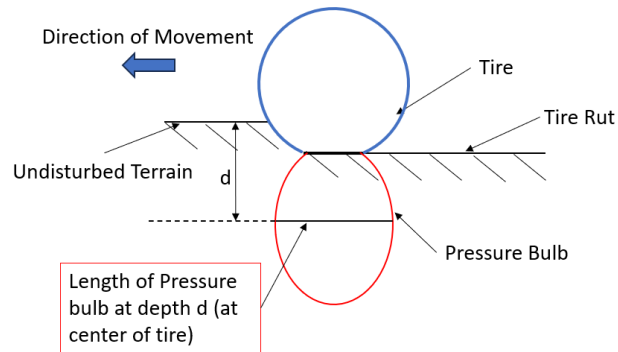


Figure 7.10. Length of pressure bulb under tire

By conducting this test by placing the grid at different soil depths, the length of the pressure bulb can be plotted with depth of soil, which in turn can be used to construct the profile of the pressure bulb in the depth direction. Also, by placing the grid just under the tire, the dynamic tire contact patch can also be measured.

Chapter 8: Inferences and Hypothesis

8.1 Hypothesis to explain correlation of drawbar pull and slip angle.

It was observed that the maximum drawbar pull occurs in the presence of a slip angle. A hypothesis is presented here to explain the reason for this increase.

It can be said that the rigidity of the terrain influences the traction forces generated in the tire, as a rigid terrain does not deform due to the forces exerted on it by the tire, it is capable of generating a greater traction force on the tire. When the terrain is loose and uncompacted, the traction force generated is low. However, as the tire interacts with the terrain and sinks into it, soil accumulates in the heading direction. It could be possible that the tire creates a localized compaction of the soil in the direction of heading. Due to this compaction, the ability of the terrain to resist deformation increases and can generate a greater traction force. The higher values of braking forces at zero slip angle could also partially be due to this phenomenon. As the slip angle is increased, the projected area of the tire increases in a direction perpendicular to the heading direction. Due to this, a greater amount of soil in front of the tire is compacted. As a result, the terrain can generate a greater force when a slip angle is induced. This theory can be tested by measuring the compaction of the terrain in front of the tire after the tire has stopped, and by instrumenting soil with stress sensors to see if there is an increase in the compaction of soil as the tire traverses the terrain.

It is to be noted that this effect is visible only due to the low compaction of the terrain under which these tests were performed. This low compaction allowed for further scope of compaction of the terrain due to the tire-terrain interaction. This effect will probably not be visible if the terrain is highly compacted, as there is no major scope for further compaction. However, if the terrain is compacted, higher forces will be generated at lower slip angles and slip ratios.

8.2 Inferences from 3D scans

The shape of the rut left behind by a tire depends on the slip angle and slip ratio. Certain parameters in the rut footprint serve as good indicators to the test conditions. In general, it can be said that distances measured in the footprint give more consistent results as compared to measurement of displaced and penetration volumes.

It was observed that the wavelength acts as a consistent parameter to the slip ratio and traction coefficient. This can be used to predict the slip ratio of the tire, especially when there is no slip angle.

Similarly, differential peak height and total rut height act as consistent parameters to describe slip angle.

Chapter 9: Conclusions and Future Work

9.1 Conclusions

The aim of the study was to perform experimental tests with an off-road tire on a non-cohesive terrain in low compaction to investigate the performance of the tire under pure slip and combined slip conditions and evaluate the use of 3D scanner to correlate the tire rut with its performance. Tests were performed under different conditions and the force, moment and 3D scan data were processed and analyzed to draw conclusions as to which parameter correlates to the input conditions and tire performance.

As expected, the drawbar pull increases with slip ratio. However, it was observed that the longitudinal force also increases due to slip angle. It was hypothesized that this occurs due to a greater area of soil undergoing localized compaction, which results in an increase in the grip between tire and terrain, leading to greater tractive forces. It was also mentioned that this effect occurs only in loosely compacted soil, and higher forces would be generated in soils with high compaction.

Lateral force was found to increase with slip angle and was not affected by increasing slip ratio. Overturning moment was found to increase with slip angle. There was no major effect of slip ratio.

Self-aligning torque increased as expected with slip angle. The magnitude of the self-aligning torque was also affected by the slip ratio and camber angles.

It can be seen that there is no major effect of camber with -4 to $+4$ degrees. It only slightly contributes to the lateral force and affects the self-aligning torque. This low influence of camber

can be attributed to the reduced camber thrust on tire due to the low compaction and non-cohesive nature of the terrain.

This study demonstrated the use of a 3D scanner to capture the tire footprint. It was found that wavelength functions as a significant parameter to accurately predict the slip ratio of the tire and the differential peak height and total rut height serve as a very good indicator of the slip angle, for this combination of tire, terrain under the conditions of compaction and inflation pressures mentioned in this study.

In this study, novel contributions were made in the field of tire performance analysis through the utilization of a 3D scanner to capture the tire footprint. The research revealed that wavelength emerges as a crucial parameter for precisely predicting the slip ratio of the tire. Furthermore, the investigation identified the differential peak height and total rut height as highly effective indicators of the slip angle. These results highlight the utility of 3D scanning as a valuable resource for the analysis of tire performance.

Efforts were undertaken to instrument the soil with a grid of sensors designed to measure the normal force exerted on the soil at a depth beneath the tire. Data collected from this system was utilized to ascertain the wheel's linear velocity and to estimate the length of the pressure bulb at a known depth beneath the tire.

The incorporation of 3D scanning technology and instrumentation of soil represent notable advancements in tire performance analysis, contributing to the broader landscape of automotive engineering and safety.

9.2 Future Work

Tests can be done with a higher terrain depth to conduct studies at 2000N and 4000N to check the effects of the rigid boundary. Similarly, the partition can be made a little bigger or entirely removed to analyze any boundary effects due to the presence of partition.

Tests can be done in terrains of high compaction to check if there will be an increase in drawbar pull due to slip angle.

System can be built for measuring real time tire deflection, and this information can be correlated with the maximum rut depth to measure the depth and volume of soil deposited in the rut center in each run. A spline curve can be fitted to the tire rut to compare the change in profile with different slip ratios, slip and camber. Post-processing of the 3D scan data can be automated using image processing techniques rather than doing it manually.

Combined slip conditions can be done in braking conditions and negative slip angles too and it can be checked if similar trends are observed in forces and moments.

Additional parameters like inflation pressure, normal load and linear velocities of the wheel can be added to the design of experiment and the effect of these parameters on the force and 3D scan parameters like wavelength can be studied to check consistency in obtained trends.

The hypothesis of local compaction of soil can be checked with the help of a cone penetrometer. Tests can be done at zero slip angle and non-zero slip angles, and the compaction can be measured at the stop point of the tire. Comparing these will let us know if there was additional compaction due to the interaction of the tire with the terrain.

The grid used for soil instrumentation can be expanded to bigger sizes and the height of the grid from the rig bottom can be varied to get more data about the variation of forces and length and width of the pressure bulb along the depth of the soil. The grid itself can be modified to be made from an elastic material like a string which will also give information about the displacement of the sensors. The resolution of the grid can be improved by reducing the spacing between the sensors and different orientations can be incorporated to measure the forces in the longitudinal and lateral directions.

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Appendix

This section contains the Safety Data Sheet for OPRUGRC-1.

OFF PLANET RESEARCH. LLC

SAFETY DATA SHEET (SDS) FOR LUNAR REGOLITH SIMULANT



Silica Sand
Safety Data Sheet
Date of Issue: 10/22/2018

Version: 3.0

1

SECTION 1: IDENTIFICATION

Product Identifier and Trade Names

OPRUGRC1 Custom Simulant Based On GRC-1

Intended Use and Restrictions On Use

For use in simulating some of the mechanical properties of lunar soils found on the surface of the Moon for the purpose of research, development, and testing.

Manufacturer/Supplier Information

Off Planet Research, LLC

1130 W Marine View Dr., Suite A-2, Everett, WA 98201

Emergency Phone: (253) 391-0293 8 AM to 5 PM Pacific Time Monday through Friday

SECTION 2: HAZARDS IDENTIFICATION

GHS-US/Canadian Classifications

Skin Irritant (Category 2)

Eye Irritant (Category 2A)

Lung Carcinogen (Category 1A)

Specific Target Organ Toxicity (STOT), Single Exposure – transitory respiratory tract irritation (Category 3)

STOT, Repeated Exposure – lungs (silicosis and other lung conditions), kidneys, immune system (Category 1)

Label Elements

Hazard Pictograms (GHS-US/CA)



Signal Word (GHS-US/CA)

DANGER

Hazard Statements (GHS-US/CA)

Exposure to respirable crystalline silica may cause:

- Lung cancer if inhaled.
- Damage to the lungs (silicosis, other possible effects) or other organs (kidneys, immune system) through prolonged or repeated inhalation exposure.

Exposure to sand, if not handled in a way that releases airborne respirable dust, may cause:

- Mechanical irritation if it gets in the eyes or on the skin.
- Respiratory irritation if inhaled.

Precautionary Statements (GHS-US/CA)

Take precautions to prevent release of and exposure to fine dust/respirable crystalline silica.

Do not handle until all safety precautions have been read and understood.

Do not breathe dust. Use only outdoors or in a well-ventilated area. Use an appropriate respirator if overexposure to respirable crystalline silica may occur. Provide additional ventilation if method of use or handling may break the product down into smaller particle sizes or generate fine airborne dust. **DO NOT use this product for sand blasting!**

Avoid getting in eyes, on skin, or on clothing. Use personal protective equipment (PPE) as required.

If skin irritation occurs, rinse the affected area with water. If in eyes, rinse well with water for at least 15 minutes. Remove contact lenses, if present and easy to do. Continue rinsing. If irritation persists, get medical advice/attention.

Store in a locked, well-ventilated place. Dispose of contents/container in accordance with local, regional, national, and international regulations.

Other Hazards

Exposure may aggravate pre-existing eye, skin, or respiratory conditions. It may increase susceptibility to tuberculosis (TB), if exposed to TB. Note that OSHA (Occupational Safety and Health Administration) has issued two new standards for respirable crystalline silica (RCS): 29 CFR 1910.1053 for General Industry/Maritime and 29 CFR 1910.1153 for Construction. This standard establishes additional requirements for employers, including specific exposure assessment and control considerations, training and information, medical surveillance, and recordkeeping. It also requires a written Exposure Control Plan. For more information, employers are referred to "OSHA Safety and Health Topics / Silica, Crystalline" on the OSHA website (www.osha.gov).

SECTION 3: COMPOSITION/INFORMATION ON INGREDIENTS

Name	CAS Registry Number	Percentage by Weight
Crystalline Silica (as Quartz)	14808-60-7	99-99.9
Aluminum Oxide	7429-90-5	0.33 (approximate)
Iron Oxide	1309-37-1	0.06 (approximate)

SECTION 4: FIRST AID MEASURES

First Aid Measures

General: Never give anything by mouth to an unconscious person. If you feel unwell, seek medical advice (show this Safety Data Sheet or the label where possible).

Inhalation: When symptoms occur, go into open air and ventilate suspected area. Obtain medical attention if breathing difficulty persists.

Skin Contact: Remove contaminated clothing. Drench affected area with water for at least 15 minutes. Obtain medical attention if irritation develops or persists.

Eye Contact: Rinse cautiously with water for at least 15 minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Obtain medical attention.

Ingestion: Rinse mouth. DO NOT induce vomiting. Obtain medical attention.

Most Important Symptoms and Effects both Acute and Delayed

Acute Symptoms and Effects: Dust may cause mechanical irritation to eyes, skin, and respiratory tract. May be irritating to gastrointestinal tract if swallowed.

Inhalation: Irritation of the respiratory tract and the other mucous membranes. This product contains crystalline silica. Prolonged or repeated inhalation of respirable crystalline silica from this product can cause silicosis, a progressive, disabling and often fatal lung disease.

Skin Contact: Prolonged exposure may cause skin irritation. Prolonged contact with large amounts of dust may cause mechanical irritation.

Eye Contact: May cause slight irritation to eyes.

Ingestion: Ingestion may cause adverse effects.

Chronic Symptoms: This product contains crystalline silica and may cause lung cancer. Repeated or prolonged exposure to airborne respirable crystalline silica dust (by inhalation) may cause silicosis, a disabling, non-reversible and often fatal lung disease. Symptoms of silicosis include progressively more difficult breathing, cough, fever, and weight loss. Progressive massive fibrosis may be accompanied by right heart enlargement, heart failure, and pulmonary failure. Exposure may also aggravate pre-existing lung diseases such as emphysema or asthma. May cause chronic bronchitis and damage to the kidneys and immune system. May increase susceptibility to pulmonary tuberculosis. Smoking aggravates the effects of exposure to respirable crystalline silica.

Indication of Any Immediate Medical Attention and Special Treatment Needed

This product is not expected to pose an immediate medical hazard, except through irritation of skin, eyes, or respiratory system. If exposed or concerned, take the first aid steps listed in this section. Get medical advice and attention if irritation persists. If medical advice is needed, have product container, label, or Safety Data Sheet at hand. For the symptoms of chronic exposure – see above – obtain medical advice and attention. See also Section 11, Toxicological Information.

SECTION 5: FIREFIGHTING MEASURES

Extinguishing Media

Suitable Extinguishing Media: Water spray, dry chemical, foam, carbon dioxide.

Unsuitable Extinguishing Media: Do not use a heavy water stream. Use of heavy stream of water may spread fire.

Special Hazards

Fire Hazard: Not flammable.

Explosion Hazard: Product is not explosive and is not known to be an explosive dust.

Reactivity: Hazardous reactions are not expected to occur under normal firefighting conditions.

Advice for Firefighters

Firefighting Instructions: Use water spray or fog for cooling exposed containers. Avoid raising dust.

Hazardous Combustion Products: None known.

SECTION 6: ACCIDENTAL RELEASE MEASURES

Personal Precautions, Protective Equipment, and Emergency Procedures

Use appropriate personal protective equipment (PPE) to prevent contact with and inhalation of dust. Refer to Section 8 for more information on choosing PPE.

Environmental Precautions

Prevent entry into sewers and public waters.

Methods and Materials for Containment and Cleaning Up

Clean up spills immediately and avoid creating dust. Vacuum spilled material using a HEPA-filtered vacuum or wet the material using a dust suppressant prior to sweeping or shoveling. Do not use dry sweeping or compressed air. Transfer spilled material to a suitable container for disposal. Dispose of spilled material appropriately. Refer to Section 13 for disposal considerations.

SECTION 7: HANDLING AND STORAGE

Precautions for Safe Handling

Additional Hazards When Processed: If processing results in the generation of airborne dusts, exposure to respirable crystalline silica dust may result. Refer to Section 4 for information on the hazards of exposure to respirable crystalline silica dust.

Precautions for Safe Handling: Specific end uses of this product include glass sand; traction sand; filtration sand; foundry sand; golf course and recreation sand; roofing sand; industrial filler sand; and equestrian sand. **This product is NOT to be used for sand blasting.** Do not handle until all safety precautions have been read and understood. If airborne dust may be generated during use and handling, conduct industrial hygiene air sampling for respirable crystalline silica. If the appropriate permissible exposure limit (PEL) is exceeded, appropriate engineering controls and/or personal protective equipment (PPE) should be worn to prevent overexposure through inhalation, contact with the eyes or skin, and contamination of clothing. Refer to Section 8 for more information on exposure controls, such as PELs, engineering controls, and PPE.

Hygiene Measures: Handle in accordance with good industrial hygiene and safety procedures, as appropriate to the task being performed and the results of industrial hygiene air monitoring.

Conditions for Safe Storage, Including Any Incompatibilities

Storage Conditions: Comply with applicable regulations. Avoid creating or spreading dust. Keep container closed when not in use. Store in a well-ventilated place. Do not store near eating facilities or locker rooms. Ensure that personnel are protected from any potential engulfment hazard due to unstable or shifting material.

Incompatible Materials: Strong oxidizers. Fluorine. Fluorinated compounds. Acetylene. Ammonia. Hydrogen peroxide. Hydrofluoric acid.

SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

Exposure Limits

Ingredient	Source of Exposure Limit	Exposure Limit
Respirable Crystalline Silica (14808-60-7) as Quartz	OSHA Permissible Exposure Level (PEL)	50 µg/m ³
	OSHA Action Level (AL)	25 µg/m ³
Aluminum Oxide (7429-90-5)	OSHA PEL (total dust)	15 mg/m ³
	OSHA PEL (respirable fraction)	5 mg/m ³
Iron Oxide (1309-37-1)	OSHA PEL (as a fume)	10 mg/m ³
	OSHA PEL (as a particulate not otherwise regulated, PNOR, total dust)	15 mg/m ³
	OSHA PEL (as a particulate not otherwise regulated, PNOR, respirable fraction)	5 mg/m ³

Note that NIOSH 7500 has recommended an exposure limit for quartz as defined by OSHA of 10 mg/m³ or ACGIH of 0.1 mg/m³. OSHA PELs and Action Levels can be found in 29 CFR 1910.1053, 29 CFR 1926.1153, and 29CFR 1910.1000. Check for current information before using this product.

Exposure Controls

Appropriate Engineering Controls: Refer to the applicable OSHA standard (29 CFR 1910.1053 for General Industry and 29 CFR 1926.1153 for Construction), or to the appropriate state or provincial standard, for required engineering controls during the handling of this product. In addition, emergency eye wash fountains and safety showers should be available in the immediate vicinity of any potential exposure. Power equipment should be equipped with properly designed dust collection devices. Maintain sufficient mechanical or natural ventilation to ensure that respirable crystalline silica concentrations remain below the PEL. Use local exhaust if necessary. Adequate ventilation is especially important in confined areas. Ensure all national, state, provincial, and local regulations are observed.

Personal Protective Equipment: Gloves. Protective clothing. Protective goggles or safety glasses. In the case of insufficient ventilation and potential for overexposure to respirable crystalline silica, also wear respiratory protection.



Materials for Protective Clothing: Materials and fabrics impervious to dusts.

Hand Protection: Protective gloves impervious to dusts and otherwise appropriate to the job.

Eye Protection: Chemical goggles or safety glasses.

Respiratory Protection: If exposure limits are exceeded or respiratory irritation is experienced, approved respiratory protection should be worn. The specific respirator worn should be based on the results of airborne industrial hygiene monitoring for respirable crystalline silica, the requirements of the OSHA standards for respirable crystalline silica (29 CFR 1910.1053 for General Industry, 29 CFR 1926.1153 for Construction), and the OSHA Respiratory Protection Standard (29 CFR 1910.134).

Other Information: When using, do not eat, drink, or smoke. Wash unprotected skin before handling food, drinks, make-up, or before smoking. Wash unprotected work clothes after each use.

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

Information on Basic Physical and Chemical Properties

Physical State	Solid
Appearance	Granular white solid
Odor	Odorless
Odor Threshold	Not applicable
pH	Not applicable
Evaporation Rate	Not applicable
Melting Point	Not applicable
Freezing Point	Not applicable
Boiling Point	≈ 4000 °F (≈ 2204 °C)
Flash Point	Not applicable
Auto-ignition Temperature	Not applicable
Decomposition Temperature	Not applicable
Flammability (solid, gas)	Not applicable
Lower Flammable Limit	Not applicable
Upper Flammable Limit	Not applicable
Vapor Pressure	Not applicable
Relative Vapor Density at 20°C	Not applicable
Relative Density	Not applicable
Specific Gravity	2.65
Solubility	Not applicable
Partition Coefficient: N-Octanol/Water	Not applicable
Viscosity	Not applicable

SECTION 10: STABILITY AND REACTIVITY

Reactivity: Hazardous reactions will not occur under normal conditions.

Chemical Stability: Stable under recommended handling and storage conditions (see Section 7).

Possibility of Hazardous Reactions: Hazardous polymerization will not occur.

Incompatible Materials: Strong oxidizers including fluorine, fluorides, acetylene, ammonia, hydrogen peroxide, and hydrofluoric acid.

Hazardous Decomposition Products: Silica compounds. Crystalline silica (quartz) will dissolve in hydrofluoric acid producing a corrosive gas, silicon tetrafluoride. Crystalline silica exists in several forms, the most common of which is quartz. If crystalline silica (quartz) is heated to more than 870°C, it can change to a form of crystalline silica known as tridymite, and if crystalline silica (quartz) is heated to more than 1470°C, it can change to a form of crystalline silica known as cristobalite. The OSHA PEL for tridymite and cristobalite is the same as for crystalline silica as quartz.

SECTION 11: TOXICOLOGICAL INFORMATION

Information on Toxicological Effects - Product

Acute Toxicity (Oral):

Crystalline Silica LD50 Oral Rat: > 5000 mg/kg

Aluminum Oxide LD50 Oral Rat: > 15900 mg/kg

Acute Toxicity (Dermal):

Acute Toxicity (Inhalation):

Crystalline Silica LC50 Inhalation Rat: > 248 mg/m³/6h

Aluminum Oxide LC50 Inhalation Rat: > 2.3 mg/l/4h

Iron Oxide LC50 Inhalation Rat: 50 mg/m³/12h

IDLH Data: 50 mg/m³ for crystalline silica as quartz, 25 mg/m³ for crystalline silica as tridymite or cristobalite

Skin Corrosion/Irritation: May cause temporary irritation through mechanical abrasion

Eye Damage/Irritation: May cause temporary irritation through mechanical abrasion

Respiratory or Skin Sensitization: Not classified

Germ Cell Mutagenicity: Not classified

Carcinogenicity:

International Agency for Research on Cancer (IARC): Group 1, carcinogenic to humans

National Toxicology Program (NTP): Known human carcinogen

OSHA: Identified as a human carcinogen (lungs)

Specific Target Organ Toxicity (Repeated Exposure): Causes damage to organs (lungs, kidneys, immune system) through prolonged or repeated exposure

Reproductive Toxicity: Not classified

Specific Target Organ Toxicity (Repeated Exposure): May cause respiratory irritation

Aspiration Hazard: Not classified

Symptoms/Injuries after Inhalation: Irritation of the respiratory tract and the other mucous membranes. This product contains crystalline silica. Prolonged or repeated inhalation of respirable crystalline silica from this product can cause silicosis, a serious progressive, disabling, and often fatal lung disease.

Symptoms/Injuries after Skin Contact: Prolonged exposure may cause skin irritation. Prolonged contact with large amounts of dust may cause mechanical irritation.

Symptoms/Injuries after Eye Contact: May cause temporary irritation to eyes

Symptoms/Injuries after Ingestion: Ingestion may cause adverse effects.

Chronic Symptoms: May cause lung cancer. Causes damage to organs (lungs) through prolonged or repeated exposure (inhalation). Repeated or prolonged exposure to respirable (airborne) crystalline silica dust will cause lung damage in the form of silicosis. Symptoms will include progressively more difficult breathing, cough, fever, and weight loss. Pre-existing lung diseases such as emphysema or asthma may be aggravated by exposure to dusts. Pulmonary function may be reduced by inhalation of respirable crystalline silica. Lung scarring produced by such inhalation may lead to a progressive massive fibrosis of the lung, which may aggravate other pulmonary conditions and diseases and which increases susceptibility to pulmonary tuberculosis. Progressive massive fibrosis may be accompanied by right heart enlargement, heart failure, and pulmonary failure. Smoking aggravates the effects of exposure.

SECTION 12: ECOLOGICAL INFORMATION

Ecotoxicity: Not applicable

Persistence and Degradability: Not applicable

Bioaccumulative Potential: Not applicable

Mobility in Soil: Not applicable

Other Adverse Effects: None expected

SECTION 13: DISPOSAL CONSIDERATIONS

Waste Disposal Recommendations: Dispose of contents/container in accordance with local, regional, national, territorial, provincial, and international regulations. Do not contaminate waterways or bodies of water with fine particulate.

Additional Information: Container may remain hazardous when empty. Continue to observe all precautions.

Ecology - Waste Materials: Avoid release to the environment.

SECTION 14: TRANSPORT INFORMATION

In Accordance with DOT: Not regulated for transport

In Accordance with IMDG: Not regulated for transport

In Accordance with IATA: Not regulated for transport

In Accordance with TDG: Not regulated for transport

SECTION 15: REGULATORY INFORMATION

US Federal Regulations

Silica Sand	
SARA Section 311/312 Hazard Classes	Immediate (acute) health hazard Delayed (chronic) health hazard
Quartz (14808-60-7)	
Listed on the United States TSCA (Toxic Substances Control Act) inventory	
Regulated, as respirable crystalline silica (RCS), by OSHA. 29 CFR 1910.1053 for General Industry/Maritime and 29 CFR 1926.1153 for Construction. Refer also to appropriate standards administered by OSHA-approved state programs. To determine if your state has an	

OSHA-approved state plan, go to "Home / State Plans" on the OSHA website (www.osha.gov).
Aluminum Oxide (7429-90-5)
Listed on the United States TSCA (Toxic Substances Control Act) inventory Subject to reporting requirements of United States SARA Section 313
Iron Oxide (1309-37-1)
Listed on the United States TSCA (Toxic Substances Control Act) inventory

US State Regulations

Crystalline Silica, Airborne Particles of Respirable Size (14808-60-7)	
US - California - Proposition 65 - Carcinogens List	WARNING: This product contains chemicals known to the State of California to cause cancer.
Quartz (14808-60-7)	
US - Massachusetts - Right To Know List US - New Jersey - Right to Know Hazardous Substance List US - Pennsylvania - RTK (Right to Know) List	
Aluminum Oxide (7429-90-5)	
US - Massachusetts - Right To Know List US - New Jersey - Right to Know Hazardous Substance List US - Pennsylvania - RTK (Right to Know) - Environmental Hazard List US - Pennsylvania - RTK (Right to Know) List	
Iron Oxide (1309-37-1)	
US - Pennsylvania - RTK (Right to Know) List	

Canadian Regulations

Quartz (14808-60-7)
Listed on the Canadian DSL (Domestic Substances List)
Aluminum Oxide (7429-90-5)
Listed on the Canadian DSL (Domestic Substances List)
Iron Oxide (1309-37-1)
Listed on the Canadian DSL (Domestic Substances List)

SECTION 16: OTHER INFORMATION, INCLUDING DATE OF PREPARATION OR LAST REVISION

Other Information

This document has been prepared in accordance with the SDS requirements of the OSHA Hazard Communication Standard 29 CFR 1910.1200 and Canada's Hazardous Products Regulations (HPR).

Revision 1

Revision Date 4/13/2022

NOTE: This information is based on our current knowledge and is intended to describe the product for the purposes of health, safety, and environmental requirements only and does not guarantee any specific property of the product. The information pertains only to the original product and does not address any additional contaminants that may arise from use or storage.

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